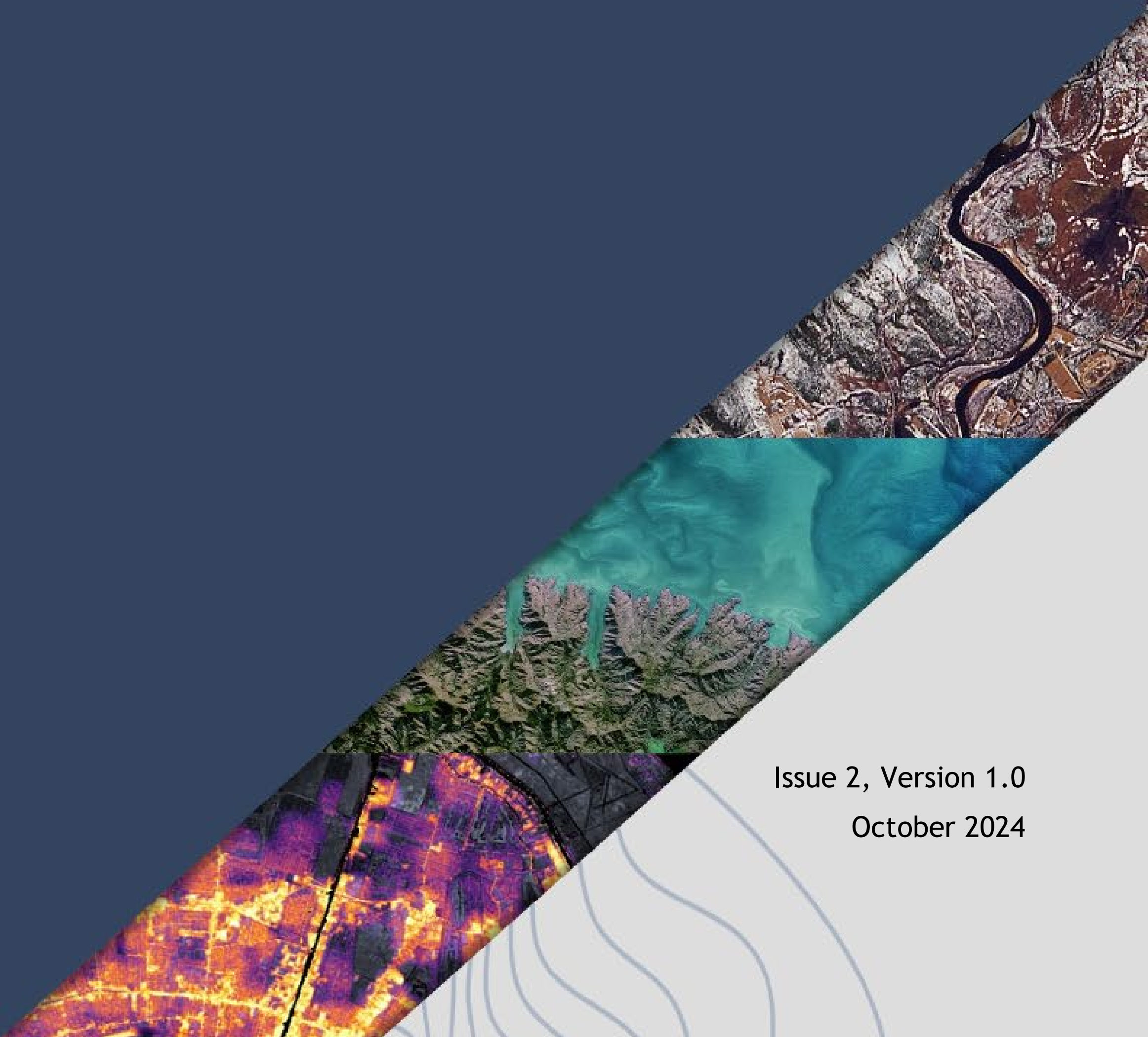
ROADMAP FOR A COORDINATED IMPLEMENTATION OF CARBON DIOXIDE AND METHANE MONITORING FROM SPACE



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Joint CEOS-CGMS Working Group on Climate

Greenhouse Gas Task Team

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Executive Summary

The Committee on Earth Observation Satellites (CEOS) and the Coordination Group on Meteorological Satellites (CGMS) recognize that high-quality, systematic observations of atmospheric carbon dioxide (CO_2) and methane (CH_4) from a constellation of space-based sensors could make critical contributions to an integrated global greenhouse gas (GHG) observing system. They therefore directed the joint CEOS-CGMS Working Group on Climate (WGClimate) to formulate a roadmap to implement a constellation architecture for monitoring CO_2 and CH_4 from space. The primary objective of this GHG Roadmap is to coordinate efforts across CEOS and CGMS agencies to maximise the quality, utility, transparency and continuity of space-based GHG products for science and policy applications. Its ultimate goal is to facilitate the development of fit-for-purpose operational systems that integrate space-based GHG estimates with ground-based, airborne and shipborne observations of CO_2 and CH_4 to address the needs of a diverse range of stakeholders.

The first issue of the CEOS/CGMS GHG Roadmap[1] (hereinafter, GHG2020), focused on delivering space-based CO_2 and CH_4 products to support the Paris Agreement's Global Stocktakes (GSTs). This issue of the roadmap continues to support that goal, but has been updated to accommodate lessons learned from the first GST. Its scope has also been expanded to support the rapid evolution of the international GHG science, inventory, policy and regulatory communities. Changes include:

- An enhanced focus on engagement and co-development with stakeholders in the international science, inventory, policy, and regulatory communities;
- Ongoing efforts to engage with new partners, including the World Meteorological Organization Global Greenhouse Gas Watch (WMO G3W) and United Nations Environment Programme International Methane Emissions Observatory (UNEP IMEO);
- An updated summary of the evolving requirements and capabilities for space-based measurements that can quantify CO_2 and CH_4 concentrations and support flux estimation;
- Updates to the space-based CO_2 and CH_4 monitoring architecture, broadening the focus from regional-scale, global mapping missions to include both public sector and non-governmental (New Space) missions that can monitor emissions at facility scales;
- A brief review of the research needed to derive CO_2 and CH_4 concentrations from space-based measurements, validate these results against internationally recognized standards, and then use them to derive budgets of CO_2 and CH_4 on spatial scales spanning individual facilities to nations;
- Efforts needed to foster the transition from research to operations (R2O) to support the development of an operational GHG Monitoring and Verification Support (GHG MVS) system that serves stakeholders in the science, inventory, policy and regulatory communities; and
- An explicit focus on capacity building to foster the use of space-based GHG products.

The updated roadmap describes specific thematic areas where CEOS and CGMS are working with stakeholders and partners to co-develop improved, fit-for-purpose space-based GHG products. It then summarises the relative roles of the joint CEOS-CGMS WGClimate GHG Task Team and other CEOS and CGMS teams in its implementation. As in GHG2020, detailed activities and action items, which are continuously evolving, are described in an Annex. With these changes, the GHG Roadmap should foster the coordination of space-based GHG products that better address the needs of an increasingly diverse stakeholder community and be more resilient to the future evolution of this rapidly evolving field.

[1] https://ceos.org/observations/documents/CEOS_CGMS_GHG_Constellation_Roadmap_V2.3_cleaned.pdf

1. Introduction and Scope

Fossil fuel combustion, land use change and other human activities have increased the atmospheric carbon dioxide (CO_2) concentration by about 50% since the beginning of the industrial age. These increases would have been much larger if natural sinks in the land biosphere and ocean had not absorbed about half of the anthropogenic CO_2 emissions. Over this same period, human activities have also contributed to a ~160% increase in atmospheric methane (CH_4) concentration. Together, these CO_2 and CH_4 increases account for about 90% of present-day global warming (IPCC AR6). Recognizing the increasing threat of climate change, in 2015, 197 nations signed the Paris Agreement, which encourages rapid reductions in the emissions of CO_2, CH_4 and other greenhouse gases (GHGs).

The Committee on Earth Observation Satellites (CEOS) and the Coordination Group on Meteorological Satellites (CGMS) recognize that high-quality, systematic observations of atmospheric CO_2 and CH_4 from a constellation of space-based sensors will be an essential component of an integrated global GHG observing system. They therefore directed the joint CEOS-CGMS Working Group on Climate (WGClimate) to formulate a roadmap to implement a constellation architecture for monitoring CO_2 and CH_4 from Space. The primary objective of this GHG Roadmap is to coordinate efforts across CEOS and CGMS agencies to maximise the quality, utility, transparency and continuity of space-based GHG products for science and policy applications. Its ultimate goal is to facilitate the development of fit-for-purpose operational systems that integrate space-based GHG estimates with ground-based, airborne and shipborne observations of CO_2 and CH_4 to address the needs of a broad range of stakeholders in the science, inventory, policy, regulatory and private sectors.

The first issue of the CEOS/CGMS GHG Roadmap (hereinafter, GHG2020), had a clear focus on delivering space-based CO_2 and CH_4 products to support the Paris Agreement's Global Stocktakes (GSTs). Following the successful delivery of pilot, space-based CO_2 and CH_4 products to support the first GST in 2023, the CEOS Strategic Implementation Team (SIT) authorised an update to the GHG Roadmap (Figure 1) to:

- Address lessons learned from CEOS efforts to support the first GST;
- Accommodate the emergence of new GHG stakeholders in the science, inventory, policy and commercial communities who can collaborate with CEOS and CGMS to co-develop fit-for-purpose, operational GHG products to their user communities;
- Recognize the emerging focus on fugitive emissions of CH_4 from intense point sources;
- Incorporate changes in space-based GHG measurement capabilities by CEOS and CGMS agencies, as well as commercial and other non-governmental "New Space" organisations; and
- Enhance the robustness of the GHG Roadmap to future developments in the rapidly-evolving arena of space-based GHG monitoring and analysis.

CEOS SIT-39 **DECISION 03**	SIT-39 agreed that an update of the CEOS GHG Roadmap should be completed for discussion at the SIT Technical Workshop in preparation for potential endorsement at 2024 CEOS Plenary. Note that the document will need to be made available in advance for CEOS Agency review.

Figure 1: Decision 03 from the 2024 CEOS SIT-39 meeting in Tokyo, Japan.

The updated GHG Roadmap continues to focus on the coordination of CEOS and CGMS efforts to deliver CO_2 and CH_4 products derived from space-based measurements in response to stakeholder needs. It also provides guidance to CEOS and CGMS agencies and their related working groups for achieving these objectives. As such, the overall goal is to design a sustained, flexible, fit-for-purpose backbone system which, in coordination with other observing and modelling capabilities (e.g., ground-based and airborne *in-situ* and remote sensing networks, flux inversion modelling community), supports the space-based GHG data and information needs of a growing list of stakeholders.

Section 2 summarises the historical context of the CEOS/CGMS GHG Roadmap development and the justification for an updated version. Section 3 introduces an updated focus on stakeholder engagement. Section 4 describes the evolving requirements and capabilities for space-based estimates of CO_2 and CH_4 concentrations and fluxes. This section also describes parallel efforts to coordinate ongoing research to improve space-based GHG products to meet rapidly evolving needs and to foster the development of an operational GHG monitoring system. Section 5 describes specific thematic areas where CEOS and CGMS are working with stakeholders and partners to co-develop improved, fit-for-purpose space-based GHG products. Section 6 summarises the relative roles of the joint CEOS-CGMS WGClimate, its GHG Task Team and other CEOS and CGMS teams in the implementation of the GHG Roadmap. Ongoing focused activities and actions are described in an Annex and are considered to be continuously evolving.

2. GHG Roadmap Context

The United Nations Framework Convention on Climate Change (UNFCCC) was established in 1994 to stabilise “greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference in the climate system.” To limit the increase in the global average temperatures to less than 2 °C above pre-industrial levels, the 21st session of the Conference of the Parties (COP21) of the UNFCCC adopted the 2015 Paris Agreement. Parties to this Agreement resolved to “reach global peaking of greenhouse gas emissions as soon as possible” and then “undertake rapid reductions thereafter.” Progress toward these and other goals of the Paris Agreement is monitored at five-year intervals as part of a Global Stocktake (GST), the first of which occurred in 2023.

To track progress toward their Nationally Determined Contributions (NDCs) and GHG emission reduction targets, each Party agreed to provide a national inventory report of anthropogenic emissions by sources and removals by sinks of GHGs, developed using best-practice methodologies accepted by the Intergovernmental Panel on Climate Change (IPCC 2006). These methods are based on “bottom-up” emission inventories, compiled from a statistical analysis of emissions reported from sources in specific sectors and categories. To ensure the effectiveness of this approach, the Agreement (Article 13) defines the implementation of an enhanced “Transparency Framework” to promote the transparency, accuracy, completeness, consistency, comparability, and environmental integrity of the stocktake.

Measurements of the atmospheric concentrations of GHGs and their changes over space and time also provide valuable information about their emissions and removals. While bottom-up inventories provide specific information about known emission sources, “top-down” methods based on atmospheric measurements provide an integrated constraint on the net amount of each gas that is exchanged between the surface and the atmosphere by natural and anthropogenic processes. Accurate, spatially- and temporally-resolved atmospheric CO_2 and CH_4 measurements can therefore provide additional information for bottom-up inventories as well as being a complementary approach for assessing collective progress towards the goals of the UNFCCC and the Paris Agreement.

At global scales, atmospheric concentrations of CO_2, CH_4 and other well-mixed GHGs are well characterised by precise, systematic, *in situ* measurements from a network of surface stations that are coordinated by WMO Global Atmosphere Watch (GAW) program. However, a dramatic expansion of the GAW GHG network would be needed to identify emission "hot spots" missed by the inventories or to assess the effectiveness of national carbon emission management strategies.

Recent advances in space-based remote sensing methods provide new opportunities to augment the spatial and temporal resolution and coverage of the ground-based GHG networks. Measurements collected by space-based sensors can be analysed to estimate the column-averaged dry air mole fractions of CO_2 and CH_4 (hereinafter XCO_2 and XCH_4, respectively), the GHGs responsible for about 90% of present-day global warming (IPCC AR6). These space-based, column-mean estimates do not provide the levels of precision and accuracy obtained from *in situ* sensors, but complement those measurements with much greater spatial resolution and coverage of the globe, including many areas that cannot easily sustain surface-based stations. A global GHG monitoring system that integrates accurate ground-based, ship-based and airborne measurements with spatially dense space-based estimates of XCO_2 and XCH_4 through the modelling framework could therefore yield atmospheric CO_2 and CH_4 budgets that complement the bottom-up statistical inventories used to track progress toward GHG emission reduction targets.

Recognizing the need for a coordinated global system to monitor the carbon cycle's response to both human activities and the changing climate, the Group on Earth Observations (GEO) commissioned the GEO Carbon Strategy (Ciais et al. 2010). This report called for an Integrated Global Carbon Observing system (IGCO) within GEO and the Global Climate Observing System (GCOS) that would incorporate advanced ground-based, airborne and space-based observations to meet the increasingly pressing needs for policy-relevant scientific information. The Committee on Earth Observation Satellites (CEOS) responded to the GEO Carbon Strategy report with the CEOS Strategy for Carbon Observations from Space (Wickland et al. 2014; hereinafter, CEOS Carbon Strategy). This report documents the state of knowledge and measurement requirements for the atmospheric, oceanic, and terrestrial carbon domains and their interfaces, and identifies several actions to be completed by its member agencies.

Given this context and the recent advances in space-based GHG measurements, CEOS recognized that high-quality observations of atmospheric CO_2 and CH_4 could be an essential component of an integrated global carbon observing system. In such systems, the space-based XCO_2 and XCH_4 estimates complement the spatial resolution and coverage of the ground-based and airborne *in situ* measurements. If the ground-based, airborne, and space-based datasets can be harmonised, they can be assimilated into atmospheric inverse systems to yield top-down global estimates of CO_2 and CH_4 fluxes with the accuracy, precision, resolution and coverage needed to serve as a complementary system for assessing collective progress toward the goals of the Paris Agreement. In addition, if these atmospheric data products were distributed freely and openly, in compliance with the CEOS open data policy, they could support the Paris Agreement's Transparency Framework.

In 2017, the CEOS chair commissioned the CEOS Atmospheric Composition Virtual Constellation (AC-VC) to develop a White Paper defining the key characteristics of a global architecture for monitoring atmospheric CO_2 and CH_4 concentrations and their natural and anthropogenic fluxes from instruments on space-based platforms to:

- reduce uncertainty of national emission inventory reporting;
- identify additional emission reduction opportunities;
- provide nations with timely and quantified guidance on progress towards their emission reduction strategies and pledges (Nationally Determined Contributions, NDCs); and

- track changes in the natural carbon cycle caused by human activities (deforestation, degradation of ecosystems, fire) and climate change.

The CEOS AC-VC Greenhouse Gas (GHG) White Paper, finalised in 2018, describes the state of the art in the space-based measurements at that time and the modelling tools needed to retrieve CO_2 and CH_4 fluxes from their data (Crisp et al., 2018). It also summarises existing and planned space-based CO_2 and CH_4 sensor types and performance, observing strategies, launch dates and operational timelines. It reviews the lessons learned from the first-generation missions and summarises the steps needed to transition from a series of scientific experiments to a sustained, space-based constellation that can operationally support an integrated global carbon observing system. To illustrate this transition, it documents the approach adopted by the European Commission Copernicus Programme to define the requirements for a future operational constellation of CO_2 Sentinels. Finally, it proposes an architecture of a future greenhouse gas constellation designed to address the objectives listed above and recommends a three-step plan to implement this architecture.

The GHG White Paper proposed a three-step plan for implementing this architecture:

1. Link the atmospheric GHG measurement and modelling communities and stakeholders in the national GHG inventory (NGHGI) and policy communities through UNFCCC/SBSTA, to refine requirements for a purpose-built top-down GHG monitoring and analysis capability;
2. Exploit the capabilities of the CEOS member agencies, Coordination Group on Meteorological Satellites (CGMS) and the World Meteorological Organization (WMO) Integrated Global Greenhouse Gas Information System (IG3IS) to integrate surface and airborne measurements of CO_2 and CH_4 with those from available and planned space-based sensors to develop a prototype, global atmospheric CO_2 and CH_4 flux product in time to support inventory builders in their development of GHG emission inventories for the 2023 GST; and
3. Use the lessons learned from this prototype product to facilitate the implementation of a complete, operational, space-based constellation architecture with the capabilities needed to quantify atmospheric CO_2 and CH_4 concentrations that can serve as a complementary system for supporting the mitigation goals of future GSTs.

The GHG White Paper was endorsed by the CEOS Agencies at the 32nd Plenary in Brussels in October 2018 (Figure 2). CGMS subsequently approved the Whitepaper during the 47th plenary in Sochi (2019). CEOS and CGMS agreed to combine their efforts to address the tasks described in the Way Forward through the Joint CEOS-CGMS WGClimate.

CEOS Plenary-32 **Decision 04**	CEOS Plenary endorsed the report *'A Constellation Architecture for Monitoring Carbon Dioxide and Methane from Space.'* It is emphasised that the three-step plan to implement the architecture contained in the paper, as well as the identified activities in the way forward, should be interpreted as recommendations to CEOS Agencies, for their consideration.

Figure 2: Decision 04 from the 2018 CEOS Plenary.

To implement the actions proposed in the GHG White Paper, the CEOS and CGMS Plenaries tasked WGClimate to form a dedicated GHG Task Team (GHG TT), to collaborate and coordinate across the CEOS Working Group on Calibration and Validation (WGCV) and the CEOS Atmospheric Composition Virtual Constellation (AC-VC), as well as other entities such as GSICS and the relevant CGMS Working Groups to develop a comprehensive roadmap for GHG activities. The first issue of the GHG Roadmap was completed in 2020 and endorsed by the CEOS Plenary-34 (Figure 3). CGMS subsequently took note of the roadmap at its 2021 Plenary.

CEOS Plenary-34 **Decision 34-07**	CEOS Plenary endorsed the *Roadmap for Implementation of a Constellation Architecture for Monitoring Carbon Dioxide and Methane from Space* (v2.4), describing an approach and resource needs for the implementation of the GHG Constellation Strategy. This is to be considered a living document and the actions in Annex C provide a current snapshot of the work plan definition which will be updated over time. CEOS Agencies will strive to provide the identified resources for the specific activities and entities.

Figure 3: CEOS Endorsement of the GHG Roadmap

The primary focus of the first issue of the roadmap was CEOS-CGMS contributions to the GST, whose primary stakeholders included the UNFCCC and the Parties to the Paris Agreement. This focus was reflected in the roadmap's primary objectives and implementation approach, which included:

1. Working with the atmospheric GHG measurement and modelling communities, stakeholders and national inventory compilers to define requirements and plans for producing and documenting CO_2 and CH_4 budgets inferred from atmospheric data;
2. Delivering pilot atmospheric CO_2 and CH_4 flux budgets in 2021 to inform the 2023 GST; and
3. Using lessons learned from these pilot inventory products to refine requirements needed to implement a purpose-built, operational, and atmospheric inventory system for future GSTs.

Interactions with stakeholders in the national inventory community were impaired prior to the first GST by the COVID-19 pandemic, which limited opportunities for in-person meetings. In spite of this, the second objective was successfully completed with the delivery of top-down, national-scale budgets of CO_2 and CH_4 to the UNFCCC in 2022. Objectives 1 and 3 continue to be primary goals of this roadmap.

To create the pilot, top-down CO_2 budgets, the GHG TT worked with members of the OCO-2 Model Intercomparison Project (MIP), which included contributions from 14 groups representing the U.S., Europe, Japan, Canada and Australia. Each group assimilated ground-based and airborne CO_2 measurements along with estimates of XCO_2 from OCO-2 to derive estimates of the net carbon exchange (NCE) between the surface and atmosphere on a 1° latitude by 1° longitude spatial grid covering the globe for 2015-2020. For these demonstration products, CO_2 fluxes from fossil fuel emissions were prescribed and subtracted from the NCE estimates to derive estimates of the Net Biospheric Exchange (NBE). These results were combined with estimates of "lateral" carbon fluxes due to crop trade, wood trade, and river export and then mapped to national boundaries to yield annual net CO_2 budgets for over 100 countries (see https://ceos.org/gst/carbon-dioxide.html).

To compile the pilot, top-down CH_4 budgets, the GHG TT worked with the CEOS AC-VC and member of the NASA Carbon Monitoring System Flux team (CMS-Flux), which used XCH_4 estimates from GOSAT to derive sector-dependent CH_4 emissions estimates at a spatial resolution of 1° latitude by 1° longitude over the globe for 2019. These data were then mapped to national boundaries to estimate CH_4 fluxes for 65 countries (see https://ceos.org/gst/methane.html).

While these pilot atmospheric CO_2 and CH_4 budgets generated substantial interest at the annual UNFCCC Climate Conferences of Parties (COPs) in 2021 and 2022, they were not widely used by the national inventory community to compile or validate the inventories submitted for the first GST. This was not due to specific shortcomings in these products, but reflected the limited use of systematic Earth observations across the board in this first GST. Many in the inventory community found it challenging to meet the minimum requirements for implementing the bottom-up inventory compilation methods specified by the Intergovernmental Panel on Climate Change Taskforce on Inventories

(IPCC TFI 2006), which are mandated by the Paris Agreement. More generally, there was too little time for the inventory community to understand these top-down GHG products or to assess their potential utility for compiling inventories or for quality assurance and quality control (QA/QC) of inventories, as suggested in the 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2019).

In spite of this outcome, these pioneering top-down, national-scale CO_2 and CH_4 budgets establish a critical baseline for use in future GSTs, and provide a transparent, complementary dataset for assessing collective progress toward the goals of the UNFCCC and the Paris Agreement. They also provide the products needed to foster capacity building efforts between the national inventory and atmospheric GHG communities.

In parallel with the first GST, there were several other developments across the international GHG science, inventory, policy and regulatory communities since the first issue of the GHG Roadmap was endorsed. These include:

- The World Meteorological Organization (WMO) gained approval for implementing the Global Greenhouse Gas Watch (G3W), which aims to provide a framework for operational GHG monitoring and thereby address the urgent need for information in support of mitigation actions taken by the Parties to the UNFCCC and the Paris Agreement. CEOS, CGMS and their member agencies are expected to play a major role in the development and delivery of data products to support this effort.
- The United Nations Environment Programme (UNEP) established the International Methane Emissions Observatory (IMEO), including its Methane Alert and Response System (MARS) to detect and notify authorities of large CH_4 leaks. Space-based CH_4 measurements play a major role in this effort.
- 155 nations committed to the Global Methane Pledge – to reduce anthropogenic methane emissions by at least 30% from 2020 levels by 2030.
- National and multinational organisations such as the U.S. Greenhouse Gas Center and the European Copernicus Atmosphere Monitoring Service (CAMS) have been established to collect and distribute GHG products developed by multiple agencies;
- International science activities, such as the Global Carbon Project (GCP) and its RECCAP2, are playing larger roles in coordinating community-wide scientific research on GHG emissions and carbon cycle science;
- Non-governmental players (New Space) have begun to play an increasing role in space-based measurements of GHGs and other climate variables.

In addition to these external developments, CEOS continued to pursue the objectives of the CEOS Carbon Strategy. CEOS agencies are preparing to expand the space-based GHG monitoring capabilities, with the upcoming launches of MicroCarb, GOSAT-GW, and the CO2M constellation (see section 5b for more details on these and other GHG missions). Members of the Land Surface Imaging Virtual Constellation (LSI-VC), Working Group on Calibration and Validation (WGCV), Global Forest Observations Initiative (GFOI) led the development of an Agriculture, Forestry and Other Land Use (AFOLU) Roadmap to coordinate space-based measurements of stocks and GHG fluxes from the land sector. This roadmap was approved at the 37th CEOS Plenary in 2023. More recently, work has begun on an Aquatic Carbon Roadmap.

In response to this rapidly evolving environment, the GHG TT proposed an update to GHG2020 at the 2024 CEOS-SIT annual meeting. The CEOS SIT authorised this update and requested that it be completed in time for discussion at the 2024 SIT Technical Workshop in preparation for potential endorsement at 2024 CEOS Plenary. This document was produced in response to that request.

3. Stakeholders and their Requirements

The prime focus of the GHG Roadmap is to support stakeholders[2] with fit-for-purpose, space-based GHG observations that enable the production of data products to meet the user needs. In GHG2020, the primary stakeholders were the CEOS and CGMS agencies, the carbon cycle science community, NGHGI and the UNFCCC. The objective was to deliver pilot, top-down national CO_2 and CH_4 budgets to support inventory development and assessments for the first GST. In the intervening years, additional stakeholders have emerged. These include the WMO G3W, UNEP IMEO, among others. These additional stakeholders themselves serve diverse user communities. In this issue of the GHG Roadmap, the focus has been expanded to track the top-level requirements of these emerging GHG monitoring organisations. We anticipate that in the next 5-10 years, CEOS and CGMS agencies will be serving a broad range of sectors directly (e.g. oil and gas industry, agricultural sector, finance) and in partnership with these new stakeholders. These stakeholders and their interactions are illustrated in Figure 4.

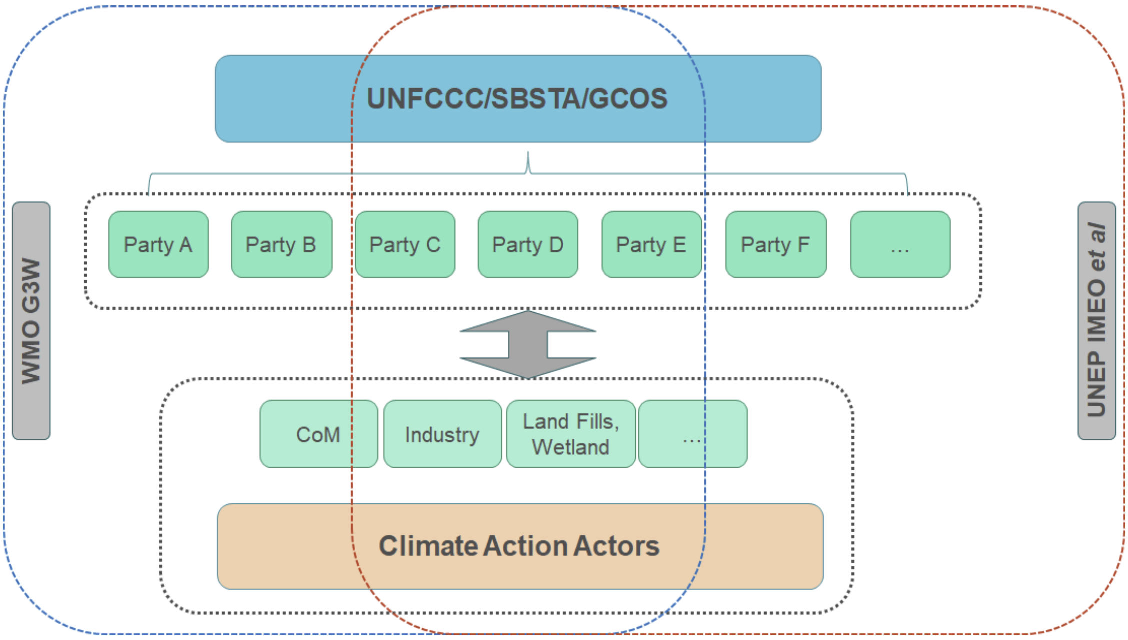

Figure 4: Stakeholders and their interactions.

To support the GST, UNFCCC and Parties to the Paris Agreement require accurate and traceable sector-specific annual/biennial national-scale inventories of GHG emissions and removals that meet internationally recognized standards. Top-down GHG budgets derived from atmospheric GHG observations and additional space-based products (e.g., land cover, land use and land use change) can contribute to the inventory development and assessment process. Changes in GHG budgets over time can also provide an integrated constraint on the collective progress toward the goals of the Paris Agreement. To encourage the use of these space-based products and derived GHG budgets, the GHG TT works through the Joint CEOS-CGMS WGClimate to maintain a regular dialog with the UNFCCC Subsidiary Body for Scientific and Technological Advice (SBSTA) and actively participates in the events such as Earth Information Day at the annual UN Climate Change Conferences of the Parties (COP).

[2]In this roadmap, we use the term, Stakeholders, to include individuals and groups that have an interest in the decisions or activities of an organisation, as well as those who receive products or services, who may be impacted by them, or those parties who may otherwise have a significant interest in space-based GHG monitoring.

Engagement with the climate modelling and assessment community (e.g., IPCC) will also be key. To understand the carbon cycle and how it will evolve with climate change, the global-scale modelling and assessment community needs precise, accurate, high spatial resolution, global estimates of GHG concentrations and fluxes. These data are used to quantify climate forcing in Earth System Models and to diagnose and predict the response of land biosphere and ocean carbon sources and sinks as they respond to climate change. The GHG TT, through their links with the CEOS AC-VC and AFOLU teams, should continue to foster continuous interactions with the climate modelling and assessment community to encourage the use of space based GHG products and identify new products and services needed to meet their needs.

WMO G3W aims to coordinate an operational framework for global GHG monitoring that brings together surface, airborne, and space-based observing systems, prior emission information as well as modelling and data assimilation capabilities. Its goal is to provide accurate and traceable global monthly GHG concentrations and net fluxes at the resolution of 1° x 1° with data latency of one month. These G3W products are intended to support scientific assessments (e.g., IPCC), national GHG emission reporting and other initiatives. The G3W Implementation plan identifies CEOS and CGMS as its key interfaces with the space-based GHG monitoring community. A sustained interaction between G3W and GHG TT is needed to identify key contributors among CEOS and CGMS agencies and affiliates, define operational interfaces, and establish product development and delivery plans.

UNEP's IMEO aims to provide the data required to target methane reductions at the speed and scale identified in the Global Methane Pledge. Its Methane Alert and Response System (MARS) requires near-real-time data availability and high spatial resolution to enable alerts of large CH_4 emissions from fossil fuel extraction, distribution and use and, in the future, from other human activities. These "alert" products have less stringent requirements on emission quantification accuracy than other IMEO CH_4 emission accounting products, but place much greater demands on high spatial resolution and data latency. Coordination of existing and planned space-based assets and analysis capabilities is critical for meeting these low-latency requirements. The GHG TT is collaborating with IMEO to identify agencies within the CEOS and CGMS community that can contribute to these near-real-time product deliveries, either through systematic observations or by coordinating "tip-and-cue" efforts, which use observations from global mappers to identify CH_4 anomalies to be targeted by facility-scale monitors. CEOS is also working with the New Space community to define internationally recognized standards and best practices for space-based GHG measurements to facilitate the combined use of civil public space agency and New Space commercial and non-governmental data.

National and Multinational GHG organisations such as the U.S. Greenhouse Gas Center and the European Copernicus Atmosphere Monitoring Service (CAMS) have been established to collect and distribute greenhouse gas products developed by multiple agencies. The U.S. Greenhouse Gas Center is one of several measurement, monitoring, reporting and verification (MMRV) activities associated with the National Strategy to Advance an Integrated U.S. Greenhouse Gas Measurement, Monitoring and Information System (GHGMMIS) released in 2023.[3] The National Strategy highlights opportunities to accelerate the distribution of greenhouse gas data to support a range of climate mitigation policies through public, private and philanthropic partnerships. The National Strategy also provides a path forward for developing an architecture for an integrated greenhouse-gas observing system that is interoperable with international programs like G3W and IMEO. The U.S. Greenhouse Gas Center is led by NASA, NOAA, NIST and EPA, with new agencies onboarding over the coming months, to provide datasets, an analysis environment and integrated framework to serve a variety of stakeholder needs.

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[3] https://www.whitehouse.gov/wp-content/uploads/2023/11/NationalGHGMMISStrategy-2023.pdf

For a decade now, CAMS has been developing and operating two major operational GHG processing chains. One is for near-real-time global analyses and forecasts of CO_2 and CH_4 atmospheric mixing ratios. The second one is for delayed-mode global atmospheric inversions for CO_2, CH_4 and N_2O surface fluxes. The latter can rely on readily available CO_2 and CH_4 satellite retrieval products, while the former compensates for the lack of publicly-available near-real-time retrievals by ingesting the upstream radiances. The two processing chains are evolving and being expanded to establish an integrated greenhouse gas monitoring and verification support capacity (GHG MVS) dedicated to the monitoring of anthropogenic CO_2 and CH_4 emissions at global and local scales. An example of the latter is the new operational CH_4 hotspot monitoring based on Sentinel-5p observations. This GHG MVS is part of the Copernicus programme of the European Union and is being implemented through a collaboration between ESA, EUMETSAT and ECMWF with the aim to be fully operational by 2027 aligned with the launch of the CO2M satellite constellation.

In addition to addressing the individual needs of this diverse range of stakeholders, the GHG TT will foster a more active collaboration among the members of these communities by helping to develop common interfaces and a common language for describing the relationship between top-down and bottom-up estimates of GHG fluxes. To encourage the use of the GHG flux products in the GST process, the GHG TT will facilitate the co-development of GHG flux products and emission information between CEOS-CGMS agencies and NGHGI communities. CEOS and CGMS agencies are encouraged to work with early adopters to demonstrate the value of the top-down GHG fluxes, and to communicate the utility of these products to the national COP delegations. This work should be effectively communicated to IPCC for inclusion in its future assessment reports, e.g., by engaging as authors of IPCC reports, and for consideration in future updates to the IPCC TFI guidelines for inventory development. These GHG TT objectives can also benefit from collaboration with the carbon modelling community such as the GCP's RECCAP2 initiative and the WCRP Earth System Modelling and Observations core project[4].

[4] https://www.wcrp-climate.org/esmo-overview

4. Monitoring Greenhouse Gases from Space

4a. Observational Requirements for Monitoring CO_2

CO_2 is a long-lived atmospheric greenhouse gas with an atmospheric residence time that spans years to centuries. Fossil fuel combustion for electrical power production, transportation, industry and agriculture added about 35 billion tonnes of CO_2 to the atmosphere each year (Gt CO_2/yr) over the decade spanning 2013–2022. Land-use change (e.g., deforestation, forest degradation, land conversion, etc.) contributed another ~5 Gt CO_2/yr to the atmosphere over that period (Friedlingstein et al. 2023). Since the beginning of the industrial era, these emissions have increased the atmospheric CO_2 concentration by ~50%, from ~270 ppm to over 420 ppm and are now still increasing by ~2.5 ppm/year.[5,6]

These anthropogenic CO_2 emissions are superimposed on an active natural carbon cycle that regulates CO_2 through photosynthesis and respiration by the land biosphere and ocean biota. The ocean also absorbs and emits CO_2 through temperature-driven solubility and carbonate chemistry coupled with circulation (c.f., Beer et al., 2010; Gruber et al., 2019). Over the past decade, sinks in the land biosphere have absorbed about 31% (~12 Gt CO_2/yr) of all anthropogenic CO_2 emissions, while ocean sinks have absorbed about 26 % (~10 Gt CO_2/yr) of these emissions (Friedlingstein et al., 2023).

These anthropogenic and natural CO_2 sources and sinks produce variations in the atmospheric CO_2 distribution over a range of spatial and temporal scales, which can be quantified by space-based measurements (c.f., Hakkarainen et al., 2019; Cusworth et al., 2021). Intense emissions from fossil-fuel-fired power plants or large wildfires produce enhancements in the column-average CO_2 dry air mole fractions (XCO_2) with amplitudes larger than 10% within ~100 metres (m) of the source, and larger than 0.25% (1 ppm) over tens to hundreds of kilometres (km) downwind. In large urban areas, industries, transportation systems and domestic activities produce more diffuse emissions distributed over hundreds of square km, producing XCO_2 anomalies with amplitudes between 0.25 and 1% (1 to 4 ppm; c.f., Ye et al., 2020; Kiel et al., 2021). CO_2 sources and sinks associated with intense agriculture or large forests vary over the diurnal and seasonal cycle, but typically produce XCO_2 anomalies with amplitudes that are no larger than 0.125 to 0.5% (0.5 to 2 ppm). Ocean sources and sinks produce CO_2 fluxes that are an order of magnitude smaller than land ecosystems, and produce correspondingly smaller variations in XCO_2 (Byrne et al., 2023), but these sources and sinks cover large areas and therefore have a large impact on atmospheric CO_2 concentrations.

Different types of requirements for space-based sensors are needed to monitor these different classes of emissions. Emissions from intense points sources, such as fossil-fuel-fired power plants emitting more than about 8 MtCO_2/year, can be quantified using high-precision (~1 ppm), kilometre-scale (1–10 km) XCO_2 observations (e.g. OCO-2 and OCO-3). However, less intense CO_2 point sources are more easily detected and quantified using high-spatial-resolution sensors that can detect the large CO_2 anomalies (5–10 ppm) within 100 m of the source. Efforts to quantify weaker, spatially distributed sources and sinks, such as large urban areas, intense agriculture or forests that typically produce CO_2 anomalies smaller than < 1 ppm, require sensors with greater precision and accuracy, which often must be traded for reduced spatial resolution (c.f., Kiel et al., 2021; Liu et al. ,2021). Even weaker, but more spatially-extensive sources and sinks, such as those over the open ocean, require sensors with much greater precision and accuracy (< 0.1 ppm; Woolf et al., 2019). Fortunately,

[5] https://gml.noaa.gov/ccgg/trends/gl_gr.html
[6] https://library.wmo.int/records/item/68532-no-19-15-november-2023

relatively low spatial resolution (~100 km) is needed to resolve known spatial variations in these weak fluxes.

When anthropogenic and natural GHG sources and sinks cannot be explicitly resolved by space-based observations, the relative contributions of combustion sources can sometimes be inferred from co-incident observations of short-lived co-emitted gases, such as CO and NO_2. Because of their short atmospheric lifetimes, these gases are most abundant near their sources and are often easier to detect than CO_2 since they have much lower background concentrations (Hakkarainen et al. 2023). Comparisons of CO and NO_2 emissions can also provide insight into the type of combustion, since CO is a byproduct of inefficient low-temperature combustion, such as wildfires, while NO_2 is more efficiently produced by higher-temperature combustion processes associated with fossil fuel use. The first generation of dedicated, space-based CO_2 sensors (e.g., GOSAT, OCO-2) relied on co-incident NO_2 and CO observations from sensors deployed on other spacecraft in low-Earth orbit (LEO), including MOPITT, OMI, and Sentinel-5P TROPOMI, and NO_2 sensors in geostationary orbit, including GEMS and TEMPO. GOSAT-2 was the first GHG mission to include a CO channel and future sensors (e.g., GOSAT-GW and CO2M) include dedicated NO_2 sensors to facilitate plume detection.

Classes of Missions to monitor Atmospheric CO_2

To address these needs, three classes of space-based sensors are being used to monitor atmospheric CO_2 concentrations (see https://database.eohandbook.com/ghg/). These include global GHG mappers, facility-scale plume monitors and operational meteorological sounders.

Dedicated, moderate-spatial resolution **Global GHG Mappers**, such as Japan's GOSAT and GOSAT-2 and NASA's OCO-2, and OCO-3 have been optimised to detect and quantify emissions and removals by distributed CO_2 sources and sinks spanning spatial scales from large urban areas to nations on seasonal to annual timescales. Future Global CO_2 Mappers including GOSAT-GW and the CO2M constellation will extend these datasets with much higher spatial resolution and coverage. These sensors record high-resolution spectra of reflected sunlight (resolving powers of 10,000 to 20,000) within the strong and weak shortwave infrared (SWIR) CO_2 bands near 1.61 and 2.06 micrometres (μm) to constrain the CO_2 column abundance. They also collect spectra within the near-infrared (NIR) molecular oxygen (O_2) A-band, around 0.765 μm, which provide a direct constraint on the dry air mass and to characterise cloud and aerosol scattering, which can otherwise compromise the accuracy of space-based CO_2 estimates.

These observations can be analysed to retrieve estimates of XCO_2 with single sounding precisions and accuracies between 0.5 and 2 ppm (0.125 – 0.5%) in surface footprints spanning 2 to 100 square km (c.f. Wunch et al., 2017; O'Dell et al., 2018). Solar Fraunhofer lines within the O_2 A-band can also be analysed to retrieve estimates of solar-induced chlorophyll fluorescence (SIF), which provide information about light-use efficiency and photosynthetic uptake of CO_2 by the land biosphere (c.f., Doughty et al., 2021). While Global Mappers can detect emissions from very large point sources, such as fossil-fuel-fired power plants (c.f., Nassar et al., 2021), they have been most useful for quantifying fluxes from the land biosphere on regional to national scales (c.f., Liu et al., 2021; Byrne, et al. 2023) and from large urban areas (Ye et al., 2020; Kiel et al., 2021).

These passive Global GHG Mappers have recently been joined by an **active LiDAR** experiment on China's DaQi-1 Satellite (Cao et al., 2024). This pioneering LiDAR collects data along a narrow (< 100 m) track near the spacecraft ground track. Its individual measurements have relatively low precision (10s of ppm), but they can be averaged along the track to yield estimates of XCO_2 with precisions of a few ppm on spatial scales of 50 to 100 km. These data are expected to be most useful for quantifying CO_2 sources and sinks at high latitudes during polar night, where the passive remote sensing observations are not possible.

High-spatial-resolution, **Facility-Scale Plume Monitors**, such as ASI PRISMA, are more sensitive to emissions from the most intense CO_2 point sources, such as large fossil-fuel-fired power plants (Cusworth et al., 2021). These sensors typically collect SWIR spectra of reflected sunlight at much lower spectral resolution than the Global mappers (l/Dl < 1000), but have spatial resolutions as high as 30 m over areas spanning 10 km x 10 km to 200 km x 200 km. Their observations can be analysed to yield single sounding precisions and accuracies of ~10 ppm, which is adequate to quantify fluxes as small as ~300 tonnes per hour from point sources. This is about a factor of four smaller than the smallest fluxes that can be quantified by Global Mappers, such as OCO-2 (Cusworth et al., 2021). However, with their high spatial resolution, these instruments typically provide limited spatial coverage, so multiple instruments are needed to cover the majority of these large emission sources.

A third class of space-based sensors, the **Operational Meteorological Sounders**, can detect and quantify atmospheric CO_2 at altitudes within the middle troposphere layer using moderate-resolution emission spectra collected at thermal infrared wavelengths. These sensors are ideal for quantifying the impact of CO_2 and other GHGs on the climate and have some sensitivity to very intense surface sources (e.g., Wilson et al., 2022), but have limited sensitivity to typical surface sources and sinks.

Gaps in the Space-based CO_2 Monitoring Architecture

Two additional types of space-based CO_2 sensors that provide complementary observing capabilities have not yet been demonstrated. The first type includes both geostationary (GEO) and highly elliptical orbit (HEO) sensors, which can return spatially-resolved XCO_2 estimates across their fields of regard multiple times throughout the day to resolve the diurnal cycle of natural and anthropogenic CO_2 sources and sinks. A single GEO satellite can give sub-daily revisits with regional coverage spanning ~120 degrees longitude. However, GEO viewing geometry prevents observations of the polar regions. HEO missions continue to be considered for rapid revisit observations of the polar and mid-latitude regions (e.g. Nassar et al. 2023). NASA attempted to address the GEO need by selecting the Earth Ventures Geostationary Carbon Observatory (GeoCarb) mission (Moore et al., 2018), but that project was cancelled prior to launch.

The second type includes sensors with the sensitivity and accuracy needed to constrain the weak, but spatially-extended ocean sources and sinks over the ocean. While global mappers typically return XCO_2 estimates with precisions and accuracies of 0.25% (1 ppm), CO_2 fluxes over the open ocean rarely produce changes in the column-average CO_2 dry air mole fraction larger than 0.05% on spatial scales of 10 to 1000 km. However, ocean fluxes and their associated XCO_2 anomalies are much less variable than those over land, such that much lower spatial resolution is needed to identify and track their changes. No new technologies are required to monitor ocean CO_2 concentration gradients on spatial scales of 1° x 1°, but existing technologies will have to be optimised to meet these needs. These space-based sensors will also require much more capable ground-based and airborne validation systems.

4b. Observational Requirements for Monitoring CH_4

Methane, a potent but short-lived greenhouse gas, accounts for nearly a third of the warming over the last 250 years. To limit warming below the Paris Agreement targets and prevent severe climate impacts, rapid and deep cuts in methane emissions are crucial (IPCC, 2022). Achieving these goals requires an accurate accounting of methane emissions to track the role of increasing emissions on atmospheric methane, ensure that methane remediation efforts are successful, and assess if feedbacks related to the natural cycle are offsetting methane emission cuts. Anthropogenic sources accounted for, on average, 63–68% of total methane emissions (Saunois et al., 2020), depending on the approach for estimating emissions. However, uncertainties across sources and locations remain large, with varied methods yielding different results. For example, estimates of fossil fuel methane emissions differ between activity-based bottom-up inventories, remote sensing, and isotopic analysis (Basu et al., 2022; Saunois et al., 2020; Worden et al., 2023). Despite discrepancies, estimates for categories of sources and sinks generally converge. The spatial scales of methane emissions span orders of magnitude (wetlands: 1 to 1000 km, fossil emissions: 1 to 100 m, waste: ~100's m), necessitating an observing system that can observe across this range of scales.

Space-based remote sensing observations collected within methane bands at near Infrared (NIR) and SWIR spectral regions (0.7 to 2.4 microns) can be analysed to yield precise, spatially-resolved estimates of the methane column abundance or dry air mole fraction (XCH_4). Two classes of remote sensing measurements have emerged that show skill in reducing uncertainties in the methane budget: (1) **Global CH_4 Mappers** that collect high spectral resolution measurements in the NIR and SWIR methane bands with ~1–10 km pixel scales to estimate total column methane (XCH_4), and (2) **Facility-Scale CH_4 Plume Monitors** that collect high-spatial resolution (~10–100 m pixel or facility scale) NIR and SWIR methane band measurements to resolve intense methane plumes from leaks, waste management, and concentrated livestock facilities. Together, these two classes of space-based measurements are used to quantify methane emissions that occur at vastly different spatial scales with strongly different temporal characteristics.

Moderate Resolution Global Mapping Measurement Requirements and Gaps

For the global mapping measurements, accuracy and precision are as important as sampling resolution and coverage because spatial variations in XCH_4 are typically smaller than 1% on these scales. For example, Qu et al. (2020) demonstrated that the initial Sentinel-5P TROPOMI XCH_4 data were no better than GOSAT XCH_4 data at quantifying global emissions, despite a nearly 1000x improvement in sampling. Future Global CH_4 Mappers including GOSAT-GW and the CO2M constellation will extend these datasets with even greater spatial resolution and coverage.

Accuracy and sampling in the tropics are also critical, as these are regions of significant wetland, livestock, and rice emissions. Joint XCO_2 measurements in a band that is spectrally close to the spectroscopic band used to estimate XCH_4 are critical for obtaining tropical measurements of XCH_4, as this measurement can substantially reduce light path error, the dominant error in XCH_4 measurements. Spectroscopic measurements of the O_2 A-band can also be used to mitigate light path error but with less efficacy than XCO_2, especially in the tropics. Ideally, the accuracy and precision of the XCH_4 measurement should be better than 5 ppb/15 ppb (Parker et al., 2020), with sufficient sampling and pixel size to detect methane over tropical wetlands (Frankenberg et al., 2024). Improvements in accuracy and sampling matter. For example, Sentinel-5P TROPOMI data, when corrected for light path errors using sub-sampled GOSAT data, can improve the information content of North American emissions by over a factor of 20 (Worden et al., 2022; Balasus et al. 2023; Nesser et al., 2024). Coverage is also an issue, especially at high latitudes during the polar night. The first active system, MERLIN, will begin to address this issue when it is launched later this decade.

Facility Scale Measurement Requirements and Gaps

Spatial resolution and sampling are critical for facility-scale measurements. Space-based measurements typically attempt to resolve methane plumes from high emitters near IR/shortwave IR methane band radiances (e.g., Jervis et al. 2021; Thorpe et al. 2023). Measurement sensitivity is typically limited by how well the instrument can detect methane plumes and their associated emission. For example, GHGSat and EMIT have a probability of detection (POD) of ~100 kg/hr under optimal conditions (e.g., low, steady winds). The POD varies considerably with aerosol/cloud distributions, albedo, and wind speed, such that plumes are more easily detected in arid to semi-arid regions such as Turkmenistan and the Permian Basin and fewer are detected in the tropics and high latitudes. It is currently unclear what fraction of the total methane budget this class of instrument can resolve, but unpublished discussions suggest they capture between 5 to 25% of total fossil and waste emissions. As this depends strongly on POD, further advances in instrument sensitivity to methane and corresponding increases in POD would greatly advance the capability to estimate these components of the methane budget using this class of instrument.

Accurate georeferencing is also needed to identify specific sources. With the current generation of facility-scale sensors (e.g., EnMAP, PRISMA, EMIT), this is limited to 60 - 300 m. This can be a problem in areas with multiple potential sources. Improved methods for establishing and validating the geolocation of facility scale sources are also needed.

Geostationary Measurements

An emerging approach for monitoring facility-scale CH_4 emissions exploits frequent (5 to 10 minute) snapshots from geostationary satellites, such as NOAA's GOES-R series Advanced Baseline Imager (ABI; Watine-Guiu et al., 2023) or EUMETSAT MTG Flexible Combined Imager (FCI). These sensors can be used to detect and quantify only very large (tons/hr) methane emissions. Their high frequency may enable much more timely alerts for large, transient CH_4 plumes. In addition, they can potentially provide estimates of the total emitted methane volume, provided the conditions facilitate capturing the whole event from start to end, which can be hampered by nighttime, clouds and other artefacts.

4c. GHG Observations by Non-governmental Organisations - New Space

CEOS and CGMS, together, are the primary international bodies for the coordination of space-based Earth observations by civil space agencies. Recently, these civil space activities have been augmented with contributions from commercial and non-governmental organisations that are collectively called "New Space". In the context of GHGs, New Space missions have primarily focused on high-spatial-resolution observations of facility-scale emissions of CH_4, such as from oil and gas extraction, processing and transport or waste management.

While CEOS and CGMS agencies have no specific mandate to collaborate with these New Space missions, individual CEOS and CGMS agencies have opened dialogues with New Space organisations to discuss data buys. CEOS and CGMS stakeholders in the science, commercial, financial, and policy communities could also benefit from closer coordination of civil space and New Space GHG measurements. A more comprehensive, international effort to coordinate civil space and New Space observations, led by CEOS and CGMS, could yield benefits to both CEOS and CGMS Agencies and their stakeholders in two areas:

- Source attribution: Coordinated "tip-and-cue" observations of intense CO_2 and CH_4 emissions plumes by civil-space global mappers and facility-scale New Space missions can be combined to identify the specific facilities responsible for these emissions. This information would enable more rapid revisits to support alerts (e.g., IMEO MARS) and mitigation action, where appropriate. This coordination would also facilitate the attribution of top-down CO_2 and CH_4 fluxes derived from inverse models to specific categories of specific emissions sectors to support the development and verification of bottom-up national inventories submitted to the UNFCCC.
- Standards and best practices: The adoption of common, internationally recognized standards for the collection, analysis, documentation and distribution of space-based GHG products could improve the interoperability and transparency of New Space GHG products, enhancing trust in their value to customers in the commercial, financial and policy communities. These coordination efforts could benefit CEOS and CGMS agencies by providing the data transparency and traceability needed to support data buys of New Space GHG data products for science applications.

Potential obstacles to progress toward these goals include concerns about the loss of intellectual property, competitive advantage, or profits by the New Space organisations and the perceived threat to civil space agencies posed by the perception that New Space can do it all. These concerns could be mitigated by sustained, constructive dialogue between civil space and New Space organisations.

4d. Research Coordination in CEOS and CGMS

Not all space-based GHG monitoring applications are addressed by existing capabilities and new stakeholder needs are continuing to emerge. To address these needs, CEOS and CGMS agencies will continue to support scientific research to produce more actionable information and to monitor changes in the natural carbon cycle associated with human activity and a changing climate.

Since the release of the CEOS white paper, good progress has been made by the research community in improving retrieval algorithms, validation, modelling and data assimilation. These methods are now providing key insights into the distribution and variation of CO_2 and CH_4 concentrations and fluxes at scales spanning large urban areas to the globe. More recently, advances have also resulted from the use of high-spatial-resolution CH_4 and CO_2 observations from hyperspectral/multispectral imaging satellite data intended for other applications, as well as dedicated New Space satellites (see sections 4a-c and 5b). Progress in all of these areas has been accelerated by active international collaboration among science teams, fostered by CEOS and CGMS. This work has enabled the start of a transition from research to operational emission monitoring.

However, in spite of this progress, important gaps and limitations remain. The GHG TT should work with its partners in CEOS and CGMS to coordinate research focused in the following key areas:

- **Reducing biases and random errors in space-based XCO_2 and XCH_4 estimates:** While the accuracy of retrieval algorithms for estimating XCO_2 and XCH_4 has improved, spatially coherent biases still limit the utility of these data for monitoring fluxes from distributed sources such as large urban areas or changes in the land biosphere associated with agriculture, forestry and other land use (AFOLU). Ongoing research is focusing on more realistic treatments of optically thin clouds and aerosols, which can introduce random errors and systematic biases in XCO_2 and XCH_4 estimates. Other work focuses on improved laboratory measurements of absorption cross sections for CO_2, CH_4, and O_2.

- **Improving retrieval algorithm speed:** The computational expense of physics-based XCO_2 and XCH_4 retrieval algorithms is currently a substantial impediment to their use for operational processing or reprocessing efforts. Their expense is expected to grow substantially over the next few years as new missions return orders of magnitude more data. The development of efficient, accurate remote sensing retrieval algorithms is a critical focus of ongoing research.
- **Leveraging ancillary observations:** NO_2, CO, solar induced fluorescence (SIF), nightlights, etc. are continually being explored due to their potential to reduce uncertainties, enable better sectoral attribution and other benefits for CO_2 or CH_4 flux quantification at various spatial and temporal scales. Moreover, the science community also needs to adapt the auxiliary data to the evolution of technology in space.
- **Improving emission estimation techniques:** comparing/evaluating emission estimation methods with satellite data at different scales such as data assimilation methods for global and regional models; or methods for urban areas or point sources (Gaussian plume model, Lagrangian transport models, Integrated Mass Enhancement, etc.). Advances are aimed at better quantifying and reducing uncertainties, quantifying smaller sources (lower detection limits) and attempts to characterise and account for source intermittency to estimate annual emissions, thus aligning emission estimates with current reporting conventions.
- **Developing practical methods for validating CO_2 and CH_4 Flux estimates:** While methods for validating XCO_2 or XCH_4 estimates against internationally recognized *in situ* standards are relatively mature (e.g., use of TCCON or AirCore comparisons to trace XCO_2 and XCH_4 back to the WMO *in situ* standards), methods for validating fluxes are much less mature and mostly focus on atmospheric concentrations which are a by-product of atmospheric inversions. Top-down CO_2 emissions estimates for fossil-fired power plants can be validated against *in situ* measurements made by stack monitors. Similarly, CH_4 fluxes from point sources in regions with simple (e.g., flat) topography and well-characterised winds can be validated against well-designed controlled release experiments. However, methods for validating inverse model estimates of CO_2 and CH_4 fluxes at scales spanning large urban areas to nations are in their infancy. These methods are critical for validating fluxes for large urban areas, AFOLU, or the natural land biosphere or ocean.
- **Improving sectoral attribution:** distinguishing between land versus ocean fluxes or vegetation and permafrost fluxes in a global/regional context, or distinguishing different anthropogenic emission sectors in an urban or national context are active areas of research.

As space-based GHG measurements improve, thanks to progress in optics and detectors, CO_2 and CH_4 spectroscopic parameters become a more important part of precision and accuracy limitations. Similarly, as the spatial resolution, coverage and repeat frequency of space-based measurements increases, much faster retrieval algorithms are needed. As the accuracy requirements become more stringent, the demands for data product validation increase, requiring expansions of the number of ground-based validation networks. Examples include TCCON (Wunch et al., 2011; 2018), COCCON (Frey et al., 2017), and AirCore(Karion et al., 2010; Membrive et al., 2017) and balloon/aircraft campaigns. However, sustaining these observations requires space agencies to recognize their value to data quality and their link to emission monitoring. Improvements in atmospheric inverse model accuracy and resolution are critical, so that these do not become limitations for flux precision and accuracy as satellite data quantity and quality improve.

New opportunities are emerging for accommodating upcoming big data streams. Artificial Intelligence (AI) in general, machine learning in particular or statistical approaches may be used at various levels in the analysis chain to couple data from different sensors, assimilate observations or estimate fluxes. Although these new approaches seem very powerful, with their use rapidly gaining in popularity, additional research is needed to assess the accuracy and range of validity of their results, as they are less closely based on traditional physical processes (Bréon et al., 2022).

Finally, it is critical to reconcile top-down and bottom-up approaches for evaluating fluxes. This has been the focus of the RECCAP project in GCP, but additional research is needed. In some cases, such as for terrestrial biospheric CO_2 or CH_4 fluxes, the coupling of atmospheric and surface models can contribute to the reconciliation of top-down and bottom-up flux estimates, but with a risk of an artificial reduction in the complexity of surface processes. In other areas, especially for CH_4, top-down research studies have identified discrepancies with reported bottom-up emissions inventories. In addition, top-down flux estimates often cannot disaggregate emissions by sectors when different types of sources (natural and anthropogenic) are mixed in the same area (e.g., wetland and oil & gas). Reconciling these differences may be an ill-posed inverse problem, but efforts could help identify methodological errors or faulty assumptions and help to ensure that major emission processes or events are not missed.

The GHG TT should work with the CEOS AC-VC and AFOLU teams to coordinate research efforts focused on the reconciliation of top-down and bottom-up flux estimates. This effort might initially focus on facilitating the exchange of research results within the international scientific community and identifying communicating gaps and the evolving needs of key stakeholders.

4e. Research to Operations (R2O)

In order to understand the transition from research to operations, it is necessary to have a clear view of what operations entails. The exact meaning varies from organisation to organisation and includes criteria such as continual operations, continuous support, and delivery of operational services with user support. An approach that combines the above is to define a service that meets associated user requirements as operational; this leaves the users to define the availability, timeliness, and quality of the service which must be met for it to be considered operational. This approach is used by EUMETSAT, among others, and corresponds to the risk-based approach used by NOAA. It is fully applicable to serve operational GHG Monitoring and Verification Support (GHG MVS) systems in support of policy making.

An operational GHG MVS system requires a set of inputs that need to be delivered by operational services. On the observational side, this encompasses accurate satellite retrievals of CO_2 and CH_4, ground and airborne measurements of CO_2 and CH_4, the provision of meteorological measurements from satellite and *in situ* data, and auxiliary satellite observations of other trace gases such as CO and NO_2, if available, as well as aerosol and cloud properties. Although the GHG TT is only responsible for delivering the satellite-based products, ground-based measurements and their timely delivery are important as well, e.g., to validate satellite products before use in GHG MVS systems or similar applications. Inherent to this, for the satellite observations to serve UNFCCC and the global stocktakes, there is the need of a sustained long-term space segment, which exists only partly today. Some progress has been made in that area, with the deployment of the preoperational Copernicus Sentinel-5P TROPOMI sensor, which will be continued by the operational Copernicus Sentinel-5 Ultraviolet Visible Near-infrared Short-wave infrared (UVNS) sensor on the EUMETSAT EPS Second Generation satellite series, the continuation of Japan's GOSAT series with GOSAT-GW and the ongoing development of the Copernicus CO2M constellation as the first dedicated operational GHG monitoring constellation.

Significant progress has been made in the acquisition and analysis of space-based GHG products since GHG2020 was released. However, the bulk of this progress was based on research products of varying accuracy from one-of-a-kind research missions, which were developed, flown and operated by individual agencies with no continuity plans. A key focus now is to use the lessons learned from this research constellation to implement a purpose-built, operational system for collecting, processing, validating and distributing high-quality space-based GHG products and auxiliary data to support operational MVS systems and future global stocktakes. Hence, a more focused effort by CEOS and CGMS is needed to integrate existing and planned space-based GHG assets into an operational observing system that can deliver sustained interoperable products to the growing list of stakeholders in the operational service, science and policy communities.

To start the transition from research to operations (R2O) for space-based GHG products, three use cases are considered. The first considers possible CEOS and CGMS contributions to G3W to support their deliveries of monthly, moderate-spatial-resolution (1°× 1°) GHG products to support climate assessments, long-term studies of the carbon cycle and its interactions with the climate and to contribute to the development and assessment of national GHG inventories. The second reviews the needs for delivering top-down, national-scale GHG products to support the global stocktakes. The third explores the possible delivery of near-real-time products to support the IMEO MARS initiative. First, we consider operational products and services common to all three use cases that can best be coordinated by CEOS and CGMS. We then consider requirements and data products that are specific to each activity and determine whether or how coordination efforts by CEOS and CGMS might contribute.

Common Requirements of Operational Services for These Use Cases

All of the use cases listed above require sustained, global, accurate, space-based observations of CO_2 and CH_4 and auxiliary data sets on time scales spanning decades. Because the lifetime of individual missions is finite and the coverage provided by an individual space-based platform is limited, an operational, space-based GHG monitoring system requires observations from multiple space-based platforms deployed and operated by a diverse range of civil-space and New Space organisations in the foreseeable future. The observations collected by these sensors must be interoperable to enable their combined use to meet spatial resolution, coverage, repeat frequency and timeliness requirements and facilitate transitions from one platform to another as the space-based infrastructure evolves. Data preservation, accessibility and transparency are also high priorities because extended GHG data records are needed to track the impacts of GHG emission reduction policies and collective progress toward the goals of the Paris Agreement.

To facilitate interoperability of the space-based measurements, these data must be cross-calibrated against internationally recognized standards. Then remote sensing retrieval algorithms and analysis needs to be applied at dedicated data processing centres that should have a reprocessing capability for reanalyses of the data. To create interoperable GHG products (e.g., column-integrated CO_2 and CH_4 dry air mole fractions, XCO_2, and XCH_4 and other geophysical parameters) the retrieved estimates derived from different sensors must be cross-validated against internationally accepted standards (e.g., TCCON, COCCON, NDACC, AirCore). For services with high timeliness requirements the timely availability of the surface-based validation data needs to be improved. These products must be operationally delivered to organisations, such as GHG MVS services, that combine the GHG concentration estimates with atmospheric transport estimates and analyse with either plume models or atmospheric inverse models to derive CO_2 and CH_4 fluxes on spatial scales spanning individual facilities, large urban areas, large forests, nations and the globe.

It is also of high importance that these products, along with their uncertainties, must be documented so that they can be harmonised with other available surface-based, airborne, and space-based GHG products to create continuous climate data records with the highest possible resolution and coverage, which is implementing the GCOS requirements. Also for the auxiliary satellite products climate data records remain essential.

All of these specific capabilities have been demonstrated using data collected by individual missions. There has also been limited effort to cross calibrate and cross validate products from more than one mission (e.g, GOSAT-1/2, OCO-2/3 and Sentinel-5P TROPOMI). However, there has been no sustained effort to develop truly operational interoperable products from multiple missions spanning space-based GHG measurements to fluxes. Coordinating these efforts across CEOS and CGMS should be a high priority.

Requirements of Operational Services for These Use Cases

Some stakeholders, such as G3W, can use the gridded concentrations and fluxes generated by an operational pipeline directly to produce products and services for the communities that they support. Others, including the NGHGI communities and science , need GHG concentration and flux products that have been validated against internationally recognized standards. They may also need additional information to help track emissions and removals of CO_2 and CH_4 to specific processes or emission sectors within specific domains. Others, such as the IMEO MARS need near real time data to meet the demanding latency requirements of an alert system. However, these data may do without the cross-calibration and cross-validation steps if not compatible with high timeliness.

Specific Activities Fostering the Transition from Research to Operations

The GHG TT and its partners in the CEOS AC-VC and WGCV demonstrated many facets of this processing pipeline to develop pilot, national-scale CO_2 and CH_4 budgets delivered to the UNFCCC to support the first GST. Only XCO_2 from OCO-2 were used to develop the CO_2 budgets and only XCH4 products from GOSAT were used to develop the CH_4 budgets, in part because there was no time, tools, or resources to harmonise XCO_2 and XCH_4 estimates from multiple space-spaced sensors. These shortcomings limited the resolution and coverage of the resulting flux budgets. They also limit the length of the climate data record, since both of these missions are well beyond their design lifetimes, and are unlikely to be operating to support the next GST. This experience suggests that the GHG TT needs to focus their efforts on data product interoperability and harmonisation to support the transition from research to operations.

The GHG TT with CGMS WGs should develop an approach on regularly capturing evolving user requirements for products and services from the stakeholders (UNFCCC, NGHGI community, G3W, and IMEO) with priority to stakeholders having operational needs. The work with G3W should be combined with the GCOS requirements process aiming at more useful user requirements for climate data records. The interaction might be executed most efficiently by creating and circulating user surveys that are distributed to these groups. Given this information, the GHG TT can work with CEOS and CGMS to identify efforts by their agencies that support the transition from research to operations.

The GHG TT and CGMS WGs should work with WMO towards establishing the sustained operational space segment needed for operational climate monitoring that will most likely consist of a mix of operational, research, and commercial missions, at least in the coming decade. This view should be integrated into the update of the WMO WIGOS 2050 vision from which the CGMS baseline is derived for implementation by CGMS agencies. This should include consultations with commercial providers to determine what role they might play or how they might plan to interact with an operational space-based GHG monitoring system. The WGClimate and its GHG TT should be able to communicate the GHG satellite capability and its evolution on behalf of CEOS and CGMS to stakeholders as indicated by G3W at CGMS-52.

WGClimate and G3W have a set of common interest regarding operational activities as discussed at the CGMS-52 Plenary[7] that could lead to joint efforts:

- identify and foster key operational centres/consortia around the world that provide GHG MVS systems or/and can operationally receive XCO_2, XCH_4 and other geophysical products from space-based instruments to derive fluxes and emission products at needed scales.
- coordination and co-developments of calibration/validation activities including the definition of standards and best practices for collecting, calibrating, analysing, validating, and documenting space-based CO_2 and CH_4 products, definition and formalisation of interfaces between the space-based effort and the surface-based calibration and validation networks, and improvements of the timely provision of ground-based validation data, from key measurement sites, e.g., down to a month in the beginning.
- organise GHG TT involvement in a G3W planned workshop on optimal network design planned for 2025.
- consider joint activities (maybe also with GCOS) on contributions to the UNFCCC COP30 in 2025 and beyond focusing on common interest themes.
- foster the establishment of standards for the preservation, accessibility and transparency of space-based GHG data products; and
- identify needs for capacity building to encourage the use of space-based GHG products by key stakeholders.

5. Thematic Activities

Following the approach in the implementation of issue 1 of the GHG Roadmap, GHG TT activities are defined along the lines of specific thematic areas. These areas are introduced below as subsections, which provide the context and scope of each thematic area, and specific challenges. Details are also provided on the type of support needed from CEOS and CGMS agencies to achieve the required activity goals. The specific short- and long-term activities of each thematic area are described in Annex C, which is maintained and available online. The Annex C is to be considered a living document, which evolves over time as activities are concluded and (potentially) new activities emerge. The progress and achievements will be reported to CEOS and CGMS principals by WGClimate or by another working group, if leading that specific thematic area and/or activity. The required resources to implement these activities are similar to those of GHG2020 and any additional required resources for specific (new or larger) activities will be reflected in the CEOS Work Plan and/or CGMS High Level Priority Plan.

5a. Fostering Stakeholder Engagement

As mentioned in Section 3, since the release of GHG2020, the CEOS and CGMS stakeholder community has evolved rapidly. While the science community, NHGHI and UNFCCC continue to be a critical focus of this roadmap, the other coordination bodies, including WMO G3W and UNEP IMEO, are now clear counterparts. In this partnership, a clear mandate has emerged with CEOS and CGMS providing the public space agency coordination entry point for accurate and traceable budgets of GHG concentrations and fluxes, and collaborating to support the GST, as well as the diverse user

[7] CGMS-52 Plenary, 4-6 June 2024, Washington DC. Summary Report (https://cgms-info.org/wp-content/uploads/2024/09/CGMS-52-Interactive.pdf)

communities targeted by G3W and IMEO. Fundamental principles that should be applied in these engagements with stakeholders and user communities are: firstly, that the space-based solutions should be co-developed with the specific users and secondly, that we strive for fit-for-purpose solutions that should be iteratively improved to reach this ambition.

Engagement with the climate modelling and assessment community (e.g., IPCC) is also key. To understand the carbon cycle and how it will evolve with changing climate, the global-scale modelling and assessment community are another key stakeholder, and we need to cooperate to establish a common lexicon and product definitions in dialogues with the diverse users. Carbon modelling efforts such as the GCP's RECCAP2 initiative could be a key interface. As mentioned in sections 3, the focus of activities should be to foster a continuous exchange of information about capabilities, products, requirements and gaps without saturating the NGHGI community's resources for dialogue.

This addresses the stakeholders that have emerged since CEOS and CGMS started discussions on coordinating these activities. However, undoubtedly there will also be additional stakeholders, especially as sectoral users emerge for different areas of action on climate mitigation. CEOS and CGMS will have to decide how to collectively address these further needs and requirements. In general, the GHG TT should foster collaboration with these stakeholders and other CEOS and CGMS activities such as the AFOLU and Aquatic Carbon roadmap efforts - reinforcing our overall role and mandate in coordinating the effort for the space-based observations.

Engagement with new stakeholder communities can be actively pursued and explored, or it is foreseeable that new stakeholders will approach one of the CEOS and CGMS agencies individually or through one of its WGs. In considering new stakeholders and their needs, the following broad criteria and approach will be adopted:

- Assess whether existing partners (e.g. G3W, IMEO, GCP) may be better positioned to provide the direct interface to these new user communities. In that case, we should confer with them to define how to best support the request with space-based data/requirements.
- Assess whether a new request may be better addressed by private sector solutions. Noting that CEOS and CGMS represents the public EO agencies. For this, we should maintain a broad understanding of private-sector capacity allowing us to redirect those requests to potentially existing solutions.
- Assess the maturity of the stakeholder and their requests as they become available.
- Assess whether a new request falls within the "category" of CEOS and CGMS core activities. In such cases, the GHG TT should assess capacity to address these requests.
- Assess whether a new request would support international initiatives such as the Global Methane Pledge, which are emerging as a common policy-tool to advance climate policy negotiations.

In some cases, CEOS and CGMS are well positioned to respond to these requests, using the approach and type of assessment described above and a process should be established to initiate such studies. In other cases, requests may be deemed inappropriate for CEOS and CGMS.

The CEOS External Requests Process Paper outlines clear steps for CEOS to consider how to respond to external requests, in particular where a large number of resources would be required.

In all cases, once a new stakeholder is identified as requiring direct engagement with CEOS and CGMS through the GHG Task Team, a similar approach should be taken as with G3W and IMEO. Specifically, points of contact should be clearly identified to serve as a clear interface between the GHG TT and the new stakeholder group.

5b. Sensor Development and Constellation Architectures

The "Sensor Development and Constellation Architectures" thematic area monitors the status of operational and planned GHG missions and their measurement capabilities plus timelines, assesses emerging trends in space-based GHG requirements and relevant technologies, and identifies measurement gaps.

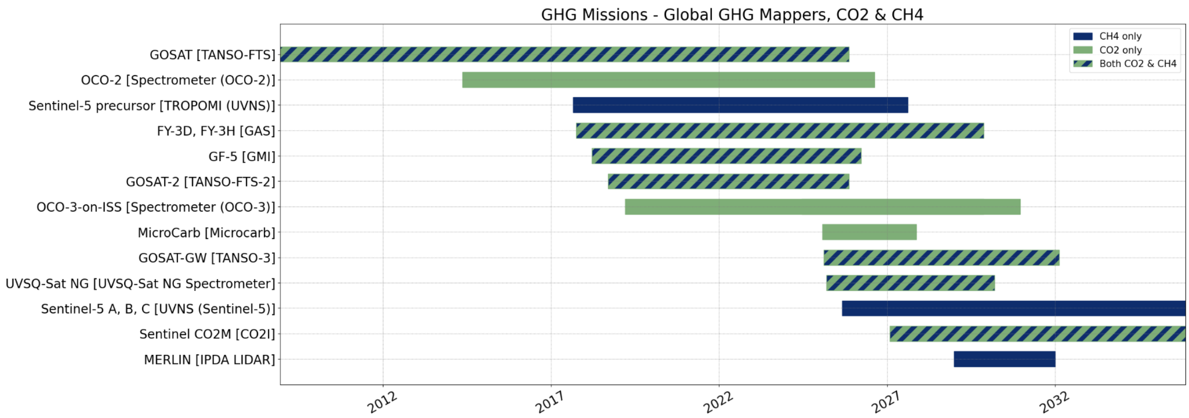

Figure 5: Global GHG Mapping Missions. Please see the [CEOS GHG Portal] for an up-to-date version.

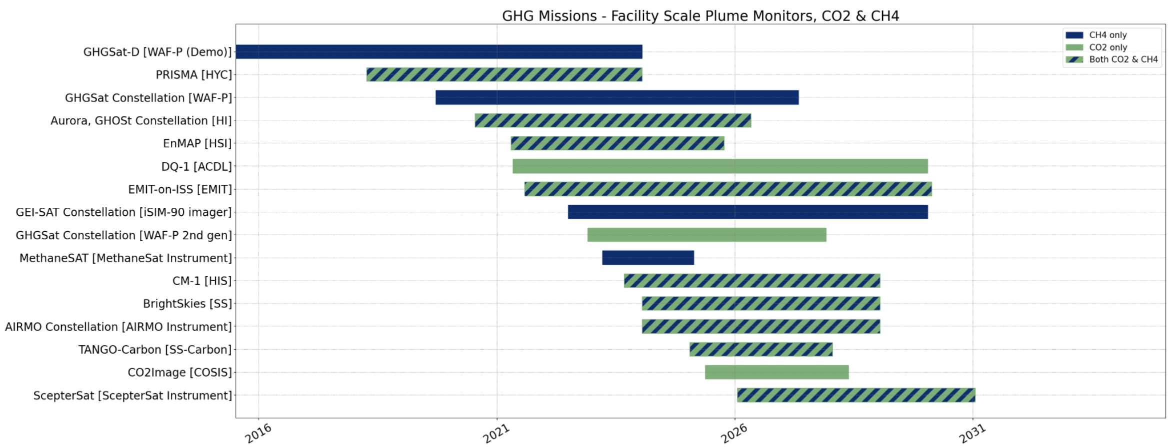

Figure 6: Facility-scale Plume Monitoring Missions. Please see the [CEOS GHG Portal] for an up-to-date version.

The GHG TT works with its partners in the CEOS AC-VC to track the status of current and upcoming satellite missions designed to monitor atmospheric CO_2 and CH_4 concentrations on spatial scales spanning individual facilities to the globe (see section 4 a,b). This task covers missions developed and operated by CEOS and CGMS agencies, as well as those flown by private New Space organisations. It identifies each mission's key measurement objectives, capabilities and planned operating lifetime. This information is used to coordinate activities among mission teams and to identify key measurement gaps. The list of missions being tracked are summarised in the CEOS GHG Satellite Missions Portal (https://ceos.org/ghg). There, existing and planned GHG missions have been divided into categories, based on their spatial resolution and coverage. Examples of timelines for Global Mapping missions and Facility-scale Plume monitors are shown in Figures 5 and 6.

The first generation of CO_2 and CH_4 Global Mapping missions (e.g., GOSAT, GOSAT-2, OCO-2, OCO-3, Sentinel-5P TROPOMI) have demonstrated the measurement precision and accuracy needed to monitor emissions from a broad range of anthropogenic and natural sources. These GHG observations are also combined with observations of SIF to constrain CO_2 uptake by the land biospheric sink. However, these missions, by themselves, did not have the spatial resolution, coverage or repeat frequency needed to track anthropogenic emission changes associated with policy initiatives or distinguish changes in emissions caused by human activities or climate change.

The second generation of GHG global mappers (e.g., GOSAT-GW, CO2M) exploits new instrument designs to support a more capable space-based GHG monitoring and verification system. Their sensors maintain the precision and accuracy of the first-generation systems, but provide much higher spatial resolution and coverage. The denser sampling promised by these systems should provide the data needed to support the initial implementation of the WMO G3W, as well as that needed to develop higher-resolution CO_2 and CH_4 budgets to support future GSTs. Active LiDAR missions, such as China's recently launched DQ-1 CO_2 LiDAR and the French/German MERLIN mission, which will launch later in this decade, will augment these global mappers with improved coverage of high latitudes during the winter months.

The Global Mappers are being joined by an increasing number of high-spatial resolution, Facility-scale Plume Monitors, optimised to monitor anthropogenic emissions from intense, localised sources. With their high spatial resolution, they can detect emissions from smaller discrete sources. They can also help to attribute the most intense CO_2 and CH_4 plumes to specific emission sources, facilitating the assessment of bottom-up GHG inventories. However, with their high spatial resolution, Facility-scale Plume Monitors have much more limited coverage than the Global Mappers. This shortcoming can be mitigated by close coordination between these two classes of GHG missions, using approaches such as "tip and cue", where a CH_4 or CO_2 anomaly is detected by a Global Mapper and the specific source is subsequently identified by a Plume Monitor. This synergy is especially valuable for rapidly identifying fugitive emissions and intermittent sources. This approach therefore supports both alerts, such as those issued by IMEO MARS, and inventory development activities.

The need for close coordination between Global Mappers and Plume Monitors poses both challenges and opportunities for the GHG TT. To fully exploit their capabilities, the GHG TT must catalogue targeting capabilities, detection limits and orbits of both types of missions. This could be accomplished by identifying key technical interfaces for each mission and encouraging their participation in regular GHG TT meetings. The information collected from these exchanges could be communicated to stakeholders, such as IMEO MARS, who can use it for implementing tip-and-cue operations.

Another key objective of this theme is identifying ongoing or emerging measurement gaps. There is a potential risk for near-term gaps, since all of the first-generation Global Mapping missions are well beyond their design lifetimes and the next-generation missions have been delayed. Other measurement types that are growing in importance are not currently in any agency's plans. For example, GHG observations from GEO and HEO could make unique contributions including rapid revisits and sampling across the daylight parts of the diurnal cycle. High-sensitivity active LiDAR missions (e.g., DQ-1, MERLIN) could make unique contributions for monitoring CO_2 and CH_4 fluxes at high latitudes during polar winter and at nighttime, but additional research into their calibration, retrieval algorithms and validation is needed to fully exploit their potential. In addition, sensors optimised to quantify CO_2 and CH_4 fluxes over wetlands, inland water bodies, and ocean are not yet in any agency's plans. Similarly, GHG monitoring systems with the combination of spatial resolution and sensitivity needed to quantify sector-specific, or at least localised GHG emissions over large urban areas are not yet planned either. These gaps should be tracked at annual AC-VC meetings and GHG TT meetings. Both civil-space and New Space opportunities, to close these gaps, should be explored.

5c. Calibration and Level 1 Products

To retrieve XCO_2 or XCH_4 from space-based observations of reflected sunlight, these data must first be time-ordered, geo-located, and then combined with radiometric, spectroscopic and geometric calibration data to yield calibrated radiances expressed in geophysical units (e.g., Watts per square metre per steradian per micron). The calibration data needed to perform these functions is typically collected prior to launch, where the sensor performance can be referenced to commonly accepted reference standards. The instrument performance is then tracked throughout the mission lifetime by collecting dedicated calibration observations of radiometric transfer standards or other targets. The algorithms that use this information to produce radiometrically and spectroscopically calibrated, geolocated radiances are called Level 1 (L1) algorithms and the calibrated, geolocated products generated by these algorithms are called L1 products.[8]

While the details of the pre-launch and in-orbit calibration measurements are often sensor specific, the traceability of these measurements to commonly accepted reference standards, with known uncertainties quantified, is critical to their down-stream use to retrieve trace gas abundances or fluxes. This information is even more essential in operational applications that must combine data from multiple sensors to improve resolution or coverage or extend the data record beyond the operating lifetime of a single space-based sensor. For these applications, multiple sensors must be cross-calibrated throughout their operating lifetimes.

For public-sector missions, the pre-launch and on-orbit calibration methodology, standards, products and associated calibration algorithms are typically documented in Algorithm Theoretical Basis Documents (ATBDs) and in refereed scientific publications. The information included in these documents is necessary, but not always sufficient for maintaining an instrument's calibration throughout its lifetime or cross-calibrating its L1 products with observations collected by different sensors. A variety of methods for addressing these needs were pioneered through active collaboration among the teams operating the first generation of dedicated GHG missions. These included:

- Direct comparisons of radiometric standards and transfer standards used in pre-flight calibration experiments;
- Comparisons of routine observations of astronomical standards, including the Sun and Moon at wavelengths within the common spectra ranges used for O_2, CO_2 and CH_4 observations;
- Near-simultaneous observations of vicarious calibration sights, such as Railroad Valley, Nevada, conducted in conjunction with joint surface field campaigns.
- Comparisons of near simultaneous observations of pseudo-invariant calibration sites (PICS) and other surface targets of opportunity; and
- Exchange of reference solar spectra and gas absorption cross-section data used to analyse in-orbit calibration observations.

Initially, these activities were managed through bi-lateral and then multilateral agreements among specific missions. More recently, these activities have become key activities within the CEOS Working group on Calibration and Validation Atmospheric Composition Subgroup (WGCV/ACSG) and the

[8] https://www.earthdata.nasa.gov/engage/open-data-services-and-software/data-and-information-policy/data-levels

WMO/CGMS Global Space-based Inter-Calibration System (GSICS) Visible and Near Infrared Subgroup (VIS/NIR) subgroup and have been tracked by the GHG TT at their annual meetings.

As this field transitions from research to operations, interoperability of L1 products will become increasingly important. The GHG TT and its partners in WGCV and GSICS should:

- Identify and encourage sharing pre-launch radiometric, spectroscopic and geometric standards and methodology for their use in calibrating GHG sensors
- Coordinate efforts to refine spectrally dependent radiometric and spectropolarimetric standards for the Moon;
- Establish best practices for in-flight solar and lunar calibrations for GHG sensors;
- Contribute to the advocacy and coordination of routine vicarious calibration campaigns;
- Compare radiances from nearly simultaneous and co-incident observations by different GHG sensors for various surface types under the defined co-incident condition and assess the spatial-temporal consistency of the spectral radiance from these sensors; and
- Define common metadata requirements for L1 products to facilitate interoperability.

5d. Level 2 Products and Validation

The increasingly stringent requirements on precision, accuracy, resolution and coverage are increasing demands on Level 2 (L2) retrieval algorithms. The L2 algorithms developed for the first generation global GHG mappers (GOSAT/OCO/Sentinel-5P TROPOMI) demonstrated end-to-end single-sounding precisions and accuracies better than 0.25 – 0.5%. Future global mapping sensors will need to reduce single sounding random errors to improve the detection of weak extended sources and sinks. They will also need to demonstrate zero net bias on spatial scales spanning large urban areas to nations for use in emission inventories.

Sensors and algorithms optimised to detect and quantify emissions from intense plumes have somewhat less stringent requirements on precision and accuracy, but these are still drivers for their L2 algorithms. In these applications, single-sounding random errors limit the ability to detect a plume and distinguish it from the surrounding background. The end-to-end accuracy of the L2 algorithm limits the ability to quantify amplitude of resulting XCO_2 or XCH_4 anomalies and the associated emission rates.

In all of these applications, the computational expense of L2 algorithms will have to be reduced to meet emerging demands for increased spatial and temporal resolution, latency, and coverage. For example, each of the three satellites in the Copernicus CO2M Constellation collects about 20 times as many observations as the OCO-2 mission and the expense of the L2 processing dominates the science operations budget for OCO-2. The high-spatial-resolution hyperspectral imagers used for facility-scale observations place even greater demands on L2 algorithm speed, due to the density of the data they can return.

The most accurate L2 algorithms employ physics-based (a.k.a. “full-physics”) forward radiative transfer (RT) models that can explicitly simulate the impacts of absorption and multiple scattering by gases, airborne particles (aerosols, clouds) and the surface on the observed radiation field. These models are typically convolved with an instrument model that simulates the instrument’s spectral response function, signal-to-noise ratio, polarisation, etc. to yield synthetic spectra that can be compared observations. These simulated spectra are then analysed with an inverse model that uses a constrained least-squares approach (e.g., Optimal Estimation or Tikhonov Regularization) or other methods (e.g. Markov Chain

Monte Carlo) to optimise the atmospheric and surface properties (e.g., GHG mixing ratios, airborne particle abundances and distributions, surface reflection) to improve the fit between the simulated and observed spectrally dependent radiances. The principal limitation of these models is their computational expense. In spite of this, full-physics models are typically used for retrieving XCO_2 and XCH_4 estimates from global GHG mappers due to their need for high accuracy.

In some applications, the full-physics L2 algorithm can be replaced by faster "proxy" methods that simulate the absorption of sunlight by gases, but do not explicitly include multiple scattering. Instead, the absorption by a reference gas, whose concentration is known, is used to assess the impacts of multiple scattering on the atmospheric optical path lengths. For example, molecular oxygen (O_2) might be used as a proxy gas for retrieving XCO_2 or CO_2 might be used as a proxy gas for retrieving XCH_4. Because they do not explicitly simulate multiple scattering, these methods can be orders of magnitude faster than full-physics methods. These models can produce reliable results when the absorption bands of the target and proxy gases are spectrally nearby and the abundance of the proxy gas is very well known.

More recently, some researchers have replaced the physics-based RT models in their L2 algorithms with data-driven methods including matched filter and machine learning (ML) techniques. These methods can be trained using the output of full-physics RT codes or combinations of measured spectra with column-average estimates from inverse models having assimilated surface air-sample measurements. The primary attraction of this approach is its potential for yielding large improvements in computational speed. In principle, it can also yield adequate precision and accuracy as long as the training set spans the full range of atmospheric, surface, and illumination conditions observed by the GHG sensor. The latter makes the continuous and large-scale availability of data provided by full-physics or equivalent L2 algorithms a prerequisite for the use of cost-efficient ML-based GHG retrieval schemes.

The precision, accuracy and coverage provided by GHG sensors is currently limited primarily by two L2 algorithm shortcomings. The first, and most fundamental, is uncertainties in gas absorption cross sections. The second is uncertainties in the atmospheric optical path lengths travelled by the light detected by the GHG sensor, introduced by multiple scattering by airborne particles (clouds, aerosols) or the surface.

To mitigate errors associated with uncertainties in gas absorption cross sections, both additional laboratory measurements and more advanced analysis techniques are needed to improve the accuracy and range of validity of these critical data. International coordination of GHG laboratory measurements and analysis efforts is critical to meet the needs of CEOS, CGMS and their stakeholders, because there are a limited number of laboratories that can produce these data and these laboratories do not always have the analysis tools needed to produce the products needed to support the precision and accuracy requirements of GHG applications. In addition, common standards for line parameter and cross section database structure, format, and metadata are needed to improve interoperability of these data products. Working with AC-VC, the GHG TT could have a significant impact on the coordination of these efforts.

More structural changes in L2 algorithms will be needed to mitigate uncertainties introduced by clouds and aerosols. These uncertainties are driven primarily by two factors. The first is the use of approximations or simplifications adopted to improve computational speed. For example, the forward RT models might neglect polarisation or 3-d effects (e.g., cloud reflections or shadows in cloud-free footprints). The second problem is that the information content of the spectra returned by space-based sensors is not adequate to fully optimise their distributions and optical properties. Because of this, many algorithms include relatively simple and restrictive cloud and aerosol retrieval schemes that contribute biases and quasi-random error in GHG retrievals. It might be possible to address both of these limitations with hybrid methods that combine physics-based methods with ML-based methods. In addition, it should be possible to increase the information content of data by augmenting the GHG observations with ancillary measurements by dedicated cloud and aerosol sensors, like those incorporated in the CO2M payloads. However, more advanced L2 algorithms that fully exploit the information from these sensors are still under development and have not yet been tested on real data.

Finally, as this field progresses from research to operations, interoperability of L2 algorithms will become increasingly important. To date, a small number of individual groups have been responsible for the development and use of L2 algorithms in custom data pipelines for specific science missions. Algorithms that are more flexible, modular, and sustainable will be needed for operational applications. This will require common standards for data input and output formats, publicly available documentation, standard metadata content and other updates that have not been supported for individual science missions.

CEOS and CGMS could contribute both to the advocacy and coordination of efforts focused on L2 GHG algorithm improvements. Advocacy is critical because there is currently very little support for GHG laboratory spectroscopy or L2 algorithm development across CEOS and CGMS agencies. Coordination is critical because the scope of work is large and the available, trained workforce is limited. A focused effort is needed to meet the increasing demands on L2 algorithms by future missions and their stakeholders. For example, L2 algorithm intercomparison activities have yielded rapid progress in this field in the past, and should become a regular feature of these coordination efforts.

L2 Product Validation

The stringent requirements for XCO_2 and XCH_4 precision and accuracy place demands on the data product validation requirements. To meet these needs, the first generation of space-based GHG sensors routinely validated through comparisons with co-incident, ground-based remote sensing estimates of XCO_2 and XCH_4 derived from Total Carbon Column Observation Network (TCCON) observations. TCCON observations were then related to the WMO *in situ* standards by collecting CO_2 and CH_4 measurements over TCCON stations using high-altitude aircraft carrying *in situ* sensors (Wunch et al., 2011; 2017) and more recently by AirCores (Karion et al., 2010). Since its inception in 2004, the TCCON network has grown to more than two dozen stations spanning latitude between Lauder, New Zealand (45.038°S) and Eureka, Canada (80.05°N). This validation approach fostered the development of L2 product bias detection and correction methods that routinely return XCO_2 accuracies better than 1 ppm (0.25%) and XCH_4 accuracies better than 10 ppb (0.5%; c.f., O'Dell et al., 2018).

The spatial coverage provided by TCCON has recently been augmented with smaller, portable spectrometers in the COCCON network (Frey et al. 2019). These sensors are not as precise or accurate as the TCCON spectrometers, but are portable enough to be deployed in a broader range of locations or in networks to validate spatially resolved space-based GHG observations over specific targets, such as large urban areas. These instruments are also being used to form the basis of a national ground-based GHG remote sensing networks like those in the UK (Humpage, N., et al., 2024) and in the U.S. by the US Greenhouse Gas Center[9], complementing the existing in situ network. The observational

9 https://nspires.nasaprs.com/external/viewrepositorydocument/cmdocumentid=983604/solicitationId=%7B0FD

capabilities of the Network for the Detection of Atmospheric Composition Change (NDACC) have also been expanded to provide e.g. routine validation of Sentinel-5P TROPOMI XCH_4 over two dozen stations from New Zealand to the Arctic (De Mazière et al., 2018; Sha et al., 2021).

This validation approach worked well for the first generation of space-based globalGHG missions, but must be sustained and expanded to support the increasing demands on GHG precision and accuracy. The sustainability of critical GHG validation networks (TCCON, COCCON, NDACC and AirCore) has been an issue since the beginning of the era of space-based GHG measurements. The primary issue is that the individual stations in these networks are supported as science experiments funded through competitive proposals to individual PIs. This funding and management model has proved adequate for supporting individual GHG science missions, but is not adequate to support the operational validation of products, like those required by WMO G3W. The current approach can also have relatively long data latency periods (greater than one year), reducing the utility of these products for validating space-based products used for inventory development or near-real-time alerts.

While the existing validation approach has been adequate to demonstrate precisions and accuracies as high as 0.25%, much greater precisions and accuracies will be needed to detect changes in XCO_2 or XCH_4 associated with policy changes on politically relevant timescales or to track changes in regional-scale natural land or ocean fluxes associated with human activities or climate change on sub-decadal time scales. To do this, and to produce useful space-based constraints on ocean carbon fluxes, the validation system must reduce biases by a factor of five. This goal does not necessarily require any new technology, but it will require an expanded validation network, improved ground-based data evaluations and more focused validation campaigns. In particular, additional TCCON stations that sample ocean environments are needed to validate space-based XCO_2 and XCH_4 estimates over the ocean. The deployment of a travelling standard is needed to improve mutual consistency across and among the three networks. Vertical profiles of CO_2 and CH_4 from AirCore and aircraft-based sensors are needed to calibrate the ground-based observations of XCO_2 and XCH_4 and to validate fluxes derived from space-based XCO_2 and XCH_4 estimates.

The validation of CO_2 or CH_4 concentration enhancements associated with discrete plumes from facility-scale sources poses a different set of challenges. In principle, these enhancements can be quantified with *in situ* measurements from surface, tower and airborne sensors, but a large number of such measurements might be needed to sample the plume and accurately quantify its rapidly changing concentration gradients. Alternatively, under ideal conditions (e.g., known, constant fluxes, steady winds, simple topography), concentration enhancements associated with plumes can be estimated if the fluxes and wind speeds are accurately measured. These and other approaches should be explored for validating CO_2 and CH_4 enhancements associated with discrete, facility-scale plumes.

A focused commitment by CEOS and CGMS could contribute substantially to both advocacy and coordination of ground based validation networks deployments and campaign activities. CEOS agencies are the primary beneficiaries of these validation efforts, but they are often implemented by partners and affiliates in other government agencies, research institutions or universities. The GHG TT should work closely with these organisations to advocate for their funding, recommend deployment sites and data quality evolutions, and organise validation campaigns.

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5e. Flux Inversion Modelling and Validation

Inverse modelling of surface-atmosphere exchange is the primary mechanism to relate observed GHG concentration variability to the underlying fluxes. With global space-based observations inverse modelling can directly relate regional carbon fluxes to the global GHG growth rates. Furthermore, ancillary measurements from satellites, e.g., solar induced fluorescence, CO, and NO_2, support the attribution of GHG to specific processes and sectors. CEOS and CGMS members have already played a crucial role in the development and application of inverse modelling to satellite data. Through CEOS support, an ensemble of inverse models constrained by satellite data provided country-scale flux estimates as a contribution to the global stocktake (Byrne et al, 2023). Similarly, GOSAT CH_4 enabled quantification of country emissions with sectoral decomposition (Worden et al, 2023). CEOS and CGMS will support a substantial increase in the GHG observing system that will offer new opportunities and pose new challenges.

GHG observations over the past decade have been dominated by Global GHG Mappers, such as GOSAT and OCO-2. These were designed to quantify the global carbon cycle on regional scales. These will continue to anchor the global space-based GHG observing system, but will be augmented with much greater spatial resolution and coverage by instruments such as CO2M. The focus of this constellation has shifted towards supporting international agreements such as the Paris Agreement through national and international efforts including the WMO G3W. Gridded fluxes derived from inverse modelling and constrained by CEOS satellite data will be expected to support these efforts. However, these fluxes will likely be substantially different in some regions depending on the CEOS and CGMS satellites used and specific inverse models used. The attribution of these differences to satellite sampling, instrument systematic errors, and retrieval methodology will require extensive CEOS and CGMS engagement. The validation of fluxes at larger regions typical of global inversions remains a considerable challenge. Methods for indirect validation against concentration data from independent data continue to advance but require a separate observing system of in-situ and aircraft data. CEOS and CGMS will benefit from coordinating with institutions managing these systems and supporting them where possible, e.g., NASA ATom and ACT-America.

Complementing global measurements, facility-scale measurements of enhanced GHG from imaging spectrometers such as EMIT or Fabry-Perot interferometers such as GHGSat are revolutionising GHG monitoring of point sources. While data from these instruments are already being used to remediate fugitive emissions, the application of inverse modelling to determine emissions over long periods of time, e.g., monthly, are still nascent. Reconciliation of inverse modelled emission estimates face similar challenges as global inversions with differences in instrumental sampling, bias, and retrieval methods as well as transport uncertainty, inverse model methodology, etc. However, inverse modelling can benefit from controlled-release experiments, where the emissions are known a priori (e.g., Simmonds et al, 2021). These can be used to calibrate multiple observations of a facility to develop GHG emission budgets for point sources.

Between global and facility scales are urban and basin. Inverse modelling has been used to estimate both using instruments such as OCO-3, Sentinel-5P TROPOMI and MethaneSAT. However, point sources can have a substantial impact on urban budgets. Mesoscale and microscale models (e.g., Wu et al., 2018; Brunner et al., 2023) can simulate the transport on these scales, but methodological advances in inverse modelling are needed to fully exploit the information provided by high-resolution satellite measurements. Validation of fluxes on this range of scales is more challenging.

Inverse modelling is the primary mechanism of mediating CEOS and CGMS GHG measurements to scientific and policy needs. Limitations from atmospheric transport, spatial resolution, computational capacity, and methodological approaches directly impacts CEOS and CGMS GHG objectives.

Consequently, CEOS and CGMS can articulate the value and support where possible advancing inverse modelling.

CEOS and CGMS instruments will be a pillar of local, regional, and global GHG information systems. This foundation will require advances in (1) intercalibration of CEOS and CGMS data (2) inverse modelling, (3) an independent observing system for validation. CEOS and CGMS should play a leadership role in (1) and a supporting role in (2) and (3).

5f. Best Practices

Recent advances in remote sensing have led to the development of greenhouse gas emissions and flux products that are increasingly used by stakeholders in the policy community. In addition to these public sector stakeholders, space-based remote sensing observations are being used by an increasingly diverse range of stakeholders in the private sector. These include national and international financial organisations, such as the World Bank, who use this information for assessing climate adaptation and sustainable development projects. Others include representatives of the fossil fuel industry, who use this data to monitor and mitigate emissions associated with the extraction, processing or distribution of natural gas.

Emissions estimates are being provided by an increasing number of missions, both public and private (New Space). The advent of New Space measurements and the increasing use of their products by the aforementioned stakeholders also necessitate a “quality” assessment of products that do not always report the entirety of the data chain from the observations (L0) to estimated emission fluxes (L4) or document the algorithmic basis or quality metrics for the corresponding algorithms. A quality assessment is also needed to harmonise, integrate, archive and distribute these emission products by organisations such as Europe’s CAMS and the the U.S. Greenhouse Gas Center, It would also support the Enhanced Transparency Framework of the Paris Agreement and foster the use of space-based GHG products in national inventories.

To standardise best practices for emissions quantification, reporting, and validation, the GHG community, through the CEOS identified a need for a “Best Practices” document that outlines community-accepted practices from L0/L1 (radiance) to L2 (concentration) to L4 (emissions). The Best Practices document also describes the state-of-the-art for validating facility-scale emissions estimates, and provides a template for assessing the quality of the reported emission products. This Best Practices effort, initially focuses on estimates of facility-scale methane concentration plumes and corresponding emissions at spatial scales of ~10-100 metres. A follow-on document will describe the Best Practices for estimating, reporting, and validating area fluxes of both CO_2 and CH_4 to support the global Stocktake and other applications.

5g. System Development

The mission of CEOS is to ensure international coordination of civil space-based Earth observation programs and to promote exchange of data to optimise societal benefit and inform decision making for securing a prosperous and sustainable future for humankind. In that context, the primary objective of the GHG Roadmap was to coordinate efforts across CEOS and CGMS agencies to maximise the quality, utility, transparency and continuity of space-based GHG products for science and policy applications. Its ultimate goal was to facilitate the development of a fit-for-purpose operational system that integrates space-based GHG estimates with ground-based, airborne and shipborne observations to address the needs of a broad range of stakeholders in the science, policy, regulatory and private sectors.

However, the landscape of new initiatives in this domain is rapidly evolving, requiring some adaptation of the aims for this updated roadmap. Various national and international activities to monitor greenhouse gas fluxes and emissions are being developed. Examples are the European Copernicus GHG MVS, the UK GHG measurement framework, the activities coordinated by the U.S. Greenhouse Gas Center, and the German Integriertes Treibhausgas-Monitoring-System (ITMS), among several others. These systems all have their own aims but share many requirements for their inputs. The development of one overall fit-for-purpose operational system is therefore not the best use of resources. Instead, the coordination of international efforts is becoming progressively more important. This should include all aspects, such as the planning of virtual satellite constellations, efficient data exchange, consistent evaluation and benchmarking, sharing of expertise, and consistent communication.

With emerging global initiatives, such as the Global Greenhouse Gas Watch (G3W) of WMO and the International Methane Emissions Observatory of UNEP, it also has become more important to align the various coordination activities as much as possible. The primary focus of CEOS is the coordination of the provision of the required satellite data that all greenhouse gas monitoring systems need. This does not only include observations of atmospheric concentrations of the main greenhouse gases, but also observations that provide information about the other parts of the carbon cycle and methane budget, such as the land surface and the marine environment. This directly links to for instance the AFOLU Roadmap. CEOS and CGMS should therefore engage with the main international coordination frameworks, such as G3W, IMEO, and the GCP, to ensure the satellite data requirements are well understood and can be used for further development of the space component. In addition, efforts should be taken to engage with national and multi-country efforts, most likely through the relevant space agencies within CEOS and CGMS.

5h. Capacity Building

Even products with high quality and value cannot be effectively used without capacity development and outreach activities. The pilot CO_2 and CH_4 flux products were under-utilised for the first GST, which was partly due to the lack of understanding of the products and their utility. To facilitate the uptake of these data products by the NGHGI communities and other users, training materials/courses and a step-by-step guidance for the NGHGI are needed on how to use them to support the bottom-up inventory development and validation. These capacity building goals can be achieved by utilising existing CEOS and CGMS capacity-building channels.

The CEOS Communication channels can be exploited to support these efforts. The CEOS System Engineering Office (SEO), led by NASA, hosts the CEOS Communications Team, which runs social media channels on X/Twitter, LinkedIn and Facebook, alongside the blog posts at ceos.org/news. These channels should be used to ensure CEOS products and efforts in the GHG domain are understood by the communities who are target users for the data. The CEOS Communications Team welcomes any contributions of content from the CEOS Community to highlight specific areas of work.

The SEO also regularly hosts CEOS Exhibition Booths at major community events such as IGARSS, GEO Week (now GEO Forum) and Living Planet Symposium (LPS). These events are a great way to hand out physical materials to broader EO community members, and a dedicated GHG flyer could be created if desired. The CEOS Communications Team could also support the development of GHG-related materials for agencies to have on hand at their respective centers during the annual UNFCCC COPs.

The Working Group on Capacity Development and Data Democracy (WGCapD) has set up the CEOS Training Calendar (training.ceos.org). This is a community resource, and provides a central place to find training events on all topics relating to Earth observation data. Any events provided by individual agencies on the topic of GHGs should be entered into this database to ensure they can reach as broad an audience as possible.

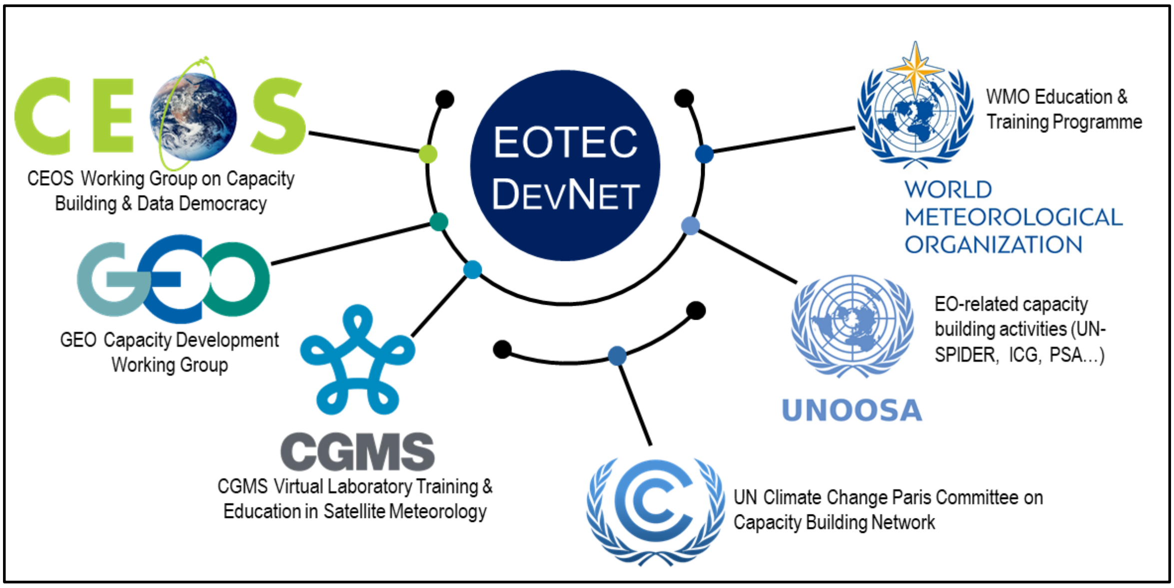

Figure 7: EOTEC DevNet partners

In addition, the Earth Observation Training Education and Capacity Development Network (EOTEC DevNet) brings together 1,000+ colleagues from across the CEOS, GEO, UNOOSA, WMO and CGMS VLab network (Figure 7). Its aim is to extend the reach of EO capacity building and increase the use of EO in decision-making. A central effort is collaboration among EO capacity building providers through regional communities of practice, thematic working groups and an online member platform. While its initial focus has been disaster risk reduction, EOTEC plans to engage members in Climate Adaptation capacity building in 2025, including a climate adaptation working group. That work will include raising awareness of CEOS-CGMS WGClimate and GHG Roadmap efforts to increase uptake of GHG products.

6. Coordination Across CEOS and CGMS Working Groups and Carbon Roadmaps

In this section, the high-level roles of the entities that are contributing to the implementation of the actions are recalled, thereby providing the reference point for associating implementing entities to be involved with the detailed implementation actions, which will be provided in in Annex C. As was already described in section 2, WGClimate was tasked and has formed a dedicated GHG TT coordinating the implementation of the GHG Roadmap. WGClimate was selected because it is the only joint working group of CEOS and CGMS, with direct links for reporting and approval and for integrating and balancing the work plans of both CEOS and CGMS. It also has an existing well-working interface with UNFCCC, SBSTA, and GCOS, representing CEOS and CGMS, providing insight to the space agencies' activities to the primary user communities. This included establishing appropriate links and cross-representation with AC-VC, WGCV and other CEOS and CGMS entities such as GSICS, and identifying the resources needed to execute the actions identified in this roadmap. The 32nd CEOS Plenary and the 47th CGMS Plenary endorsed the revision of the Terms of Reference of WGClimate to accommodate these changes.

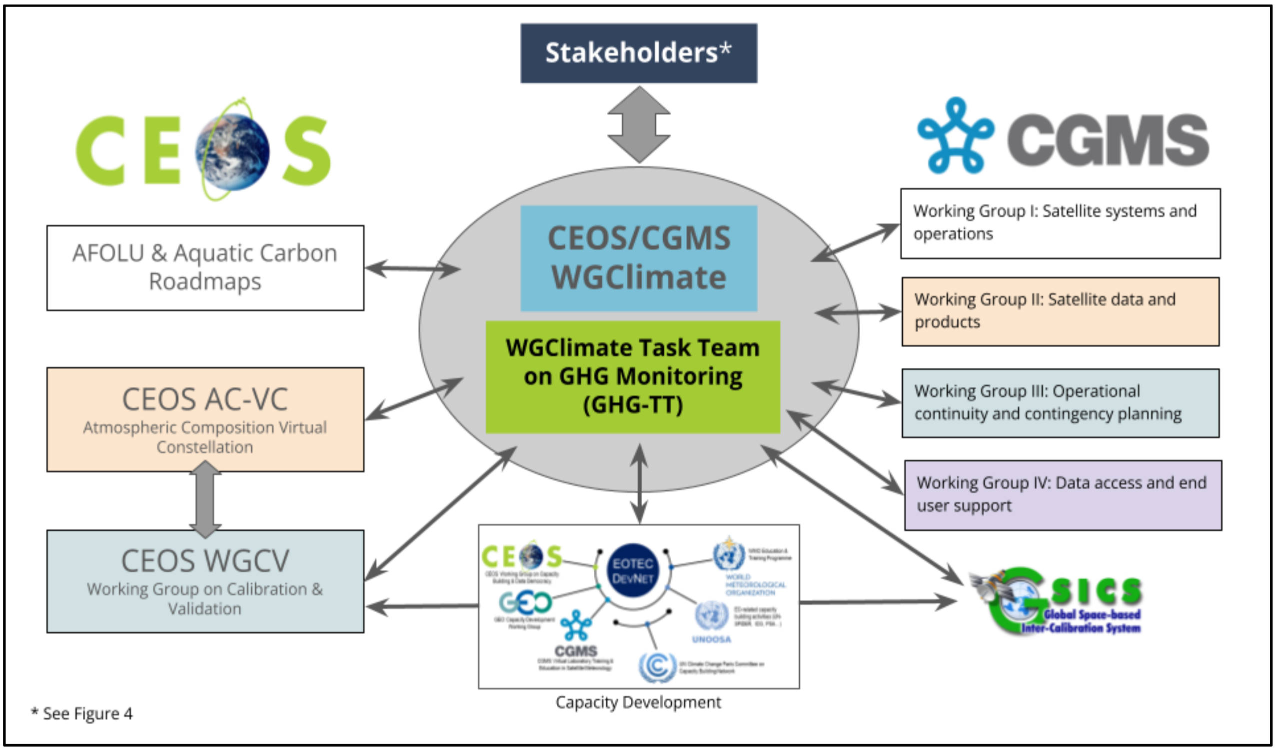

Figure 8: CEOS, CGMS and WMO GSICS entities currently included in the task team. At a later stage, additional entities may contribute. For interactions with Stakeholders, see Figure 4.

6a. Joint CEOS and CGMS Implementing Entities

The GHG TT is an internal mechanism within the joint CEOS-CGMS WGClimate. The respective roles of WGClimate and the GHG TT are described in the following subsections and summarised in Figure 8.

WGClimate

CEOS and CGMS gave the mandate to WGClimate for the implementation of the GHG coordination activities. WGClimate has the responsibility to report on the GHG Roadmap implementation at CEOS and CGMS Plenaries. In addition, and in synergy with this GHG coordination role, WGClimate represents CEOS and CGMS in all matters regarding climate.

Thus, in order to support the implementation of the GHG monitoring activities, WGClimate shall:

- Supervise the GHG TT and the implementation of the GHG Roadmap and report on its progress to CEOS and CGMS principals;
- Continue to be the effective interface to UNFCCC, UNEP, IPCC, GCP, GCOS, and WCRP and provide links to the WMO G3W and IG3IS. Engage with these communities and report CEOS-CGMS activities at their meetings;
- Oversee and coordinate the implementation of the CEOS Carbon Strategy;
- Promote the GHG coordination activities at CEOS and CGMS bodies and stimulate the participation of member agencies and – if needed – additional entities.
- Promote the space-based GHG and AFOLU products to national inventory compilers and COP delegations to foster proponents for these products.

GHG TT

To support this effort, the GHG TT shall:

- Develop and maintain the roadmap defining the overall distributed work plan;
- Coordinate all CEOS and CGMS efforts needed to execute all the necessary actions, including those designed to implement the recommendations of the GHG Whitepaper;
- Exploit the complementary viewpoints of CEOS and CGMS to advance the implementation of a system that incorporates both research and operational elements in cooperation with WGClimate;
- Ensure the critical link to the diverse user communities, with a particular focus on product co-development with the national inventory community, to ensure the uptake of the products provided;
- Actively ensure representation of CEOS and CGMS bodies by identifying Points of Contact (PoCs) for tasks to be executed by these bodies (AC-VC, WGCV/ACSG, GSICS/VIS-NIR WG, etc.)
- Encourage additional CEOS and CGMS agencies representation on the GHG TT to ensure a complete representation of the GHG missions and that technical expertise is provided to facilitate the system level competence and linkages to the modelling and inventory communities; and;
- Support WGClimate in embedding the user requirements into the respective gathering process of GCOS and IPCC TFI and facilitate the development of system requirements for the operational system;
- Report on a regular basis to the WGClimate Chair about progress and achievements.

The GHG TT has been formed to execute the coordination activities with a balanced representation of the involved entities (see Annex A for the current constitution of the GHG TT). To avoid duplication of structures and activities of the contributing bodies, the roadmap development makes use, as appropriate, of the existing individual work plans of the different contributing bodies.

This coordination activity is expected to require some additional effort by WGClimate, WGCV, AC-VC, GSICS, and other CEOS and CGMS entities.

6b. CEOS Entities

Initially, the Atmospheric Composition Virtual Constellation (AC-VC) and the Working Group on Calibration and Validation (WGCV) have been identified as contributing CEOS entities. However, at a later stage, the know-how of other CEOS bodies could provide very valuable contributions. For example, future collaboration with the Working Group on Information Systems and Services (WGISS) and the CEOS Analysis Ready Data (CEOS-ARD) Oversight Group are cited below. Additionally, a close collaboration with the CEOS WGCapD, and CGMS and WMO Virtual Lab that could facilitate the engagement in required capacity building activities related to, e.g., the usage of GHG inventory products by national inventory compilers.

Atmospheric Composition – Virtual Constellation (AC-VC)

AC-VC has not only been the driver and lead author of the GHG Virtual Constellation White Paper, but combines the research elements on GHG flux emission derivation together with the mission definitions in its portfolio. Thus, the AC-VC is the natural core element to evolve the research but also to support the implementation of the GHG focus within WGClimate including:

- Space borne GHG sensor development;
- GHG retrieval algorithm development and product development;
- Contributions to atmospheric GHG flux inversion model development;
- Data type definition that must be exchanged to derive and validate fluxes from a constellation of space-based sensors to facilitate open data access; and
- Contributions to the establishment of end user and system requirements for the pilot datasets and operational system.

Working Group on Calibration and Validation (WGCV)

The WGCV Atmospheric Composition Subgroup (ACSG) has cooperated closely with the AC-VC on the Virtual Constellation White Paper on the Geophysical Validation Needs for the Geostationary Satellite Constellation for Observing Global Air Quality. We anticipate that WGCV/ACSG will conduct a similar effort to develop a comprehensive calibration and validation strategy and to document lessons learned and best practices for the CO_2 and CH_4 constellation. It is expected that WGCV/ACSG will support the implementation of methods and procedures into the operational system by WMO/CGMS GSICS. WGCV/ACSG areas of expertise are:

- Pre- and post-launch calibration of individual sounders;
- Monitoring in-flight instrument performance;
- Methods for inter-calibration of satellite instruments;
- Methods and protocols for the validation of the level 2 products;
- Fiducial Reference Measurements of atmospheric composition, including support to network design and evolution;
- Operational systems for calibration and validation;
- Tying the satellite measurements to absolute references and standards; and
- Cal/Val contributions to the establishment of end user and system requirements for the pilot data sets and operational systems.

Working Group on Information Systems and Services (WGISS)

The GHG Roadmap adopts the Interoperability Framework, which was endorsed by CEOS Plenary in 2023. This Framework defines five factors of interoperability:

- **Vocabulary (Semantics)**: The (narrow) semantic aspect refers to the naming and meaning of data elements. It includes developing, harmonising, and maintaining vocabularies and schemata supporting provision, exchange, and analysis of data, and ensures that terms and data elements are understood in the same way by all communicating parties
- **Architecture:** Architecture describes the organisational structure of concepts, processes, and assets, including data and workflows. It comprises of the structural aspects of models and standards that govern the collection, storage, arrangement, integration, and use of data
- **Interface (Accessibility):** Data exchange protocols, and application interfaces. These provide the means necessary to access and exchange data.
- **Quality:** References of data and schemes that are used as benchmarks for (observational) data comparison or analysis. This could include instances such as geographic locations, product numbers, or official (authoritative) data and statistics.
- **Policy:** Legal frameworks, policy and strategies regulating the relation between the different stakeholders.

The GHG Task Team will collaborate with WGISS to ensure the definition of interoperability produced by CEOS is compatible with the needs of the GHG community.

CEOS Analysis Ready Data (CEOS-ARD)

The CEOS-ARD concept defines Analysis Ready Data to be:

"satellite data that have been processed to a minimum set of requirements and organised into a form that allows immediate analysis with a minimum of additional user effort and interoperability both through time and with other datasets."

The CEOS-ARD Framework builds off Product Family Specifications (PFS).
The GHG TT will work with the CEOS-ARD Oversight Group to define PFS for GHG flux products. The framework also allows products to be assessed against the specifications, to become certified as CEOS-ARD compliant.

6c. CGMS Entities

CGMS Working Groups

CGMS Working Groups I - IV cover a broad range of required competences and therefore each can provide a valuable contribution to different areas of the GHG Roadmap implementation. The current focus of these working groups include:

- Working Group I: Satellite systems and operations
- Working Group II: Satellite data and products
- Working Group III: Operational continuity and contingency planning
- Working Group IV: Data access and end user support

The CGMS working groups could make significant contributions to the GHG Roadmap. For example, involvement of CGMS Working Group-I could help to ensure that the implementation of the GHG roadmap addresses the objectives of the WIGOS vision. Interactions with CGMS Working Group-II could facilitate the definition and application of standards for operational GHG constellation products and operational aspects of the satellite data production systems at international level. CGMS Working Group-IV could address operational access and end user support for GHG constellation products in cooperation with CEOS WGISS.

Global Space-based Inter-Calibration System (GSICS)

GSICS is an international collaborative effort initiated in 2005 by the WMO and CGMS to improve and to harmonise the quality of observations from operational weather and environmental satellites of the WMO Integrated Global Observing System (WIGOS). GISCS is regularly reporting to the CGMS Working Group II.

Through its Reflective Solar Spectrometers Subgroup (UVSG) it is closely cooperating with CEOS WGCV by emphasising the aspects of harmonisation of calibration and pre-launch characterization. In addition, GSICS ensures due to its mechanisms the consistency of calibrated sensor data between different satellite systems. GSICS provides support (in close collaboration with WGCV) in the following areas:

- Operational monitoring instrument performance;
- Operational inter-calibration of satellite instruments;
- Enhancement of radiometric calibration sources such as solar irradiances and/or lunar radiances;
- Tying the measurements to absolute references and standards; and
- Contributions to the establishment of end user and system requirements operational systems.

CGMS Futures 2022+ Strategic Theme on Research to Operations

As part of a broad scale exercise to reassess its long-term activities, CGMS identified a small number of Strategic Themes to be analysed in detail. Among these was R2O - the work is being led by Working Group IV with support from Working Group II. NASA and NOAA agreed to co-champion the CGMS Futures 2022+ Research to Operations Pilot during the CGMS-51 Plenary in Tokyo, Japan. The short-to-medium term activities including a survey of CGMS Members to collect the R2O methods/experiences (in progress); proposing a consistent, flexible, and adaptable CGMS R2O Baseline Process to facilitate the participation of R&D agencies; and encouraging CGMS agencies to incorporate the R2O Baseline Process into their planning and to report on their experiences and challenges.

Responses to the survey are currently being collected and consolidated. Common approaches will be identified and captured as a set of Good Practices which will be proposed to CGMS for adoption, and used to coordinate the research to operations activities of members. The GHG TT can benefit from the definition of these Good Practices, thus providing a direct link between CGMS and CEOS.

6d. Coordination of Aquatic, AFOLU and GHG Carbon Roadmaps

Observations of the Earth collected by CEOS-CGMS agencies provide critical insights into impacts of human activities and climate change across the atmosphere, land surface and ocean carbon domains. This roadmap focuses on efforts to coordinate observations of CO_2 and CH_4. These two GHGs are responsible for about 90% of the observed global warming, and thus provide a direct link between the carbon cycle and the climate. These observations are already being used to provide top-down, integral constraints on the net emissions and removals of these gases by all anthropogenic activities and natural processes on spatial scales spanning individual facilities to large urban areas or forests to nations and the globe. They are therefore playing a growing role in efforts to manage GHG emissions. For example, they provide a direct measure of collective progress toward the goals of the UNFCCC's Paris Agreement. GHG flux budgets derived from atmospheric measurements can also be compared with national or regional totals derived from bottom-up inventories of emissions and removals of CO_2 and CH_4 to determine what fraction of their emissions can be attributed to known anthropogenic or natural sources and sinks.

However, observations of these two greenhouse gases, alone, are not adequate to monitor and manage the GHG emissions and removals and their contributions to climate change. While space-based measurements of CO_2 and CH_4 provide an integrated constraint on their net fluxes, they often do not distinguish the relative roles of different anthropogenic and natural processes that control their sources and sinks. This is particularly true for the land biosphere and ocean, which play critical roles in controlling the emissions and removals of these gases from the atmosphere. An improved understanding of land and ocean sources and sinks is critical for managing the atmospheric CO_2 and CH_4 concentrations or predicting their contributions to climate change.

Fortunately, observations collected by CEOS agencies also provide critical constraints on bottom-up inventories of GHG emissions and removals from both the land biosphere and ocean. Observations of land cover, vegetation indices, Solar Induced Fluorescence, above-ground biomass, and disturbance (e.g., wildfire burned area) provide critical constraints on land carbon stocks, and their changes over time, which provide process-specific insights into the emissions and removals of CO_2 and CH_4. Similarly, observations of ocean colour provide constraints on ocean carbon stocks, while observations of surface wind stress, temperature, salinity and topography provide information about ocean carbon transport. This information can be combined with *in situ* observations of ocean surface CO_2 partial pressure, pCO_2, to provide a bottom-up constraint on ocean carbon fluxes.

Recognizing the critical need for a better understanding of the land carbon cycle and its response to continuing human activity and climate change, the CEOS Land Surface Imaging Virtual Constellation worked with members of the land carbon cycle community to develop a CEOS Roadmap for Agriculture, Forestry, and Other Land Use (AFOLU). This roadmap was approved at the 37^{th} CEOS Plenary in 2023 and reviews existing and planned space-based observations of AFOLU, and the products that they will deliver. It then shows how this information can be used to quantify activity and estimate emission factors at increasing spatial and temporal resolution for the land biosphere, providing critical inputs to bottom-up inventories of emissions and removals of CO_2, CH_4, and N_2O from AFOLU.

Similarly, members of the CEOS ocean carbon community have initiated an effort to develop a CEOS Aquatic Carbon Roadmap. This roadmap reviews the roles of the open ocean, coastal blue carbon ecosystems, inland waters and the land-carbon continuum on the global carbon cycle. It then provides an overview of the existing and planned ocean observations focused on each of these domains, identifying gaps and opportunities. Key objectives include the development and delivery of products that will support scientific investigations of the impact of climate change on the critical ocean carbon sink and encourage the use of these space-based ocean carbon products to support the global stocktakes.

Recognizing these synergies, the CEOS SIT initiated an effort to coordinate activities across the GHG, AFOLU, and Aquatic Carbon Roadmaps. One approach for implementing this coordination would be to define a series of use cases that require contributions across the individual roadmap communities. For example:

- To what extent can space-based measurements of land use and land use change be combined with space-based measurements of greenhouse gases to produce a more complete and accurate description of emission and removals of GHGs from the land sector?
- Can space-based activity observations be combined with space-based GHG estimates to provide more realistic regional-scale constraints on emission factors associated with land use change and disturbance that could be used in bottom-up inventories?
- Can soil carbon fluxes be estimated accurately as a residual from AFOLU activity and atmospheric GHG observations?
- Can space-based observations of sea surface temperature, winds, salinity and ocean colour be combined with available *in situ* observations of ocean pCO_2 and carbon (DOC, DIC, etc.) to produce ocean models that better exploit available *in situ* data?
- How do we reduce the uncertainties on the transport of carbon between land ecosystems and the ocean? How is this carbon flux changing due to human activity and climate change?
- Can the GHG, AFOLU, and Aquatic Carbon teams work together with NGHGI community to co-define best practices for combining top-down and bottom-up data for using in inventory development and assessment?
- How can the GHG, AFOLU, and Aquatic Roadmap teams work with the CEOS SIT and the UNFCCC to coordinate their inputs to support the CEOS GST strategy?

Further, the three carbon related roadmaps require interaction with G3W and a coordinated effort could be beneficial. It is proposed to have regular meetings between the PoCs of each roadmap toward G3W and exchange on establishing effective interfaces for the collaboration with G3W.

ANNEX A. GHG Task Team Membership and Co-Authors

The GHG Task Team (GHG TT) is coordinating across various WGs, below is the current list of team members, their organisations and roles within the team. While the roles are less likely to change, the person in that role might change and this will be maintained online. The below list also reflects the list of co-authors of GHG Roadmap issue 2. In addition, mailing lists are maintained for both the broad GHG TT, as well as a smaller list for the Area Leads outlined in section 4. To be included in the mailing list, please contact the GHG TT lead. Contact information can be found online at the GHG TT webpage: https://ceos.org/ourwork/workinggroups/climate/ghg-tt/

Table A.1. Co-author list of GHG Roadmap issue 2

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ANNEX B. References Cited

Balasus, N., et al.: A blended TROPOMI+GOSAT satellite data product for atmospheric methane using machine learning to correct retrieval biases, Atmos. Meas. Tech., 16, 3787–3807, doi:10.5194/amt-16-3787-2023 (2023).

Basu, S. et al.: Estimating emissions of methane consistent with atmospheric measurements of methane and δ13C of methane. Atmos. Chem. Phys. 22, 15351–15377 (2022).

Bréon, F.-M., et al.: On the potential of a neural-network-based approach for estimating XCO_2 from OCO-2 measurements, Atmos. Meas. Tech., 15, 5219–5234, doi:10.5194/amt-15-5219-2022 (2022).

Brunner, D., et al., Evaluation of simulated CO2 power plant plumes from six high-resolution atmospheric transport models, Atmos. Chem. Phys., 23, 2699–2728, doi:10.5194/acp-23-2699-2023 (2023).

Byrne, B., et al., National CO_2 budgets (2015–2020) inferred from atmospheric CO_2 observations in support of the global stocktake, Earth Syst. Sci. Data, 15, 963–1004, doi: 10.5194/essd-15-963-2023 (2023).

Cao, X., et al., Averaging Scheme for the Aerosol and Carbon Detection LiDAR Onboard DaQi-1 Satellite. IEEE Transactions on Geoscience and Remote Sensing, 62, doi: 10.1109/TGRS.2024.3380639 (2024).

Ciais, P., Dolman, A.J., Dargaville, R., Barrie, L., Bombelli, A., Butler, J., Canadell, P., Moriyama, T., GEO Carbon Strategy. Geo Secretariat Geneva,/FAO, Rome, 48 pp. (2010).

Crisp, D., et al., 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_Constellations/ACC/Documents/CEOS_AC-VC_GHG_White_Paper_Version_1_20181009.pdf (2018).

Cusworth, D. H., et al. Quantifying Global Power Plant Carbon Dioxide Emissions With Imaging Spectroscopy. AGU Advances, 2, e2020AV000350. doi: 10.1029/2020AV000350 (2021).

De Mazière, M., et al. The Network for the Detection of Atmospheric Composition Change (NDACC): history, status and perspectives, Atmos. Chem. Phys., 18, 4935–4964, https://doi.org/10.5194/acp-18-4935-2018 (2018).

Doughty, R., et al. Global-Scale Consistency of Spaceborne Vegetation Indices, Chlorophyll Fluorescence, and Photosynthesis. Journal of Geophysical Research: Biogeosciences, 126, e2020JG006136. doi: 10.1029/2020JG006136 (2021).

Frankenberg, C. et al. Data Drought in the Humid Tropics: How to Overcome the Cloud Barrier in Greenhouse Gas Remote Sensing. Geophys. Res. Lett. 51, e2024GL108791 (2024).

Frey, M., et al., Building the COllaborative Carbon Column Observing Network (COCCON): long-term stability and ensemble performance of the EM27/SUN Fourier transform spectrometer. Atmospheric Measurement Technologies, 12, 1513–1530. doi: 10.5194/amt-12-1513-2019 (2019).

Friedlingstein, P., et al., Global Carbon Budget 2023, Earth Syst. Sci. Data, 15, 5301–5369, 2023. doi: 10.5194/essd-15-5301-2023 (2023).

GHG2020, GHG Roadmap, issue 1, doc. ref. WGCL/REP/20/1168457, version 2.3 (2020) https://ceos.org/observations/documents/CEOS_CGMS_GHG_Constellation_Roadmap_V2.3_cleaned.pdf

Hakkarainen, J., et al. Analysis of Four Years of Global XCO_2 Anomalies as Seen by Orbiting Carbon Observatory-2, Remote Sensing, 11, 850. doi:10.3390/rs11070850 (2019).

Hakkarainen, J., et al. Building a bridge: characterizing major anthropogenic point sources in the South African Highveld region using OCO-3 carbon dioxide snapshot area maps and Sentinel-5P/TROPOMI nitrogen dioxide columns. Environmental Research Letters, 18, 035003, doi: 10.1088/1748-9326/acb837 (2023).

Humpage, N., et al., GEMINI-UK: a new UK network of ground-based greenhouse gas observing spectrometers to help track progress towards net-zero targets, EGU General Assembly 2024, Vienna, Austria, 14–19 Apr 2024, EGU24-15956, doi:10.5194/egusphere-egu24-15956 (2024).

IPCC 2006, 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Prepared by the National Greenhouse Gas Inventories Programme, Eggleston H.S., Buendia L., Miwa K., Ngara T. and Tanabe K. (eds). Published: IGES, Japan.

IPCC 2019, 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, Calvo Buendia, E., Tanabe, K., Kranjc, A., Baasansuren, J., Fukuda, M., Ngarize S., Osako, A., Pyrozhenko, Y., Shermanau, P. and Federici, S. (eds). Published: IPCC, Switzerland.

IPCC AR6. Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge Univ. Press, 2022).

Jervis, D. et al. The GHGSat-D imaging spectrometer. Atmos. Meas. Tech. 14, 2127–2140 (2021).

Karion, A., et al., AirCore: An Innovative Atmospheric Sampling System, J. Atmos. Ocean. Technol., 27, 1839–1853, doi:10.1175/2010JTECHA1448.1 (2010).

Kiel et al., Urban-focused satellite CO_2 observations from the Orbiting Carbon Observatory-3: A first look at the Los Angeles megacity. Remote Sensing of Environment, 258. doi: 10.1016/j.rse.2021.112314 (2021).

Liu, J. et al. Carbon Monitoring System Flux Net Biosphere Exchange 2020 (CMS-Flux NBE 2020). Earth Syst. Sci. Data, 13, 299–330, doi: 10.5194/essd-13-299-2021 (2021).

Membrive, et al., AirCore-HR: a high-resolution column sampling to enhance the vertical description of CH_4 and CO_2, Atmos. Meas. Tech., 10, 2163–2181, doi:10.5194/amt-10-2163-2017 (2017).

Moore et al., The Potential of the Geostationary Carbon Cycle Observatory (GeoCarb) to Provide Multi-scale Constraints on the Carbon Cycle in the Americas. Frontiers in Environmental Science, 6, Article 109, doi: doi: 10.3389/fenvs.2018.00109 (2018).

Nassar et al., Advances in quantifying power plant CO_2 emissions with OCO-2. Remote Sensing of Environment, 264, 112579. doi: 10.1016/j.rse.2021.112579 (2021).

Nassar et al. Intelligent pointing increases the fraction of cloud-free CO_2 and CH_4 observations from space, Frontiers in Remote Sensing, 4, doi:10.3389/frsen.2023.1233803 (2023).

Nesser, H. et al. High-resolution US methane emissions inferred from an inversion of 2019 TROPOMI satellite data: contributions from individual states, urban areas, and landfills. Atmos. Chem. Phys. 24, 5069–5091 (2024).

O’Dell, C. W, et al. Improved retrievals of carbon dioxide from Orbiting Carbon Observatory-2 with the version 8 ACOS algorithm, Atmospheric Measurement Techniques, 11: 6539–6576. doi:10.5194/amt-11-6539-2018 (2018).

Parker, R. J. et al. A decade of GOSAT Proxy satellite CH_4 observations. Earth Syst. Sci. Data 12, 3383–3412 (2020).

Qu, Z. et al. Global distribution of methane emissions: a comparative inverse analysis of observations from the TROPOMI and GOSAT satellite instruments. Atmos. Chem. Phys. 21, 14159–14175 (2021).

Saunois, M. et al. The Global Methane Budget 2000–2017. Earth Syst. Sci. Data 12, 1561–1623 (2020).

Sha, M. K., et al. Validation of methane and carbon monoxide from Sentinel-5 Precursor using TCCON and NDACC-IRWG stations, Atmos. Meas. Tech., 14, 6249–6304, https://doi.org/10.5194/amt-14-6249-2021 (2021).

Simmonds, P. G., et al. Tracers for evaluating computational models of atmospheric transport and oxidation at regional to global scales, Atmos. Env., 246, 118074, https://doi.org/10.1016/j.atmosenv.2020.118074 (2021).

UNFCCC/SBSTA: United Nations Framework Convention on Climate Change / Subsidiary Body for Scientific and Technology Advice.

Worden, J. R. et al. The 2019 methane budget and uncertainties at 1∘ resolution and each country through Bayesian integration of GOSAT total column methane data and a priori inventory estimates. Atmos. Chem. Phys. 22, 6811–6841 (2022).

Worden, J. R. et al. Verifying Methane Inventories and Trends With Atmospheric Methane Data. AGU Adv. 4, e2023AV000871 (2023).

Watine-Guiu et al., Geostationary satellite observations of extreme and transient methane emissions from oil and gas infrastructure, PNAS, 120 doi: 10.1073/pnas.2310797120 (2023).

Wickland, et al., *CEOS Strategy for Carbon Observations from Space.* The Committee on Earth Observation Satellites (CEOS) Response to the Group on Earth Observations (GEO) Carbon Strategy. (D. Wickland and M. Nakajima, Carbon Task Force Co-Chairs and Eds.) JAXA and I&A Corporation. 202 pp. (2014).

Wilson, et al, Quantifying large methane emissions from the Nord Stream pipeline gas leak of September 2022 using IASI satellite observations and inverse modelling, Atmos. Chem. Phys., 24, 10639–10653, https://doi.org/10.5194/acp-24-10639-2024 (2024).

Woolf, D. K., et al. Key uncertainties in the recent air-sea flux of CO_2. Global Biogeochemical Cycles, 33, 1548-1563. doi:10.1029/2018GB006041 (2019).

Wu, D., et al. A Lagrangian approach towards extracting signals of urban CO2 emissions from satellite observations of atmospheric column CO2 (XCO2): X-Stochastic Time-Inverted Lagrangian Transport model ("X-STILT v1"), Geosci. Model Dev., 11, 4843–4871, doi:10.5194/gmd-11-4843-2018 (2018).

Wunch, D., et al. The total carbon column observing network, Philosophical Transactions of the Royal. Society A, 369, 2087–2112, doi:10.1098/rsta.2010.0240 (2011).

Wunch, D., et al., Comparisons of the Orbiting Carbon Observatory-2 (OCO-2) XCO_2 measurements with TCCON, Atmospheric Measurement Techniques, 10, 2209–2238. doi: 10.5194/amt-10-2209-2017 (2017).

Ye, X., et al., Constraining fossil fuel CO_2 emissions from urban area using OCO-2 observations of total column CO_2. Journal of Geophysical Research: Atmospheres, 125, e2019JD030528. doi: 10.1029/2019JD030528 (2020).

ANNEX C. Detailed Activities

The GHG Task Team, introduced in Annex A, will maintain a list of detailed activities, which has been subdivided into thematic areas, that have been divided into long-term objectives (see Section 5 above) and short-term tangible goals. The short-term activities are managed online (see https://ceos.org/ourwork/workinggroups/climate/ghg-tt/). This allows frequent updating, inclusion of new activities and closing activities that have been completed. The thematic leads will report on the activities in their area at each GHG TT meeting and completion of higher level objectives will be reported in WG Climate and potentially as well at higher CEOS (SIT TW and Plenary) and CGMS level.

ANNEX D. Acronyms and Abbreviations

List of used acronyms and abbreviations as used throughout this document

ACSG	Atmospheric Composition Sub-Group (of WGCV)
AC-VC	Atmospheric Composition Virtual Constellation (of CEOS)
AFOLU	Agriculture, Forestry and Other Land Use
ARD	Analysis Ready Data (of CEOS)
CAMS	Copernicus Atmosphere Monitoring Service
CEOS	Committee on Earth Observation Satellites
CGMS	Coordination Group for Meteorological Satellites
COCCON	Collaborative Carbon Column Observing Network
COP	Conference of the Parties (of UNFCCC)
EOTEC Devnet	Earth Observation Training Education and Capacity Development Network
FTIR	Fourier Transform Infra-Red
FRM	Fiducial Reference Measurement
G3W	Global Greenhouse Gas Watch (of WMO)
GCP	Global Carbon Project
GHG	Greenhouse Gas
GHG2020	Issue 1 of the CEOS/CGMS GHG Roadmap
GHG MVS	Greenhouse Gas Monitoring and Verification Support capacity
GHG TT	Greenhouse Gas Monitoring Task Team (within the Joint CEOS-CGMS WGClimate)
GSICS	Global Space-based Inter-Calibration System (of WMO-CGMS)
GST	Global Stocktake (under the UNFCCC 2015 Paris Agreement)
IG3IS	Integrated Global Greenhouse Gas Information System (of WMO)
IMEO	International Methane Emission Observatory (of UNEP)
IPCC	Intergovernmental Panel on Climate Change
MARS	Methane Alert and Response System
ML	Machine Learning
NDACC	Network for the Detection of Atmospheric Composition Change
NGHGI	National Greenhouse Gas Inventory
PFS	Product Family Specifications (as used in CEOS-ARD)
POD	Probability of Detection
R2O	Research to Operations

RECCAP	REgional Carbon Cycle Assessment and Processes
RT	Radiative Transfer
SBSTA	Subsidiary Body for Scientific and Technological Advice (of UNFCCC)
SIT	Strategic Implementation Team (of CEOS)
SWIR	Shortwave Infra-Red
TCCON	Total Carbon Column Observing Network
TT	Task Team
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
WGCapD	Working Group on Capacity Development and Data Democracy (of CEOS))
WGCV	Working Group on Calibration and Validation (of CEOS)
WGISS	Working Group on Information Systems and Services (of CEOS)
WIGOS	WMO Integrated Global Observing System
WMO	World Meteorological Organisation
XCH_4	refers to column-averaged dry air mole fractions of CH_4
XCO_2	refers to column-averaged dry air mole fractions of CO_2