Committee on Earth Observation Satellites

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

in cooperation with the

Coordination Group for Meteorological Satellites (CGMS)
&
WMO Global Space-based Inter-Calibration System (GSICS)

Committee on Earth Observation Satellites

WGClimate

CEOS CGMS

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1 Context

The United Nations Framework Convention on Climate Change (UNFCCC) was established in 1994 to stabilize “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 globally average temperatures to less than 2 °C above pre-industrial levels, the 21st session of the Conference of the Parties (COP21) of the UNFCCC implemented the Paris Agreement, an ambitious global effort to reduce GHG emission. Parties to the 2015 Paris Agreement defined nationally determined contributions (NDCs) to a global GHG emissions reduction effort. Each party agreed to report their anthropogenic GHG emissions and removals to the UNFCCC, which would evaluate their progress toward their NDCs at 5-year intervals through a “Global Stocktake”, the first of which is scheduled for 2023.

To track their progress toward their NDCs and the global GHG emission reduction targets, each Party agreed to provide a national inventory report of anthropogenic emissions by sources and removals by sinks of GHGs, prepared using best-practice methodologies accepted by the Intergovernmental Panel on Climate Change (IPCC). 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 CO_2 and CH_4 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 a complementary approach for assessing NDCs.

At global scales, atmospheric concentrations of CO_2, CH_4 and other well-mixed greenhouse gases (GHGs) are well characterized by precise, systematic, ground-based in situ measurements from a network of ~145 surface stations that are coordinated by WMO Global Atmospheric Watch (GAW) program. However, this network still does not provide the spatial resolution and coverage needed to identify or quantify the sources emitting CO_2 and CH_4 into the atmosphere on the scale of individual nations, or to localize or quantify the natural sinks that remove these gases. 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 network. Measurements collected by space-based sensors can be analyzed to estimate the column-averaged dry air mole fractions of CO_2 and CH_4 (hereinafter XCO_2 and XCH_4, respectively). These space-based concentration estimates are not as accurate as those obtained from the ground-based and airborne sensors, but they can provide much greater resolution and coverage of the globe, including areas that are too geographically or politically inaccessible to support ground-based stations. A global GHG monitoring system that integrates accurate airborne and ground-based measurements with spatially dense space-borne estimates of XCO_2 and XCH_4

could therefore yield atmospheric CO_2 and CH_4 inventories that complement the bottom-up inventory statistical inventories used to track progress toward GHG emission reduction targets.

Space agencies responded to these challenges by supporting pioneering space-based experiments designed to retrieve spatially resolved estimates of atmospheric CO_2 and CH_4 concentrations from high spectral resolution observations of reflected sunlight. The first of these included the combined German-Dutch-Belgian contribution in kind SCanning Imaging Absorption spectroMeter for Atmospheric CartograpHY (SCIAMACHY) onboard the European Space Agency (ESA) Environmental Satellite (ENVISAT), Japan's Greenhouse gases Observing SATellite (GOSAT) Thermal and Near Infrared Sensor for Carbon Observation-Fourier Transform Spectrometer (TANSO-FTS), and the National Aeronautics and Space Administration (NASA) Orbiting Carbon Observaotry-2 (OCO-2) mission. The free and open distribution of the data from these missions has fostered rapid progress in the development of a new generation of remote sensing retrieval algorithms optimized to retrieve XCO_2 and XCH_4 from space-based spectroscopic measurements.

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- 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 by convening a Carbon Task Force (CTF), which compiled the CEOS Strategy for Carbon Observations from Space (Wickland et al. 2014; hereinafter, CEOS Carbon Strategy). The CEOS Carbon Strategy report documents the state of knowledge and measurement requirements for the atmospheric, oceanic, and terrestrial domains and their interfaces, and identifies several actions to be completed by its member agencies.

Given the recent progress with SCIAMACHY, GOSAT, and OCO-2, the CEOS Chair recognized that high-quality observations of atmospheric CO_2 and CH_4 could be an essential component of an integrated global carbon observing system (Figure 1), such as that advocated by the WMO IG^3IS. 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 harmonized, they can be assimilated into atmospheric inverse systems to yield top-down global inventories of CO_2 and CH_4 fluxes with the accuracy, precision, resolution and coverage needed to serve as a complementary system for estimating NDCs, as proposed in the 2016 New Delhi Declaration. In addition, if these atmospheric data products were distributed freely and openly, in compliance with the CEOS data policy, they could support the Transparency Framework.

2 CEOS AC-VC Greenhouse Gas Whitepaper

In this context, the 2017 CEOS Chair commissioned the CEOS Atmospheric Composition Virtual Constellation (AC-VC) to write a Whitepaper 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) Whitepaper was finalised in 2018 and is a 166-page document with contributions from 88 authors representing 47 organizations. It consists of a 2-page executive summary followed by a 75-page body, summarizing the science requirements, existing and planned measurement and modeling capabilities, and proposing a constellation implementation architecture and the 3-step implementation plan. This Whitepaper explains how estimates of XCO_2 and XCH_4 from space-based sensors can be integrated into a global carbon monitoring system and summarizes the state of the art in the space-based measurements and the modeling tools needed to retrieve CO_2 and CH_4 fluxes from these data. It then describes 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 SCIAMACHY, GOSAT, and OCO-2 missions and summarizes the steps needed to transition from a series of scientific experiments to an operational constellation that can 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.

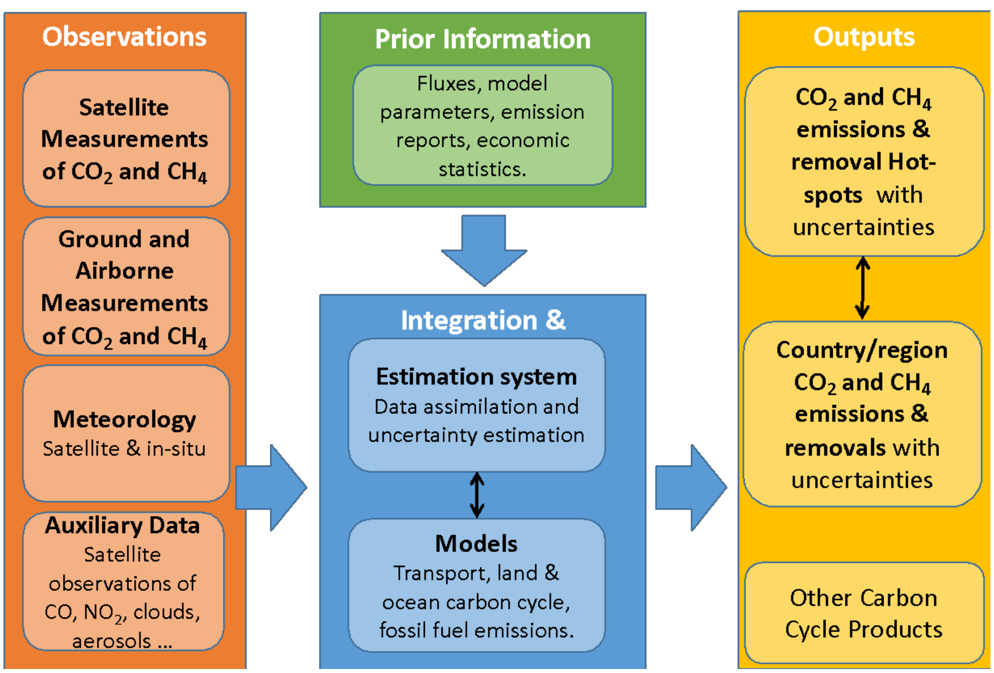


Figure 1: System functional overview an atmospheric CO_2 and CH_4 monitoring system, showing the key inputs, outputs, and interactions.

The proposed three-step plan for the implementation of this architecture consists of:

1) Linking the atmospheric GHG measurement and modeling communities and stakeholders in the national inventory and policy communities through UNFCCC/SBSTA[1], to refine requirements;

2) Exploiting 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 (IG^3IS) 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 Global Stocktake; and

3) Using 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 estimating NDCs in time to support the 2028 Global Stocktake.

To meet these goals on this ambitious timeline, the Way Forward section of the Whitepaper recommends a series of 16 specific actions by CEOS and its partners.

The Whitepaper was endorsed by the CEOS agencies at the 32nd Plenary in Brussels (October 2018). However, at that point the three-step plan to implement the architecture as well as the identified activities in the Way Forward were interpreted as recommendations to CEOS Agencies, for their consideration (Figure 2).

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.

In addition, CGMS approved the Whitepaper during the 47th plenary in Sochi (2019). CEOS and CGMS can therefore combine their efforts to address the tasks described in the Way Forward through the Joint CEOS/CGMS Working Group on Climate (WGClimate).

To make further progress toward the actions proposed in the Whitepaper, the CEOS and CGMS Plenaries tasked WGClimate to perform the coordination for the implementation of the recommendations of GHG White Paper. In March 2019 WGClimate formed a dedicated GHG Task Team to work with the CEOS Working Group on Calibration and Validation (WGCV) and the 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 results of these efforts are presented in this document.

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

3 Roadmap Objectives

This roadmap takes, as a starting point, the final chapter of the CEOS AC-VC GHG Whitepaper which lists a series of recommendations for the way forward (see Annex A).

The first two recommendations in Annex A are viewed as the overarching objectives and capture the main goals of the endeavour, namely the delivery of:

- A prototype end-to-end system that yields estimates of CO_2 and CH_4 and fluxes; and
- An Initial Operational System for producing future atmospheric CO_2 and CH_4 flux products for use in future Global Stocktakes.

In order to establish a more rigorous approach to the terminology used, from this point forward we will refer to the efforts in support of the first Global Stocktake as the "*pilot phase providing access to targeted products from individual CEOS and CGMS Agency Programmes to establish appropriate relationships with stakeholders and users (e.g. National Inventory Agencies) to enhance to uptake of Earth Observation based datasets informing the national reporting needs*".

It should also be noted that the delivery of each system version is accompanied by a requirements refinement process which starts at the top-level user requirements that are driven by the needs of the global stock take inventory builders, resulting in the companion objective of:

- Establishing the end-to-end requirements for a system that delivers atmospheric CO_2 and CH_4 flux products for use in stocktakes (with requirements apportioned to each system version).

The remaining 14 recommendations in Annex A can be viewed as supporting the fulfilment of these three main objectives.

In order to ensure that there is a shared understanding of the implications of these objectives, some of the main characteristics of these two deliveries are summarized in the following subsections, together with the core purposes of the requirements refinement process.

4 Implementation Approach

The implementation approach follows the roadmap objectives and will be supported by the implementation actions which are provided in annex C. Note that the update of the implementation actions is an ongoing task depending on the status of the implementation and the response of the implementation bodies.

4.1 Delivery of Pilot datasets to enhance the uptake of Earth Observation datasets

4.1.1 Usage Scenario(s) and Expected Output(s)

The main usage scenario is to provide support to inventory builders in their development of the GHG inventories for the 2023 Global Stocktake through the provision of global high-resolution atmospheric CO_2 and CH_4 flux products addressing the corresponding emissions.

4.1.2 Functional Scope

The functional scope of the Pilot datasets should be developed, distributed and communicated in a manner that encourages the full System Functional Overview depicted in Figure 1, whilst understanding that this is not fully implemented in this phase of developments, and being explicitly clear that the precision, accuracy, resolution, and coverage of the observations and the capabilities of the modeling tools will be limited to those available and offered on a best efforts basis at the time the system is assembled from the individual contributions from CEOS and CGMS Agencies. We anticipate that this product will primarily be useful for quantifying CO_2 and CH_4 fluxes from the natural carbon cycle and providing a baseline for tracking future changes in the natural carbon cycle associated with human activities and climate change.

4.1.3 Schedule

In order to be able to support the GHG inventory builders in due time for the 2023 stocktake, the initial global atmospheric CO_2 and CH_4 flux products must be available by 2021, although as long as the datasets themselves are available from the beginning of 2021, additional refinements can continue throughout 2021 and in the first half of 2022.

4.2 Delivery of an Initial Operational System

4.2.1 Usage Scenario(s) and Expected Output(s)

The main usage scenario is to integrate observations from the evolving pre-operational ground-based, airborne, and space-based atmospheric GHG observing network into flux inversion models to yield global, gridded estimates of atmospheric CO_2 and CH_4 fluxes with the precision and accuracy needed to address the corresponding emissions at national scales. The delivered system should support the Global Stocktake in 2028 by:

- Reducing uncertainty of national emission inventory reporting;
- Identifying additional emission reduction opportunities;
- Providing timely and quantified guidance on progress towards national emission reduction strategies and pledges (Nationally Determined Contributions, NDCs); and
- Tracking changes in the natural carbon cycle caused by human activities (deforestation, degradation of ecosystems, fire) and climate change.

4.2.2 Functional Scope

The functional scope of the Initial Operational System is the full scope of the System Functional Overview depicted in Figure 1, but will employ an operational functional architecture to ensure accuracy, traceability, redundancy, and meet product latency delivery requirements.

4.2.3 Schedule

In order to be able to fulfil its intended purpose and support the 2028 Global Stocktake, the Initial Operational System needs to be in place (and operating) with science quality data available as of January 2026. Preparatory work on the operational system shall start in parallel to the activities on the pilot data sets including learning from the experience made during 2021.

4.3 Refine User Requirements

4.3.1 Usage Scenario(s) and Expected Output(s)

The main usage scenario described above requires a formulation of the user expectations and needs on the deliveries from the operational system, namely threshold and goal requirements for the global, gridded estimates of atmospheric CO_2 and CH_4 fluxes. The requirements shall ensure that the listed aims in support of the Global Stocktake in 2028 are adequately addressed and should be developed together with national inventory compilers and similar user communities, e.g., AFOLU.

Discussions should be held with UNFCCC Secretariat, GCOS and the IPCC TFI process responsibles to agree on how these requirements and needs to be codified and curated in their respective requirement gathering processes. The expected output is a high-level user requirements documentation, which provides the baseline for the pilot datasets and the operational system requirements and their deliverables. The requirements for all parts of the operational system sketched in Figure 1 need to be developed with the principal stakeholders (implementers), i.e., ground-based and space-based GHG observing and modeling communities. Based on the experience made with the pilot datasets the requirements will be refined and further refinements will follow on a regular basis.

The CEOS/CGMS WGClimate GHG Task Team will further provide support to the UNFCCC Secretariat and the Parties in the Synthesis and Assessment phase of the first Global Stocktake process and will actively engage in the newly established *adhoc* group on Systematic Observations on support of the Global Stocktake.

Specific activities will be further codified as additional specific Action as they become better defined, but in broad terms these should address:

1. CEOS and CGMS entities will support the secretariat in preparing the first Synthesis Report providing baseline space-based earth observation datasets for regional and global scale analysis, as well as guidance for their interpretation and comparison (Q1-Q2 2022)
2. CEOS and CGMS entities will support the Secretariat and Parties in the technical assessment of the first Global Stocktake, with guidance documents, reference datasets and tools for data integration and hotspot identification as well as uncertainty assessment. (Q1-Q2 2023)

Based on the lessons learned in the context of the Synthesis and Technical Assessment phases of the first Global Stocktake, CEOS and CGMS will prepare adapted input to those activities in the 2nd and subsequent Global Stocktakes.

4.3.2 Schedule

In order to support the development of the pilot atmospheric CO_2 and CH_4 flux inventory for use in the 2023 stocktake, the initial requirements must be developed and documented before the end of 2020. These requirements should be introduced into the GCOS Implementation Plan update process during 2021. Further refinement of the requirements (user and system) based on experience with the pilot data sets and their usage could be done before the end of 2024, after further consultation with the end-user community.

5 Roles of Implementing Entities

Before describing the implementation actions, the high-level roles of the entities expected to contribute to the implementation of the actions are recalled, thereby providing the reference point for associating implementing entities to be associated with each implementation action.The 32nd CEOS Plenary and the 46th CGMS Plenary tasked WGClimate to coordinate the joint efforts between CEOS and CGMS to monitor

GHGs from space. In March 2019 WGClimate formed a dedicated GHG Monitoring Task Team to coordinate the CEOS Carbon Strategy and develop a GHG monitoring roadmap based on the endorsed recommendations in the CEOS AC-VC GHG Whitepaper.

WGClimate was tasked 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 the WGClimate to accommodate these changes (in Figure 3).

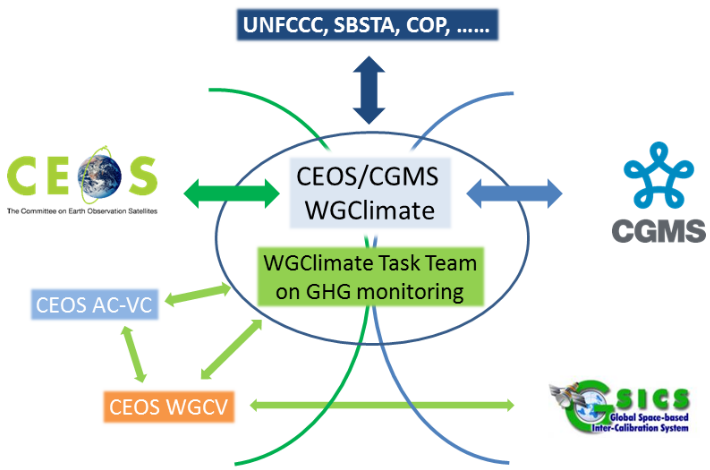


Figure 3: CEOS, CGMS and WMO GSICS entities currently included in the task team. At a later stage, additional entities may contribute.

5.1 Joint CEOS CGMS Implementing Entities

As noted previously, WGClimate has been identified by CEOS and CGMS as the coordination mechanism for the GHG monitoring activities. In order to implement the GHG coordination activities WGClimate created the GHG Task Team as an internal mechanism that sits within the Working Group structure. The respective roles of WGClimate and the GHG Task Team are described in the following subsections.

5.1.1 WGClimate

CEOS and CGMS gave the mandate to WGClimate for the implementation of the GHG coordination activities so that WGClimate has the final responsibility vis-à-vis CEOS and CGMS Plenaries for the discharge of this mandate. 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 Task Team and report on its progress to CEOS and CGMS principals;
- Continue to be the effective interface to UNFCCC, GCOS, and WCRP and provide links to the WMO IG3IS and perform communication of results of the CEOS/CGMS GHG activities at their meetings;
- Build and maintain an active interface with the National carbon inventory communities;
- Oversee 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.

5.1.2 GHG Task Team

The GHG Task Team has both a leader and a deputy leader with nominal, 2-year terms. The WGClimate Chair selects the Task Team leader who takes guidance from the WGClimate Chair, while the deputy will always be the Vice-Chair of the WGClimate to assure the coordination with the WG Chair; with the understanding that the Vice-Chair would not become the Task Team leader. The meetings of the Task Team will nominally be arranged to occur together with a WGClimate meeting, allowing CEOS and CGMS agencies to participate in both, and offering a transparent insight into the progress of the initiative and its activities.

To support this effort, the GHG Task Team 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 the national inventory community, to ensure the uptake and feedback of the various versions of 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/UVWG, etc.)
- Encourage additional CEOS and CGMS agencies representation on the GHG Task Team to ensure that the main Agencies GHG missions are represented and that technical expertise is provided to facilitate the System level competence and linkages to the modelling and Inventory communities; and;
- Support the 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 regular basis to the WGClimate Chair about progress and achievements.

The Task Team has been formed to execute the coordination activities with a balanced representation of the involved entities (see Annex B for the current constitution of the Task Team). 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. The resources needed for this effort are outlined in Section 7 of this roadmap.

5.2 CEOS Entities

To date, the AC-VC and WGCV have been identified as contributing CEOS entities. However, it shall be noted that at later stage the know-how of other CEOS bodies could provide very valuable contributions. For example, the CEOS Working Group on Information Systems and Services (WGISS) could provide contributions in the areas of data access and system services. In addition, a close collaboration with the CEOS Working Group on Capacity Building and Data Democracy (WGCapD) and CGMS and WMO Virtual Lab could facilitate the engagement in necessary capacity building activities related to the usage of GHG inventory products by national inventory compilers, etc.

5.2.1 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.

5.2.2 Working Group on Calibration and Validation (WGCV)

We anticipate that the WGCV Atmospheric Composition Subgroup (ACSG) will lead the effort to develop a comprehensive calibration strategy and to document lessons learned and best practices. It is expected that ACSG will strongly support the implementation of methods and procedures into the operational system by WMO/CGMS GSICS. ACSG areas of responsibility are:

- Monitoring instrument performance;
- Calibration of individual sensors;
- Methods for inter-calibration of satellite instruments;
- Methods and protocol for validation of the level 2 products in the operational system;
- Tying the measurements to absolute references and standards; and
- Contributions to the establishment of end user and system requirements for the pilot data sets and operational systems.

5.3 WMO-CGMS Entities

5.3.1 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 harmonize the quality of observations from operational weather and environmental satellites of the WMO Integrated Global Observing System (WIGOS). Through it's newly re-established Reflective Solar Spectrometers Subgroup (UVSG) it is closely cooperating with CEOS WGCV by emphasizing the aspects of calibration harmonization and pre-launch characterization. In addition, GSICS ensures due to its mechanisms the consistency of calibrated sensor data between different satellite systems.

GSICS will provide 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.

5.3.2 CGMS Working Group

A clear stated objective of these efforts is to start immediately with efforts for the development of the long-term operational capacity. In this context, CGMS Working Groups will play a critical role in ensuring the efficient operational transition.

CGMS Working Groups 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 WGs 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

Specific contributions include 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-III is maintaining the overall baseline for the CGMS observing system. It will map the CGMS agency plans for CO_2 and CH_4 relevant measurements onto the CGMS baseline. It then should identify continuity issues and make proposals for contingency planning addressing potential gaps in the GHG constellation. Finally, CGMS Working Group-IV could address operational access and end user support as well as training for GHG constellation products in cooperation with CEOS WGISS.

6 Expected Outcomes

The expected outcomes are related to

- The delivery of pilot datasets to enhance the uptake of Earth Observation satellite data sets to support the Global Stocktake 2023;
- The delivery of an operational system to support the Global Stocktake 2028; and
- The refinement of user requirements in preparation of the implementation of the operational system.

Having in mind that CEOS and CGMS is based on best effort and rely on the resources of its members; we recall that the physical implementation of a system is an effort by one member or multiple members. Because of the importance of the added value of satellite data products and the layout of such an integrated system for the derivation of GHG emissions for the Global stock-take, it is fundamental that the user or stakeholder which shall be later rely on such a system, won't be worried by eventually different outputs from different system implementations because of system-immanent biases, under- or over-estimations. For thus, it is an absolute need that *best practices* are provided as output for those parts of the system which can be served by CEOS or CGMS agencies (or its partners). In addition, in the context of CEOS and CGMS several parts of the system can be studied as a research but also as an operational endeavor.

From that, the expected outcome shall be for the pilot phase supporting the Global Stocktake in 2023 and in preparation of an operational system ready in 2026:

- A maintained and updated catalogue of GHG satellite systems which may contribute to a virtual constellation in 2021/2023 timeframe including a future system estimate;
- A most complete listing of consistent and harmonized data sets from satellite observations existing at date (2021/2023) which can serve as input with given uncertainties and documentation about their impact on the flux estimates with traceable consistency and data quality;
- An observation requirements repository based on the 2021/2023 GHG virtual constellation maintained for future constellations;
- Quality-monitoring means and continuously validation by well-characterized means, especially in operational modes (see cross-calibration and validation plan for inclusion);
- Inventory of reference standards suitable for inter-comparison of GHG data products from multiple missions;
- Report about GHG calibration and validation capabilities including shortcoming, gaps, sustainability and opportunities with mid- and long-term recommendations. This report shall also include the improvement/gaps of the inter-calibration of GHG sensors, the Level 2 validation infrastructure, and the identification of long-term needs. A first draft of an operational reporting about data quality shall be included;
- Draft of a cross-calibration and validation plan of GHG products for a virtual constellation ;
- Progress report on the GHG task team developments; and
- Risk register including mitigation means.

The expected outcomes shall be augmented by a report about the usage of satellite observation based flux estimates for the derivation of GHG emission estimates in cooperation with various inventory stakeholders.

The output for the operational system (2026, resp. 2028) may maintain and sustain the above documents and reports in terms of amendments and consolidation. In addition, the operational system approach does need an appropriate system engineering approach which describes not only the functional part of the system but also the product tree, the data flow, and interfaces based on consolidated requirements. A more detailed description about those parts will be presented together with the detailed work plan. Most emphasis will be taken to the sustained definition of interfaces between the different functional sub-systems and formats used therein allowing the comparability of different implementation instances.

7 Resource Implications

A preliminary estimate of the resource needs was compiled based on the scope of activities based on the scope of the effort described above and earlier experience with these types of coordination and product delivery efforts. We anticipate that these resource estimates will evolve somewhat as the detailed task plan is developed and as we gain experience from the first rounds of product prototyping. This should provide CEOS and CGMS Agencies with an overview of both the types and amounts of contributions that are anticipated so that their individual agencies can assess where they feel best suited to make contributions.

We anticipate that contributions will be needed both from the agencies that are planning to launch satellites contributing the envisaged GHG monitoring constellation, as well as those that plan to contribute to other aspects of the overall system architecture. This includes agencies with competences/interests in the necessary Cal/Val infrastructure, ancillary in-situ observations, modelling capability, interface to the user and inventory communities and application development, as well as agencies with the system engineering experience to ensure the longer-tern transition to a fully integrated end-to-end global data-assimilation framework. Within CEOS and CGMS, there are many additional agencies with these complimentary competences and it is hoped that they will contribute to this endeavor.

As a specific observation for CGMS agencies, it should be clear that despite initial emphasis on the activities supporting the first Global Stocktake in parallel activities and resources should be provided from the outset supporting the transition to a more pre-operational context where the competences and experience of CGMS agencies will be invaluable.

Three broad categories of resources are envisaged and requested for consideration by Agencies:

1. Human resources from CEOS members and external experts supported through Agency programmes & grants. These resources are described in greater detail below.
2. Support for travel and hosting of workshops and networking activities. This will be critical in the first phase of this effort to develop the necessary interfaces with the national inventory community, the atmospheric GHG measurement and modelling communities, and stakeholders (e.g. UNFCCC/SBSTA).
3. On longer time scales, additional, more substantial requests for resources will be addressed by individual agencies through internal funding mechanisms supporting research, development and infrastructure for priorities identified by GHG Task Team and Roadmap implementation. The GHG Task Team will provide periodic and prioritized assessments to Agencies highlighting areas where research and infrastructure investments are required to ensure adequate implementation and evolution of the system.

Dedicated human resources are required from both Agency staff and experts that Agencies support on research funding and grants.

- Agencies are asked to continue, and in some cases increase support to the GHG relevant staff (time & travel) contributing to the technical implementation tasks in AC-VC and WGCV.
- For the WGClimate GHG Task Team, the following specific "profiles" are required:
    - Core team ensuring linkages to internal CEOS/CGMS entities (i.e. WGClimate, AC-VC, WGCV, and others)
    - Agency staff representing GHG missions/programmes
    - Agency staff from "operational" agencies to ensure operational transition

Agency Staff/Experts with links to Inventory CommunityAgency Staff/Experts involved in modelling aspectsWith specific reference to CGMS Working Groups, as mentioned above the contribution from these entities is appreciated from the beginning. It is recommended that CGMS Agencies identify a Point of Contact from each Working Group to become a member of the GHG Task Team, therefore providing the interface as well as a direct reporting line back to that specific area of CGMS competence.

We envisage that the GHG Task Team would include ~12-15 members, with each member typically dedicating one person-month of effort each year. Those leading specific activities will need to dedicate closer to 2 person months per year. Support should include necessary travel budgets for attending meetings/workshops.

8 High-level Timeline

The high-level timeline is driven by the overarching goal to provide a GHG constellation architecture for the Global Stocktake in 2023, 2028 and so on. This leads to a "governed-by due-date" schedule which can be displayed as such.

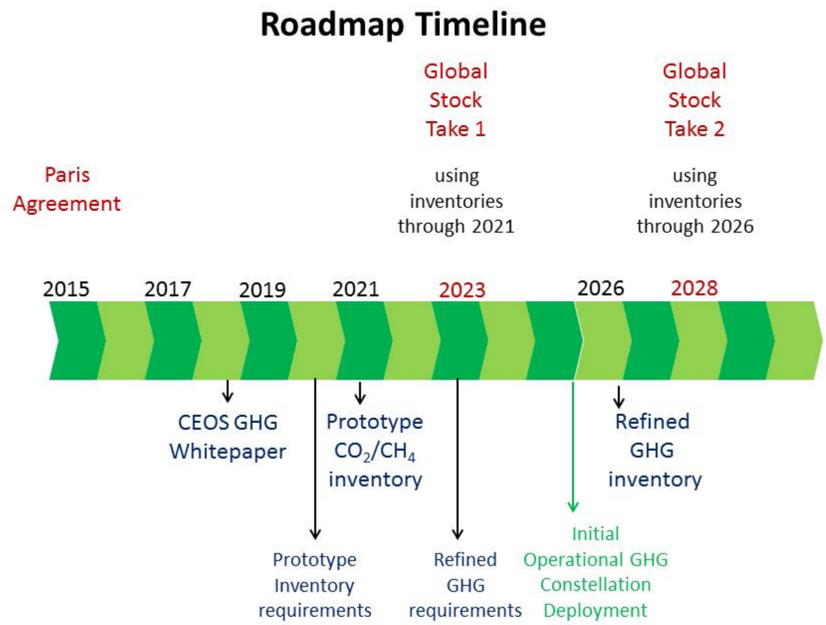
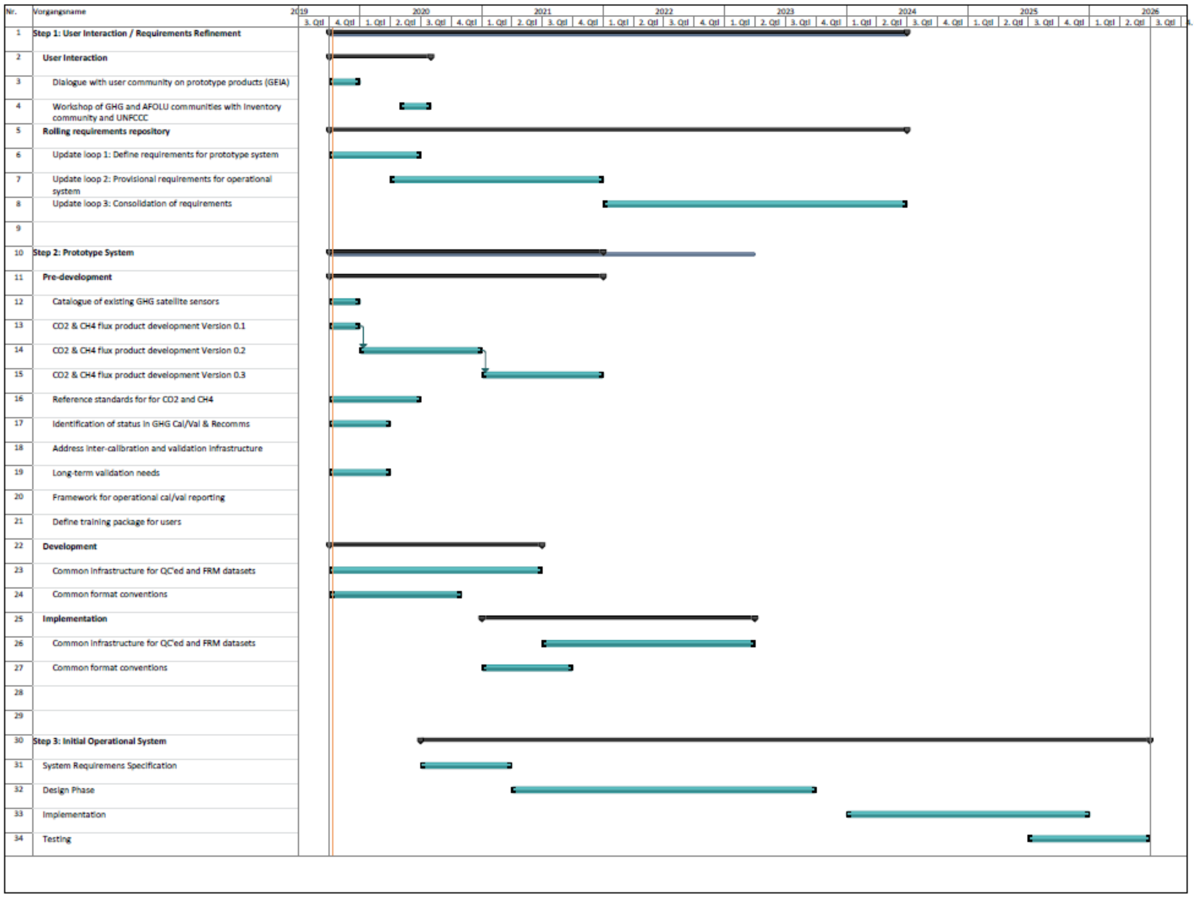


Figure 3: Roadmap timeline underlining the target dates as boundary conditions

However, the timeline can be detailed into four streams reflecting also the above mentioned due dates and the allocated actions:

1) *Refinement of user requirements*
   includes the interaction with the envisaged user community and the overall user requirements refinement or update
2) *Pilot phase: Delivery of pilot datasets to enhance the uptake of Earth Observation satellite datasets*
   includes the deliverables as outlined in the previous chapter
3) *Delivery of an operational system*
   includes roughly the typical system engineering steps for the implementation of the operational system from the very beginning and the lessons-learned from the pilot phase
4) *Management packages*
   includes all review and progress reporting items and the risk register as well.



Please note that the current timeline is a guideline for the work plan implementation and will be substituted when a more detailed work plan will be in place.

ANNEX A: RECOMMENDATIONS FROM THE CEOS AC-VC GHG WHITEPAPER

1. A prototype system, based on available space-based and ground-based atmospheric measurement assets and modelling capabilities, should be designed and implemented in time to inform the first Global Stocktake in 2023. To support this stocktake, the initial global atmospheric CO2 and CH4 flux products must be available by 2021.
2. The initial operational system should exploit the lessons learned from the development and use of the prototype product as well as new space-based measurement and modelling capabilities to produce space-based CO2 and CH4 flux products in time to support the second Global Stocktake in 2028.
3. To meet these goals within a decade, it is imperative that individual research and operational space agencies work within CEOS, CGMS and other international coordination bodies (i.e. WMO IG3IS, GCOS, GEO-C) to define a roadmap with specific programmatic milestones for developing virtual and then dedicated constellations that can deliver harmonized, space-based climate data records for CO2 and CH4.
4. The preparation of this report has demonstrated the benefits of the complementary viewpoints provided by CEOS and CGMS for advancing the implementation of system that incorporates both research and operational elements within the timeframe available. In particular, the CGMS partners could provide insight into the process of gathering user requirements for timeliness, reliability, traceability, reprocessing, quality assurance, and providing user support for an operational product. A continued engagement by both entities is required and some formalisation of the relationship would be advantageous. The joint CEOS/CGMS Working Group on Climate could lead this effort.
5. As recognised in Chapter 2, a broad system approach is required to develop a top-down atmospheric inventory approach that complements the bottom-up inventories. This system integrates the satellite observations, in situ (surface, aircraft, and balloon) measurements, modelling components (retrieval, inversion, biogeochemical processes and transport), prior information and ancillary data.
6. To ensure that the space agencies are working together and building the necessary partnerships with the relevant stakeholders (i.e. UNFCCC/SBSTA) to address the overall system implementation goals, they should work through CEOS and CGMS to strengthen the ties to these stakeholders.
7. In Chapter 6, the GCOS requirements were adopted as the basis in the formulation of a baseline operational CO2/CH4 constellation because GCOS provides an independent basis for the requirements. However, these requirements predated the Paris Agreement, which changed the focus of CO2 and CH4 monitoring efforts to anthropogenic emissions at national scales. Further analysis and revision of the space-based measurement and analysis requirements are needed to address this new focus. The CEOS and CGMS agencies should work with GCOS and other partner organizations and stakeholders in an iterative approach to further refine those requirements over the next few years.
8. CEOS, CGMS and their partners should continue to support the necessary OSSE experiments, which remain of critical importance in further refining the detailed requirements of the space-based

elements of the constellation (sensor precision, accuracy, and resolution, orbit and mission coordination). The near-term objective is to develop a prioritized list of the required OSSE experiments and end-to-end system simulations to optimize the overall system design, resolve system-level uncertainties, and facilitate the coordination of activities among the CEOS and CGMS agencies. The output from these experiments should be made available to the CEOS and CGMS Principals periodically, in a format conducive to discussions with their mission and orbit planning organizations.

9. Over the last 15 years, research missions have provided considerable insight into instrument calibration, validation and the broader aspects of uncertainty quantification and quality control. Appendix 4 of this report summarizes the lessons learned from SCIAMACHY, GOSAT, and OCO-2. In the short-term, these lessons represent best practices that should be extracted and generalised by the CEOS/CGMS Working Group on Calibration and Validation (WGCV) and the Global Space-based Intercalibration System (GSICS) so that they are available as Cal-Val strategy "protocols" for space agencies that are now considering missions.

10. The strategy for cross-calibrating the GOSAT and OCO-2 instruments has employed common standards, including observations of the sun, Moon, and surface vicarious calibration sites, such as Railroad Valley, Nevada, U.S.A. Additional effort by WGCV and GSICS is needed to maintain and improve the quality of these standards to better address the calibration needs of space-based CO2 and CH4 sensors.

11. TCCON has provided the primary transfer standard to relate space-based XCO2 and XCH4 estimates to the ground-based in situ standards maintained by the WMO GAW network. This network must be maintained and augmented using portable, ground-based remote sensing instruments (e.g. EM27/SUN), in situ sensors on fixed-wing aircraft (commercial aircraft, such as CONTRAIL, IAGOS) and balloons (AirCore), and airborne remote sensing instruments (MAMAP, CHARM-F etc.) to provide a more robust and accurate operational validation approach.

12. CGMS and CEOS should work with their member agencies to identify and promote standards in product specification, formats, pre-processing etc. and product intercomparisons should be routinely undertaken and supported on a sustained basis to produce seamless, interoperable datasets that can be used in the broader system implementation.

13. Agencies should consider a centralized (but possibly geographically distributed) repository for hosting quality-controlled CO2 and CH4 products, with internal capability for product inter-comparison.

14. The capabilities required to meet the needs of the UNFCCC and the Parties to the Convention are already at the limit of the state-of-the-art for existing, space-based measurement technology. The CEOS and CGMS agencies should therefore continue to pursue complimentary technologies for both sensors (e.g. wide swath passive CO2 and CH4 imagers, active lidar) and mission design (e.g. HEO). These development efforts should be coordinated to keep the Principals updated on additional needs and capabilities that would be useful to consider for future mission opportunities.

15. There is a significant need for systematically produced ancillary measurements. These measurements are needed both to improve the accuracy of the XCO2 and XCH4 retrievals (i.e. coincident observations of clouds and aerosols) and to facilitate their interpretation within the context of the anthropogenic and natural carbon cycle (i.e. SIF, NO2 and CO). Here, the proposed

atmospheric CO_2 and CH_4 monitoring system could substantially benefit from the full scope of carbon cycle observations included in the CEOS Carbon Strategy. The CEOS partner agencies should therefore continue to support that strategy. The coordination mechanism identified to address follow-up to the current work should provide an assessment of prioritized products to be addressed in a coherent way, across agencies, to ensure seamless input to the system.

16. To ensure that the initial operational constellation and associated atmospheric CO_2 and CH_4 monitoring system can meet the sustained operational needs, a system engineering effort should be undertaken early in the implementation. This effort is needed to ensure that the requirement-reliability-traceability-fitness-for-purpose cycle is adequately planned and that the user uptake, user support and training and capability building elements are defined and prototyped. The CEOS and CGMS agencies and their partners at WMO have the necessary competences to start addressing these requirements and can help to assess the scope of these activities at the different levels of the implementation.

ANNEX B: WGClimate Task Team membership

- Mark Dowell (EC, WGClimate, Task Team lead)
- Albrecht von Bargen (DLR, WGClimate Vice-chair, deputy Task Team lead ex officio)
- Frederic Chevallier (LSCE/IPSL)
- David Crisp (NASA, CEOS AC-VC)
- Carole Deniel (CNES)
- Richard Engelen (ECMWF)
- Hiroshi Suto (JAXA)
- Akihiko Kuze (JAXA, CEOS WGCV)
- Rüdiger Lang (EUMETSAT)
- Yasjka Meijer (ESA)
- Paul Palmer (UKSA)
- Hiroshi Tanimoto (NIES)
- Alisa Young (NOAA)
- N.N. (agency representative*)
- N.N. (CGMS WG representative)
- N.N. (CGMS WG representative)
- N.N. (GSICS representative)

*Representatives shall be chosen from agencies not being represented in the current membership

ANNEX C: IMPLEMENTATION ACTIONS

AREA	ACTION ID	ACTION DESCRIPTION	APPLICABILITY		LEAD	CONTRIBUTORS	DUE DATE	IMPLEMENTATION STATUS
			PS	IOS				
Stakeholder Engagement	Stake-1	Link the atmospheric GHG measurement and modeling communities and stakeholders in the national inventory and policy communities (through UNFCCC/SBSTA), to **refine requirements** for the PS and IOS. In this respect it is noted that the GHG Whitepaper adopts the GCOS (2016) accuracy, resolution and coverage requirements as the baseline requirements for the space-based elements of CO2/CH4 management system. However, these requirements predated the Paris Agreement. Further analysis of these requirements is needed to address this new focus.	X	X	WGC Chair with WGC-TT lead	Various	As specified	
	Stake-2	In close cooperation with the WGClimate lead, as the CEOS PoC to UNFCCC, SBSTA, and COP, the Task Team shall support **outreach activities** during COP and Earth Information Days (EID), increasing awareness and establishing contacts with the national GHG inventory communities. To actively engage its user communities and bridge the gap between satellite products and national statistical GHG inventories, the Task Team will interact with the national inventory community and the modelling communities by: • Seeking an annually exchange with the inventory and modelling communities; • Supporting feedback utilization from user community on product development. A first meeting is envisaged in Q4 / 2019 aside the annual GEIA meeting; • Planning a workshop with modelling community ideally in combination with WMO IG3IS/TRANSCOM (Q2 / 2021), detailed planning for further regular workshops/meetings.	X	X	WGC Chair with WGC-TT lead	Various	As specified	
System Development Facilitation	Sys-1	**Monitor the development** status of the PS and IOS and provide summary regular status reports to CEOS and CGMS (including the maintenance of a high-level schedule showing dependencies between the PS and IOS)	X	X	WGC-TT	All	CEOS & CGMS Plenaries	
	Sys-2	Compile, and maintain, a **register of the main contributing components to the Prototype System** in the form of a physical architecture that is traceable to the functional overview provided in figure 1 and its further decompositions as they become available	X		WGC-TT	All	6 monthly	
	Sys-3	Compile, and maintain, a **register of the main contributing components to the Initial Operational System** in the form of a physical architecture that is traceable to the functional overview provided in figure 1 and its further decompositions as they become available		X	WGC-TT	All	6 monthly	
	Sys-4	Establish and maintain a **Critical Issues Register** (CIR), covering both the PS and IOS, that describes the main design uncertainties/challenges, their impact on the performance of the system if unresolved and the proposed resolution approach, including, if appropriate, suggestions for further work in the context of specific projects and programmes (e.g. further investigation/characterisation within the framework of end-to-end simulations). The scope of the CIR will include the critical issues being addressed by the OSSEs (and any potential linkages to end-to-end simulations)	X	X	WGC-TT	Various	6 monthly	
	Sys-5	Establish and maintain an overview of the approach adopted for the **apportionment of system requirements to components**, and provide feedback as appropriate	X	X	WGC-TT	Various	Annual	

AREA	ACTION ID	ACTION DESCRIPTION	APPLICABILITY		LEAD	CONTRIBUTORS	DUE DATE	IMPLEMENTATION STATUS
			PS	IOS				
Operational Preparation and Training	Ops-1	Establish and maintain an overview of the process followed for achieving **operational readiness** of the PS and IOS (including system commissioning and beta testing prior to the declaration of operational readiness) and provide feedback as appropriate	X	X	WGC-TT	Various	Annual	
	Ops-2	Establish and aintain an overview of the **governance arrangements** for the operation of the PS and IOS and provide feedback as appropriate	X	X	WGC-TT	Various	Annual	
	Ops-3	Establish and maintain an overview of the arrangements and documentation for **preparing end-users to exploit the outputs of the system**, including training, and provide feedback as appropriate	X	X	WGC-TT	Various	Annual	
Sensor Development	Sens-1	Contribute to the implementation of a prototype system that **incorporates products from a virtual constellation of sensors** by 2021 (Rec#1)	X		AC-VC	?	?	
	Sens-2	Contribute to the **definition of the requirement records** for an operational system or dedicated constellations of space-based sensors (Rec#2)		X	AC-VC	?	?	
	Sens-3	Define **best practices and facilitate exchange and harmonization of approaches for instrument cross-calibration** in coordination with CEOS WGCV and GSICS - text from Rec#10: The strategy for cross-calibrating the GOSAT and OCO-2 instruments has employed common standards, including observations of the sun, Moon, and surface vicarious calibration sites, such as Railroad Valley, Nevada, U.S.A. Additional effort by WGCV and GSICS is needed to maintain and improve the quality of these standards to better address the calibration needs of space-based CO2 and CH4 sensors	X	X	WGCV-ACSG	AC-VC, GSICS		
	Sens-4	Facilitate exchange of expertise and support in **defining mission requirements** (Rec#7)	?	?	?	?	?	
	Sens-5	Coordinate discussion on **auxiliary observations enhancing data quality** (e.g., aerosol properties for light path correction) - see extract from Rec#15: *Ancillary measurements are needed both to improve the accuracy of the XCO2 and XCH4 retrievals (i.e. coincident observations of clouds and aerosols) and to facilitate their interpretation within the context of the anthropogenic and natural carbon cycle (i.e. SIF, NO2 and CO). Here, the proposed atmospheric CO2 and CH4 monitoring system could substantially benefit from the full scope of carbon cycle observations included in the CEOS Carbon Strategy. The CEOS partner agencies should therefore continue to support that strategy*	?	?	?	?	?	
	Sens-6	**Track implementation and operations of space-based GHG sensors** and identify and propose solutions for observational gaps - see extract from Rec#14: *The capabilities required to meet the needs of the UNFCCC and the Parties to the Convention are already at the limit of the state-of-the-art for existing, space-based measurement technology. The CEOS and CGMS agencies should therefore continue to pursue complimentary technologies for both sensors (e.g. wide swath passive CO2 and CH4 imagers, active lidar) and mission design (e.g. HEO). These development efforts should be coordinated to keep the Principals updated on additional needs and capabilities that would be useful to consider for future mission opportunities*	?	?	AC-VC	?	?	

AREA	ACTION ID	ACTION DESCRIPTION	APPLICABILITY		LEAD	CONTRIBUTORS	DUE DATE	IMPLEMENTATION STATUS
			PS	IOS				
L1 & L2 GHG Product Development	Prod-1	Document the **performance of existing and near term L1 and L2 products** and their ability to meet WGClimate needs for ECV and FCDRs	?	?	AC-VC	?	?	
	Prod-2	**Establish product accuracy, precision, resolution, and coverage requirements** needed to meet the flux requirements on various scales	X	X	AC-VC	?	?	
	Prod-3	Facilitate coordination between national and international development efforts to **identify best practices and develop a prototype product**	X		AC-VC	?	?	
	Prod-4	Pursue **consistency in product content, format, units, variable names**, etc. to facilitate interoperability	X	X	AC-VC	?	?	
	Prod-5	Pursue **traceability of data quality**	X	X	AC-VC	?	?	
	Prod-6	Coordinate **algorithm inter-comparisons** to improve accuracy and speed of retrieval algorithms	X	X	AC-VC	?	?	
	Prod-7	Facilitate exchange and harmonization of approaches to **calibration and retrieval challenges**	X	X	AC-VC	?	?	
	Prod-8	Follow and provide recommendations on development of **laboratory spectroscopy** needs	?	?	AC-VC	?	?	
	Prod-9	Define types of **data (calibration, L1, L2) that must be exchanged** to enable the integration of space-based systems into a constellation.	X	X	AC-VC	?	?	

AREA	ACTION ID	ACTION DESCRIPTION	APPLICABILITY		LEAD	CONTRIBUTORS	DUE DATE	IMPLEMENTATION STATUS
			PS	IOS				
Flux Inv Model Devmt	Inv-1	Identify **accuracy and precision requirements sufficient for policy applications**	X	X	AC-VC	?	?	
	Inv-2	Coordinate research on **flux estimation** (local to national scale; Level-4 products) (Rec#3)	X	X	AC-VC	?	?	
	Inv-3	Coordinate between **CAMS/C3S and NASA OCO-2/CMS/GMAO eff**orts - see extract from Rec#12: *CGMS and CEOS should work with their member agencies to identify and promote standards in product specification, formats, pre-processing etc. and product inter-comparisons should be routinely undertaken and supported on a sustained basis to produce seamless, interoperable datasets for use in the broader system implementation*	X	X	AC-VC	?	?	
	Inv-4	Coordinate **OSSE studies** dedicated to flux estimation - see text from Rec#8: *CEOS, CGMS and their partners should continue to support the necessary OSSE experiments, which remain of critical importance in further refining the detailed requirements of the space-based elements of the constellation (sensor precision, accuracy, and resolution, orbit and mission coordination). The near-term objective is to develop a prioritized list of the required OSSE experiments and end-to-end system simulations to optimize the overall system design, resolve system-level uncertainties, and facilitate the coordination of activities among the CEOS and CGMS agencies. The output from these experiments should be made available to the CEOS and CGMS Principals periodically, in a format conducive to discussions with their mission and orbit planning organizations*	X	X	AC-VC	?	?	
	Inv-5	Identify synergies between **observation strategies for GHGs and air quality gases** and aerosols	X	X	AC-VC	?	?	
	Inv-6	Consolidate **mission requirements for auxiliary observations** (e.g. plume tracers like NO2) (Rec#14)	X	X	AC-VC	?	?	
	Inv-7	Pursue **consistency in the product content** (Rec#12)	X	X	AC-VC	?	?	
	Inv-8	Ensure **traceability of data quality** (Rec#12, 13)	X	X	AC-VC	?	?	
	Inv-9	Define types of **data that must be exchanged to derive and validate fluxes** from a constellation of space-based sensors to facilitate open data access - see text from Rec#11: *TCCON has provided the primary transfer standard to relate space-based XCO2 and XCH4 estimates to the ground-based in situ standards maintained by the WMO GAW network. This network must be maintained and augmented using portable, ground-based remote sensing instruments (e.g. EM27/SUN), in situ sensors on fixed-wing aircraft (commercial aircraft, such as CONTRAIL, IAGOS) and balloons (AirCore), and airborne remote sensing instruments (MAMAP, CHARM-F etc.) to provide a more robust and accurate operational validation approach*	X	X	AC-VC	?	?	

AREA	ACTION ID	ACTION DESCRIPTION	APPLICABILITY		LEAD	CONTRIBUTORS	DUE DATE	IMPLEMENTATION STATUS
			PS	IOS				
	CV-1	Address existing CEOS Action by Q1 2020 on "Greenhouse gas reference standards for interoperability": Develop a list of **reference standards for CO_2 and CH_4 products** that are suitable for use in inter-comparison of multiple missions.	X	X	WGCV/ACSG or GSICS/UVSG?	GSICS/UVSG or WGCV/ACSG?	?	
	CV-2	Identify the current **shortcomings/gaps/sustainability in GHG calibration and validation capabilities**, and formulate recommendations on the medium- to long-term way forward, that is with a specific focus on GHG Fiducial Reference Measurement (FRM).	X	X	WGCV/ACSG or GSICS/UVSG?	GSICS/UVSG or WGCV/ACSG?	?	
Calibration & Validation	CV-3	Identify gaps and suggest improvements in the **inter-calibration of a future LEO/GEO constellation of GHG sensors**		X	WGCV/ACSG or GSICS/UVSG?	GSICS/UVSG or WGCV/ACSG?	?	
	CV-4	Define **protocols for comparing and validating GHG retrieval algorithms**		X	WGCV/ACSG or GSICS/UVSG?	GSICS/UVSG or WGCV/ACSG?	?	
	CV-5	Identify gaps and suggest improvements in **ground-based and airborne validation infrastructure** (i.e. geographical/geophysical gaps for FRM) and other long-term validation needs (at horizon 2025-on).		X	WGCV/ACSG or GSICS/UVSG?	GSICS/UVSG or WGCV/ACSG?	?	
	CV-6	Work towards an **operational reporting on the quality of space-borne GHG measurements** and the underlying calibration and validation infrastructure.		X	WGCV/ACSG or GSICS/UVSG?	GSICS/UVSG or WGCV/ACSG?	?	
	CV-7	Identify a repository for hosting quality-controlled CO2 and CH4 products - see Rec#13: CEOS and CGMS agencies should consider a [centralized or possibly geographically distributed] repository for hosting quality-controlled CO2 and CH4 products, with internal capability for product inter-comparison	X	X	WGCV/ACSG or GSICS/UVSG?	GSICS/UVSG or WGCV/ACSG?	?	