



CO<sub>2</sub>  
Human  
Emissions

# Strategic Research Agenda 3

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# CO<sub>2</sub> Human Emissions

## D6.3 Strategic Research Agenda 3

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# CO<sub>2</sub> Human Emissions

## CHE: CO<sub>2</sub> Human Emissions Project

Coordination and Support Action (CSA)  
H2020-EO-3-2017 Preparation for a European  
capacity to monitor CO<sub>2</sub> anthropogenic emissions

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# 1 Executive Summary

This roadmap document is the third version of the Strategic Research Agenda (SRA) summarising current research activities, within and outside CHE, and to outline the future strategies required for establishing the anthropogenic CO<sub>2</sub> emissions Monitoring and Verification Support (MVS) capacity and the required capabilities. The current version documents the objectives of CHE and VERIFY, provides an overview of the various ESA scientific studies and of the current and planned satellite observation system, as well as the various outcomes of the project and studies.

## 2 Introduction

### 2.1 Background

CHE is the response to the H2020 Call for a Coordination and Support Action (“Preparation for a European capacity to monitor CO<sub>2</sub> anthropogenic emissions”), which stated that the development, the implementation and eventually the operation of a European capacity to monitor CO<sub>2</sub> emissions will need the involvement of various players, such as space agencies, operators of in-situ measurement stations and of numerical weather prediction, and leading experts for modelling and data assimilation. CHE therefore has a work package (WP6, International Stakeholder Coordination and Liaison) focusing on the liaison of the project with the various external stakeholders through coordination and networking, laying a foundation for the operational integration of all relevant European capacities as a subsequent step. The work package will also ensure the interaction with the CO<sub>2</sub> Monitoring Task Force and the ESA Copernicus Anthropogenic CO<sub>2</sub> Monitoring Mission Advisory Group (MAG), acting as accompanying scientific and technical support. In addition, CHE will look for collaboration opportunities within existing coordination activities (e.g., WMO, UNEP, and UNFCCC). A key element of the work package is the production of this Strategic Research Agenda document that will summarise the activities relevant to the aims of the CHE project, both inside and outside the project, and provide recommendations for further research and development activities in support of realizing the goal of a European capacity to monitor CO<sub>2</sub> anthropogenic emissions. This is particularly of relevance because of the tight timeline that is envisaged for the build-up of the Copernicus CO<sub>2</sub> monitoring and verification support capacity, which should become operational in 2026. The document will therefore in future versions also link with the risk analysis outcomes of the CHE and VERIFY projects and identify areas where deviations from the original work plans were necessary.

### 2.2 Scope of this deliverable

#### 2.2.1 Objectives of this deliverable

The aim of this roadmap document (Strategic Research Agenda (SRA)) is to summarise current research activities, within and outside CHE, and to outline the future research strategies required for establishing the CO<sub>2</sub> monitoring and verification support capacity and the required capabilities.

CHE will produce a clear set of outputs in reports summarizing the current state-of-affairs, including a gap analysis, providing recommendations on needed developments including first innovative steps for current systems and system integration, and the operational aspects of the various needed components.

In addition, other H2020 projects (most notably VERIFY) and ESA studies are running in parallel producing results that are very relevant for the foreseen Copernicus CO<sub>2</sub> monitoring and verification support capacity.

Outcomes of the various projects and studies are summarized and suggestions for further research are outlined in this Strategic Research Agenda document that the European Commission and the CO<sub>2</sub> Monitoring Task Force can use to support the decision-making

process for enhancing our current capacity to observe and understand the variability of CO<sub>2</sub> human emissions and monitor their temporal evolution. This is especially relevant as input to the planned follow-on project for CHE and to the Horizon Europe Work Programme.

### **2.2.2 Work performed in this deliverable**

This deliverable is the third version of the SRA and documents the most relevant research projects and ESA studies and their recommendations for further research and development. This version has updated the existing text in various parts, with a focus on the latest outcomes from the CHE project and specifically, the documents produced by WP5.

## **3 Current status of CO<sub>2</sub> MAG and CO<sub>2</sub> task Force**

The European Commission (EC) and the European Space Agency (ESA) have set up two expert panels that support the definition of the overall system and the space segment of such a system. The CO<sub>2</sub> Monitoring Task Force started its third phase in May 2020 and the ESA CO<sub>2</sub> Mission Advisory Group (MAG) entered its second phase in May 2020 as well. Both expert panels drive the research agenda on which especially CHE and the ESA science studies act. In addition, CHE supports the CO<sub>2</sub> Monitoring Task Force by providing advice based on its research outcomes.

Regarding the CO<sub>2</sub> MAG, version 3 of the Mission Requirements Document (MRD) was published in October 2020 and is available on-line (Meijer et al., 2020). The MRD defines aspects, such as the detailed requirements for the CO<sub>2</sub> imager, the need for aerosol measurements on board the same platform, and the requirements of the NO<sub>2</sub> sensor.

The CO<sub>2</sub> Monitoring Task Force is focusing on questions related to the system design, the operational implementation of such a system and the requirements for in-situ observations. The latest report (the so-called Green report) was published in June 2019 and focuses on the requirements for in situ measurements ([https://www.copernicus.eu/sites/default/files/2019-09/CO2\\_Green\\_Report\\_2019.pdf](https://www.copernicus.eu/sites/default/files/2019-09/CO2_Green_Report_2019.pdf))

## **4 CHE objectives and outcomes**

### **4.1 Objectives**

The CO<sub>2</sub> Human Emissions (CHE) project coordinates efforts towards developing a European operational monitoring and verification support capacity for anthropogenic CO<sub>2</sub> emissions. This challenging target is aligned with the European Commission's stepwise approach for a requirement-driven integration of Earth observations, from remote sensing, in-situ, as well as other data sources with enhanced modelling capabilities for CO<sub>2</sub> fossil fuel emissions, along with other natural and anthropogenic CO<sub>2</sub> emissions and transport. The project pursues a consolidated methodology for integrating the monitoring system components, as well as innovation for estimating fossil fuel CO<sub>2</sub> fluxes. These include reconciling bottom-up and top-down constraints and handling systematic errors of satellite sensors as well as of the ground segment (i.e. of the bottom-up inventories as priors and of the atmospheric transport models). Earth observations from satellites will be combined with in-situ CO<sub>2</sub> observations and information from co-emitters or isotopes to support the attribution of fossil fuel emissions and uncertainty reduction. Methodological advances will include a representation of anthropogenic CO<sub>2</sub> variability in space and time, responding to documented shortcomings and needs, and a carbon cycle / fossil fuel data assimilation system also providing estimates of emission uncertainties. Strategies to separate anthropogenic CO<sub>2</sub> emissions from biogenic fluxes at country to global scales using observations and models will be documented. CHE will also support a large community by providing a library of realistic CO<sub>2</sub> simulations from global to city scale to examine the capacity for monitoring future fossil fuel (and even more general anthropogenic) CO<sub>2</sub> emissions and to adequately dimension space mission requirements.

CHE is organised in seven work packages, five of which will provide scientific results, analyses and summaries. These five work packages are listed below together with their objectives.

### **WP1 - Coordinating Efforts on Reconciling top-down and bottom-up estimates**

1. Deliver a cross section of remote-sensing data products needed in the data assimilation chain to constrain anthropogenic carbon emissions
2. Develop novel techniques to constrain anthropogenic and natural carbon emissions from joint surface and space-based carbon cycle data
3. Reconcile top-down and bottom-up CO<sub>2</sub> source/sink estimates at multiple levels of integration using a community access platform
4. Document current shortcomings and needed developments in space-based monitoring of fossil fuel CO<sub>2</sub> emissions

### **WP2 - Coordinating Efforts on Library of simulations for emissions and atmospheric transport**

1. Generate a library of realistic "nature" simulations of atmospheric CO<sub>2</sub> from the global to the point-source scale as a basis for designing an operational capacity for monitoring anthropogenic CO<sub>2</sub> emissions and adequately dimensioning a future space mission
2. Conduct simulations for present-day and future (2030) emission scenarios and include auxiliary tracers such as CO as well as tagged CO<sub>2</sub> tracers to support attribution to different sources and the separation into natural and anthropogenic components
3. Using satellite orbit simulators, generate a library of realistic synthetic satellite XCO<sub>2</sub> observations for a representative set of scenarios with variable orbit, swath, resolution, precision, and constellation
4. Analyse the influence of cloud cover and atmospheric aerosol load and type on satellite XCO<sub>2</sub> retrievals, especially in plumes from localised sources (urban areas such as megacities, industrial complexes such as power plants)

### **WP3 - Coordinating Efforts on Uncertainty trade-off for fossil fuel emissions**

1. Determine uncertainties in current inverse modelling, carbon cycle modelling and carbon cycle data assimilation systems to dimension expected uncertainties in emission estimates, in particular of the anthropogenic sources (after good split from the biogenic sources)
2. Evaluate possible improvements arising from enhanced space-borne and in-situ (based on the assessment in WP4) observation scenarios for fossil fuel CO<sub>2</sub> emissions quantification and elaborate on potential uncertainty reductions making use of space-borne non-CO<sub>2</sub> tracers (NO<sub>x</sub>, CO)
3. Determine the sensitivity of the emissions on relevant parameters at a variety of scales (at a balanced, reasonable time/space resolution and uncertainty)
4. Assess emission uncertainties and prepare uncertainty gridmaps and covariance matrices.

### **WP4 - Coordinating Efforts on Attributing CO<sub>2</sub> emissions from in-situ measurements**

1. Survey current European in-situ observation capacity.
2. Define an operational strategy to separate anthropogenic CO<sub>2</sub> emissions from biogenic fluxes at regional and global scales through the use of additional tracers or the ratio of co-emitted gases.
3. Shape the appropriate dimension and distribution of the corresponding in-situ network.



**WP5 - Towards a prototype of a European anthropogenic emission monitoring system**

1. Characterise and consolidate the building blocks of data, model and model-data fusion techniques that will feed into the design of a future CO<sub>2</sub> anthropogenic emission monitoring system based upon the project's outcome and best practices worldwide.
2. Identify potential synergies between different components in the data, model and model-data fusion building blocks.
3. Analyse service element aspects of an integrated CO<sub>2</sub> anthropogenic monitoring system such as computing costs, timeliness and availability of required input data and feasibility to achieve required target output.
4. Synthesise results and recommendations from WPs on the architecture of a future prototype
5. Recommend minimum and desirable requirements for an end-to-end CO<sub>2</sub> anthropogenic emission monitoring system

**4.2 Recommendations for further research**

This section provides an overview of the recommendations for further research based on the research and development outcomes of CHE over the duration of the project. These recommendations are recorded in the CHE Quarterly reports as well as in various deliverables. So far, the following recommendations have been made:

**4.2.1 WP1 Coordinating Efforts on Reconciling top-down and bottom-up estimates**

In addition to the input that has been provided to the various reports in WP5, the following recommendations came out of this work package:

- Operational NWP centres usually focus on the atmospheric state rather than on surface fluxes. To gain experience in estimating surface fluxes in the proposed hybrid data assimilation system, CO surface flux estimation using Sentinel-5P TROPOMI data should receive high priority.

**4.2.2 WP2 Coordinating Efforts on Library of simulations for emissions and atmospheric transport**

In addition to the input that has been provided to the various reports in WP5, the following recommendations came out of this work package:

- Simulations of NO<sub>2</sub> should receive more attention to be able to address the question of potential use of an NO<sub>2</sub> instrument on the CO<sub>2</sub> Monitoring mission. Accurately simulating NO<sub>2</sub> needs models with full interactive chemistry, although a simplified NO<sub>2</sub> tracer with a constant lifetime could be sufficient for some applications, such as identifying the location of plumes.
- Synthetic satellite observations are a key input for OSSEs. The product of CHE task T2.4 is very valuable but has some limitations that should be addressed in the future: it only covers a single year (2015), only the domain of Europe and does not account for the potential of the MAP instrument to reduce systematic errors due to aerosols. Furthermore, since the CO<sub>2</sub>M mission will carry an aerosol instrument (MAP), a significant upgrade of the product to account for the impact of MAP on the errors will be needed. It would also be good to produce data for other regions with higher AOD, e.g., China.



### 4.2.3 WP3 Coordinating Efforts on Uncertainty trade-off for fossil fuel emissions

In addition to the input that has been provided to the various reports in WP5, the following recommendations came out of this work package:

- The CCFDAS quantitative network design system needs to be improved in terms of available observational data streams (e.g. co-emitted species, socio-economic data), representation of surface flux models and their sectorial resolutions, as well as temporal and spatial resolution to the atmospheric component (to match those of the observations anticipated from the CO<sub>2</sub>M mission). The prototype CCFDAS quantitative network design system has evolved into a powerful tool for quick exploration/assessment of design options of the MVS capacity. Initial assessments of the sensitivity with respect to observational data streams, prior information, and temporal domains in flux and observation spaces have demonstrated the potential of the approach.
- Provide reference input datasets (e.g. for the anthropogenic emissions and their uncertainty, the biogenic emissions and their uncertainty, the meteorological data – ERA5, ...) to increase the consistency within the different models contributing to the CO<sub>2</sub> MVS capacity. This should include the data that go into calculating the emissions; eventually these can be used in the empirical models that go into the calculations of the emissions from the reported data.
- Uncertainty estimation of the bottom-up data-driven products. The uncertainties are key in the inversion system, but quantifying them in an appropriate way, such that they meet the requirements of the inverse setup and facilitate optimal synergy between bottom-up and top-down, requires further research. This is particularly true for the critically needed spatial-temporal error covariance matrix. This effort would also require and would strongly benefit from close collaboration between the bottom-up land flux and top-down inversion communities.

### 4.2.4 WP4 Coordinating Efforts on Attributing CO<sub>2</sub> emissions from in-situ measurements

In addition to the input that has been provided to the various reports in WP5, the following recommendations came out of this work package:

- Improve the modelling framework for <sup>14</sup>CO<sub>2</sub>, CO and APO. The current project can only reach some degree of sophistication / realism in the simulation of these tracers that relate to the anthropogenic emissions of CO<sub>2</sub> and the model improvement is required to improve the uncertainty quantification of the Observation System Simulation Experiments.
- Compilation of and access to in-situ measurements (flux towers) of net carbon exchange is critical but still an issue. It would be important to foster this, which goes beyond collecting data from operational networks (like ICOS and NEON). There is a need for more and good quality data from tropical, sub-tropical, and arctic ecosystems - such flux towers do exist, but the data are not being shared (FLUXNET managed to collect data from approx. only 20% of the existing towers worldwide). This is a very tedious effort as it requires communication and building trust with individual PIs.

### 4.2.5 WP5 Towards a prototype of a European anthropogenic emission monitoring system

Work package 5 integrates the developments from the other work packages to provide recommendations on the architecture of a future prototype. It also recommends minimum and desirable requirements for an end-to-end CO<sub>2</sub> anthropogenic emission monitoring system. In addition, it provides some recommendations for further research and development, which are summarised below. The early recommendations from the draft reports have been updated based on the final reports and are listed below.

**Service elements for CO<sub>2</sub> Earth Observation integration:**

- Data assimilation: Identify contributions from direct or indirect observations of anthropogenic activity (co-emitted tracers, activity data, ...) for the separation between fossil fuel and non-fossil fuel fluxes and possibly for some sectoral attribution.
- Data assimilation: Identify contributions from direct or indirect observations of vegetation activity (SIF, COS, ...) for the separation between fossil fuel and non-fossil fuel fluxes.
- Modelling: Identify contributions from direct or indirect observations of atmospheric transport (plume orientation in the CO<sub>2</sub>M mission images, wind vector retrievals, measurements of radon, ...) for the improvement of transport simulation.
- Observations: Develop a realistic modelling framework (observation operators) for each new observation (radiocarbon, NO<sub>2</sub>, etc.), including corresponding error statistics.

**Service elements for CO<sub>2</sub> emission and transport model integration:**

- Transport: Test new transport schemes developed in NWP, e.g. MPDATA advection in FVM IFS (Kühnline et al, 2019).
- Transport: Integrate plume rise model in emission hotspots (Guevara et al, 2014, Brunner et al., 2019).
- Transport: Evaluate PBL wind profiles crucial for plume modelling (Sandu et al., 2013).
- Anthropogenic emissions: Extend FFDAS approach using all available human activity proxies.
- Anthropogenic emissions: Merge mosaic of regional inventories (Tier 2,3) with global inventory (Tier1, Tier2).
- Biogenic fluxes: Use SIF and COS to constrain biogenic fluxes.
- Biogenic fluxes: Introduce crop modelling and relevant land management information (crop rotation/harvesting, grazing, etc.).
- Other tracers: Implementation of APO and radiocarbon in forward/inverse model.

**Service elements requirements for data assimilation methodology:**

- Within the community, there is increasing recognition that underneath the rapidly changing carbon fluxes across space and time, a smaller number of system “traits” exerts important control over these fluxes. This is true for the biosphere, where physiological responses of plants are more constant than the fluxes, they result in. But similarly, for anthropogenic emissions, responses to outside temperature (household, cars) or to cloudiness (solar energy) are more similar than the traffic patterns or energy demand- and hence CO<sub>2</sub> emissions - they result in. A CCFFDAS system that embodies such relationships between fast environmental changes and slower responses will likely offer efficient ways to estimate anthropogenic emissions. From the observational side, it will allow us to tap into the enormous wealth of so-called “activity data” such as traffic patterns, shipping motions, real-time energy demand, and solar/wind production capacity, which also during the COVID19 crisis turned out to be an important resource. We therefore recommend continued R&D on this approach is prioritized alongside the envisioned prototype.
- The current COVID-19 crisis, the developments on the CO<sub>2</sub>-M mission, and the new insights from TropOMI make it abundantly clear that the overall goal of getting independent constraints on anthropogenic CO<sub>2</sub> emissions can only be reached when different data streams are integrated. Despite the realization that remote sensing data will bring in the bulk of the signals to assimilate, the value of additional evaluation of DA system results with more sparse surface datasets is recognized strongly in the community. To ensure that the Copernicus systems can tap into the development of new tracer measurements and derived metrics, we recommend research to proceed with the IFS system also on tracers that have a lower promise for inclusion as DA

constraints. This means that based on the framework, we develop capacity for predictions of atmospheric  $\Delta^{14}\text{C}$ ,  $\delta^{13}\text{C}$ , COS, SIF, and APO from the multi-year flux reanalysis.

- A proposed multi-model system could be used to integrate spatiotemporally heterogeneous posterior emission products. This system, outlined by Boussez et al. (2019, Tech Memo), would treat the local and regional posterior flux products as observations in a global IFS-driven CO<sub>2</sub> inversion. In practice, each regional and local inversion output to be assimilated in the global multi-model system would be required to provide an ensemble of prior and posterior samples of 4D CO<sub>2</sub> emissions and CO<sub>2</sub> concentration fields. To avoid any detrimental effects from the integration of poorly estimated posterior emissions and/or inaccurately prescribed posterior errors on the multi-model product, a strict quality control mechanism will need to be implemented. The complexity of assimilating inversion products across different spatiotemporal scales in consistent manner may require an efficient integration tool similar to CIF (VERIFY), in particular to standardize model inputs/outputs. Within the IFS global model, the multi-model assimilation algorithm will be implemented using the modular OOPS DA system.

#### Service elements requirements for uncertainty representation:

- Research into feasible co-emitters and uncertainty in their co-emission factors and emissions.
- Develop anthropogenic emission models and quantify their uncertainty.
- Investigate the feasibility of using (i.e., acquisition) citizen data (such as traffic counts or mobile network utilisation) for constraining sectoral activity.
- Investigate the uncertainties of observations constraining biogenic fluxes (SIF, COS) and their observation operators.
- Investigate measurement techniques for radiocarbon and their uncertainties.
- Research uncertainties related to contamination of radiocarbon proxy by nuclear power plants and terrestrial disequilibrium.
- Investigate the numerical uncertainties within all models involved within the CHE/CoCO<sub>2</sub> prototype.
- Improved inventories, e.g., NRT data and uncertainties for different sectors.
- Maintain alternative (potentially lighter) approaches for cross checks.

## 5 VERIFY objectives and outcomes

### 5.1 Objectives

VERIFY proposes to quantify more accurately carbon stocks and the fluxes of carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O) across the EU based on independent observations in support of inventories that rely mainly on self-reported statistical data. The same approach will also be tested for the United States, China and Indonesia, in collaboration with foreign partners. Accurate characterization of the space-time variations of GHG fluxes, separating their anthropogenic and natural components and their drivers, will be based on advanced modelling approaches using atmospheric GHG measurements, tracer transport inversions and various arrays of land observations, in-situ and from space. The improved knowledge of GHG budgets from VERIFY will be used to improve national inventories, in collaboration with national inventory agencies, and to deliver policy-relevant information to track progress of the EU mitigation efforts to meet the targets of the Paris Agreement on Climate, in line with international cooperation mechanisms promoted by the UNFCCC, the IPCC and the WMO.

The main objective of **WP1** is to assess the current and future needs of inventory agencies and of the international climate process, and to help design the framework of the project's subsequent work packages based on the identified MRV (measurable, reportable and

verifiable) requirements. To this aim, WP1 will create a User Requirement Document (URD) for a monitoring and verification system of GHGs to be developed by the subsequent work packages. To do this, it will define accuracy, comparability and comprehensiveness targets for the products of such a system, with the aim to serve policy at various temporal and spatial scales. The work package will provide an overview of approaches used in GHG inventories at the national scale, and of available methods for verification and their gaps and obstacles. Specific objectives are:

- Assess the MRV policy and inventory needs in the enhanced transparency framework MRV under the Paris Agreement (inputs to WP 2,3,4)
- Build a network of policy makers, scientists and inventory agencies

The overarching objective of **WP2** is to develop the components of the observation-based monitoring and verification system (summarized in an Algorithm Description Document, ADD and a Product Description Document, PDD) dedicated to fossil fuel CO<sub>2</sub> emissions (ffCO<sub>2</sub>), using in situ and remotely sensed atmospheric measurements of CO<sub>2</sub> and co-emitted tracers. They will become part of the Community Inversion Framework (CIF). To address this objective, VERIFY will construct a Fossil Fuel Data Assimilation System (FFDAS) to estimate ffCO<sub>2</sub> emissions at a sub-national resolution (25-50 km) by combining spatio-temporal information from a dynamical emission (inventory) model for ffCO<sub>2</sub> and co-emitted species (CO, NO<sub>x</sub>), natural CO<sub>2</sub> fluxes estimates, and independent in situ and space-borne observations of atmospheric CO<sub>2</sub>, <sup>14</sup>CO<sub>2</sub>, and co-emitted species (CO, NO<sub>2</sub>, Black Carbon). The dynamical emission model and the inverse modeling strategy using ffCO<sub>2</sub> proxies like CO and NO<sub>x</sub> will be evaluated using measurements from dedicated field campaigns. To prepare for the future, VERIFY will explore the theoretical potential of new and future satellite data products (e.g. Sentinel-5P). Specific objectives are:

- To deliver high resolution bottom-up anthropogenic (including fossil fuel and biofuel, no land-use) emission estimates of CO<sub>2</sub> and co-emitted tracers by sector across Europe from 2005 up to last year (with only one year time lag between the time of latest emissions and the time of reporting) [current year -1], with annual updates.
- To provide data for a proof-of-concept region to evaluate and deliver proxy/ffCO<sub>2</sub> ratios close to emission hot spots, such as cities, and conduct independent <sup>14</sup>C-based validation of the proxy-ffCO<sub>2</sub> approach.
- To develop the computing framework to support the independent monitoring of ffCO<sub>2</sub> emissions from different sectors at the national scale using space-borne measurements of CO and NO<sub>x</sub>.
- To demonstrate the potential of i) (future) space-borne and ground-based pollutant and isotope data, and ii) jointly estimating natural and anthropogenic emissions to improve national-scale ffCO<sub>2</sub> emission budgets.

The overall goal of **WP3** is to build a pre-operational system and deliver the respective Algorithm Description Document ADD and Product Description Document PDD (as a component of the overall policy-relevant observation system) to deliver national and sub-national annual budgets of land-based CO<sub>2</sub> fluxes, including quantified uncertainties, and to improve our understanding of the key processes and drivers contributing to these budgets. New multi-data model fusion strategies will further reduce uncertainties of CO<sub>2</sub> budgets and trends at regional scale, with a focus on Eastern Europe. To achieve these goals, the work package has the following specific objectives:

- Collate state-of-the-art driving datasets for use in modelling and inversions including data on climate, land use change and biomass, soil properties and soil erosion risk, terrestrial CO<sub>2</sub> flux datasets, cropland management, grassland management, forestry

management, nitrogen deposition, freshwater fluxes and river exports, coastal ocean CO<sub>2</sub> fluxes, and other lateral fluxes (harvest / trade).

- Construct a bottom-up budget of terrestrial CO<sub>2</sub> fluxes using a few complementary models, informed by various data streams through model data fusion techniques, or direct use of key observational constraints.
- Construct Europe-wide inversions of NEE using in situ observations of atmospheric CO<sub>2</sub>, a high-resolution transport model with a detailed representation of CO<sub>2</sub> atmospheric boundary conditions (the influence of fluxes outside Europe).
- Develop new multi-data model fusion strategies to further reduce uncertainties of CO<sub>2</sub> budgets and trends at regional scale, with a specific focus on Eastern Europe.

The overarching goals of **WP4** are to deliver estimates of CH<sub>4</sub> and N<sub>2</sub>O surface to atmosphere fluxes, including anthropogenic as well as natural sources, and to build this capacity into a pre-operational system, the Community Inversion Framework (joint development with WPs 3 and 2, described via an Algorithm Description Document, ADD, and a Product Description Document, PDD). WP4 will also improve the understanding of the processes driving surface-atmosphere fluxes of CH<sub>4</sub> and N<sub>2</sub>O and reduce the uncertainties in their budgets and trends at national, regional and continental scales. Specific objectives are:

- To deliver detailed bottom-up (BU) estimates of CH<sub>4</sub> and N<sub>2</sub>O fluxes by source type and at high spatial resolution (0.1°x0.1°) and at appropriate temporal resolutions (daily to monthly) as input to atmospheric inversions and to provide detailed information on source sectors.
- To deliver top-down (TD) estimates of CH<sub>4</sub> and N<sub>2</sub>O fluxes based on atmospheric inversions at 0.5°x0.5° and weekly resolution.
- To improve the understanding of key source processes, such as wetland production of CH<sub>4</sub>, by using atmospheric and flux observations to improve process-based model estimates.
- To explore the potential of new data streams, such as from the planned satellite mission, TROPOMI, to improve flux estimates from atmospheric inversions.
- To explore the potential of additional atmospheric species (such as ethane and δ<sup>13</sup>C-CH<sub>4</sub>) for better constraining CH<sub>4</sub> emissions by source type.

The overall objective of **WP5** is to provide the process through which different scientific data-streams on GHG budgets from WP2, WP3, and WP4 will be synthesized for comparison with official inventories in WP6. Specific objectives are:

- Quantify structural uncertainties of the components and methods for the GHG budgets
- Reconcile bottom-up and top-down observation-based methods to provide a peer-reviewed scientific assessment of the GHG budgets at country scale
- Provide synthesis annual GHG budgets at the country scale based on the products of WPs 2 to 4 (National GHG Budget Fact Sheets, BFCs) that will be compared with official UNFCCC inventories within WP6 (jointly with WP1)
- Provide near-term projections to assess process understanding for real-time verification
- Analysis of the impacts of climate trend and variability on natural GHG fluxes, to constrain, climate carbon cycle feedbacks in coupled models used for IPCC projections and the effect of climate extremes.

**WP6** will provide a prototype of a decision support tool informed by an observation-based system to monitor GHG sources and sinks and to verify the consistency of reported emission trends and atmospheric observations. This prototype will integrate scientific results from the



approaches used in WP2 - WP5 to quantify GHG budgets and their uncertainties and will translate them into actionable, policy-relevant information. 'Actionable' refers to best practices anchored to data standards, transfer of information and tools to improve national and EU emissions and assess their trends. These tools will be designed to be applicable to other countries outside Europe. Specific objectives are:

- Harmonizing the GHG budgets and inventories for the EU as a whole (the EU being part of the COP cycles together with each EU member-state).
- Testing and applying the harmonization/verification methodology to selected other large emitting countries - US, China and Indonesia - in collaboration with foreign academic and administrative institutions, based on results available from the global modelling of WP2 - WP4 and regional datasets from foreign partners, providing National GHG Budget Fact Sheets (BFCs).
- Establishing a database and data management system at project level, fostering transparency and the promotion of data and meta-data standards. Prepare the data flow from the pre-operational research developments of VERIFY to established services (Copernicus services, ICOS-Carbon Portal) to ensure the legacy of the project to the UNFCCC stock-take process by 2023, and its long-term operability, documented in a System Design Document (SDD).
- Developing a new actionable policy support tool to track the evolution of EU GHG inventories for climate action targets by 2030 (Nationally Determined Contribution – NDCs) and monitor the effectiveness of GHG emission reductions.
- Developing a data visualization application to provide regional emission uncertainty reduction potentials and how the observation-based system to monitor GHG sources & sinks could be improved by additional observations.

### 5.2 Research outcomes

The VERIFY project is currently at the end of its third year with officially one more to go. VERIFY has therefore not produced any specific statements about future research needs yet. We therefore will refer to some of the more relevant deliverables that are available from the VERIFY website to guide further exploration of the VERIFY results.

D1.2 Terminology analysis ([https://verify.lsce.ipsl.fr/images/D12\\_Terminology\\_Analysis.pdf](https://verify.lsce.ipsl.fr/images/D12_Terminology_Analysis.pdf))

D1.3 Consolidated reporting requirement assessment  
([https://verify.lsce.ipsl.fr/images/D13\\_Consolidated\\_reporting\\_requirement\\_assessment.pdf](https://verify.lsce.ipsl.fr/images/D13_Consolidated_reporting_requirement_assessment.pdf))

D1.4 Verification requirements assessment  
([https://verify.lsce.ipsl.fr/images/D14\\_Verification\\_requirements\\_assessment.pdf](https://verify.lsce.ipsl.fr/images/D14_Verification_requirements_assessment.pdf))

D5.1 Structural uncertainties  
([https://verify.lsce.ipsl.fr/images/D51\\_Structural\\_uncertainties.pdf](https://verify.lsce.ipsl.fr/images/D51_Structural_uncertainties.pdf))

D5.2: First report - Reconciliation of bottom-up and top-down methods at sub-national scales  
([https://verify.lsce.ipsl.fr/images/D52\\_First\\_report-Reconciliation\\_of\\_bottom-up\\_and\\_top-down\\_methods\\_at\\_sub-national\\_scales.pdf](https://verify.lsce.ipsl.fr/images/D52_First_report-Reconciliation_of_bottom-up_and_top-down_methods_at_sub-national_scales.pdf))

D5.9 First scientific review article on multi-gas GHG budgets  
([https://verify.lsce.ipsl.fr/images/VERIFY\\_D59\\_First\\_scientific\\_review\\_article\\_on\\_multi-gas\\_GHG\\_budgets\\_v1.pdf](https://verify.lsce.ipsl.fr/images/VERIFY_D59_First_scientific_review_article_on_multi-gas_GHG_budgets_v1.pdf))

## 6 ESA studies

As part of the writing of the Sentinel-CO<sub>2</sub> Mission Requirements Document (MRD) and in support of the CO<sub>2</sub> Task Force A, ESA funds several studies to investigate certain aspects of a future Sentinel mission focused on the observation of atmospheric CO<sub>2</sub> concentrations in support of the envisaged anthropogenic CO<sub>2</sub> emissions monitoring and verification support



(MVS) capacity. The outcomes of these studies are not only relevant for the specification of the MRD, but also for the development of the full MVS capacity. This section therefore tries to summarize the main outcomes of the most CHE-pertinent studies as they get published over time.

### 6.1 SMARTCARB

SMARTCARB assesses the potential synergies of measurements of CO and NO<sub>2</sub> for observing and quantifying anthropogenic CO<sub>2</sub> of localised sources such as large cities and power plants in Europe, at the example of the Berlin area. It investigates the impact of different satellite specifications (e.g., overpass time and spatial coverage) as well as the time separation between the measurements of CO<sub>2</sub> and those of CO and NO<sub>2</sub> in case these are measured on different satellites. The tools for addressing these questions are high-resolution atmospheric transport simulations and inverse methods combined with synthetic satellite observations extracted from the simulations. The study formulates requirements for accuracy, coverage and other factors affecting the satellite measurements needed to quantify the CO<sub>2</sub> emissions of individual sources with a certain level of accuracy.

Detailed descriptions of the system set-up (model simulations and synthetic observations) are available in the first three Deliverable documents that are available on the SMARTCARB web site: <https://www.empa.ch/web/s503/smartcarb>. The study proved the usefulness of NO<sub>2</sub> measurements for detection of the anthropogenic CO<sub>2</sub> plumes with the main conclusion stating that CO<sub>2</sub> emission estimates depend less on the precision of the CO<sub>2</sub> instrument for large plumes, e.g. a city plume, when an NO<sub>2</sub> instrument is used for detecting the location of the plume and estimating the CO<sub>2</sub> background. For these cases, a wider swath and somewhat worse CO<sub>2</sub> single sounding precision might be a reasonable trade-off. For smaller plumes e.g. from power plants, a high precision of the CO<sub>2</sub> instrument is more relevant because of the small number of pixels contained in the plume. Also, in terms of NO<sub>2</sub> a high precision instrument is preferred considering that the next generation removal technology will likely further reduce NO<sub>x</sub> emissions from power plants.

In its final report (available at [https://www.empa.ch/documents/56101/617885/FR\\_Smartcarb\\_final\\_Jan2019.pdf](https://www.empa.ch/documents/56101/617885/FR_Smartcarb_final_Jan2019.pdf)), specific recommendations for further research are the following:

- Perform Monte Carlo experiments to better constrain the number of observable plumes with different constellations
- Development of more advanced and robust plume detection algorithms
- Analysis of the potential of estimating CO<sub>2</sub> emissions from NO<sub>2</sub> observations
- Further improvements of the mass-balance method for CO<sub>2</sub> emission estimation
- Estimating annual mean emissions and their uncertainties from single overpass estimates
- Analysis of the sensitivity of the representation of city plumes to different transport models and model settings
- Application of methods to a city in a developing country
- Inversions in a more realistic setup without assuming a perfect transport model
- Development of an advanced data assimilation system

### 6.2 PMIF

The PMIF (Poor Man's Inversion Framework) study aims to define the XCO<sub>2</sub> precision and temporal resolution requirements for the Sentinel mission by assessing detection thresholds and fraction within each country of fossil fuel (or more in general anthropogenic) CO<sub>2</sub> emissions, from power plants and cities, that would be detected by the space-borne system. The study also assesses the constellation of CO<sub>2</sub> Sentinels and the impact of various assumptions in the inversion process, such as prior uncertainty and error correlation.

PMIF defines and tracks emission hotspots in the form of so-called clumps, clusters of emitting pixels that can be detected from space, on a global scale. It then estimates the number of days the emissions can be significantly constrained (defined by relative posterior uncertainty smaller than 50% compared to prior uncertainty of 100%) from space-based observations for all the clumps in China, Europe, and North America, with different configurations of the plume length, temporal prior error correlation, number of satellites, taking into account cloudiness and the limited signal-to-noise for nadir observations over ocean. First detailed results are available in Deliverable 3, "The potential of a single satellite equipped with CO<sub>2</sub> imagery to estimate fossil fuel CO<sub>2</sub> emissions." Initial results show that the detectability of emissions from inland locations is promising, but problems arise for coastal emission sources. Also, areas with extensive cloud cover, such as south-China, might be difficult to monitor consistently over time.

In its final report the PMIF study provided the following recommendations:

- The impact of temporal and spatial prior error correlations needs to be better quantified. The results of PMIF show that the uncertainties in the estimated fossil CO<sub>2</sub> emissions at annual and national scales are largely dependent on the hypothesis on the prior error correlations. The way forward is to collect more inventory data to strengthen the estimate of the statistics on the plausible temporal and spatial prior error correlations of the emissions for different sectors. These new temporal and spatial prior error correlations should be tested in the PMIF inversion system to inform what percentage of the emission field will be rigorously constrained by XCO<sub>2</sub> observations at the clump and daily scales up to the annual and national scales.
- To better understand the impact of systematic errors in the XCO<sub>2</sub> on the quantification of fossil CO<sub>2</sub> emissions, it is recommended to analyze the impact of the spatial and temporal structure of systematic errors associated to the retrievals. The PMIF system shall be modified to account for these systematic errors. A specific question is whether the systematic error can or cannot be correlated with the CO<sub>2</sub> plumes (results from AEROCARB could be used here).
- The impact of transport error in the detection of plumes from fossil CO<sub>2</sub> emissions should be included in the OSSE. These errors may be quantified e.g. by analyzing the differences between the wind fields from two wind products (ECMWF vs. CCMP) and by further analysis of the validity of the Gaussian plume hypothesis.<sup>1</sup>
- The confounding effect of vegetated fluxes on the XCO<sub>2</sub> images should be analyzed. The large-scale patterns of vegetation-induced XCO<sub>2</sub> may add a random error contribution. Some vegetation patterns may also generate atmospheric structures that are correlated with the XCO<sub>2</sub> plume, which would then lead to biases on the anthropogenic emission estimates.
- The impact of spatial sampling distance, as instrument concepts lead to non-continuous imagery, has not been investigated. The errors associated with representativeness will add additional errors to the observations. Combining the new sampling and the representativeness error makes it possible to investigate the impact on the quantification of fossil CO<sub>2</sub> emissions using satellite observations. This analysis can be made at clump and daily scales and also at national and annual scales.
- One should investigate the impact of glint observations to constrain emissions near the coast and in shallow waters. With the current configuration, no observations over the oceans were assumed, which may penalize the estimates for coastal cities. Observation acquired in glint mode over the ocean may provide additional information that could prove useful for these specific cases.
- It is recommended to assess the impact of European CO<sub>2</sub>M imagers to the overall reduction of uncertainties of fossil fuel CO<sub>2</sub> emissions within CEOS constellations of

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<sup>1</sup> Results and discussions from the CHE project indicate that this topic needs a more extended approach. Comparing two global models might not be sufficient and the use of higher-resolution local models might be required to further assess the errors and find ways to correct them.

imagers and sounders. The PMIF system is ideally suited to assimilate XCO<sub>2</sub> observations from European CO<sub>2</sub> Sentinel constellation and other LEO and GEO imagers at the same time at high spatial and temporal resolution with worldwide coverage of all emissions hotspots.

### 6.3 CCFFDAS

The Quantitative Assessment of CO<sub>2</sub> mission design options in a CCFFDAS (Carbon Cycle and Fossil-Fuel Data Assimilation System) study aims to define XCO<sub>2</sub> precision, spatial and temporal coverage requirements for the Sentinel mission, as well as provide design options for the CO<sub>2</sub> monitoring system including all system components, by assessing uncertainty reductions in fossil fuel and biogenic fluxes considering several system design options.

In its final report the CCFFDAS study provided the following recommendations:

- Spatial and temporal correlations in the systematic error of XCO<sub>2</sub> retrievals have a large impact on posterior emission uncertainty. Their magnitude and specification should be further investigated.
- The setup and operation of the first CCFFDAS achieved by this study was a challenging task and had to rely on coupling of existing components. Therefore, the system could only be set up and operated over a single one-week period. Many factors that impact the CO<sub>2</sub>M performance assessments show temporal variability, including the atmospheric transport, the terrestrial fluxes, the fossil fuel emissions as well as cloud cover and aerosol load in combination with the particular orbits in that week. It would be worthwhile to systematically assess the CO<sub>2</sub>M performance in other seasons.
- The study has also indicated the performance gain to be expected from an extended data assimilation system with a temporal dimension in the control vector. For example, such a system would be capable of computing the sensitivity of atmospheric observations made in one week to emissions in the preceding weeks and of exploiting this sensitivity to better constrain such emissions by also including longer-range constraints.
- As the focus of the current CCFFDAS was the quantification of fossil emissions at the national scale for selected countries around the world, it was computationally infeasible to operate an atmospheric transport model at the planned spatial resolution of the CO<sub>2</sub>M sensor. The current system can thus not benefit from the mission's imaging capability. We recommend developing a data assimilation system with a high-resolution transport model. Such a system can be used to assess the accuracy requirements for XCO<sub>2</sub> alone and in combination with NO<sub>2</sub> for quantification of the fossil fuel emissions over a hot-spot/mega-city region and also to quantify the added value of a multi-angular polarimeter (MAP) for the quantification of fossil fuel emissions.
- A final recommendation is to investigate the synergies within a virtual constellation of CO<sub>2</sub>M with existing and planned missions observing CO<sub>2</sub> in terms of their combined constraint on CO<sub>2</sub> emissions. GeoCarb and its imaging over the Americas is likely to propagate information on the terrestrial biosphere improving estimates over Europe for example. Other relevant missions may be OCO, GOSAT, MicroCarb, or IASI(-NG).
- In an extension of the study, a system running at the spatial resolution of CO<sub>2</sub>M is being constructed and will be employed to the accuracy requirements for XCO<sub>2</sub> alone and in combination with NO<sub>2</sub> for quantification of the fossil fuel emissions over a hot-spot/mega-city region (Berlin) and also to quantify the added value of a multi-angular polarimeter (MAP) for the quantification of fossil fuel emissions.

### 6.4 AEROCARB

AEROCARB assesses the AEROSol monitoring for enhanced monitoring of fossil fuel CARBon. The study contributes to the design of the Multi-Angle Polarimeter and evaluates (i)

the correction for the light path because of the aerosol scattering and (i) the potential use of aerosol measurements to observe anthropogenic CO<sub>2</sub> of localised sources.

## 7 Observation system

The envisaged Copernicus anthropogenic CO<sub>2</sub> emissions monitoring and verification support (MVS) capacity will be an observation-based information system complementary to and in support of existing and well-defined inventory-based methods. It is therefore important to consider the existing and planned observation system, both satellite-based and non-satellite-based. For the satellite element, international coordination between the various space agencies exists through CEOS. A CEOS white paper was published in November 2018 ([http://ceos.org/document\\_management/Virtual\\_Constellations/ACC/Documents/CEOS\\_AC-VC\\_GHG\\_White\\_Paper\\_Publication\\_Draft2\\_20181111.pdf](http://ceos.org/document_management/Virtual_Constellations/ACC/Documents/CEOS_AC-VC_GHG_White_Paper_Publication_Draft2_20181111.pdf)) outlining in detail the space component for monitoring atmospheric CO<sub>2</sub> and CH<sub>4</sub>. Most of these instruments aim to improve our understanding of the carbon cycle with the planned CO2M mission currently being the only platform specifically designed to estimate anthropogenic CO<sub>2</sub> emissions. In the CEOS document the following instruments have been identified:

Instrument	Platform	Space Agency	Observed species	(Expected) observation period
SCIAMACHY	EnviSat	ESA	CO <sub>2</sub> , CH <sub>4</sub> , CO, NO <sub>2</sub>	2002 - 2012
TANSO-FTS	GOSAT	JAXA	CO <sub>2</sub> , CH <sub>4</sub>	2009 -
OCO-2	OCO-2	NASA	CO <sub>2</sub>	2014 -
GHGSat	GHGSat		CH <sub>4</sub>	2016 -
ACGS	TanSat	MOST	CO <sub>2</sub>	2016 -
TROPOMI	Sentinel-5p	ESA	CH <sub>4</sub> , CO, NO <sub>2</sub>	2017 -
GAS	Feng Yun-3D	CNSA	CO <sub>2</sub> , CH <sub>4</sub> , CO	2017 -
GMI	GaoFen-5	CNSA	CO <sub>2</sub> , CH <sub>4</sub> , CO, NO <sub>2</sub>	2018 -
TANSO-FTS-2	GOSAT-2	JAXA	CO <sub>2</sub> , CH <sub>4</sub>	2018 (TBC) -
OCO-3	ISS	NASA	CO <sub>2</sub>	2019 (TBC) -
MicroCarb		CNES	CO <sub>2</sub>	2020 (TBC) -
Sentinel 5	MetOp-SG	ESA/EUMETSAT	CO <sub>2</sub> , CH <sub>4</sub> , CO, NO <sub>2</sub>	2022 (TBC) -
MERLIN		CNES	CH <sub>4</sub>	2021 (TBC) -
GeoCarb		NASA	CO <sub>2</sub> , CH <sub>4</sub> , CO	2022 (TBC) -
TANSO-FTS-3	GOSAT-3	JAXA	CO <sub>2</sub> , CH <sub>4</sub> , CO	2023 (TBC) -
Sentinel-CO2		ESA	CO <sub>2</sub> , (CH <sub>4</sub> , NO <sub>2</sub> )	2025 (TBC) -
GAS-2	Feng Yun-3G	CNSA	CO <sub>2</sub> , CH <sub>4</sub> , CO	2021 (TBC) -
ACGS	TanSat-2	MOST	CO <sub>2</sub> , CH <sub>4</sub> , CO	TBC

All these instruments (will) provide measurements of CO<sub>2</sub> and related species that can be used to further improve our understanding of the carbon cycle, to test aspects of a prototype system that is focused on anthropogenic CO<sub>2</sub> emissions, and to contribute to the overall system that is envisaged within Copernicus.

## 8 Recommendations

Based on the information presented in the previous sections, this section aims to present the main research & development recommendations.

1. The correlation between emissions of co-emitted species, such as CO<sub>2</sub>, CH<sub>4</sub>, NO<sub>2</sub> and CO, as a function of fuel type, country and sector should be further explored. This will allow better harmonization between emission estimates for the CO<sub>2</sub> service and for air quality in CAMS as well as potentially improve the estimates for each individual species. There are significant uncertainties in the so-called emission factors, which quantify the amount of emission for each species for a specific burning process. Atmospheric concentrations of these species are indeed observed independently from space and, because they have very different atmospheric lifetimes, information can be extracted from the differences between their spatial distributions by means of data assimilation techniques.
2. The CO<sub>2</sub> MVS capacity focuses on extracting relevant information from the CO<sub>2</sub>M satellite mission and the various in situ networks. However, to better separate the anthropogenic signal from the natural signal in the observed CO<sub>2</sub> concentrations, it is critical to exploit additional observations, such as those directly sensitive to anthropogenic emissions, <sup>14</sup>C (radio-carbon) and APO (Atmospheric Potential Oxygen), and those directly sensitive to the natural fluxes, SIF (Solar Induced Fluorescence), Carbonyl Sulfide (COS) and others. Research is needed to develop methods and modelling capabilities to make use of these additional types of observations within the foreseen global and regional CO<sub>2</sub> inverse modelling systems. This should also include observations of human activity, which is likely the best proxy for emissions. An investment is needed in our capacity to obtain/use real-time power generation data, household heating (smart meters), traffic data (Google, or national), ship transponders, aircraft trackers, and industrial production numbers.
3. Accurate modelling of the atmospheric transport of CO<sub>2</sub> and related species is critical to the success of the MVS capacity. Targeted efforts to improve mass conservation (at a reasonable computational cost), to better model winds in the planetary boundary layer, and to include plume rise models in the modelling systems has potential to help abate these errors.
4. An accurate representation of the uncertainties in the outputs of the foreseen CO<sub>2</sub> MVS capacity is vital for a correct uptake of the emission estimates. Further research is therefore needed to characterise the uncertainties of all elements of the CO<sub>2</sub> MVS (observations, priors, process-based flux models, transport, and representativity). This should include the representation of temporal and spatial error correlations. In terms of the inversion/data assimilation methodology research needs to be performed addressing the question of adequately representing posterior uncertainties by the chosen method.
5. The hot spot integration & attribution is one of the key elements of the CO<sub>2</sub> MVS capacity. Further research & development is needed to develop more advanced plume detection systems and plume inversion models (mass balance methods and direct inversion methods). These should consider the observations of NO<sub>2</sub> from the CO<sub>2</sub>M mission as well.
6. Data assimilation methods should be further developed. Especially, the use of parameter estimation, more specifically CCFFDAS, should be further explored and viable methods to combine the information from data assimilation systems at different scales should be developed. The complexity of assimilating inversion products across different spatiotemporal scales in a consistent manner may require an efficient integration tool similar to CIF (VERIFY) or OOPS (ECMWF), in particular to standardize model inputs/outputs. In the context of CCFFDAS, a more general



investigation of how emissions could be effectively represented in the data assimilation control vector. This could also assess the performance gain to be expected from an extended data assimilation system with a temporal dimension in the control vector. For example, such a system would be capable of computing the sensitivity of atmospheric observations made in one week to emissions in the preceding weeks and of exploiting this sensitivity to better constrain such emissions by also including longer-range constraints.

7. The COVID-19 crisis has made it clear that more use could/should be made of so-called “activity data”, such as traffic patterns, shipping motions, real-time energy demand, and solar/wind production capacity. Although the activity data do not cover all sectors and have larger uncertainties than the inventory data, it does provide a much timelier estimate of changes in emissions. Continued research and development on this approach, both as stand-alone and as input to the envisioned prototype, should be carried out.

The above recommendations are not listed in order of priority, but they have been fed into the writing of the CoCO<sub>2</sub> proposal, the writing of the Technical Annex for the next phase of CAMS, and the writing of the proposed Copernicus development topics as part of the Horizon Europe programme. The combination of the three frameworks ensures that both short-term and long-term research and development can be funded benefitting the overall development and implementation of the Copernicus CO<sub>2</sub> Monitoring and Verification Support capacity.

## 9 References

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

Committee on Earth Observation Satellites Greenhouse Gas White Paper, Prepared by the CEOS Atmospheric Composition Virtual Constellation Greenhouse Gas Team (2018)

Ciais, P., D. Crisp, H. Denier Van Der Gon, R. Engelen, M. Heimann, G. Janssens-Maenhout, P. Rayner and M. Scholze (2015) Towards a European Operational Observing System to Monitor Fossil CO<sub>2</sub> emissions, European Commission – ISBN 978-92-79-53482-9; doi 10.2788/350433.

Yasjka Meijer, and Copernicus CO<sub>2</sub> Task Force with sub-task A (H. Boesch, A. Bombelli, D. Brunner, M. Buchwitz, P. Ciais, D. Crisp, R. Engelen, K. Holmlund, S. Houweling, G. Janssens-Maenhout, J. Marshall, M. Nakajima, B. Pinty, M. Scholze, H. ) and ESA (J.-L. Bezy, M.R. Drinkwater, T. Fehr, V. Fernandez, A. Loescher, H. Nett, B. Sierk), (2020) Copernicus CO<sub>2</sub> Monitoring Mission Requirements Document, [https://esamultimedia.esa.int/docs/EarthObservation/CO2M\\_MRD\\_v3.0\\_20201001\\_Issued.pdf](https://esamultimedia.esa.int/docs/EarthObservation/CO2M_MRD_v3.0_20201001_Issued.pdf)

Pinty B., G. Janssens-Maenhout, M. Dowell, H. Zunker, T. Brunhes, P. Ciais, D. Dee, H. Denier van der Gon, H. Dolman, M. Drinkwater, R. Engelen, M. Heimann, K. Holmlund, R. Husband, A. Kentarchos, Y. Meijer, P. Palmer and M. Scholze (2017) An Operational Anthropogenic CO<sub>2</sub> Emissions Monitoring & Verification Support capacity - Baseline Requirements, Model Components and Functional Architecture, doi: 10.2760/39384, European Commission Joint Research Centre, EUR 28736 EN.



Super, Ingrid, Denier van der Gon, Hugo, van der Molen, Michiel, Sterk, Hendrika, Hensen, Arjan, Peters, Wouter. (2017). A multi-model approach to monitor emissions of CO<sub>2</sub> and CO from an urban–industrial complex. *Atmospheric Chemistry and Physics*. 17. 13297-13316. 10.5194/acp-17-13297-2017.

Super, Ingrid, Denier van der Gon, Hugo, van der Molen, Michiel, Dellaert, Stijn, Peters, Wouter. (2019). Optimizing a dynamic fossil fuel CO<sub>2</sub> emission model with CTDAS (v1.0) for an urban area using atmospheric observations of CO<sub>2</sub>, CO, NO<sub>x</sub>, and SO<sub>2</sub>. 10.5194/gmd-2019-283.

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