CO2 Human Emissions

Strategic Research Agenda 2

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Coordination and Support Action (CSA)
H2020-EO-3-2017 Preparation for a European capacity to monitor CO2 anthropogenic emissions

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1 Executive Summary

This roadmap document is the second 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_2 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. Next versions will contain more information on the various outcomes of the project and studies and will also add a section on existing and potential future in-situ capabilities.

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_2 anthropogenic emissions"), which stated that the development, the implementation and eventually the operation of a European capacity to monitor CO_2 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_2 Monitoring Task Force and the ESA Copernicus Anthropogenic CO_2 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_2 anthropogenic emissions. This is particularly of relevance because of the tight timeline that is envisaged for the build-up of the Copernicus CO_2 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_2 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_2 monitoring and verification support capacity.

Outcomes of the various projects and studies will be summarized and suggestions for further research will be outlined in this Strategic Research Agenda document that the European

Commission and the CO_2 Monitoring Task Force can use to support the decision-making process for enhancing our current capacity to observe and understand the variability of CO_2 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 second 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 some of the existing text, but most importantly added section 4.2, extended sections 6.1, 6.2 and 6.3, and added section 8.

3 Current status of CO_2 MAG and CO2 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_2 Monitoring Task Force started its second phase on 19th March 2018 and the ESA CO_2 Mission Advisory Group (MAG) had its first meeting on 12 and 13 June 2018. Both expert panels will drive the research agenda on which especially CHE and the ESA science studies act. In addition, CHE will support the CO_2 Monitoring Task Force by providing advice based on its research outcomes.

Regarding the CO_2 MAG, version 2 of the Mission Requirements Document (MRD) was published in September 2019 and is available on-line (https://esamultimedia.esa.int/docs/EarthObservation/CO2M_MRD_v2.0_Issued20190927.pdf). The MRD defines aspects, such as the detailed requirements for the CO_2 imager, the need for aerosol measurements on board the same platform, and the requirements of the NO_2 sensor.

The CO_2 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)

4 CHE objectives and outcomes

4.1 Objectives

The CO_2 Human Emissions (CHE) project coordinates efforts towards developing a European operational monitoring and verification support capacity for anthropogenic CO_2 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_2 fossil fuel emissions, along with other natural and anthropogenic CO_2 emissions and transport. The project pursues a consolidated methodology for integrating the monitoring system components, as well as innovation for estimating fossil fuel CO_2 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_2 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_2 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_2 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_2 simulations from global to city scale to examine the capacity for monitoring future fossil fuel (and even more general anthropogenic) CO_2 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_2 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_2 emissions

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

1. Generate a library of realistic "nature" simulations of atmospheric CO_2 from the global to the point-source scale as a basis for designing an operational capacity for monitoring anthropogenic CO_2 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_2 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_2 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_2 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_2 emissions quantification and elaborate on potential uncertainty reductions making use of space-borne non-CO_2 tracers (NO_x, 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_2 emissions from in-situ measurements

1. Survey current European in-situ observation capacity.

2. Define an operational strategy to separate anthropogenic CO_2 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_2 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_2 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_2 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_2 should receive more attention to be able to address the question of potential use of an NO_2 instrument on the CO_2 Monitoring mission. Accurately simulating NO_2 needs models with full interactive chemistry, although a simplified NO_2 tracer with a constant lifetime could be sufficient for some applications, such as identifying the location of plumes.

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 CCFFDAS 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 CO2M mission). The prototype CCFFDAS 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 CO2 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 CO2 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 $^{14}CO_2$, 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_2 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 form 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_2 anthropogenic emission monitoring system. In addition, it provides some recommendations for further research and development, which are summarised below. The resulting reports are still in draft mode with final versions planned for 2020, but some early recommendations are listed below.

Service elements for CO_2 Earth Observation integration:

- Development of SIF retrievals and observation operators as well as radiocarbon measurements will aid development of biogenic flux attribution.
- Emission factors and activity rates are still highly uncertain. Other issues on emission ratios need to be understood before they can be used (variations of ratios associated with fuel type and other factors such as temperature). This still needs to be investigated before emission ratios can be used in the operational system**.**
- Within CAMS there is the ambition to cover NO_2 and CO emissions and within Copernicus there is the ambition to connect work from different services. Therefore, the potential assimilation of co-emitters should be further exploited.
- Related to the previous bullet point, we need more direct measurements of emission ratios.
- The estimation of emission ratios could be done by estimating the emissions of all co-emitters.
- The potential use of citizen data such as traffic counts might have some potential. This type of information could be very valuable (e.g. when and where traffic is).

Service elements for CO_2 emission and transport model integration:

- Testing needed for new transport schemes developed in Numerical Weather Prediction (NWP), e.g. MPDATA advection in Finite Volume Method (FVM) in ECMWF's Integrated Forecasting System (IFS) (Kühnline et al, 2019)
- Integrate plume model in emission hotspots (Freitas et al., 2007, Super et al., 2017)
- Improve planetary Boundary Layer (PBL) wind profiles crucial for plume modelling (Sandu et al., 2013)
- Extend FFDAS approach using all available human activity proxies and introduce higher level of sectorialisation (Super et al., 2019)
- Use SIF and COS to constrain biogenic fluxes
- Introduce crop modelling and relevant land management information (crop rotation/harvesting, grazing, etc.)
- Implementation of APO and radiocarbon in forward/inverse model.

Service elements requirements for data assimilation methodology:

- A proposed multi-model system could be used to integrate spatiotemporally heterogeneous posterior emission products. This system, outlined by Bousserez et al. (2019, Tech Memo), would treat the local and regional posterior flux products as observations in a global IFS-driven CO_2 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_2 emissions and CO_2 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.
- An important recommendation for all scales, and all systems, is to start investing in multi-species data assimilation. This is based on the recognition that anthropogenic CO_2 emissions can never completely be constrained with CO_2 observations alone, and the signal-to-noise of co-emitted species is often much better than that of CO_2

(and especially XCO2). Global, local, and regional scale DA systems so far have only focused on one or two species simultaneously. A large leap is needed.

Service elements requirements for uncertainty representation:

- Estimate uncertainties relating to co-emitted species, co-emission factors, and CO_2 emission factors
- Estimate uncertainties in process-based flux models (some of which have not yet been developed)
- Perform further investigations related to observations constraining biogenic fluxes (SIF, COS) and their observation operators
- Develop measurement techniques for radiocarbon that are cheaper and more accurate and can ideally deliver continuous radiocarbon data
- Estimate uncertainties related to contamination of the radiocarbon proxy by nuclear power plants and terrestrial disequilibrium
- Estimate numerical uncertainties within all models involved within the prototype
- Estimate representation error and mapping errors in the prior fluxes. Mapping errors include accounting for missing fluxes beyond the uncertainty ranges, for example, missing power stations in the anthropogenic inventories
- Develop improved inventories, e.g. NRT data and uncertainties for different sectors
- Perform further investigations related to the representation of posterior uncertainties by the chosen inversion/data assimilation method underlying the CO2 monitoring system

5 VERIFY objectives and outcomes

5.1 Objectives

VERIFY proposes to quantify more accurately carbon stocks and the fluxes of carbon dioxide (CO2), methane (CH4), and nitrous oxide (N2O) 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_2 emissions ($ffCO_2$), using in situ and remotely sensed atmospheric measurements of CO2 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 $ffCO_2$ emissions at a sub-national resolution (25-50 km) by combining spatio-temporal information from a dynamical emission (inventory) model for $ffCO_2$ and co-emitted species (CO, NO_x), natural CO_2 fluxes estimates, and independent in situ and space-borne observations of atmospheric CO_2, $^{14}CO_2$, and co-emitted species (CO, NO_2, Black Carbon). The dynamical emission model and the inverse modeling strategy using $ffCO_2$ proxies like CO and NO_x 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_2 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/$ffCO_2$ ratios close to emission hot spots, such as cities, and conduct independent ^{14}C-based validation of the proxy-$ffCO_2$ approach.
- To develop the computing framework to support the independent monitoring of $ffCO_2$ emissions from different sectors at the national scale using space-borne measurements of CO and NO_x.
- 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 $ffCO_2$ 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_2 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_2 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_2 flux datasets, cropland management, grassland management, forestry management, nitrogen deposition, freshwater fluxes and river exports, coastal ocean CO_2 fluxes, and other lateral fluxes (harvest / trade).
- Construct a bottom-up budget of terrestrial CO_2 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_2, a high-resolution transport model with a detailed representation of CO_2 atmospheric boundary conditions (the influence of fluxes outside Europe).
- Develop new multi-data model fusion strategies to further reduce uncertainties of CO_2 budgets and trends at regional scale, with a specific focus on Eastern Europe.

The overarching goals of **WP4** are to deliver estimates of CH_4 and N_2O 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_4 and N_2O 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_4 and N_2O fluxes by source type and at high spatial resolution (0.1°×0.1°) 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_4 and N_2O fluxes based on atmospheric inversions at 0.5°×0.5° and weekly resolution.
- To improve the understanding of key source processes, such as wetland production of CH_4, 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 δ13C-CH_4) for better constraining CH_4 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

This section will provide a summary of the research outcomes of VERIFY, when they become available.

6 ESA studies

As part of the preparation for the first version of the Sentinel-CO2 Mission Requirements Document (MRD) and in support of the CO2 Task Force A, ESA funds several studies to investigate certain aspects of a future Sentinel mission focused on the observation of atmospheric CO2 concentrations in support of the envisaged anthropogenic CO2 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_2 for observing and quantifying anthropogenic CO_2 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_2 and those of CO and NO_2 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_2 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 NO2 measurements for detection of the anthropogenic CO2 plumes with the main conclusion stating that CO2 emission estimates depend less on the precision of the CO2 instrument for large plumes, e.g. a city plume, when an NO2 instrument is used for detecting the location of the plume and estimating the CO2 background. For these cases, a wider swath and somewhat worse CO2 single sounding precision might be a reasonable trade-off. For smaller plumes e.g. from power plants, a high precision of the CO2 instrument is more relevant because of the small number of pixels contained in the plume. Also, in terms of NO2 a high precision instrument is preferred considering that the next generation removal technology will likely further reduce NOx emissions from power plants.

In its final report (available at 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_2 emissions from NO_2 observations
- Further improvements of the mass-balance method for CO_2 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 XCO2 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_2 emissions, from power plants and cities, that would be detected by the space-borne system. The study also assesses the constellation of CO2 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_2 imagery to estimate fossil fuel CO_2 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_2 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 XCO2 observations at the clump and daily scales up to the annual and national scales.
- To better understand the impact of systematic errors in the XCO2 on the quantification of fossil CO_2 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_2 plumes (results from AEROCARB could be used here).

- The impact of transport error in the detection of plumes from fossil CO_2 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.[1]
- The confounding effect of vegetated fluxes on the XCO2 images should be analyzed. The large-scale patterns of vegetation-induced XCO2 may add a random error contribution. Some vegetation patterns may also generate atmospheric structures that are correlated with the XCO2 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_2 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 CO2M imagers to the overall reduction of uncertainties of fossil fuel CO_2 emissions within CEOS constellations of imagers and sounders. The PMIF system is ideally suited to assimilate XCO2 observations from European CO_2 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_2 mission design options in a CCFFDAS (Carbon Cycle and Fossil-Fuel Data Assimilation System) study aims to define XCO_2 precision, spatial and temporal coverage requirements for the Sentinel mission, as well as provide design options for the CO2 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 XCO2 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 CO2M 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 CO2M performance in other seasons.

[1] 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.

- 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 CO2M 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 XCO2 alone and in combination with NO2 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 CO2M with existing and planned missions observing CO_2 in terms of their combined constraint on CO_2 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 CO2M is being constructed and will be employed to the accuracy requirements for XCO2 alone and in combination with NO_2 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_2 of localised sources.

7 Observation system

The envisaged Copernicus anthropogenic CO_2 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) outlining in detail the space component for monitoring atmospheric CO_2 and CH_4. 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_2 emissions. In the CEOS document the following instruments have been identified:

Instrument	Platform	Space Agency	Observed species	(Expected) observation period
SCIAMACHY	EnviSat	ESA	CO2, CH4, CO, NO2	2002 - 2012

TANSO-FTS	GOSAT	JAXA	CO2, CH4	2009 -
OCO-2	OCO-2	NASA	CO2	2014 -
GHGSat	GHGSat		CH4	2016 -
ACGS	TanSat	MOST	CO2	2016 -
TROPOMI	Sentinel-5p	ESA	CH4, CO, NO2	2017 -
GAS	Feng Yun-3D	CNSA	CO2, CH4, CO	2017 -
GMI	GaoFen-5	CNSA	CO2, CH4, CO, NO2	2018 -
TANSO-FTS-2	GOSAT-2	JAXA	CO2, CH4	2018 (TBC) -
OCO-3	ISS	NASA	CO2	2019 (TBC) -
MicroCarb		CNES	CO2	2020 (TBC) -
Sentinel 5	MetOp-SG	ESA/EUMETSAT	CO2, CH4, CO, NO2	2022 (TBC) -
MERLIN		CNES	CH4	2021 (TBC) -
GeoCarb		NASA	CO2, CH4, CO	2022 (TBC) -
TANSO-FTS-3	GOSAT-3	JAXA	CO2, CH4, CO	2023 (TBC) -
Sentinel-CO2		ESA	CO2, (CH4, NO2)	2025 (TBC) -
GAS-2	Feng Yun-3G	CNSA	CO2, CH4, CO	2021 (TBC) -
ACGS	TanSat-2	MOST	CO2, CH4, CO	TBC

All these instruments (will) provide measurements of CO_2 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_2 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_2, CH_4, NO_2 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_2 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 CO2 MVS capacity focuses on extracting relevant information from the CO2M satellite mission and the various in situ networks. However, to better separate the anthropogenic signal from the natural signal in the observed CO_2 concentrations, it is critical to exploit additional observations, such as those directly sensitive to anthropogenic emissions, ^{14}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_2 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_2 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_2 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_2 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_2 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 NO2 from the CO2M 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.

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