CO_2 Human Emissions

Strategic Research Agenda

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D6.1 Strategic Research Agenda

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CHE: CO2 Human Emissions Project

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 first version of the Strategic Research Agenda (SRA) summarising current research activities, within and outside CHE, and outlining the future strategies required for establishing the CO_2 monitoring system 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 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.

2.2.2 Work performed in this deliverable

This deliverable is the first version of the SRA and documents the most relevant research projects and ESA studies. It also documents the current and expected observation capacity, for now focused on the space segment only. Because this first version comes relatively early in the lifetime of the CHE and VERIFY projects, it does not contain too many outcomes yet. These will be added once they are officially delivered. As such this deliverable is therefore a living document.

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, a first version of the Mission Requirements Document (MRD) was produced in April 2018 by the precursor CO_2 Monitoring Task Force A, which is now being further fine-tuned in parallel to the ESA Phase A studies. This will further define aspects, such as the detailed requirements for the CO_2 imager, the need for aerosol measurements on board the same platform, 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.

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 and in-situ, 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 extended to enable 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 Research outcomes

This section will provide a summary of the research outcomes of CHE over the duration of the project. So far, the following deliverables have been made available:

- D2.1, Model systems and simulation configurations
- D6.6, Report on Synergies and Complementarities between CHE and VERIFY

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 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.

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.

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.

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. Currently, a CEOS white paper is being drafted outlining in detail the space component for monitoring atmospheric CO_2. Most of these instruments aim to improve our understanding of the carbon cycle with the planned Sentinel-CO_2 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.

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