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CO_2

An Operational Anthropogenic CO_2 emissions Monitoring & Verification Support Capacity

Space

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Europe's eyes on Earth

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An Operational Anthropogenic CO_2 emissions Monitoring & Verification Support Capacity

Baseline Requirements, Model Components and Functional Architecture

Report from the CO_2 monitoring Task Force - sub-task B

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Legal Notice

Foreword

Copernicus – Europe’s eyes on Earth - is the largest environmental space programme ever designed and operated in Europe to monitor our dynamic Earth. This program builds on state of the art knowledge and expertise in areas such as space-based observation technologies and the holistic interpretation of input data from a wide range of sources in order to extract information relevant to the general public and policy makers.

We are acutely aware that one of the largest challenges mankind faces today concerns the Earth’s climate and the manner in which it responds in a complex and sophisticated manner to the increase of greenhouse gases in the atmosphere associated with anthropogenic emissions.

In 2015, in anticipation of COP-21, we solicited a study from a group of international experts. This study resulted in a series of recommendations addressing the needs of an operational CO_2 emission monitoring system strongly underpinned by space-based observations. As a consequence the Commission has set up a specific task force to elaborate on the space-based and ground-based elements required to set up an operational capacity in support of the monitoring and verification of the anthropogenic CO_2 emissions. This operational capacity shall, for instance, provide Europe and each individual country with a unique and unprecedented asset in evaluating the implementation and effectiveness of the many CO_2 emission reduction strategies proposed by each of the signatories of the Paris Agreement.

I am extremely grateful to the group of distinguished experts who developed the current report, bringing together the key European players involved in the development of the individual system components to contribute to this common goal. We also seek cooperation at the international level with other relevant institutions to join forces and share scientific and technical knowledge and means using the most appropriate frameworks.

The present report provides a first step in advancing the definition and development of the envisaged system. Providing insight into the underpinning requirements and foundational building blocks required. We acknowledge and understand the responsibility and long-term commitment in building this system for the greater benefit of European and international community, and we are committed to continue in our endeavour. You should expect to hear more from us in the future.

This Copernicus CO_2 initiative constitutes a significant positive step in the direction given by President Jean-Claude Juncker in his State of the Union Address in 2017: '*I want Europe to be the leader when it comes to the fight against climate change*'.

Philippe Brunet
Director
Directorate 'Space policy, Copernicus and defence'

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Executive Summary

The Monitoring and Verification Support (MVS) capacity is a technical capacity to provide support to the policy makers and the scientific community. The MVS aims at supplying extra evidence on the emissions levels and trends, coupling anthropogenic activities and associated emissions with the atmospheric patterns in greenhouse gas concentrations. The MVS thus intends to support enhancing the quality of national greenhouse gas emission inventories and complement the data available under the UNFCCC measurement, reporting and verification framework. The MVS will include top-down verification of emissions using independent atmospheric observations and, in particular, observations acquired by space-borne sensors at high temporal and spatial resolutions all over the globe.

The Paris Agreement signed in 2015 has entered into force less than one year later. The Paris Agreement includes both mitigation and adaptation actions. The 195 participating countries have agreed to reduce global emissions of greenhouse gases and, amongst other actions, to implement a transparency framework for monitoring the impact of the Nationally Determined Contributions (NDCs) and the global stock take. The changes in the global stock take should be evaluated every 5 years starting from year 2023. Governments also agreed to track their progress towards the long-term goal, using a robust transparent and accountable system. The Paris Agreement designs a transparency system that is to be implemented bottom-up by individual countries through national reports. The latter would also be the primary input to the global stock takes. A global CO_2 Monitoring and Verification Support (MVS) capacity using an ensemble of independent, observation-based atmospheric data is needed to complement this bottom-up transparency framework and contribute to increase the reliability and accuracy of the national reports.

This report describes the baseline requirements, functional architecture and system elements needed to implement such an operational capacity. It is based on recommendations elaborated by an international group of experts in a report[1] published by the Commission prior the Conference of Parties (COP) 21 in Paris. On the basis of decadal emission projections and subsequent in-depth analyses, section 1 of this report lists the capabilities required for such an operational capacity to be a relevant tool for supporting policy implementations.

These capabilities include:

1. Detection of emitting hot spots such as megacities or power plants,
2. Monitoring the hot spot emissions to assess emission reductions of the activities,
3. Assessing emission changes against local reduction targets to monitor impacts of the NDCs,
4. Assessing the national emissions and changes in 5-year time steps to estimate the global stock take.

Satisfying this minimum set of capabilities requires:

(i) Enhancing globally the current capacities for each of the system elements, in particular the in situ and space-borne CO_2 observations, the emission inventories, the carbon cycle process models and the atmospheric transport models;

(ii) Achieving the integration of all required elements into a support system designed to optimally combine all relevant information and knowledge available from observations and geophysical models of the Earth system as well as fossil fuel emission models;

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[1] 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_2 emissions, European Commission – ISBN 978-92-79-53482-9; doi 10.2788/350433.

(iii) Mobilizing the key European players involved in the development of each individual system element to contribute to the common goal, such as the European Commission (EC), the European Space Agency (ESA), the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT), the European Centre for Medium-Range Weather Forecasts (ECMWF) , the European research infrastructure Integrated Carbon Observation System (ICOS) and the national inventory agencies and research centres;

(iv) Cooperating at the international level with other relevant institutions to join forces and share scientific and technical knowledge and means.

No existing network of in situ observations, space-borne measurements and emission inventories as they currently stand can provide sufficient information at the appropriate space and time scales. Observing capabilities for atmospheric concentrations of CO_2 need to be expanded and dense and frequent measurements from space- borne devices must become an essential component of such a support capacity. Under the leadership of ESA and the EC, specific activities are currently conducted to elaborate the adequate set of satellite based observations that will fulfil the identified objectives within the context of the European Union Copernicus programme. These findings will be published in separate reports including one devoted to the Mission Requirements Document.

The development of an operational capacity represents a major challenge for the science and environmental policy communities. Therefore, it is essential to put in place an end-to-end simulation programme to inform and guide system design and development, and ultimately to demonstrate, using simulated realistic observations and representative prior information, that an integrated modelling and data assimilation system is capable of producing anthropogenic emission information that meets the requirements outlined in section 1.

As there is no capability currently available mature enough to satisfy the identified requirements, there is thus no precursor of a comprehensive anthropogenic CO_2 emission monitoring and verification support capacity. The pathway towards successful implementation of such a capacity requires a holistic view. The system must be designed to be capable of homogeneously and optimally integrating all available observations together with prior information while quantifying the uncertainties associated with the estimated emissions. The core of such a system is an integration component that capitalizes on our knowledge of the Earth system encapsulated in geophysical models, to optimally combine the various input sources to generate anthropogenic emission information at the required temporal and spatial scales. As described in section 2 of this report, this integrated approach is being pursued for natural carbon fluxes by the carbon cycle research community and is also familiar in numerical weather forecast and reanalysis activities. In the present context of atmospheric CO_2 monitoring in support of the Paris Agreement, the coupling involves a number of functional elements such as Carbon Cycle and Fossil Fuel Data assimilation Systems (CCDAS and FFDAS) that are discussed in section 2 and its associated annexes.

Following the first global stock take, which is planned for 2023 at the COP 29, the Parties will be asked to revise and strengthen their NDCs. A crucial global stock take will subsequently take place in 2028 based on inventories collected during 2026-2027. The 2028 global stock take is expected to show a reduced global total, but verification based on top-down interpretation of CO_2 observations will be required to gain confidence on and validate the reported greenhouse gases emission trends.

A constellation of satellites, which constitute a strong asset to the observing system, should therefore be in operation by 2026 in order to deliver atmospheric observations globally for verifying the global stock take and supporting estimates from current inventories. By that time the proposed observation-based CO_2 monitoring and verification capacity must have reached a pre-operational status hence a series of preparatory research and development actions must be supported on the various fronts discussed in this report.

An operational observation-based CO_2 emission monitoring and verification support capacity will provide the basis for sound decisions in response to increasing greenhouse gases in the atmosphere as could be proposed by the European Union and other nations. The European Union has been at the forefront of international efforts towards a global climate deal and this operational capacity will constitute a strong asset to re-assess its leadership in fighting climate change.

Background & Rationale

In the context of the evolution of the European Union Copernicus programme, the Commission is currently considering expanding its space component with space-borne instruments designed to support the monitoring of anthropogenic CO_2 emissions at high resolution over the globe. This initiative follows an in-depth analysis of the issue and a series of recommendations elaborated by an international group of experts in a report[2] produced by the Commission.

An initiative of the European Union to establish an operational capacity to monitor fossil CO_2 emissions supported by a space-based observing system is consistent with the significant involvement and leadership expressed by the European Union with regard to climate change issues in general and the reduction in Greenhouse Gases (GHGs) emissions in particular. Such an operational capacity will constitute a unique and unprecedented asset for assessing, for instance, the impact of Nationally Determined Contributions (NDCs) on the CO_2 budget thereby helping countries to evaluate the effectiveness of the implementation of their CO_2 emission reduction strategies. It shall, in the long term and in some well-identified instances and situations, provide extra evidence on the amount of anthropogenic CO_2 emissions reported by national statistical offices and, in particular, help identifying and assessing the uncertainties and gaps associated with these emission inventories. More generally, this large-scale initiative will provide the European Union with a more comprehensive and consistent picture on the actual level of emissions and their reductions by all countries world-wide.

The development of an operational capacity is challenging from an engineering, scientific and technological perspective; it must involve European entities, already contributing to the Copernicus programme, and the operational processing and analysis of large data streams from in situ and space-borne observations together with the most advanced models, tools and techniques for interpreting these data. The success of this enterprise is as well dependent on the readiness to coordinate the required efforts in an international context within the related relevant structures and organisations.

Achieving the overarching goal of monitoring anthropogenic CO_2 emissions crucially depends on a substantial increase in worldwide atmospheric CO_2 observations that can be supplied predominantly by dedicated satellite missions. The space-borne sensors have the potential to routinely acquire relevant observations all over the globe with a density and a periodicity needed to resolve both natural and anthropogenic emissions with the selected satellite constellation concept complemented by in situ and space-borne observations made available routinely by international partners. The technological design and capabilities of this space component should allow the European Union, as a minimum to: 1) verify the trends of the emissions from hot spots at high resolution over the globe, 2) detect future hot spots, e.g., from new oil production sites and growing urban areas, 3) assess whether the global emission reductions promised by the NDCs are actually measurable in the atmosphere as part of the global stock take and 4) acquire uniform, homogeneous and indisputable global datasets made available to monitor anthropogenic CO_2 emissions.

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[2] 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_2 emissions, European Commission – ISBN 978-92-79-53482-9; doi 10.2788/350433.

The generation of these observations of atmospheric CO_2 concentrations will be dependent on a ground-based infrastructure that is devised, developed and implemented with the most advanced technology expected to be available at the end of this decade. Such a system should notably include the capability to interpret such large data streams with data assimilation systems incorporating the best understanding of the many bio-geophysical processes controlling the carbon cycle in order to reliably assess the atmospheric component related to anthropogenic CO_2 emissions. Moreover, the spatial and temporal distribution of emissions from human activities needs further attention to link the sampled observations with continuous monitoring of emissions. Accordingly, such a system and associated sub-systems must be agile and deployed in order to accommodate evolutions and improvements over time in both the density and quality of the data streams as well as the improved understanding of the underpinning processes leading to atmospheric CO_2 emissions at megacity, regional as well as global scales.

This report presents the first outcome from a group of experts contributing to the CO_2 monitoring Task Force. The objective of this group, identified as sub-Task B, – complementing the objectives of sub-Task A activities concerning the definition of the space component – aims at providing in-depth analyses and guidance on the many issues associated with the implementation of a ground-based infrastructure in support of an operational capacity to monitor anthropogenic CO_2 emissions[3]. More specifically this report focuses on 1) the consolidation of requirements at various space-time scales emanating from the policy related background of emission inventories, 2) the assessment of the typology, state-of-the-art and expected evolution of relevant direct and inverse Earth system modelling approaches and, 3) the high level functional architecture of the system needed for delivering operationally the expected information on anthropogenic CO_2 emissions.

The document describes the current state-of-play in the various areas and is complemented by a set of recommendations expressed in the section 'Way Forward' on the critical components of the system that merit further actions and activities to be implemented by the European Commission in the coming years.

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[3] The report focuses on the monitoring of atmospheric CO_2 concentration in relation with the anthropogenic emissions. The functional architecture and technical concepts envisaged for the ground-based infrastructure as well as for the space component will, in addition and as a secondary objective for the operational system, support the monitoring of methane at high resolution and worldwide (see section 2.2.3.1).

1. Emissions and Policy Requirements

The Paris Agreement signed in 2015 by 195 countries entered into force less than one year later. In addition to the mitigation and adaptation actions, the Agreement designs a transparency framework that shall build upon and eventually supersede the current measurement, reporting and verification system and that is to be implemented bottom-up by individual countries through national reports. The Paris agreement acknowledges explicitly the need to ensure environmental integrity and implicitly asks to complement the bottom-up information with atmospheric measurements for verification. Complementary to the bottom-up emission inventories, reported to the United Nations Framework Convention on Climate Change (UNFCCC), Greenhouse Gases (GHG) emissions can be estimated top-down using atmospheric measurements and inverse modelling. Although not yet mandatory within the official UNFCCC reporting process, the Inter-governmental Panel on Climate Change (IPCC) Guidelines (2006) recommend nevertheless to implement verification procedures using such top-down estimates in order to improve the accuracy and reliability of national inventory systems and to contribute to the verification procedures. Several national inventory agencies in Europe have already put such top-down verification procedures in place and several others expressed their interest for such a Monitoring and Verification Support (MVS) capacity for anthropogenic CO_2 and non-CO_2 greenhouse gas emissions.

In addition, the 5-yearly global stock take, which is planned by UNFCCC to start in 2023 (Paris Agreement, art. 14), must be assessed for each region/country with independent data. The MVS should provide evidence with measured atmospheric concentrations of GHG/CO_2 in Europe, as it would do for other regions, within some uncertainty range. This level for 2023 needs then to be compared with the level estimated for 2018 and with successive levels in 2028 and following 5-year time steps for all regions/countries world-wide. The changes of CO_2 over the 5-year time steps should assess the effectiveness of the implementation of the GHG reduction measures that the countries/regions committed under their NDCs. An observation-based MVS is needed to build trust in the mitigation efforts by validating the emissions changes with independent, observations-based data. In our vision, the CO_2 MVS should be operational at global scale but could be calibrated regionally, such as over the European area, where detailed and comprehensive information on the emission inventory is available. It is necessary that gridded emissions are reported in addition to the country totals, as the case under the Convention on Long-range Transboundary Air Pollution[4]. With two global 1990-2050 scenarios or pathways, one with Business-As-Usual growth (BAU) and one with Climate Change (CC) policies, Section 1 of this report discusses the prerequisite the MVS needs to have in order to distinguish the CO_2 trend between the two pathways (BAU or CC scenario) over Europe and globally.

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[4] The Convention on Long-Range Transboundary Air Pollution is intended to protect the human environment against air pollution and to gradually reduce and prevent air pollution, including long-range transboundary air pollution. It is implemented by the European Monitoring and Evaluation Programme (EMEP), directed by the United Nations Economic Commission for Europe (UNECE).

1.1 Policy background

In November of 2016 at the COP22 in Marrakech, the Paris Agreement was enforced, with an agreement of the 195 countries-signatories on the following key elements: 1) global emissions must be reduced and should peak as soon as possible with rapid reductions thereafter, and 2) a transparency framework to track progress towards the targets of the NDCs and to conduct a global stock take every 5 year (for setting thereafter more ambitious targets). The common Modalities, Procedures and Guidelines (MPGs) of the enhanced transparency framework established under the Paris agreement were discussed extensively at the COP22 in view of the global stock take. These MPGs are largely procedural, emphasizing the existing 'Measuring-Reporting-Verifying (MRV)' framework. In order to advance the planning of the stock takes starting from 2023, it was concluded that the IPCC 6th Assessment Report (AR6) should provide an input to the UNFCCC on GHG verification.

Box 1 the Paris Agreement (UNFCCC, 2015; EC-DG CLIMA, 2016)

The Paris Agreement, which was adopted on 12 December 2015, is a global milestone for enhancing collective action and accelerating the global transformation to a low-carbon and climate-resilient society. The Paris Agreement entered into force in October 2016, after having been ratified by 55 countries, and accounts for at least 55% of global emissions.

The Paris Agreement includes both mitigation as well as adaptation actions and the countries agreed on reducing global emissions and, amongst others, on a transparency framework for monitoring contributions and the global stock-take with the commitments: (i) to submit national climate action plans, the so-called NDCs, (ii) to present successive NDCs reflecting progression and higher ambition, (iii) to report to each other and the public on how well they are doing on the implementation of their targets, (iv) to track their progress towards the long-term goal, using a robust transparency and accountability system, and (v) to contribute every 5 years, in making a global stock take to set more ambitious targets as required by science.

Under the Paris Agreement (in contrast to the Kyoto Protocol), all countries are requested to report national GHG inventories on a regular basis. The IPCC (2006) guidelines for GHG inventory reporting are presented as a reference. The Task Force on National Greenhouse Gas Inventories started a technical assessment of IPCC (2006) guidelines through a survey and some expert meetings and revealed that abundant new scientific and empirical knowledge (especially on emission factors) should be taken into account. IPCC decided in 2016 to establish a 'Refinement of 2006 IPCC Guidelines for National Greenhouse Gas Inventories', that updates, supplements and/or elaborates the 2006 IPCC Guidelines where gaps or out-of-date science have been identified. In addition to the guidance for greenhouse gases inventories, it is expected that the IPCC AR6 will provide policymakers with a complete picture of the global and regional greenhouse gas budgets. The Paris Agreement calls for the need to ensure environmental integrity and requires verification or monitoring.

Policymakers are confronted with the typical policy-science questions, of which text box 2 gives an example, and need scientific input and information. A MVS for emissions of CO_2 or other greenhouse gases should provide the information on the emissions and emission trends that policymakers need. The information expected from MVS should span the full time-series of inventories, including the reference or base years[5] (e.g., 1990, 2005, 2005-2007) and the target years (e.g., 2020, 2030) for tracking the progress towards the NDC targets.

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[5] 2005 might be important as a base year in contrast to 1990 where few measurements only were available.

Not only EC- Directorate General for Climate Action (DG CLIMA) but also some individual countries in the EU are looking, with their national inventory agencies (e.g., the German Umweltbundesamt), for extra evidence to increase and/or confirm the quality of their recent inventories with independent data, using atmospheric measurements and inverse modelling. It is not foreseen that these atmospheric measurements (in situ or space-borne) will replace inventories, which are required by the transparency framework of the Paris Agreement. However, to improve the quality of inventories and to assess the trends and the trend uncertainties, officially reported GHG time-series can be compared with the time-series of atmospheric observation-based estimated GHG budgets.

Box 2: Scoping policy-science questions

Some examples:
1) Do we understand the GHG concentration trends in the atmosphere by monitoring the reported GHG emissions time-series?
2) Can inconsistencies in the trends of some GHGs from different data sources be understood (e.g., with the trend of natural sources to explain potentially opposing trends of emissions and of atmospheric measurements) with presently available scientific information? What additional developments does the scientific community require to make to provide the required verification of GHG emissions trends?
3) Can the trends observed at particular locations be allocated to source regions?
4) Can the effectiveness of GHG reduction measures implemented in a given region be monitored remotely?
5) Can hot spots or top emitting areas be localized, such that impact of local measures can be identified and monitored?
6) What is the potential of a European system for observation-based monitoring and verification of GHGs to assess GHG inventories of countries and which limitations are known upfront?

For the global budget, much can be gained by reducing uncertainties in high-emitting countries with emerging economies. However a top-down atmospheric observation-based GHG monitoring and verification support capacity can be best calibrated in a data-rich region, such as Europe. To be a global player at the climate negotiations, DG CLIMA needs information on all countries, in particular the largest emitting countries. Moreover, UNFCCC will encourage knowledge transfer between countries (and in between the country groups defined under the UNFCCC as Annex I and non-Annex I countries) to establish a GHG reporting system, bringing together the two groups of countries under one reporting system.

To define requirements for an observation-based GHG MVS we must first identify the capabilities needed and the limitations that are acceptable. While the system should ideally aim at a global coverage with frequent measurements, the minimum continuity of knowledge over high-emitting regions shall set the first prerequisites.

These include:
- The region-specific effectiveness/capability to reduce the emissions uncertainty should be presented/assessed on the basis of the current network of in situ measurements[6];
- The sensitivity of the GHG verification support capacity to the measurement network needs to be quantified and the limitations of the current GHG verification support capacity should be indicated in a transparent way.

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[6] The network of in-situ towers or mobile monitoring systems are limited in geographical coverage, and therefore less effective in regions with low coverage of measurements regardless of their potential for uncertainty reduction.

The value of a dense atmospheric measurements network (in situ or space-borne) will become apparent in this way, and will inform policymakers how and where the (national) GHG verification support capacity should be strengthened.

1.2 Input from National Inventory Agencies as stakeholders

All 28 national inventory agency representatives of the Climate Change Committee Working Group I of DG CLIMA were invited to participate in a questionnaire, aiming to assess the strengths and weaknesses of inventory agencies and their potential needs for support with an greenhouse gas monitoring and verification support capacity. The questionnaire addressed the following issues:

1. **operation** of the inventory compilation with the needed resources, the share of outsourcing while guaranteeing continuity of knowledge, the Quality Assurance/Quality Control (QA/QC) procedures, the inventory reviews and verification;

2. **collaboration** between the reporting of GHGs and of air pollutant for different conventions, and interlinkage with the point source data which are reported under the European Union directives for industrial emissions (IED), large scale combustion plants (LSCP), the European Pollutant Release Transfer Register (EPRTR) and the Emissions trading system (ETS);

3. areas where **support** is needed due to existing and acknowledged uncertainties: the land-use, land-use change and forestry (LULUCF) sector, other sectors with large uncertainties.

The results of the questionnaire were consolidated in an informal workshop with the national inventory agencies in Paris on 6th December 2016. The detailed input from the participating national inventory agencies is presented in the table of Annex 1 and summarized here below.

The following conclusions were obtained for the three major issues of the questionnaire:

1. **Operation**: Most countries outsource more than half of the emission inventory compilation to agencies with long term contracts to guarantee continuity of knowledge. These agencies themselves rely on data provided by central administrations and by different organisations (sometimes from the private sector for a facility emitting a given GHG). The QA/QC procedures and review measures for inventory improvement are established. Inventory reviews recommend changes almost yearly but with minor impact. The need for substantial methodological changes is mainly detected after exhaustive in-country-reviews; several years are then needed to resolve the detected issues. Verification so far is limited with little or no input from atmospheric concentration measurements and inverse modelling approaches. The agencies' focus on compliance with international reporting requirements is often limited to the calculation of the emissions in accordance with IPCC requirements. The priority is on improving the methodologies for calculating the emissions and the governments are more focused on trends than on the absolute levels. The attention to verification comes from Non-Governmental Organisations and scientists;

2. **Collaboration**: Emissions reporting occur for greenhouse gases (under UNFCCC) and for air pollutants in a generally consistent way by most EU Member States. Moreover, all inventory agencies make use of data reported by the industrial facilities and large scale combustion plants (for the IED, LSCP, EPRTR, ETS directives). Spatial distribution, as required for the reporting under the Convention on Long-range Transboundary Air Pollution, is 0.1°x0.1° for Europe, at least, but a higher resolution is available for several EU countries (e.g., $1x1km^2$ for The Netherlands with facility emissions on the actual location). The temporal resolution remains at annual level. Outreach and knowledge transfer to Non-Annex I countries is currently carried out by all the national inventory agencies of the larger EU countries;

3. **Support** for the bottom-up inventory compilation by national inventory agencies is most desirable for anthropogenic sources with large uncertainties, such as diffusive sources (in particular of non-CO_2 emissions) or from land sectors. Whereas CO_2 emissions from fossil fuel are rather well known and relatively accurately accounted for, non-combustion sectors (7% of the world total according to Figure 6a) are much less certain.

Verification (utilizing also inverse modelling and observations as independent source of information) was considered promising for gaining extra evidence of the current inventories. The national inventory agencies of Ireland and of Germany explicitly expressed their interest in using the outcome of an inverse model or to use the inverse model system. This is already done for the national inventories of the United Kingdom and Switzerland. Other national inventory agencies (of landlocked and/or smaller countries) are more reserved and want first to determine what would be an appropriate allocation between the anthropogenic and the natural fractions, in order to quantify the anthropogenic emissions, preferably at the sector level.

Specific discussions with the national inventory agency of the Netherlands revealed also that the current financial pressure on the inventory agencies leads to the active search for alternative, less work-intensive methods to compile and to check the inventory. National inventory agencies are also looking forward to knowledge transfer, exchange of best practices in workshops or in bilateral collaborations, not only within EU 28 but also outside Europe, where even more progress can be made. The output of the MVS capacity will provide national inventory agencies information at a higher spatial and temporal resolution than required by UNFCCC (country-total and annual) but will allow us to identify and characterize hot spots in a timely manner on, e.g., 10x10 km^2 grids over the globe.

1.3 Scenarios to assess the required CO_2 sensitivity

In this section we explore the accuracy or sensitivity required to monitor changes in anthropogenic CO_2 emissions at a national and at a city/hotspot scale to monitor agreed/proposed emission reductions and/or increases projected along two global emission scenarios. To do this, we focus on anthropogenic CO_2 emissions, which arise from all human activities, excluding those associated with the land-use, land-use change and the forestry sector. For the sake of simplicity we define these CO_2 emissions (CO_2_ff) as the sum of CO_2 emissions from fossil fuel combustion and for a remaining smaller part (7%) from non-combustion sources (i.e., cement production, from metal (ferrous and non-ferrous) production processes, urea production, agricultural liming and solvents use). Biofuel combustion is denoted as CO_2_bf. For the changes due to the agreed / proposed emission reductions, we consider two global emission scenarios, a Climate Change and a Business As Usual scenario developed by the CIRCE project (Doering et al., 2010) to be indicative[7] of the magnitude and temporal change of emissions (ton CO_2/yr). These two CIRCE scenarios for CO_2, CH_4, N_2O, CO, NOx, SO_2, VOC, BC and OC from 1990-2050 span the range of emissions from no global action on climate change and air pollution (i.e., the BAU scenario) to emissions resulting from a global climate policy (i.e., the CC scenario).

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[7] The CIRCE scenarios are up to date and do not reflect the real or NDC emission changes to be expected as the projections originally started from 2005. However, the magnitude and temporal pattern (change /yr) is assumed to be representative for the "sensitivity" a system needs to follow future realistic changes (more information available at http://edgar.jrc.ec.europa.eu/FP6-project.php). The BAU scenario explores the situation when no further climate and air pollution policies are implemented beyond what is in place since the year 2005. This means that energy consumption from 2005 to 2050 is driven by population and economic growth (POLES baseline scenario).

In the Business-as-Usual scenario[8] the GHG emissions increase from the year 2005 onwards as no further climate policies are implemented. The Climate Change scenario[9], derived with the European Commission model of Russ et al. (2007), assumes a full implementation of a global climate policy (CC) with fuel shift and decreased fuel demand (in the EU28 benefiting from renewables and energy efficiency policies), resulting in global emission reductions (emissions compared to BAU in 2050) of GHG: CO_2 (-63 %), CH_4 (-60 %) and N_2O (-26 %).

An overview of the consequences of these two CO_2 emission scenarios is illustrated in Figure 1. Examples of a gridded Emission Database for Global Atmospheric Research (EDGAR) emission inventory and a gridded Netherlands Organization for Applied Scientific Research (TNO) emission inventory are given in Figure 2a and b respectively. Two international gridded emission inventories were applied to avoid large biases that could be caused by the choice of, for instance, spatial proxy datasets for the distribution of the country totals.

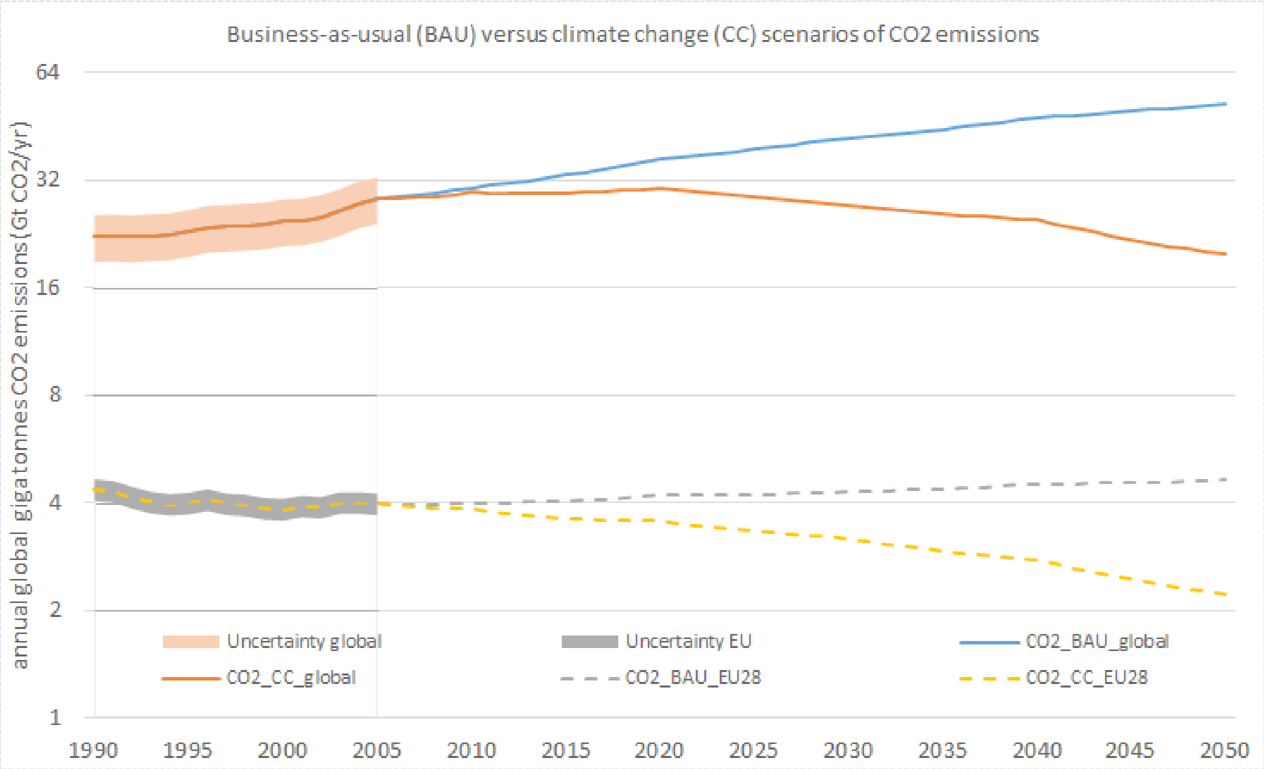

Figure 1. *Overview of the two different CO_2 emission scenarios, Business-As-Usual scenario (BAU) and Climate Change scenario (CC), for the world total (global) and for the 28 European Member States EU28.*

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[8] The BAU scenario explores the situation when no further climate and air pollution policies are implemented beyond what is in place since the year 2005. This means that energy consumption from 2005 to 2050 is driven by population and economic growth (POLES baseline scenario).

[9] The CC scenario assumes that global climate policies (which are decoupled from air pollution policies) are implemented. Energy consumption from 2005 to 2050 is not only driven by population and economic growth but also by energy efficiency and climate policies and measures aiming at a global 25% reduction of GHG emissions by 2050 compared to 1990 (excluding emissions from agriculture and land use change).

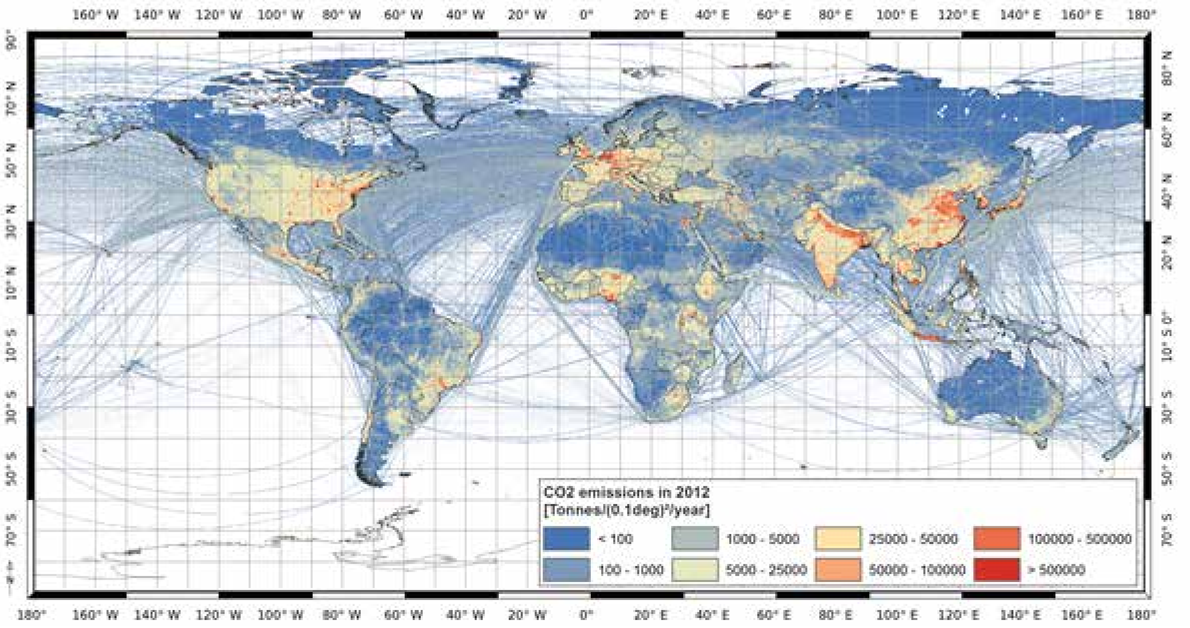

Figure 2a. *Global total CO_2 emissions of EDGAR from anthropogenic sources excluding the land use, land-use change and forestry sectors for 2012 gridded at a resolution of 0.1°x 0.1° (from Janssens-Maenhout et al., 2017).*

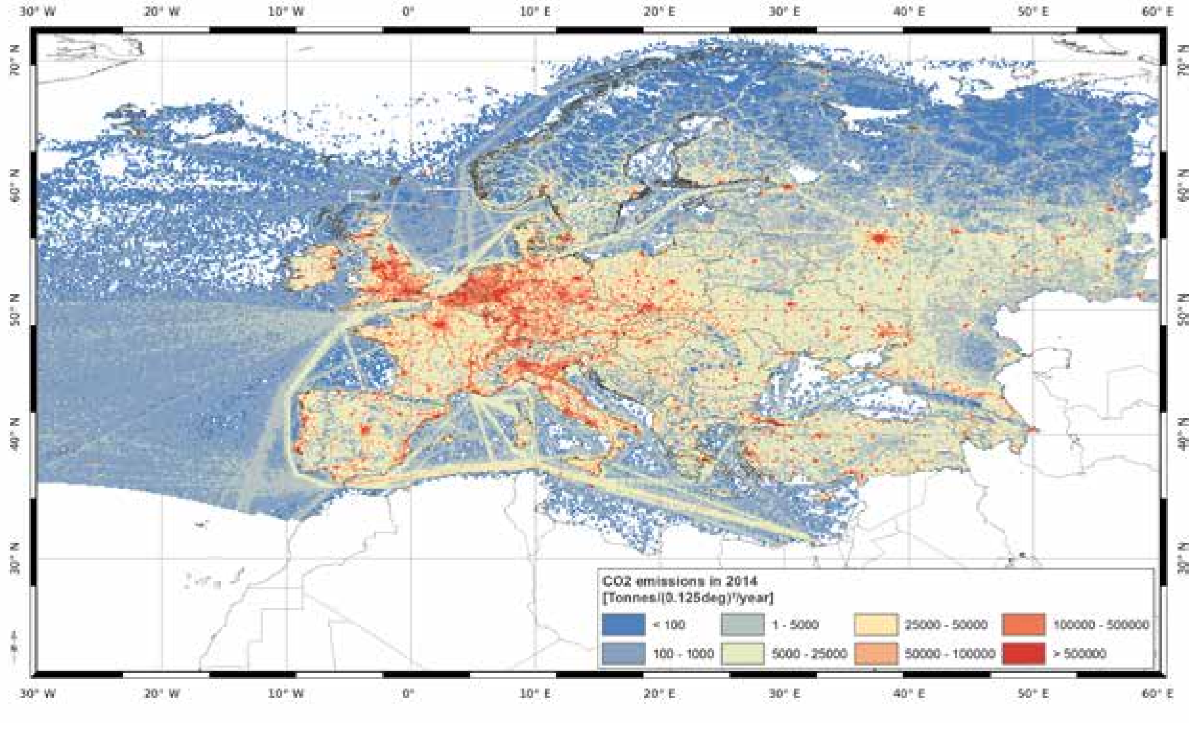

Figure 2b. *European total CO_2 emissions of the TNO-CAMS inventory of anthropogenic sources excluding the land use, land-use change and forestry sectors for 2014, gridded at a resolution of 0.125°x 0.0625° (a preliminary version of this dataset is described in Kuenen et al., 2014 and 2015).*

The two CIRCE scenarios contain detailed information about the development of individual source sector categories. By coupling these scenarios to the EDGAR or TNO-CAMS gridded data, the emission changes in each grid-cell and for each region can be estimated in a spatially explicit manner. A first estimate of the corresponding change in concentration can be simulated based on knowledge about the source/receptor relationships from available atmospheric transport (inverse model) simulations without running a full transport model (see section 2.2.3.1).

1.3.1 Implication of the two scenarios for Europe

The major changes in the CIRCE scenarios are incorporated into the global EDGAR emission grid maps (see Figure 1) and the TNO-CAMS emissions when focusing on Europe. The changes projected for EU countries are substantial, but do not take into account the latest NDCs under the Paris Agreement (2015) and the European Commission's legislative proposal 'Clean Energy for all Europeans' baptized the 'winter package' (2016)[10].

The TNO-CAMS CO_2 dataset covers the years 2000-2014[11] and at the national scale is mostly consistent with the reporting to UNFCCC, using the same emission model as for the TNO-CAMS dataset for air pollutants (Kuenen et al., 2014). Figure 3 shows the CO_2 emission change over time for five countries (Germany, Spain, France, Great Britain and Poland) and the entire European domain according to the TNO-CAMS dataset in 2014 and following the BAU and CC scenarios.

The TNO-CAMS data are projected from the base year 2014 onwards till 2050 using the sector-specific trends of the CIRCE scenarios. The two CIRCE scenarios project two different path ways, both starting from the same TNO-CAMS 2014 base year; the BAU scenario show emission increases whereas, in constrast, the CC scenario represents emissions decreases. The projection is done for the future years 2020 and 2030 as well (data not shown) but, in Figure 3, we show 5-year time steps except for the final step from 2033 to 2050. These 5-year steps coincide with the global stock take planned by UNFCCC under the Paris Agreement. The relative change compared to the most recent year in the TNO-CAMS data set (=2014) by country for the BAU and CC scenario, with a proportional time scale, is shown in Figure 4. The 5-year time steps of the global stock take and the reference years with the targets of the Nationally Determined Contributions are indicated with the blue arrows. Figure 3 shows CO_2 emissions from fossil combustion and biofuel use. The share of biofuel CO_2 grows in the BAU and CC scenarios because there is no special policy to reduce it, and as part of the CC scenario biofuels partly replace fossil fuel.

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[10] The Commission's legislative proposal 'Clean Energy for all Europeans' covers measures relating to energy efficiency, renewables, and also proposes changes to reorganize the electricity market and tackle energy poverty.

[11] This dataset is not yet released at time of writing but it was made available for this report. A preliminary version is described by Kuenen et al. (2015).

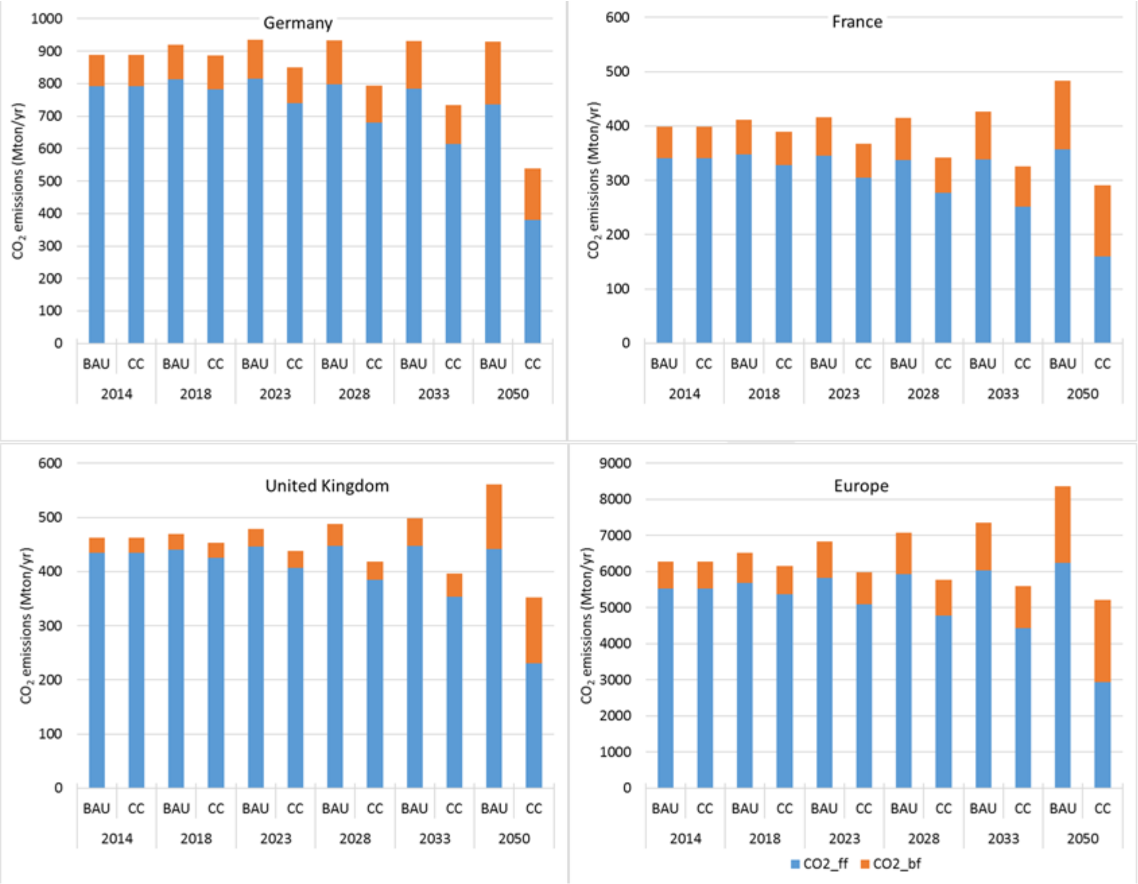

Figure 3. *Emission of CO_2 from fossil fuel (CO_2_ff) and biofuel (CO_2_bf) for three large EU countries namely Germany (DEU), Spain (ESP), France (FRA), Great Britain (GBR) and Poland (POL) according to the TNO-CAMS dataset in 2014 and projected following the CIRCE scenarios for Business-as-Usual (BAU) and Climate Change (CC) scenarios. The bottom right panel shows the emissions change for the entire European domain.*

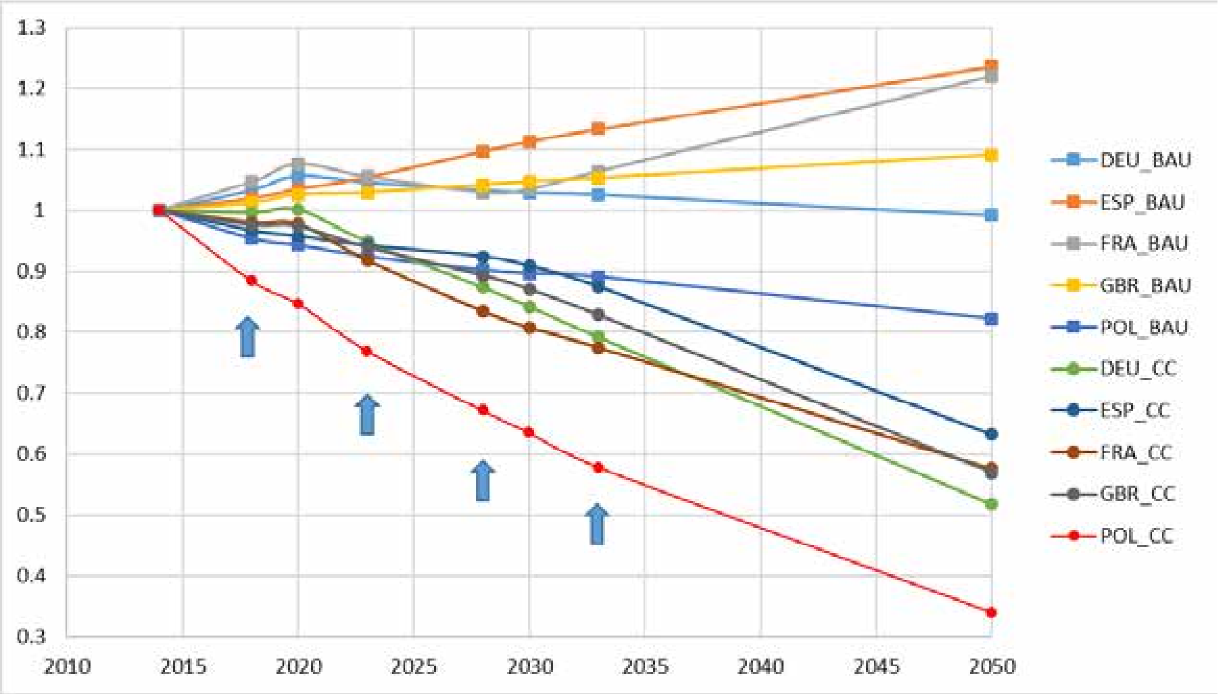

Figure 4. *Relative change from base year 2014 towards 2050 by country for the TNO-CAMS dataset based on the BAU and CC scenarios in the case of Germany (DEU), Spain (ESP), France (FRA), UK (GBR) and Poland (POL). Blue arrows indicate 5-year time steps, coinciding with global stock takes in 2018, 2023, 2028 and 2033, respectively.*

1.3.2 Spatial patterns of the emission changes

To accurately quantify the projected emission changes the observational support capacity should be able to monitor over 5-year stock take time steps. Table 1 shows the emission reductions for five large European countries by source sector as well as the national total. The source sectors are relevant here because energy industries (defined as power generation plants, refineries and oil/gas extraction and fuel transformation plants) and the manufacturing industries (large scale industrial combustion and process emissions) will mainly produce emissions from point sources (stack emissions) while other sectors will mostly consist of more spatially distributed sources. Table 1 shows that the total CO_2 emission reduction is smaller than the emission reduction in CO_2 from fossil fuels. This is to be expected, since biofuels will play a role in the phasing out of fossil fuels. It may, however, imply an additional challenge for the observing system as the net changes in CO_2 concentrations will be substantially smaller than the reduction in fossil fuel CO_2 (CO_2_ff)[12] would suggest. This is particularly detected during the 2028-2033 period for Spain, France and Poland (see Table 1).

Table 1. Changes in CO_2 emissions (kton/yr) over 5-year time steps from 2023-2028 and 2028-2033 in the CIRCE_CC scenario for fossil fuel CO_2 (CO_2_ff) and total CO_2 (CO_2_ff + CO_2_biofuel). Negative numbers indicate an emission reduction.

CO2_ff (kton/yr)	Germany		Spain		France		United Kingdom		Poland	
5-year period	2023-28	2028-33	2023-28	2028-33	2023-28	2028-33	2023-28	2028-33	2023-28	2028-33
Energy Industries	-21984	-28523	3936	868	-4832	-30	-488	-6294	-20297	-13271
Residential combustion	-15978	-14145	-3202	-4350	-8534	-9195	-8127	-9449	-4626	-9381
Road transport	-15473	-14991	-6574	-7571	-11689	-12551	-11758	-10951	-2255	-4823
Industry	-5745	-8812	-975	-3715	-1830	-4299	-2216	-3987	-4499	-4105
Other	-393	-448	152	-138	-438	-121	-70	-296	-513	-466
Total CO2_ff	-59573	-66918	-6663	-14906	-27323	-26196	-22659	-30976	-32189	-32046
CO_2 (ff+bf) (kton/yr)										
Energy Industries	-18745	-24018	3971	945	-4938	2456	-430	-4993	-11157	-4703
Residential combustion	-17024	-13197	-2682	-3315	-8351	-7572	-7068	-6689	-572	-6679
Road transport	-14657	-12984	-6284	-6654	-11353	-10975	-10363	-9569	-2457	-4560
Industry	-5745	-8812	496	712	-852	-425	-1199	-557	-2960	-1070
Other	-393	-448	152	-138	-438	-121	-70	-296	-513	-466
Total CO2_ff + bf	-56565	-59458	-4347	-8450	-25931	-16637	-19130	-22104	-17659	-17478

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[12] According to UNFCCC reporting, strict distinction is made between CO_2 from fossil and biofuel combustions. The biofuel combustion emissions are according to the IPCC guidelines for the UNFCCC not reported under the combustion sectors, but instead the net carbon emissions and change in biomass is reported in the land sectors. We denote fossil CO_2 as CO_2_ff and biofuel combustion CO_2 as CO_2_bf. The sum of both is CO_2_ff+bf.

These emission change projections are gridded using EDGAR and TNO proxy data. The differences between years 2023 and 2028 in the maps of Figure 5 show where emission estimates vary significantly. These locations would need to be followed more closely with observations to measure the changes and verify the reported emission changes for the monitoring of emissions reductions of some facilities under the NDCs. Figure 5 shows the difference between years 2023 and 2028 for the CC scenario and the BAU scenario, respectively gridded with EDGAR (Figure 5a and Figure 5b) and with TNO spatial proxy data (Figure 5c). We thus anticipate negative differences under the CC scenario (see Table 1), whereas under the BAU scenario, close to zero differences correspond to a situation with no or limited changes in fossil fuel use.

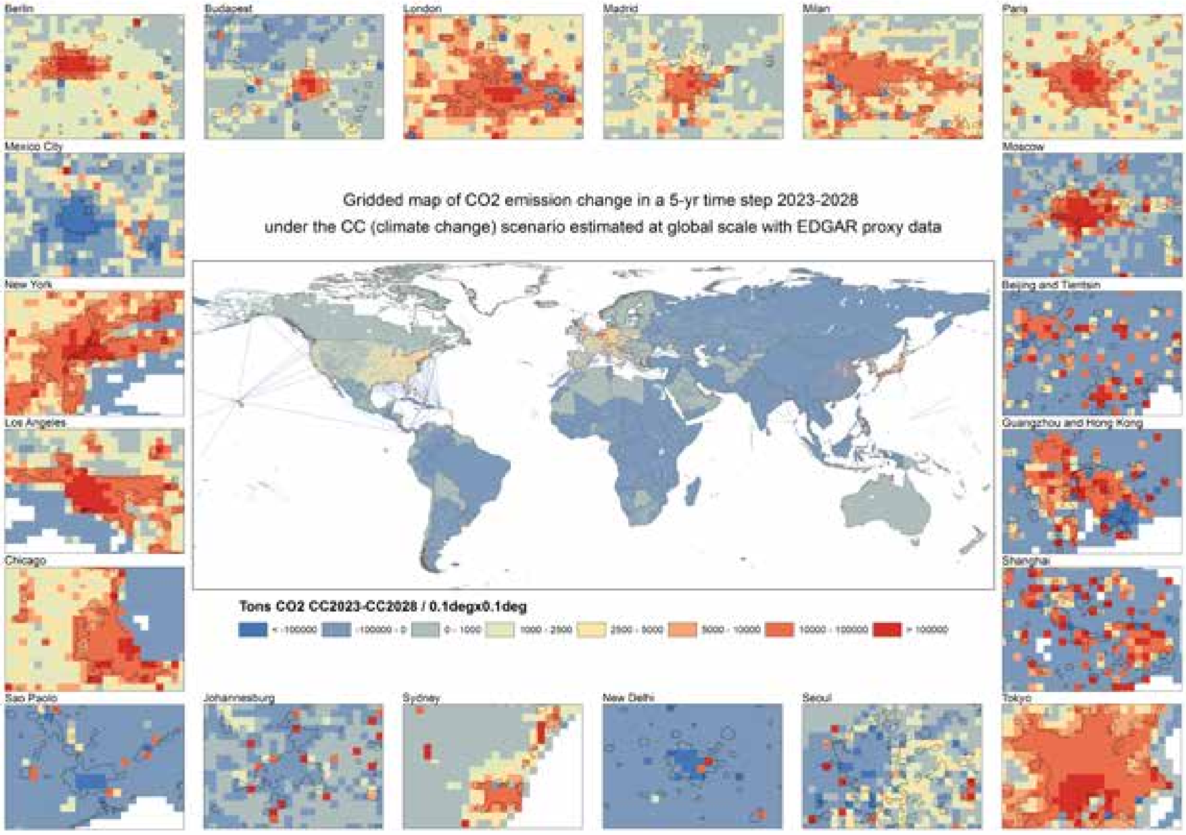

Figure 5a. *Global map of CO_2 emission changes for a 5-year time step 2023-2028 under the Climate Change scenario from the EDGAR database. Red values show a reduction reaching 500 kton/yr/0.1°x0.1°. Blue encoded values represent an increase up to 500 kton CO_2/yr/0.1°x0.1°.*

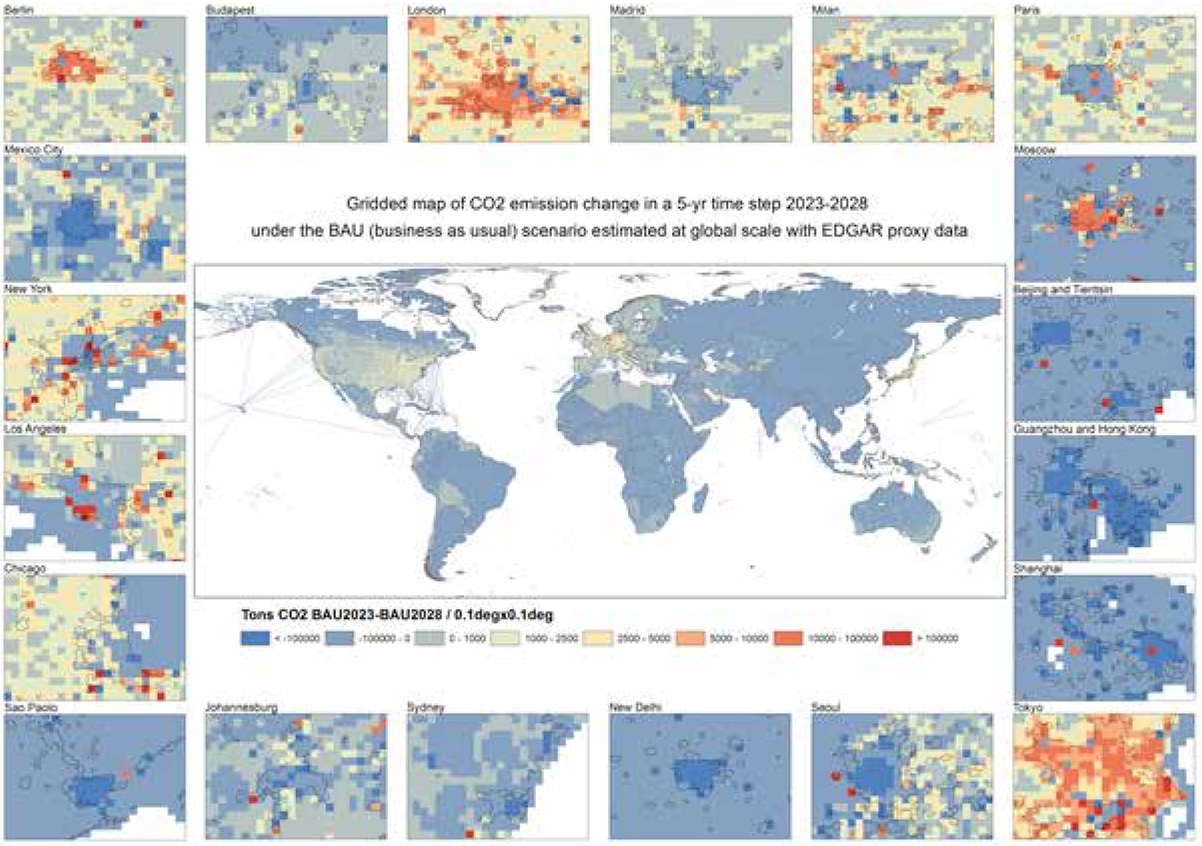

Figure 5b. *Global map of CO₂ emission changes for a 5-year time step 2023-2028 under the Business As Usual scenario from the EDGAR database. Red values show a reduction reaching 500 kton/yr/0.1°x0.1°. Blue encoded values represent an increase reaching 500 kton CO₂/yr/0.1°x0.1°.*

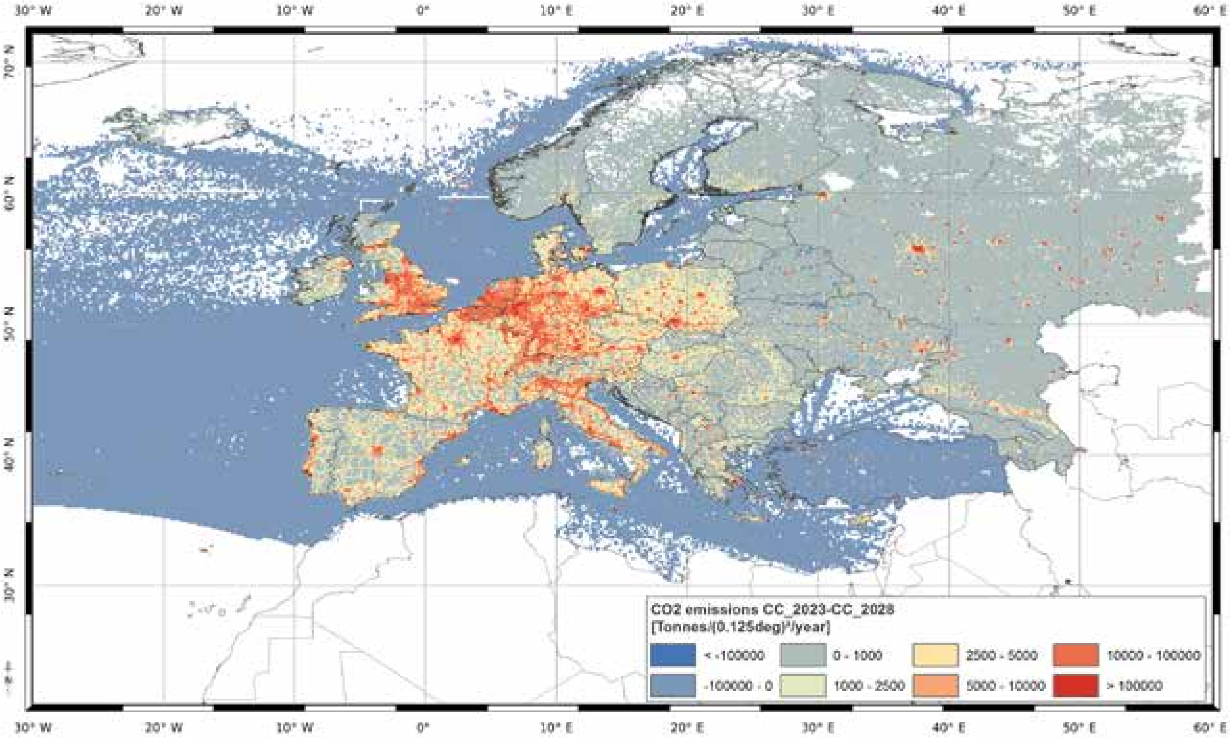

Figure 5ca. *European map of CO$_2$ emissions changes for a 5 year time step between 2023 and 2028 from the TNO-CAMS dataset following the Climate Change scenario. Red values show the mitigation efforts with reductions in emissions up to 500 kton/yr/0.125°x0.06125° whereas blue values indicate lacking mitigation actions with corresponding increases in emissions up to 500 kton/yr/0.125°x0.06125°.*

Zooming in on some regions, allows us to depict the concentration difference for city hot spots (e.g., over Paris and Madrid) and to see the point source changes (in particular of energy industries) over Europe, which the CO_2 MVS would need to detect. More generally, the CO_2 MVS should be sensitive enough to detect whether countries are engaged on a BAU scenario track or a CC scenario track.

1.4 Global versus regional and versus local scales

1.4.1 International perspective

The previous sections of this chapter focus on the European scale. What are the needs of EU policy makers and, what would the requirements on a potential space-based observational system be to meet such needs? It should be acknowledged that the uncertainty in European fossil fuel combustion (CO_2_ff) emissions is small thanks to the appropriate bottom-up infrastructure to derive reliable statistics about fuel sales and uses. The uncertainties are much larger when it comes to the non CO_2 GHG (CH_4 and N_2O) as well as the potential biosphere CO_2 source or sink in Europe (see section 2). It is envisaged that the foreseen observational system will significantly contribute to reducing those uncertainties.

It is, however, extremely important to stress the significance of the global developments and the possible role that the envisaged system will need to play on the global scale. This is a direct need for European policies if the ambition is to prevent dangerous climate change. While we have consulted national policy makers concerning their needs, the overarching European goal should be to become a global data provider.

Comparing the years 1990 to 2014 in Figure 6a demonstrates that, in terms of absolute CO_2 fossil fuel emissions, the EU 28 is an important but no longer dominant contributor since 2000. This leaves the need to further reduce emissions in the EU 28 and further reduce the per capita CO_2_ff unchallenged. China is now at a similar per capita emission level as the EU (see Figure 6b). This is, however, partly related to energy intensive production of goods for the European market shifting from Europe to countries like China. India is also rapidly becoming important in absolute terms of CO_2_ff emissions (top panel in Figure 6). CO_2 has a long lifetime[13] and is well-mixed in the atmosphere. For an emitted CO_2_ff molecule to contribute to global warming, it is irrelevant where it is emitted. So, even in the theoretical case for which the EU 28 would be able to completely eliminate its CO_2_ff emissions, this would not be enough to stay below the 2°C global target. The above are relatively simple observations but convey an important message. European policy makers, therefore, need information beyond the European scale to abate climate change.

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[13] CO_2 is stable in the atmosphere and thus has in principle an indefinite lifetime.

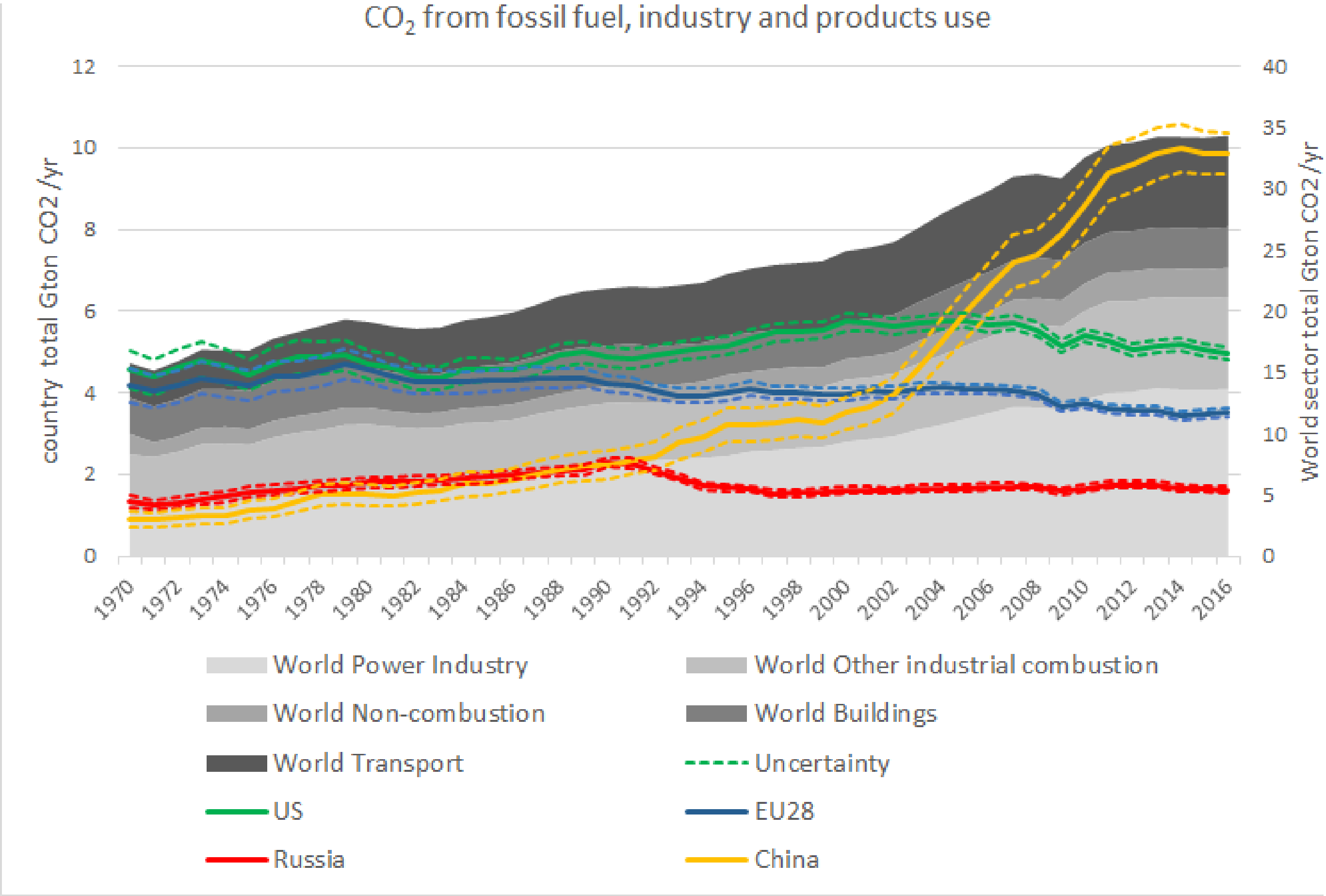

Figure 6a. *Global CO₂ emission trends from EDGAR for the EU28 and the three largest emitting countries (left axis) and for the world total (right axis).*

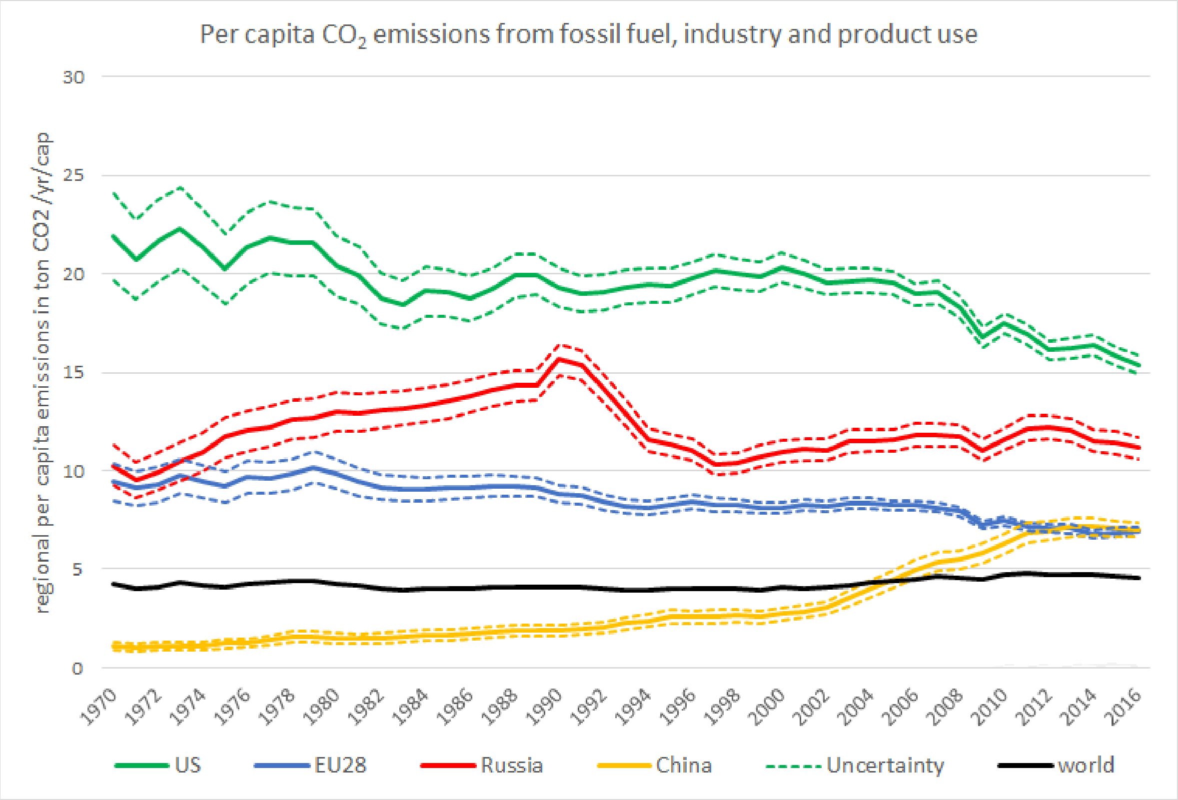

Figure 6b. *Per capita CO_2 emissions trends for the world, EU28 and the three largest emitting countries based on EDGAR.*

An interesting aspect of the global versus the European situation is the difference in the urban fabric. In Europe, the major CO_2 point sources such as coal-fired power plants are often located outside the city boundaries. This is different in many less developed countries. As a result, megacities outside of Europe are hotspots of CO_2 emission and a system with the envisaged capabilities will also be able to provide megacities with actual information about their CO_2 emissions and thereby assist in monitoring progress towards the achievement of objectives. Figure 7 shows the difference in 2023 for the two scenarios BAU and CC for the world with several zooms on selected megacities and illustrates the importance of focusing on CO_2 point sources (power plants, megacities and more). As mentioned previously, the monitoring and verification support facility should thus be sensitive enough to detect whether countries are engaged on a BAU scenario track or a CC scenario track.

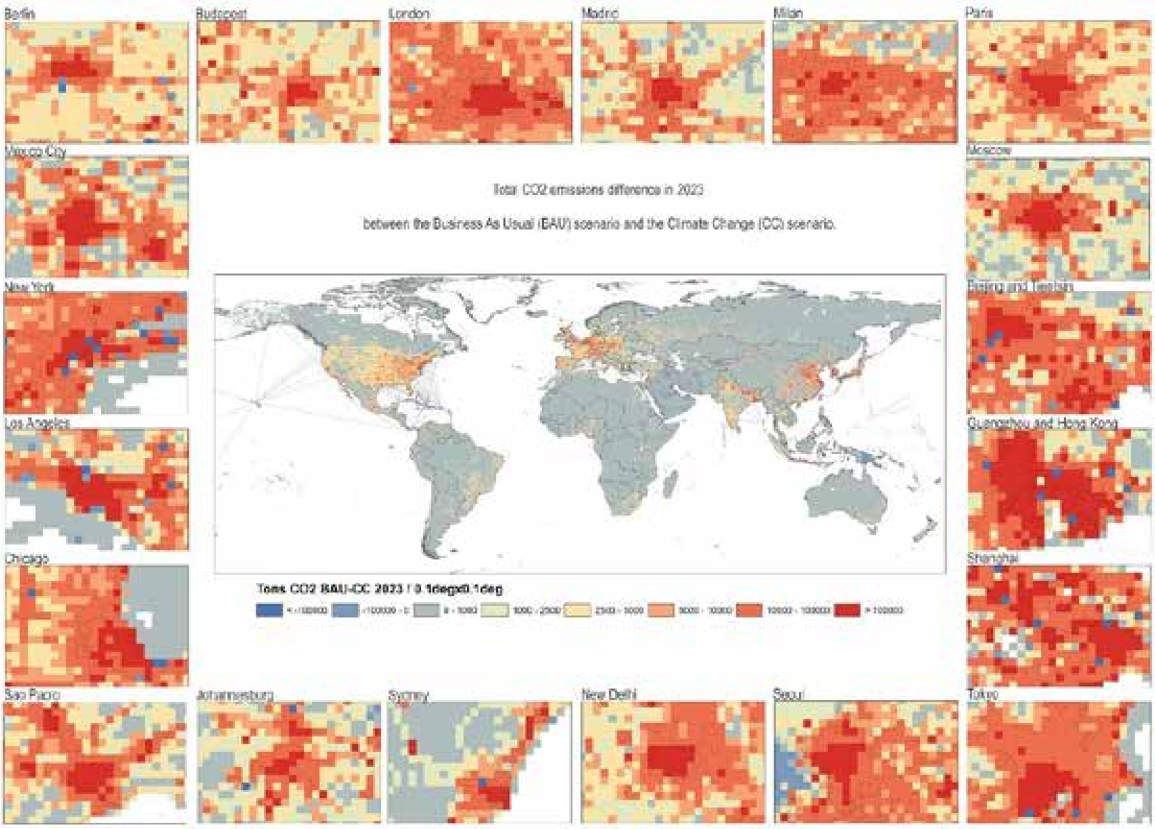

Figure 7. *Emissions Changes in tons CO_2 total /0.1°x0.1° from the Business As Usual to the Climate Change scenario in 2023 estimated with the EDGAR CO_2 dataset.*

1.4.2 Focus on hot spots and megacities

Cities all appear as CO_2 hot spots due to the accumulation of human activity in the densely populated areas. However the sector-specific composition of the CO_2 emissions can vary from region to region. Figure 8 indeed shows a large contribution to the emissions from power plants located inside cities such as, for instance, Moscow, Hong Kong, Beijing and Shanghai. Reduction of emissions in the power sector or a fuel shift shall therefore be measurable over these large scale cities.

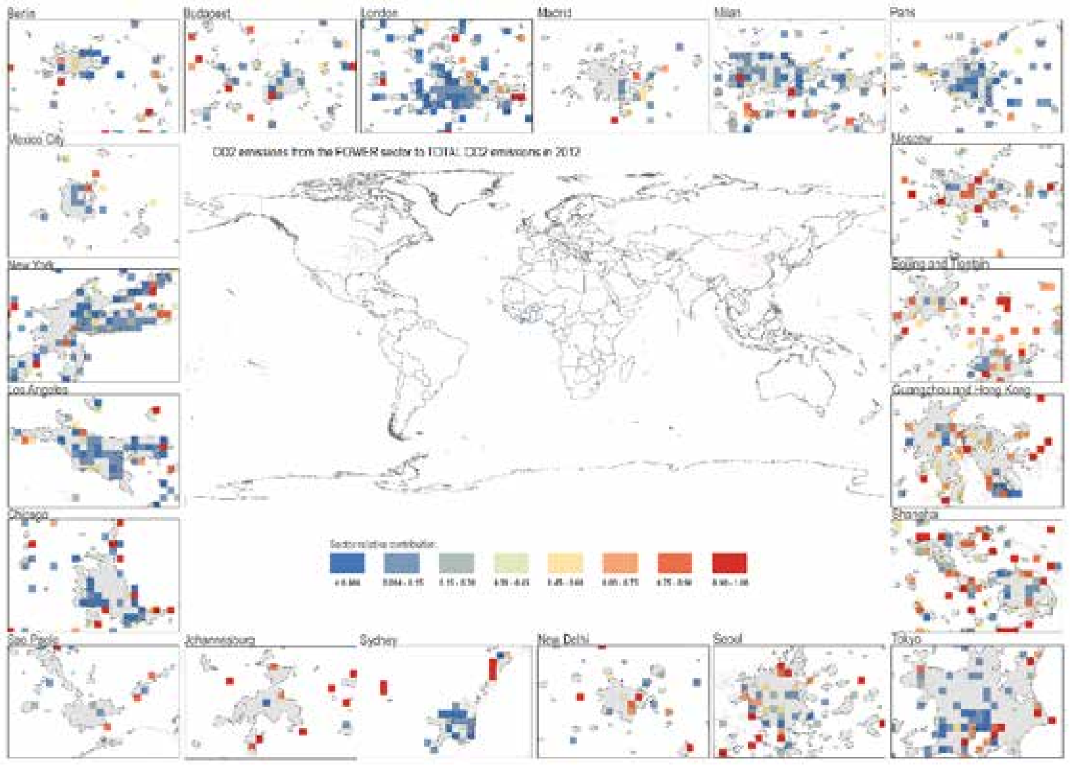

Figure 8. *Share of large combustion power plants in CO_2 emissions (ranging relatively from 0-1) for selected megacities from Janssens-Maenhout et al. (2017). The red pixels in the megacities are caused by the presence of a public power and/or a heat production plant and/or a district heating or co-generating plant.*

1.5 Needs and capabilities for a CO_2 emissions MVS

1.5.1 Stepwise approach for a CO_2 emissions MVS capacity

The need and capabilities for a Monitoring and Verification Support capacity have been illustrated in previous sections using projections of emissions based on current inventories and two plausible scenarios. These analyses have highlighted the necessity for this system to properly address the following set of capabilities:

C1. Detection of hot spot. A hot spot is defined as a small area surrounded by a strong CO_2 concentration gradient, because the area contains a large emitting CO_2 source. This can be a large power plant, a megacity or any other activity characterized by strong CO_2 emissions with different time evolution;

C2. Monitoring the emissions of the hot spot. Consecutive measurements are needed to link the measured emission level to previous measurements and to monitor local emission reductions of the activities within the hot spot. The accuracy of the measurements must ensure the capability to attribute CO_2 emissions anomalies relative to the CO_2 concentration background level;

C3. Assessing emission changes against local reduction targets. This concerns the monitoring of the implemented emission reduction strategies on the hot spots, which all add up to achieve NDC targets. In the EU this requires the monitoring, at the most appropriate time scale, of not only the point source facilities (which are under the Emissions Trading System) but also the megacities with peak emissions of transport and buildings;

C4. Assessing the national emissions and changes with 5 year time steps. This requires the entire screening of the full area covered by the country, in order to account for changes in emission patterns with new or occasional hotspots.

Capability ‘1’ calls for relatively high spatial and temporal resolutions, that is of the order of a kilometer resolution and at daily frequency. Here the point source databases (such as the European Pollutant Release and Transfer Register for Europe) must be further developed at a higher temporal resolution than currently available. The space segment will make an important contribution to the overall system, given that this cannot be covered with the current network of in situ stations (mainly background stations). A frequent revisit typically at a kilometer scale resolution (to allow the detection of emitted CO_2 plumes) is indeed required for the hot spot detection and monitoring.

By contrast, capability ‘4’ is setting the most demanding requirements in terms of precision and accuracy. The full system shall indeed be able to capture changes that are of the order of magnitude of those analyzed in the previous subsections. Detection of changes of the order of 0.1-0.5 Mton CO_2_ff /yr for a small country (few grid cells of 0.1°x0.1° corresponding to 5x5 km^2 to 10x10 km^2 over Europe) and a coverage of the entire land area of all the world's countries would be needed in order to contribute significantly to the estimates provided by the current self-reporting methodologies based on inventories.

An important objective of the proposed monitoring and verification support capacity is to encapsulate and optimize all information available with the support of the appropriate models (see section 2) at any resolved time step and space scale. This implies that all system elements, i.e., the space and in situ observations, the transport and process models as well as the databases used in inventories, identified in section 2 must be able to accommodate with such requirements. These listed capabilities will enable Europe to deliver an assessment of CO_2 trends, localizing hotspots and identifying further specific emission reduction measures within a time frame that is shorter than the one made possible from national statistics (typically 1.5 - 2 years).

The first global stock take is planned for 2023 at the COP29, where the total sum of reported GHG (CO_2) emissions inventories of 2021/2022, will be compared to the scientifically estimated global budget of GHGs. After this first exercise, the Parties will be asked to revise and strengthen their NDCs. A crucial global stock take will occur in 2028 with inventories of 2026/2027. This global stock take of 2028 is expected to show a reduced global total, but verification with top-down observations will be required to gain confidence on and validate the GHG emission trends. Operationally derived satellite observations are critically needed by 2026 as part of the CO_2 observing system in order to deliver atmospheric observations globally for verifying the global stock take.

1.5.2 Preliminary use of top-down verification for non-CO_2 GHG emissions

Unlike the constraints on CO_2 from fossil fuel combustion by the fuel statistics with relative small uncertainty, other sources of CO_2, e.g., the combustion of biofuels, or other greenhouse gases, e.g., CH_4 from coal mining and unconventional oil-gas exploration sites, are less constraint, more uncertain and could benefit from extra evidence using independent observations. Satellites have been shown to be particularly instrumental for monitoring diffuse GHG emissions from land use as well as from CH_4 emissions. Top down verification has been introduced already two decades ago in a few instances and the motivation for further applications by national inventory agencies is currently increasing.

Examples of the use of atmospheric observations as input to improve national greenhouse gas inventories concern the synthetic fluorinated greenhouse gases, given that the global budget of these gases are constrained by atmospheric measurements. Brunner et al. (2017) illustrated some inconsistencies in the national reporting of some European countries for some F-gas emissions in Europe. Emissions of the hydrofluorocarbon gas 125 estimated by inverse modeling and in-situ measurements are larger than those reported to UNFCCC by Germany and Ireland; in contrast, the reported values from France and UK to UNFCCC are consistent with the estimates delivered by the inverse procedure. By comparison, the reported values for sulfur-hexafluoride to UNFCCC are much lower than the estimates from the inverse procedure for Italy, France and Spain but consistent in the case of Germany.

The case of the CH_4 inventory of Switzerland that is part of the National inventory report (with the atmospheric measurements in appendix) illustrates the benefits from applying top-down techniques. Henne et al. (2016) demonstrated that, although the inverse modeling retrievals and the national inventory report estimates compares favorably for Swiss CH_4 emissions, three improvements to the national inventory report are made possible: (1) in the agricultural sector, (2) in the gas distribution in urban areas and (3) for the localization of an unknown source. For instance, a posteriori distribution and seasonality of the emissions suggest a 10% overestimation of agricultural emissions in the national inventory report of Switzerland. Leakages of gas distribution networks in cities were found to be smaller than anticipated suggesting thus to adopt the lower range of UNFCCC emission factors.

UK has provided observation-based verification of the reported inventories for all Kyoto greenhouse gases for more than a decade. In the case of CH_4, Manning et al. (2011) found, for instance, that the agreement between the CH_4 values reported to UNFCCC and the inverse procedure estimates is relatively poor in the nineties but much better in the 2000s, when the emissions from less well characterized emission sources such as some coal mining and landfills were reduced. In addition, extra evidence on the CH_4 emission levels were found using the SCIAMACHY and GOSAT satellite retrievals, providing additional information on the emissions at regional scales by Bergamaschi et al. (2009).

2. System Overview & Architecture

Neither ground- nor space-based techniques on their own are capable of providing information at the spatial and temporal scales to meet the requirements outlined in section 1.

Therefore a system is proposed that is capable of integrating a wide range of available observations that are heterogeneously distributed in space and time. The core of the system is the integration component that makes extensive use of our knowledge of the behavior of the Earth system and of the processes governing fossil fuel emissions, both captured in models, to optimally combine the various sources of information to generate anthropogenic emission fields at the required temporal and spatial scales together with uncertainty information - the main building blocks of the system are illustrated in Figure 9.

As there are no comparable pre-cursors, the development of such a system represents a major challenge. Therefore it is considered essential that an end-to-end simulation programme is put in place to inform and guide the design and development process of the system. Such an end-to-end simulation has to follow the requirements as formulated in section 1, such as the accuracy of both the inferred emission fields and uncertainty ranges. Therefore it needs to demonstrate, using realistic observations (simulated from realistic space-time variant fossil fuel emission fields) including realistic uncertainties, and representative prior information, that the integration process is capable of retrieving the initial fossil fuel emission fields within the required accuracy. A further requirement on the system concerns its capability to quantify the added value of an extension of the set of available observational data streams. In addition the end-to-end simulator needs to be capable of quantifying (through rigorous uncertainty propagation) the impact of additional observational information into an uncertainty reduction in inferred emission fields.

2.1 Architecture

Understanding the dynamics of atmospheric CO_2 concentrations requires a better quantification and understanding of the processes controlling the global carbon cycle, including the natural components and the anthropogenic contributions. The current state of the science can neither confidently account for the processes governing the CO_2 average growth rate nor for its inter-annual variations.

The carbon exchanged by vegetation or emitted by anthropogenic activities is efficiently mixed in the atmosphere, first at a scale of minutes to hours in the boundary layer, then zonally, and then at a scale of years globally. This implies that the system has to account for the spatial scales of the sources and sinks of carbon, which are as diverse as large power plants, megacities, countries and continents. Therefore, as indicated in section 1, for an observing system to be policy relevant, it should be able to resolve and represent these different spatial and temporal scales.

Ground-based observations provide the most accurate measurements of atmospheric carbon and, whilst the networks could be regionally dense, their overall global coverage is sparse. Currently, measurements of atmospheric CO_2 concentrations are taken at discrete levels in the boundary layer from a network of tall towers distributed over the globe. These observations and those acquired from the surface network of about 150 CO_2 stations that are part of the CO_2 network, are particularly useful to study regional trends and provide a global constraint, albeit an insufficient one, on estimates of sinks and sources from inverse modelling systems. Total Carbon Column Observing Network (TCCON) observations provide the CO_2 concentration within an atmospheric column (total column CO_2, XCO_2) that is more directly comparable to observations from a satellite, but this network is currently limited to about 25 stations worldwide. Satellites on the other hand can provide global coverage, but with limitations in spatial resolution and temporal coverage and accuracy as well in some instances.

Neither ground- nor space-based techniques on their own are capable of providing atmospheric CO_2 concentration observations at the required spatial and temporal scales, with the required precision and accuracy to resolve small scale large emitting hot spots of high emissions over small spatial scales. Therefore, an integrated system is needed that optimally combines such observations, together with other inputs, within a modelling framework that incorporates knowledge about the Earth system and human behavior and activities.

The design of an optimized monitoring and verification support capacity will also need to take into account the homogenization of data from various sources that may be part of the data preparation and assimilation sub-systems of the modeling component of the system; it will also involve the accurate characterization and reliable calibration of the various instruments involved. In addition to the observational uncertainties, the uncertainties associated with the individual components of the modelling system, i.e., of anthropogenic and natural fluxes and in the observation operators such as the atmospheric transport, need to be accounted for because it is the combined observational and model uncertainty that determines the weight of an observation.

Furthermore, the monitoring and verification support capacity will have to integrate data from various emission inventories, and databases on known emission sources. It will also have to ensure the consistent use of ancillary data throughout the system. An example of the need for consistency in the use of such data concerns the general state of the atmosphere which may be used in the modelling component as well as for the derivation of higher level products, like XCO_2 from satellite data. The retrieval of a CO_2 emission flux, from a set of spatially-resolved atmospheric concentration measurements, indeed requires a comprehensive and accurate description of the atmospheric vertical and horizontal structure and the vertical transport on scales ranging from the microscale (resolving the stack height of a power plant), through the mesoscale, to the synoptic and global scale.

Finally, it should be noted that, whilst the capacity will be based on existing networks and infrastructure, there will be a need to provide data access, archiving and data distribution functionalities in order to ensure that the information will be provided in a timely, structured and consistent manner from existing network that needs to be sustained. The associated capabilities may be different for the various components of the capacity, and will also be determined by practical implementation issues, like the realization of the data circulation of large amounts of space-based data.

With this general context in mind the core elements of the system (excluding data access, archiving and distribution functionalities) are depicted in Figure 9 below.

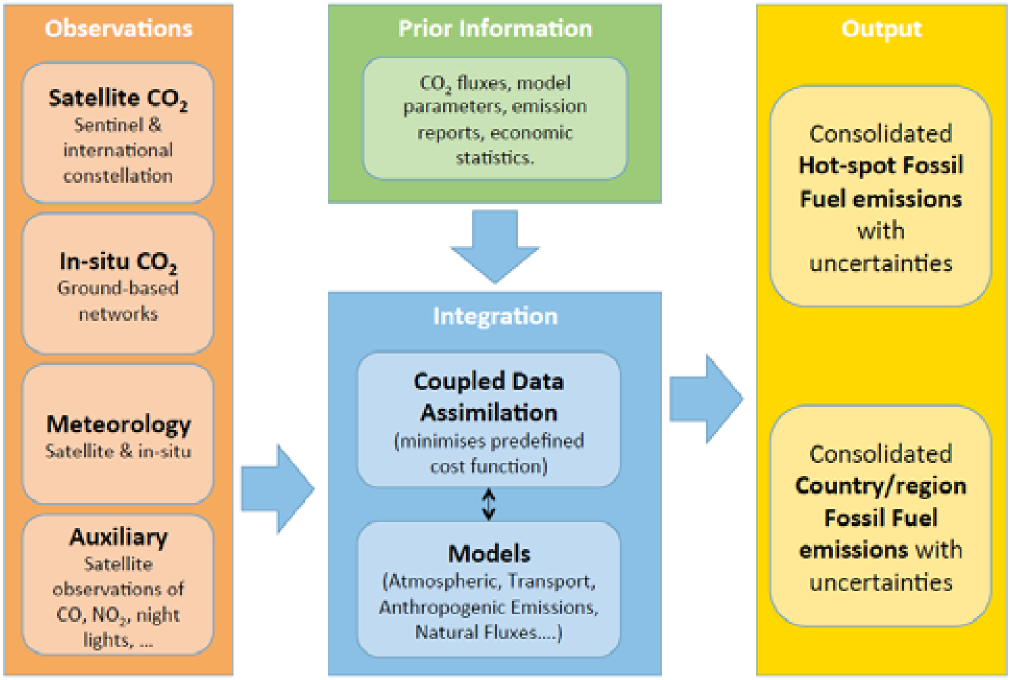

Figure 9. *Core Elements of the Monitoring and Verification Support capacity*

This Monitoring and Verification Support capacity has no precursor to inform its design, and breakthroughs are needed in both our observing and modeling capability, together with the support of a simulation platform to optimize the overall system performance, and to refine the required contributions from the individual system elements. For example, the current in situ network is not focused on detecting anthropogenic emissions, and there is no clear understanding of the impact that different observing strategies and characteristics, such as orbit and swath width, of space borne sensors would have on the accuracy of the overall system. Also, if there is a need to be able to determine synoptic scale disturbances, the observing networks need to be spaced in such a way that the synoptic scale can be resolved. Overall the role of the end-to-end simulation is to prioritize development steps according to their impact on the system performance, i.e. on the degree to which it can infer accurate flux fields and uncertainty ranges.

2.2 System Functional Elements

The following sections highlight some of the main characteristics and unknowns concerning the main elements of the system depicted in Figure 9, starting with the integration element (Coupled Data Assimilation and Models) as this is the core of the system.

An alternative, broadly consistent but more detailed functional representation of the system described in Figure 9 is also provided in Annex 3. It is envisaged that the representation format[14] used in Annex 3 will be increasingly used as the design and development progresses as it will, amongst other things, facilitate the functional specification of what is a complex system, as well as providing a structured repository for recording the major design and development unknowns/ risks.

It should be noted that whilst an integrated coupled data assimilation system is at the core of an overall Monitoring and Verification Support capacity, there is also a need to develop additional products for additional analysis, process studies and validation. Also the need to provide additional data and products for down-stream services need to be taken into account.

2.2.1 Coupled Data Assimilation

The integration of the model components with observations and prior information can be achieved in a unified statistical data assimilation (or joint inversion) framework. Such a framework is based on minimizing a pre-defined objective function that adds the cost of the mismatch between the model and observations, the cost of deviating from prior information, as well as other cost elements expressing additional constraints, e.g., related to physical consistency conditions. Through minimization of the total objective function, the framework achieves an optimal balance of all pieces of information over a fixed period in time, the so-called assimilation window. In this framework, the weights of the individual pieces of information are determined by the uncertainties we assign to them, i.e., the combined uncertainty in the observations and our capability to simulate it. This includes uncertainty correlations in space and time, which have been shown to have considerable impact on inferred surface fluxes from observed XCO_2 (Kaminski et al., 2017), as well as among variables.

The framework achieves the minimization of the objective function through variation of a control vector that covers the key uncertainties in the simulation of the fossil fuel emissions and the observation equivalents. These are expected to be: the initial state of the modelling system, e.g., the terrestrial and atmospheric carbon pools, the anthropogenic CO_2 emissions or parameters of an emission model; the atmospheric transport; natural fluxes or parameters of a natural flux model, and the parameters needed to model biases in observations. Parameters in this context are defined as constants (at least over the assimilation window) in a model representation of the relevant processes that have an uncertainty and therefore can be adjusted through the use of observations. This is different from variables such as the emissions or fluxes themselves, which can vary at a wide range of temporal scales (minutes to years).

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[14] Integrated Definition For Function Modeling - www.idef.com/wp-content/uploads/2016/02/idef0.pdf.

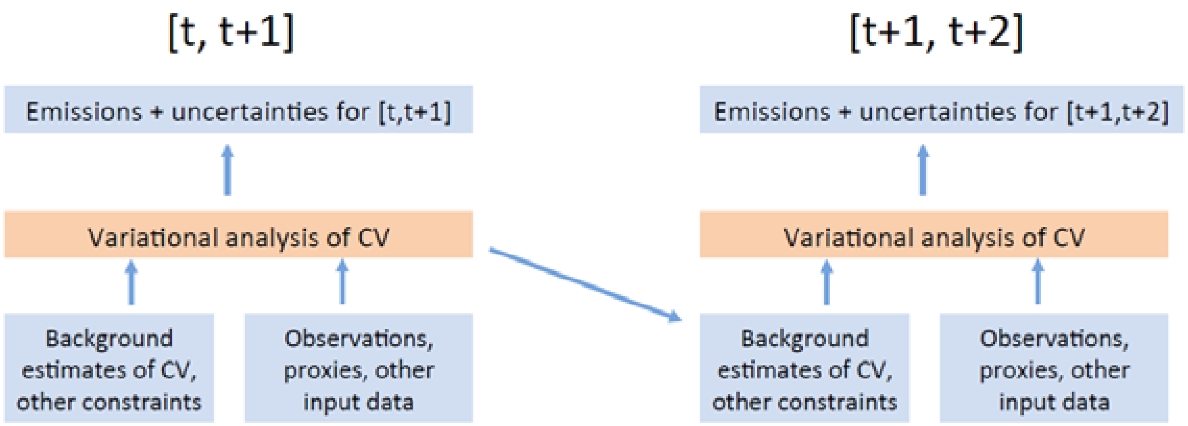
The data assimilation method therefore must be designed on the basis of a control vector that can include both parameters and variables in order to constrain all aspects of the system as best as possible.

The data assimilation scheme must be designed to process very large data volumes and capable to assimilate them in high-resolution models that can accurately represent the information content of the data. Data processing and quality control procedures need to be implemented to handle all data streams. As noted in Section 1, updated emission products are required on km-scale grids at sub-daily intervals, together with estimates of uncertainties. One option to meet these requirements is a forward-in-time-stepping ensemble-based data assimilation approach, similar to what is used for Numerical Weather Prediction (NWP), with a reasonably short analysis window. An early task is to assess the efficiency of such systems in constraining parameters.

Given the spatial and temporal scales of the physical processes involved, frequent exchange of information between model components is needed to optimize the use of data for reducing uncertainties in surface emissions. The data assimilation approach has to be implemented accordingly, i.e., it needs to respect the essential coupled nature of the problem. This means that all model components, i.e., models of atmospheric transport and surface fluxes, must be tightly coupled within the data assimilation process. A detailed analysis of all required components is described in Annex 2. While it is clear that a variety of potential solutions need to be further explored, it is also clear that an optimal system needs consistency among all components. To minimize internal errors, the (inverse) modelling of emissions, natural fluxes, transport, and satellite retrievals need to be aligned and, in particular, make use of prior information as consistently as possible. The important requirements of consistency and mass conservation are challenging because of the range of temporal scales involved (from minutes to decades). Some approximations may be required to render the data assimilation problem tractable (see Annex 2.3.2). For example, exploiting the linear behavior of the atmospheric transport of CO_2 on the relevant time-scale, a mass conserving online simulation scheme, consistently driven with output of a physical assimilation system can be used (likewise for the ocean circulation, see Annex 2.3.5, or auxiliary variables needed for the simulation of radiances or retrievals).

The end-to-end simulator allows us to investigate the impact of such approximations on the system's performance. However, these approximations are also expected to simplify the minimization of the objective function and possibly allow for a long assimilation window. A practically feasible solution will lie somewhere between completely separated modules and a fully integrated system. Conceptually, there are different starting points for the design of a MVS. An example, based on current practice in coupled atmosphere-land-ocean-sea ice data assimilation in NWP, is shown in Figure 10 showing separate modules embedded in a fully integrated forward model (Dee et al., 2014).

Another example, illustrated in Figure 11, based on experience in carbon cycle data assimilation in the carbon cycle research community achieves mass conservation and consistent use of observational information through the use of a single, long assimilation window (Kaminski et al., 2013). Fully consistent uncertainty ranges (including their correlations) are propagated from the observations to the control vector and then to the inferred fluxes. A final solution will need, anyhow, to be based on thorough investigation of the options and constraints outlined in Annex 2. Another crucial prerequisite for a system to be capable to infer accurate emissions fields is that it focuses on minimizing the errors related to the conservation of carbon (essential for a system capable of quantifying long-term trends in emissions as outlined in section 1). This requirement must therefore also guide the selection and coupling of the components of the forward model as well as the selection of the data assimilation approach.



CV = control vector
Output: hourly emission estimates for a 24-hour period (for example)
All output generated by the coupled Earth System Model (ESM)

Figure 10. *Example of sequential data assimilation forward in time.*

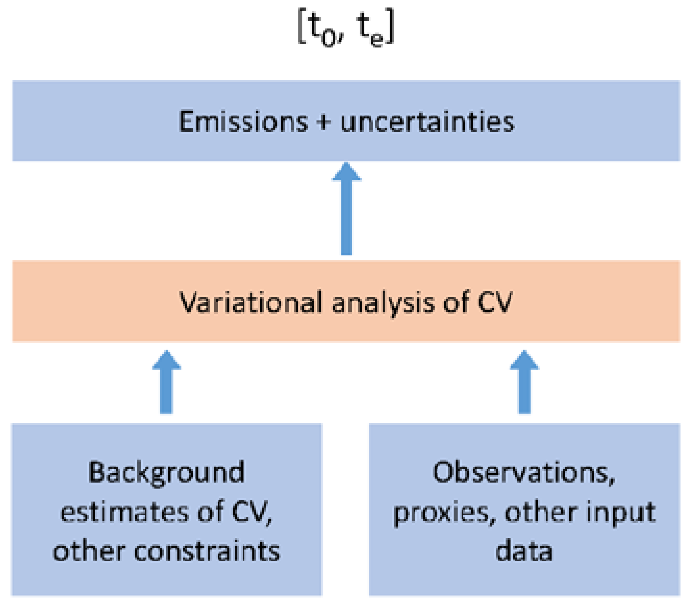


Figure 11. *Example of variational data assimilation using a single assimilation window covering the whole analysis period (t0 start of the analysis period, te end of the analysis period).*

2.2.2 Models

The report from the expert group on CO_2 emissions (Ciais et al., 2015) envisions an operational monitoring system capable of combining top-down observations with bottom-up information on greenhouse gas emissions. The report identifies two core model components as essential ingredients for such a system. The first is an anthropogenic CO_2 emission model that can use Near-Real Time (NRT) information to provide up-to-date emission estimates with a high spatial and temporal resolution. The second is an atmospheric inversion modelling and data assimilation component that is able to simulate fossil and non-fossil CO_2 emissions and sinks, as well as the various observations used to constrain the emissions, including their impact on atmospheric CO_2.

The role of the models together is to provide a physically consistent framework for assimilating all relevant data from observations, inventories, industrial and socio-economic statistics. In particular, the framework has to support the use of observations from space for reducing uncertainties in global estimates of surface emissions.

Any inconsistencies introduced in the implementation of the modelling and data assimilation framework will limit the achievable accuracy of emission estimates. Errors due to physical inconsistencies are however inevitable when different components of the climate system are treated separately. For example, current approaches to carbon data assimilation often use separately produced wind fields to invert stand-alone atmospheric tracer transport models.

This gives rise to interpolation errors and other approximations due to inconsistent use of input data. Therefore, in planning a new and comprehensive system for monitoring future emissions, design decisions should be guided as much as possible by the concept of a fully integrated modelling approach. However, the design decisions should also follow a strategy to reduce overall emission uncertainties, and thus should consider these components first which contribute most to the posterior emissions uncertainty and consider simplifications that improve the performance of the integrated model in a data assimilation framework (see Annex 2.3.2).

The following paragraphs describe the main elements of a fully coupled modelling and data assimilation approach, representing the long-term ambition for optimal estimation of global emissions. Initial implementations of the system will require approximations that effectively decouple or simplify some of the components depicted in Figure 12, but these should be minimized and removed in due course.

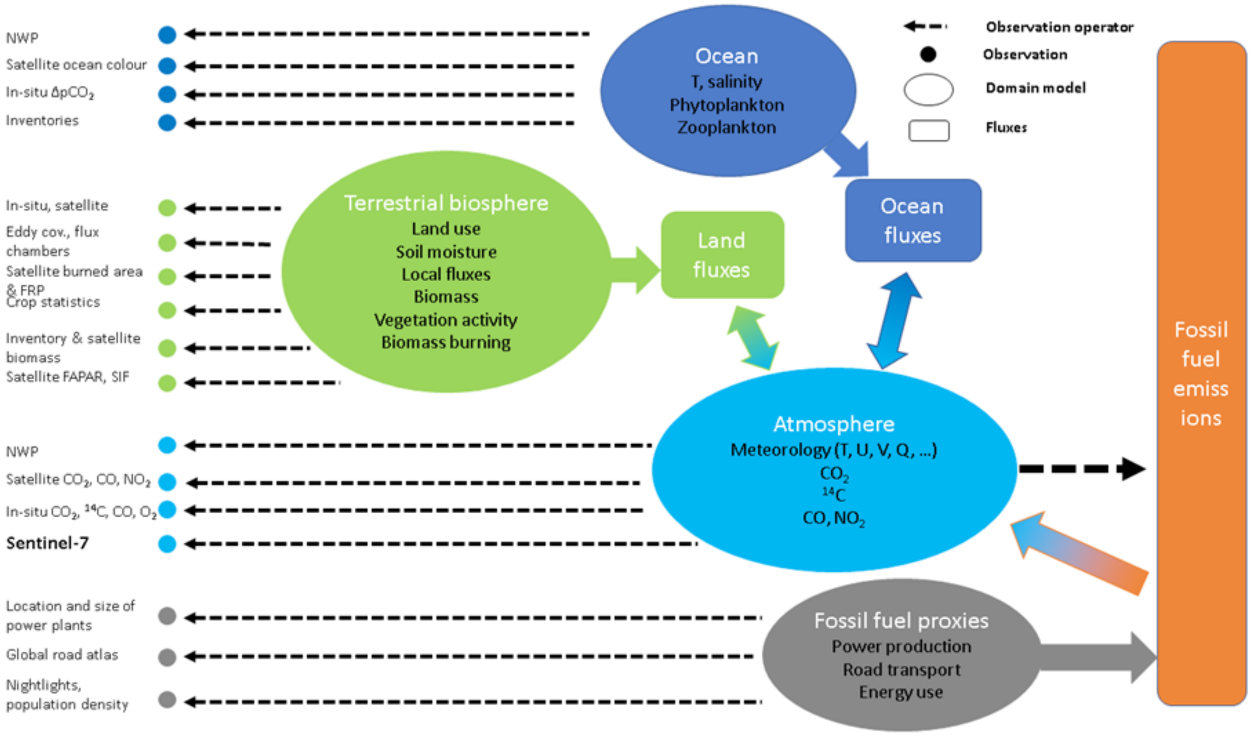


Figure 12. *Schematic overview of a fossil fuel emission inversion system showing the various required model blocks as well as the potential observations that can be used to constrain the system.*

1. Atmospheric Transport Models

The overarching modelling requirement in the context of data assimilation derives from the fact that the accuracy of the model simulation must be consistent with the observational uncertainty. If this is not the case, then the observation may deteriorate the final product. It is also important to note here that the radiances being observed by a satellite can, in principle, be used directly in a data assimilation system for optimal consistency, but they can also be converted to intermediate variables, e.g., atmospheric CO_2 values, which are then being assimilated, for computational reasons.However, in the latter case, great care has to be taken in using prior information in the retrieval and data assimilation steps that is as consistent as possible (Chevallier et al., 2015).

It follows that the atmospheric model component of the system must be capable of simulating the variability of atmospheric CO_2 concentrations using the underlying emissions and fluxes that is needed to simulate the satellite observed radiances or atmospheric CO_2 concentrations. If not, much of the valuable synoptic information available in the satellite products must be discarded and the observational capacity will be greatly under-utilized. Spatial resolution of the model therefore has to be on the order of 1 to 5 km in the horizontal dimension. Since most emissions occur near the Earth's surface, the model must be able to represent local mixing in the boundary layer as well as vertical transport in convective clouds, typically 10 to 100 m in vertical resolution, with less than 1 hour regarding the temporal resolution.

In order to use observations of related chemical species dynamically consistent atmospheric chemistry is required on similar temporal and spatial scales. Fully integrated atmospheric chemistry models can achieve this by design, but these are rather demanding in terms of resources for an implementation at the resolutions mentioned. Use of a chemical transport model based on prescribed atmospheric circulation, while less demanding, will give rise to interpolation errors and inconsistencies. The impact of this is difficult to quantify but may well affect the anthropogenic signal of interest. Several centres have implemented global atmospheric models with fully coupled chemistry modules that support data assimilation applications (see e.g., Flemming et al., 2015; Nielsen et al., 2017). However, a linear atmospheric transport could be a sufficient approximation for the time scales of interest for atmospheric CO_2 and XCO_2 (see Annex 2.3.2).

2. Anthropogenic CO_2 emission models

Surface emission models are required that can provide reasonably accurate prior estimates of carbon emissions resulting from human activities. Such estimates can be produced based on a combination of inventories and spatial and temporal profiles derived from observations and statistics, the greater our confidence in the models underlying such inventories the more information is carried in their parameters and the more observational power can be brought to bear on each unknown. Output from this model can be used as background information for the assimilation of additional information available NRT, e.g., in situ observations of CO_2, carbon isotopes, CO, proxies such as night lights, and more (see e.g., Hooker-Strout, 2008; Rayner et al., 2010; Asefi-Najafabady et al., 2014). However, further research on the robustness of the conversion between CO, NOx and fossil fuel CO_2 is required before these proxy tracers can be used in an operational monitoring system (see Annex 2).

3. Natural Carbon Fluxes

Forward integration of the atmospheric transport model requires information on carbon fluxes at the Earth surface that result from natural processes on land and in the ocean. Since these fluxes are variable and large, high accuracy is required to be able to simulate the relatively small effect of human emissions on satellite observations of atmospheric CO_2 concentrations. Sophisticated land biosphere and ocean biogeochemistry models are available for this purpose. A range of simplified biosphere models exists and have been evaluated over European sites (see e.g., Balzarolo etal., 2014); however, observation requirements, data assimilation performance and computational complexity need to be assessed.

Specification of physically plausible surface fluxes on the relevant spatial and temporal scales would require a high-resolution, fully interactive Earth-system model. The computational cost to constrain a fully interactive Earth system model has led to practical solutions that constrain component models of the Earth system such as the terrestrial carbon cycle (see e.g., Kaminski et al., 2002; Rayner et al., 2005; Kaminski et al., 2013).

Given the high accuracy requirements for the integrated system, it is imperative that the carbon cycle model components as well as the meteorological data used to drive them are consistent. In any case, the impact on emission estimates at the required scales of the various approximations and inconsistencies introduced by separating components that are inherently coupled needs to be exposed and carefully evaluated.

2.2.3 Observations

2.2.3.1 Space-based observations

1. Capability to detect CO_2 fluxes from satellite sensors

A simplified calculation yields that for a 1 ppm increase of column CO_2 (XCO_2) to be realized assuming a constant emission during 3 hours on a day without winds (i.e., a conservative case with the accumulation of all emissions in the CO_2 column) a total emission flux F of 0.00522 kg CO_2/hr/m2 for the 3 hours during that day is needed. The 1 ppm increase of XCO_2 is taken as the individual sounding precision of a satellite CO_2 imager with a 1x1 km image pixel resolution.

The emission (F) giving an atmospheric CO_2 change in the air column of NCO_2 moles of CO_2 after 3 hours of emissions is given by

$$F[\mathrm{kg\ CO_2/hr/m^2}] = MCO_2[\mathrm{kg\ CO_2/mol}] * NCO_2[\mathrm{mol/m^2}]/3\mathrm{hr}$$

where MCO_2 represents the molar mass of CO_2. A 1 ppm atmospheric CO_2 column change is chosen as the maximum accuracy of an individual satellite sounding.

This assumes that for an individual sounding emission giving a change above this threshold will be detected, and emissions below this threshold will not be reliably detected with a single sounding. The need to oversample to detect emissions of a given magnitude will degrade the spatial and temporal resolution of emissions estimates and place great demands on the systematic accuracy of the measurement. A change of 1 ppm corresponds to NCO_2 = 1ppm*Nair. Thus, the minimum emissions F* that could be detected from a single sounding is on the order of:

$$F^* = MCO_2 * 1ppm * Nair/3$$
$$F^* = MCO_2 * 1E\text{-}6 * Psurf\ [Pa] / Mair\ [kg/mol] / g\ [m/s^2] / 3\ hr$$
$$F^* = 0.00522\ kg\ CO_2/hr/m^2$$

The indicative threshold sensitivity of the minimum annual flux for a 1x1 km satellite image pixel to give a detectable atmospheric signature of 1 ppm during the satellite overpass and amounts to 46 kt CO_2 /yr/km^2 (assuming emissions equally distributed during the day as satellites will only allow the quantification of emissions within about 6 hours before overpass). If a higher fraction is emitted during the 6 hours preceding satellite overpass, i.e., between 5 AM and 11 AM, than during the rest of the day the sensitivity would increase and the threshold would be lower. Further, adjacent pixels of emissions below this threshold can still form a source detectible as a single plume by satellites. Hence the estimate presented here is rather conservative. Here we first approximate using the conservative threshold of 46 ktCO_2 /yr/km^2, which is probably too optimistic as it assumes no wind. The emission of the point source will spread beyond the 1km^2 grid cells to 3 or 4 cells, so we made the detection calculation conservatively for an arbitrary ≈ four times larger threshold of 170 kt CO_2/yr (which is in the order of the annual emission of medium size thermal plants or of medium size cities).

Starting from the gridded TNO-CAMS emission inventory for 2014 (Figure 2b) we separately identified all point sources and all area sources emitting above the 170 Gg/yr/pixel threshold (see Annex 4). The pixels are 1/8 by 1/16 longitude-latitude (or roughly 7x7 km^2) in which all diffuse area source emissions have been aggregated to the point source. It is important to note that a point source could be located in an area source pixel, and will be accounted in the large pixel of 7x7km^2. While there is no double counting in the emissions (as point sources and area sources are classified separately) the number of area sources and point sources cannot be summed to give a total number of uniquely identifiable emission locations. To define this total number further processing of the data is needed. Similar results were obtained with the EDGAR emission inventory (see Figure 2a and Annex 4).

This shows that the percentage of daily emission emitted during the 3 to 6 hour period before the satellite overpass is a critical quantity for the ability of a satellite based system to quantify a significant fraction of anthropogenic emissions. This quantity can be obtained from hourly temporal profiles of emissions such as for instance those developed under CARBONES project by Thiruchitampalam (2012) or used by air pollution models benchmarked under the AQMEII project.

For an emission area forming a group of 1x1 km^2 emitting pixels as the case for a city, various adjacent pixels will contribute jointly to form an enhancement of XCO_2, i.e., one city plume that can be detected by a satellite with imaging capabilities and hence provide together a stronger signal than individual pixels alone. This will be addressed in a scientific study supported by ESA and led by LSCE and University of Bremen where a simplified atmospheric transport model is coupled for the first time to 1 x 1 km hourly CO_2 emission map over the entire globe to determine the error reduction on the emissions of hot-spots worldwide that would be delivered by a constellation of imagers, and to aggregate these estimates to the scale of countries.

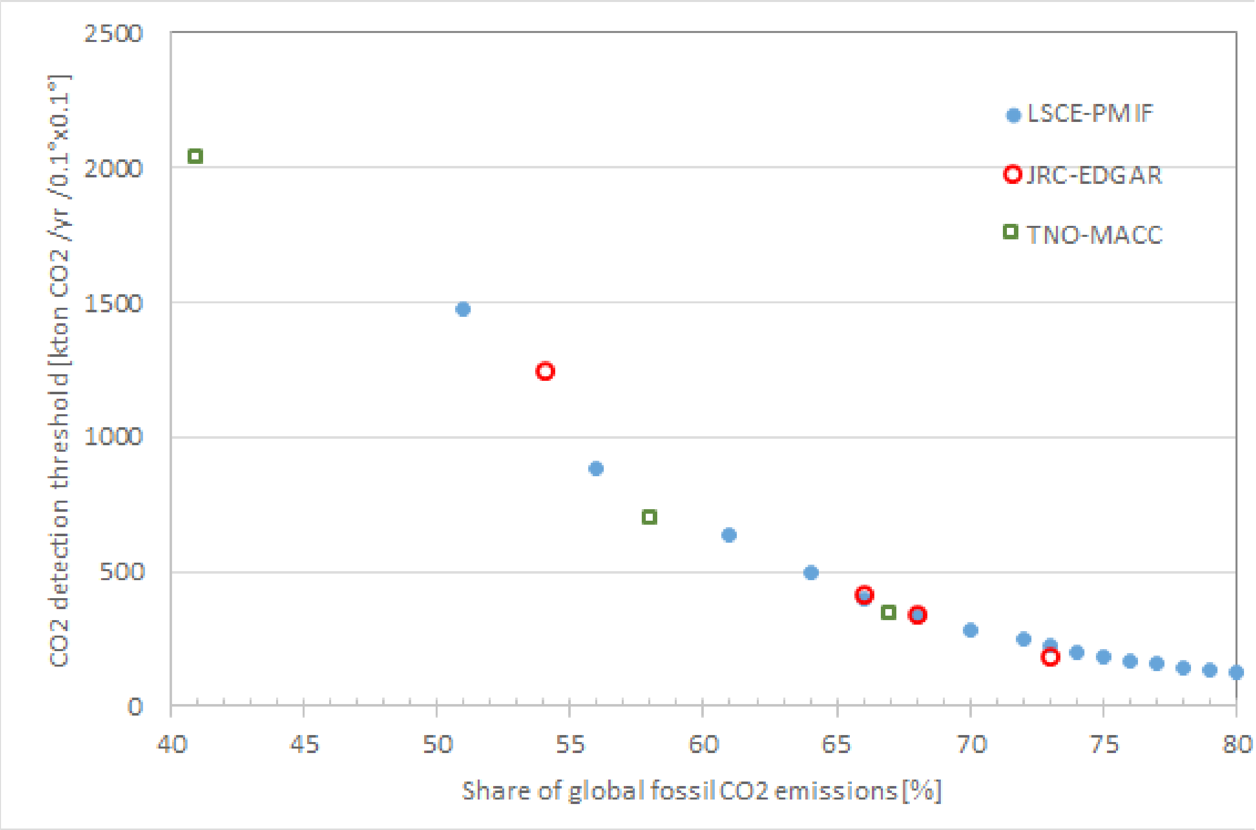


Figure 13. CO_2 detection threshold in function of the percentage of global fossil CO_2 emissions to be observed by the system, derived with the LSCE Poor Man Inversion Framework (PIMF), JRC's EDGAR emission map and TNO's CAMS emission map.

In theory 170 kton CO_2/yr/pixel plumes would be detectable by the instrument. Note that the pixel is the area of emission, which varies between 1x1 km^2 and 10x10 km^2. It should be noted that the representativeness assumption of the applied spatial proxy data influences these results. The foreseen instrument will have a resolution higher than 7x7 km^2 but coarser than 1x1 km^2. So area cells that are above the threshold of 7x7 km^2 pixel may then be below the threshold when split in, for instance, 3x3 km^2 grid cells. On the other hand, neighboring emitting cells, as often the case for area sources like cities, will enhance the sensitivity of the instrument by adding their emissions to form a detectable plume. Clearly further research studies are needed to offer more precise estimates than the indicative numbers provided in Annex 4.

We assume that these pixels and points sources (having exact coordinates) would be visible and could be monitored. Once mitigation starts, sources just above the threshold would fall below our detection capacity. For lower thresholds the share of diffuse area sources is high but decreases with increasing threshold values and point sources (such as power plants and industries) dominate. Even with a threshold of 170 kton CO_2/yr/pixel, corresponding to 347 kton CO_2/yr/0.1°x0.1° using emission grid maps of EDGAR or TNO over Europe, 67% of global emissions are still covered, under the ideal conditions of no clouds, no wind and constant emission rate. Figure 13 presents the CO_2 threshold to detect CO_2_ff emissions as a function of the share of global emissions that the system should capture. Annex 4 provides in tabular format the derived thresholds; emissions share and pixel share for the three systems (see Annex 4). This is encouraging because future CO_2 mitigation policies are more likely to be driven by the high emitting point sources and intensive CO_2 areas rather than from the low emitting diffuse sources. So, while 67% of the emissions are covered, it is likely that a larger share of the mitigations will be monitored.

2. Hot spots monitoring

Estimating fossil fuel emissions by observing so-called 'hot spots' relies on three assumptions: (i) monitoring of geographically distinct large point sources such as large cities (megacities) or industrial complexes; (ii) sources emit CO_2 at an approximately constant rate, at least over the time taken for multiple satellite overpasses, so that observed atmospheric variations are not misinterpreted; and (iii) CO_2 emission rates are sufficiently large that they can be observed from space or ground-based networks on top of observed variations determined by upwind CO_2 fluxes and weather patterns. In addition, one should note that clouds may block a significant fraction of the field-of-view in many instances. At synoptic time scales, the hot-spot approach requires (almost) simultaneous observation of CO_2 concentrations within and outside the plume, so the anthropogenic component can be derived by simple differencing of the observed concentrations.

The hot-spot approach allows detection of known and unknown sources of CO_2 by satellite, which would confirm and/or improve our current knowledge of emission sources. Current state-of-the-art has already illustrated this approach, although significant temporal averaging (multi-year) is required to detect smaller emission sources (see e.g., Hakkarainen et al., 2016, for CO_2 and Schneising et al., 2014, for CH_4). Improved spatial and temporal coverage from space-borne sensors will increase the observability of these CO_2 plumes in clear-sky conditions on top of an evolving CO_2 background and provide information on the location and relative strength of these emission sources with higher temporal resolution than the multi-annual time scales.

More quantitative information can be obtained if the following conditions are met:

- An emission source with sufficient strength to produce a plume of atmospheric CO_2 that is visible above the background levels;

- An emission source that is located in an area for which the natural biosphere activity (land and ocean) is sufficiently small, or dormant[15], not to dominate the atmospheric CO_2 variability (e.g., desert, coastal, high-latitude wintertime);

- An observation network (satellite and ground-based) that has sufficient accuracy and is sufficiently dense at synoptic time scales to characterize the atmospheric CO_2 concentrations within and outside the plume given the normal level of cloudiness.

Initial studies have shown how current and potential future space-borne technology can isolate large point sources (see e.g., Kort et al., 2012, and references therein; Pillai et al., 2016), but further study is needed to fully scope and exploit the hot-spot estimation method. Observation requirements need to be further fine-tuned and an assessment needs to be made about how many megacities (and therefore which part of the global emissions) could be monitored this way. Also, because this method relies on relatively simple differencing methods, it is unlikely that absolute values for the emissions can be provided. The method is therefore more suitable for estimating changes in the emission strength over time at seasonal to annual timescales.

3. Measuring CO_2 and CH_4 from space

In addition to meeting the challenging requirements on precision and accuracy, space-based observations are limited by the orbital geometry of the satellite and the presence of clouds. Satellites deployed in Low Earth Orbits (LEO), GEostationary orbits (GEO), and Highly Elliptical orbits (HEO) offer distinct capabilities for covering the globe. In addition, instruments that retrieve CO_2 and CH_4 data from observations of reflected sunlight are limited to the sunlit hemisphere. It is therefore important to design a system that maximizes the opportunities for collecting cloud-free data even in partially-cloudy regions.

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[15] Auxiliary information on solar induced fluorescence derived from CO_2 space borne sensors would be relevant for that purpose.

Most existing and planned CO_2 and CH_4 satellites are deployed in near polar, low Earth orbits. These satellites can observe most of the globe with a single instrument. This approach reduces biases associated with observations from instruments that can observe only part of the globe. The principal disadvantage of LEO observations, in particular for CO_2 or CH_4, is that they provide only a snapshot of the distribution along the orbit track, and a specific location cannot be observed again until days or weeks later, when the satellite once again travels along that orbit track. Sun synchronous LEO orbits, like those used by GOSAT, OCO-2 and TanSat sample the Earth at a fixed time of day. This is ideal for tracking seasonal to inter-annual trends in CH_4 and CO_2, but precludes observations of the systematic changes in the emission sources of natural sinks of these gases over the diurnal cycle. Instruments in low-inclination precessing orbits, such as OCO-3, which will be deployed on the International Space Station (ISS), provide coverage of the entire diurnal cycle, but can only collect observations over a limited range of latitudes (± 51° for the ISS), and the orbit track never repeats exactly, complicating repeat observations of specific cites to track long-term trends.

A geostationary mission stationed over the Equator at a fixed longitude can acquire measurements of targets within its field of view multiple times each day. These observations therefore have a higher probability of capturing cloud-free conditions in partly cloudy regions, since clouds move. Time-resolved imaging observations of CO_2 or CH_4 from a GEO platform can also resolve the effects of transport to facilitate the discrimination of concentration variations due to local sources and sinks from those associated with synoptic scale weather phenomena. Rapid temporal sampling also reduces the risk of introducing temporal sampling biases into eventual composites. A drawback from geostationary instruments is that they cannot observe the sun-glint over ocean, which limits their measurement of CO_2 over ocean. At the time of writing, no geostationary mission has been launched, whilst the GeoCarb mission has now been selected as a NASA Earth Venture mission (Polonski et al., 2014; O'Brien, 2016).

Geostationary satellites cover low to mid-latitudes, but have significantly reduced performance above mid-latitudes and none at high latitudes. Selecting a Highly Elliptical Orbit (HEO) with an apogee over the Polar regions enables quasi-geostationary observations of high latitudes with similar advantages as viewing the Earth from geostationary orbit. At the time of writing, no HEO mission has been selected, but Canada has been investigating mission concepts for HEO for many years (Nassar et al., 2014).
In the longer term, an optimized constellation could be envisaged that includes a combination of observations from satellites in LEO, GEO and HEO orbits, using a variety of different contribution mechanisms, e.g., dedicated space segments, contributing missions, third party data provider agreements and more. The architecture of the monitoring and verification support capacity should include the flexibility to exploit this range of potential sources of satellite observations.

In the short to medium term, the focus will be on sensing from low-Earth orbit satellites, likely flying in constellation, with such satellites having the benefit of global, uniform observations, thereby improving the overall spatial coverage and reducing the revisit times.

To date, the main technologies for observing column CO_2 are based on observations in the visible, near-infrared or infrared spectral bands. At present, several space agencies are flying hyperspectral infrared instruments such as IASI by EUMETSAT, AIRS and CrIs by NASA and NOAA and GIIRS by CMA. Whilst the latter is an instrument in geostationary orbit, CMA will also be launching HIRAS in a polar-orbit in late 2017. The polar orbiting hyperspectral instruments have large swath-widths and provide good daily coverage. However, the spatial resolution is low (generally over 10 km) leading to some issues for instance due to cloud contamination. As CO_2 sources and sinks are highly variable at fine scales, and observations are made over a high background level (around 400 ppm) the precision required is of the order of 0.5% (1-2 ppm) or better (0.2-0.3%). Whilst the precision of the observations provided by these instruments approaches 1 to 2 ppm with suitable spatial and temporal accumulation (from weekly to monthly averages), they are predominantly sensitive to the middle tropospheric CO_2 and have very limited sensitivity near the surface. Therefore, they are generally not suitable for observing near-surface contributions and fluxes, but are able to contribute to an overall characterization of CO_2 and CH_4. It should also be noted that these instruments are part of baseline committed satellite programmes, ensuring continued observations until 2040 and beyond.

GOSAT, OCO-2 and Tansat observe reflected sunlight in the near-infrared and short-wave infrared bands and provide the promise of improved observations, in terms of precision, accuracy, resolution and coverage. The principal limitation of the first-generation solar-IR systems is that they sample only a small fraction of the Earth's surface with their individual soundings (GOSAT) and narrow swaths (OCO-2, TanSat). Further polar orbiting missions are under preparation like Sentinel 5 and 5P, GOSAT-2, OCO-3, Gaofen-5 and MicroCarb. GOSAT, launched in 2009, can detect strong sources with a precision of about 2 ppm, while the GOSAT-2 is targeting a precision of 0.5 ppm. OCO-2, optimized for high sensitivity and resolution routinely returns soundings with 0.5 ppm precision at solar zenith angles as high as 70 degrees and can reach the 1 ppm accuracy. For these satellites, long-term continuity is not guaranteed.

4. Satellite observations of CO and NO_2

In addition to CO_2 and CH_4 observations, the current fleet of satellites can also provide observations of CO and NO_2 (for source attribution purposes). As well as the previously described instrument capabilities, that in some cases can be extended to CO and NO_2, there are other instruments available that provide column averaged observations of CO and NO_2, like MOPITT (CO) and GOME-2 (NO_2). The capabilities of these instruments will in some cases be continued into the next generation of satellites. Recent results that combine OCO-2 data with NO_2 data from OMI (Hakkarainen et al., 2016) and CO (Heymann et al., 2017) clearly show the value of combining CO, NO_2 and CO_2 measurements for tracking and attributing CO_2 emissions.

2.2.3.2 In situ Observations & Networks

The Global Atmosphere Watch (GAW) program of the World Meteorological Organization (WMO) oversees systematic and reliable observations of the global atmospheric environment. Ground-based measurement systems for GHGs such as the various surface flask networks, the tall tower network and the TCCON network are of particular importance. The ground based networks often operate under continental scale monitoring programmes such as, for instance, the Integrated Carbon Observation System (ICOS) in Europe.

The Total Carbon Column Observing Network (TCCON; https://tccon-wiki.caltech.edu/ and www.tccon.caltech.edu) is a ground-based network of high resolution Fourier Transform Spectrometers (FTSs) that records the near infrared solar absorption spectrum and retrieves column-average mixing ratios of CO_2, CH_4, N_2O and several other gases with high precision and accuracy. TCCON data are a valuable complement to in situ surface data. The column measurements serve to validate satellite measurements from the current satellites GOSAT and OCO-2 and provide a link between the satellite observations and the surface flasks.

Figure 14. *Location of stations contributing to the Total Carbon Column Observing Network (TCCON) network.*

The WMO GAW data are collected and distributed by the World Data Centre for Greenhouse Gases (WDCGG) located at the Japan Meteorological Agency. All data that are acquired and distributed by WMO-GAW is subject to QA/QC that includes full support of the GCOS climate monitoring principles; network-wide use of only one reference standard or scale (primary standard) and full traceability to the primary standard of all measurements made by global, regional and contributing GAW stations. The delay between acquisition and distribution is about 1 to 2 years. A small subset of GAW stations, most notably the ICOS stations, also provide NRT data that has undergone automated quality checks only. This data acquisition process is already being improved as part of the Copernicus Atmosphere Monitoring Service. ICOS provides all data as open linked data under a license with minimal delays.

For the oceans, repeat hydrography is the only global method capable of observing long-term trends in ocean carbon. These take place in an internationally agreed manner with GLODAP (www.cdiac.ornl.gov/oceans/glodap/) and SOCAT (www.socat.info/) under fair data use conditions.

Several other relevant integrated data products from the GLOBALVIEW (www.esrl.noaa.gov/gmd/ccgg/globalview/) and FLUXNET (http://fluxnet.fluxdata.org/) and FAO Global Forest Resources Assessments (www.fao.org/forestry/) are made publicly available.

Next to these networks, individual observations take place, often in campaign mode around cities or power plants. The data are generally, sometimes with restriction, available through the institutions. WMO is currently promoting the IG3IS system for this kind of very relevant GHG data (see http://www.wmo.int/pages/prog/arep/gaw/ghg/IG3IS-info.html).

According to current knowledge, measuring $^{14}CO_2$ (radiocarbon) which is a quasi-direct tracer of CO_2 emissions represents the most promising solution to address the attribution problem (Levin et al., 2003; Turnbull et al., 2006). Rayner et al. (2010) have shown in a synthetic observation system simulation experiment that adding $^{14}CO_2$ measurements provide a considerable regional constraint of the order of a further 70% reduction in the uncertainty. The potential to estimate national fossil fuel emissions of the US using $^{14}CO_2$ measurements has been suggested by Pacala et al. (2010). The uncertainty reduction, from an inversion based on $^{14}CO_2$ measurements, in the US fossil fuel emissions, could indeed be quite significant even with a somewhat limited network of measurement locations (Ray et al., 2014). With current sampling of $^{14}CO_2$ measurements available in 2010 over North America (969 measurements per year) the annual (monthly) mean of these emissions can be constrained up to a precision of about 1% (5%) according to Basu et al. (2016). It is noteworthy that the performance of these inversions are depending on the mismatch between the actual dimension of the emitting fossil fuel sources and the grid size of transport models used in global, i.e., 100 to 500 km, as well as regional, i.e., 50 to a few kms, inversions. This issue needs to be formally addressed in such inversion studies and it calls for enhancing the spatial resolution of the transport models.

$^{14}CO_2$ measurements can only be performed in situ by collecting flask air samples to be analyzed in the laboratory with accelerator mass spectrometer for instance. Such measurements are thus rather costly and the development of low-cost measurement techniques has to be promoted. The ICOS infrastructure has recently developed a somewhat dense network of continuous high precision atmospheric measurements of atmospheric CO_2 in Europe including ^{14}C measurements for some of these sites. The ICOS atmospheric network aims at sampling 2-week integrated ^{14}C at about 40 stations, representing 1,000 analyses per year, which corresponds to the typical capacity of an accelerator mass spectrometer.

Studies for an optimal design of $^{14}CO_2$ network needs to be conducted, notably in Europe, to consolidate the promising findings from the US-related investigations. A preliminary study to quantify fossil fuel CO_2 emissions at the scale of a mid-size European country was performed by Wang et al. (2017b) involving coarse resolution transport models and relying on continental scale network such as the ICOS. This study has assessed the ‘uncertainty reduction’ estimated from a Bayesian inversion (i.e. the reduction of the prior uncertainty on emissions by adding observations) and the performance of the inversion scheme to retrieve a 'true' emission field. The latter was done by generating a 'true' CO_2 field based on an emission inventory (taken from EDGAR with hourly profiles from Thiruchittampalam, 2012), and running the inversion with a 'false' prior emission field given by a different inventory (taken from Pekin University (PKU) CO_2 inventory with no temporal profiles). The performance of the inversion is assessed by the uncertainty reduction in the retrieved fossil emissions as well as the misfit reduction between the 'true' and the retrieved emission values over a given region (see Figure 15). The annual averaged uncertainty reduction and misfit reduction using a network of 17 stations measuring CO_2 continuously and ^{14}C in flask air samples reaches 50% as compared to the prior emission uncertainty. As expected, better performance can be obtained with a denser network of stations especially with an increase of the sampling frequency, i.e., daily instead of bi-weekly. Thus, despite the coarse model grid selected in this study, this inversion provides a reasonable estimate of the potential offered by ^{14}C measurements to constrain the annual emissions at regional scales such as those delineated by the solid lines in Figure 15.

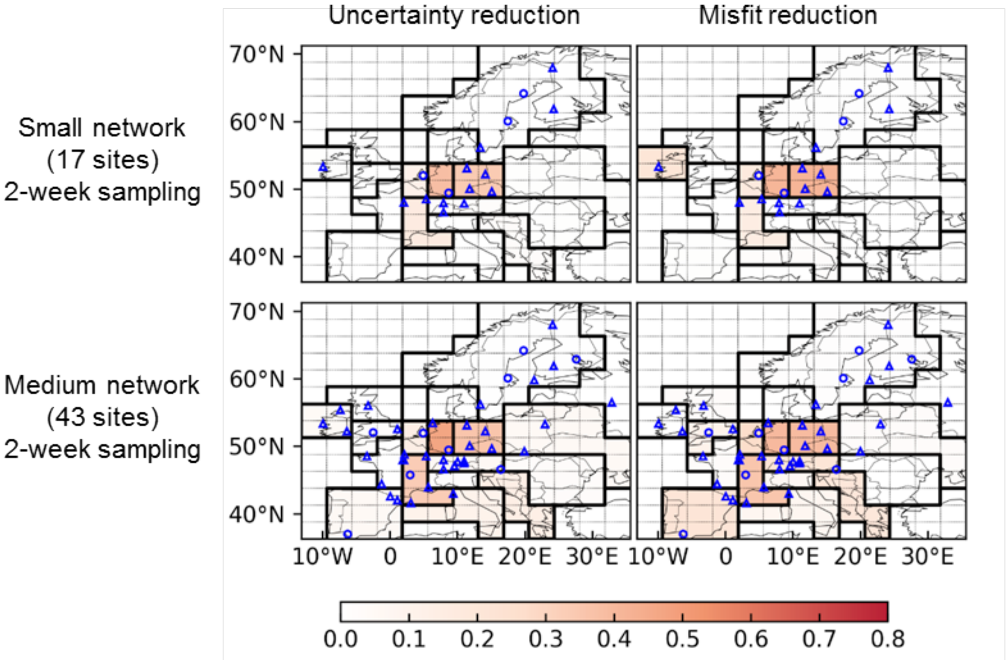

Figure 15. *Performances of ^{14}C and CO_2 networks given a coarse resolution inversion framework Top: Average annual uncertainty reduction (left) and misfit reduction (right) using a network of 17 stations measuring CO_2 continuously and ^{14}C in flask air samples. Bottom: Same for a larger network of 43 stations. In both cases, it is assumed that flask air samples collect air to provide 2-weeks averaged ^{14}C data for mid-afternoon periods. The left-hand column of plots shows the theoretical uncertainty reduction on emissions from the Bayesian inversion and the right-hand one the misfit reduction, both as a fraction of the prior emission uncertainty. Dots (triangles) correspond to 'urban' ('rural') stations. The coarse grid of the transport model used in this study is shown in gray thin lines. Despite the coarse model grid, this inversion accounts for aggregation and representation errors and thus provides a fair estimate of the ability of ^{14}C measurements to constrain the annual emissions from the regions delineated by the black lines. Adapted from Wang et al., 2017b.*

More generally, in the context of the system proposed here, the combination of local in situ measurements and global satellite measurements to determine anthropogenic emissions poses the question as to the optimal design for ground networks and satellite observations. This is, however, a system level design issue that needs to be addressed as part of the simulations of the overall system performance using a variety of different assumptions and take the complementarity of available data streams into account. In other words, it makes no sense, to optimize networks for an isolated subset of observations (see e.g., Kaminski and Rayner, 2017; Nickless et al., 2015).

Quantitative network design studies have been carried out, such as those described in Kaminski et al. (2012) require setting a target quantity, e.g., the overall net exchange of an area, the exchange per land use type, or any other domain area, and evaluate the posterior uncertainty using an atmospheric transport model and a priori estimates of the fluxes for several candidate networks. Most of these studies have been done so far on either biospheric fluxes, using only in situ networks, or biospheric fluxes using satellites or a combination of both. Very few studies have been done at regional/country scale and virtually none on anthropogenic and biospheric fluxes together. An issue that appears here quite strongly is that most in situ observation sites were not chosen for their proximity to anthropogenic emission sources, in fact rather the opposite; they tend to be located in more areas remote from large surface fluxes to monitor the large-scale CO_2 concentration. This may imply that the current network design of, for instance, ICOS may need to be rethought if the focus is moving to precise estimation of anthropogenic sources, rather than biospheric sinks. Quantitative network design studies using integrated modelling systems simultaneously assessing all relevant land and atmosphere (and possibly ocean) observations may be needed to achieve a more accurate picture of the best design of a combined satellite and ground-based observation system for detection of anthropogenic emissions.

2.2.3.3 Meteorology

Observation requirements for constraining meteorology and atmospheric transport for the purpose of monitoring global emissions are essentially the same as those for global NWP. Operational NWP systems require a continuous feed of in situ and space-based observations to be able to generate and disseminate forecasts in a timely manner. For example, the ECMWF forecast system uses approximately 108 observations per day for this purpose. A large proportion of these originate from instruments on polar orbiting and geostationary satellites, but many are in situ weather observations taken at surface stations, ships, aircraft, radiosondes and other conventional platforms. See https://www.ecmwf.int/en/forecasts/quality-our-forecasts/monitoring-observing-system for a breakdown by data type, instrument and variable.

WMO is responsible for coordinating the operation and evolution of the global meteorological observing system, including the communication networks that are needed for rapid delivery of the observations to the NWP centres. Through a Rolling Review of Requirements (RRR) by experts in the field WMO has produced an Implementation Plan for the Evolution of Global Observing Systems (EGOS-IP 2013) for the period 2012-2025. A comprehensive overview of the current status of the global observing system for weather and climate is provided by the recently published Global Climate Observing System (GCOS) Status Report (GCOS 2015). It should also be noted that in the WMO Integrated Global Observing System Vision 2040, which is under preparation and available for review, the need for improved space observations for carbon monitoring is called for.

2.2.3.4 Auxiliary Data

In addition to satellite observations of atmospheric CO_2, as anticipated in the context of the present report, various other observations can be used to constrain anthropogenic CO_2 emissions. These observations can roughly be divided into observations that provide information on fossil fuel emission proxies, on atmospheric species other than CO_2 that are affected by anthropogenic emission sources, on variables that control the contribution of the land carbon cycle to atmospheric CO_2 concentrations, and on variables that control the contribution of the ocean carbon cycle to atmospheric CO_2 concentrations. Many of these observations are already being explored within their own scientific domain, such as in Fossil Fuel data Assimilation Systems (FFDAS) and Carbon Cycle Data Assimilation Systems (CCDAS) (see section Annex 2.3). A non-exhaustive overview is displayed in Figure 9, which lists the various types of observations on the left hand side.

Typical examples are night lights observations from various satellite sensors that provide information on human activities and which can be used as a proxy for anthropogenic emissions. For the terrestrial biosphere domain, one can think of observations of biomass or Solar Induced fluorescence (SIF) to provide information on the activity of the land biosphere. For the oceanic domain, ocean color observations are available to provide information on phytoplankton activity. Most of these observations provide indirect, though crucial information, on anthropogenic CO_2 emissions and they should be used where meaningful. More detailed information on the use of these auxiliary observations is available in Annex 2 of this report.

2.2.4 Prior Information

The role of prior information in the MVS cannot be underestimated. A complex inverse modelling system, as currently envisaged, is under-constrained, which means that observations cannot pin down all uncertainty elements, i.e., the control vector, of the system. Observational networks can simply not provide information on all relevant variables all the time and at all geographic locations. It is therefore unavoidable to bring model and prior information together into the estimation system. Models aim to fit the observations through the use of well-determined physical equations and therefore provide a physically-based interpolation and extrapolation system to relate the anthropogenic emissions to the observed quantities. However, not all processes can be expressed using a full set of physical equations and approximations have to be introduced. Prior information covers all the knowledge, other than the processes explicitly represented and the various observations that can be brought into the estimation system as well. Examples of prior information are for instance emission estimates from a previous year, climatological data sets of natural fluxes of CO_2 for land and ocean, country-based economic statistics and more. In an ideal inversion system, satellite observations would be assimilated as radiances, which is what the satellite instruments do measure.

However, practical constraints might require running satellite retrieval algorithms outside the inversion system, as is currently often done for the assimilation of satellite observations in the ultraviolet, visible and near infra-red part of the solar spectrum. For this latter approach it is however crucial that the priors are as consistent as possible between the various inversion algorithms to avoid introducing additional error sources (Chevallier et al., 2015). In the end, the main purpose of the prior information is to reduce the number of possible solutions to the inverse problem by indicating initial estimates of the relevant parameters including an uncertainty range. This means that great care has to be taken in defining the prior information and especially its uncertainty.

2.2.5 Data Access, Archiving and Distribution

In addition to the core functions depicted in Figure 9, data access, archiving and distribution functions will need to form part of the system. The approach for the design and implementation of these functions should take into account that data, infrastructure and knowledge are, and will remain, distributed geographically across Europe and international partners in several centres, and will rely on existing infrastructures. A key requirement is to enable services to be provided without this underlying geographical distribution being noticeable, or affecting the user's perception of the service.

It should be noted that the types and volumes of data, as well as the timeliness requirements, will vary significantly and are also dependent on the downstream functions. The associated distribution mechanisms will therefore be driven by the data types and may have different service levels. It can be anticipated that the high-volume satellite data will be redistributed in a near-real time fashion, albeit not with the most stringent timeliness requirements. This will ensure a continuous data-flow, avoiding the potential bottlenecks of off-line distribution. Typically these types of system involve either satellite or ground-based multicast methodologies. In situ/ground-based observations may come with similar timeliness requirements to satellite data. However, due to the lower data volumes, terrestrial networks like the WMO Global Telecommunication System may be employed. In addition internet/web-based approach may provide sufficient capability and reliability.

For the various data sets required for the overall system, data holdings are already in place, therefore, instead of centralized archiving, a distributed system allowing efficient access to geographically distributed data and products, e.g., in a cloud with interoperable archives, specifically with other existing Copernicus elements, could be foreseen. Interoperability with existing Copernicus elements is also critical. This would also ensure accessibility of the data by all contributors to the system. A critical part of the system will be a Data and Information Management function that will coordinate the interfaces and data circulation across all parties, and manage additional services like web-access to the data.

Way Forward

This document provides the first step in the development of a framework for an anthropogenic CO_2 emission monitoring and verification support capacity which takes advantage of space-based observations as an integral part of a system including the required modelling components, in situ elements and the existing emission inventories. In recognition of the need to obtain a complete system overview and the implementation of a holistic approach at an early stage, as a strong foundation for further development and as a template for resource and programmatic planning, an initial representation of the functional architecture has been provided in Figure 9, with the understanding that this architecture will be updated and refined as additional information emerges from future activities of this CO_2 monitoring Task Force.

The system proposed is intentionally modular and flexible to accommodate future iterations as the state-of-the art progresses in the forthcoming years. Furthermore, as the system depicted in Figure 9 is functional in nature, it is agnostic with respect to individual existing European competences and potential infrastructure and programmatic contributions. However, when considering a way forward, we should consider leveraging the capabilities of current assimilation systems while assessing, in parallel, their fitness for this purpose.

The present report represents the outcome of the first phase of the Task Force's (sub-task B) deliberations. It has followed the original terms of reference which foresee an initial two phase period of 20 months total: with a first phase (the current one) lasting 8 months and a second for a further 12 months. The next phase of work will continue to develop the activities based on the original terms of reference and will additionally build on the outcomes of the first phase, and gaps in knowledge identified in that process, in order to prioritize additional activities to be undertaken.

Specifically, items to be addressed in the near future include:

1. A recurrent issue raised in the deliberations of the Task Force in the initial phase has been the need for substantial dedicated experiments on observation system simulations and quantitative network design analyses. There are a number of planned efforts both within the context EU R&D funded projects as well as in efforts by individual European institutions. The Task Force should review and synthesize the outcomes of these experiments, and ensure that the current system definition is fit-for-purpose;

2. In this report the baseline requirement analysis undertaken has purposefully focused on the overall system output, in response to the policy needs. In the next phase, and taking advantage of the outcomes of the analysis in '1' above, a dedicated requirements apportionment activity will need to be undertaken to place the requirements on individual system components and their propagation through the system. This requirement apportionment process will be guided by the outcomes of the system simulations, and will support the further elucidation of the resourcing needs of individual system components;

3. With the analyses conducted in '1' and '2' and the work undertaken in the present report, the Task Force should be thus in a position to make a detailed assessment of outstanding and critical issues in the system design and to formulate a plan and monitoring process to ensure that the actions are addressed. This assessment should also include the identification of any further needs for targeted R&D on specific system components;

4. In the present report the system specification is only defined to the level of the output of the integration component, i.e., concentration and fluxes of CO_2 /GHGs. It is foreseen that in an operational realisation of this system there should also be a decision support element which is available to policy makers and other users of the system. In the next phase a further stakeholder consultation should be undertaken to better define the needs and requirements of this additional component and its implications for, and integration in, the overall system architecture. One additional activity in support of this, which would also have potential outreach benefits, would be the development of a compendium of case studies demonstrating the value of the system approach and benefits that users can expect from the complete value chain (this could also be used to provide an indirect verification of the MVS architecture);

5. As a critical step, based on the initial rendition of the functional architecture included in the present report, potential physical realisations of the functional architecture should be identified. This would include conducting a survey of existing capabilities, assessing institutional needs for additional developments, and identifying re-use opportunities of existing components;

6. In complement to '5' initial efforts should be made to look at governance options for the delegation of the system development and operations and to assess the programmatic setting and inter-institutional agreements required to underpin these options;

7. Based on the outcomes of the assessments in '5' and '6' and taking advantage of the developments arising from ongoing and planned R&D projects (e.g., in H2020-Space) a prototype implementation of the overall system should be put in place. This prototype should take advantage of relevant third party and existing Sentinel space segment elements, where appropriate, and will provide a testbed for real-life trials of the robustness of the in-situ, inventory and model components and their integration. Programmatic considerations accounting or the necessary resourcing of this prototype system should be foreseen;

8. As a consequence of the work undertaken in the first phase of the Task Force, and benefiting from the work on items '1' and '2' above, a dedicated activity should be undertaken to further address the in situ component and it's requirements for additional infrastructure, technology development, network development and collaboration agreements. This should include a further assessment of relevant European competences and infrastructures, as well as identification the necessary international partnerships to be developed;

9. Complimentary to this, and also identified in the Task Force discussions in the initial phase, is the need for a bespoke calibration and validation strategy. This strategy should be developed in a context that it is not mission-specific but addresses the needs for calibration and validation of the overall system, understanding that such an approach would also have programmatic implications, like the development and deployment of independent calibration-validation sites, to be considered. As in '7' there is also an obvious need to develop such a strategy in collaboration with international partners (e.g., for the space component through the Committee on Earth Observation Satellites (CEOS) and the Coordination Group for Meteorological Satellites (CGMS), for in situ with the WMO and other entities coordinating ground-based observation networks);

10. In addition as the ground-based network is fairly heterogeneous in terms of data policy, access, availability, and data circulation and archiving the need to have routine sustained access and exchange to these data sets has to be considered and coordinated;

11. And whilst an integrated coupled data assimilation system is at the core of the MVS, there is also a need to develop additional products for additional analyses, process studies and validation as well as for down-stream services.

The above additional activities will provide a means of progressing and building on the initial work undertaken in the context of the current report.
Finally, from an organizational and external engagement perspective of the Task Force's work, the following considerations are made:

- For those items which have implications for the development of the space component of the system, the interactions with the sub-task A, led by ESA and the Commission, should continue and be reinforced, particularly where these have implications for the mission definition and requirements;

- The broad range of tasks described above may require additional competences on the Task Force (including from non-EU experts) the Commission should ensure that membership is updated to address these needs where appropriate;

- There are a number of ongoing international initiatives and efforts (e.g., within CEOS/CGMS, WMO and other UN bodies and programmes). The European Commission and its institutional partners should remain fully engaged, and take a leading role where and when appropriate, in these efforts both in consolidating the necessary partnerships in view of the envisaged operational system as well to take advantage of identified common best practices in the implementation of the European system, to ensure interoperability and consistency.

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List of Abbreviations and Definitions

A

adjoint model	a powerful tool for many studies that require an estimate of sensitivity of model output (e.g., a forecast) with respect to input
anthropogenic	used here to designate fossil fuel CO_2 emissions
AIRS	Atmospheric Infrared Sounder from NASA - in operation (https://airs.jpl.nasa.gov/)
AQMEII	a US-EU project on air quality model inter-comparisons (Air Quality Modelling Evaluation International Initiative)
AR6	Sixth Assessment Report of IPCC

B

bottom-up	used for emission inventories obtained by aggregating statistical data from relevant economic sectors at a given terrestrial scale relevant for mitigation policy
BAU	Business As Usual scenario of CIRCE

C

CAMS	Copernicus Atmospheric Monitoring Service
CARBONES	FP7 project to deliver high resolution history of the carbon cycle
Carbon DA	Carbon Data Assimilation

CC	Climate Change scenario of CIRCE
CCDAS	Carbon Cycle Data Assimilation System
CH_4	Methane
CIRCE	FP6 project on Climate Change and Impact Research
CEOS	Committee on Earth Observation Satellites
CFC	Chlorofluorocarbons, artificially produced greenhouse gases
CGMS	Coordination Group for Meteorological Satellites
COPxx	UNFCCC Conference of Parties Session No. xx
CO	Carbon monoxide, an air pollutant and a tracer when incomplete combustion occurs
CO_2	Carbon dioxide
CO_2_bf	CO_2 produced from biofuel combustion
CO_2_ff	fossil carbon dioxide, including fossil fuel combustion emissions and process emissions from cement, lime, ammonia, urea, steel, but excluding emissions from biofuel and from land-use, land-use change and forestry activities
CrIs	Cross track Infrared Sounder from NASA/NOAA – scheduled for launch on JPSS-1 in 2017 – (https://jointmission.gsfc.nasa.gov/cris.html)
C3S	Copernicus Climate Change Service

^{14}C	Radiocarbon, a radioactive carbon isotope with 6 protons and 8 neutrons
$\delta^{13}C$	gives the abundance of a carbon isotope in ^{13}C (with 6 protons and 7 neutrons) over ^{12}C (with 6 protons and 6 neutrons) and is an isotopic signature for instance in case of organic burial

D

Data assimilation	a process by which observations of the actual system are incorporated into the model state of a numerical model of that system
DG CLIMA	Directorate General Climate Action of the European Commission

E

EC	European Commission
ECCO	Estimation of the Circulation and Climate of the Ocean (http://www.ecco-group.org/)
ECMWF	European Centre for Medium-Range Weather Forecasts
EDGAR	Emission Database for Global Atmospheric Research
EPRTR	European Pollutant Release and Transfer Register
ESA	European Space Agency
ETS/EU-ETS	European Union Emissions Trading System
EU	European Union

EU/EU 28	European Union with 28 Member States
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites
Eurostat	Statistical Office of the European Union
ERC	European Research Council

F

FAO	Food and Agriculture Organisation of the United Nations
FFDAS	Fossil Fuel Data Assimilation System
FLUXNET	a network of regional networks to coordinate regional and global analysis of observations from micrometeorological tower sites. (http://fluxnet.fluxdata.org/)
FP6	6th framework programme of the European Union for funding research
FP7	7th framework programme of the European Union for funding research
FTS	Fourier Transform Spectrometer
FVM	finite volume method (in computational fluid dynamics)

G

GeoCarb	Geostationary satellite from USA – planned - (https://www.nasa.gov/press-release/nasa-announces-first-geostationary-vegetation-atmospheric-carbon-mission)

Gaofen-5	Satellite from China - planned – (https://chinaspacereport.com/spacecraft/gaofen/)
GAW	Global Atmosphere Watch of the World Meteorological Organization
GCP	Global Carbon Project
GHG	Greenhouse gas
GIIRS	Interferometric Infrared Sounder from CMA – in operation- (http://www.nsmc.org.cn/NSMC/Channels/FY4A_GIIRS_en.html)
GLOBALVIEW	data products to enhance the spatial and temporal distribution of atmospheric observations of CO_2, CH_4 and other related atmospheric measurements (from NOAA ESRL) (www.esrl.noaa.gov/gmd/ccgg/globalview/)
GLODAP	a cooperative effort to coordinate global synthesis projects (from NOAA, DOE, NSF as part of the Joint Global Ocean Flux Study - Synthesis and Modelling Project). (http://cdiac.ornl.gov/oceans/glodap/)
GOME	Satellite from EUMETSAT and ESA - in operation
GOSAT	greenhouse Gas Observing SATellite from Japan (JAXA) - in operation
Gridcell	Emissions input in atmospheric models needs to be spatially distributed over a grid, for which mostly the entire globe is covered by a Cartesian system with a resolution of, for instance, 0.1°x0.1°. The TNO-CAMS input is gridded (spatially distribution) with a higher resolution of 0.125°x0.0625°

H

HIRAS	Hyperspectral Infrared Atmospheric Sounder from China (CMA) –planned – (https://directory.eoportal.org/web/eoportal/satellite-missions/f/fy-3)

I

IASI	Interféromètre Atmosphérique de Sondage Infrarouge from France (CNES) and EUMETSAT - in operation - (https://www.eumetsat.int/website/home/Satellites/CurrentSatellites/Metop/MetopDesign/IASI/index.html)
ICOS	Integrated Carbon Observation System of the EU
IEA	International Energy Agency
IED	EU's Industrial Emissions Directive
IPCC	Intergovernmental Panel on Climate Change

J

JRC	Joint Research Centre, Directorate General of the European Commission

K

kton	Kilotonnes (=1 Gigagramme = 907 metric tonnes)

L

LSCP	Large Scale Combustion Plants
LULUCF	Land Use, Land-Use Change and Forestry

M

MicroCarb	Micro satellite from France (CNES) – planned – (https://microcarb.cnes.fr/)
MOPITT	Satellite from USA (NASA) - in operation- (https://terra.nasa.gov/about/terra-instruments/mopitt)
Mton	Megatonnes (1 million metric tonnes = 106 metric tonnes)
MRV	Measuring-Reporting-Verifying framework of the UNFCCC
MVS	Monitoring and Verification Support capacity of the Copernicus programme

N

NDC	Nationally Determined Contribution (national emission mitigation action plan under the Paris Agreement)
NASA	National Aeronautics and Space Administration of the USA
NOAA	U.S. National Oceanic and Atmospheric Administration NOAA/ NCDC U.S. National Oceanic and Atmospheric Administration/ National Climatic Data Centre
N_2O	Nitrous Oxide, a greenhouse gas
NOx	Nitrogen oxides, the sum of nitric oxide (NO, reactive product oxidizing quickly to NO_2) and nitrogen dioxide (NO_2), acidifying and eutrophying air pollutants
NRT	Near-Real Time
NWP	Numerical Weather Predictions

O

OCO-2	Orbiting Carbon Observatory from USA (NASA) - in operation
OSSE	Observing System Simulation Experiments
O_2/N_2	Oxygen/Nitrogen ratio
$\delta^{18}O$	Gives the abundance of an oxygen isotope in ^{18}C (with 8 protons and 10 neutrons) over ^{16}C (with 8 protons and 8 neutrons) and is an isotopic signature for instance in case of methanogenesis

P

PantaRhei	FP7/2012/ERC project to develop an interdisciplinary forecasting system for simulating multi-scale fluid flows
PKU	Pekin University
POLES	EC's world energy-economy partial equilibrium model: Prospective Outlook on Long-term Energy Systems

Q

QA/QC	Quality assessment/Quality control

S

Semi-Lagrangian	A Lagrangian description of a system (such as the atmosphere) focuses on following individual air parcels along their trajectories as opposed to the Eulerian description, which

	considers the range of change of system variables fixed at a particular point in space. A semi-Lagrangian scheme uses Eulerian framework but the discrete equations come from the Lagrangian perspective
SF_6	Sulfurhexafluoride, an artificially produced greenhouse gas
SOCAT	A collection of surface ocean CO_2 quality controlled observations (from IOCCP). (http://www.socat.info/)

T

top-down	refers to the approach to determine sources and sinks of greenhouse gases from observations of the atmospheric concentration variations of these gases
TanSAT	Mini satellite for CO_2 detection and monitoring from China (MOST) - in operation - (https://directory.eoportal.org/web/eoportal/satellite-missions/t/tansat)
TCCON	Total Carbon Column Observing Network
TNO	The Netherlands Organisation for applied scientific research
TNO-MACC	gridded emissions inventory for Europe established by TNO under the Monitoring Atmospheric Composition and Climate FP7 project
TNO-CAMS	The gridded emissions inventory for Europe established by TNO for Copernicus Atmospheric Monitoring Service
TROPOMI	Satellite instrument on board of the Copernicus Sentinel-5 Precursor satellite

U

UN	United Nations

UNFCCC	United Nations Framework Convention on Climate Change
UNEP	United Nations Environment Programme
UNPD	United Nations Population Division

W

WMO	World Meteorological Organization
XCO_2	column-weighted CO_2 mixing ratio estimated from satellite

Annexes

Annex 1 Input from National Inventory Agencies

A questionnaire was sent to a dozen national inventory agencies, which engaged to contribute to the H2020 research project proposal "Observation-based system for monitoring and verification of greenhouse gases". Six[16] national inventories replied to the questionnaire, representing the following EU countries: France, Ireland, Germany, Italy, The Netherlands and Norway (which in total represent about 47% of the total EU 28 + EFTA countries' emissions or about 1.7Gton CO_2 in 2015). The output was also discussed in a stakeholders meeting of 6 December 2016 in Paris, organized by LSCE. Table A.1 below gives an overview on their operation, collaboration and areas where support is needed.

Box 3: Questionnaire to the national inventory agencies

A- Establishing a greenhouse gas inventory is work-intensive, time-consuming and requires resources

a. What percentage of this work is outsourced? How does your country guarantee continuity of knowledge?

b. How frequent was the review by the UNFCCC roster experts leading to changes in the inventory?

c. How much is the update of the inventory (for an additional year) automated? Does your country have tools for automatic input of updated activity data? How many years backward in time are in average annually updated?

d. How many times were the time series updated completely? Was the justification directly accepted by the UNFCCC?

e. How does your country find the right balance between the level of detail (tier1/2) and what is feasible with the available resources? What type of support would be helpful for improving certain sectors?

B- What Quality Assurance/ Quality Control procedures are in place in your country for checking the GHG inventory

a. How are the uncertainties for the GHG emission evaluated?

b. Does your country face difficulties to get good quality data for some sectors or some compounds?

c. Is your country following the IPCC guidelines (2006)? Are these providing sufficient information for estimating uncertainties on the inventory and on the emissions trend?

C- EU28 is not only Party of UNFCCC but also of the UNCLRTAP. For the latter air pollutant inventories need to be compiled. Is there a link/communication between the GHG inventory compilation and the Air Pollutant one?

a. Are these inventories prepared by different entities in your country? Are these inventories prepared by different entities in your country?

b. CH_4 is a common compound? Is there one CH_4 inventory put forward by the country?

c. Is there an interest to compare ratios of air pollutant to greenhouse gas compound? (e.g., NO_2/CO_2)?

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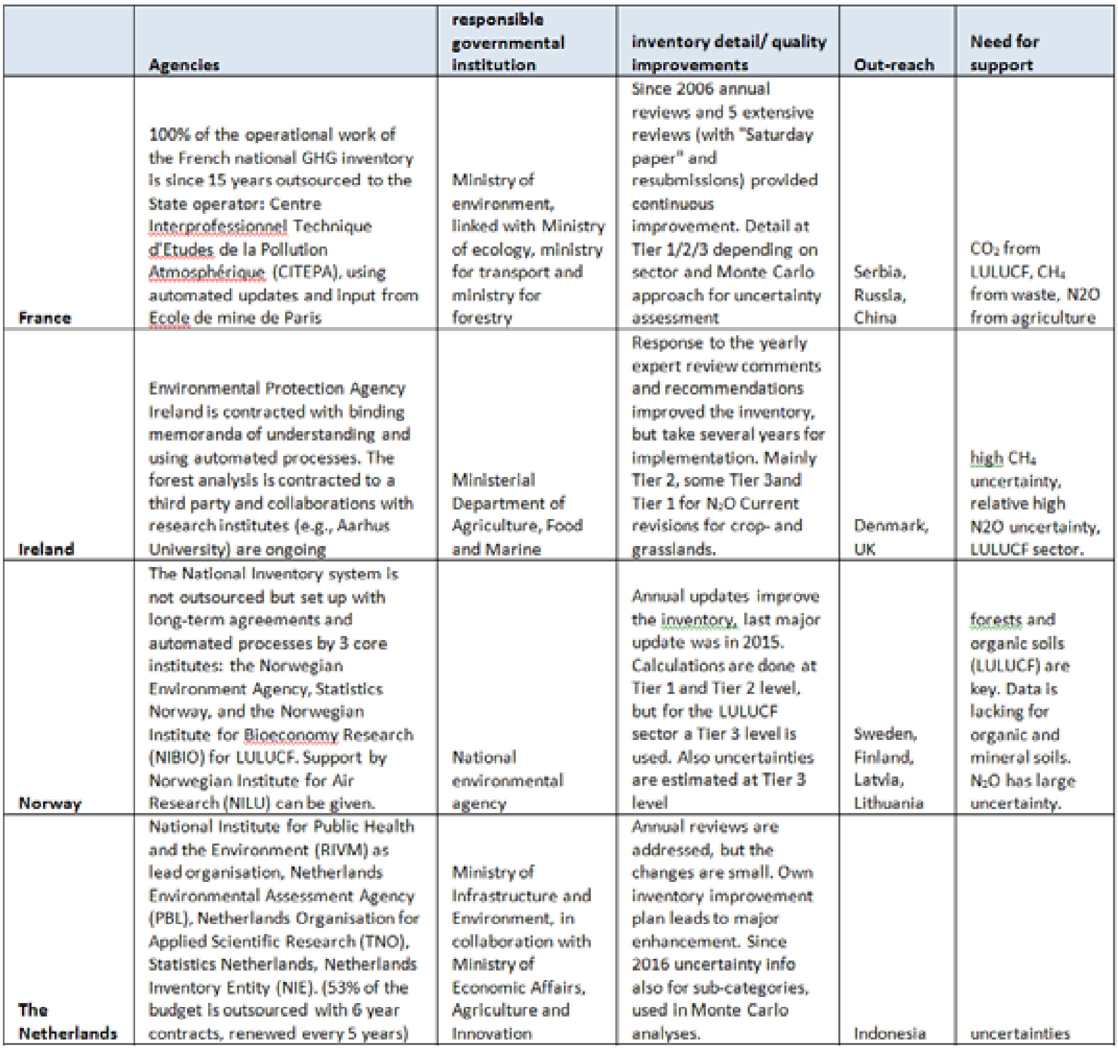
[16] UK presented the response at the Stakeholders meeting held in Paris on December 6, 2016.

D- Some years ago the EMEP board required to provide emission grid maps at 0.1degx0.1deg resolution to CEIP (for the CLRTAP)
a. Does your country face difficulties in doing so?
b. Would your country be able to provide gridded greenhouse gas emissions data and if so, at what resolution?
c. Does your country have a set of country-specific proxy data?

E- Does your country link the GHG inventory update with the monitoring of point sources?
a. Is the information collected for the Large Scale Combustion Plant directive also flowing into the GHG inventory?
b. Is your country revising the European Pollutant Release Transfer Register? Is the information of the EPRTR database also used for the GHGs inventory?

F- The LULUCF sector is particularly complex and challenging
a. Which are the main challenges encountered in estimating LULUCF fluxes?
b. Is there any verification activity ongoing on LULUCF, a (full or partial) comparison of GHG inventory with independent estimates to increase scientific understanding and to gain confidence in the trend of the reported GHG data?

Table A.1 - Overview of the response of the National Inventory Agencies to the questionnaire



	Agencies	responsible governmental institution	inventory detail/ quality improvements	Out-reach	Need for support
France	100% of the operational work of the French national GHG inventory is since 15 years outsourced to the State operator: Centre Interprofessionnel Technique d'Etudes de la Pollution Atmosphérique (CITEPA), using automated updates and input from Ecole de mine de Paris	Ministry of environment, linked with Ministry of ecology, ministry for transport and ministry for forestry	Since 2006 annual reviews and 5 extensive reviews (with "Saturday paper" and resubmissions) provided continuous improvement. Detail at Tier 1/2/3 depending on sector and Monte Carlo approach for uncertainty assessment	Serbia, Russia, China	CO_2 from LULUCF, CH_4 from waste, N2O from agriculture
Ireland	Environmental Protection Agency Ireland is contracted with binding memoranda of understanding and using automated processes. The forest analysis is contracted to a third party and collaborations with research institutes (e.g., Aarhus University) are ongoing	Ministerial Department of Agriculture, Food and Marine	Response to the yearly expert review comments and recommendations improved the inventory, but take several years for implementation. Mainly Tier 2, some Tier 3and Tier 1 for N_2O Current revisions for crop- and grasslands.	Denmark, UK	high CH_4 uncertainty, relative high N2O uncertainty, LULUCF sector.
Norway	The National Inventory system is not outsourced but set up with long-term agreements and automated processes by 3 core institutes: the Norwegian Environment Agency, Statistics Norway, and the Norwegian Institute for Bioeconomy Research (NIBIO) for LULUCF. Support by Norwegian Institute for Air Research (NILU) can be given.	National environmental agency	Annual updates improve the inventory, last major update was in 2015. Calculations are done at Tier 1 and Tier 2 level, but for the LULUCF sector a Tier 3 level is used. Also uncertainties are estimated at Tier 3 level	Sweden, Finland, Latvia, Lithuania	forests and organic soils (LULUCF) are key. Data is lacking for organic and mineral soils. N_2O has large uncertainty.
The Netherlands	National Institute for Public Health and the Environment (RIVM) as lead organisation, Netherlands Environmental Assessment Agency (PBL), Netherlands Organisation for Applied Scientific Research (TNO), Statistics Netherlands, Netherlands Inventory Entity (NIE). (53% of the budget is outsourced with 6 year contracts, renewed every 5 years)	Ministry of Infrastructure and Environment, in collaboration with Ministry of Economic Affairs, Agriculture and Innovation	Annual reviews are addressed, but the changes are small. Own inventory improvement plan leads to major enhancement. Since 2016 uncertainty info also for sub-categories, used in Monte Carlo analyses.	Indonesia	uncertainties

Germany	Umweltbundesamt (permanent staff) using a centralised database, in collaboration with research institutes and coordinated by a committee (plant data at Bundesland level without central QA/QC)	Federal Environment Ministry in collaboration with Federal Ministry for Economic Affairs and Energy	Yearly review (either centralized or more extensive "in-country-review" brings improvements (incl. QA/QC methods etc.) Calculations at Tier 2 and Tier 3 for key categories.	Ghana, Chile, Dominican Republic, South Korea	Efforts on LULUCF will be intensified in the future. Also support on uncertainties, independent inventory assessment is desired.
Italy	Institute for Environmental Protection and Research (ISPRA Ambiente) (permanent staff) using a national GHG inventory system	Ministry for the Environment, Land and Sea	Annual UNFCCC reviews are addressed. QA/QC at sector level is done. Detail at Tier 2 and Tier 3. Only non-key sectors use Tier 1. For uncertainties the Monte Carlo approach is used.		LULUCF
UK	Inventory is outsourced by the UK Government to Ricardo Energy & Environment and Rothamsted Research (for Agriculture). Atmospheric observations and modelling for inventory verification is undertaken by the University of Bristol and the UK's Meteorological Office.	Ministerial Department for Environment, Food, Rural Affairs and the Ministerial Department for Business, Energy & Industrial Strategy			Annual improvement programme is informed by UNFCCC Reviews, verification using atmospheric observations, uncertainty and Key Category analyses, bilaterals with other countries and analysis of the latest literature. Higher tier methods are used wherever possible. QA/QC undertaken at data, model, inventory system and national system level.

Annex 2 Detailed description of the modelling sub-components

A 2.2 Inversion strategies

To reduce uncertainties of emission inventories, a wide range of information can be used to better constrain current fossil fuel emission estimates. However, available observations typically represent only an indirect measure of the emission flux. For example, although road traffic statistics and fuel sold are used to estimate fossil fuel emissions from cars, they are a proxy with various assumptions to link the statistics with the emission estimate. Also, while CO_2 plumes in the atmosphere resulting from megacities can be detected and measured by satellites or in situ instruments, these plumes represent the net surface flux as observed by the instrument. Linking the observed quantities to the actual surface fluxes therefore requires an observation operator that describes the, often complicated, relationship between the surface emission, 3-dimensional atmospheric dispersion of those emissions, and the measurement that is collected by the space-borne instruments.

The observation operator for atmospheric CO_2 and its related quantities, e.g., ^{14}C or CO, is non-trivial. Observed variations of atmospheric CO_2 are determined by fossil fuel emissions and by fluxes from the land and ocean biospheres.

The observation operator for atmospheric CO_2 therefore needs to be able to describe natural and anthropogenic fluxes as well as the atmospheric transport that simulates the atmospheric response to these fluxes to enable the detection of the anthropogenic signal in the CO_2 concentrations. This requires an accurate atmospheric transport model that is driven by accurate models of the land biosphere and ocean, and accurate estimates of, for example, wildfire emissions. Additional observations are typically used to ensure these models faithfully reproduce the real world. A fossil fuel emission monitoring system needs to integrate the various components using prior information as well as a comprehensive set of observations to determine the CO_2 emissions and their uncertainties, as is depicted in Figure 9.

Developing models to comprehensively describe the many interacting components of the carbon cycle has been an ongoing process for many decades, and it will take significant additional time to bring these models to further maturity. To achieve our primary near-future objective of estimating fossil fuel emissions we must therefore consider simplifications to existing models so they could already be implemented as part of a pre-operational system. For instance, hot-spot detection, as outlined in section 2.2.3.1, makes use of the fact that emissions from large megacities are visible above the background CO_2 variability and therefore can be quantified. Elevated plumes can be more easily attributed to fossil fuel at mid and higher latitudes during winter months when the land biosphere is relatively dormant. In addition, in a full inversion system, it might be possible to use simplifications of the transport as well as the land and ocean biosphere (see sections 2.1 and Annex 2.3.5) in a pre-operational data assimilation system that still allow the estimation of fossil fuel emissions with uncertainties that are sufficient for use by end-users of the system. A more comprehensive data assimilation system could then follow as an extension of the pre-operational system through innovation and development of various aspects. This approach would require a careful analysis of what assumptions can be made while still fulfilling the user requirements.

A 2.3 The Carbon Data Assimilation System

A 2.3.1 General description of a Carbon Data Assimilation System

The aspirational vision of a Carbon Data Assimilation (Carbon DA) system is to solve for all variables that define the full carbon cycle in a consistent way. To achieve this vision, one needs to collect and process a heterogeneous set of observations that vary over a wide spectrum of time scales. So far, only parts of such a comprehensive system have been built using various assumptions. For instance, current net flux inversions using in situ and satellite XCO_2 observations prescribe the anthropogenic emissions to solve for the net land and ocean fluxes. The feasibility of direct assimilation of XCO_2 into a Carbon Cycle Data Assimilation Systems (CCDAS) around a diagnostic biosphere model was recently demonstrated by Kaminski et al. (2017). Even though most current CCDAS implementations are focused on the land biosphere, and specify fossil fuel and ocean fluxes as a fixed background, first steps to include representations of these processes have been undertaken (Hooker-Stroud, 2008; Scholze et al., 2013).

Inferring fossil fuel emissions on a global scale without the specific limitations of a hot-spot estimation system will require a comprehensive (inverse) modelling system that accurately models all components of the carbon cycle, i.e., emissions, land biosphere, agriculture and ocean. It will also require accurate observations constraining as many parts of the system as possible and directly linked to that, accurate observation operators. Observations, in their widest definition, can range from satellite observations of CO_2 to car traffic statistics. Observation operators, linking the observations to the relevant model variables/parameters, will include an accurate representation of atmospheric meteorology and transport as well as maybe less traditional ones, such as the link between nightlight observations and emission sources.

The application of data assimilation to the carbon cycle has essentially been spearheaded by the study of Fung et al. (1987) where they adjusted respiration parameters in a simple biosphere model so that the seasonal cycle of atmospheric CO_2 concentration better matched the observed seasonal cycle at some stations. The first formal data assimilation study was performed by Kaminski et al. (2002) on a similar model but with more observations. Similar developments can be seen in the estimation of CO_2 fluxes from atmospheric inversions (e.g., Tans et al., 1990; Chevallier et al., 2010). In all cases, atmospheric CO_2 observations played a key role. Major observational programmes from various institutions in many different countries have created a global network that provides spatial gradients of CO_2 concentrations to constrain location and strength of mainly natural (terrestrial and oceanic) CO_2 sources and sinks. However, the spatial resolution of the in situ network is poor, particularly over the tropics, such that the current network is too sparse to infer CO_2 sources and sinks on regional to continental scales with existing atmospheric data (Peylin et al., 2013), illustrating the under-determinancy of the inference problem. This under-determinancy is a fundamental problem of atmospheric trace gas inversions, where a 3-dimensional flux field is determined from essentially point measurements of the trace gas. The data assimilation approach overcomes this problem by adding process information that might be, for example, embedded in a dynamical model. The resulting posterior solution is then a weighted mean of the prior information and the measurements subject to their respective uncertainties. Using a process-based model of the land biosphere, for example, allows the use of additional observations of the carbon cycle, such as, the Fraction of Absorbed Photosynthetically Active Radiation (Knorr et al., 2010) or soil moisture (Scholze et al., 2016), that can complement the information provided by the atmospheric data. This principle should be extended to include model of ocean fluxes, agricultural processes and fossil fuel emissions as well and thus enable the use of further observational data streams (see, e.g., Kaminski et al., 2017).

Building a comprehensive Carbon DA system must also have to address the significant differences in spatial and temporal scales between the components and the observations.

A 2.3.2 Overall Layout

The Carbon DA system for estimation of fossil fuel emissions should be constructed around a forward modelling chain that includes models of the major components and dedicated observation operators for each data type, such that it can simulate equivalents of each relevant observation (see also Figure 12). It also needs the capability to produce estimates of fossil fuel emissions from the observation-constrained parameters. This is typically a two-step procedure. The first step (assimilation mode) solves for the fundamental unknowns (control vector), in our case a combination of process parameters, initial-and boundary conditions. The second step (diagnostic mode) computes the fossil fuel emissions from the control vector.

While certain observations (such as ^{14}C) almost directly constrain the estimates of fossil fuel emissions, there is a clear consensus that additional information needs to be brought into the system in the form of atmospheric CO_2 observations. An important data stream will be the total column observation of atmospheric CO_2 at sufficiently high spatial resolution, so the forward modelling chain needs to be capable of simulating an equivalent with sufficient accuracy. As already outlined above, this introduces a significant amount of complexity, because atmospheric CO_2 concentrations not only depend on fossil fuel emissions, but also on fluxes from the natural biosphere (the land and the ocean) and other anthropogenic ally induced emissions such as fires and land-use change.

The forward model components will inevitably need to make simplifications/approximations (e.g., in terms of resolution, complexity of process representation) for the inverse modelling system to be numerically tractable. Similar simplifications will be necessary in the layout of the inversion system including the definition of its control vector. All these simplifications must be made such that the flux estimates derived by the inverse modelling system have the best possible quality. It may well be that the limit on the accuracy of the fossil flux estimated by the Carbon DA system is determined by the least accurate component model and a higher level of sophistication in the modelling of the other components is of secondary importance.

An example for such an approximation is the application of a mass conserving online simulation scheme for atmospheric transport, that could be consistently driven with output of a physical assimilation system (in an NWP setup). The approach regards CO_2 as a passive tracer that on the relevant time scales does not feedback on the atmospheric circulation or source processes and renders the transport simulation linear. This simplification of the transport is expected to drastically simplify the minimization of the objective function and allow for a long assimilation window. A similar approach can be taken for the simulation of the ocean biogeochemistry (see Annex 2.3.5). Also auxiliary variables needed for simulation of radiances or retrievals can be taken from a physical assimilation scheme.

Another approximation concerns the representation of the transport of fluxes that are remote (in time and space) from the area of interest with simplified response functions, possibly accompanied by a reduction in the length of the control vector (see Kaminski et al., 2010, 2017).

A 2.3.3 Fossil Fuel Data Assimilation System

During recent years, the approach of data assimilation has been adopted to estimate fossil fuel emissions in a so-called Fossil Fuel Data Assimilation Systems (FFDAS). Here, the interpretation of the data provided by a fossil fuel observing system relies on data assimilation systems which include process modules that simulate fossil fuel CO_2 (ffCO_2) emissions. A FFDAS does not solve directly for the spatio-temporal distribution of ffCO_2 emissions, but it optimizes an emission inventory model with unknown parameters. The parameters of the emission inventory model are then determined by minimizing the mismatch between the simulated observables and the observations. Optimized fossil fuel CO_2 emissions maps are then produced based on a small number of optimal (with respect to the observations) controlling parameters. With this approach, the data assimilation problem usually becomes non-linear, and, depending on the complexity of the emission inventory model, computationally expensive. On the other hand, this approach typically reduces the number of unknowns and thus regularizes the assimilation problem, essentially using prior process information as represented in the emission inventory model.

A first attempt of such a FFDAS has been made by Hooker-Strout (2008) by coupling an empirical emission inventory model to a Carbon Cycle data Assimilation System by replacing the prescribed fossil fuel background flux. The model of the fossil fuel emissions was then calibrated jointly with the terrestrial biosphere model BETHY (Knorr, 2000) to constrain both the biogenic and the ffCO_2 surface fluxes simultaneously with in situ atmospheric CO_2 concentration observations. The study showed that the in situ atmospheric CO_2 concentration measurements provided only a weak constraint on the ffCO_2 emissions.

Rayner et al. (2010) developed a FFDAS based on national statistics of fossil fuel CO_2 consumption and other census data to provide optimized fossil fuel emissions of CO_2 at 0.25° resolution together with uncertainties consistent with the ingested observations. The FFDAS applies the same two-step procedure as the CCDAS (see Annex 2.1) and estimates fossil fuel CO_2 emissions based on the Kaya identity (Kaya, 1990; Nakicenovic, 2004), which relates CO_2 emissions from human sources to areal population density, per capita economic activity, energy intensity of the economy, and carbon intensity of energy. As observations, they used population data, nightlights and estimates of annual country-level fossil fuel emissions. Nightlights data have been shown to correlate fossil fuel emissions before (Doll et al., 2000). Here, nightlight data are assumed to be proportional to the areal density of energy consumption (Raupach et al., 2010), which can be expressed as the product between population density, per capita gross domestic product and energy intensity. This system has recently been refined by Asefi-Najafabady et al. (2014) by updating the underlying observation-based data sources (both population density and nightlights) and, more importantly, by separating emission processes into two sectors (power generation and all others) and including a new pointwise database of global power plant emissions with improved information and individual power plant uncertainties. Estimates of annual fossil fuel emissions and their accompanying uncertainty have been generated at a spatial resolution of about 0.1° for the period 1997 to 2010.

The way forward in fossil fuel data assimilation would be to add additional observations. First the FFDAS approach by Asefi-Najafabady et al (2014) can be extended by including further observations into the assimilation system that separate the fossil fuel emissions into more sectors. A first candidate sector is the emissions from road transport which goes along with adding observations of major roads provided by detailed global road atlases. Additional economic data directly will allow the analysis of the carbon intensity and energy efficiency of national and

subnational economies, and thus provide a better estimate of the gridded emissions.
As already indicated above, the greatest advance in estimating $ffCO_2$ with a FFDAS will come when the system will be integrated in a more comprehensive carbon data assimilation system. This will allow us to use a whole range of additional observations in the assimilation. First of all, using $^{14}CO_2$ measurements (see section 2.2.3.2) as a direct constraint on $ffCO_2$ emissions appears promising and realistic. Rayner et al. (2010) have shown in a synthetic observation system simulation experiment (which calculates the additional reduction of uncertainty on the $ffCO_2$ fluxes) that adding $^{14}CO_2$ measurements provide a considerable regional constraint of the order of a further 70% reduction in the uncertainty. Radiocarbon observation will also allow us to provide estimates at a higher (than annual) temporal resolution; however, currently, radiocarbon observations are rather expensive and further research is needed in low-cost measurement techniques as explained below.

Additional atmospheric trace gases such as NOx and CO can also be used as proxy observations for fossil fuel emissions because they are co-emitted during the combustion process. Konovalov et al. (2016) have demonstrated this approach with a regional atmospheric transport inversion system focussing on Europe. Adding these measurements into a Carbon DA will allow to further separating the emissions into sectors because of the sector specific emissions of these proxies. However, there is a high uncertainty in the conversion between the pollutants and $ffCO_2$ due to the high variation in time and space of the pollutant emission factors. Therefore, further research on the robustness of the conversion between CO, NOx and $ffCO_2$ is required before these proxy tracers can be used in a pre-operational monitoring system.

There is potentially also added value to be gained from embedding the CO_2 data assimilation system in a larger atmospheric data assimilation system. As mentioned above the correlations between various species such as CO_2 and CO can provide additional information on source attribution, but also the assimilation of meteorological observations in the system can reduce errors in the transport, which maybe apparent in offline tracer transport simulations using pre-calculated wind field (Massart et al., 2016). The main issue in such a comprehensive assimilation system is the significant difference in time scales of the various processes that determine the atmospheric CO_2 variability. Correctly constraining both the high variability of winds and atmospheric boundary layer processes, and the much slower evolution of surface fluxes in one system is a challenging task. The approximations suggested in Annex 2.3.2 render the inverse problem tractable, e.g., by exploiting the fact that on the relevant time scales CO_2 can be considered a passive tracer.

A 2.3.4 Land

The terrestrial biosphere is currently a net global sink of atmospheric CO_2, responsible for sequestering approximately 25% of the mass emitted into the atmosphere per year from the (in) combustion of fuel. Tropical terrestrial ecosystems have the highest rates of gross primary productivity and consequently represent the largest contribution to the net global sink.

The largest of these regions (South America and central Africa) cover vast geographical areas, which are not sampled adequately by the sparse available in situ measurement networks. However, these large homogenous scenes (on km scales) are ideal for observing from space but space-borne observed scenes are often compromised by clouds or by atmospheric aerosols. Leaf stomata open to allow diffusion of CO_2 from the air into the leaves for photosynthesis. During this process, the plant transpires water vapor. Broadly speaking, as the air above the forest canopy is heated it rises and condenses to form clouds. This process is particularly evident during wet seasons when large geographical regions are cloudy. Even during the dry season, small patchy clouds are prevalent. Currently, these cloudy scenes are removed from the analysis of satellite data due to on-going challenges associated with the processing of clear-sky scenes. Eventually, partial CO_2 columns that sit above cloud decks will increase the data volume available for understanding the carbon cycle.

A larger challenge over the tropics is associated with aerosols emitted during the burning of biomass during the dry season. Depending on the combustion phase (e.g., flaming or smoldering) and atmospheric processes (e.g., aerosol mixing state) these aerosols can include a wide range of single scattering albedo values. Current knowledge of primary and secondary aerosol formation precludes the confident application of atmospheric chemistry models informing algorithms to retrieve atmospheric CO_2.

Because of these sampling challenges, past work has shown the value of CO_2 observations collected downwind of large tropical ecosystems where clouds are less frequent and aerosol loading is greatly reduced. Similar challenges are faced elsewhere there are large forested regions upwind of ocean (e.g., Siberia).

Temperate coniferous forests populate extensive geographical regions over North America, Europe, and Asia. They are typically embedded within, or border with, metropolitan and industrialized regions where there are other large sources of CO_2; similar issues are relevant for Southeast Asia. Here, the challenge is to separate the land biosphere signal from the fossil fuel signal. It is the converse of the challenge associated with isolating the fossil fuel signature.

We discuss two strategies to address these challenges: 1) using correlative data to improve source attribution of CO_2 and 2) higher-resolution models to exploit geographical separation of individual sources. The latter is more relevant to the large, more homogenous tropical ecosystems. The correlative data can be categorized broadly as atmospheric and land surface data. Atmospheric data will include gases associated with the natural carbon cycle (e.g., carbon sulphide, isoprene, and methanol), incomplete combustion (e.g., ethane, carbon monoxide, formaldehyde, nitrogen dioxide, and aerosol optical depth), or other sources (e.g., ammonia from agricultural fertilizer). Land surface data include variables associated with photosynthesis (e.g., fraction of absorbed photosynthetically active radiation, solar induced fluorescence, soil moisture, and soon biomass from the ESA BIOMASS mission) or leaf phenology. Collectively these data provide complementary and independent insights into the emission and uptake of atmospheric CO_2.

There are many challenges associated with exploiting correlative data and currently we are far from an optimal exploitation of all available constraints on understanding the global carbon cycle. With the possible exception of solar induced fluorescence (SIF), none of these data are collected on the same instrument used to measure CO_2. This means that different data are measured at different local times of the day and with different ground footprint resolution. This is less problematic of variables that do not vary over timescales corresponding to repeat time for observations as generally the case with land surface properties. Atmospheric gases are fitted over a wide range of spectral wavelengths, associated with differences in their sensitivity of changes in the atmosphere. Differences in chemical lifetimes of these gases make them difficult to interpret without the aid of computational models that account for atmospheric chemistry and transport processes.

The interpretation of land surface properties also presents scientific challenges. Absorption of visible light by chlorophyll molecules, associated with photosynthesis, peak around 430-453 nm (blue) and 642-662 nm (red). This is responsible for the green colour of chlorophyll. Fluorescence represents one of three pathways in which the molecules can return to their ground state. A chlorophyll fluorescence spectrum ranges from 650 nm to beyond 800 nm. Several space-borne instruments deliver SIF retrievals.

The higher-resolution SWIR instruments focused on CO_2 (GOSAT, OCO-2) infer SIF over a narrow spectral window (757-775 nm) while SBUV instruments (GOME-2, TROPOMI) retrieve SIF over a spectral range (650-790 nm) that describes more of the fluorescence signal. Intrinsic timescales associated with changes in, for example, fluorescence and soil moisture, and changes with CO_2 preclude a naïve analysis of observed correlations between CO_2 and land surface properties without a model of the responsible biological processes.

Clearly, the optimal approach for future carbon cycle modelling is to exploit all available data in a self-consistent manner. This can be achieved using a modelling infrastructure that can link macroscale physical and biological parameters, thus avoiding the need for molecular scale modelling, with all or some subset of land surface and atmospheric observations. Inferring model parameters from observations would ultimately improve the predictive capability of carbon cycle models. Such a modelling framework for the temperate coniferous forests would also have to incorporate a similar modelling framework for fossil fuel emission. We acknowledge this in an ambitious strategy but one that would make large strides towards an improved understanding of the terrestrial biosphere. The spatial resolution of these models would need to be guided by the underlying physics and biology but also by the data that will eventually be used to confront it. Many observations of land surface properties are resolved at sub-km resolution so that gradients can be observed on a km scale.

With a modelling infrastructure in place we could then envisage DA systems that could digest all available observations to infer simultaneously fossil fuel and natural fluxes of CO_2. Assimilation of these data would help overcome the difficulties associated with integrating different kinds of data that are sampled at different times of the day and representative of different spatial and temporal scales. The challenge would then be to quantify the magnitude of uncertainties associated with the different measurements and the correlation of that uncertainty. Similarly we need to assess the magnitude of the uncertainty in modelling observation equivalents and the correlation in that uncertainty. Correlations in these uncertainties can originate from common physical and biological processes, atmospheric loss processes, and atmospheric transport. Some of these uncertainty correlations can be directly derived from the model formulations or be informed by comparison of model simulations with observations but further studies will be needed to fill knowledge gaps.

Greater self-consistency between data will also come from exploitation of level 1 data that has not been subject to a Bayesian retrieval algorithm that requires prior information. Integrating the varied atmospheric data (including aerosol properties), for instance, could be possible now but some retrieval groups will use empirical climatology while others use time-dependent model output. Even small changes in these assumptions impact CO_2 fluxes.

Integrated field campaign over key ecosystems that included a wide range of atmospheric and land surface properties would help link new and emerging in situ and ground-based remote sensing technologies with space-borne assets. Coordinated deployment of such technologies could also help improve the spatial and temporal resolution of CO_2 fluxes, particularly relevant over regions where there is an overlap of natural and anthropogenic ecosystems.

A 2.3.5 Ocean

The global ocean currently takes up about 25% of the global CO_2 emissions from fossil fuel burning and changes in land use (Le Quéré et al., 2016). It constitutes thus a major component in the global carbon cycle and is expected, on centennial time scales, to provide the major longer-term sink for anthropogenic CO_2. The local air-sea flux of CO_2, however, is not only reflecting the uptake of atmospheric excess CO_2, but is also controlled by natural oceanic biogeochemical processes, such as photosynthesis and respiration of the local marine biota and the local mixing of waters with the interior of the ocean. In contrast to atmosphere-land exchange fluxes, open ocean atmosphere-ocean fluxes are less heterogeneous in space, and exhibit substantially smaller temporal variability, at least on time scales up to a decade. The main reason is the relatively slow air-sea gas exchange in part caused by the large ocean chemical carbonate system which buffers changes of dissolved CO_2 caused for instance by plankton blooms or upwelling events. In addition to the large scale open ocean air-sea exchange fluxes of CO_2, there exist much stronger varying exchange fluxes in coastal regions due to continental shelves, marginal seas and estuaries. These are caused in part by coastal upwelling, but also by direct and indirect anthropogenic effects including the export of nutrients and pollutants from land.

The spatio-temporal atmospheric CO_2 concentration is dominated by land exchanges and fossil fuel emissions. Because of this, current top-down inversion systems can barely capture the very large spatial signatures of ocean exchange fluxes, e.g., between the tropics and the extratropical latitudes (Peylin et al, 2013). Conversely, bottom-up approaches rely primarily on in situ measurements of the partial pressure difference (ΔPCO_2) between the air and the sea, measured now routinely not only on research vessels and buoys but also continuously on commercial ships (like freighters and ferries) as well as increasingly on autonomous platforms (for instance floats, gliders and wave riders). These measurements are being transferred to a global data base (SOCAT), where they are integrated and extrapolated into global monthly flux maps using a variety of data assimilation approaches (Bakker et al., 2016). Climatological flux fields (mean and seasonal cycle) are also available from ocean circulation models which include the carbon cycle biogeochemistry.

A global DA system for supporting the quantification of anthropogenic sources needs to take ocean-atmosphere fluxes into account, since they induce a significant background concentration field. Ideally, this would include a full ocean-land-atmosphere data assimilation system, in which the ocean component is represented by a general circulation model which includes biological and chemical processes and the transport of the various ocean carbon species. In principle, such a system could integrate the multiple data streams from in situ and remote sensing platforms. These include currently in situ observations of the physical ocean state (temperature, salinity, sea level, ocean currents) as well as biogeochemical observations (ΔPCO_2, ocean color, pH, total carbon, alkalinity as well as other chemical species). The development of such a comprehensive ocean DA is, however, still at a rather early scientific development stage, most likely also because in situ ocean observations of the physical state are too sparse to reliably constrain the dominant transient mixing and circulation structures (in contrast to the atmosphere as exploited routinely in weather forecast systems).

On a near-term (5 years) time scale the DA system will profit from a dual development approach:

- The application of the 'simpler' diagnostic ΔPCO_2 based ocean-atmosphere flux map data assimilation (Rödenbeck et al., 2015), which can be extended by utilizing additional parameters and measurements, e.g., mixed layer depth, gas exchange parametrisations (Rödenbeck et al., 2013, 2014), ocean color, and additional gases linked to CO_2 such as molecular oxygen (Rödenbeck et al., 2008);

- The independent further development of a comprehensive ocean-atmosphere data assimilation system as described above. The development of a comprehensive ocean-atmosphere data assimilation system benefits from a two-step strategy: The ocean carbon cycle model should first be run offline from the physical ocean model in the DA system using pre-computed circulation fields (i.e. velocity, temperature, salinity, convection). These circulation fields should originate from physical ocean reanalysis products such as for instance the Estimation of the Circulation and Climate of the Ocean (ECCO) project (Forget et al. (2015)) to ensure an optimal physical ocean state. This approach is similar to atmospheric transport inversions, in which the atmospheric tracer transport model is run offline with pre-computed wind fields from atmosphere re-analyses/analyses, and reduces the complexity of the ocean-atmosphere data assimilation system. It has already been demonstrated for ocean biogeochemical tracer modelling (Khatiwala, 2007). In a subsequent development step the ocean carbon cycle model can be included in the physical ocean data assimilation system and both physical ocean state and carbon cycling can be constrained simultaneously in the comprehensive ocean-atmosphere data assimilation system.

A 2.4 Atmospheric transport and meteorology

Observed variations of atmospheric CO_2 or any other atmospheric constituent is determined by surface emissions and uptake, atmospheric chemistry (production and loss, as relevant), and atmospheric transport. Models of atmospheric transport therefore play a key role in interpreting CO_2 data.

On-going developments in atmospheric transport models have led to substantial improvements in the description of physical processes and subsequently in model resolution. Current models are now approaching the spatial resolution of current column CO_2 measurements from passive space-borne technology, necessary to interpret the sub-1% variations that are due to weather patterns and surface fluxes.

However, despite these technical developments the climate community has not moved far from the original implementation of general circulation models described on a regular lattice grid. The community has also developed no rigorous methodology to determine errors in model atmospheric transport, with only ad hoc approaches pursued by individual groups, with implications for inferring CO_2 fluxes.

Atmospheric CO_2 concentration is determined by large-scale but diffuse ecosystem exchanges and small-scale point sources like cities and power plants. Current modelling strategies have used a hierarchy of models or used a nested-model approach usually on a static grid. An alternative approach is to use an adaptive irregular grid that can dynamically adapt its horizontal resolution to changes in data availability or over particular regions of interest. Irregular tiling arrangements require a re-statement of the equations of motion but can result in higher computational efficiency, and advantages associated with dynamics at the poles (relevant to future active space-borne observations of CO_2) and mass transport between neighboring grid cells. Although irregular grid model representations have been used since the 1960s they have not been widely adopted by the larger NWP centres. However, triggered by increasingly demanding efficiency requirements, there is a significant new focus within the NWP community to develop new methods. For instance, the PantaRhei project funded by the European Research Council is developing new mathematical tools that combine the strengths of well-established methods in numerical weather prediction with methods originating from other computational fluid dynamics disciplines. A Finite Volume Module (FVM) is being developed that contains features recognised as important areas for future developments in global atmospheric modelling, such as a non-hydrostatic deep-atmosphere formulation with fully compressible Euler equations, a generalized time-dependent vertical coordinate, and flexible horizontal discretization enabling mesh adaptivity, to name but a few. Such developments will likely bring significant benefits to the global modelling of CO_2 and related tracers.

These and similar developments also relate to the question of how to optimally constrain the meteorology in any CO_2 data assimilation system, as was also pointed out in previous sections. While some NWP systems are already integrating CO_2 and other species in their modelling systems (as the case for instance at ECMWF, NASA and NOAA), most current inversion models are run off-line with prescribed meteorology. While this is an efficient way to deal with the widely varying time scales (e.g., synoptic meteorology versus slower variability of the surface fluxes and their impact on the atmospheric concentrations), it is currently not well understood what level of uncertainty is being introduced by such coupling of very different modelling systems. On the other hand, while for instance Semi-Lagrangian advection schemes in current NWP systems are very efficient, they are generally not fully mass conservative. Also, NWP systems have been developed to provide optimal initial conditions for short- to medium-range forecasts and data assimilation by itself can introduce inconsistencies. Developments like PantaRhei might enable using best of both worlds in the long term, but in the meantime better understanding of the error sources in the various configurations need to be explored.

Evaluating large-scale and sub-grid scale transport processes described in an atmospheric model is critical before it is used to interpret observed variations of CO_2 and other trace gases. Past work has used long-lived tracers (chlorofluorocarbons and sulphur hexafluoride) to evaluate model large-scale motions such at the inter-hemispheric exchange of air. Tracers such as carbon monoxide (CO) have an atmospheric lifetime long enough such that it is transported over 1000 km before mixing into a hemispheric mean background concentration and short enough such elevated values from source can be observed above this background (using MOPITT for instance) to evaluate intermediate-scale transport such as intercontinental transport.

CO has a number of primary and secondary (oxidation) sources and is chemically removed by oxidation by OH, whose variations are poorly understood. Radon (222Rn), which has a radioactive half-life of about 3.8 days and emitted naturally at low levels by rocks and soils, has been used extensively to study subscale convective processes. Radon emissions from soil are highly variable, and are not always elevated over regions of interest. The marine convection tracer methyl iodide suffers from similar weaknesses. A sustained measurement programme for 222Rn and CH3I would nonetheless represent a major resource for the atmospheric science community. The alternative to finding a natural, well-characterized emission of a short-lived trace gas is to develop a synthetic tracer with a lifetime of a few days that could be measured with a low limit of detection. A synthetic tracer would be ideal for intentional release experiments. However, demands for such a short lifetime means that it would have to react with the atmosphere and would therefore be classed a geo-engineering experiment.

Annex 3 Functional architecture for the MVS

As a complement to the high-level functional diagram of the system (see figure 9 of section 2) the following diagrams provide a more detailed insight into the anticipated functional scope of the system.

As the system is rather complex, to facilitate its functional specification and future design/ development a structured functional model has also been developed to assist the work of the Task Force. This functional representation differs optically to that of Figure 9 of section 2 (which was constructed for maximum reader accessibility) but shares all its main attributes (e.g., inputs, outputs and functions).

The modelling approach[17] involves the detailing of the functional scope of the system through the progressive decomposition of functions into sub-functions (with associated inputs/outputs/ controls described at each level of decomposition).

The first diagram (sometimes termed the 'Context' diagram - see P1) identifies the system boundaries in terms of inputs/outputs/controls, defines the functional name of the system and assigns the function 'box' the identifier 'A0'. In subsequent diagrams the A0 function box is decomposed into sub-functions A1, A2, A3, A4 and A5, and then A1, A2, A3, A4 and A5 are themselves further decomposed in subsequent diagrams, until the necessary degree of clarity has been obtained on the functional scope. There is no upper limit on the number of decompositions - it is purely determined by the required level of functional precision.

By convention:
- 'inputs' are always depicted by arrows entering the left-hand side of a function box;
- 'outputs' are always depicted by arrows exiting the right-hand side of a function box;
- 'controls' are always depicted by arrows entering the top-side of a function box.

As a minimum all function boxes should have inputs and outputs (as the rationale for a function is to transform inputs into outputs).

It is emphasized that this model representation is a starting point, and will be further developed as necessary to support the Task Force activities.

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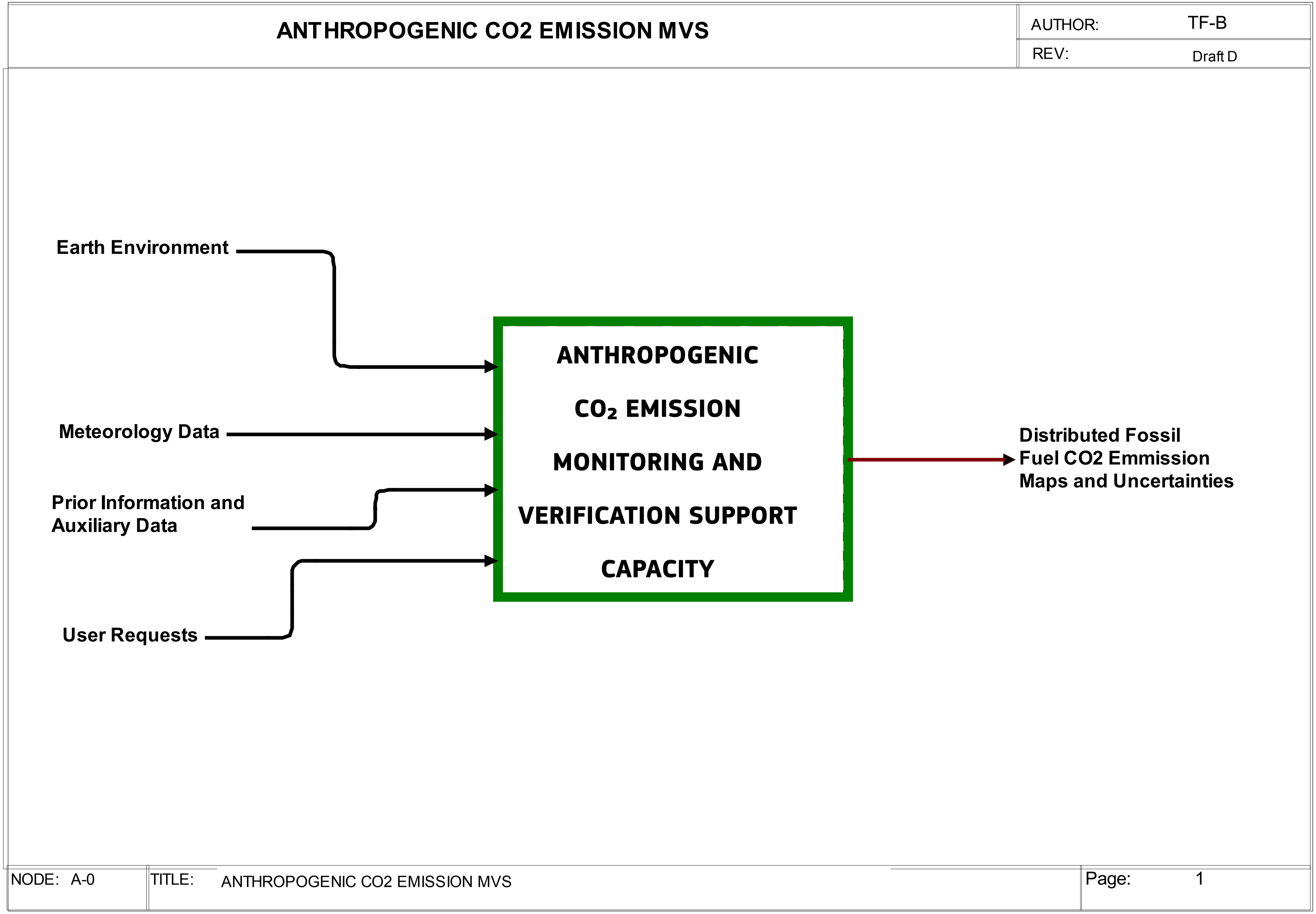
[17] Integrated Definition For Function Modeling - IDEF0: www.idef.com/wp-content/uploads/2016/02/idef0.pdf.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REV: Draft D
Earth Environment
Meteorology Data
Prior Information and Auxiliary Data
User Requests
ANTHROPOGENIC CO₂ EMISSION MONITORING AND VERIFICATION SUPPORT CAPACITY
Distributed Fossil Fuel CO2 Emmission Maps and Uncertainties
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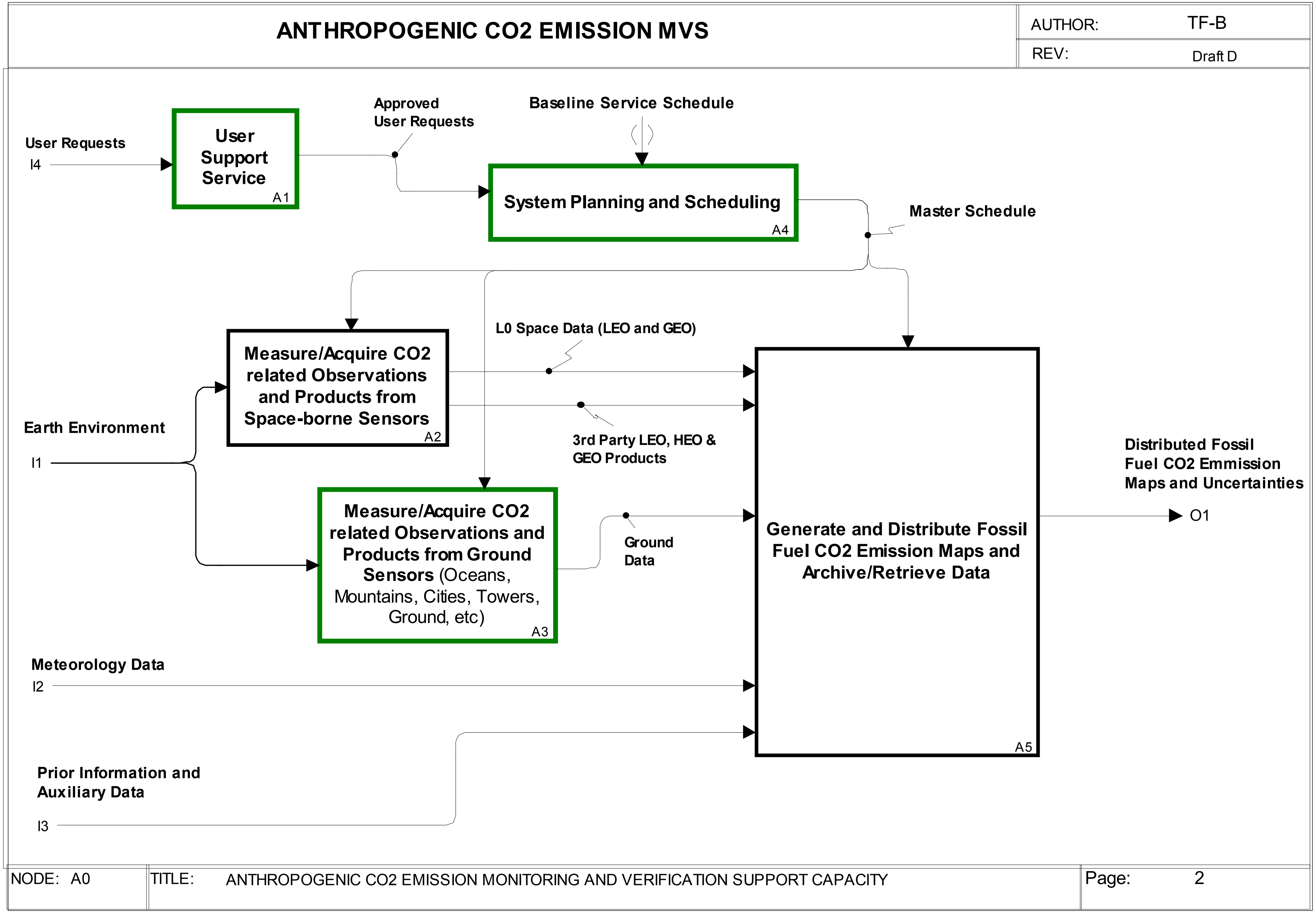
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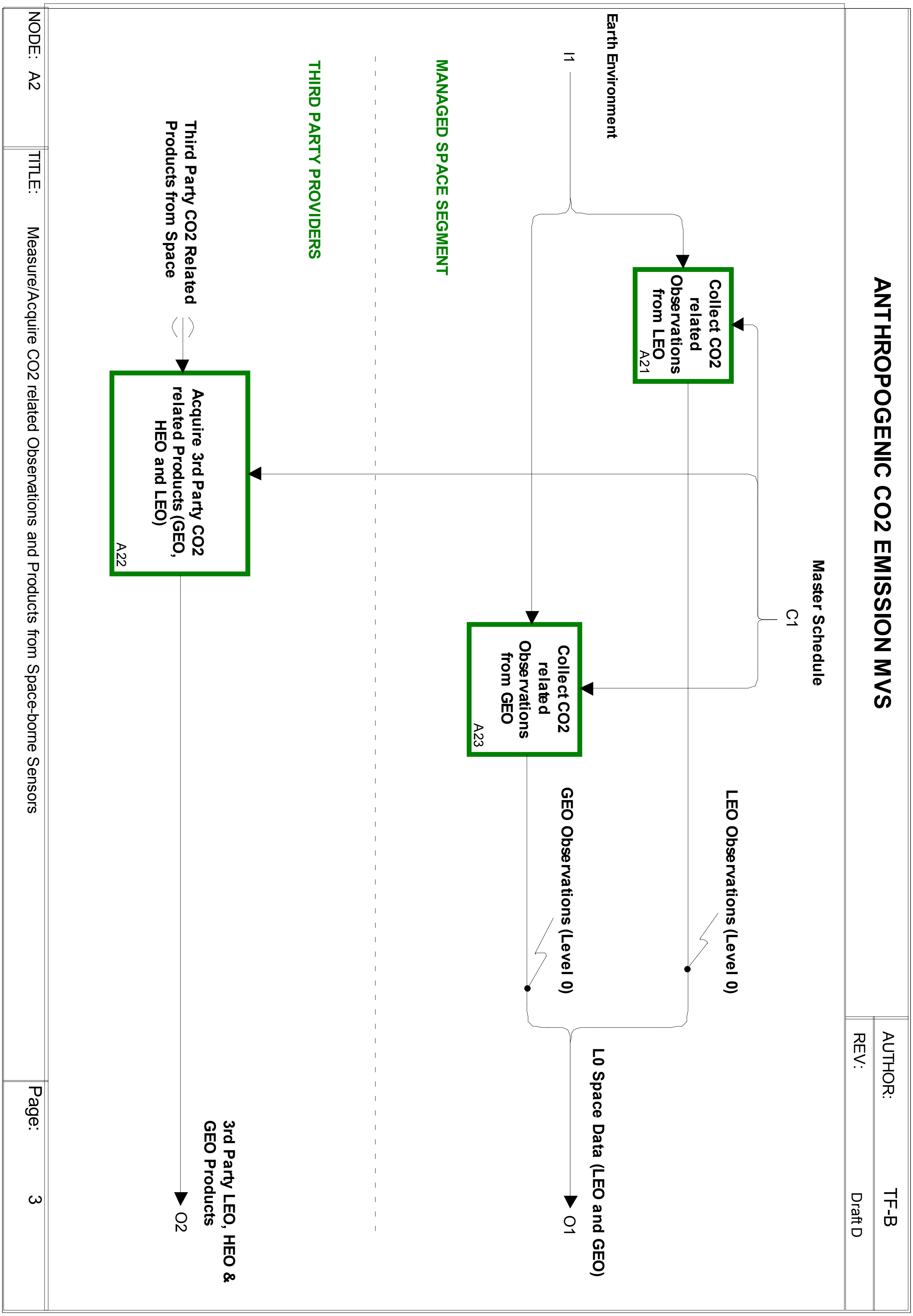
REV: Draft D
User Requests
I4
User Support Service
A1
Approved User Requests
Baseline Service Schedule
System Planning and Scheduling
A4
Master Schedule
Measure/Acquire CO2 related Observations and Products from Space-borne Sensors
A2
L0 Space Data (LEO and GEO)
3rd Party LEO, HEO & GEO Products
Earth Environment
I1
Measure/Acquire CO2 related Observations and Products from Ground Sensors (Oceans, Mountains, Cities, Towers, Ground, etc)
A3
Ground Data
Generate and Distribute Fossil Fuel CO2 Emission Maps and Archive/Retrieve Data
A5
Distributed Fossil Fuel CO2 Emmission Maps and Uncertainties
O1
Meteorology Data
I2
Prior Information and Auxiliary Data
I3
NODE: A0
TITLE: ANTHROPOGENIC CO2 EMISSION MONITORING AND VERIFICATION SUPPORT CAPACITY
Page: 2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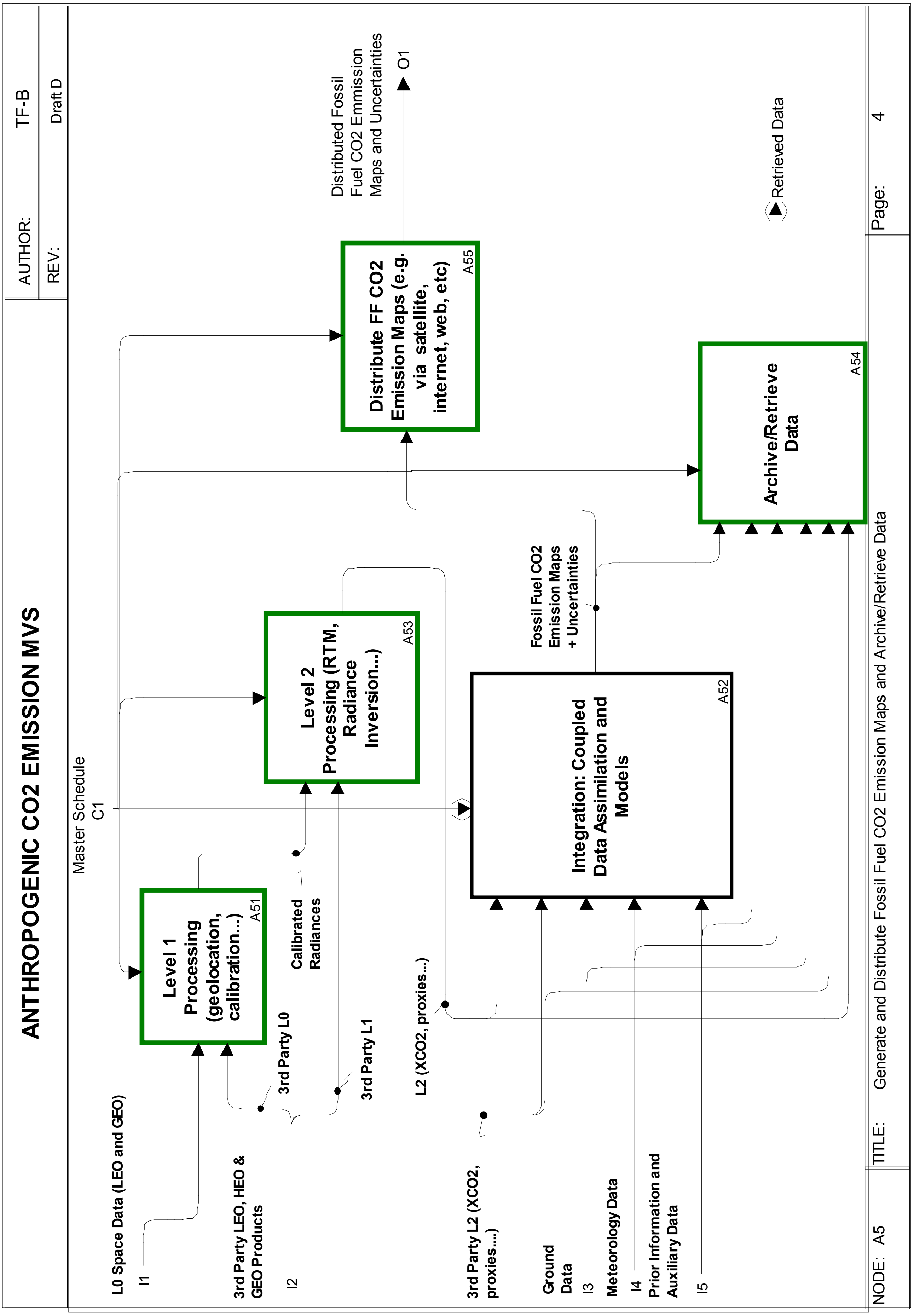
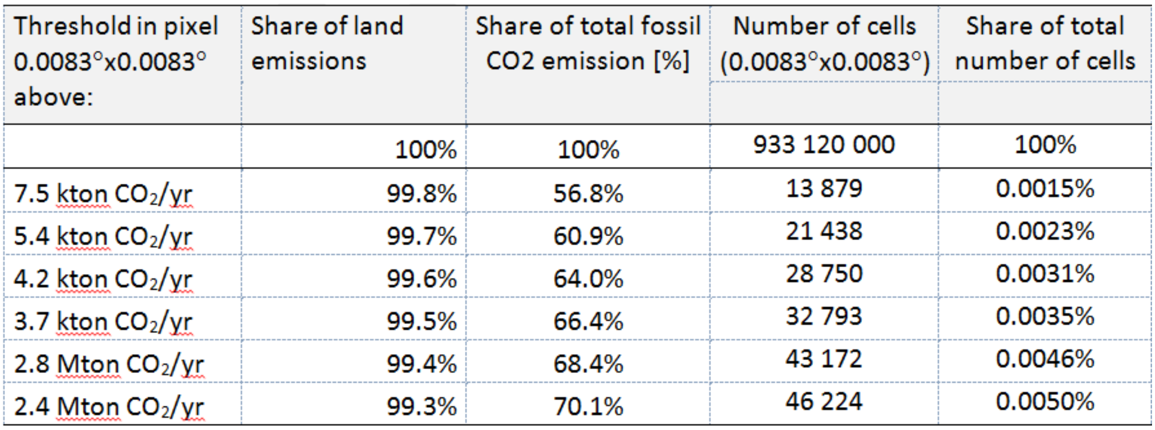
REV: Draft D
Master Schedule
C1
Earth Environment
I1
MANAGED SPACE SEGMENT
THIRD PARTY PROVIDERS
Collect CO2 related Observations from LEO
A21
Collect CO2 related Observations from GEO
A23
Third Party CO2 Related Products from Space
Acquire 3rd Party CO2 related Products (GEO, HEO and LEO)
A22
LEO Observations (Level 0)
GEO Observations (Level 0)
L0 Space Data (LEO and GEO)
O1
3rd Party LEO, HEO & GEO Products
O2
NODE: A2
TITLE: Measure/Acquire CO2 related Observations and Products from Space-borne Sensors
Page: 3


ANTHROPOGENIC CO2 EMISSION MVS
AUTHOR: TF-B
REV: Draft D
Master Schedule
C1
L0 Space Data (LEO and GEO)
I1
3rd Party LEO, HEO & GEO Products
I2
3rd Party L2 (XCO2, proxies...)
Ground Data
I3
Meteorology Data
I4
Prior Information and Auxiliary Data
I5
3rd Party L0
3rd Party L1
L2 (XCO2, proxies...)
Calibrated Radiances
Level 1 Processing (geolocation, calibration...)
A51
Level 2 Processing (RTM, Radiance Inversion...)
A53
Integration: Coupled Data Assimilation and Models
A52
Fossil Fuel CO2 Emission Maps + Uncertainties
Distribute FF CO2 Emission Maps (e.g. via satellite, internet, web, etc)
A55
Distributed Fossil Fuel CO2 Emmission Maps and Uncertainties
O1
Archive/Retrieve Data
A54
Retrieved Data
NODE: A5
TITLE: Generate and Distribute Fossil Fuel CO2 Emission Maps and Archive/Retrieve Data
Page: 4

Annex 4 Detectable Emission fractions for various thresholds

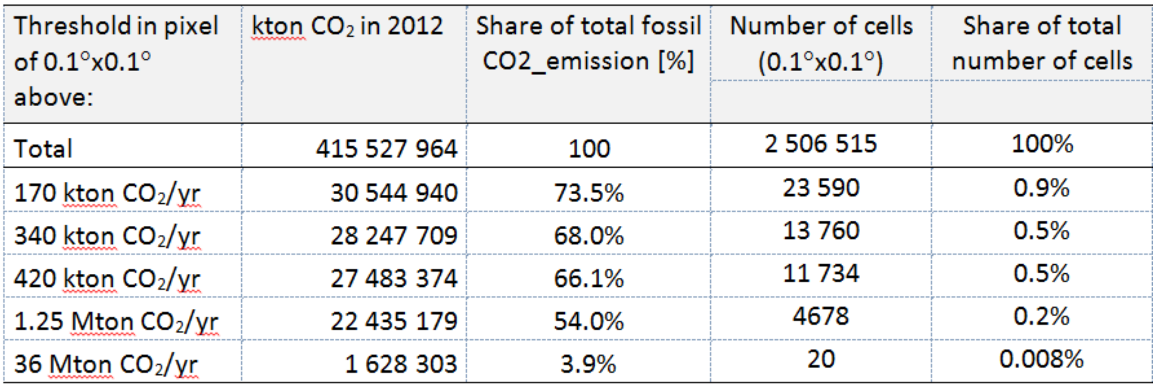
Using the Poor Man's Inversion Framework (proposed by the Laboratoire des Sciences du Climat et de l'Environnement, LSCE) (Table A 4.1) and the emissions gridmaps of EDGAR (Table A 4.2) or TNO-CAMS (Table A 4.3), a threshold of 7.5 kton CO_2/yr /pixel has been selected, corresponding to an averaged emission of 170 kton CO_2/yr normalised over the area of 0.1°x0.1°, and taking into account the different pixel size. The number of individual sources or pixels that emit twice as much (340 kton CO_2/yr/pixel) or more and also the group of very high sources emitting above 1000 kton CO_2/yr/pixel has been identified. The data below provides and indication of the structure of the sources.

Table A 4.1 - Share of the land emissions as a function of various detection thresholds, according to the study of Ciais et al. (2017). Note: Percentage of land area (2rd column) and of global fossil fuel CO_2 emissions (3rd column) above a fixed threshold set in the 1st column. Note that the size of a pixel is 1/120°x1/120°. The thresholds are chosen around the potential operational domain of the satellite imager.



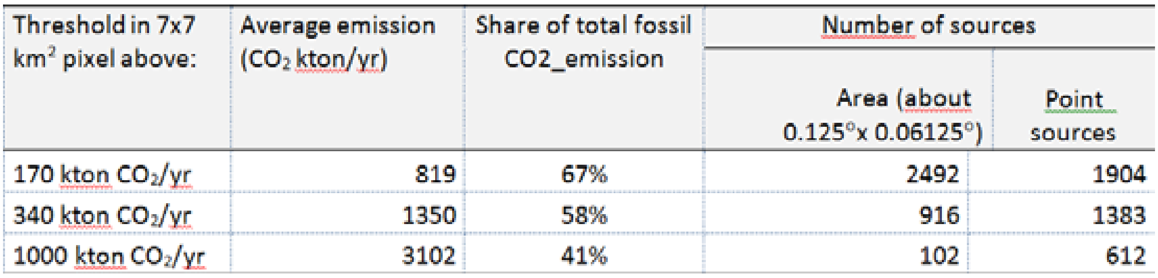
Threshold in pixel 0.0083°x0.0083° above:	Share of land emissions	Share of total fossil CO2 emission [%]	Number of cells (0.0083°x0.0083°)	Share of total number of cells
	100%	100%	933 120 000	100%
7.5 kton CO_2/yr	99.8%	56.8%	13 879	0.0015%
5.4 kton CO_2/yr	99.7%	60.9%	21 438	0.0023%
4.2 kton CO_2/yr	99.6%	64.0%	28 750	0.0031%
3.7 kton CO_2/yr	99.5%	66.4%	32 793	0.0035%
2.8 Mton CO_2/yr	99.4%	68.4%	43 172	0.0046%
2.4 Mton CO_2/yr	99.3%	70.1%	46 224	0.0050%

Table A 4.2 - Share of emission sources identified above various emission thresholds (kton CO_2/yr/(0.1°x0.1°) in the EDGAR emission grid (Figure 2a) to the total, and the number of grid cells globally.



Threshold in pixel of 0.1°x0.1° above:	kton CO_2 in 2012	Share of total fossil CO2_emission [%]	Number of cells (0.1°x0.1°)	Share of total number of cells
Total	415 527 964	100	2 506 515	100%
170 kton CO_2/yr	30 544 940	73.5%	23 590	0.9%
340 kton CO_2/yr	28 247 709	68.0%	13 760	0.5%
420 kton CO_2/yr	27 483 374	66.1%	11 734	0.5%
1.25 Mton CO_2/yr	22 435 179	54.0%	4678	0.2%
36 Mton CO_2/yr	1 628 303	3.9%	20	0.008%

Table A 4.3 - Number and type of sources identified above emission thresholds of 170, 340 and 1000 kton CO_2/yr/(1/8°x1/16°) in the TNO-CAMS emission grid (Figure 2b), the average source strength per group and the share of total fossil fuel CO_2 emissions in the domain.



Threshold in 7x7 km^2 pixel above:	Average emission (CO_2 kton/yr)	Share of total fossil CO2_emission	Number of sources	
			Area (about 0.125°x 0.06125°)	Point sources
170 kton CO_2/yr	819	67%	2492	1904
340 kton CO_2/yr	1350	58%	916	1383
1000 kton CO_2/yr	3102	41%	102	612

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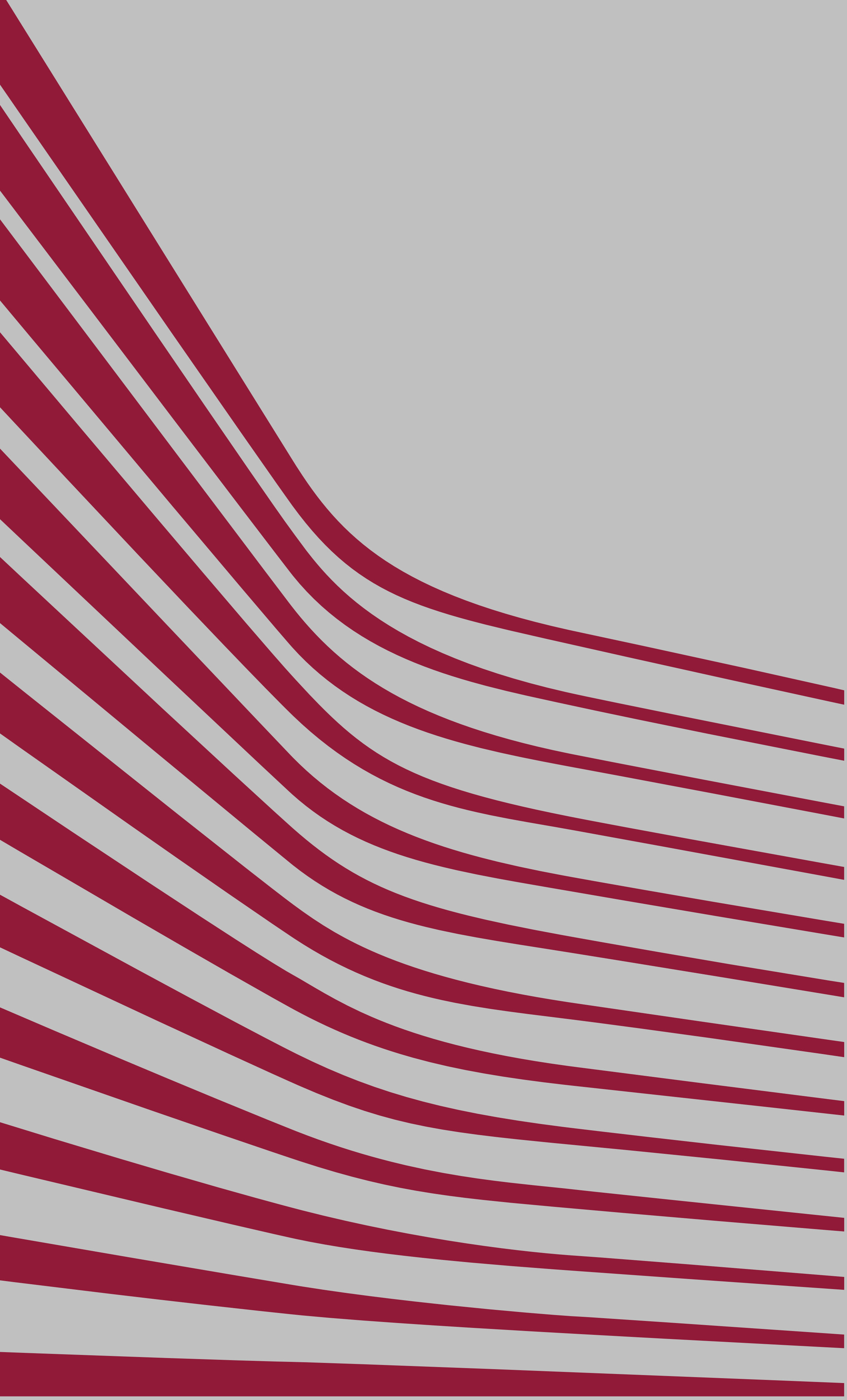

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