CoCO2

Prototype system for a Copernicus CO_2 service

Decision Support Blueprint

WP8

Co-ordinated by ECMWF

D8.5 Decision Support Blueprint

Dissemination Level:	Public/ Confidential
Author(s):	Glen Peters (CICERO), Robbie Andrew (CICERO), Ragnhild Børke (CICERO), Perugini Lucia (CMCC), A. M. Roxana Petrescu (VU Amsterdam), Richard Engelen (ECMWF)
Date:	19/12/2023
Version:	0.5
Contractual Delivery Date:	30/06/2023
Work Package/ Task:	WP8/T8.2
Document Owner:	CICERO
Contributors:	CICERO, VU Amsterdam, CMCC, ECMWF
Status:	Final

CoCO2: Prototype system for a Copernicus CO_2 service

Coordination and Support Action (CSA)
H2020-IBA-SPACE-CHE2-2019 Copernicus evolution – Research activities in support of a European operational monitoring support capacity for fossil CO2 emissions

Project Coordinator: Dr Richard Engelen (ECMWF)
Project Start Date: 01/01/2021
Project Duration: 36 months

Published by the CoCO2 Consortium

Contact:
ECMWF, Shinfield Park, Reading, RG2 9AX,
richard.engelen@ecmwf.int

The CoCO2 project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 958927.

Table of Contents

Figures

Tables

1 Executive Summary

The Copernicus CO_2 emissions Monitoring and Verification Support capacity (CO2MVS) is being developed to help support emission verification activities, particularly with the influx of new space-based observations (such as through CO2M). The proposed CO2MVS framework is made of several components: **prior information** (e.g., initial emission estimates) and **observations** (e.g., meteorology, satellites) that require **integration** (e.g., use of models) to produce **outputs** (e.g., revised emission estimates), that are then condensed into a **Decision Support System** (e.g., user functions). This deliverable is about the Decision Support System (DSS). The DSS translates the complex data and methods into a format that meets user needs, depending on the spatial and temporal scale of interest.

This Decision Support Blueprint is the first step in a process to develop the DSS as a part of the CO2MVS. This process will continue after CoCO2, taken up via the CAMS Implementation Team. This version of the Decision Support Blueprint has been through a review process mainly involving potential users of a DSS (inventory agencies). The blueprint also considers steps inventory agencies and the inverse modelling community can take to help developed the DSS, and user involvement with applications more broadly.

The CO2MVS landscape is growing given new demands stemming from the Paris Agreement and its Global Stocktake. New technology (e.g., new satellites) and improved methods and computing power (for inversions), also open new opportunities for monitoring and verification support. The IPCC reporting guidelines (2006 Guidelines and 2019 Refinement) give guidance on using verification to support National Greenhouse Gas Inventories (NGHGIs), and several countries are already applying verification methods in their national inventory reports. Through research projects, some inventory agencies are also exposed to ongoing verification activities, providing feedback, and preparing for longer term activities. The lessons learnt through various user events has helped to provide a clear path forward for a Decision Support Blueprint.

The current state-of-the-art in verification activities is to bring the different datasets together and make them comparable. The UK and Switzerland perform the most comprehensive comparisons in their national inventory reports, though several other countries do make comparisons. Generally, the comparisons confirm the general emissions levels and trends reported in the NGHGIs, but there is limited experience of these comparisons leading to changes in the NGHGIs, though exceptions exist (e.g., UK). It is hoped that new observations (e.g., CO2M) and closer collaboration will help move beyond the current state-of-the-art, to provide more concrete support into NGHGIs compilation.

The overall verification process using observations is still resource intensive, difficult, and often with unclear outcomes to justify investments. As a first step, there is a need for a simple representation of what is behind the observation-based inventories, what they represent, and what is their uncertainty. To make comparisons with NGHGIs that are not superficial, inventory agencies need more detailed data and understanding what causes the differences between inventory- and observation-based estimates: are differences due to an obscure methodological reason or is it evidence of a misreporting in the NGHGI. Inventory agencies and observation-based data providers still do not have a clear understanding of each other's needs, or a common understanding of the limitations of various methods. Inventory agencies probably need direct exchange with modellers and data providers, to explain and understand the inversions, suggesting that there may be a greater need to focus on specific case studies.

We have suggested six areas where we see the most productive gains to be made: 1) Building a common understanding and knowledge base, 2) Case studies, 3) Improving technical aspects of inverse modelling, 4) Graphical material and analysis tools, 5) Communication, and 6) Collaboration. Many of these activities have already been initiated but need to be improved and expanded.

2 Introduction

2.1 Background

The scientific community has long focused on understanding the relationship between emissions and atmospheric concentrations. Most research has focused around closing the biogeochemical cycles (Canadell et al. 2021), with particular attention on the global carbon budget (Friedlingstein et al. 2022), the global methane budget (Saunois et al. 2020), and the N_2O budget (Tian et al. 2020). It is now time to operationalise the science in a policy context. The Paris Agreement has essentially shifted the demands on the science community from diagnosing the problem to monitoring and verifying climate action (Peters et al. 2017). The five-yearly Global Stocktakes (GSTs) and ratcheting of policy ambition through updated Nationally Determined Contributions (NDCs) depend on contributions from the scientific community. Policy makers are putting faith in the science, by enhancing observational capabilities, such as through new satellite programmes (e.g., CO2M).

In the EU, a CO2 Monitoring Task Force translated the identified needs into a conceptual framework (Janssens-Maenhout et al. 2020): CO_2 emissions Monitoring and Verification Support (CO2MVS). The structure of the CoCO2 project directly maps to the proposed CO2MVS framework (Figure 1). The CO2MVS is made of several components: **prior information** (e.g., initial emission estimates) and **observations** (e.g., meteorology, satellites) that require **integration** (e.g., via models) to produce **outputs** (e.g., revised emission estimates), that are then condensed into a **Decision Support System** (e.g., user functions). The DSS is where a user can extract and present relevant information. It requires translating the complex material into a more comparable and digestible format for users, depending on the spatial and temporal scale of interest. However, to facilitate this it is necessary to understand several concepts associated with the entire CO2MVS framework.

Anthropogenic emissions have been estimated for several decades now (Andrew 2020), typically using **bottom-up** or **inventory-based approaches**. The term *bottom-up approach* can be ambiguous, as it means different things depending on the context. Generally, a bottom-up estimate is a collection of sub-estimates (e.g., at the sector level) which are then combined to get a total. Emission inventories are generally constructed with activity data (AD) times an emission factor (emissions per unit activity, EF). This is usually performed at the sector level. It is also the case that emissions can be estimated using models or observations, often outside of the notion of *bottom-up*. This is particularly the case in the land-based or agricultural sectors. The level of complexity of the estimate is often referred to as Tiers, with Tier 1 the simplest and Tier 3 the most complex. For this reason, the term *inventory-based approach* may be more appropriate than 'bottom-up' as it refers directly to the emission inventories that countries construct and report to the UNFCCC[1] based on the IPCC guidelines (IPCC 2006). Most countries construct their own emission estimates (e.g., as reported to the UNFCCC), but some organisations make country-level estimates (e.g., EDGAR[2]). Emission inventories can be at different spatial and temporal scales (e.g., country-level annual estimates versus gridded monthly estimates). For a more extensive discussion of the history of CO_2 estimates and why they vary, refer to Andrew (2020).

It is also possible to estimate emissions using what is known as a **top-down**, **observation-based**, or **inversion-based approach**. In a *top-down approach* aggregated information, usually based on observations, is used to estimate emissions indirectly. This method works well for trace gases with long lifetimes that have few natural sources and sinks. A simple example is the use of globally averaged observations of SF_6 concentrations combined with a simple first-order chemical decay equation to estimate globally average SF_6 emissions. To obtain the spatial distribution, or regional level emission estimates, requires use of additional

[1] United Nations Framework Convention on Climate Change (UNFCCC)

[2] Emissions Database for Global Atmospheric Research (EDGAR)

observational data and linking to a more complex model with transport of trace gases. For trace gases with shorter lifetimes or natural sources and sinks, such as CO_2 and CH_4, additional observational information is needed on the sources and sinks together with a model of atmospheric transport. Even though CO_2 has a long lifetime, it has complex interactions with the ocean and land sinks, requiring the use of a carbon-cycle model. CH_4 has a relatively short lifetime (about a decade) but has a complex chemical interaction with other species in the atmosphere, via the OH radical, requiring a chemical transport model. An **inverse model** is often used to estimate emissions from observations. An inverse model is not dissimilar to the simple first-order decay equation for SF_6, just considerably more complex and data intensive. This complexity is essentially why a CO2MVS is needed and explains the dominance of the boxes on **observations** and **integration** (Figure 1).

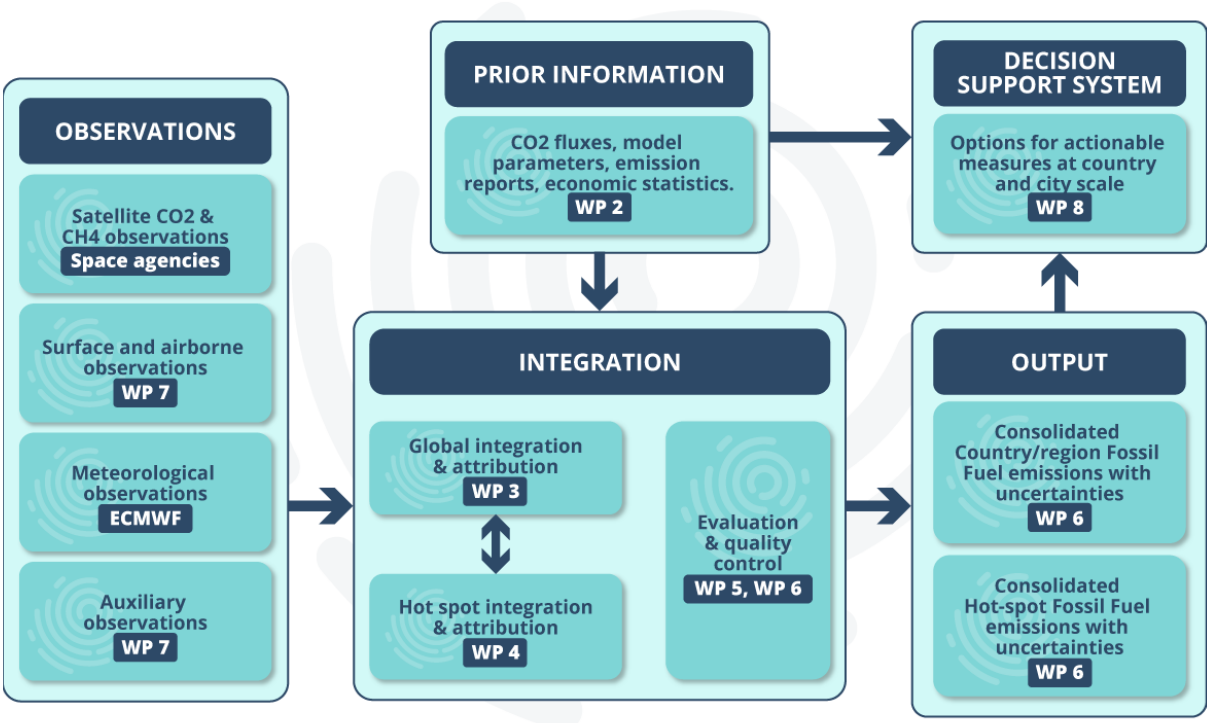


Figure 1: The CO2MVS and linkages to Work Packages in CoCO2.

The existence of top-down and bottom-up approaches, or, preferably, inventory- and observation-based approaches, is where the notion of **verification** arises and why a **Decision Support System** is needed. If an inventory agency estimates their country's emissions following the IPCC guidelines, then those estimates may need to be compared with independent estimates. While obtaining estimates that are fully independent of inventories is rarely possible (Petrescu et al. 2020), those provided by observation-based approaches may serve this purpose reasonably well. Providing independent estimates is a complex process. Depending on the trace gas there needs to be a sufficient observational network (ground- or space-based), particularly to resolve country-level estimates. Inversion approaches can be differentiated into those that provide a sectoral resolution (e.g. CCFFDAS (Kaminski et al. 2022)) and those that don't (see CHE Deliverable 5.6).

Observational-based approaches have been used to identify reporting problems with CO_2 emissions in China (Akimoto et al. 2006), CH_4 in China (Cheewaphongphan, Chatani, and Saigusa 2019), HFCs in Europe (Keller et al. 2011) and China (Rigby et al. 2019), to name a few examples. However, the current observational networks and modelling capacity are not sufficient to routinely resolve country-level estimates in most countries to sufficient accuracy, particularly for the key greenhouse gases CO_2, CH_4, and N_2O (Deng et al. 2022; Byrne et al. 2023). The current CO2MVS developments are largely in preparation for an influx of space-based observations, which will complement but not replace ground-based observations. At a minimum, land-based observations are still needed as an important calibration tool to the more extensive space-based observations (also see CoCO2 Deliverable 6.7).

To prepare for the influx of observational data and new inversion results the CAMS CO2MVS, this deliverable is a first step in preparing a DSS. There is increasing activity comparing inventory-based and observation-based emission estimates, primarily in the scientific literature (Andrew 2020; Petrescu, et al. 2021a,b; Petrescu et al. 2020;) but also in some National Inventory Reports (e.g., Switzerland or UK). This existing work will act as a starting point, together with dialogues between researchers and inventory agencies in the EU projects VERIFY and CoCO2, and similar ongoing activities (EYE-CLIMA, AVENGERS, Paris).

2.2 Scope of this deliverable

2.2.1 Objectives of this deliverable

The **objective** is to develop a *blueprint* for a DSS, with a focus on useable *graphical and analytical comparisons* of inventory-based and observation-based emission estimates at the country level. As a *blueprint*, this deliverable is considered one step in a much longer path towards an operational DSS.

In principle, the DSS is quite broad, and targets different user groups both at global, regional (e.g., EU), national, and sub-national (e.g., city) level. However, in this deliverable, we focus primarily on the country level and how independent inventory-based and observation-based approaches can be used to monitor and support emissions that are reported to the UNFCCC. Consequently, the **primary user group** of the DSS envisaged in this deliverable is national inventory agencies. Other users of a DSS could include scientists, city-scale inventory agencies, policymakers at various levels, etc.

The DSS is only one potential element of the inventory compilation process. The UNFCCC process also has quality assurance, quality control, verification, and review processes. However, verification by observational methods is far less developed. This deliverable, and the DSS more broadly, is focussed on observation-based verification and support methods.

This deliverable will focus on tools and methods to compare different estimates of emissions, in a format that is easily accessible and understandable to the users. We recognise that users will come from very different backgrounds and levels of expertise, and the DSS will need to cater for this. As with many situations of tracking progress, our general approach is to start with a broad and aggregated perspective, and then iteratively zoom in until the necessary level of detail is reached (c.f., Peters et al 2017). We expect some users to go beyond the level of detail possible in a generic DSS, and we will therefore explore different reporting formats, with suggested tools to automate the development of a range of quality outputs.

A preliminary version of the Decision Support Blueprint was delivered in January 2023 (CoCO2 D8.4). The ideas have been presented and discussed in user consultation meetings and through a written consultation in the first half of 2023. This document is an updated version, considering the feedback received from potential inventory agency users and the scientific community.

2.2.2 Intended audience

While the primary users of the DSS in this report are inventory agencies, the recommendations in this report are targeted to the **CAMS Implementation Team**, who will be responsible for the further development of the DSS and who will codesign and codevelop the DSS.

A second audience are those working on country-level emission estimates, such as national inventory agencies, policy makers at national and regional level, but this will more broadly encompass the European Commission CO2 Monitoring Taskforce and those developing the CO2MVS and its components.

A third audience is the scientific community which will generate much of the data products in the CO2MVS, and user communities interested in smaller spatial and temporal details. The relevant spatial scales could be regions, countries, cities, companies, and point sources.

2.2.3 Work performed in this deliverable

The initial version of this document was based on document analysis, informal discussions with scientists and users (D8.4), while this version additional includes written consultation of potential users and scientific communities.

2.2.4 Deviations and counter measures

Not applicable

3 Current verification activities involving users

This section gives an overview of the current verification ecosystem in the context of emission inventories, the use of atmospheric observations for verification or supporting the construction of NGHGIs in a broader sense, and a summary of various relevant user interactions. This acts as a basis for outlining the current knowledge gaps that can be addressed in the decision support blueprint (Section 4).

3.1 Overview of the verification ecosystem

Under the UNFCCC, official reporting of national greenhouse gas emission inventories (NGHGIs) is currently required by a subset of countries (Annex I, mainly developed countries). According to the Enhanced Transparency Framework of the Paris Agreement, from 2024 onwards, reporting will be required by all Parties to the Paris Agreement, either annually (developed countries) or biennially (developing countries). The UNFCCC and the Enhanced Transparency Framework of the Paris Agreement follows the IPCC reporting guidelines (IPCC 2006), which now have expanded provisions for quality assurance, quality control, and verification (IPCC 2019). According to the IPCC guidelines glossary:

> **Quality Assurance** (QA) activities include a planned system of review procedures conducted by personnel not directly involved in the inventory compilation/development process to verify that data quality objectives were met, ensure that the inventory represents the best possible estimate of emissions and sinks given the current state of scientific knowledge and data available, and support the effectiveness of the quality control (QC) programme.
>
> **Quality Control** (QC) is a system of routine technical activities, to measure and control the quality of the inventory as it is being developed. The QC system is designed to:
>
> i. Provide routine and consistent checks to ensure data integrity, correctness, and completeness;
> ii. Identify and address errors and omissions;
> iii. Document and archive inventory material and record all QC activities.
>
> QC activities include general methods such as accuracy checks on data acquisition and calculations and the use of approved standardised procedures for emission calculations, measurements, estimating uncertainties, archiving information and reporting. More detailed QC activities include technical reviews of source categories, activity and emission factor data, and methods.
>
> **Verification** refers to the collection of activities and procedures that can be followed during the planning and development, or after completion of an inventory that can help to establish its reliability for the intended applications of that inventory. Typically, methods external to the inventory are used to check the truth of the inventory, including comparisons with estimates made by other bodies or with emission and uptake

measurements determined from atmospheric concentrations or concentration gradients of these gases.

Understanding these definitions and the associated processes is important. Emission inventories reported to the UNFCCC by the so-called Annex I countries (essentially developed countries) already undergo formal and extensive QA/QC (Perugini et al. 2021) and is something that other independent inventory compilers do not go through, with the exception of the irregular peer review process in scientific journals (Janssens-Maenhout et al. 2019). Given the already existing QA/QC procedures, one expects that emission inventories reported by Annex I countries to the UNFCCC have the highest quality. The QA/QC identifies problems, all of which must be addressed, and thus one can clearly see an evolution of inventory estimates over time as improvements are made (Figure 2).

The **verification** process is to ensure the reliability of the inventory estimates, for their intended purpose, and in the IPCC Guidelines verification includes both inventory-based comparisons and observation-based comparisons. While for some sectors, countries, or GHGs the estimates may be accurate and well beyond the capability of current observation-based approaches, even with a QA/QC system, there are cases where independent verification can help support the improvement of inventories. Given the uncertainties in land CO_2 fluxes, CH_4, or N_2O the observation-based estimates may be a powerful complementary method to support inventory-based approaches in regions with sufficient observations, with less obvious gains in the short term for fossil CO_2 emission inventory estimates as they generally have lower uncertainty. The UNFCCC inventories already do comparisons of the sector-based estimates with a less accurate reference approach, which is one form of verification that can identify mass balance inconsistencies. A careful comparison across independent inventory-based approaches can reveal causes of differences (Andrew 2020; Deng et al. 2022) and identify errors (e.g., CoCO2 D8.1 on EIA estimate of oil).

Beyond formal verification, as defined in the IPCC guidelines, observation-based methods can be used to improve the inventory-based methods in a broader sense. In most cases, the pathway is that a discrepancy between atmospheric information and inventory information is identified; the inventory methodology is probed to identify where known (but often poorly constrained) uncertainties and biases may occur; the inventory is re-assessed. As an example, the discrepancies may be attributed to poorly constrained emission factors, which is then revised and results in a better consistency between the inventory and atmospheric information.

When an improvement in methodologies, emissions factors or activity data is available (whether this has been triggered by atmospheric observations or other information), the whole time series of the relevant emissions sector is recalculated. Figure 2 illustrates that for certain sectors, recalculations may lead to significant changes in the emissions estimates. For Russian energy sector CH_4 emissions, revisions have been substantial, indicating a potentially fruitful sector for inversion activities. For the UK HFC-134a emissions, inversions have been used to improve emission factors and bring the inventory and inversion results together over time, representing a successful application of inversions to improve inventories (Manning et al. 2021; WMO 2018).

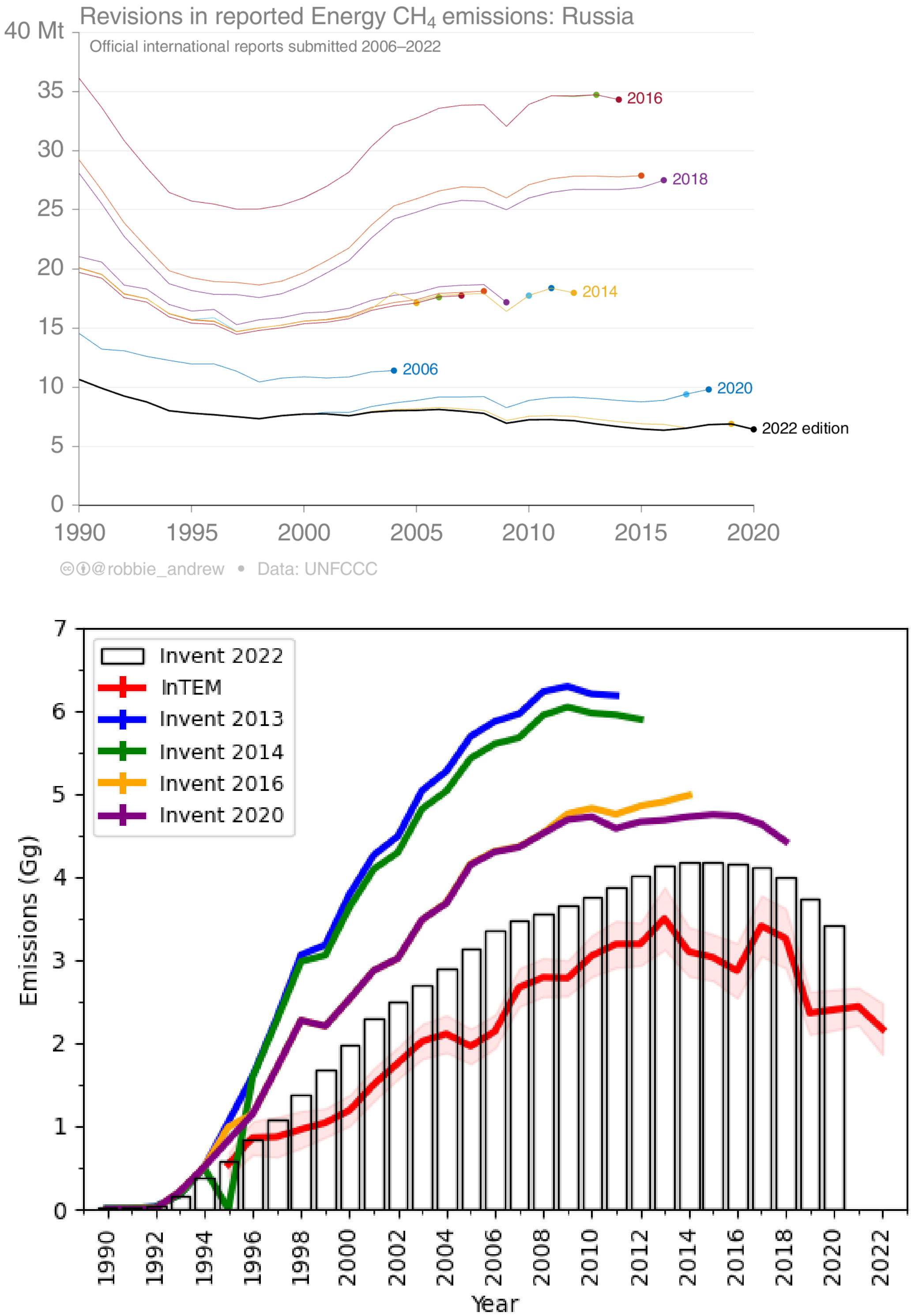


Figure 2: Recalculations in reported CH_4 emissions from Russia in the energy sector (top) and HFC-134a in the UK (bottom), demonstrating how different versions of the inventories have different estimates. The top panel shows revisions to Russian CH_4 emissions, with each line indicating the edition of the different inventory reports (as N-2). The bottom panel shows successive revisions to the UK inventory (Invent) based on inversion results (InTEM), figure provided by Alistair Manning (Manning et al. 2021; WMO 2018).

3.2 Verification practices in official UNFCCC national inventory reports

It is good practice to implement quality assurance/quality control (QA/QC) and verification procedures in the development of national greenhouse gas inventories to ensure that the quality of the inventory can be readily assessed. Verification refers specifically to those methods that are external to the inventory and apply independent data. There are two main methods of verification: 1) independent inventory-based estimates, 2) observation-based emission estimates.

A challenge with comparisons against *independent inventory-based estimates* is that none are truly independent (Andrew 2020) as they may rely on, for example, the same energy data reported by a country. Experience has shown that performing detailed comparisons can help clarify differences in system boundaries or even identify errors (Andrew 2020). Improving independent emission inventories also has value, as these are often used in global studies where common methods across all countries are desired.

Observation-based estimates require observations of atmospheric concentrations or fluxes, that are then coupled to a transport model. These methods are often more complex, uncertain, and computationally expensive, but are also more independent and globally consistent than inventory-based comparisons (although inversions do need prior input on inventories).

In both cases, correspondence between the NGHGI and independent estimates increases the confidence and reliability of the inventory estimates by confirming the results. Since most developed countries have reported UNFCCC inventories for decades and these have been continually refined, most focus is on observation-based estimates. As an increasing number of developing countries begin more detailed and frequent reporting, comparisons with independent emission inventories will initially be an important method of verification for those countries.

In the 2019 refinement of the IPCC guidelines, the guidance on the use of *observation-based* methods for verification was extended (IPCC 2019). The refined guidelines highlight that notable advances that have been achieved in the application of inverse models of atmospheric transport for estimating emissions at national scale. Consequently, there are several countries that now use atmospheric measurements for verification of parts of their inventories (Table 1). Several countries use observations to help validate estimates of fluorinated gases as they are most easy to work with due to the absence of natural sources. Australia and New Zealand have estimated regional CH_4 emissions to help better understand the methods and their potential. Germany performs various cross validation checks with available data, some of which is based on observations. The UK and Switzerland, however, have developed more comprehensive methods based on inverse modelling, covering fluorinated gases in addition to CH_4 and N_2O. Building on modelling experience, the country reporting confirms that most potential lies in using observations to verify fluorinated gases, the uncertainty in CH_4 and N_2O gives potential for verification but requires more comprehensive inverse modelling, while challenges remain high to verify CO_2 emissions from both fossil and land sources.

Table 1: Current use of atmospheric measurements for verification (as reported in respective National Inventory Reports 2020, published in 2022)

Country	Gases	Notes
Australia	HFCs, SF_6	HFCs and SF_6 estimates done by CSIRO based on observations at the Cape Grim Baseline Air Pollution Station in Tasmania
	CH_4 (one year, one region)	In 2019, the CSIRO undertook analysis of CH_4 plumes in the Surat Basin, Queensland, using two flux towers to obtain a 'top-down' estimate of CH_4 emissions, & the regional estimate was within 10% of the top-down estimate
Germany	CO_2, CH_4, N_2O	Verified with the help of the data sets recommended by the 2019 IPCC Refinements: EDGAR inventory, ECMWF's CAMS inverse-modelling data, Pollution Release and Transfer Register (PRTR), EU's Emission Trading System (ETS). The data are compared on Figure 104 (NIR, 2022), with a descriptive discussion of differences.
New Zealand	CO_2, CH_4 (regional)	Inverse modelling was tested on regional and national emission estimates for 2011 to 2013 and 2018 using two observing stations. For the South Island results were reasonable, but more observations & research is required. The North Island results are not as robust.
Switzerland	HFCs, SF_6	Selected observations from Jungfraujoch are used with a simple formula to estimate emissions, with a discussion of divergences for each species.
	CH_4, N_2O	Inverse modelling used to validate total Swiss CH_4 and N_2O emissions, particularly the spatial extent, using Swiss observations. Due to variability & uncertainty, it is not possible to validate the reported emissions.
UK	(CO_2), CH_4, N_2O, HFCs, PFCs, SF_6, NF_3	Inversions are based around observations at Mace Head and supplemented with additional observations since 2012. A dispersion model is used with data from different sites for each species. Results for each species is discussed. Methods for verifying CO_2 estimates are being improved.
USA	HFCs	Additional quality control is performed by comparing the emission estimates derived from atmospheric measurements to the bottom-up emission estimates. Given the magnitude of the uncertainties relative to the size of any apparent emission changes, and the limited time-period of the analysis, overall trends in most of the gases are hard to discern with confidence except in the case of HFC-32.

It is important to understand why there are different challenges, and thereby opportunities, using observation-based emission estimates. These challenges and opportunities vary by the different greenhouse gases (IPCC 2019) and are now discussed in turn.

Fossil CO_2: Estimated uncertainties in inventories of fossil CO_2 emissions are generally quite low in developed countries (a few percent for annual estimates), making it challenging for observation-based approaches to provide useful input. The opportunities are larger in developing countries, where studies identified problems with Chinese CO_2 emission estimates around the year 2000 (Akimoto et al. 2006). Currently, observation-based approaches focus on the use of observations of co-emitted NO_x/CO, but as more space-based observations of CO_2 emerge this may change. Recent studies have shown that fossil CO_2 emissions can be estimated from atmospheric observations of CO_2 and $\Delta^{14}CO_2$ (Basu et al. 2020; Byrne et al. 2023).

Land CO_2: Inventories of land-based CO_2 emissions are highly uncertain, but large natural sources and sinks make verification of anthropogenic sources difficult. There are also significant challenges with how anthropogenic land CO_2 fluxes are defined (Grassi et al. 2018). However, there are multiple approaches to verify land-based CO_2 emissions (inventories, process models, inversions), and thus this is a fruitful area to make progress (Steinkamp et al. 2017; Deng et al. 2022; Petrescu, McGrath, et al. 2021; McGrath et al. 2023).

CH_4: Even though inversions currently have high uncertainty, verification of CH_4 emissions is still possible since the inventories are also uncertain (Petrescu et al. 2020; Petrescu, Qiu, et al. 2021; Petrescu et al. 2022; Saunois et al. 2020). In geographic areas with sufficiently strong ground-based observation networks, the inversions will have more value. In some cases, natural emissions, their extent and their seasonality can be additional challenges.

N_2O: As for CH_4, N_2O emissions are a good candidate for inverse modelling since the inventories have high uncertainty, which may compensate for the high uncertainty in the inversions. Again, a strong ground-based observational network in the relevant geographic area could improve the inversion.

Fluorinated gases: The use of atmospheric measurements is currently most prevalent for F-gases (HFCs, PFCs, SF_6). F-gases are particularly well suited for inverse modelling as they are solely of anthropogenic origin and are often sufficiently long-lived. In addition, bottom-up inventories for F-gases are generally derived from very limited data and simple models and therefore have large uncertainties. As a positive example, the UK has modified its inventory of HFC-134a based on the outcome of inversion analysis (Manning et al. 2021).

This short summary by GHG is consistent with the activities seen in individual countries (Table 1). Nearly all countries using observation-based verification consider fluorinated gases. The analysis is essentially embedded in the inventory-based estimates of emissions, as the inventory-based estimates suffer from insufficient data and high uncertainties. The countries with the most elaborate verification activities (UK and Switzerland) focus on CH_4 and N_2O, which represent a good opportunity for verification. Other countries have explored CH_4 inversions at a regional level where there is higher uncertainty (e.g., leaks in oil and gas infrastructure). No country has yet performed detailed verification for CO_2, either fossil- or land-based, indicating the challenges (Germany does a comparison with off-the-shelf inversion results).

One element that is clear from the country activities is that they generally focus on single models. Much of the inversion analysis in the research community, however, uses multiple models. Inventory agencies, so far, seem to prefer individual models or studies, where they can perform a more detailed analysis and interpretation of the results. The countries doing the most elaborate inversion analysis also have a close working relationship with the inventory agencies and the inverse modelers, indicating that sufficient resources are needed to do a sufficiently detailed analysis for an inventory report.

3.3 Feedback from user experiences with verification

3.3.1 Key activities

There have already been considerable efforts to build competence with verification activities. The work of the European Commission CO_2 Monitoring Task Force laid the foundation for EU funded projects such as CHE (2017-2020), VERIFY (2018-2022), and CoCO2 (2021-2023). Three new EU projects started in 2023 (EYE-CLIMA, AVENGERS, Paris). The US National Academies formed a committee to write a report on Greenhouse Gas Information for Decision Making, which covers many relevant aspects of a CO2MVS. Many individual countries are ramping up activities, particularly given the influx of data and opportunity to come with new satellites (e.g., CO2M). The IPCC already gives guidance to using verification to complement existing QA/QC activities (IPCC 2019). The present Decision Support Blueprint builds on this work. Here we indicate key documents from specific projects that provide information on user needs and experiences.

The European Commission CO_2 Monitoring Task Force provides 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:

- CO_2 Blue Report (2015)[3]: Assesses the need and opportunity for an independent European space-borne observation capacity for CO_2 to monitor and to verify the compliance of parties to international climate agreements (Ciais et al. 2015).
- CO_2 Red Report (2017): Describes the baseline requirements, functional architecture and system elements needed to implement an operational CO2 Monitoring and Verification Support capacity (Pinty et al. 2017).
- CO_2 Green Report (2019): Describes the needs and high-level requirements of in situ measurements to help establish an operational Monitoring & Verification Support (MVS) capacity to quantify anthropogenic CO_2 emissions (Pinty et al. 2019).
- The reports are summarised in a scientific publication: Janssens-Maenhout *et al* (2020), Toward an Operational Anthropogenic CO_2 Emissions Monitoring and Verification Support Capacity, *Bulletin of the American Meteorological Society (BAMS)*.

Most relevant deliverables from the EU Horizon 2020 Coordination and Support Action “CO_2 Human Emissions” (CHE[4]):

- D1.3 Reconciliation of top-down and bottom-up estimates of the carbon balance
- D1.4 Stakeholder report on the requirements for future space-based instruments to deliver products suitable for CO2 emission monitoring

Most relevant deliverables from the EU Horizon 2020 Research and Innovation Action “Observation-based system for monitoring and verification of greenhouse gases” (VERIFY[5])

- Work Package 1: Inventories
    - D1.1 MRV User Requirement Document
    - D1.2 Terminology analysis
    - D1.4 Verification requirements assessment
    - D1.5-D1.7: First, second, and third ad hoc meeting for networking between national inventory agencies and the scientific community
    - D1.8: Report on the connection of VERIFY and the IPCC process
- Work Package 5 & 6: Synthesis and Products
    - A comparison of estimates of global carbon dioxide emissions from fossil carbon sources, *Earth System Science Data* (Andrew 2020)

[3] It appears that this report was completed before the task force was formally established
[4] https://www.che-project.eu/resources
[5] https://verify.lsce.ipsl.fr/index.php/repository/public-deliverables

    - European anthropogenic AFOLU greenhouse gas emissions: a review and benchmark data, *Earth System Science Data* (Petrescu et al. 2020)
    - The consolidated European synthesis of CH_4 and N_2O emissions for the European Union and United Kingdom: 1990–2017, *Earth System Science Data* (Petrescu, Qiu, et al. 2021)
    - The consolidated European synthesis of CO_2 emissions and removals for the European Union and United Kingdom: 1990–2018, *Earth System Science Data* (Petrescu et al. 2021b)
    - The consolidated European synthesis of CH_4 and N_2O emissions and removals for the European Union and United Kingdom: 1990–2020, *Earth System Science Data* (Petrescu et al. 2023)
    - D6.11: Report on the future operational transition of the VERIFY observation-based GHG monitoring system
- Work Package 7: Input to international programs and society
    - D7.6: First progress report on the VERIFY cooperation with the GEO initiative on C and GHG
    - D7.9: Second and final report on the research needs for verification
    - D7.11: Second and final progress report on the VERIFY cooperation with Global Initiatives including UNFCCC/ SBSTA, GCOS and WMO/IG3IS

Key deliverables EU Horizon 2020 Coordination and Support Action “Prototype system for a Copernicus CO_2 service” (CoCO2[6]):

- D6.1 Fact sheets with national observation-based carbon budgets from T6.1 for year 2021
- D6.2 Scientific review article on carbon budgets for year 2021
- D6.3 User Requirement Document
- D6.4 Functional Requirements Specification Documents
- D6.5 Emission estimates for year 2021
- D6.6 Fitness for Purpose Documents
- D8.1-8.3 Budget Estimates for CO2 and CH4 V1-3
- D8.4-8.5 Decision Support Blueprint (this document)

The US National Academies Committee on Development of a Framework for Evaluating Global Greenhouse Gas Emissions Information for Decision Making:

- Greenhouse Gas Emissions Information for Decision Making: A Framework Going Forward (National Academies of Sciences, Engineering, and Medicine 2022)

IPCC

- 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2006)
- 2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC 2019)
- IPCC Expert Meeting on Use of Atmospheric Observation Data in Emission Inventories (5-7 September 2022)

Various governmental, intergovernmental, and non-governmental bodies have closely connected activities (see VERIFY D7.6, D7.11)

- UNFCCC (through COPs and SBSTAs)
- Group on Earth Observations (GEO)
    - GEO Carbon and Greenhouse Gas Initiative (GEO-C)
- World Meteorological Organization (WMO)
    - Integrated Global Greenhous Gas Information System (IG3IS)

[6] https://coco2-project.eu/resources

  - Global Greenhouse Gas Watch (GGW)[7]
  - Global Atmosphere Watch Programme (GAW)[8]
- Integrated Carbon Observation System (ICOS)
- Global Carbon Project (GCP)
  - REgional Carbon Cycle and Assessment Processes (RECCAP 1 & 2)
- Global Emissions InitiAtive (GEIA)

3.3.2 The VERIFY fact sheets

Through the VERIFY project several synthesis studies were performed (Andrew 2020; Petrescu, Qiu, et al. 2021; Petrescu et al. 2020; Petrescu, McGrath, et al. 2021). these synthesis studies were restricted to the aggregated EU level, with only little detail at the country level. However, the key synthesis figures for each country and region were compiled into “fact sheets”. There is an individual fact sheet for fossil CO_2, land CO_2, CH_4, and N_2O. These fact sheets are compiled for 79 countries and regions (individual countries in Europe, plus a variety of aggregations to make the content more relevant for policy or more scientifically robust due to the size of the region). This means that there are over 300 individual fact sheets. Because of this, the process is highly automated and the text on each fact sheet is general (Figure 3). In addition to the fact sheets, the VERIFY website hosts additional figures and the data behind them.

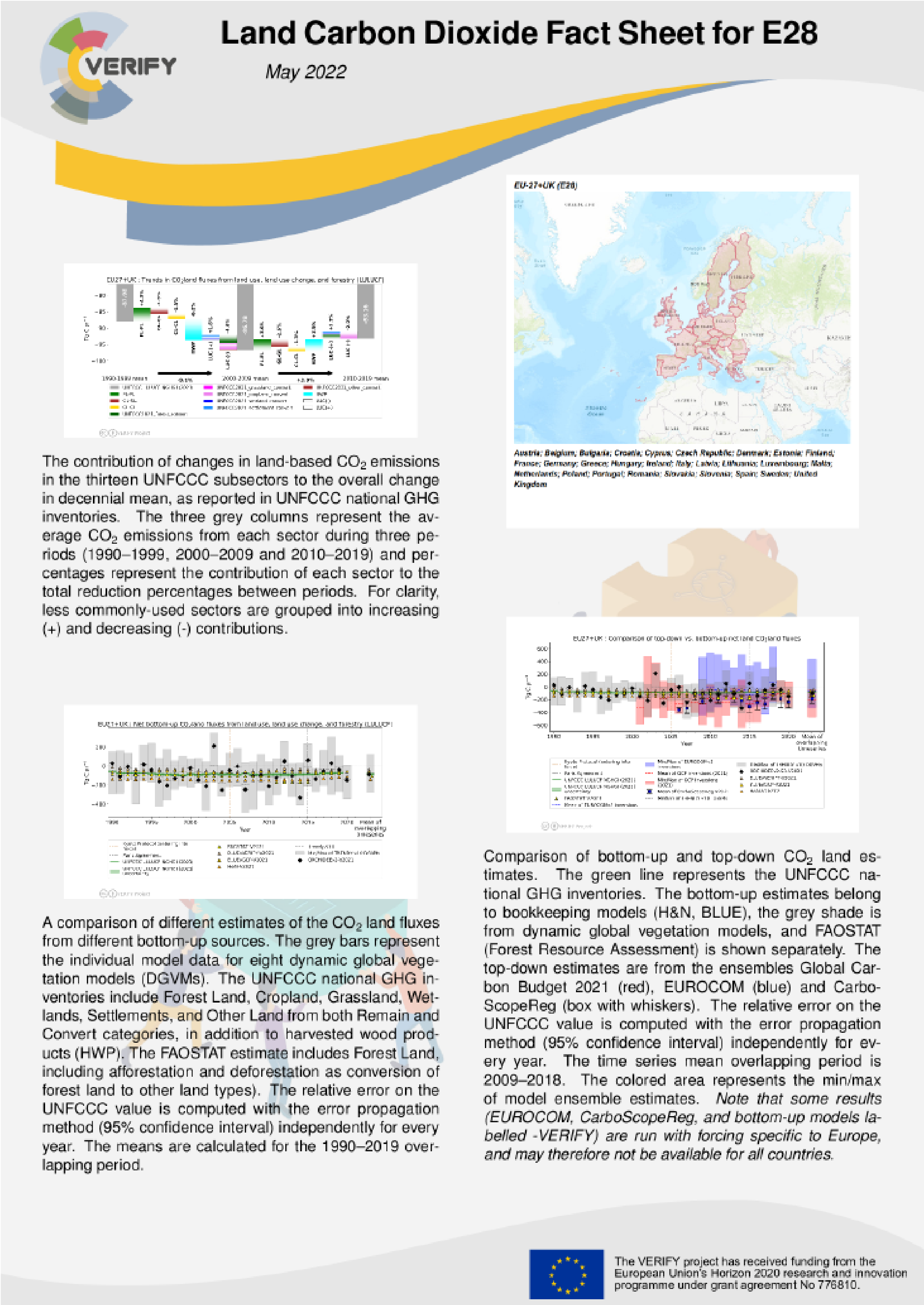
The VERIFY fact sheets completed one milestone, which was to compile all the information in an accessible, and necessarily automated, format. Many of the figures are too complex for the untrained reader to fully understand but also have limited utility to a user that wants to do more than a simple comparison of datasets. The goal in CoCO2 was to build on, improve, and expand the figures used in the fact sheets, to find ways to make them more accessible to users, without having the burden of users compiling the data and constructing independent figures. These figures have evolved though D6.1, 6.2, D8.1-3, and this document (D8.4-5). It is further necessary to develop and transition the VERIFY operational software into the CO2MVS system (VERIFY D6.11[9]).

3.3.3 VERIFY Inventory Networking Meetings

Through the VERIFY project three networking meetings between the project partners and inventory agencies were organised. Based on the final networking meeting, organized in May 2022, some key elements about the feedback from the inventory compilers are summarized in this section. The feedback from the inventory compilers was based on their work with VERIFY data products throughout the project.

A recurring topic was the need to build **competence** in inventory agencies. The starting point for most inventory agencies was a very limited knowledge of inverse modelling. Consequently, there was a broad request for an approach that would not require previous knowledge (“inversion for dummies”). Some of the inventory agencies would welcome specific training in the use of data products, e.g., through workshops and guided hands-on training with Jupyter notebooks. While building competence in inventory agencies was considered crucial, it was also strongly emphasised that continual cooperation between scientists and inventory compilers would be needed. Switzerland was used as an example of how inventory compilers and scientists have worked together for a decade on how to use observational data for inventory compilation.

7 https://public.wmo.int/en/our-mandate/focus-areas/environment/greenhouse-gases/global-greenhouse-gas-monitoring-infrastructure
8 Global Atmosphere Watch Programme (GAW) | World Meteorological Organization (wmo.int)
9 Report on the future operational transition of the VERIFY observation-based GHG monitoring system



Land Carbon Dioxide Fact Sheet for E28

May 2022

The contribution of changes in land-based CO_2 emissions in the thirteen UNFCCC subsectors to the overall change in decennial mean, as reported in UNFCCC national GHG inventories. The three grey columns represent the average CO_2 emissions from each sector during three periods (1990–1999, 2000–2009 and 2010–2019) and percentages represent the contribution of each sector to the total reduction percentages between periods. For clarity, less commonly-used sectors are grouped into increasing (+) and decreasing (-) contributions.

A comparison of different estimates of the CO_2 land fluxes from different bottom-up sources. The grey bars represent the individual model data for eight dynamic global vegetation models (DGVMs). The UNFCCC national GHG inventories include Forest Land, Cropland, Grassland, Wetlands, Settlements, and Other Land from both Remain and Convert categories, in addition to harvested wood products (HWP). The FAOSTAT estimate includes Forest Land, including afforestation and deforestation as conversion of forest land to other land types). The relative error on the UNFCCC value is computed with the error propagation method (95% confidence interval) independently for every year. The means are calculated for the 1990–2019 overlapping period.

EU-27+UK (E28)

Austria; Belgium; Bulgaria; Croatia; Cyprus; Czech Republic; Denmark; Estonia; Finland; France; Germany; Greece; Hungary; Ireland; Italy; Latvia; Lithuania; Luxembourg; Malta; Netherlands; Poland; Portugal; Romania; Slovakia; Slovenia; Spain; Sweden; United Kingdom

Comparison of bottom-up and top-down CO_2 land estimates. The green line represents the UNFCCC national GHG inventories. The bottom-up estimates belong to bookkeeping models (H&N, BLUE), the grey shade is from dynamic global vegetation models, and FAOSTAT (Forest Resource Assessment) is shown separately. The top-down estimates are from the ensembles Global Carbon Budget 2021 (red), EUROCOM (blue) and CarboScopeReg (box with whiskers). The relative error on the UNFCCC value is computed with the error propagation method (95% confidence interval) independently for every year. The time series mean overlapping period is 2009–2018. The colored area represents the min/max of model ensemble estimates. *Note that some results (EUROCOM, CarboScopeReg, and bottom-up models labelled -VERIFY) are run with forcing specific to Europe, and may therefore not be available for all countries.*

The VERIFY project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 776810.

Figure 3: An example of one of the more than 300 VERIFY fact sheets, showing land CO_2 emissions in the EU28.

The inventory agencies need to understand **what lies behind the data** from inverse models. In this respect inventory agencies pointed out several challenges. The variations in system boundaries (e.g., geographical and sectorial scopes) of the inverse models constituted a limitation for making comparisons with inventory data. Inventory agencies would need more information about the system boundaries and would ideally like data products to be further aligned to the IPCC inventory guidelines. Similarly, from the perspective of the inventory agencies, it would be an advantage to use the terminology from IPCC inventory guidelines.

There are **large variations in the estimates** from different observation-based approaches. Inventory compilers need to understand what causes these variations and how to choose among the various estimates or whether it is feasible to use a compilation of all available estimates. Furthermore, information on what data has been used as input to each top-down estimate were requested, as well as clear descriptions of the uncertainties in the models. Another challenge is that inverse models produce results close to the prior information if there is not sufficient information to shift the model emissions away from the prior. This may falsely be interpreted as if the model confirms the inventory (if this is used as prior). There is a need to find ways to communicate whether results depend strongly on prior information, as this information is generally within the inversion analysis.

In addition to clearer communication of what is behind the data, some questions that were raised during the networking meetings would require **further improvements** in the top-down modelling and/ or in the interpretation of the results. First, uncertainties in top-down models are often very large. These uncertainties need, in many cases, to be reduced before the results become useful for verification purposes. Second, the spatial resolution of inventory-based estimates needs to be improved in many cases, with inventory agencies unable to provide prior spatial resolution. Third, data products from VERIFY reveal discrepancies between inventory-based and observation-based approaches, but there is a need to dig deeper into the reasons for these discrepancies. Likewise, in cases where there is a good match between inventory-based and observation-based approaches, it would be useful to understand the drivers behind the result to understand whether it indicates that the estimates are good, or whether the match is coincidental.

If using observation-based approaches in their **National Inventory Reports**, inventory agencies expect that they may get questions about these data and methodologies from reviewers during the UNFCCC inventory review. One inventory agency suggested that EU Member States should have a common approach to integrate VERIFY results in national Inventory Reports to lower the burden on each individual country in terms of explaining the use of the data products.

The feedback from inventory agencies during the VERIFY network meetings largely confirms the findings of the European Topic Centre on Climate and Energy (German, Matthews, and Ruyssenaars 2021). They found that the Land Use, Land-Use Change and Forestry sector (LULUCF) was an area where uncertainties are large, but concerns were raised over the utility of comparisons against inverse model estimates of land-based biogenic CO_2 fluxes due to fundamental differences between LULUCF carbon stock changes and the land-surface exchange of CO_2.

3.3.4 Findings from the IPCC Expert Meeting

The IPCC Task Force on National Greenhouse Gas Inventories organised an IPCC Expert Meeting on the Use of Atmospheric Observation Data in Emission Inventories (5-7 September 2022). The aim of the meeting was to discuss issues relating to the use of atmospheric observation data and models in verification of national GHG inventories, building on the guidance provided in the *2019 Refinement* (IPCC 2019). The meeting was separated into four break-out groups: CO_2 emissions from fuel combustion, fugitive CH_4 emissions, AFOLU GHG emissions, and F-gases. Some of the key findings were:

- Verification may not lead to direct changes in inventories, but rather be a starting point for improvements
- Inverse modelling systems need more standardisation and improvement of the ability to detect robust differences between inverse models and inventory data
- The use of atmospheric observations is a rapidly maturing science, and there is a critical need for dialogue and development of capacity between GHG inventory compilers and atmospheric observation researchers.
- There are some examples of comparisons between atmospheric observations and national inventories.

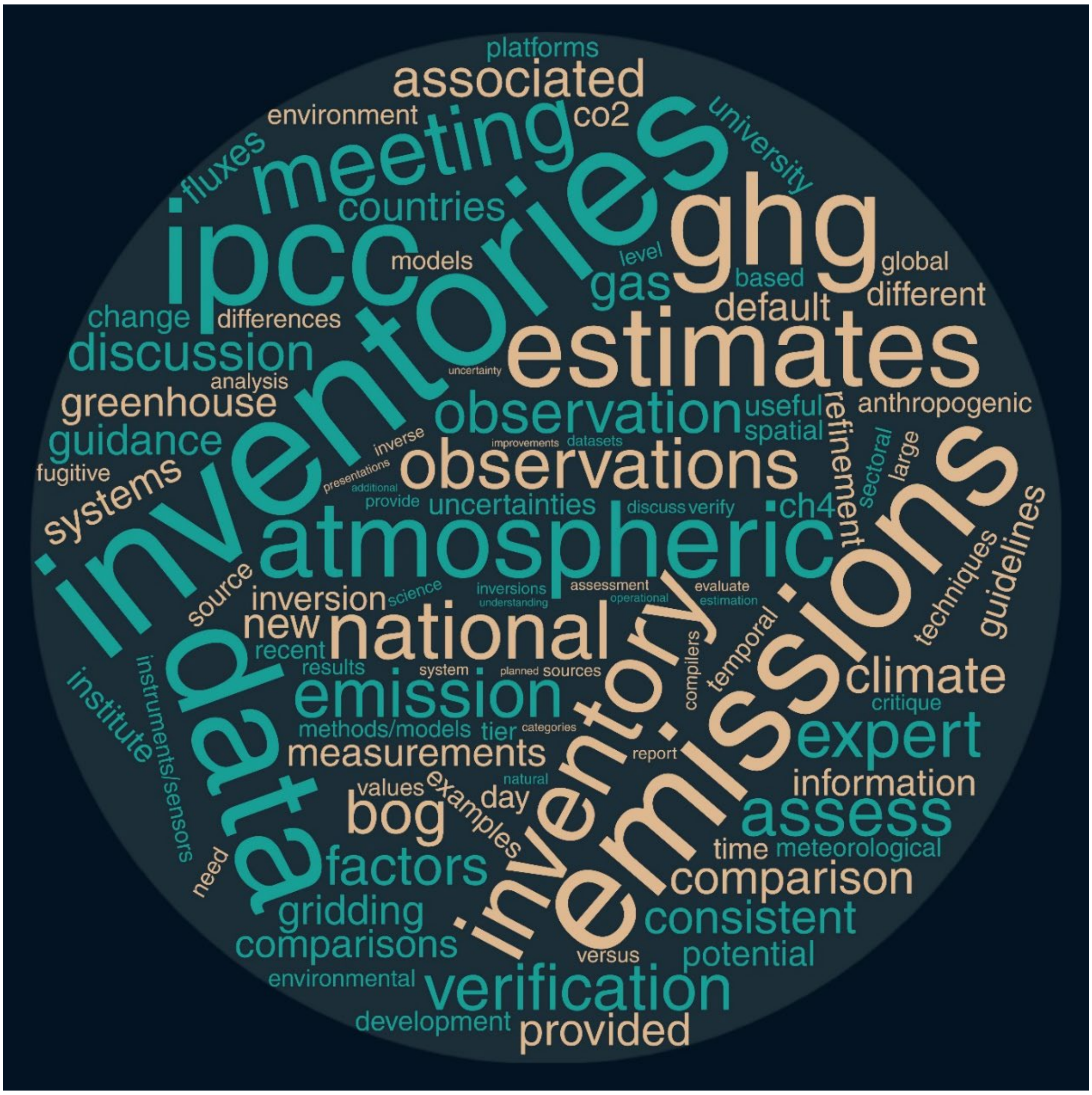


Figure 4: Word cloud of the IPCC Expert Meeting on the Use of Atmospheric Observation Data in Emission Inventories.

Each breakout group had specific recommendations in their summary notes (Figure 4). Many overlap, unsurprisingly, with the outcomes from the VERIFY Network Meetings and other dialogues between inventory agencies and inverse modellers. Inventory compilers need to be actively involved in comparisons and modellers need more experience evaluating GHG inventories. Recurring themes in breakout groups include topics such as: terminology, gridding, emission factors, dialogue with modellers and data providers, and similar. Whilst many technical themes around inverse modelling were discussed, most of the recurring themes related to ensuring a common understanding of common objectives. Any blueprint of the path forward will necessarily require building much stronger bridges between communities with traditionally quite different foci.

3.3.5 User consultation on the preliminary blueprint for a DSS

The preliminary version of a Decision Support Blueprint (D8.4, delivered in January 2023) was shared with stakeholders, including the inventory agencies of EU Member States (Working Group 1 of the Climate Change Committee), EU projects on related topics (PARIS, AVENGERS and EYE-CLIMA), the CoCO2 Inventory Agency Advisory Board, the CoCO2 External Expert Group and the CO2 Task Force. The feedback from this consultation is summarised below and incorporated into other relevant sections of the report.

In line with feedback from VERIFY (chapter 3.3.3) and the IPCC expert meeting (chapter 3.3.4), users expressed interest in data that could help analyse emission levels and trends, and be used for prioritising inventory improvements. Specific input on what the DSS should deliver included:

- An accessible system which delivers data in time to be analysed and incorporated in annual inventory reports to the EU and UN.
- Dashboards and clear graphical presentations of results. Expertise on graphical presentation should be involved. The format from VERIFY factsheets was found useful.
- Ability to indicate (together with an uncertainty) whether current net greenhouse emissions are consistent with those required for the desired temperature target, or whether additional measures are needed.
- Earth Observation data to be used within CO2MVS should be provided with the label "analysis-ready" as defined by CEOS.
- The prior and posterior datasets, in their maximum spatial and temporal resolution should be accessible.
- Where nationally reported emissions differ to estimates from inverse models, the reasons for the differences should be explained.

Input on the steps towards a DSS included:

- Hands on trainings with the datasets (e.g., using R and Python). This could be done through webinars based on example code where users go through some processing and analysis steps together.
- Issues of interoperability, standardization, and terminology need to be properly addressed before the CO2MVS is set up.
- The idea of conducting case studies and/or pilot projects (see chapter 4.3) was welcomed.
- Managing expectations from inventory agencies (what a DSS will/will not deliver). Modellers should gain a greater understanding of the IPCC guidelines for inventories and work on practical demonstrations together with inventory teams to build confidence in the system.
- The intended users of the DSS should be clarified.

Finally, the inputs included suggestions for methodological improvements that would be important for the use of observation-based data for inventory verification/improvements:

- Not all inverse models directly optimize sectoral emissions from observations, whereas national GHG inventories are constructed on a sector basis. For inverse models that cannot produce sector level estimates, alternative approaches may be needed to map to the GHG inventories. .
- Plume segmentation, specifically for relatively low excess over background values, as is often the case for CO_2: Deep learning methods might be useful to distinguish plume-specific spatial features from background or instrument features.

- Specifically at high latitudes, the issue of retrieval over light surfaces like snow and open water needs to be addressed, also considering that retrievals in sun-glint mode may not be reliable at high latitudes. Open water retrievals are specifically important for CH_4 emissions in subsea permafrost areas, while emissions from snow covered areas are relevant for terrestrial permafrost areas as well as generally for Soil Organic Carbon in boreal forests.
- Uncertainties in observations-based estimates are still large, and there is significant variation between air-sample-driven inversions and satellite-driven inversions. These differences need to be explained and uncertainties reduced.

4 Decision Support System (DSS) blueprint

4.1 Identified knowledge gaps

The core challenge to a CO2MVS Decision Support System (DSS) is to translate the high volume of detailed data at fine temporal and spatial resolution into a format that is useful to a user which might be interested in annual emissions in a larger geographic location (city or country). Different users will have different levels of competence and therefore different needs. At one level a user might just want a quick comparison of country-level emission estimates, while another user might have the capacity to perform a detailed analysis across multiple datasets. The DSS is essentially a translation tool, that maps the highly detailed scientific data into a format that meets the user needs.

A synthesis in the VERIFY project identified several areas where further research is needed to meet verification needs (Figure 5), and many of these aspects overlap with the needs of the CO2MVS. This report was focused mainly on the scientific aspects but identified many gaps relevant to meet the some of the needs of the CO2MVS. The need for more observations was clear, and in part, missions such as CO2M will partly respond to that challenge. Greater interactions between the scientific and inventory communities are needed, particularly, in the context of making datasets more comparable. Community simulation tools, such as the community inversion framework, need further development. Targeting specific gases and sectors was identified as a key priority, in contrast to aiming for complete global coverage. Many of the points identified in VERIFY are also identified below in our independent analysis.

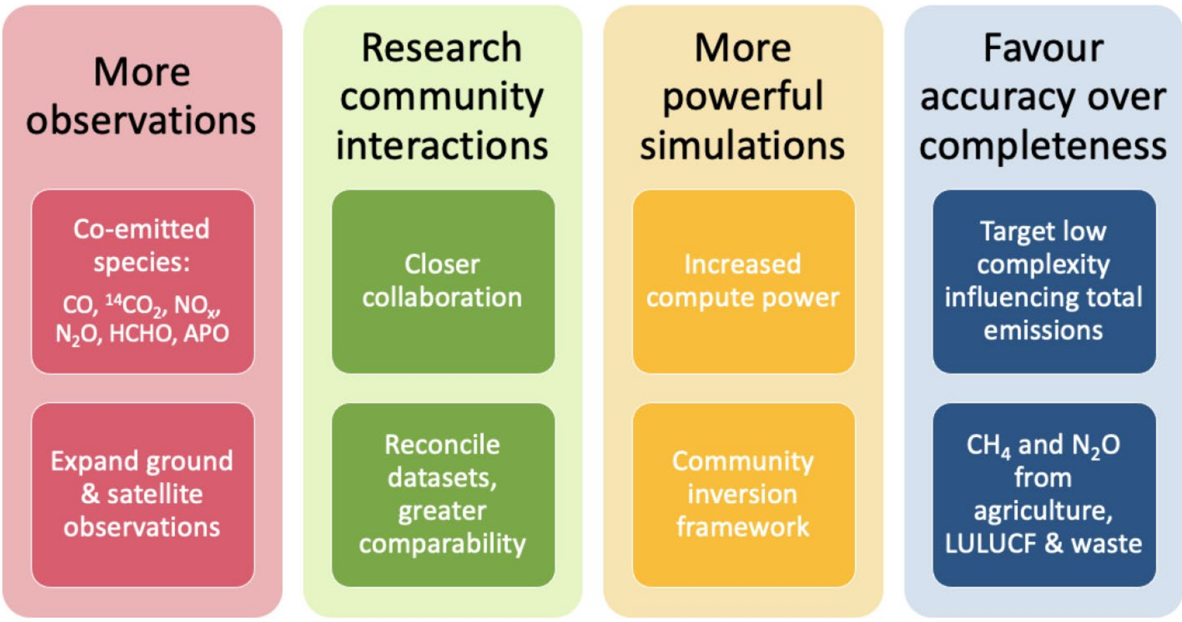


Figure 5: A summary of the future research needs identified in the VERIFY project (D7.9).

In the following, we provide a synthesis of user needs and challenges that need to be dealt with in a DSS. This is based on the author team's summary of user interactions (Section 3), experience in various projects (e.g., VERIFY, CoCO2), and the broader literature.

Clarifying the aim and managing expectations

Different users see different issues as important, depending on the demands in their current work tasks. These issues likely differ substantially to the issues modellers face in their current work tasks. To take an example, through the UNFCCC inventory review process, and/or internal inventory improvement planning, it may be identified that the estimates of emissions of individual subsectors should be improved (sourcing new/updated activity data and/or emission factors, moving to higher Tier methods). The CO2MVS may not be able to provide any support in improving/verifying such subsector recalculations, particularly if the sources are relatively small in magnitude. Nonetheless, the comparison between the inventory and inverse estimates before and after substantial recalculations could be informative to both inventory compliers and inversion analysts. Thus, the challenge is to identify the key questions which are relevant for both inventory compilers and inverse modellers, and the relevant spatial and temporal detail to cooperate.

It is important from the start to clarify the objective of the analysis. What is the research question or what does the user need? Not all inventory questions can be dealt with through a CO2MVS, and not all inversion analysis is relevant for an inventory compiler. Clarifying these issues is important to manage expectations, and to help find areas where common understanding is fruitful and mutually beneficial, and therefore partnerships grow.

Building a common understanding and knowledge base

A common theme across nearly all interactions with users is the need to gain a common understanding with inverse modellers and build a common knowledge base. Particularly through the VERIFY project, it was clear that modellers and inventory experts spoke different languages, often about the same topics (see VERIFY D1.2[10]). Many users don't know what an inversion system is, where the input data comes from, and what are the key assumptions which may affect inversions. Likewise, many inverse modellers do not understand the background, methods, and rationale for approaches used in emission inventories, or why inventories are based on certain assumptions. Without this common understanding, comparing different estimates has little benefit, and the comparison quickly becomes overwhelmed with questions of clarity. Users have a particularly difficult job, understanding outputs from inverse models, as "the techniques and descriptions can even be hard for other scientists to understand" (National Academies of Sciences, Engineering, and Medicine 2022).

For a CO2MVS to be useful, it is necessary to build up the knowledge base of both users and providers (researchers) and ensure they have a common understanding.

Optimising temporal and spatial resolution

Inverse models can produce estimates at a potentially fine grid scale (kilometres) and fine temporal detail (hours). Users can also be interested in fine temporal and spatial resolution, such as city-level estimates or at a particular facility or site (e.g., landfill), though official reporting is usually at the national level for annual emissions.

Emission inventories are generally on an annual time scale, though policy makers often have demand for higher temporal resolution. Several statistical offices report emissions on a monthly or quarterly level, preferably with a low time lag. Inversions operate at a much finer scale, even down to hourly, but this also requires prior emission estimates at an hourly resolution, which require a variety of data and methods to estimate. The inversions can then be aggregated up to give monthly, quarterly, and annual outputs. In an operational system, these estimates from inversions could have a low time lag (the order of months). There are

[10] Terminology analysis

also organisations estimating near real-time emissions with high spatial or temporal resolution, such as Carbon Monitor and ClimateTRACE, using a mix of inventory and observation-based approaches, but they often lack detailed verification.

Emission inventories are generally on a national territorial basis, but inventories are often estimated using data at a finer spatial or sectoral resolution. Some individual facilities report emission estimates, though these estimates also require verification (Lu et al. 2023). At a sector level, more diffuse emission sources can be hard to estimate (Plant et al. 2019). There may also be individual events, which are hard to incorporate into inventories (acute pipeline or facility leaks). Inversions can play a clear role in supporting disaggregated inventories. However, the uncertainty of inversions is high at the level of a grid point, but scaling up to city, regional, or national level reduces those uncertainties (see CoCO2 Deliverable 4.3).

Another important element is the time lag in producing estimates. Early estimates relying on proxy data may be published with a monthly time lag (e.g., Carbon Monitor), official quarterly estimates may be published with a lag of a few months (e.g., The Netherlands), preliminary estimates of full year emissions may come with a six-month lag (e.g., Norway), while submission of official estimates of annual emissions of a country may come with a two-year lag (e.g., UNFCCC). All these estimates are additionally subject to recalculation and revision as time passes (Figure 2). It is not yet clear what time lag operational inverse model estimates of real-time emissions may have, but it could potentially be the order of months. It remains unclear what level of accuracy, with a given time lag, is needed by users for different use applications.

It is expected that uncertainty will be higher at a higher spatial and temporal resolution, but there is also potential to improve the accuracy at specific locations and times. There needs to be further interactions between users, inventory compilers, and inverse modellers on the optimal level of spatial and temporal resolution to operate, and for which applications. There needs to be a better understanding on the preferred level of spatial and temporal resolution to meet user needs, and if and how observation-based approaches can meet those needs. The spatial and temporal unit of comparison may be a critical design feature in a DSS.

Aggregating results to reduce uncertainties

Inversions are affected by the size of the country, location (latitude, longitude), geography, albedo, number of observations, types of observations, and so on. An experienced modeller may implicitly (and even subconsciously) weigh this information when analysing results from a given country but would not mention this information explicitly as it is common knowledge within the inversion community (National Academies of Sciences, Engineering, and Medicine 2022). This makes it hard for a user to understand the implicit weights put into different comparisons. There are, potentially, some methods to alleviate some of these issues, such as through maps which show the uncertainty across geographic regions, and how they change with given factors (such as new observations, VERIFY D6.13). Because of some of these aspects, modellers often aggregate countries together as there is more confidence in the aggregated results. The reasons for some groupings and the optimal size of regions as an element analysis are often unclear and unstated.

Further, many countries border with other countries, requiring a method to aggregate the grid level inversion data to a country. Particularly for inverse models with a coarser grid, aggregation of the grid cells will not necessarily be a perfect match to country boundary. This problem becomes smaller with bigger regions, or regions with long coastlines, and is one reason that VERIFY aggregated many smaller countries together to bigger regions.

Assessing trends and managing variability

Observation-based approaches generally incorporate interannual variability, particularly for land-based emissions, as they are highly dependent on temperature and precipitation. Inventory-based approaches are reported at the annual level, and inventory-based approaches often do not consider variability by design (e.g., the forest inventory approach for the land sector). Further, the Paris Agreement is set around five yearly global stocktakes, which indicates a desire to average trends over different time periods. While understanding the interannual variability is critically important from a scientific perspective, when comparing observation-based and inventory-based approaches is often necessary to remove interannual variability to make meaningful comparisons. Standard methods could include averaging over time-periods (e.g., 5-year or 10-year) or by analysing trends. There is the additional issue of identifying if a difference between two independent datasets is statistically significant, particularly when one dataset does not include interannual variability and the other does.

There is a clear need to better develop methods to better deal with interannual variability, trends, and statistical significance. While inventories do often include trends and uncertainty information, this information is not routinely provided in observation-based estimates. A distinct challenge is understanding temporal and spatial correlations, for which there is little prior information. The methods used to compare aggregated emissions and trends, how to deal with temporal and spatial resolution, and how to deal with interannual variability, will be important for the design and usefulness of a CO2MVS.

Statistical significance

One method that modellers use to determine if an inversion gives an improvement over the prior emission estimate is to assess a reduction in the uncertainty. The prior emissions used as input into an inverse model should have uncertainties, and a full inversion analysis will include uncertainties on the posterior estimate, with the reduction in uncertainty between the two estimates of particular interest. In a well constrained inversion, the uncertainty of the posterior emissions should decline, and the posterior emissions should converge to the 'true' value. If the difference between the prior and posterior estimates are far from each other with respect to their uncertainty, then this would suggest that the inversion has identified an incorrect prior emission estimate. The inventory-based emission estimate will additionally have uncertainties, though some argue these are not sufficiently robust for verification purposes (National Academies of Sciences, Engineering, and Medicine 2022). It is not generally clear how inventory uncertainties can be compared to inversion uncertainties, as the methods to produce the uncertainties differ.

There needs to be more effort to report and fully characterise prior and posterior uncertainties, so that statistically significant levels or trends can be identified. There are often offsets in inverse models, because of inconsistencies in observations, which may make trends more robust. In a policy context, the uncertainty on the emission trend may be more important, but also this is harder to estimate as it requires knowledge of correlations in emission estimates over time.

Model ensembles

Research projects often focus on multiple model analysis (ensembles). The UNFCCC emission inventory would be compared against, for example, 17 land surface models and five inverse models (McGrath et al. 2023). From a scientific perspective, the model ensemble is often considered a more robust estimate of the mean and uncertainty, as inherent model biases can be captured. From an inventory perspective, individual model comparisons may be more productive, as various input variables or processes can be compared directly to the inventory. Doing this for each model becomes time consuming. The CO2MVS system is currently envisaged to be one global modelling and data assimilation system based on ECMWF's Integrated Forecasting System (IFS). Understanding the implications of these different choices, and how to capture structural uncertainties across models and methodologies, will be a challenge for a single IFS that needs to be resolved. Currently, most inventory comparisons in UNFCCC National Inventory Reports (UK, Switzerland) use single model comparisons.

Anthropogenic and natural fluxes

Most emission inventories aim at estimating anthropogenic emissions, while most inverse models see both anthropogenic and natural emissions. Thus, methods are needed to separate the anthropogenic flux from the total flux (Deng et al. 2022), unless delt with directly in the inversion system (Kaminski et al. 2022). This is a particularly important issue for CH_4 and N_2O where globally natural emissions are of similar magnitude as anthropogenic emissions, with bigger variations at the regional level. The natural fluxes are also considerable for CO_2, though inversions tend to focus on either natural fluxes or on anthropogenic fluxes. Further, climate change may mean the natural emissions change in ways that models can't yet resolve, for example, a warmer climate may increase natural emissions of CH_4.

For land-based CO_2 emissions, there are significant issues with definitions of anthropogenic, with the science and inventory communities using different definitions of anthropogenic (Grassi et al. 2018). Science-based estimates of net land CO_2 emissions focus on anthropogenic land-use changes and direct CO_2 effects, such as afforestation or deforestation. The inventory-based estimates of net land CO_2 focus on a self-defined managed land proxy and direct, indirect, and natural effects, such as increased carbon uptake due to CO_2 fertilisation. This effect has been quantified in several studies (Grassi et al. 2018; 2021; Schwingshackl et al. 2022; Friedlingstein et al. 2022), but comparing independent estimates of net land CO_2 emissions requires making adjustments for these differences.

Prior emission estimates (natural and anthropogenic)

The prior emission estimates are an important input to the CO2MVS and the specific inversion systems, both prior estimates of natural and anthropogenic emissions. When combined with observation data, the inversion system produces a new posterior estimate of emissions, which can then be compared back to the prior estimate, preferably incorporating a full uncertainty analysis. This comparison is a core objective of inversion systems and thereby the CO2MVS: if the uncertainty reduction in the posterior is not statistically significant relative to the prior, then, all-else-equal, there is less confidence the observations are adding value to the inversion results.

The UNFCCC inventory data is rarely used as a prior, as it 1) rarely has the necessary spatial and temporal resolution, and 2) the UNFCCC data does not have global coverage. Other data sets are often used, such as EDGAR or derivates based on EDGAR. Further, quite often older datasets are used as they have the preferred resolution: EDGAR version 4.2, from 2012, is often used because of its spatial and temporal resolution, and global coverage, with various extrapolation schemes used to extend the data to the most recent years (Steinbach et al. 2011). The Global Carbon Budget ensures its gridded data products map directly to UNFCCC reported totals, but only provides monthly temporal resolution (Jones et al. 2021).

The prior emissions can often differ substantially from the UNFCCC National GHG Inventories. It is hard to determine the importance of the prior estimate on the posterior estimate and the resulting uncertainties, based on data that is commonly reported (Petrescu et al. 2022). In many countries, prior estimates can already differ from UNFCCC estimates by up to a factor of ten (e.g., CH_4 in the Nordic countries). Key reasons for differences are often the fact that global datasets (e.g., EDGAR) do not use country specific emission factors or activity data (CoCO2 D8.2). While there are many initiatives to produce datasets of high spatial and temporal resolution (e.g., in CoCO2), often national inventory agencies do not have sufficient resources or mandate to provide spatially or temporally resolved datasets for CO_2 and CH_4. However, many of these agencies provide gridded data (0.1°C×0.1°C) to EMEP for air pollution monitoring, suggesting it may be possible to provide this data also for CO_2 and CH_4 emissions.

There is a need to improve the prior estimates used as input into inversion systems. This has three components: 1) ensuring the availability of updated emissions data at an appropriate level of sector, temporal, and spatial detail, 2) ensuring inversions systems use the latest data estimates from reliable sources, and 3) ensuring that prior estimates have uncertainties at the necessary levels of sector, temporal, and spatial detail.

Geographical and structural boundaries

When comparing datasets, a variety of system boundary issues arise (Andrew 2020; Grassi et al. 2018). Additional issues arise when comparing results from inversion products. Key issues are mentioned here.

Country borders. Transforming a gridded dataset into country totals requires dealing with grid cells that overlap country boundaries.

Domestic aviation. Domestic aviation occurs at altitude, and only the take-off and landing emissions may be relevant for some inversion systems. It is necessary to ensure that the prior emission dataset allocates aviation, and the altitude of emissions, that is consistent with the inversion system, and that they are consistency compared to the inventory-based emission estimate.

International bunkers (aviation and maritime). In addition to height effects, additional care is needed for international bunkers (fuels used in international aviation and maritime activities). Bunker fuels are not allocated to country emission totals but are reported as a 'memo' based on the territorial sale of bunker fuels. A prior inventory into an inversion will need to consider the take-off and landing cycle for international aviation, in addition to included inland shipping that crosses borders (e.g., The Netherlands to Germany), as this will be seen by the inversion system. For consistency, the resulting emission estimates need to be compared with a consistent emission inventory.

Managed forests. In the IPCC reporting guidelines, anthropogenic emissions on land are defined based on a self-defined managed land proxy. In addition, the methodology includes indirect emissions, such as resulting from CO_2 fertilisation. In the carbon cycle community, anthropogenic is defined as only the direct emissions from the activity and only on land where the land use category has changed. These two definitions lead to a significant difference in estimated LULUCF emissions (Grassi et al. 2018). To make any sensible comparison with LULUCF emissions, the managed land issue needs to be addressed.

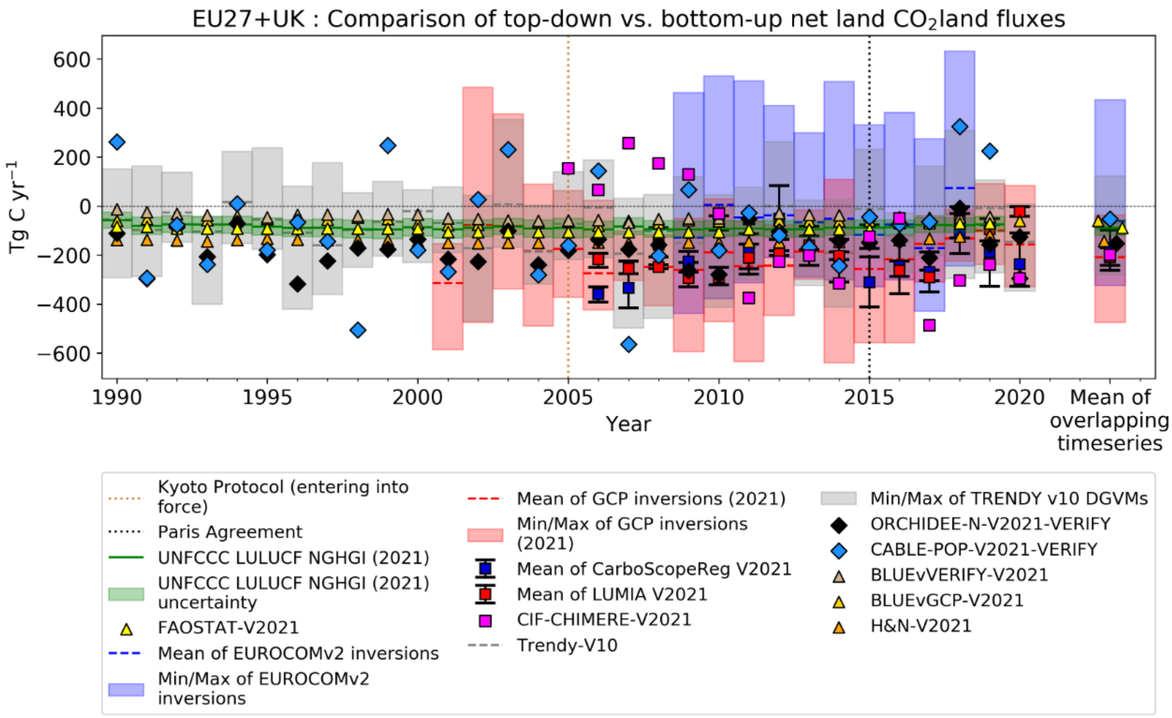
Lateral fluxes. Carbon can cross national borders in a variety of methods, not all of which are well captured in models. Key processes include river transport and trade in agriculture commodities.

Standardisation

Inverse analysis systems are not yet standardized. The Community Inversion Framework (CIF) is a move in this direction. However, improvements are still needed to ensure common formatting and presentation of the results, in addition to the use of common language and terminology, as discussed earlier. It is important that these standardisation efforts occur at an international level to capture a diversity of views.

4.2 Improvements of figures and graphical communication

The figures produced in the VERIFY project generally compared multiple datasets on one figure, with various explanations of the differences when available (Andrew 2020; Petrescu et al. 2020; Petrescu, a,b et al. 2021;). These figures were reproduced in the VERIFY fact sheets (D5.6, D5.7, D5.8). Figure 6 shows a sample figure used in VERIFY for the net CO_2 land fluxes, which shows a variety of bottom-up and top-down estimates. These figures show an immense amount of information, which are hard to separate and digest – there is simply too much content on the figure. The purpose of graphical displays of data is to communicate messages more clearly than tables of data would, but it's unclear whether this was achieved in these examples.



VERIFY Project

Figure 6: A VERIFY figure showing observation-based (top-down) and inventory-based (bottom-up) estimates of net land CO_2 fluxes.

Initial work in CoCO2 simplified these figures somewhat (e.g., Figure 7, D8.1), but further work is required (see D8.2/D8.3). The general approach is to start with coarse overview figures, but then allow an iterative process to obtain more detail until the user needs are met (analogous to the hierarchical approach proposed in Peters et al 2017). Initial steps will be to do more one-on-one figures, such as comparing the UNFCCC inventories with only inventory-based estimates (Figure 8), UNFCCC with land surface models, and UNFCCC with observation-based inversions. Within these three variants of figures, other more detailed versions are possible. Inventory-based comparisons can compare estimates by sector or by sources (for land, this may be afforestation, deforestation, forestry, and similar, as done in Friedlingstein et al 2022). Similar details are likely to be taken for inventories estimated with land-surface models, but with the added advantage of being able to bridge the different definitions of managed land (e.g., Grassi et al 2022). Particularly for net land CO_2 fluxes, there are multiple layers of definition issues, making comparisons of raw data sets difficult. These sorts of improvements were gradually included in D8.2 (December 2022) and D8.3 (December 2023).

Very few figures have sufficiently incorporated uncertainty. On the inventory side, UNFCCC National Inventory Reports contain uncertainties, which are now harmonised across the EU in work supported by the EEA. EDGAR provides uncertainties for the year 2015 (Solazzo et al. 2021). Most other inventories do not provide uncertainties. For most inversion and land-surface models, uncertainty is indicated by model spread. However, more can be done. For inverse models, a full analysis can generate prior and posterior uncertainties, to give some understanding of statistical significance. However, this requires considerable analysis, and such uncertainty information is not readily available. The land-surface models (DGVMs) do not provide uncertainty information. Without uncertainty information, it is impossible to determine with confidence if an estimate differs from a NGHGI in a statistically meaningful way.

One challenge with the graphical based approaches is to show if differences are statistically significant. An inversion may agree quite well with a UNFCCC inventory, but this could also be coincidental. The figures need to come with additional information, whether embedded within the figure or alongside it in a text, to provide key assumptions which may affect the results, and given some indication on whether the similarity or differences between datasets is statistically significant.

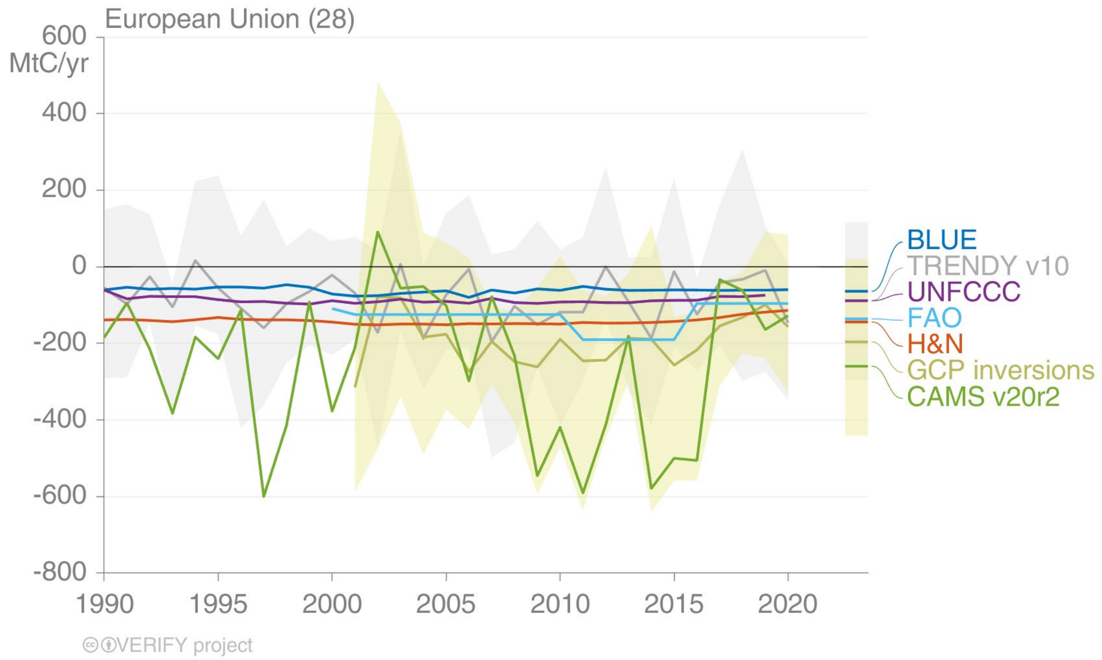


Figure 7: A CoCO2 figure showing observation-based and inventory-based estimates of net land CO_2 fluxes.

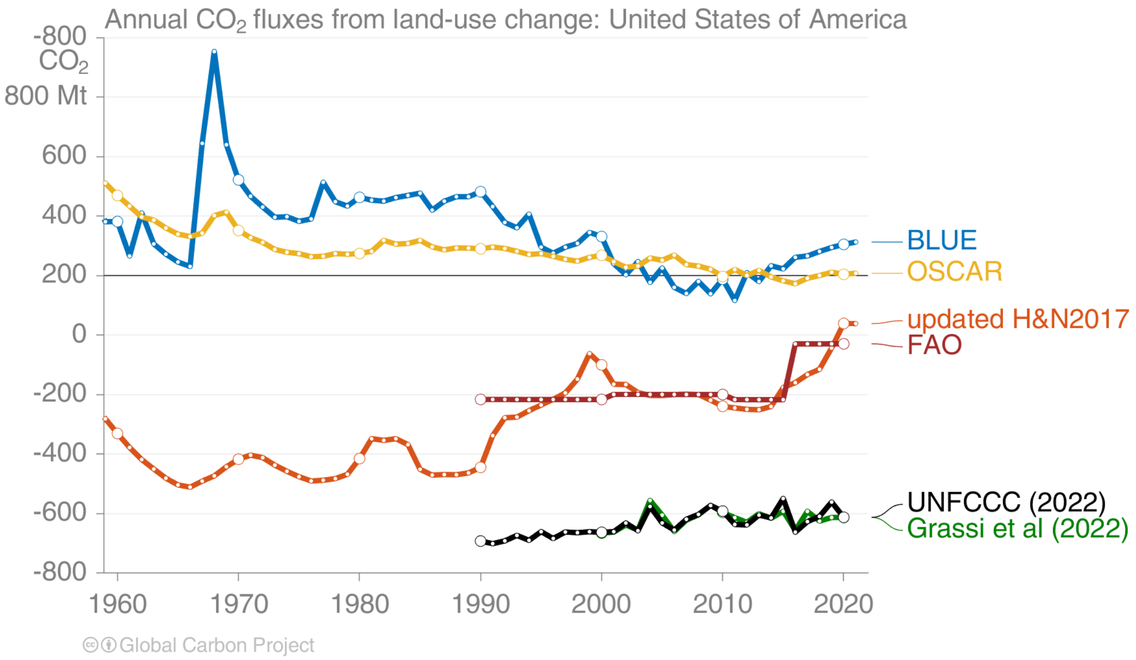


Figure 8: A CoCO2 figure showing only inventory-based emission estimates of net land CO_2 fluxes, with separate figures making comparisons based on the methodology (e.g., a figure for land-surface models and a figure for inversions).

It is of critical importance on how to disentangle the reasons why different estimates differ. To achieve this, it is likely necessary to decompose the various estimates to a more detailed level where comparisons can be carefully made, bringing in country-specific information and knowledge as necessary. The method to deliver these types of products or tools within the CO2MVS is something that needs design, but there is a considerable base to build on through the Copernicus Atmosphere Monitoring Service (CAMS) and the Copernicus Climate Change Service (e.g., applications and tools).

An approach that will be used going forward is to shift from a goal of presenting all data on a plot to a goal of deciding what the intention behind each plot is and what messages it should be designed to convey. When too many messages are conveyed in a single plot, the burden on the user to interpret it grows substantially. Given the quantity of data available to present in the CO2MVS, choosing to reduce the amount on each plot could lead to an explosion in the number of plots, but this can be mitigated by keeping in mind the key messages that we intend to present with the graphical representations of the data.

Important next steps will be specifically to identify what the core messages are that we wish to present in graphical material (or analysis tools), and to more consciously address whether a plot is designed to present a conclusion or whether it is designed to initiate a discussion. The latter is an approach more often used in the process of research rather than in the process of communicating results to an audience.

4.3 A roadmap forward

The current state-of-the-art is to bring the different datasets together and make them comparable (e.g., VERIFY fact sheets and synthesis products). The overall process is still a black box and not many inventory agencies understand details. There is a need for a simple representation of what is behind the data, what it represents, and what is the uncertainty. To make comparisons that are not superficial, inventory agencies need targeted and disaggregated data, as the total is always the aggregation of very different components. Inventory agencies and researchers still do not have a clear understanding of each other's needs, or a common understanding of the limitations of various datasets. Inventory agencies probably need direct and specific exchange with modellers, to explain and understand the inversions, suggesting that there may be a greater need to focus on specific case studies as opposed to automation and generalisations.

Approaches		Pillars					
		Usability and Timeliness	Information Transparency	Evaluation and Validation	Completeness	Inclusivity	Communication
Activity-based	*Methods*	Medium	High	Medium	Medium	Low	Medium
	Data	Medium	Medium	Low	Medium	Low	Medium
Atmospheric-based	*Methods*	Low	High	Medium	Medium	Low	Low
	Data	Medium	Medium	High	Medium	Low	Medium
Hybrid	*Methods & Data*	Low	Low	Medium	Medium	Low	Low

Figure 9: The six pillars and their assessment in "Greenhouse Gas Emissions Information for Decision Making: A Framework Going Forward" (National Academies of Sciences, Engineering, and Medicine 2022). A low score indicates the criteria are not well addressed. A high score indicates that the existing approach can consistently address the pillar criteria.

Through this section we bring together the key lessons from this report and structure them into concrete actions moving forward that can help bring the inventory agencies and inverse modellers together with a common understanding of the challenges and common objectives to ensure that observations can make a meaningful impact on the emission inventory estimates. Many of our conclusions map well with a US-based study with similar goals (National Academies of Sciences, Engineering, and Medicine 2022). They identified six pillars where improvements are needed: useability and timeliness, information transparency, evaluation and validation, completeness, inclusivity, and communication. Most of these pillars were assessed as having a low or medium evaluation (Figure 9). While we do not perform such a comprehensive analysis, many of our conclusions are consistent.

Building a common understanding and knowledge base

A recurring theme is that there needs to be a common understanding and the knowledge base must be expanded. Various EU projects have had a variety of deliverables that help in this regard but are not widely known or assessable. There are also some very fundamental concepts where common understanding is required: what is the objective, what is verification, what is an inverse model, what is a CO2MVS, common glossary of terms, and so on. With a common knowledge base, more detailed and productive discussions on model results and comparisons can happen. The common knowledge base also serves two purposes that related to different time periods: 1) quickly get the current community to a common knowledge base (e.g., via fact sheets), 2) allow for future generations to obtain the common knowledge base over time (e.g., textbook or enhanced IPCC guidelines).

Suggested paths forward are to co-produce a range of fact sheets or courses of the agreed level of detail. It may be necessary to set up specific working groups, involving different levels of competence, to develop this material. Over time, these materials may lead to a more elaborate document, such as a book, or specific chapter in the IPCC reporting guidelines, building on, and expanding, the current 2019 refinement. The ongoing EU project (CoCO2), new EU projects (EYE-CLIMA, AVENGERS, PARIS), ongoing US processes (e.g., the National Academy report) are ideal forums to initiate these processes, but it is critical that inventory compilers and modellers from the global South are integrated into these processes, through larger and broader initiatives like the WMO IG3IS and WMO GGGW.

An ecosystem of case studies

The CO2MVS is designed to have broad appeal and be generic to a wide range of users. Most dialogues with inventory agencies and inverse modellers have been short workshops and large groups, making it difficult to progress on details. These larger groups serve a purpose in engaging a broader community, however, there is also a need for more intensive engagement with smaller and more focused groups. Making specific comparisons between observation- and inventory-based emission estimates for individual countries often lead to very specific and technical discussions, that often map to specific national circumstances (geographic location, coastline, mountains, forests, types of industries and sectors, etc). To identify the generic needs, it may be necessary to have a much deeper focus on case studies. This can already be seen in the Swiss and UK inventories, where the most elaborate verification activities are the result of detailed collaboration between inventory compilers and modellers. Additional case studies are needed in other countries, to help draw out lessons for different regional context and knowledge levels. Through these case studies, generic lessons that are applicable to all users at different levels can then help inform the CO2MVS.

Steps to achieve more case studies is to identify willing inventory agencies and modellers who have the time, capacity, and interest to perform detailed verification exercises. The lessons learnt need to be documented and can inform more generic lessons for a wider user group. Case studies may need to be bottom-up processes with a coalition of willing participants but could be done under the auspices of ongoing projects (e.g., in the EU CoCO2, EYE-CLIMA, AVENGERS, Paris). More case studies are needed in a variety of regions, particularly in countries where NGHGIs are less developed and in greater need of external support. Many of these activities could be achieved through WMO IG3IS.

Technical aspects of inverse modelling

There is a range of technical details that need to be discussed and solved at the more technical modelling level. The most relevant need is for developments that lead to better quantified estimates of statistical significance and robustness of results. Inverse modellers often have a good sense of the key issues and their significance, but quantifying them and communicating them to inventory agencies, or users more generally, is difficult.

A potential avenue here is a scientific publication which brings together in a concrete way the knowledge needs and knowledge gaps in current inverse modelling practices that currently inhibit the ability of inventory agencies to verify emissions. The relative importance of certain factors is likely to vary by gas and by geographic location. But there is a need to explicitly outline the issues that need resolving and a pathway for how they can be resolved. This is also a potential avenue to build a common knowledge base. The VERIFY deliverable D7.9 was a step in this direction but needs a more focused community effort. This could be a constructive collaborative exercise across ongoing projects (e.g., in the EU CoCO2, EYE-CLIMA, AVENGERS, PARIS). The WMO has also initiated a modelling intercomparison exercise through IG3IS and will release Good Practice Guidelines to complement the existing guidelines for urban scale emissions.

Graphical material and analysis tools

Particularly for a CO2MVS with a broad user base, there is a need for common operational graphical material and tools. Understanding the needs requires interaction and feedback from users. Some steps have been made in VERIFY and CoCO2 (Section 5.2), but a hierarchical system that can flexibly zoom into more details is important. Also, a method of communicating key assumptions behind different graphical material and analysis tools is key: robustness, uncertainty distributions, system boundaries, etc. It is also clear that the needs will vary depending on the specific users. There is already a wealth of experience from existing activities, such as the Copernicus Climate Change Service (applications and tools). The VERIFY project has also made a range of products available, ranging from reports, visualisation tools, data repositories, and the community inversion framework which make a useful starting point for user orientated services (Figure 10).

The most productive pathway to elicit this feedback is through case studies (see previous points on this) and dialogue with user communities. Experience has shown that inventory agencies have very specific questions and needs. Inventory agencies focus on national totals, that are build up through sector level analysis, while inverse modelling is built up through grid level data to estimate national totals. The annual national totals are the common language between the inventories and inversions, despite different methods of arriving at those totals. The CoCO2 deliverables D8.1, D8.2, D8.3, and D6.2 offer a useful starting point, in connection with this deliverable, and dialogue is planned for the first half of 2023.

Collaboration

There are several new projects in the EU (EYE-CLIMA, AVENGERS, Paris), other regional/continental focused scientific initiatives (e.g., RECCAP2, OCO-2), interest amongst some inventory agencies to expand capabilities, and likely activities outside of the EU, that all move in the same direction of verification and need for a CO2MVS. International agencies such as the WMO and its initiatives like IG3IS work on similar issues and offer more longevity and a broader international network. Many of these projects and initiatives have similar tasks and interests where there are many synergies in collaborating. There are already good signs of collaboration, such as through the Community Inversion Framework (CIF, http://community-inversion.eu/) developed under VERIFY. Collaboration is possible to standardize prior data compilation, which could increasingly integrate with inventory agencies who often compile gridded prior data for other initiatives (e.g., EMEP and air pollution). The development of graphical material and analysis tools could also be a collaborative and open-source activity shared among cooperating projects. Several projects and initiatives also have objectives to develop guidelines (WMO, EYE-CLIMA, AVENGERS, PARIS), and it makes sense for greater collaboration on these issues instead of developing parallel and competing guidelines or standards. Many of the current activities tend to run in parallel, with many duplicated meetings and events, leading to an increasing need to ensure communication across initiatives. It remains important to anchor activities to user needs. The air quality community has a long history of linking to user needs, with high spatial and temporal detail, but there has historically been limited collaboration between the GHG and air quality communities (National Academies of Sciences, Engineering, and Medicine 2022), indicating another area of potential fruitful collaboration.

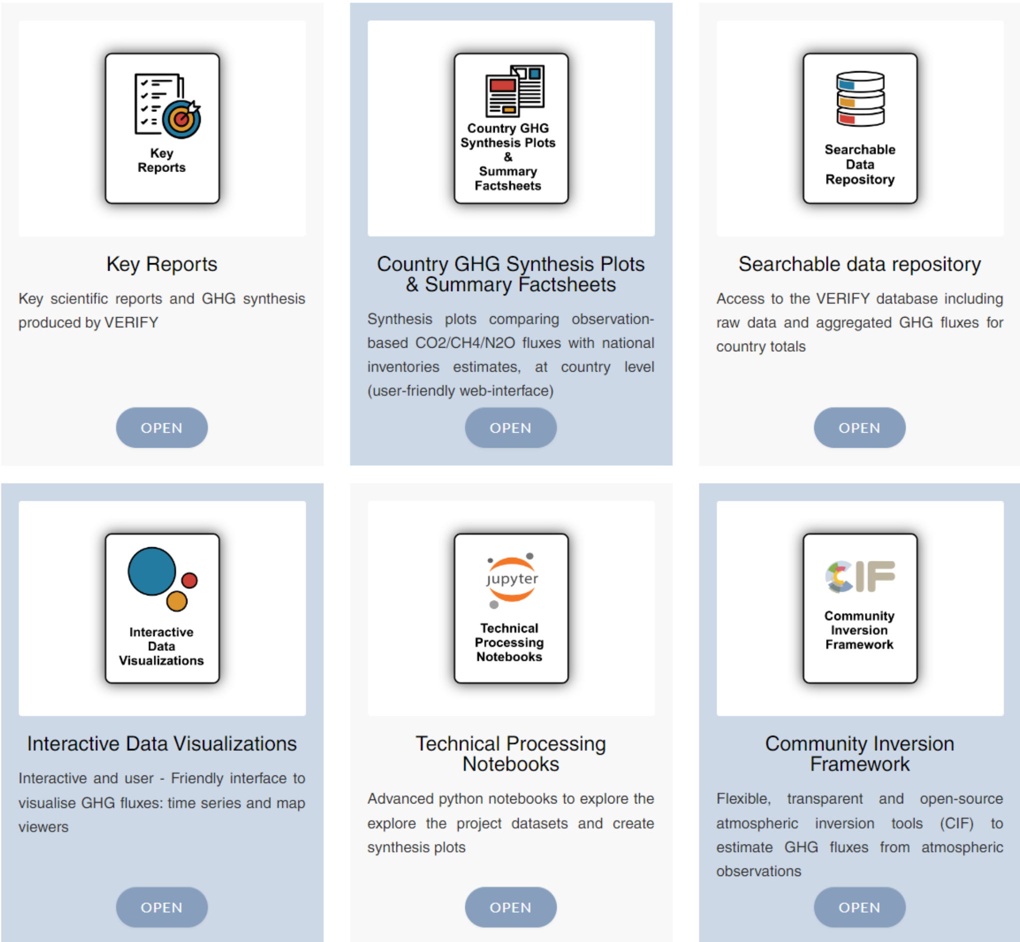


Figure 10: A screenshot of the VERIFY website giving a flavour for the user orientated material developed.

Communication

A key advantage of increasing communication activities is that it forces the communicator to develop material that the reader (user) wants to read and can understand. A scientific audience already working on inversions will likely be able to parse the text produced by colleagues working on the same topic. However, to communicate the underlying data, methods, and associated uncertainties to inventory communities, even with scientifically trained backgrounds, requires additional efforts. Researchers should be encouraged to write about their work to a broader audience, including those in the global South, to ensure greater understanding and eventually uptake of their work. While *translators* may help facilitate this work, such as through synthesis products (e.g., VERIFY and CoCO2), they are still dependent on explanations on input data, methods, and explicit and implicit assumptions to provide synthesis products.

5 Conclusion

This Decision Support Blueprint is the first step in a process to develop the DSS for the upcoming CO2MVS capability, initiated in CoCO2 but to be continued beyond. A *preliminary* version of this blueprint was prepared at the end of 2022 and this version has been improved through dialogue with users in the first half of 2023. This document is the final version to be published in CoCO2.

The verification landscape is growing given new demands stemming from the Paris Agreement and its Global Stocktake. New technology (satellites), and improved methods and computing power (inversions), open new opportunities for monitoring and verification support. The IPCC reporting guidelines (2006 Guidelines and 2019 Refinement) give guidance on using verification in inventories, and several countries are already using verification to different degrees. Many inventory agencies are familiarising with verification activities. The lessons learnt through various user events provide a clear path forward for a Decision Support Blueprint, ultimately to be implemented by the CAMS Implementation Team.

The current state-of-the-art in verification activities is to bring the different datasets together and make them comparable. To date, there has been limited ability to fully explain differences between datasets. The UK and Switzerland perform the most comprehensive comparisons in their inventory reports. While there have been many scientific studies comparing observation- and inventory-based studies, this has not yet infiltrated to inventory agencies who may see the methods as too complex, resource intensive, and offering few improvements to their inventory results.

To move beyond the current state-of-the-art, verification activities need to be rolled out across a range of countries to create lasting examples of how inversions can support inventories. Inversion results are often difficult for non-modellers to understand: there is a need for a simple representation of what is behind the data, what it represents, and what is the uncertainty. To make comparisons that are not superficial, inventory agencies need more detailed data and explanations, as the total is always the aggregation of very different sectoral components where emissions are estimated. Inventory agencies and researchers still do not have a clear understanding of each other’s needs, or a common understanding of the limitations of various datasets and methods. Inventory agencies probably need direct and specific exchange with modellers, to help explain and understand the inversions, suggesting that there may be a greater need to focus on specific case studies. An ecosystem of case studies, focussed on detailed analysis of results for individual countries is an effective way to build competence, create examples, and move beyond the current state-of-the-art.

To help achieve a common understanding, we suggest researchers and inventory compilers co-produce a range of fact sheets or courses of the agreed level of detail. It may be necessary to set up specific working groups, involving different levels of competence, to develop this material. Over time, these materials may lead to a more elaborate document, such as a book, or specific chapter in the IPCC reporting guidelines, building on, and expanding, the current 2019 Refinement. Inventory agencies probably need direct and specific exchange with modellers, to explain and understand the inversions, suggesting that there may be a greater need to focus on specific case studies as opposed to automation and generalisations. Steps to achieve more case studies are to identify willing inventory agencies and modellers who have the time, capacity, and interest to perform detailed verification exercises.

We have suggested six areas where we see the most productive gains to be made: 1) Building a common understanding and knowledge base, 2) An ecosystem of case studies, 3) Technical aspects of inverse modelling, 4) Graphical material and analysis tools, 5) Collaboration, and 6) Communication. Many of these activities have already been initiated but need to be improved and expanded.

6 References

Akimoto, Hajime, Toshimasa Ohara, Jun-ichi Kurokawa, and Nobuhiro Horii. 2006. "Verification of Energy Consumption in China during 1996–2003 by Using Satellite Observational Data." *Atmospheric Environment* 40 (40): 7663–67. https://doi.org/10.1016/j.atmosenv.2006.07.052.

Andrew, Robbie M. 2020. "A Comparison of Estimates of Global Carbon Dioxide Emissions from Fossil Carbon Sources." *Earth System Science Data* 12 (2): 1437–65. https://doi.org/10.5194/essd-12-1437-2020.

Basu, Sourish, Scott J. Lehman, John B. Miller, Arlyn E. Andrews, Colm Sweeney, Kevin R. Gurney, Xiaomei Xu, John Southon, and Pieter P. Tans. 2020. "Estimating US Fossil Fuel CO2 Emissions from Measurements of 14C in Atmospheric CO2." *Proceedings of the National Academy of Sciences* 117 (24): 13300–307. https://doi.org/10.1073/pnas.1919032117.

Byrne, Brendan, David F. Baker, Sourish Basu, Michael Bertolacci, Kevin W. Bowman, Dustin Carroll, Abhishek Chatterjee, et al. 2023. "National CO_2 Budgets (2015–2020) Inferred from Atmospheric CO_2 Observations in Support of the Global Stocktake." *Earth System Science Data* 15 (2): 963–1004. https://doi.org/10.5194/essd-15-963-2023.

Canadell, Josep G., Pedro Scheel Monteiro, Marcos H. Costa, Leticia Cotrim da Cunha, Peter M. Cox, Alexey V. Eliseev, Stephanie Henson, et al. 2021. "Global Carbon and Other Biogeochemical Cycles and Feedbacks." In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by Valérie Masson-Delmotte, Panmao Zhai, Anna Pirani, Sarah L. Connors, Clotilde Péan, Sophie Berger, Nada Caud, et al., 673–816. Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press. https://doi.org/10.1017/9781009157896.001.

Cheewaphongphan, Penwadee, Satoru Chatani, and Nobuko Saigusa. 2019. "Exploring Gaps between Bottom-Up and Top-Down Emission Estimates Based on Uncertainties in Multiple Emission Inventories: A Case Study on CH4 Emissions in China." *Sustainability* 11 (7): 2054. https://doi.org/10.3390/su11072054.

Ciais, Philippe, D. Crisp, Hugo A. C. Denier van der Gon, Richard Engelen, M. Heimann, Greet Janssens-Maenhout, P. Rayner, and Marko Scholze. 2015. *Towards a European Operational Observing System to Monitor Fossil CO2 Emissions*. European Commission Joint Research Centre. https://doi.org/10.2788/350433.

Deng, Zhu, Philippe Ciais, Zitely A. Tzompa-Sosa, Marielle Saunois, Chunjing Qiu, Chang Tan, Taochun Sun, et al. 2022. "Comparing National Greenhouse Gas Budgets Reported in UNFCCC Inventories against Atmospheric Inversions." *Earth System Science Data* 14 (4): 1639–75. https://doi.org/10.5194/essd-14-1639-2022.

Friedlingstein, Pierre, Michael O'Sullivan, Matthew W. Jones, Robbie M. Andrew, Luke Gregor, Judith Hauck, Corinne Le Quéré, et al. 2022. "Global Carbon Budget 2022." *Earth System Science Data* 14 (11): 4811–4900. https://doi.org/10.5194/essd-14-4811-2022.

German, Richard, Bradley Matthews, and Paul Ruyssenaars. 2021. "Inverse Modelling as a Tool to Support National Greenhouse Gas Monitoring in Europe." ETC/CME Eionet Report | 4/2021. https://www.eionet.europa.eu/etcs/etc-cme/products/etc-cme-reports/etc-cme-report-4-2021-inverse-modelling-as-a-tool-to-support-national-greenhouse-gas-monitoring-in-europe.

Grassi, Giacomo, Jo House, Werner A. Kurz, Alessandro Cescatti, Richard A. Houghton, Glen P. Peters, Maria J. Sanz, et al. 2018. "Reconciling Global-Model Estimates and Country Reporting of Anthropogenic Forest CO2 Sinks." *Nature Climate Change* 8 (10): 914–20. https://doi.org/10.1038/s41558-018-0283-x.

Grassi, Giacomo, Elke Stehfest, Joeri Rogelj, Detlef van Vuuren, Alessandro Cescatti, Jo House, Gert-Jan Nabuurs, et al. 2021. "Critical Adjustment of Land Mitigation

Pathways for Assessing Countries' Climate Progress." *Nature Climate Change* 11 (5): 425–34. https://doi.org/10.1038/s41558-021-01033-6.

IPCC. 2006. *IPCC Guidelines for National Greenhouse Gas InventoriesInventories, Prepared by the National Greenhouse Gas Inventories Programme*. Edited by H.S. Eggleston, L. Buendia, K. Miwa, T. Ngara, and K. Tanabe. Japan: IGES. https://www.ipcc-nggip.iges.or.jp/public/2006gl/.

———. 2019. *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories*. Edited by E. Calvo Buendia, K. Tanabe, A. Kranje, B. Jamsranjav, M. Fukuda, S. Ngarize, A. Osaka, Y. Pyrozhenko, P. Shermanau, and S. Federici. Switzerland: IPCC. https://www.ipcc-nggip.iges.or.jp/public/2006gl/.

Janssens-Maenhout, Greet, Monica Crippa, Diego Guizzardi, Marilena Muntean, Edwin Schaaf, Frank Dentener, Peter Bergamaschi, et al. 2019. "EDGAR v4.3.2 Global Atlas of the Three Major Greenhouse Gas Emissions for the Period 1970–2012." *Earth System Science Data* 11 (3): 959–1002. https://doi.org/10.5194/essd-11-959-2019.

Janssens-Maenhout, Greet, B. Pinty, M. Dowell, H. Zunker, E. Andersson, G. Balsamo, J.-L. Bézy, et al. 2020. "Toward an Operational Anthropogenic CO2 Emissions Monitoring and Verification Support Capacity." *Bulletin of the American Meteorological Society* 101 (8): E1439–51. https://doi.org/10.1175/BAMS-D-19-0017.1.

Jones, Matthew W., Robbie M. Andrew, Glen P. Peters, Greet Janssens-Maenhout, Anthony J. De-Gol, Philippe Ciais, Prabir K. Patra, Frederic Chevallier, and Corinne Le Quéré. 2021. "Gridded Fossil CO2 Emissions and Related O2 Combustion Consistent with National Inventories 1959–2018." *Scientific Data* 8 (1): 2. https://doi.org/10.1038/s41597-020-00779-6.

Kaminski, Thomas, Marko Scholze, Peter Rayner, Michael Voßbeck, Michael Buchwitz, Maximilian Reuter, Wolfgang Knorr, et al. 2022. "Assimilation of Atmospheric CO2 Observations from Space Can Support National CO2 Emission Inventories." *Environmental Research Letters* 17 (1): 014015. https://doi.org/10.1088/1748-9326/ac3cea.

Keller, Christoph A., Dominik Brunner, Stephan Henne, Martin K. Vollmer, Simon O'Doherty, and Stefan Reimann. 2011. "Evidence for Under-Reported Western European Emissions of the Potent Greenhouse Gas HFC-23." *Geophysical Research Letters* 38 (15). https://doi.org/10.1029/2011GL047976.

Lu, Xiao, Daniel J. Jacob, Yuzhong Zhang, Lu Shen, Melissa P. Sulprizio, Joannes D. Maasakkers, Daniel J. Varon, et al. 2023. "Observation-Derived 2010-2019 Trends in Methane Emissions and Intensities from US Oil and Gas Fields Tied to Activity Metrics." *Proceedings of the National Academy of Sciences* 120 (17): e2217900120. https://doi.org/10.1073/pnas.2217900120.

Manning, Alistair J., Alison L. Redington, Daniel Say, Simon O'Doherty, Dickon Young, Peter G. Simmonds, Martin K. Vollmer, et al. 2021. "Evidence of a Recent Decline in UK Emissions of Hydrofluorocarbons Determined by the InTEM Inverse Model and Atmospheric Measurements." *Atmospheric Chemistry and Physics* 21 (16): 12739–55. https://doi.org/10.5194/acp-21-12739-2021.

McGrath, Matthew J., Ana Maria Roxana Petrescu, Philippe Peylin, Robbie M. Andrew, Bradley Matthews, Frank Dentener, Juraj Balkovič, et al. 2023. "The Consolidated European Synthesis of CO_2 Emissions and Removals for the European Union and United Kingdom: 1990–2020." *Earth System Science Data* 15 (10): 4295–4370. https://doi.org/10.5194/essd-15-4295-2023.

National Academies of Sciences, Engineering, and Medicine. 2022. *Greenhouse Gas Emissions Information for Decision Making: A Framework Going Forward*. Washington, DC: The National Academies Press. https://doi.org/10.17226/26641.

Perugini, Lucia, Guido Pellis, Giacomo Grassi, Philippe Ciais, Han Dolman, Joanna I. House, Glen P. Peters, Pete Smith, Dirk Günther, and Philippe Peylin. 2021. "Emerging Reporting and Verification Needs under the Paris Agreement: How Can the Research Community Effectively Contribute?" *Environmental Science & Policy* 122 (August): 116–26. https://doi.org/10.1016/j.envsci.2021.04.012.

Peters, Glen P., Corinne Le Quéré, Robbie M. Andrew, Josep G. Canadell, Pierre Friedlingstein, Tatiana Ilyina, Robert B. Jackson, et al. 2017. "Towards Real-Time Verification of CO2 Emissions." *Nature Climate Change* 7 (12): 848–50. https://doi.org/10.1038/s41558-017-0013-9.

Petrescu, Ana Maria Roxana, Matthew J. McGrath, Robbie M. Andrew, Philippe Peylin, Glen P. Peters, Philippe Ciais, Gregoire Broquet, et al. 2021. "The Consolidated European Synthesis of CO_2 Emissions and Removals for the European Union and United Kingdom: 1990–2018." *Earth System Science Data* 13 (5): 2363–2406. https://doi.org/10.5194/essd-13-2363-2021.

Petrescu, Ana Maria Roxana, Glen P. Peters, Greet Janssens-Maenhout, Philippe Ciais, Francesco N. Tubiello, Giacomo Grassi, Gert-Jan Nabuurs, et al. 2020. "European Anthropogenic AFOLU Greenhouse Gas Emissions: A Review and Benchmark Data." *Earth System Science Data* 12 (2): 961–1001. https://doi.org/10.5194/essd-12-961-2020.

Petrescu, Ana Maria Roxana, Chunjing Qiu, Philippe Ciais, Rona L. Thompson, Philippe Peylin, Matthew J. McGrath, Efisio Solazzo, et al. 2021. "The Consolidated European Synthesis of CH_4 and N_2O Emissions for the European Union and United Kingdom: 1990–2017." *Earth System Science Data* 13 (5): 2307–62. https://doi.org/10.5194/essd-13-2307-2021.

Petrescu, Ana Maria Roxana, Chunjing Qiu, Matthew J. McGrath, Philippe Peylin, Glen P. Peters, Philippe Ciais, Rona L. Thompson, et al. 2022. "The Consolidated European Synthesis of CH_4 and N_2O Emissions for EU27 and UK: 1990–2020." *Earth System Science Data Discussions*, September, 1–97. https://doi.org/10.5194/essd-2022-287.

Pinty, B., P. Ciais, D. Dee, H. Dolman, M. Dowell, R. Engelen, K. Holmlund, et al. 2019. *An Operational Anthropogenic CO_2 Emissions Monitoring & Verification Support Capacity – Needs and High Level Requirements for in Situ Measurements*. EUR 29817 EN. European Commission Joint Research Centre. 10.2760/182790.

Pinty, B., Greet Janssens-Maenhout, M. Dowell, H. Zunker, T. Brunhes, Philippe Ciais, D. Dee, et al. 2017. *An Operational Anthropogenic CO_2 Emissions Monitoring & Verification Support Capacity - Baseline Requirements, Model Components and Functional Architecture*. EUR 28736 EN. European Commission Joint Research Centre. 10.2760/39384.

Plant, Genevieve, Eric A. Kort, Cody Floerchinger, Alexander Gvakharia, Isaac Vimont, and Colm Sweeney. 2019. "Large Fugitive Methane Emissions From Urban Centers Along the U.S. East Coast." *Geophysical Research Letters* 46 (14): 8500–8507. https://doi.org/10.1029/2019GL082635.

Rigby, M., S. Park, T. Saito, L. M. Western, A. L. Redington, X. Fang, S. Henne, et al. 2019. "Increase in CFC-11 Emissions from Eastern China Based on Atmospheric Observations." *Nature* 569 (7757): 546–50. https://doi.org/10.1038/s41586-019-1193-4.

Saunois, Marielle, Ann R. Stavert, Ben Poulter, Philippe Bousquet, Josep G. Canadell, Robert B. Jackson, Peter A. Raymond, et al. 2020. "The Global Methane Budget 2000–2017." *Earth System Science Data* 12 (3): 1561–1623. https://doi.org/10.5194/essd-12-1561-2020.

Schwingshackl, Clemens, Wolfgang A. Obermeier, Selma Bultan, Giacomo Grassi, Josep G. Canadell, Pierre Friedlingstein, Thomas Gasser, et al. 2022. "Differences in Land-Based Mitigation Estimates Reconciled by Separating Natural and Land-Use CO2 Fluxes at the Country Level." *One Earth* 5 (12): 1367–76. https://doi.org/10.1016/j.oneear.2022.11.009.

Solazzo, Efisio, Monica Crippa, Diego Guizzardi, Marilena Muntean, Margarita Choulga, and Greet Janssens-Maenhout. 2021. "Uncertainties in the Emissions Database for Global Atmospheric Research (EDGAR) Emission Inventory of Greenhouse Gases." *Atmospheric Chemistry and Physics* 21 (7): 5655–83. https://doi.org/10.5194/acp-21-5655-2021.

Steinbach, J., C. Gerbig, C. Rödenbeck, U. Karstens, C. Minejima, and H. Mukai. 2011. "The CO_2 Release and Oxygen Uptake from Fossil Fuel Emission Estimate (COFFEE) Dataset: Effects from Varying Oxidative Ratios." *Atmospheric Chemistry and Physics* 11 (14): 6855–70. https://doi.org/10.5194/acp-11-6855-2011.

Steinkamp, Kay, Sara E. Mikaloff Fletcher, Gordon Brailsford, Dan Smale, Stuart Moore, Elizabeth D. Keller, W. Troy Baisden, Hitoshi Mukai, and Britton B. Stephens. 2017. "Atmospheric CO_2 Observations and Models Suggest Strong Carbon Uptake by Forests in New Zealand." *Atmospheric Chemistry and Physics* 17 (1): 47–76. https://doi.org/10.5194/acp-17-47-2017.

Tian, Hanqin, Rongting Xu, Josep G. Canadell, Rona L. Thompson, Wilfried Winiwarter, Parvadha Suntharalingam, Eric A. Davidson, et al. 2020. "A Comprehensive Quantification of Global Nitrous Oxide Sources and Sinks | Nature." *Nature* 586: 248–56.

WMO. 2018. "WMO Greenhouse Gas Bulletin: No. 14." WMO. https://library.wmo.int/viewer/58673.

Document History

Version	Author(s)	Date	Changes
V0-1	All	01/09/2023	Draft incorporating reviewer comments
V0-2	All		Draft sent to participants of the CoCO2 GA (November 2023)
V0-3	All		Draft submitted to peer review
V0-4	Peters	18/12/2023	Implemented review comments
V0-5	Peters	19/12/2023	Finalisation of document

Internal Review History

Internal Reviewers	Date	Comments
Johanna Tamminen (FNI)	7/12/2023	Minor comments
Thomas Kaminski (iLab)	6/12/2023	Minor comments and reformulations

Estimated Effort Contribution per Partner

Partner	Effort
CICERO	3.0
VU Amsterdam	1.0
CMCC	0.5
ECMWF	0.5
Total	**5.0**

This publication reflects the views only of the author, and the Commission cannot be held responsible for any use which may be made of the information contained therein.