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Toward an Operational Anthropogenic CO_2 Emissions Monitoring and Verification Support Capacity

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ABSTRACT: Under the Paris Agreement (PA), progress of emission reduction efforts is tracked on the basis of regular updates to national greenhouse gas (GHG) inventories, referred to as bottom-up estimates. However, only top-down atmospheric measurements can provide observation-based evidence of emission trends. Today, there is no internationally agreed, operational capacity to monitor anthropogenic GHG emission trends using atmospheric measurements to complement national bottom-up inventories. The European Commission (EC), the European Space Agency, the European Centre for Medium-Range Weather Forecasts, the European Organisation for the Exploitation of Meteorological Satellites, and international experts are joining forces to develop such an operational capacity for monitoring anthropogenic CO_2 emissions as a new CO_2 service under the EC's Copernicus program. Design studies have been used to translate identified needs into defined requirements and functionalities of this anthropogenic CO_2 emissions Monitoring and Verification Support (CO_2MVS) capacity. It adopts a holistic view and includes components such as atmospheric spaceborne and in situ measurements, bottom-up CO_2 emission maps, improved modeling of the carbon cycle, an operational data-assimilation system integrating top-down and bottom-up information, and a policy-relevant decision support tool. The CO_2MVS capacity with operational capabilities by 2026 is expected to visualize regular updates of global CO_2 emissions, likely at 0.05° x 0.05°. This will complement the PA's enhanced transparency framework, providing actionable information on anthropogenic CO_2 emissions that are the main driver of climate change. This information will be available to all stakeholders, including governments and citizens, allowing them to reflect on trends and effectiveness of reduction measures. The new EC gave the green light to pass the CO_2MVS from exploratory to implementing phase.

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Policy context

Since the establishment of the United Nations Framework Convention on Climate Change (UNFCCC) 25 years ago, many actions have been undertaken by the Conference of Parties (COP) and the Intergovernmental Panel for Climate Change (IPCC), but global emissions of greenhouse gases (GHGs) have not yet been curbed. In 2015, transparency and collaborative efforts were high on the agenda.[1] This concluded with the Paris Agreement (PA) (UNFCCC 2015), representing a paradigm shift because it downplays the distinction between Annex-I (developed) and non-Annex-I (developing) Parties[2] for committing to emission reduction and establishes an *enhanced transparency framework*, freely accessible to all Parties. The enhanced transparency framework builds on the monitoring–reporting–verifying framework, under which Parties provide their national GHG inventories compiled in line with the IPCC (2006) guidelines.

The UNFCCC's Subsidiary Body for Scientific and Technological Advice (UNFCCC-SBSTA 2017, 2019) as well as the IPCC Task Force on the 2019 Refinement to the 2006 Guidelines (Witi and Romano-TFI, 2019) acknowledged the complementary capability offered by GHG monitoring through in situ as well as satellite observations. Currently, only a few countries (the United Kingdom, Switzerland, Australia, and New Zealand) complement their national inventory data, based on annual statistics of human activities, with atmospheric observations (Bergamaschi et al. 2018).

More encouragement is needed to bridge the gap between the IPCC Task Force on inventories, the IPCC Working Groups for assessments, and more generally the science community

[1] The 2030 Agenda for Sustainable Development in New York and the Climate Action agenda at COP21 in Paris.

[2] Defined by the UNFCCC in its Annex.

involved in atmospheric GHG measurements and flux estimation (e.g., Le Quéré et al. 2018). From 2023 onward, the IPCC is expected to provide important input to the review of the national GHG inventories at the biennial Facilitative Multilateral Considerations of Progress (FMCP) or the 5-yearly Global Stocktake (GST). Responding to the policy impetus at national, European Union (EU), and global scales, an expert panel from the European Commission (EC) (Pinty et al. 2019) identified the high-level needs of Table 1 that have been translated into technical requirements.

Responsibilities and commitments are not only taken at the governmental level, but also by cities (e.g., the Covenant of Mayors), power plant operators, oil/gas multinationals, and more. Multilevel governance schemes, involving municipal, regional, and national authorities, ask for GHG monitoring, not only with annual national totals, but also with spatiotemporally resolved emissions. The tracking of emission reductions, as intended under the Nationally Determined Contributions (NDC), is facilitated by higher spatial resolution. As shown for air pollutants, the Convention of Long-Range Transboundary Air Pollution (UNECE-CLRTAP 2013) imposed from 2014 onward that Parties report emissions (including point sources) on spatial grids.

Five building blocks of the anthropogenic CO_2 emissions Monitoring and Verification Support (CO_2MVS) capacity

Through the CO_2 Monitoring Task Force, the EC elaborated the space- and ground-based elements for an operational capacity, the so-called CO_2MVS, to monitor and verify anthropogenic CO_2 emissions with observation-based evidence in support of climate policymakers. The policy needs of Table 1 require the quantification of the anthropogenic GHG emissions at high spatiotemporal resolution. The CO_2MVS capacity focuses initially on the major contribution of the fossil fuel combustion emissions of CO_2 ($ffCO_2$), and then expands to include other human activities[3] and other GHGs (e.g., CH_4). Figure 1 shows a schematic diagram of the functional architecture of the fully integrated CO_2MVS capacity that includes five building blocks: prior information, observations (spaceborne and in situ), integration processes, output/results, and decision support.

In a first exploratory phase, this CO_2MVS architecture was outlined by Ciais et al. (2015) and further elaborated in Pinty et al. (2017). Moreover, it appears in the Integrated Global GHG Information System of the World Meteorological Organization (WMO) (DeCola et al. 2019) and the White Paper of the Community of Earth Observation Satellites (CEOS) (Crisp et al. 2018). In December 2019, the EC agreed under the Green Deal to start the implementation phase of this CO_2MVS with the Directorate-General Climate Action (DG CLIMA) and EU Member States as main policy users.

[3] In particular the CO_2 sources and sinks of agriculture, forestry, and land use (AFOLU).

GHG emission inventories as prior information. With the creation of the UNFCCC came the request for bottom-up emission inventories, especially of Annex-I countries, which were historically contributing the most to the cumulative emissions. The bottom-up accounting of $ffCO_2$

Table 1. High-level policy needs as identified by Pinty et al. (2017).

High-level requirements for the CO_2MVS for policymakers	Technically implied accuracy requirement[a]	Space and time resolution
Detection of emitting hot spots such as megacities or power plants	46 kton CO_2 yr^{-1} km^{-2}	2 km x 2 km pixel; daily
Monitoring the hot-spot emissions to assess emission reductions/increases	1 kton CO_2 yr^{-1} km^{-2}	2 km x 2 km pixel; daily
Assessing emission changes against local reduction targets to monitor NDCs	0.2 kton CO_2 yr^{-1} km^{-2}	0.1° x 0.1°; monthly
Assessing the national emissions and changes in 5-yr time steps for the GST	0.2 kton CO_2 yr^{-1} per country	Country area; yearly

[a] First-order estimate from the Pinty et al. (2017) report.

emissions requires rigorous energy statistics, which are based on monthly and annual fuel stock exchanges with a closed balance at global and annual scales. With surveys and measurements, the oxygenation factor and the net caloric value for each fuel type were quantified and $ffCO_2$ emissions were computed. The PA Rulebook, published at the end of 2018, explained how the GST of 2023 will be undertaken with the inventories of the emissions from anthropogenic activities occurring during 2021. High-quality inventories (with uncertainties ≤3%) are not available for all countries (Janssens-Maenhout et al. 2019).[4]

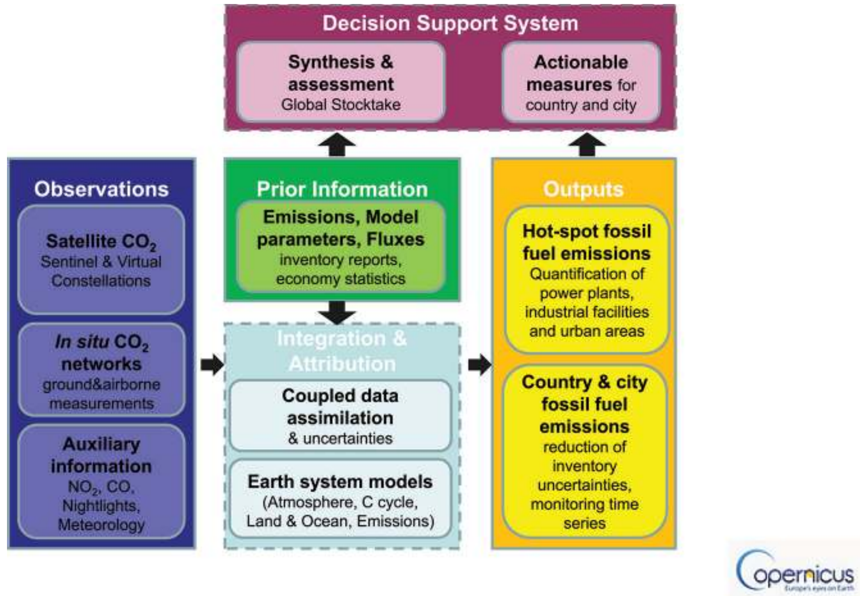


Fig. 1. Schematic overview of the planned anthropogenic CO_2MVS capacity: prior information with first best estimate of the GHG emission inventories and their uncertainties (green, discussed in "GHG emission inventories as prior information"), observations with spaceborne, in situ, auxiliary data including meteorology data (dark blue, discussed in "Atmospheric observations and auxiliary data"), integration and attribution processes with a core model (light blue, discussed in "Integration and attribution system"), the output with consolidated results (yellow, discussed in "Output of the models"), and the decision support process with actionable information for policy-makers (purple, discussed in "Decision support tool with a posteriori evaluation of the GHG inventories"). Data-focused components have a full border, whereas process-focused components have a dashed border.

Regional differences in processing model-ready input emission grid maps, subsequently used as prior information, can influence model results, as illustrated by Pouliot et al. (2012). More recently for CO_2, Wang et al. (2019) proposed an algorithm to aggregate grid cells of similar emission fluxes and define a "clump" of area and point sources emitting plumes that will be observable by the current generation of spaceborne sensors, Nassar et al. (2013) emphasized the need to include temporal variations of urban emissions, and Brunner et al. (2019) highlighted the importance of the injection height and velocity of the CO_2 emissions from power plants and industrial facilities.

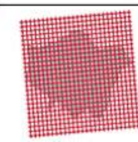
Atmospheric observations and auxiliary data.

Spaceborne Observations. The European Environmental Satellite (ENVISAT), 2002–12, was a pioneering spaceborne mission with various instruments measuring the concentration of many atmospheric species. The Scanning Imaging Absorption Spectrometer for Atmospheric Cartography (SCIAMACHY) instrument measured, among others, GHGs, such as the column-averaged dry-air mole fractions of CO_2 and CH_4, denoted XCO_2 and XCH_4 (e.g., Schneising et al. 2013; Buchwitz et al. 2015, 2018). Since 2009, the Japanese *Greenhouse Gases Observing Satellite (GOSAT)* with the thermal and near-infrared Fourier transform spectrometer for carbon observations and a cloud and aerosol imager has also been delivering XCO_2 and XCH_4 products (Yoshida et al. 2013; Crisp et al. 2012; Buchwitz et al. 2015). *GOSAT-2* was launched in 2018 with considerably improved concentration measurement (see Table 2).

NASA's *Orbiting Carbon Observatory 2 (OCO-2)*, including a three-channel imaging grating spectrometer, started delivering XCO_2 data with an unprecedented high signal-to-noise

[4] Uncertainties for national fossil fuel emission inventories range between 3% and 10% for different countries (Olivier et al. 2016).

Table 2. Comparison of the technical specifications of the Copernicus CO_2M satellite to some currently available sensors (with input of Buchwitz et al. 2018). A constellation of three CO_2M satellites by 2026 is considered.

Requirements for XCO_2	GOSAT2 (Japan)	OCO-2 (USA)	TanSat (China)	CO_2M (EU)
Random Error and systematic biases	≤0.5 ppm (CO_2) ≤5ppb (CH_4)	≤0.5 ppm	≤1-4 ppm	≤0.5-0.7 ppm
Spatial resolution	 74km^2	 2.3x1.3km^2	 2x2km^2	 2x2km^2
Swath width	 5-point sampling on 1000km track	 10km	 10km	 240 km
Revisit	3 days	16 days	16 days	2-3 days with 3 satellites
Orbit equator crossing	13:00 (ascending)	13:36 (ascending)	13:39 (ascending)	11:30 (descending)

ratio in 2014. The instrument yields the spatial structure of XCO_2 variations across megacities (Schwandner et al. 2017) and allows quantification of $ffCO_2$ plumes from individual power plants (Nassar et al. 2017). China's carbon dioxide–monitoring satellite *TanSat*, launched in late 2016 with an atmospheric CO_2 grating spectrometer, may add another XCO_2 data stream in the near future.

A constellation of European low-Earth-orbit (LEO) CO_2 satellite imagers (CO_2M) are now committed by the EC under the aegis of the Copernicus program, with the main objective to contribute significantly to the policy needs of Table 1 by increasing high-quality satellite observations of XCO_2. The European Space Agency (ESA) leads the design of these CO_2M LEOs with a broad-swath imaging grating spectrometer for CO_2, CH_4, NO_2, and aerosols and plans to deliver science data from January 2026 onward. The main technical specifications of the CO_2M spectrometer,[5] as described in detail in ESA's (2019) mission requirements document v2.0, are summarized in Table 2 and compared to those of other, currently active sensors.

The rationale for collocated observations of NO_2 is to better identify the location and shape of the CO_2 plumes. This takes advantage of the signal-to-noise ratio for NO_2 enhancements, which is much larger than for CO_2 and not contaminated by biospheric emissions. Kuhlmann et al. (2019) demonstrated that auxiliary NO_2 measurements[6] greatly enhance the detection capability for $ffCO_2$-plume locations. Collocated regional enhancements of XCO_2 observed by *OCO-2* and NO_2 from the *Sentinel-5 Precursor (S5P)* satellite have already been used by Reuter et al. (2019) to estimate $ffCO_2$-plume cross-sectional fluxes and to assess the usefulness of simultaneous satellite observations of NO_2 and XCO_2. Auxiliary aerosol measurements are used to account for perturbations in the optical path of the CO_2 sensor due to aerosol scattering (Frankenberg et al. 2012).[7]

In situ measurements. The envisioned CO_2MVS requires in situ observations for the following purposes:

1) *To calibrate and validate the space component that will consist of column-integrated CO_2 measurements from the ground to the top of the atmosphere*. This can be based on the global TCCON[8] network, comprising large, upward-looking Bruker sun

[5] Auxiliary instruments on the same platform of the Copernicus CO_2M satellite include a NO_2 spectrometer, a multiangle polarimeter, and a cloud imager.

[6] Rather than CO as tracer of incomplete fossil fuel combustion.

[7] For local sources such as power plants, CH_4 measurements support the accuracy of satellite-retrieved XCO_2 through the proxy retrieval method (Frankenberg et al. 2005).

[8] Total Carbon Column Observing Network (http://tccon.caltech.edu/).

spectrometers, supplemented by a similar network of smaller instruments, COCCON.[9] Under clear-sky conditions, these data can be used after conversion using the WMO-standard mole fraction CO_2 scale (Tans 2009). Collocated vertical CO_2 profile measurements are required to calibrate XCO_2 data from upward-looking spectrometers. Such profiles can be acquired using regular air-core measurements (Karion et al. 2010) and/or using alternatives such as vertical CO_2 profiles collected by regional aircraft.[10]

2) *As a backbone network providing high-quality controlled, homogeneous surface-layer observations (with expanded spatiotemporal coverage).* In Europe, the in situ measurements are coordinated by ICOS.[11] Currently, the ICOS network is not homogeneously distributed and provides samples biased toward rural locations, focusing more on biospheric than anthropogenic fluxes. Consequently, the current network configuration does not sufficiently constrain $ffCO_2$ estimates.

3) *Expansions of coordinated and interoperable urban in situ CO_2 networks, including observations of ^{14}C and other additional tracers*. Measuring ^{14}C concentrations in atmospheric CO_2 is the best approach identified so far for separating $ffCO_2$ from the natural fluxes because fossil fuels do not contain ^{14}C (Levin et al. 2003; Turnbull et al. 2006). Observations of ^{14}C and $ffCO_2$ co-emitted species across major $ffCO_2$ emitting regions will provide complementary information to satellites for quantifying anthropogenic emissions from hot spots and for attributing the large-scale CO_2 signal.

The CO_2MVS spans a range of scales, from large point sources to country scales, which adds additional requirements for the in situ component: denser networks of sun spectrometers, denser continental-scale networks of ground-based CO_2, tracers and ^{14}C and portable instruments and local/regional CO_2 networks around selected hot spot areas for city-scale and large industrial complexes to validate the gradients up and downwind of the emitting sources. International coordination and standardization by WMO[12] and sustained operational and scientific funding are recommended for a successful implementation of the CO_2MVS capacity by Pinty et al. (2019).

Meteorological and Other Auxiliary Data. Meteorology is an important driver for the natural carbon cycle, and meteorological fields can be used as a proxy for the spatiotemporal distribution of temperature-dependent anthropogenic emissions.[13] In addition, meteorological data are key to constrain the atmospheric transport that links the observed atmospheric GHG concentrations and the actual emissions. The foreseen CO_2MVS capacity can fully benefit here from the heritage of numerical weather prediction (NWP), with its operational data-exchange mechanisms, and developments are well underway for a global high-resolution CO_2 ensembles-based system (Agustí-Panareda et al. 2019; McNorton et al. 2020).

In addition, FLUXNET,[14] a global network of eddy covariance measurements of CO_2 and H_2O exchange fluxes between the Earth and the atmosphere, can provide important independent data. Similarly, observations of other trace gases and particulate matter co-emitted with CO_2 can help identify spatiotemporal distribution of $ffCO_2$ emission sources. Some constituents are already monitored for air quality purposes (e.g., AERONET,[15] EIONET[16] for aerosols) and temporal profiles are devised in air quality models (e.g., Denier van der Gon et al. 2011).[17]

[9] Collaborative Carbon Column Observing Network (https://www.imk-asf.kit.edu/english/3221.php).

[10] With passenger aircraft CO_2 profiles [e.g., the IAGOS (https://www.iagos.org/) and CONTRAIL (www.cger.nies.go.jp/contrail/contrail.html-initiatives)] collocation of sun spectrometers is not achieved today and will require an extension of the TCCON and COCCON networks around airports.

[11] Integrated Carbon Observation System (https://www.icos-ri.eu/).

[12] For example, via the Global Atmosphere Watch (www.wmo.int/pages/prog/arep/gaw/gaw_home_en.html).

[13] For example, heating degree-days for the distribution of the residential heating emissions.

[14] About 40 micrometeorological tower sites, included in the FLUXNET infrastructure, are measuring CO_2 emissions in urban areas (http://fluxnet.fluxdata.org/).

[15] Aerosol Robotic Network is a federation of ground-based remote sensing aerosol networks (https://aeronet.gsfc.nasa.gov/).

[16] European Environment Information and Observation Network.

[17] As selected for being implemented in the Copernicus Atmosphere Monitoring Service.

Integration and attribution system. The integration and attribution system makes use of an ensemble of inverse modeling systems or data assimilation schemes with the scientific and operational attributes listed in Table 3. Such inversion systems or data assimilation schemes rely on atmospheric transport models linking the concentration observations to surface exchange fluxes. These can be defined on a model grid or represented by emission models and process parameters of these models. Both methods usually combine the information from various observational datasets with information from prior knowledge (e.g., model forecast or climatology) in a Bayesian framework, i.e., by minimizing a cost function that takes the uncertainties of all the datasets into account.

Table 3. Scientific and operational attributes of the core models. The attributes in italics are considered optional.

	Qualitative model attributes
Technical scientific attributes	High spatial resolution (a few kilometers) to minimize representation errors and averaging of observations
	High vertical resolution to match ground-based data (including emission injection height variations)
	Global coverage (in which regional models could be nested
	Atmospheric chemistry scheme for at least NO_2 and tracers
	Vegetation model driven by in situ measurements and using remotely sensed phenology
	Consistent vegetation energy budget and CO_2 flux simulation with atmospheric tracer transport, which is systematically evaluated against wind and tracer data
	Urban land surface scheme coupled with atmospheric model
Operational attributes	Near-real-time response capability of the data assimilation system
	Including the atmospheric transport uncertainties in the data assimilation core model
	Capability to assimilate near-real-time information about emissions
	Capability for reanalysis—reprocessing of all data (including data storage)
	Forecast capabilities
	Emission modeling capabilities

Estimates of the model errors are accounted for by combining them to the observational uncertainties or through the use of model ensembles.[18] Examples for a gridded inversion system can be found in Basu et al. (2013) or Gaubert et al. (2019) and for a process-based scheme in T. Kaminski et al. (2020, manuscript submitted to *Nat. Commun.*). Both approaches require consistency between all input datasets (preferably steered with a realistic prior) or a bias correction within the data assimilation system itself (e.g., Dee and Uppala 2009).[19] Earth observations are a key driver for Earth system modeling developments (Balsamo et al. 2018) representing natural and human-induced disturbances in the water, energy, and carbon cycle at the surface that are affecting CO_2 fluxes.

Super et al. (2017) explored the need for plume modeling to understand point sources in an urban-industrial complex, under the impact of different scales of meteorology. Experience with plume modeling has been gained mainly by the air quality community (e.g., Leelőssy et al. 2014) but also by the CO_2 community (e.g., Kuhlmann et al. 2019; Nassar et al. 2017). Although the long-lived CO_2 plume, with relatively small enhancement over the ambient background, diffuses differently from the plume of a short-lived NO_2 air pollutant, with relative high concentration enhancement in the atmosphere, both plumes show similar structures and the NO_2 plume is a good marker of the CO_2 plume. For the plume or puff modeling, there is know-how available from dispersion studies of (radioactive) air pollution. The modeling strategy for the CO_2MVS capacity combines different scales, from global to local, in order to cover ultimately the NDCs over a region/country. Figure 2 illustrates the challenge to link the local CO_2 flux footprint region of the in situ observations with the country scale of the national inventories and NDCs.

[18] This is also envisaged in the Community Inversion Framework (CIF), under development in the H2020 project VERIFY (see section "Way forward and challenges ahead").

[19] The various input data streams are then bias corrected to a common baseline, which is defined by a dataset with high accuracy and precision.

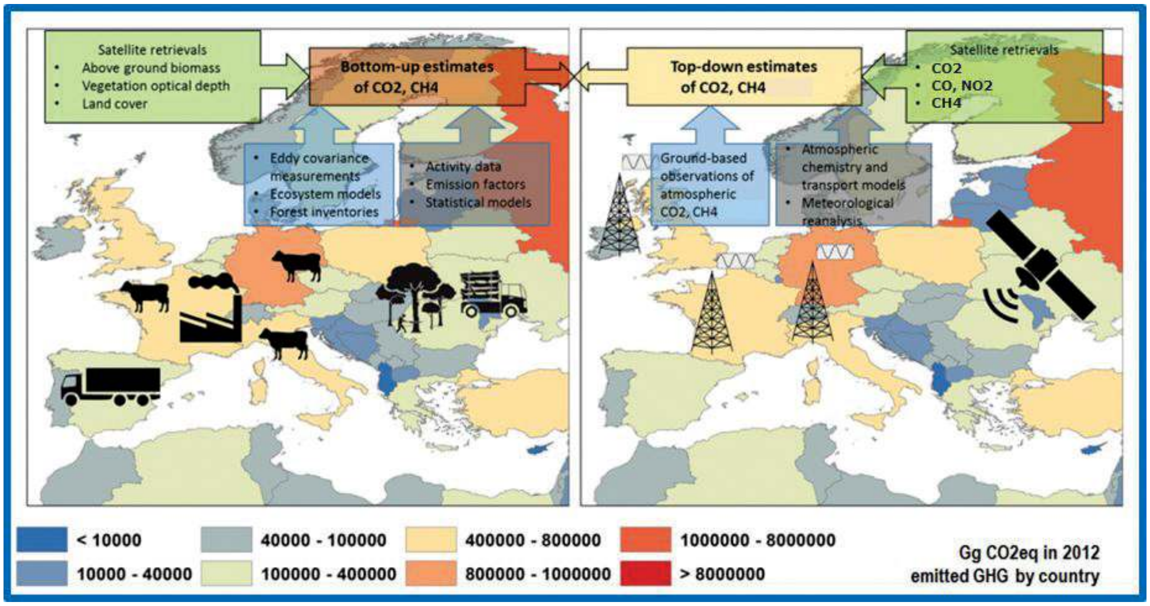


Fig. 2. Interplay between (left) bottom-up estimates (based on human activity data) and (right) top-down estimates (based on spaceborne or in situ observations) in the modeling chain, covering different scales from global to local. Obviously, it is challenging to monitor and verify a country's annual inventory (represented by the colored patchwork over Europe) based on atmospheric observations over time.

Output of the models. Output of the CO_2MVS will address a variety of spatiotemporal scales and various user communities.

- *At the global level*, the GST is in line with the implementation of the PA. In 2028 the CO_2MVS capacity should help evaluating the bottom-up GHG estimates and their difference with respect to 2023, assessing the effectiveness of the reductions of the NDCs.
- *At the country level*, the CO_2MVS needs to support the review of country budgets and to quantify through rigorous uncertainty propagation the impact of additional observational information into an uncertainty reduction in inferred emission fields [as illustrated for CH_4 by Bergamaschi et al. (2010)].
- *At the level of substate actors*, such as cities or industrial complexes, the spatiotemporal view on the emissions might reveal insights on the effectiveness of initiatives related to, e.g., carbon trading, greening of cities, and others. This new area of applications is where a significant contribution of an observation-driven operational CO_2MVS can be expected.

Decision support tool with a posteriori evaluation of the GHG inventories. An important spin-off from the CO_2MVS could be the provision of an assessment tool, open to UNFCCC and its Parties for monitoring NDC implementation worldwide. This still demands significant studies to determine the trends expected from the implementation of the NDCs, and more specifically where, when, and at what rate these trends are occurring. Most likely one of the robust results of a space-based observation system will be the monitoring of XCO_2 trends and change in posterior emission fluxes over multiple years. These results will yield spatiotemporal resolutions higher than possible on the sole basis of the national inventories and should provide evidence for tracking progress toward the NDCs' reduction targets. Moreover, maps of uncertainty reductions will inform where extra efforts such as additional measurements and/or more accurate GHG accounting infrastructures would best reduce the $ffCO_2$-budget uncertainty.

Long-term operations with an institutional framework consolidated by international collaboration

To develop the operational CO_2MVS capacity, the EC coordinates efforts from three major European institutions—ESA for developing the space segment, the European Organisation for the Exploitation of Meteorological Satellites (EUMETSAT) for operating the space segment, and the European Centre for Medium-Range Weather Forecasts (ECMWF)—for providing the modeling capacity required to integrate the overall observations. The initiative builds on existing modeling infrastructures, includes the design of a series of unprecedented satellite and ground-based CO_2 and CH_4 observation systems, and capitalizes on model-based analysis. EUMETSAT and ESA define the system requirements (for the space segment, the operations, and the ground segment) and take care of the operation of the satellite with continuous calibration/validation and data transmission. EUMETSAT foresees full automatic dissemination of the geophysical product data at native instrument resolution within 48 h, such that ECMWF and its partners with full model setup can provide a Copernicus CO_2 service with quasi-near-real-time products.

After calibration and operational tests of the CO_2MVS capacity over selected European countries, it will be possible to apply the CO_2MVS globally. The global applications, for regions outside Europe, will require extra in situ data, whose availability and access should be fostered by international collaborations. The EC and the relevant European institutional partners are already engaged bilaterally and multilaterally with international organizations[20] for the strategic, policy-relevant, and technical dimensions related to the setup of a global CO_2 monitoring capacity.

Way forward and challenges ahead

Monitoring of the anthropogenic CO_2 emissions in a consistent and systematic manner for all countries enables the identification of sources that can be further reduced in the GST assessments. This monitoring requires continuity of knowledge and data with sufficient spatiotemporal coverage, because of the significant and expectedly increasing variability of emission sources (e.g., with the renewables progressively replacing the fossil fuels). Quantification of the CO_2 plumes from power plants remains challenging, in particular when they are located in morphologically complex areas, such as near coastlines. Industrial complexes and urban areas add another level of heterogeneity and complexity to the plumes to be monitored. Various aspects of the challenges faced in building up the CO_2MVS capacity are discussed in the so-called "blue", "red," and "green" reports of the EC with a series of recommendations for actions.

Figure 3 sketches the planned development of the CO_2MVS and highlights the main milestones including the research components, namely:

> The ESA and EUMETSAT support studies[21] provide first input to the satellite system and product processing design, the product continuous calibration/validation and monitoring, and conclude with the need for collocated measurements of NO_2 and aerosols (with both an NO_2 spectrometer and a multi-angle polarimeter on the CO_2M platform). The spatiotemporal coverage with a series of constellation configurations as well as the impact of the technical parameter ranges have been estimated using well-defined assumptions.

[20] For example, WMO, Committee on Earth Observation Satellites (CEOS), and Coordination Group for Meteorological Satellites (CGMS).

[21] Carbon Cycle Fossil Fuel Data Assimilation System (CCFFDAS); Poor Man's Inversion Framework (PMIF); Satellite Measurements of Auxiliary Reactive Trace Gases for Fossil Fuel Carbon Dioxide Emission Estimation (SMARTCARB); Study on Use of Aerosol Information for Estimating Fossil Fuel CO_2 Emissions (AEROCARB); spectral sizing study; error budget study; E2F Simulator; system and instrumentation predevelopment; Airborne Carbon Dioxide Imager for Atmosphere (ACADIA); GHG product processing and continuous calibration/validation requirements definition; level 1 processing requirements for CO_2 monitoring mission; definition of requirements for an integrated function for calibration, validation, and monitoring of level 1 and level 2 products for CO_2 monitoring mission; top-of-atmosphere simulations for the evaluation of data processing for the CO_2 monitoring mission..

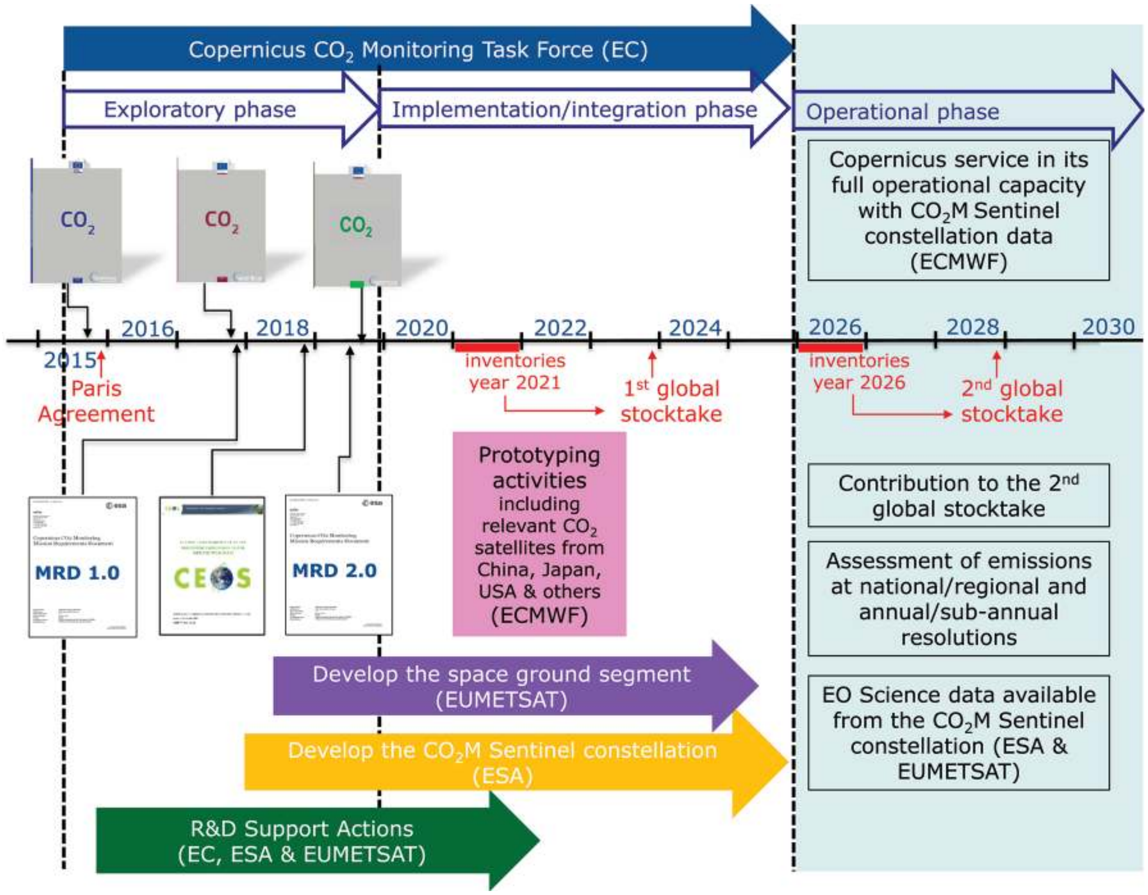


Fig. 3. Timeline for the development of a European operational GHG Monitoring and Verification Support capacity with the exploratory phase, the implementation/integration phase, and the operational phase. The exploratory phase is concluded with the reports of the CO_2 Monitoring Task Force [the blue CO_2 report of Ciais et al. (2015), the red CO_2 report of Pinty et al. (2017), and the green CO_2 report of Pinty et al. (2019)], the Mission Requirements Document (MRD) of ESA (versions 1.0 and 2.0), and the CEOS white paper of Crisp et al. (2018). In the exploratory phase, different Research and Development studies have been launched by the EC (under the Horizon 2020 Research Framework program), ESA, and EUMETSAT in support of the CO_2MVS design (green arrow). In addition, ESA and EUMETSAT launched studies to further develop the space component (orange arrow) and the ground segment (purple arrow), respectively.

The H2020 projects CHE[22] and VERIFY[23] prepare for an improved modeling and data assimilation, quantifying more accurately fluxes of CO_2 and CH_4 across Europe with enhanced, more detailed emission inventories, separating the anthropogenic and natural emission components and their drivers by advanced modeling and accurate characterization of the space–time variations of GHG fluxes.

Since 2015, the feasibility of the CO_2MVS has been explored. This phase is now successfully concluded with the go-ahead for the concrete phase of implementation and integration. The UNFCCC-SBSTA (2019) recognized the full system approach for monitoring CO_2 and CH_4 from space, combining satellite, in situ, and modeling components for emission estimates and encouraging Parties to the Convention to engage the necessary resources and competence to this endeavor. At a more public outreach level, it is also true that the visualization of the

[22] CHE stands for CO_2 Human Emissions and is the H2020 coordination support action project of the EC (https://che-project.eu/).

[23] VERIFY stands for Observation-Based Monitoring and Verification of Greenhouse Gases and is a H2020 scientific research project of the EC (https://verify.lsce.ipsl.fr/)

CO_2 emissions might be part of the more general solution to call for urgent climate action in implementing the PA.

We have a clear understanding of the CO_2MVS, and the system architecture implementation, although challenging, is within the means of EC, ESA, EUMETSAT, and ECMWF and the necessary coordination mechanisms. The timeline for implementation is demanding but well defined, and the system is expected to provide from 2026 onward pre-operational outputs and insight, by visualizing CO_2 emission plumes, and in particular the effects of non-implemented reductions, globally. As the CO_2MVS will have been calibrated over Europe, collaboration with our international partners is being actively pursued since the beginning to make the best out of the observations outside Europe as well.

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