CoCO2
Prototype system for a Copernicus $CO_2$ service

# Emission estimates for year 2021

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Co-ordinated by
ECMWF

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**Dissemination Level**: Public

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# 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**

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# 1. Introduction

## 1.1 Background

In the context of providing recommendations for the implementation of an observation-based operational anthropogenic $CO_2$ emissions Monitoring and Verification Support capacity (CO2MVS) within the Copernicus programme, one of the main objectives of CoCO2 is to provide inputs to the Global Stocktake (GST) process in time for the 1st GST in 2023, as well as more comprehensive inputs for the subsequent five-year GST cycles.

Specifically, it was foreseen that CoCO2 will already provide appropriate $CO_2$ anthropogenic emission products for the 1st GST, at a spatial scale consistent with GST requirements. For the longer term, research developments within other CoCO2 work packages will be channelled into building a comprehensive multi-scale prototype that will serve as the basis for the pre-operational Copernicus $CO_2$ service, with the view of delivering $CO_2$ emission and removals estimates on time for the 2nd GST with the best possible accuracy.

## 1.2 Scope of this deliverable

### 1.2.1 Objectives of this deliverable

The current deliverable is the result of three separate tasks in WP6. Task 6.2 (“Identify relevant needs for the periodic Global Stocktake”) has updated the User Requirement Document of VERIFY given the needs of the periodic GST process that should be based on best available science, taking advantage from observation-based emission monitoring systems. This already resulted in D6.3, “User Requirement Document”. It was the starting point to define the prototype functionalities for a timely support of the GST, according to the process and concepts defined in the decision 19/CMA.1, further refined on the basis of the guiding questions to be established in 2021 by the Chairs of the UNFCCC Subsidiary Bodies.

Task 6.3 (“Prepare prototype systems and data flow for the 1st GST”) has prepared the codes of, and the input data to, the prototypes in a coordinated way. It has integrated relevant results that have been obtained in WP2 - WP5 early enough to be used for the 1st GST. It documents them in dedicated Functional Requirements Specification Documents (FRSDs) that explain what the codes do and how they do it (D6.4).

Task 6.4 (“Provide emission estimates and corresponding evaluation for the 1st GST”) has run the codes to assimilate real observations acquired for year 2021 (as much as possible) for the 1st GST. It has provided a specific document of monitoring statistics and visual results of the outputs and is presented in the Appendix. The performance of the prototypes with respect to the user requirements is also documented in Fitness for Purpose Documents (FPDs) (D6.6).

### 1.2.2 Work performed for this deliverable

The present document successively introduces existing data from five CoCO2 prototype systems, each exploring and prefiguring different aspects of the future CO2MVS but without possessing its full integration power yet. Three of them are specifically for fossil fuel emissions: **local** large fossil fuel $CO_2$ emissions estimated from observed $CO_2$ plume cross-sections, **regional** fossil fuel $CO_2$ emissions estimated by an atmospheric inversion assimilating satellite retrievals of co-emitted species, and **global** fossil fuel $CO_2$ emissions estimated by a Carbon Cycle Fossil Fuel Data Assimilation System. The fourth prototype is for the Agriculture, Forestry and Other Land Use sector (AFOLU) emissions estimated by $CO_2$ atmospheric inversions. The fifth prototype addresses all global emissions and absorptions synergistically using an extension of the ECMWF Numerical Weather Prediction system. The diversity of these five approaches and of their driving observations both illustrate the current research & development axes of CoCO2 and the potential of the CO2MVS. A last section outlines some of the longer-term developments that are being made for the second GST. Specific attention was paid to ensure that the performance demonstration will be based on as much evidence as reasonably possible, from a quantitative point of view (uncertainty of the delivered variables) and from a qualitative point of view (realism of the space-time variations of the delivered variables).

It is important to note here that the results presented in this document are the results of many efforts within and outside the CoCO2 project. They represent the current state of methodologies from a large community effort towards the implementation of a more integrated CO2MVS capacity.

### 1.2.3 Deviations and counter measures

The main deviation from the original plan is the delay of this deliverable from M18 to M24. The outputs of several of the prototype systems were considered to be insufficiently mature for submission to the UNFCCC at the original deliverable date. With the GST being open for submissions until Q1 2023, the decision was taken to provide more time to the relevant CoCO2 partners to further improve their prototype systems and their outputs to allow a better submission to UNFCCC from the project. This also allowed to make better use of observational data for the year 2021.

A more positive deviation to the original proposal is the inclusion of 5 different prototype systems. The proposal stated that at least two prototypes are expected to contribute: the global IFS and a local plume inversion system developed at CEA. Adding three more prototype systems clearly shows the commitment from the consortium partners to contribute to this important 1st Global Stocktake.

# CoCO2 submission to 1st Global Stocktake

## 1. Introduction

The Paris Agreement, a milestone of the UNFCCC to combat climate change and adapt to its effects, entered into force on November 4, 2016. It asks each signatory to define and communicate its planned climate actions, known as Nationally Determined Contributions, and to report their progress towards their targets. To enable the European Union (EU) to move towards a low-carbon economy and implement its commitments under the Paris Agreement, the European Commission (EC) committed to cut its emissions by at least 55% by 2030. This was further consolidated with the release of the Commission's European Green Deal setting the targets for the European environment, economy, and society to reach zero net emissions of greenhouse gases in 2050. To independently assess the progress of countries towards their targets, the EC indicated that an objective way to monitor anthropogenic $CO_2$ emissions and their evolution over time was needed. Such a capability would provide consistent and reliable information to support informed political and decision-making processes. The European Commission is therefore establishing an operational observation-based anthropogenic $CO_2$ emissions monitoring and verification support capacity (**CO2MVS**) as part of its Copernicus Earth Observation programme (**Figure 1**).

The prototype systems for the European CO2MVS are being developed in the Prototype System for a Copernicus **$CO_2$** service (CoCO2) project. It is funded by the Space 2018-2020 Work Programme of the European Union for a three-year period (2021-2023). CoCO2 brings together expertise, existing capacities, and innovative ideas from a wide range of European and international players. It builds on the recommendations from the European Commission's $CO_2$ monitoring Task Force, developments and recommendations from the precursor VERIFY and CHE research projects, and from support studies funded by the European Space Agency.

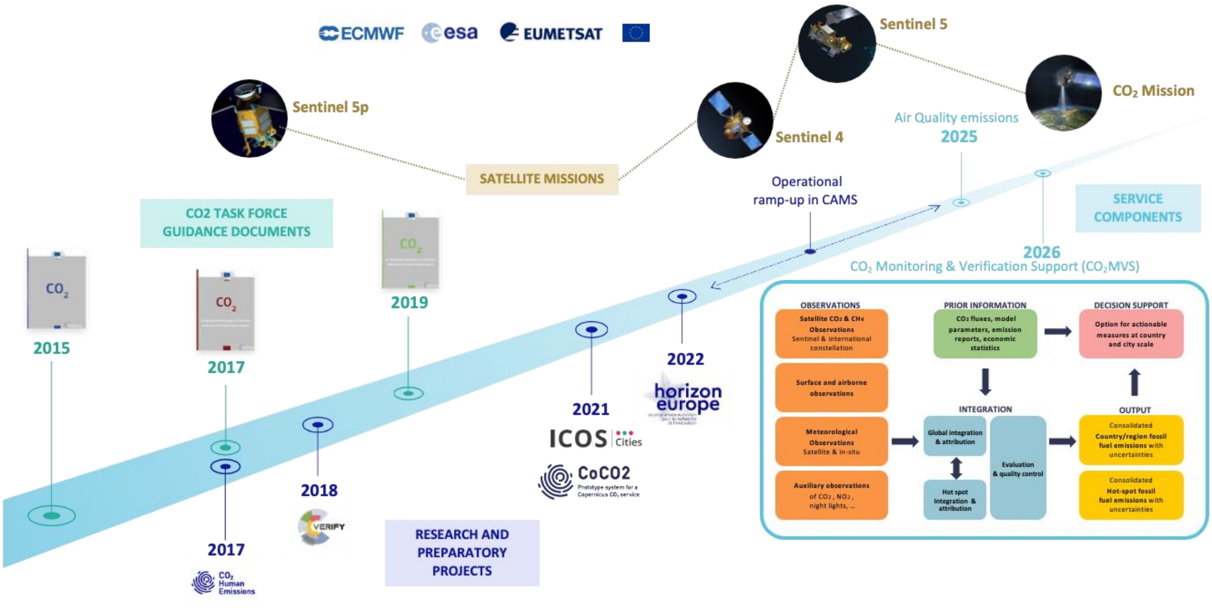

*Figure 1 – Pathway towards the Copernicus anthropogenic $CO_2$ and $CH_4$ emissions monitoring and verification support capacity.*

The CO2MVS concept combines information from different observational datasets and from existing knowledge about emissions together with detailed computer models of the Earth system. Its statistically robust framework enables exhaustive emission estimates of anthropogenic $CO_2$ and $CH_4$ at different scales with a similar level of mathematical rigour that has proven critically important in other applications, such as numerical weather prediction and air quality prediction.

As an observation-based system, the CO2MVS receives, as its main inputs, observations collected by satellite and in situ sensors. Satellite data are from existing or new Copernicus Sentinel satellites and various other sensors from national and international space agencies. In situ data are provided by various surface networks, coordinated by national, European, or international efforts. None of these observation systems directly measure anthropogenic emissions, but instead provide information on atmospheric $CO_2$ and co-emitted species, which result from anthropogenic emissions. Observations can also provide information about the processes that are responsible for the exchange of $CO_2$ and $CH_4$ between the Earth's surface and the atmosphere such as photosynthesis or human activity.

The signal of anthropogenic emissions in the variables we can observe, like atmospheric $CO_2$, is weak compared to the signal of natural emissions and removals between land and ocean surfaces and the atmosphere, especially on time scales shorter than a year. Moreover, the variability of atmospheric $CO_2$ concentrations due to human activity is small compared to average background concentrations and large-scale variability. To address these challenges, the CO2MVS needs state-of-the-art computer models of the Earth system capable of well simulating observed variables based on prescribed or modelled emissions and removals. Advanced data assimilation methods can then make adjustments to emissions and removals that are consistent with information from observations and constrained by the physical knowledge encapsulated in the models.

The planned CO2MVS will include and connect models and observations at three different scales: i) a global integration and attribution system will provide global coverage integrating all available observations, ii) local hotspot integration and attribution systems will directly assess emissions from individual plumes, and iii) regional systems will focus on specific areas with very dense observing infrastructure around them to provide a reference for the global system.

The CO2MVS will translate the generated data into user-friendly services. For some users, this could mean providing raw production data, for other user sectors specific tools need to be developed and implemented. The main objective of the CO2MVS is to serve the policy sector at international, national and local scales, to help countries develop their own specific emission monitoring capabilities, and to stimulate adoption by businesses and the finance sector within the framework of a green economy.

As part of the ramping-up activities towards the operational CO2MVS, CoCO2 is contributing to the 1st Global Stocktake data and information collection by providing accurate information about anthropogenic emissions based on current prototype systems that best exploit available observations. The full power of the CO2MVS will come after the end of CoCO2 with enhanced modelling capabilities and with the advent of new dedicated observation systems, most notably the future Copernicus $CO_2$ Monitoring (CO2M) satellite constellation, that will image $CO_2$ columns from space frequently over most locations over the globe. The aim is to have a fully operational system in 2026.

The present document successively introduces existing data from five CoCO2 prototype systems, each exploring and prefiguring different aspects of the future CO2MVS but without possessing its full integration power yet. Three of them are specifically for fossil fuel emissions:

- **local** large fossil fuel $CO_2$ emissions estimated from observed $CO_2$ plume cross-sections (section 2)
- **regional** fossil fuel $CO_2$ emissions estimated by an atmospheric inversion assimilating satellite retrievals of co-emitted species (section 3)
- **global** fossil fuel $CO_2$ emissions estimated by a Carbon Cycle Fossil Fuel Data Assimilation System (section 4)

The fourth prototype is for the Agriculture, Forestry and Other Land Use sector (AFOLU)

- **global** AFOLU emissions estimated by $CO_2$ atmospheric inversions (section 5)

The fifth prototype addresses all global emissions and absorptions synergistically:

- **global** data from an extension of the ECMWF Numerical Weather Prediction system (section 6)

The diversity of these five approaches and of their driving observations both illustrate the current research & development axes of CoCO2 and the potential of the CO2MVS. A last section outlines some of the longer-term developments that are being made for the second GST.

# 2. Estimates of large point source fossil fuel $CO_2$ emissions based on satellite observations

## 2.1. General presentation

A key component of the CO2MVS will be the capacity to monitor emissions from large point sources and significant urban areas. While this requires a further significant improvement of our satellite observation capabilities, such as foreseen with the future CO2M satellite mission, current satellite missions can already be used to provide estimates to test the methodology. NASA's second and third Orbiting Carbon Observatories (OCO-2 and -3) scientific missions, that continuously sample the Earth along their orbit line with a resolution of 3 $km^2$, are the closest existing instruments to a $CO_2$ imager.

OCO-2 started its measurements in September 2014 and is still operating at the time of writing, which extends its data record to more than eight years. OCO-3 measurements started in August 2019, but in a different orbital configuration that allows sampling diverse local daytime hours, while OCO-2 data are all close to local midday. The $CO_2$ column estimates retrieved by NASA from the radiance measurements of the two OCOs achieve exceptional accuracy by today's standards[1]. By analysing the transects of visible $CO_2$ plumes over the globe, CoCO2 retrieves $CO_2$ emissions from the burning of fossil fuels at these local sources.

## 2.2. Method

The emission estimation method automatically and systematically selects isolated enhancements in observed atmospheric $CO_2$ column-averaged concentrations along the satellite orbits that could correspond to transects of plumes from nearby upwind sources. To this end, each OCO orbit is analysed with a 200 km moving window successively centred on each of the validated column retrievals. If a retrieval value stands out of the variability of the retrievals in the window, the procedure attempts to fit a function that represents a bell curve on top of a linear background, which is a neutral shape to represent a plume cross-section. If the fit passes quality control, the procedure then estimates the corresponding $CO_2$ column line densities and multiplies these by the wind speed in the direction normal to the OCO-2 tracks to estimate the corresponding fossil fuel $CO_2$ emissions. The wind speed is taken from the fifth generation of ECMWF atmospheric reanalyses of the global climate at a geometric altitude of about 250 m.

This set of emission estimates is then filtered to keep only the fresh plumes, defined here as plumes mostly from coal plants or steel plants which are less than 3 hours old, because older ones have a more complex transport history. The location of the coal plants or steel plants is taken from the detailed time series reported by https://globalenergymonitor.org/. Medium-to-large emissions, that is emissions larger than 0.5 $ktCO_2\ h^{-1}$, can be estimated by this technique.

The method targets isolated plumes within a 200 km-wide orbit segment, but visual examination of the selected enhancement transects suggests that many of them are made up of several plumes. These CoCO2 emission estimates therefore correspond to values

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[1] O'Dell et al. (2018, http://dx.doi.org/10.5194/amt-11-6539-2018).

aggregated in space, typically over a few thousand km$^2$, and along sectors, with a composition that varies with the wind. There is temporal aggregation as well but limited to a few hours because of the rapid dispersion of anthropogenic emission plumes. Comparisons to independent estimates and numerical simulation experiments suggest that the product uncertainty is large for individual cases, of the order of 30%, but is mostly random, so that trends can be robustly calculated if enough data is available.

## 2.3. What we learn from the data

Because the random error of the individual emission estimates is large and because of their aggregated nature, only the variations of ensembles of point source estimates make sense. For instance, the temporal variations of the ensemble of emission estimates at diverse time scales, from the year to the average morning and afternoon, were found robust[2]. **Figure 2** displays the cumulative observed emissions per year. For OCO-3, the data only covers the period after the launch of the instrument in 2019. For OCO-2, a distinction is made between the emissions estimated from version 10 of NASA's official column-retrieval algorithm and version 11. Version 10 covers the full OCO-2 record until February 2022, while version 11 has taken over since then, but with only a portion of the past OCO-2 record having been reanalysed by NASA so far. Version 11 generates more data than version 10, and with enhanced quality, so that the two data streams are not fully comparable.

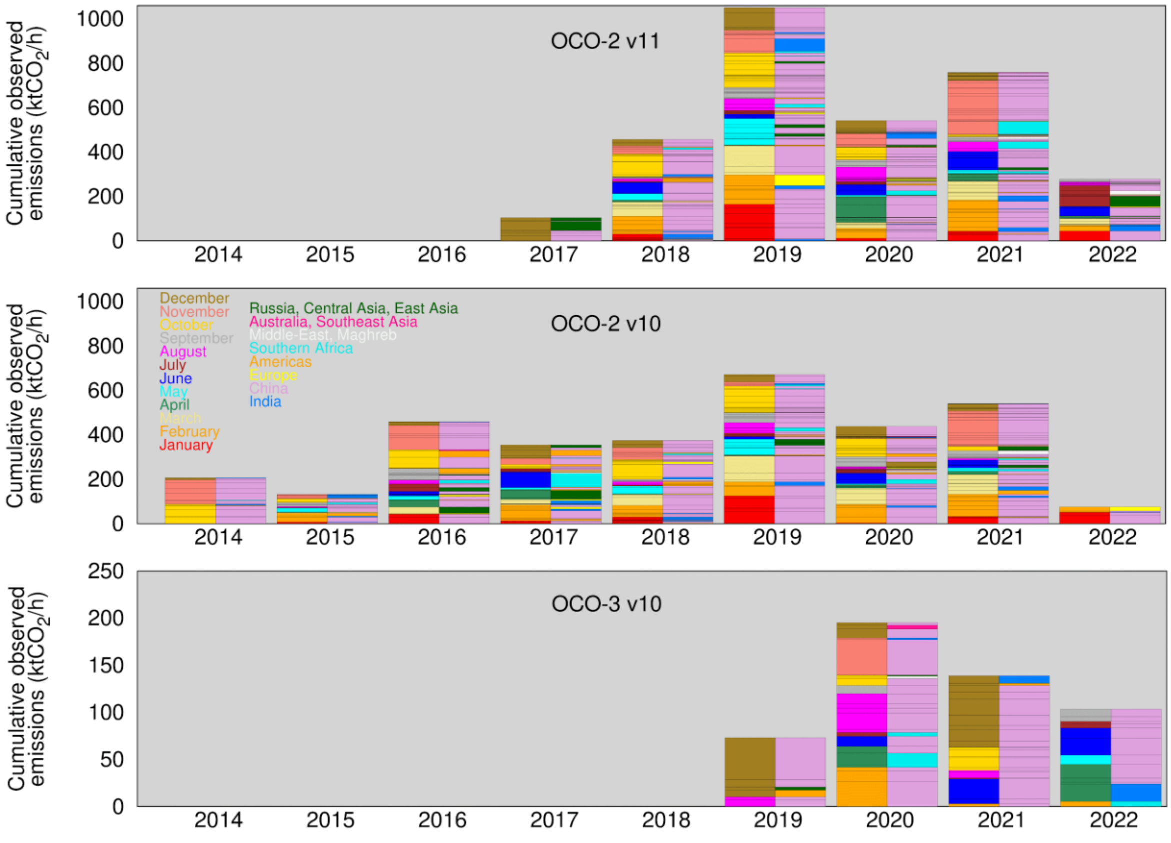

*Figure 2 – Cumulative emissions observed each year using NASA's OCO-2 column retrievals version 11 (top), OCO-2 column retrievals version 10 (middle), OCO-3 column retrievals version 10 (bottom). Each individual rectangle corresponds to a validated individual $CO_2$ fossil fuel emission estimate by the CoCO2 algorithm. Its colour reflects the month of the year (left part of the bars, starting from January or the earliest month at the bottom of each stack) or the geographical location (right part of the bars). Central Asia and East Asia include the validated emission estimates from Japan, Kazakhstan, Mongolia, Russia and South Korea. South East Asia is for Australia and Thailand. Europe is for the 27-member European Union, Moldova, Serbia, and Ukraine. For Middle-East and Maghreb, cases were found in Iran, Morocco, Saudi*

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[2] Chevallier et al. (2022, https://doi.org/10.1029/2021GL097540)

*Arabia and Turkey. Americas gather Mexico and the USA. Southern Africa only includes South Africa so far. The first and last month of each time series do not cover the full year.*

**Figure 2** first highlights the current capability to track high-emission hot-spots over the globe with low latency. Most of these high emissions are found over China, India and Southern Africa. The cumulative emissions peak in 2019, consistent with the known trend of global emissions during the last decade, go down during the first year of the COVID-19 pandemic and partially recover in 2021. Years 2015 and 2017 in the OCO-2 version 10 data are difficult to interpret in the time series due to long instrument downtimes then.

### 2.4. Prospects

This emerging asset using OCO-2 and OCO-3 is guiding the evolution of such an emission retrieval product toward a transparent indicator of trends in large fossil fuel emissions and for an appropriate range of hours in the day. The method will gain in complexity when the future satellite $CO_2$ imagers provide an order of magnitude more data, that will allow refining the statistics for well-observed administrative regions of the size of, or larger than, countries like Kuwait, Slovenia, New Caledonia, etc. It can serve both the scientific debate and the general public. Within the CO2MVS, it will allow fast emission retrieval of emission hot-spots from $CO_2$ imagers like CO2M.

## 3. Estimates of fossil fuel emissions from regional inversions using co-emitted species

### 3.1. General presentation

The burning of fossil fuels is not only responsible for increased atmospheric $CO_2$ concentrations, but also for increased values of various atmospheric pollutants. The correlation between emissions of co-emitted species, such as carbon dioxide ($CO_2$), nitrogen oxides (NO and $NO_2$, denoted $NO_x$) and carbon monoxide (CO), as a function of fuel type, country and sector contains significant potential for consistent additional constraints on the estimation of the emissions, both at global and local scale. This is especially relevant for the estimation of $CO_2$ emissions at present and for the past decades during which the $CO_2$ observation infrastructure was still limited.

The analysis presented here assesses the current potential of regional fossil fuel $CO_2$ emission estimates based on observations of these co-emitted species, specifically $NO_2$ and CO. It is based on atmospheric inversions targeting the national emissions from the EU27+UK countries since 2005 at annual to monthly scales. At annual scales, these observation-based estimates can be evaluated against the accurate national reported inventories in Europe, while the analysis of monthly budgets over more than 15 years allows investigating the trends, inter-annual variations and the ability to complement national inventories with information at sub-annual scales.

### 3.2. Method

The estimation of the national-scale fossil fuel $CO_2$ emissions in Europe follows two steps. The first step consists of atmospheric inversions of $NO_x$ or CO emissions over Europe during 2005-2021 at high temporal and spatial resolution (1 day and 0.5°, respectively). The $NO_x$ inversions are based on two $NO_2$ satellite datasets: one from the OMI instrument on-board the EOS Aura[3] satellite, covering the inversion period until March 2021, and one from the TROPOMI instrument onboard the Sentinel-5P[4] satellite, available since 2019 and until mid-November 2021. The CO inversions are based on CO data from the MOPITT instrument onboard the

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[3] the OMI-QA4ECV-v1.1 product; Boersma et al: http://doi.org/10.21944/qa4ecv-no2-omi-v1.1, 2017.

[4] the PAL product; Eskes, H., et al: https://data-portal.s5p-pal.com/product-docs/no2/PAL_reprocessing_NO2_v02.03.01_20211215.pdf, 2021.

NASA EOS-Terra satellite[5]. The atmospheric inversion methodology optimizes the geographic and temporal distribution of $NO_x$ or CO emission estimates in Europe by minimising the difference between the satellite observations and simulated observations from the regional chemistry transport model CHIMERE[6] using the Community Inversion Framework (CIF[7]).

The inversion procedure iteratively corrects emission maps to approach the optimal estimate, starting from a prior estimate based on the TNO-GHGco-v3 inventory[8] of the $NO_x$, CO and fossil fuel $CO_2$ emissions in Europe for the period 2005-2018. This inventory is based on the last European Monitoring and Evaluation Programme/Centre on Emission Inventories Projection (EMEP/CEIP) and UNFCCC official country reporting for air pollutants and greenhouse gases respectively. The emissions for the year 2019 have been extrapolated with an in-sample approach[9], and, here, the emissions for 2020 and 2021 are fixed to the values for 2019.

The second step consists in the conversion of the daily maps of $NO_x$ or CO anthropogenic emissions into estimates of the fossil fuel $CO_2$ emissions at the national and monthly scale for five large groups of sectors of emitting activities (energy, industry, residential, road transport and the rest of the emitting anthropogenic activities). The conversion relies on the sectoral maps of emissions for the three species and on the emission ratios between the species for each sector, country and month from the TNO-GHGco-v3 inventory.

### 3.3. What we learn from the data

The inversions of the $NO_x$ and CO anthropogenic emissions stay close to the prior estimates. This is partly due to a good level of consistency between the inventory and the satellite data. However, the currently large uncertainty in the observations and in the atmospheric transport modelling also plays a role.

The national and annual fossil fuel $CO_2$ budgets derived from the $NO_x$ inversions are larger than that of the inventory (**Figure 3**), with differences ranging from -0.2% to +5% across the countries in 2015. On the contrary, the inverted fossil fuel $CO_2$ emissions derived from the CO inversions are smaller than those from the inventory (**Figure 3**), ranging from 0% to -6.8% across the countries in 2015. At national and monthly scales, however, these differences are relatively small with the fossil fuel $CO_2$ emissions derived from the inversions being quite consistent with the TNO-GHGco-v3 inventory.

Two layers of uncertainties are propagated in the process: (i) those associated to the observations and atmospheric transport modelling and (ii) those in the spatial distribution of the sectoral emissions and of the emission ratios across species in the inventory. Therefore, the resulting estimates of emissions are in good agreement with the accurate inventory of the fossil fuel $CO_2$ annual emissions, and they show identical trends over the past 15 years, but they bear significant uncertainties. This is highlighted by the opposite signs of the corrections applied to the inventory by the $NO_x$ and CO inversions.

An analysis of the results during March-May 2020 is used to assess the ability of the methodology to quantify significant emission changes resulting from the impact on the emissions of the shutdown of socio-economic activities during the Covid-19 crisis. At the European scale, the fossil fuel $CO_2$ emission estimates derived from the OMI and MOPITT data do not show the expected decrease in March and April 2020 compared to March and April

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[5] the MOPITT-v8J CO product; Deeter, M. N., et al: https://doi.org/10.5194/amt-12-4561-2019, 2019.

[6] Menut, L., et al: doi:10.5194/gmd-6-981-2013, 2013.

[7] Berchet, A., et al: https://doi.org/10.5194/gmd-14-5331-2021, 2021.

[8] Dellaert, S.N. C., et al: https://verify.lsce.ipsl.fr/images/PublicDeliverables/VERIFY_D2_3_TNO_v1.pdf, 2021.

[9] Super, I.et al: https://verify.lsce.ipsl.fr/images/PublicDeliverables/VERIFY_D25_Second_present_year-1_emission_inventory_and_grids_v1.pdf, 2021.

2019. The fossil fuel $CO_2$ emission estimates derived from TROPOMI, which provides observations with higher accuracy and with more spatial detail than both OMI and MOPITT, show a decrease of emissions between these two periods, which is stronger when focusing on April than when focusing on March (**Figure 4**). This is consistent with the fact that European countries implemented their nation-wide social distancing measures in mid or late March. However, the amplitude of these decreases is much smaller than generally reported[10].

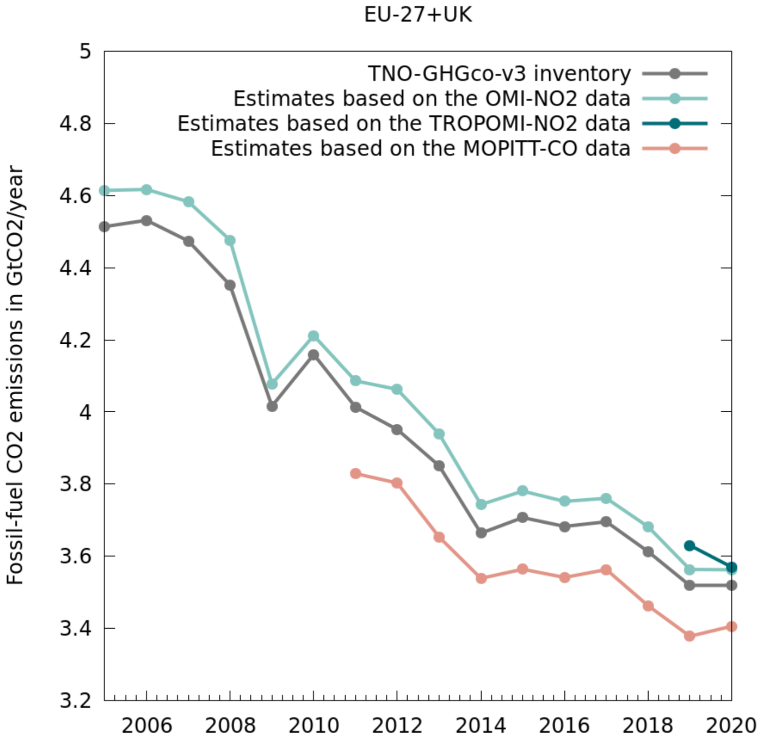

*Figure 3 – Estimates of the annual budgets of fossil fuel $CO_2$ emissions over 2005-2020 from the TNO-GHGco-v3 inventory (in grey) and from the regional inversions (colours corresponding to each satellite product).*

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[10] Liu et al : https://arxiv.org/abs/2004.13614, 2020.

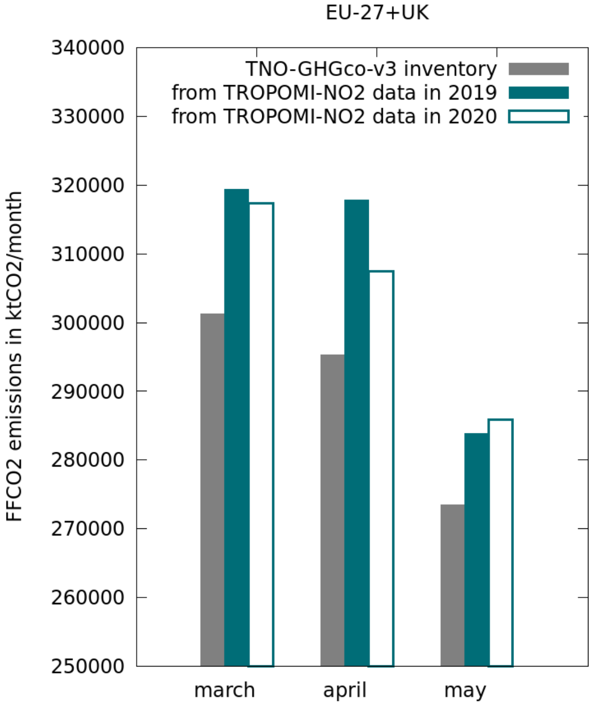

***Figure 4 – monthly fossil fuel $CO_2$ emissions of the EU-27+UK area (in $ktCO_2$/month) estimated by the TNO-GHGco-v3 inventory (in grey) and from the regional inversions assimilating TROPOMI data (in green). Solid bars correspond to March-May 2019 while thick contour bars correspond to March-May 2020.***

### 3.4. Prospects

Despite the large uncertainties and the lack of sensitivity to major changes in fossil fuel $CO_2$ emissions in these current inversions, these analyses demonstrate the capability to assimilate satellite data on co-emitted species for the estimate of fossil fuel $CO_2$ emissions and the overall consistency between these data and current inventories. The relevance of this assimilation will grow with the availability and co-assimilation of data at high spatial resolution from satellite missions dedicated to fossil fuel $CO_2$, like CO2M, with the regular improvement of satellite products and spatial resolution for all species, and with the precise characterization of the uncertainties in the spatial distribution and emission ratios in pollutant and spatialized and temporalized inventories of greenhouse gases. The latter is being addressed through dedicated research projects in support of the implementation of the Copernicus CO2MVS.

## 4. Estimates from a Carbon Cycle Fossil Fuel Data Assimilation System

### 4.1. General presentation

The Carbon Cycle Fossil Fuel Data Assimilation System (CCFFDAS[11]) pursues an innovative approach to the estimation of fossil fuel emissions in that it combines top-down (inverse modelling) and bottom-up (forward modelling) of sectoral fossil fuel emissions and of the terrestrial biosphere. The inclusion of such forward models enables the CCFFDAS to complement atmospheric concentration measurements with additional data streams, e.g., from emission statistics, from satellite-observed night-light intensity, on vegetation activity, or climate data in the estimation procedure. This feature extends the capabilities of traditional atmospheric inverse modelling and data assimilation systems such as those presented in sections 2, 5, and 6. The CCFFDAS is here used to provide an estimate of the 2021 sectoral

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[11] Kaminski et al.(2022, https://doi.org/10.1088/1748-9326/ac3cea)

fossil fuel emissions globally at a spatial resolution of 0.1 by 0.1 degree and monthly temporal resolution.

### 4.2. Method

The CCFFDAS consists of a series of numerical, process-based models simulating the global atmospheric transport of $CO_2$[12], the sectoral emissions from fossil fuel usage[13] and the exchange fluxes (photosynthetic uptake and respiratory release) from the terrestrial biosphere[14]. The $CO_2$ fluxes from these models depend on a set of variable model parameters in the equations used for calculating the fluxes. The CCFFDAS calibrates these variable parameters by assimilating various observational or other data streams. Technically, this is achieved by minimising the misfit of the modelled output against these data streams within their respective uncertainty ranges. Contributions from surface fluxes to the atmospheric $CO_2$ concentrations that are not explicitly simulated by the models (i.e., ocean-atmosphere exchange fluxes and biomass burning) are added as prior information from external databases. The models with the calibrated parameters are then used to simulate sectoral fossil fuel emission fields with uncertainty ranges that are consistent with the observations.

### 4.3. What we learn from the data

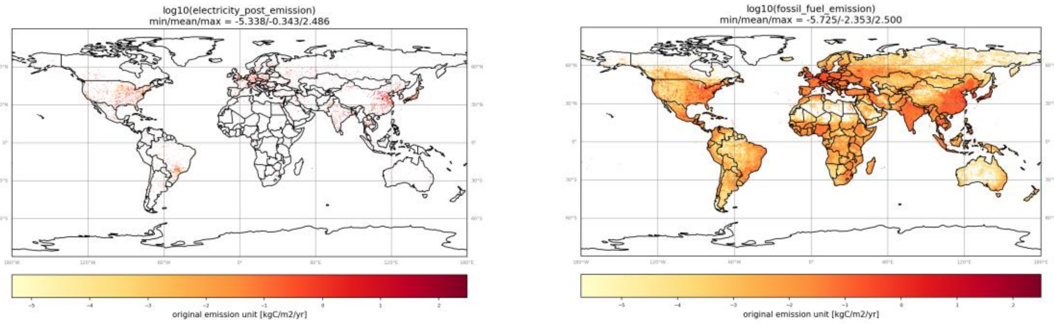

*Figure 5 – 2021 fossil fuel and biofuel emissions inferred by CCFFDAS in kgC $m^{-2}$ $yr^{-1}$ on a logarithmic scale for the energy generation sector (left) and for the total over all sectors (right).*

For illustration, **Figure 5** provides maps of the 2021 fossil fuel and biofuel emissions from the energy generation sector (left) and of the 2021 total fossil fuel and biofuel emissions (right). These maps provide a best estimate of the fossil fuel and biofuel emissions that combines the modelling chain presented in Section 4.2. with a range of data streams, including:

- 2018 sectoral national emission totals from the International Energy Agency (IEA)[15]
- Night-light intensities observed by satellites[16]
- Atmospheric $CO_2$ concentrations from measurements provided by the Greenhouse Gases Observing Satellites 1 and 2 and from the Orbiting Carbon Observatory 2[17]

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[12] Heimann and Koerner (2003, https://www.bgc-jena.mpg.de/www/uploads/Publications/TechnicalReports/tech_report5.pdf)

[13] Asefi-Najafabadi et al. (2003, https://doi.org/10.1002/2013JD021296)

[14] Kaminski et al. (2017, http://dx.doi.org/10.1016/j.rse.2017.08.017)

[15] https://www.iea.org/data-and-statistics/data-product/greenhouse-gas-emissions-from-energy

[16] Elvidge et al. (2021, doi:10.3390/rs13050922)

[17] Reuter et al. (2013, https://doi.org/10.5194/acp-13-1771-2013)

- Fraction of Absorbed Photosynthetically Active Radiation by plants derived by the Joint Research Centre-Two-stream Inversion Package from satellites[18]
- A map of population density[19]
- Meteorological data from the fifth generation of ECMWF atmospheric reanalyses of the global climate
- Locations of and emissions from power plants for the year 2018 derived within CoCO2[20]

These flux fields can be aggregated in the spatial and temporal domains, for example to provide fossil fuel emission estimates at the level of countries or provinces.

This demonstrates what can be referred to as the *synergistic* mode of operating the system, because it includes the IEA sectoral national emission totals as an observation used in the model parameter calibration. This mode provides a best estimate of the spatiotemporal distribution of the emissions given the assimilated data. Alternatively, CCFFDAS can be operated in *verification* mode, i.e., without using the IEA sectoral national emission totals. This mode provides emission estimates that are largely independent of data used for the bottom-up estimations of emission.

### 4.4. Prospects

Refinements of the process representations in the models of fossil emissions, of the terrestrial biosphere and of the atmospheric transport are expected to improve emission estimates. For example, within CoCO2, the sectoral resolution of the fossil fuel emission model is being extended by adding sectoral models of fossil fuel emissions from road transport and heating. Inclusion of further input data streams such as census or economic data or traffic counts are expected to improve the emission estimates. The emission estimate provided here relies on partly outdated input data sets available in September 2022. Updates of those are expected to improve the emission estimate provided in **Figure 4**. The CCFFDAS approach is also suited for local or regional domains[21]. This demonstrates the applicability of the approach at city scale. This regional CCFFDAS also demonstrates the use of co-emitted species by using other atmospheric trace gases as well (such as $NO_2$) at the 2 km by 2 km resolution of the future CO2M satellite images to constrain fossil fuel emissions.

## 5. Estimates of AFOLU emissions from $CO_2$ atmospheric inversions

### 5.1. General presentation

Observations of atmospheric $CO_2$ based either on remote sensing techniques from space or on direct measurements in air samples provide information on the emissions and removals of $CO_2$. By using sophisticated statistical inversion schemes, atmospheric transport models, and prior information, independent estimates can be made of emissions and removals to compare with national inventories.

All of these ingredients are still the topic of active research, but the domain has reached enough maturity in recent years to allow first comparisons with estimates reported for the

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[18] Pinty et al. (2011, https://doi.org/10.1029/2010JD015373)

[19] Sims et al. (2022, https://doi.org/10.48690/1527702)

[20] see Hugo Denier van der Gon and CoCO2 WP2 team; D2.1 Prior Emission data 2018 documentation report, available at https://coco2-project.eu/node/327

[21] Kaminski et al. (2022, http://dx.doi.org/10.3389/frsen.2022.887456)

AFOLU sector by some of the UNFCCC Parties in their National Inventory Reports (NIRs)[22]. For a like-for-like comparison, some emission and removal terms not included in the NIRs need to be subtracted from the inversion estimates[23] and the terrestrial biospheric carbon input to the inland water network needs to be added to the inversion system. These correction terms are estimated from the scientific literature and from living databases like the one maintained by the FAO.

## 5.2. Method

CoCO2 post-processes the time series of the sum of emissions and removals estimated by the already operational atmospheric inversions of the Copernicus Atmosphere Monitoring Service (CAMS)[24]. CAMS provides two inversion products depending on the type of assimilated data: either surface air-sample measurements, from 1979 onwards, or satellite $CO_2$ soundings, from 2015 onwards[25]. The CAMS products are the sum of emissions and removals at grid point scale[26] over the globe and with a temporal resolution of a couple of weeks[27]. They come with Bayesian uncertainty statistics that suggest better estimates from the assimilation of the satellite data, due to their better spatial coverage (**Figure 6**). In line with the UNFCCC reporting guidelines on annual inventories, CoCO2 aggregates the the sum of emissions and removals of managed areas in each grid point and their uncertainty at the annual national scale, corrects them to fit UNFCCC definitions as explained above, and compares them with the numbers reported in the NIRs by 10 Parties with very large geographical area, a spatial scale at which these CAMS products are most robust: Brazil, Canada, China, the Democratic Republic of the Congo, the 27-member European Union and United Kingdom together, India, Kazakhstan, Mongolia, Russia and the United States. From the NIRs, CoCO2 uses the sum of the net $CO_2$ emissions and removals from the agriculture sector and the land-use, land-use change and forestry sector.

## 5.3. What we learn from the data

**Figure 5** shows the time series of emissions and removals combined together for the AFOLU sector in ten large Parties to UNFCCC. The values have been estimated by the Parties themselves (green points and curves) or by the two latest CAMS inversions (blue for the air-sample-driven inversion and orange for the satellite-driven inversion). It shows that the differences between the two inversions are well explained by their error bars overall. This consistency is remarkable given the spatial scale studied and the very different nature of the assimilated data that drive this interannual variability: column retrievals from polar-orbiting satellites outside the high latitudes of the winter hemisphere and in cloud-free areas, versus pointwise measurements near surface at less than 150 sites over the globe. The uncertainty in decadal averages remains significant because the uncertainty in the annual estimates are correlated in time.

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[22] Chevallier (2021, https://doi.org/10.1029/2021GL097540), Deng et al. (2022, https://doi.org/10.5194/essd-14-1639-2022)

[23] The carbon absorbed by crop, emitted by human or animal respiration, or emitted by the lakes and rivers

[24] https://ads.atmosphere.copernicus.eu/cdsapp#!/dataset/cams-global-greenhouse-gas-inversion

[25] The CAMS satellite inversion product also assimilated earlier satellite data between 2009 and 2014, but they are lower quality and are not discussed here.

[26] A grid point here has a size of 3.75º in longitude and 1.90º in latitude.

[27] The product has a resolution of 3 hours, but the information provided by the observations is coarser, depending on their nature, either surface measurements or satellite soundings, and depending on their density. This observation information is therefore supplemented by prior information.

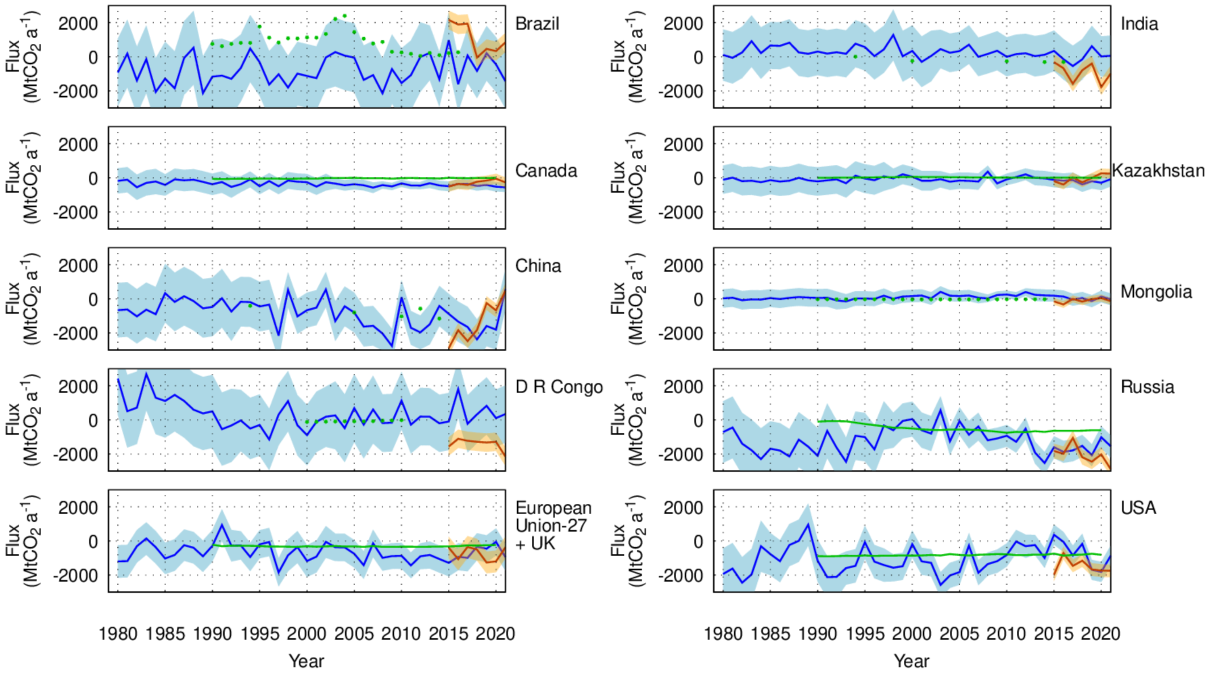

***Figure 6 - Annual $CO_2$ flux (the sum of emissions and removals) from the AFOLU sector in ten large Parties to UNFCCC estimated by the Parties themselves (green lines for the Annex-I parties, green disks for the non-Annex-I parties when available) and from the 1-σ uncertainty envelope of the two latest CAMS inversions (blue for the air-sample-driven inversion and orange for the satellite-driven inversion). Positive values indicate that the party is a source of $CO_2$ to the atmosphere. For a fair comparison, the surface fluxes from the inversions have been corrected for crop and river fluxes.***

The comparison to UNFCCC numbers reveals some similarities for the mean value and some consistent variations, but also a larger variability and some offsets that are being analysed. An important issue is the absence of a mask that unambiguously defines the land areas (plots) considered by each Party as managed from year to year, while some of the NIRs describe very sophisticated approaches involving, for example, manual photo-interpretation or the collection of details about the local administration. The lack of exhaustiveness of the NIRs, that unevenly report the evolution of the carbon stocks, is another issue, in particular for less accessible or not dominant carbon pools[28]. Finally, the temporal support of the values reported in the NIRs for a given year, blurred by interpolations between infrequent plot measurements, sometimes separated in time by large natural disturbances, is another important limitation for the comparison.

## 5.4. Prospects

Given the challenging comparison of UNFCCC numbers with inversion results, for all the reasons listed above, we recommend the design, by the reporting Parties themselves, of additional information to facilitate comparisons, such as detailed maps on what land is defined as managed and unmanaged.

Atmospheric inversions can serve both the scientific debate and the general public with products generated in quasi-near-real time[29] and in a consistent manner for all countries, in particular through the use of remote sensing and standardized processing, but with less detailed process attribution than inventories. The planned increase in resolution of their underlying transport models, together with the extension of the observation systems, will also allow studying smaller countries or groups of countries than shown here. To allow a more accurate comparison between UNFCCC reported estimates for the AFOLU sector with

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[28] soil carbon, below-ground biomass, smaller or understory vegetation, mixed land uses

[29] weeks compared to more than a year for the UNFCCC Annex-I reports

inversion results, additional information is necessary, especially for detailed maps on what land is defined as managed and unmanaged in each country.

CoCO2 is currently extending the inversion datasets beyond the two CAMS ones shown in **Figure 5** with results from the CarbonTracker Europe[30] system. These inversion systems are designed to provide consistent estimates at all time scales and will provide guidance and support to the implementation of the CO2MVS..

# 6. Estimates of $CH_4$ emissions from the extended Copernicus Atmosphere Monitoring Service global monitoring system

## 6.1. General presentation

The European centre for Medium-Range Weather Forecasts, which is responsible for the implementation of the new Copernicus CO2MVS, operates its Integrated Forecasting System (IFS) to provide world-class operational global numerical weather and atmospheric composition prediction services. CoCO2 is extending the IFS to form the core of the global component of the CO2MVS. Here we present preliminary results from the first version of the prototype, with applications to $CH_4$ emissions. The estimation of $CO_2$ emissions with this system requires further development to ensure accurate results are obtained from the relatively small observational signal.

## 6.2. Method

The inversion algorithm follows the general Bayesian approach, wherein prior knowledge of the quantities of interest, here the greenhouse gas emissions, is updated using observations, taking into account the errors associated with each source of information. In this application, the prior knowledge consists of the CAMS-GLOB-ANT[31] anthropogenic emission product and a combination of prescribed or modelled natural fluxes. The observations are retrievals of the $CH_4$ atmospheric column or partial column from a series of satellites[32]. The inversion consists in rescaling, at a resolution of about 80 km and 12 hours, the prior global $CH_4$ emissions and removals so as to find the best fit between the full global atmospheric model and the satellite retrievals. The IFS inversion system jointly optimises the anthropogenic emissions and the natural fluxes, such as from wetlands. Using this configuration, global $CH_4$ inversions have been performed for the years 2019 and 2021.

## 6.3. What we learn from the data

**Figure 7** shows both the average monthly posterior $CH_4$ anthropogenic emissions (x-axis) and the corresponding correction to the prior inventory (y-axis) for top emitting countries and for the first half of 2019. While the corrections to the prior emission inventories are small (< 1%) for most countries at this temporal scale, they are more significant for India and China, with a decrease by 3 and 5%, respectively. This overestimation in China's $CH_4$ emission inventories is in agreement with previous findings[33].

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[30] https://www.carbontracker.eu/

[31] https://ads.atmosphere.copernicus.eu/cdsapp#!/dataset/cams-global-emission-inventories

[32] GOSAT, MetOp, and Sentinel 5P

[33] Cheewaphongphan et al. (2019,https://doi.org/10.3390/su11072054)

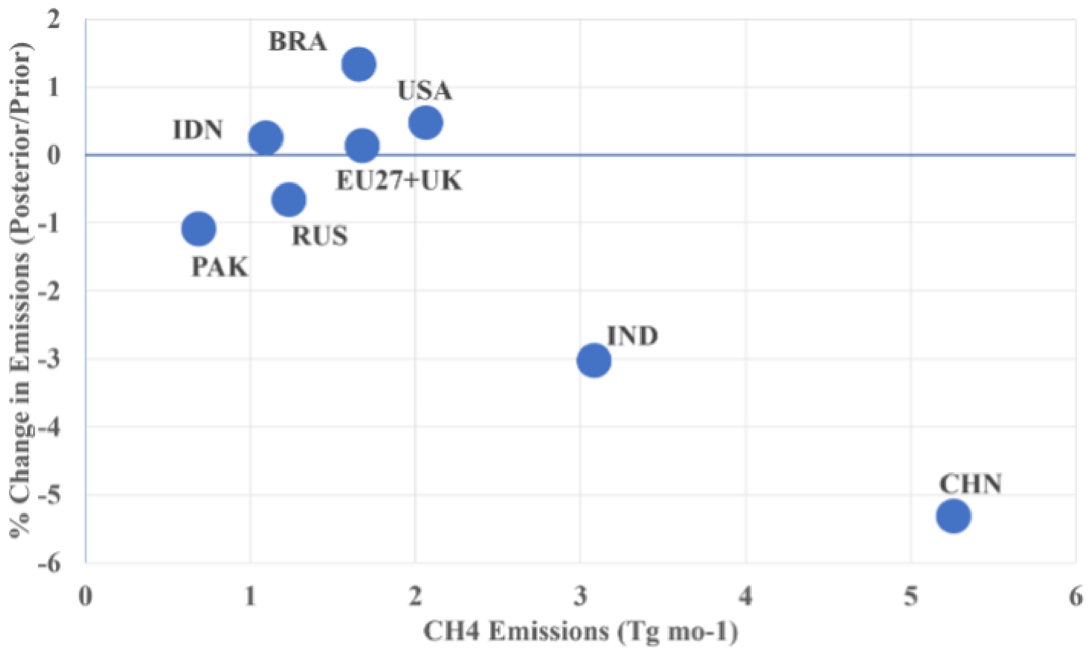

*Figure 7 – Posterior $CH_4$ emissions (x-axis) for several major emitting countries and difference between posterior and prior emissions (y-axis) averaged between January and June 2019, derived from the global IFS[34].*

In addition to estimating national budgets, the inversion system can be used to detect and quantify local $CH_4$ emissions. An example of such capability is demonstrated in **Figure 7**, which shows the estimation of methane leaks from the Permian basin, the largest oil and gas producing region in the United States. Our posterior estimate of 2.5 Tg.yr$^{-1}$, which represents an increase of about 30% compared to the prior inventory, is consistent with previous findings[35]. In the context of a future operational inversion system, such a fast detection and quantification approach could be used routinely over the entire globe, allowing to monitor $CH_4$ emission anomalies in near-real time and to improve responsiveness of public authorities and/or industries.

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[34] from McNorton et al. (2022, https://doi.org/10.5194/acp-22-5961-2022)

[35] Zhang et al. (2020, https://doi.org/10.1126/sciadv.aaz5120)

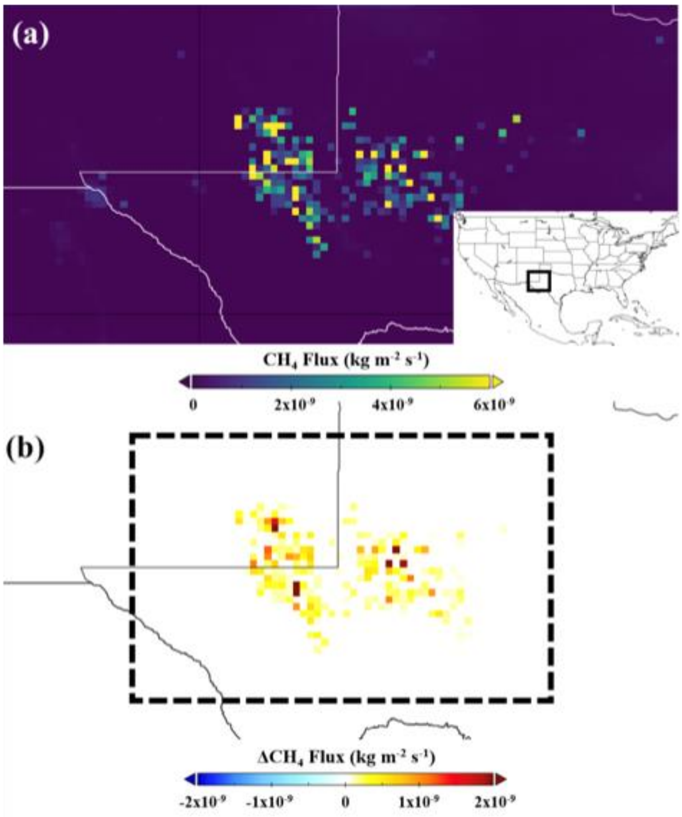

*Figure 6 – (a) Average prior Permian Basin CH4 emissions for 2019. (b) Average of posterior minus prior anthropogenic CH4 emissions over the Permian Basin for January–June 2019, derived from the IFS 4D-Var system*[36]*.*

### 6.4. Prospects

An ensemble approach based on the IFS is under development to provide an approximation of the uncertainty in the estimated $CH_4$ (and $CO_2$) fluxes. Moreover, an extension of the current 12-hr assimilation window to several weeks is being implemented. Using a longer window will allow us to better constrain the greenhouse gas fluxes by taking advantage of the long lifetime of these gases and the persistence of the flux signal in the observed atmospheric columns. Finally, additional constraints will be provided from observations of co-emitted species (e.g., $NO_2$, CO) in order to better separate the anthropogenic signal from their biogenic counterpart. In that respect, the use of data from the future CO2M imager, providing co-located and simultaneous high-quality measurements of $CO_2$, $CH_4$ and $NO_2$, will be an unprecedented opportunity to monitor anthropogenic GHG emissions globally in near-real time. The future IFS-based CO2MVS, with its unique operational and Earth-system-modelling capability, will be well equipped to generate timely information on those emissions by fully exploiting the wealth of data from the new Sentinel satellites.

## 7. Additional developments at local and national scale

### 7.1. Introduction

Monitoring emissions at the local and national scale will play a central role in the future CO2MVS as well as in similar national activities in EU member states. The national scale is of particular importance, because the signatories of the Paris Agreement are individual nations that need to track and verify the emissions within their country boundaries. The local scale is relevant because a dominant fraction of the $CO_2$ emitted over the globe comes from strong

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[36] from McNorton et al. (2022, https://doi.org/10.5194/acp-22-5961-2022))

localised sources including cities, power plants and other industrial point sources. Quantifying these local sources would provide a key support to the monitoring of large emitters, for the application of climate action plans by local authorities, and for the development of services to industry. Emissions from strong localised sources can be observed in satellite $CO_2$ images as plumes of enhanced $CO_2$. Therefore, their quantification can directly rely on dedicated plume detection and inversion methods.

A national-scale monitoring system will have to cover not only point sources but also the remaining more dispersed sources and sinks that do not show up as plumes but rather contribute to large-scale gradients in atmospheric $CO_2$ concentrations. Accurately quantifying the point source emissions may improve the estimation of these remaining sources and sinks, which illustrates the potential benefit of coupling local and national scale inversions.

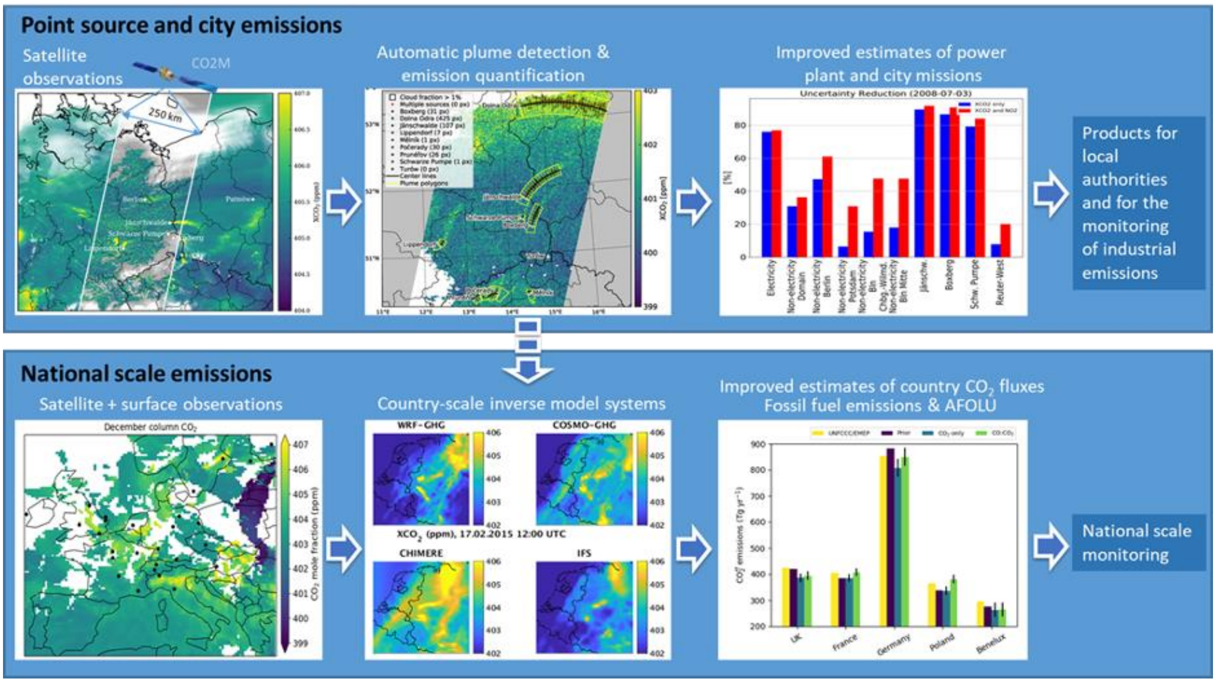

*Figure 8 – Principle of local and national scale inversions for the provision of information on $CO_2$ anthropogenic emissions corresponding to relevant industrial and political entities. The dashed arrow illustrates a potential coupling between the scales by providing information on local emissions to national scale inversion.*

Therefore, in CoCO2, a major effort is devoted to the development of robust and standardised approaches for the national and local scale inversions of the $CO_2$ emissions, and for their coupling, as illustrated in **Figure 8**. Existing and novel national and local scale inversion strategies and techniques are benchmarked via an extensive set of tests and comparisons, demonstrating their capabilities, assessing the corresponding levels of uncertainties, and identifying the best options for the monitoring of the anthropogenic emissions of $CO_2$.

### 7.2. Strategy for the monitoring of localised emissions

In CoCO2, two different classes of methods to quantify $CO_2$ emissions from localised point sources are explored. The first class detects the plumes in the satellite images, quantifies the amount of $CO_2$ within the plume, and combines this information with wind data from a meteorological model to estimate the transport speed of the plume and finally the emission. These methods need to be able to deal with complicating factors such as partial cloud cover, overlapping plumes or low signal-to-noise. Therefore, it is also explored whether measurements of additional trace gases co-emitted with $CO_2$ can be exploited to improve the emission quantification. As already outlined above, a promising candidate is nitrogen dioxide ($NO_2$), which can be detected more easily in satellite images and will be measured by the future satellite mission CO2M together with $CO_2$. The second class of methods is based on atmospheric transport simulations with a model that has sufficiently high resolution to represent the plumes in a realistic manner. The emissions are then estimated by comparing the simulated and observed plumes and applying inverse methods. CoCO2 will identify methods that optimally balance accuracy, robustness and computation speed that are suitable to be applied in an operational setting within the CO2MVS.

## 7.3. Strategy for the national-scale inversion

The assessment of the national scale inversion in CoCO2 is based on tests with systems mapping the $CO_2$ emissions and natural sinks of one, few or all of the European countries at spatial resolutions ranging from 25 down to 4 km spatial resolution. They rely on regional and mesoscale atmospheric chemistry transport models. They assimilate various types of data, including continuous near surface measurements from ground stations and satellite observations of $CO_2$ and of pollutants tracing the signal from fossil fuel combustion. These systems rely on complex Bayesian statistical frameworks (mainly with ensemble and variational approaches) that are able to tackle the high dimensionality of such inversion problems. The inversions correct prior estimates of the $CO_2$ surface fluxes from inventories and land surface and ecosystem models, in order to support the extrapolation of information to areas and periods poorly covered by the observation systems. The assessment aims at identifying the most suitable definition of the parameters to be controlled when correcting the prior estimates, and the optimal configuration for the assimilation of the various types of observations. CoCO2 also evaluates how additional information that may be available for selected countries (detailed inventories, additional observation sites) can complement the standard and operational products used by the global CO2MVS. The different options will be assessed in terms of statistics of uncertainties (delivered by the Bayesian framework) and in terms of comparisons to independent data and to the official national inventories. Different approaches will be considered for the ingestion of information from local scale inversions into the national scale inversion process.

## 7.4. Perspectives: a critical increase of the current capabilities

The assessment of the inversion approaches at both the local scale and the national scale accounts for the near-term availability of the $CO_2$ images from the CO2M mission with dedicated experiments assimilating pseudo-data. The set-up of a standardised and optimal approach for local and national scale inversion in CoCO2 together with the major upgrade of the CO2MVS with CO2M should ensure a dramatic increase in the capabilities for the monitoring of $CO_2$ emissions. This will improve the accuracy and spatial resolution of the estimates for both the anthropogenic emissions of $CO_2$ associated with the use of fossil fuels and for the $CO_2$ sink associated with land-use and ecosystem management.

# 2 Acronyms

| | |
|---|---|
| AFOLU | Agriculture, Forestry and Other Land Use sector |
| CAMS | Copernicus Atmosphere Monitoring Service, https://atmosphere.copernicus.eu/ |
| CEIP | Centre on Emission Inventories Projection |
| CCFFDAS | Carbon Cycle Fossil Fuel Data Assimilation System |
| CHE | CO2 Human Emissions, https://www.che-project.eu/ |
| CIF | Community Inversion Framework, http://community-inversion.eu/ |
| CO2M | Copernicus $CO_2$ Monitoring Mission |
| CO2MVS | anthropogenic $CO_2$ emissions monitoring and verification support capacity |
| CoCO2 | Prototype system for a **Co**pernicus **$CO_2$** service, https://coco2-project.eu/ |
| ECMWF | European Centre for Medium-Range Weather Forecasts, https://www.ecmwf.int/ |
| EMEP | European Monitoring and Evaluation Programme/ |
| FAO | Food and Agriculture Organization, https://www.fao.org/ |
| IEA | International Energy Agency |
| IFS | Integrated Forecast System |
| MOPITT | Measurements of Pollution In The Troposphere |
| NASA | National Aeronautics and Space Administration, https://www.nasa.gov/ |
| NIR | National Inventory Report |
| OCO-2 | Orbiting Carbon Observatory-2, https://ocov2.jpl.nasa.gov/ |
| OCO-3 | Orbiting Carbon Observatory-3, https://ocov3.jpl.nasa.gov/ |
| OMI | Ozone Monitoring Instrument |
| TNO-GHGco-v3 | TNO inventory for greenhouse gases and co-emitted species, version 3 |
| TROPOMI | The TROPOspheric Monitoring Instrument |
| UNFCCC | United Nations Framework Convention on Climate Change, https://www.unfccc.int |
| VERIFY | Observation-based system for monitoring and verification of greenhouse gases, https://verify.lsce.ipsl.fr/ |

# 3 Further reading

Balsamo, G. et al., The CO2 Human Emissions (CHE) Project: First Steps Towards a European Operational Capacity to Monitor Anthropogenic CO2 Emissions, Frontiers in Remote Sensing, doi:10.3389/frsen.2021.707247

Janssens-Maenhout, G., Pinty, B., Dowell, M., Zunker, H., Andersson, E., Balsamo, G., et al. (2020). Towards an operational anthropogenic CO2 emissions monitoring and verification support capacity. Bulletin of the American Meteorological Society, 101. https://doi.org/10.1175/BAMS-D-19-0017.1

Petrescu, A. M. R., et al. (2021). The consolidated European synthesis of $CH_4$ and $N_2O$ emissions for the European Union and United Kingdom: 1990–2017, Earth Syst. Sci. Data, 13, 2307–2362, https://doi.org/10.5194/essd-13-2307-2021.

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| Version | Author(s) | Date | Changes |
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| | | | |

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| Internal Reviewers | Date | Comments |
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