CO2MVS RESEARCH ON SUPPLEMENTARY OBSERVATIONS

CORSO
CO2MVS Research on Supplementary Observations

D5.9 Final Dissemination and Exploitation Report

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1 Executive Summary

The project's dissemination and exploitation activities present a crucial element in the success of the CORSO project, as they ensure that results are taken up by the wider community and are sustainable beyond the initial funding period, thus providing value for money.

D5.3 was the first version of this Dissemination and Exploitation (D&E) Plan and provided the initial plans for the D&E work. A mid-term Dissemination and Exploitation Report D5.7 provided an update of the dissemination and exploitation activities halfway through the project. This report is the final Dissemination and Exploitation Report and contains detailed descriptions of dissemination activities, exploitable results and recommendations for CO2MVS.

The initial dissemination plan identified instruments and targets. These included activities organised by CORSO (including workshops, website, news items, etc.) as well as important events attended by CORSO members (i.e. workshops, conferences, seminars, etc.).

This final deliverable provides the potential exploitation avenues in terms of outputs as well as respective exploitation activities during and after the end of the project, thus fulfilling the requirements of the Description of Action (DoA).

Section 5 also includes a comprehensive review of recommendations for CO2MVS from each of the Work Packages.

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2 Contents

3 Introduction

The following builds on the details of the initial plan for the project's visual identity and describes the promotional exploitation options and communication channels that have been used in CORSO. This D5.9 deliverable summarises the aims at supporting partners' communication and dissemination activities and efforts in promoting the project as well as providing a review of the exploitation and dissemination activities of the CORSO project.

3.1 Background

To enable the European Union (EU) to move towards a low-carbon economy and implement its commitments under the Paris Agreement, a binding target was set to cut emissions in the EU by at least 40% below 1990 levels by 2030. European Commission (EC) President von der Leyen committed to deepen this target to at least 55% reduction by 2030. This was further consolidated with the release of the Commission's European Green Deal on the 11th of December 2019, setting the targets for the European environment, economy, and society to reach zero net emissions of greenhouse gases in 2050, outlining all needed technological and societal transformations that are aiming at combining prosperity and sustainability. To support EU countries in achieving the targets, the EU and EC recognised the need for an objective way to monitor anthropogenic CO_2 emissions and their evolution over time.

Such a monitoring capacity will deliver consistent and reliable information to support informed policy- and decision-making processes, both at national and European level. To maintain independence in this domain, it is seen as critical that the EU establishes an observation-based operational anthropogenic CO_2 emissions Monitoring and Verification Support (MVS) (CO2MVS) capacity as part of its Copernicus Earth Observation programme.

The CORSO research and innovation project will build on and complement the work of previous projects such as CHE (the CO2 Human Emissions), and CoCO2 (Copernicus CO2 service) projects, both led by ECMWF. These projects have already started the ramping-up of the CO2MVS prototype systems, so it can be implemented within the Copernicus Atmosphere Monitoring Service (CAMS) with the aim to be operational by 2026. The CORSO project will further support establishing the new CO2MVS addressing specific research & development questions.

The main objectives of CORSO are to deliver further research activities and outcomes with a focus on the use of supplementary observations, i.e., of co-emitted species as well as the use of auxiliary observations to better separate fossil fuel emissions from the other sources and sinks of atmospheric CO_2. CORSO will deliver improved estimates of emission factors/ratios and their uncertainties as well as the capabilities at global and local scale to optimally use observations of co-emitted species to better estimate anthropogenic CO_2 emissions. CORSO will also provide clear recommendations to CAMS, ICOS, and WMO about the potential added-value of high-temporal resolution $^{14}CO_2$ and Atmospheric Potential Oxygen (APO) observations as tracers for anthropogenic emissions in both global and regional scale inversions and develop coupled land-atmosphere data assimilation in the global CO2MVS system constraining carbon cycle variables with satellite observations of soil moisture, LAI, SIF, and Biomass. Finally, CORSO will provide specific recommendations for the topics above for the operational implementation of the CO2MVS within the Copernicus programme.

3.2 Scope of this deliverable

3.2.1 Objectives of this deliverable

This Deliverable 5.9 report provides the end of project update for the CORSO dissemination and exploitation.

The Exploitation Plan initiated in D5.3 explains the exploitation work within the CORSO project by identifying initial exploitation routes and innovation ideas. This report also includes a review by work package of recommendations to CO2MVS

3.2.2 Work performed in this deliverable

As per the DoA, D5.9 should "outline the dissemination activities as well as identify the potential for exploitation and their routes".

The work to create the plans included collection of feedback from the partners in the form of questionnaires and the identification of the relevant aspects pertaining to both dissemination and exploitation.

3.2.3 Deviations and counter measures

No deviations have been encountered.

3.3 Project partners:

Partners	
EUROPEAN CENTRE FOR MEDIUM-RANGE WEATHER FORECASTS	ECMWF
AKADEMIA GORNICZO-HUTNICZA IM. STANISLAWA STASZICA W KRAKOWIE	AGH
BARCELONA SUPERCOMPUTING CENTER - CENTRO NACIONAL DE SUPERCOMPUTACION	BSC
COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES	CEA
KAMINSKI THOMAS HERBERT	iLab
METEO-FRANCE	MF
NEDERLANDSE ORGANISATIE VOOR TOEGEPAST NATUURWETENSCHAPPELIJK ONDERZOEK TNO	TNO
RIJKSUNIVERSITEIT GRONINGEN	RUG
RUPRECHT-KARLS-UNIVERSITAET HEIDELBERG	UHEI
LUNDS UNIVERSITET	ULUND
UNIVERSITE PAUL SABATIER TOULOUSE III	UT3-CNRS
WAGENINGEN UNIVERSITY	WU
EIDGENOSSISCHE MATERIALPRUFUNGS- UND FORSCHUNGSANSTALT	EMPA
EIDGENOESSISCHE TECHNISCHE HOCHSCHULE ZUERICH	ETHZ
UNIVERSITY OF BRISTOL	UNIVBRIS
THE UNIVERSITY OF EDINBURGH	UEDIN

4 Project Communication & Dissemination

4.1 Report on Dissemination activities

As a project, we have taken an active role in conferences, workshops and seminars explaining the project aims and initial results. International liaison work also continued to be an important aspect of the project.

Since the midterm report (M18), CORSO has been presented 32 times at conferences and workshops, in talks and posters.

The project has been presented at the ICOS Science conferences, EGU, ESA Living planet and EUROGeo Workshop, amongst others .

The project has continued to liaise with other Horizon Europe Projects, (E.g. CAMEO and CATRINE, amongst others) to ensure synergies were identified and developed.

The project Coordinator Richard Engelen presented, for instance, at the CAMEO GA in December 2025 and the CATRINE Project lead is an invited observer to all the CORSO Executive Board meetings.

The project is also liaising with the Copernicus Services, CAMS and C3S and was represented at the CAMS annual General Assembly in September 2025.

Throughout the project, the coordinator has presented CORSO progress at the CO2M Mission Advisory Group meetings and meetings of the CO2 Monitoring Task Force.

CORSO results are also used, when relevant, in CAMS interactions with international stakeholders, such as WMO, ICOS, UNEP, and Commission DGs.

The CORSO management decided to not set up a formal Advisory Board. Instead, some collaboration with specific experts outside the consortium was seen as more productive, as the CORSO project is addressing 4 specialised topics without a harmonization phase at the end. The latter will happen as part of the CO2MVS implementation within CAMS, which is guided by the CO2 Monitoring Task Force. Examples of interaction with external experts are Heather Graven, Imperial College London, and Ralph Keeling, Scripps Institution of Oceanography, both of them being involved in WP3.

Finally, the second General Assembly of CORSO was co-organised with the first General Assembly of the CATRINE project to encourage the exchange of information between the two projects, while they were still both active. This combined GA happened 2nd and 3rd December 2024 in Bonn Germany. More information can be found here: CORSO and CATRINE projects joint GA | CORSO. During this GA, Heather Graven from Imperial College and Laurence Rouil from CAMS were invited to give talks at the opening of the meeting.

The final General Assembly meeting of CORSO was held in Bonn from the 5th to 6th November 2025hosted at the ECMWF office. The meeting started with an update from the Director of CAMS (Launce Rouil) followed by an update of the CATRINE project by the coordinator (Anna Agusti-Panareda). The CORSO project highlights were presented by Richard Engelen after which we heard several scientific speakers on the work achieved. Day 1 ended with a poster session that facilitated in-depth discussion. The second day focused on discussion looking across the project, and identifying elements and recommendations for implementation into the CAMS CO2MVS in the coming years. These are described in section 5 below.

The CORSO website has provided regular updates and news items along with information on our recent publications; 4 journal publications thus far and 1 in pre-print.

As a reminder, our dissemination methods are listed as:

1. Scientific and technical results through
   a. Scientific Publications
   b. Conference Talks
   c. Organised Workshops, providing updates on the project results
   d. Reports to and feedback from Committees and Boards
2. Products through dissemination of
   a. Datasets and accompanying material (e.g. descriptions, meta data)
   b. Algorithms / Specifications
   c. Graphics and animations
3. Progress information through provision of
   a. News items
   b. Public Deliverables
   c. Dissemination Materials (brochures, posters, flyers)
   d. Website and social media

4.1.1 Scientific and technical results

a) Scientific Publications – articles in Journals since M18

Title/ DOI	Status
Knorr, W., Williams, M., Thum, T., Kaminski, T., Voßbeck, M., Scholze, M., Quaife, T., Smallman, T. L., Steele-Dunne, S. C., Vreugdenhil, M., Green, T., Zaehle, S., Aurela, M., Bouvet, A., Bueechi, E., Dorigo, W., El-Madany, T. S., Migliavacca, M., Honkanen, M., Kerr, Y. H., Kontu, A., Lemmetyinen, J., Lindqvist, H., Mialon, A., Miinalainen, T., Pique, G., Ojasalo, A., Quegan, S., Rayner, P. J., Reyes-Muñoz, P., Rodríguez-Fernández, N., Schwank, M., Verrelst, J., Zhu, S., Schüttemeyer, D., and Drusch, M.: **A comprehensive land-surface vegetation model for multi-stream data assimilation, D&B v1.0,** Geosci. Model Dev., 18, 2137–2159, https://doi.org/10.5194/gmd-18-2137-2025, 2025	published
Koene, E. F. M., Kuhlmann, G., and Brunner, D.: **Bayesian denoising of satellite images using co-registered NO2 images,** EGUsphere [preprint], https://doi.org/10.5194/egusphere-2025-4477, 2025.	preprint
Gómez-Ortiz, C., Monteil, G., Basu, S., and Scholze, M.: **A CO_2–$\Delta^{14}CO_2$ inversion setup for estimating European fossil CO_2 emissions,** Atmos. Chem. Phys., 25, 397–424, https://doi.org/10.5194/acp-25-397-2025, 2025.	published
Gómez-Ortiz, C., Monteil, G., Karstens, U., and Scholze, M.: **Modeling support for an extensive Δ14CO2 flask sample monitoring campaign over Europe to constrain fossil CO2 emissions,** Atmos. Chem. Phys., 25, 10747–10771, https://doi.org/10.5194/acp-25-10747-2025, 2025.	published
Raoult, N., Douglas, N., MacBean, N., Kolassa, J., Quaife, T., Roberts, A. G., et al. (2025). **Parameter estimation in land surface models: Challenges and opportunities with data assimilation and machine learning.**	published

Journal of Advances in Modeling Earth Systems, 17, e2024MS004733. https://doi.org/10.1029/2024MS004733	
Sébastien Garrigues, Patricia de Rosnay, Peter Weston, Christoph Rüdiger, Cédric Bacour, David Fairbairn, Pierre Vanderbecken, Oscar Rojas-Munoz, Ewan Pinnington, Anna Agusti-Panareda, Souhail Boussetta, Jean-Christophe Calvet, Richard Engelen (2025). **Assimilation of Solar Induced Fluorescence Satellite Observations in the ECMWF Integrated Forecast System.** Q.J.Roy.Met.Soc.	accepted

b) Conference outreach since M18 (Talk/ Poster)

Name	Date	Location	Presenter	Presentation title
IGARSS 2024 in Athens.	9/7/2024	Athens, Greece.	Sebastien Garrigues	Machine learning-based observation operators to assimilate microwave and SIF satellite observations into the ECMWF integrated forecast system. (Talk)
ESA ATMOS 2024	1-5/7/2024	Bologna, Italy	Sandro Meier	A light-weight NO2 to NOx conversion model for quantifying NOx emissions of point sources from NO2 satellite observations (Talk)
ESA ATMOS 2024	1-5/7/2024	Bologna, Italy	Erik Koene	Bayesian de-noising of noisy trace gas satellite images using co-registered trace gas imag-es for improved hot-spot emission estimation. (Talk)
EMS Conference 2024	2-6/09/2024	Barcelona, Spain	Jasmin Vural	A neural network as observation operator for the assimilation of microwave satellite observations. (Poster)
ICOS Science Conference 2024	10-12 Sept 2024	Versailles, France	Hannah Allen	Assessing atmospheric fossil fuel emissions using 14CO2 measurements and global atmospheric simulations with the CIF-LMDZ transport and inverse modeling system. (Poster)
ICOS Science Conference 2024	10-12 September 2024	Versailles, France	Auke Visser	Characterizing background errors in IFS greenhouse gas emission inversions. (Talk)
46th EWGLAM and 31th SRNWP Meeting 46th EWGLAM & 31th SRNWP	30 September - 3 October	Prague, Czech Republic	Patricia de Rosnay (online)	One slide on the CORSO WP4 SIF forward model developments. (Talk)

Name	Date	Location	Presenter	Presentation title
NWP SAF Workshop on Satellite Observations of the Earth System Interfaces	19-22 November 2024	Reading UK	Sébastien Garrigues	Observation Operators to Assimilate Microwave and Solar Induced Fluorescence (SIF) Satellite Observations into the ECMWF Integrated Forecast System (IFS) (Talk)
8th SALGEE and LSA SAF User Workshop on Monitoring Drought Impacts on Vegetation & Feedback	25-26 November	Darmstadt	Patricia de Rosnay (Online)	Presentation with slides on CORSO. (Talk)
AGU24 Annual Meeting	9-13 December 2024	Washington D.C, United States	Thierno Doumbia	QUANTIFICATION OF UNCERTAINTIES ON ANTHROPOGENIC SURFACE EMISSIONS (Poster)
AGU24 Annual Meeting	9-13 December 2024	Washington D.C, United States	Thomas Kaminski (1), Marko Scholze (2), et al	Estimating 2021 fossil fuel emissions with a Carbon Cycle Fossil Fuel Data Assimilation System (Poster)
IM4CA project kick-off meeting	12-13 February 2025	Wageningen, The Netherlands	E. Koffi	IM4CA Synergies & Cooperation program: CORSO project and focus on examples on how the project's outcomes are implemented in CAMS. (Talk)
ECMWF Annual Seminar 2025	7-11 April 2025	Bonn, Germany	Patricia de Rosnay	Progress and prospects on coupled data assimilation for exploitation of interface observations and in support of climate monitoring and weather prediction. (Talk)
EGU25-8135 | Orals | AS3.27	Mon, 28 Apr, 16:55–17:05 (CEST) Room 0.11/12	Vienna, Austria	Thierno Doumbia**,** Claire Granier, Hugo Merly, Gerrit Kuhlmann, Oscar Collado, and Marc Guevara	Detection of hotspot areas using Sentinel-5P and GEMS imagery for evaluating bottom-up emission inventorie. (Talk)

Name	Date	Location	Presenter	Presentation title
EGU25-8613 |ECS| Orals | AS3.30	Wed, 30 Apr, 09:50–10:00 (CEST) Room D1	Vienna, Austria	Hugo Merly, Thierno Doumbia, Catherine Liousse, Marc Guevara, and Claire Granier	A web-based tool for exploring and visualizing GHG emissions from transportation and their uncertainties: the Copernicus Online Computation of Anthropogenic emission Uncertainties (COCAU). (Talk)
ESA Living Planet Symposium	23-25 June 2025	Vienna, Austria	Auke Visser	Using satellite observations of co-emitted species to better constrain CO2 emissions. (Poster)
ESA Living Planet Symposium	23-25 June 2025	Vienna, Austria	Gerrit Kuhlmann	Time series of NOx point source emissions from one year of TROPOMI NO2 observations. (Poster)
ESA Living Planet Symposium	23-25 June 2025	Vienna, Austria	Kaminski T , Knorr W , Voßbeck M et al	Verification of Terrestrial Carbon Sinks with the Terrestrial Carbon Community Assimilation System (TCCAS). (Poster)
ESA Living Planet Symposium	23-25 June 2025	Vienna, Austria	Knorr W , Williams M , Thum T , Kaminski T Et al	A Novel Observation Operator for Assimilating Microwave Vegetation Optical Depth into Vegetation / Carbon Cycle Models. (Poster)
ESA Living Planet Symposium	23-27 June 2025	Vienna, Austria	Sébastien Garrigues	Toward the development of coupled carbon and water cycle land data assimilation in the ECMWF Integrated Forecast System (IFS) by leveraging machine learning and new types of Earth observation. (Talk)
ESA Living Planet Symposium	23-27 June 2025	Vienna, Austria	Jasmin Vural	Assimilating Brightness Temperatures of Microwave Sensors Into the LDAS-monde System Using a Neural Network. (Talk)

Name	Date	Location	Presenter	Presentation title
ESA Living Planet Symposium	23-27 June 2025	Vienna, Austria	Pierre Vanderbecken	Assimilating SIF in the LDAS-Monde system using a deep learning operator: application on global cropland. (Talk)
EGU Mary Anning	10-12 June 2025	Bordeaux, France	Fabienne Maignan et al.	Improving the GPP of boreal evergreen needleleaf forests estimated by a land surface model through a physiologically-based representation of NPQ and co-assimilation of space-borne SIF and *in situ* GPP. (Poster)
ESA Living Planet Symposium	23-27 June 2025	Vienna, Austria	Fabienne Maignan et al.	Improving the GPP of boreal evergreen needleleaf forests estimated by a land surface model through a physiologically-based representation of NPQ and co-assimilation of space-borne SIF and *in situ* GPP. (Talk)
ESA Living Planet Symposium	23-27 June 2025	Vienna, Austria	Cédric Bacour	Reliability-Enhanced GPP Simulations Within a Land Surface Model Through the Co-Assimilation of Space-Borne SIF Retrievals and In Situ GPP Estimates. (Poster)
CAMS GA	3-5 September 2025	Prague, Czech Republic	Auke Visser	An overview of the CORSO project (2023-2025): Project overview and contribution to emission monitoring in CAMS. (Talk)
CWCC2025 - Climate and Weather Change Conference	12-16 October 2025	Benguerir, Morocco	Thierno Doumbia et al.	Quantifying and reducing uncertainties in anthropogenic emissions inventories. (Talk)

c) Workshops/ Seminars, providing updates on the project results

Name	Date	Location	Presenter	Presentation title
CESOC DETECT Land and Climate seminar	8 November 2024	Online	Patricia de Rosnay	Presentation with slides on CORSO. (Talk)
International Earth System WG meeting (IESWG 2025)	11-13 June 2025	DWD, Germany	S. Garrigues	Assimilation of active microwave and solar induced chlorophyll fluorescence (SIF) satellite observations in the ECMWF Integrated Forecast System (IFS) at global scale using machine learning-based observation operators (Talk)
ISDA online seminar on machine-learning data assimilation	10 July 2025	Online	S. Garrigues	Toward the development of coupled carbon and water cycle land data assimilation in the ECMWF Integrated Forecast System (IFS) by leveraging machine learning and new types of Earth observations. (Talk)
Machine Learning for Earth System Modelling	25-27 August 2025	In-person	S.Garrigues	Leveraging machine learning to advance the assimilation of new types of satellite observations to better constraint the land carbon cycle in the ECMWF Integrated Forecast System (IFS). (Talk)
Workshop in Numerical Wildfires and AI Weather	3-7 November 2025	Cargèse, France	Jean-Christophe Calvet	Monitoring vegetation's response to drought by assimilating in situ and satellite data (Talk)

4.1.2 Products through dissemination of

a. Datasets and accompanying material (e.g. descriptions, meta data)
b. Algorithms / Specifications
c. Graphics and animations

Where possible, datasets have been loaded onto the Zenodo EU Open Research repository for the CORSO project.

Figure 1 shows the dedicated site:

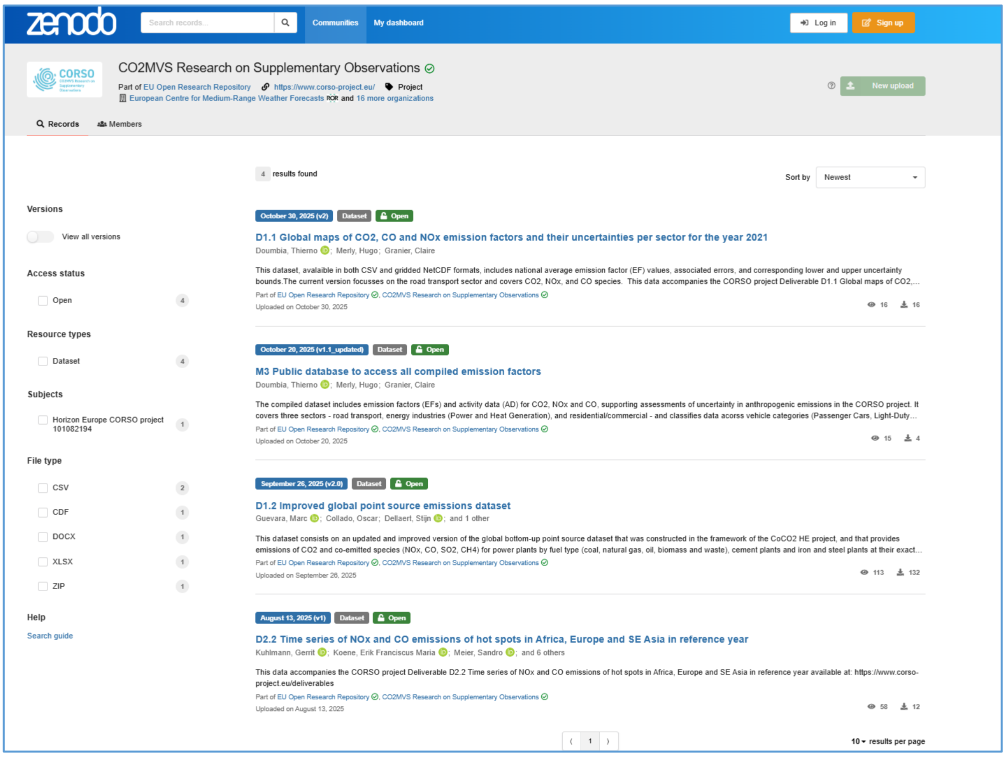


Figure 1: CORSO Zenodo Data Page

We have also updated the page on the CORSO website for CORSO produced public datasets showing the final locations and respective redirections.

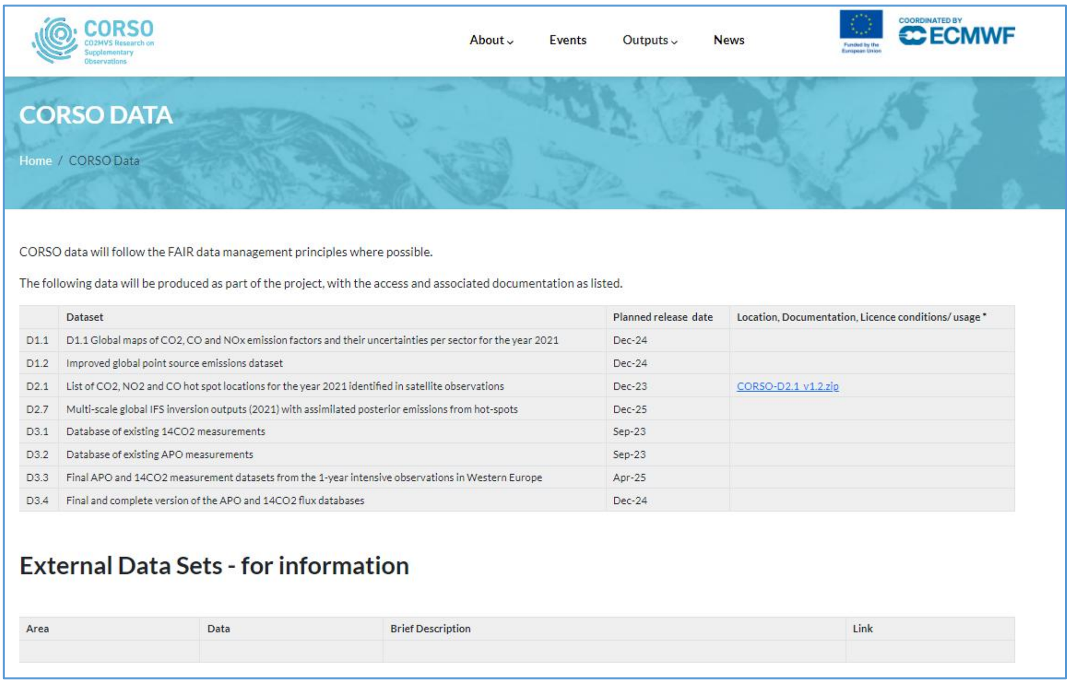


Figure 2: CORSO Website: Data Page

4.1.3 Progress information through provision of

a. *News items*
b. *Public Deliverables*
c. *Dissemination Materials (brochures, posters, flyers)*
d. *Website and social media*

The CORSO website has been used for News items, public deliverables and listing the scientific papers (Figures 3, 4 and 5 respectively).

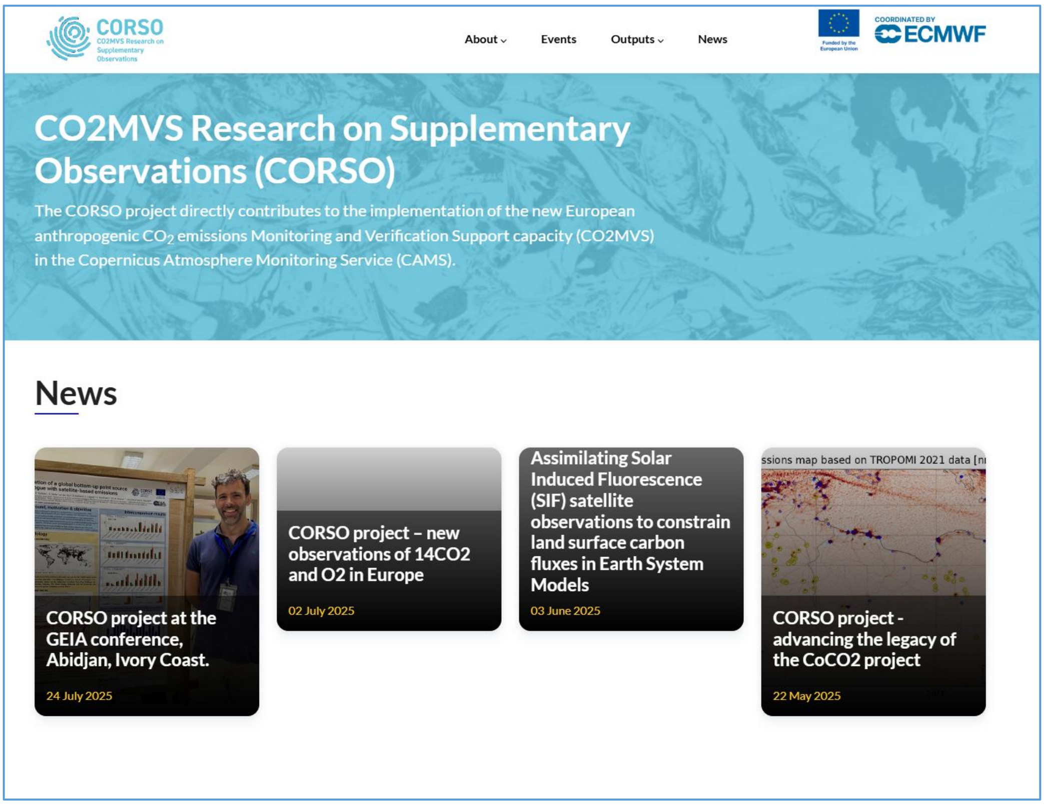
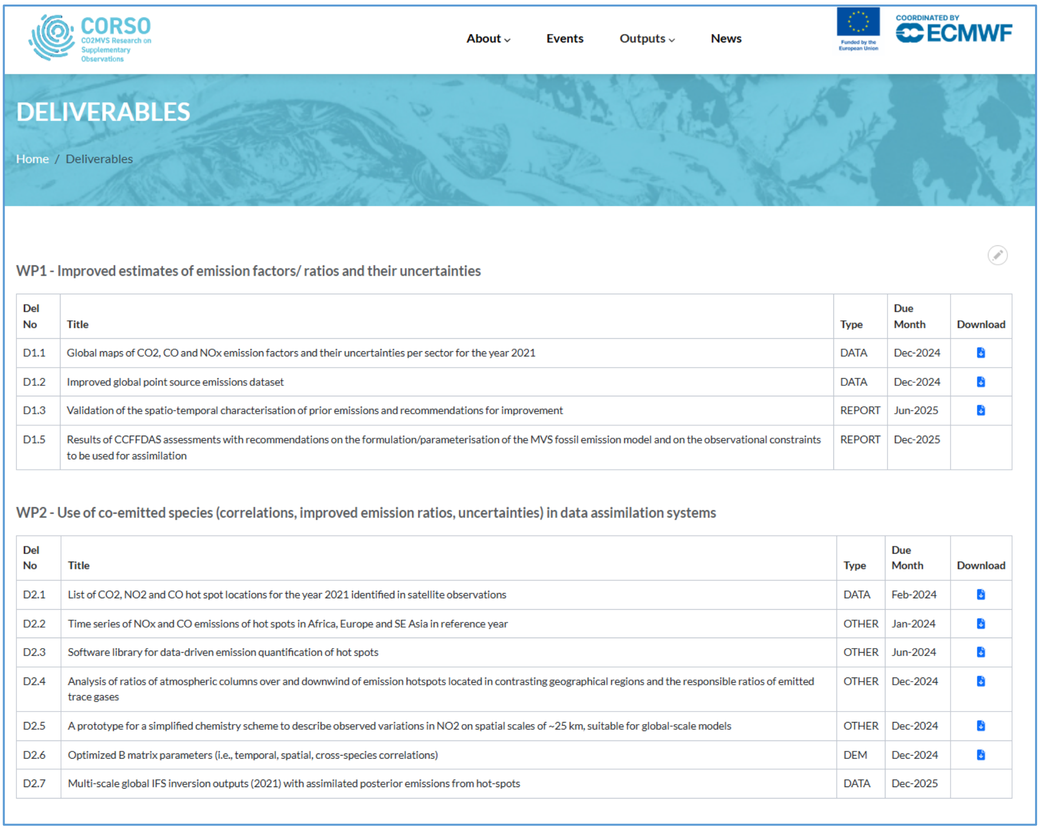


Figure 3: CORSO Website: News Page



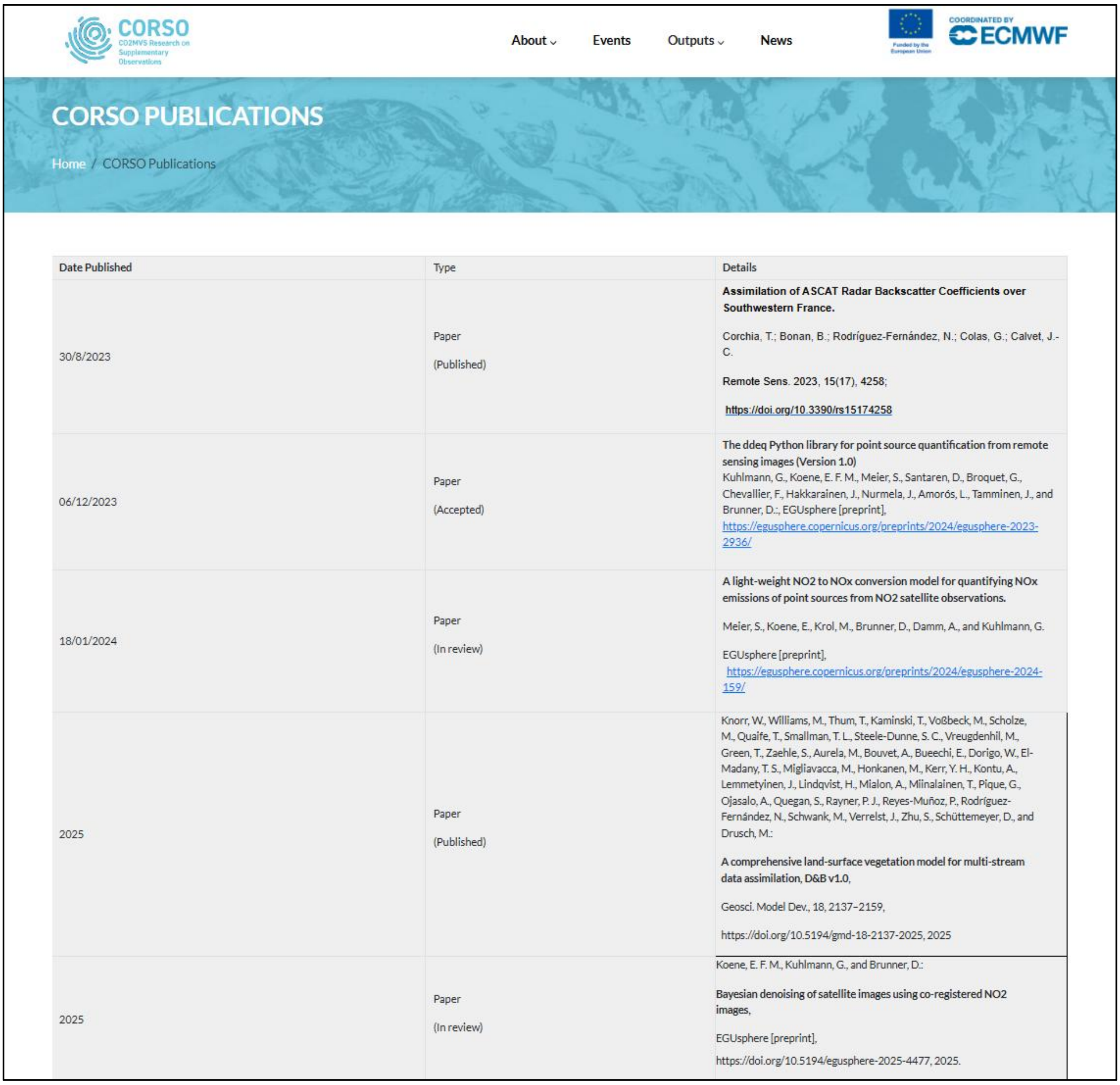
WP1 - Improved estimates of emission factors/ ratios and their uncertainties

Del No	Title	Type	Due Month	Download
D1.1	Global maps of CO2, CO and NOx emission factors and their uncertainties per sector for the year 2021	DATA	Dec-2024	
D1.2	Improved global point source emissions dataset	DATA	Dec-2024	
D1.3	Validation of the spatio-temporal characterisation of prior emissions and recommendations for improvement	REPORT	Jun-2025	
D1.5	Results of CCFFDAS assessments with recommendations on the formulation/parameterisation of the MVS fossil emission model and on the observational constraints to be used for assimilation	REPORT	Dec-2025	

WP2 - Use of co-emitted species (correlations, improved emission ratios, uncertainties) in data assimilation systems

Del No	Title	Type	Due Month	Download
D2.1	List of CO2, NO2 and CO hot spot locations for the year 2021 identified in satellite observations	DATA	Feb-2024	
D2.2	Time series of NOx and CO emissions of hot spots in Africa, Europe and SE Asia in reference year	OTHER	Jan-2024	
D2.3	Software library for data-driven emission quantification of hot spots	OTHER	Jun-2024	
D2.4	Analysis of ratios of atmospheric columns over and downwind of emission hotspots located in contrasting geographical regions and the responsible ratios of emitted trace gases	OTHER	Dec-2024	
D2.5	A prototype for a simplified chemistry scheme to describe observed variations in NO2 on spatial scales of ~25 km, suitable for global-scale models	OTHER	Dec-2024	
D2.6	Optimized B matrix parameters (i.e., temporal, spatial, cross-species correlations)	DEM	Dec-2024	
D2.7	Multi-scale global IFS inversion outputs (2021) with assimilated posterior emissions from hot-spots	DATA	Dec-2025	

Figure 4: CORSO Website: Deliverables Page



Date Published	Type	Details
30/8/2023	Paper (Published)	**Assimilation of ASCAT Radar Backscatter Coefficients over Southwestern France.** Corchia, T.; Bonan, B.; Rodríguez-Fernández, N.; Colas, G.; Calvet, J.-C. Remote Sens. 2023, 15(17), 4258; https://doi.org/10.3390/rs15174258
06/12/2023	Paper (Accepted)	**The ddeq Python library for point source quantification from remote sensing images (Version 1.0)** Kuhlmann, G., Koene, E. F. M., Meier, S., Santaren, D., Broquet, G., Chevallier, F., Hakkarainen, J., Nurmela, J., Amorós, L., Tamminen, J., and Brunner, D.:, EGUsphere [preprint], https://egusphere.copernicus.org/preprints/2024/egusphere-2023-2936/
18/01/2024	Paper (In review)	**A light-weight NO2 to NOx conversion model for quantifying NOx emissions of point sources from NO2 satellite observations.** Meier, S., Koene, E., Krol, M., Brunner, D., Damm, A., and Kuhlmann, G. EGUsphere [preprint], https://egusphere.copernicus.org/preprints/2024/egusphere-2024-159/
2025	Paper (Published)	Knorr, W., Williams, M., Thum, T., Kaminski, T., Voßbeck, M., Scholze, M., Quaife, T., Smallman, T. L., Steele-Dunne, S. C., Vreugdenhil, M., Green, T., Zaehle, S., Aurela, M., Bouvet, A., Bueechi, E., Dorigo, W., El-Madany, T. S., Migliavacca, M., Honkanen, M., Kerr, Y. H., Kontu, A., Lemmetyinen, J., Lindqvist, H., Mialon, A., Miinalainen, T., Pique, G., Ojasalo, A., Quegan, S., Rayner, P. J., Reyes-Muñoz, P., Rodríguez-Fernández, N., Schwank, M., Verrelst, J., Zhu, S., Schüttemeyer, D., and Drusch, M.: **A comprehensive land-surface vegetation model for multi-stream data assimilation, D&B v1.0,** Geosci. Model Dev., 18, 2137–2159, https://doi.org/10.5194/gmd-18-2137-2025, 2025
2025	Paper (In review)	Koene, E. F. M., Kuhlmann, G., and Brunner, D.: **Bayesian denoising of satellite images using co-registered NO2 images,** EGUsphere [preprint], https://doi.org/10.5194/egusphere-2025-4477, 2025.

Figure 5: CORSO Website: Publication Page

Other instruments used by the CORSO project to disseminate its results have included:

- Web / wiki pages
- Dissemination of information through relevant social media,
- Linked communication with the CAMS and ECMWF communication sites

CORSO uses the confluence pages for communication and dissemination within the project. Social media, (Linkedin and X (formerly known as "Twitter") are not used directly by CORSO but instead we rely on the established communication channels of the Project Coordinator, CAMS and ECMWF(Figure 6). ECMWF and Copernicus social media accounts are also being used to like/ follow project updates.

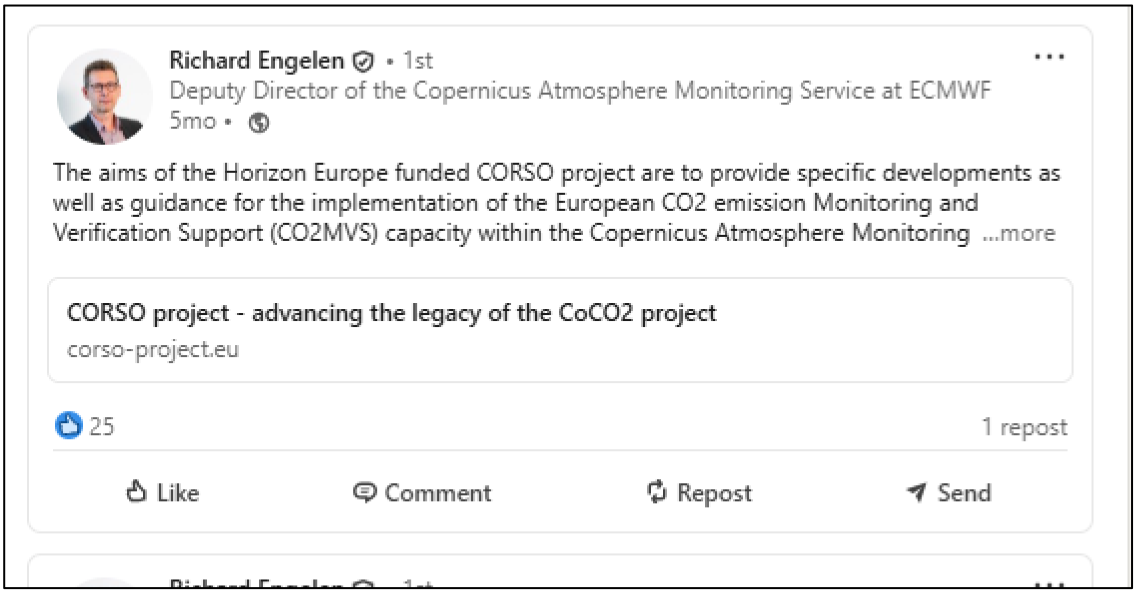


Figure 6: LinkedIn

The CORSO team was also presented at the CAMS General Assembly 2025 (Figure 7) Presenting in "CAMS supporting R&D Projects" and mentioned in "Emissions and Fluxes".

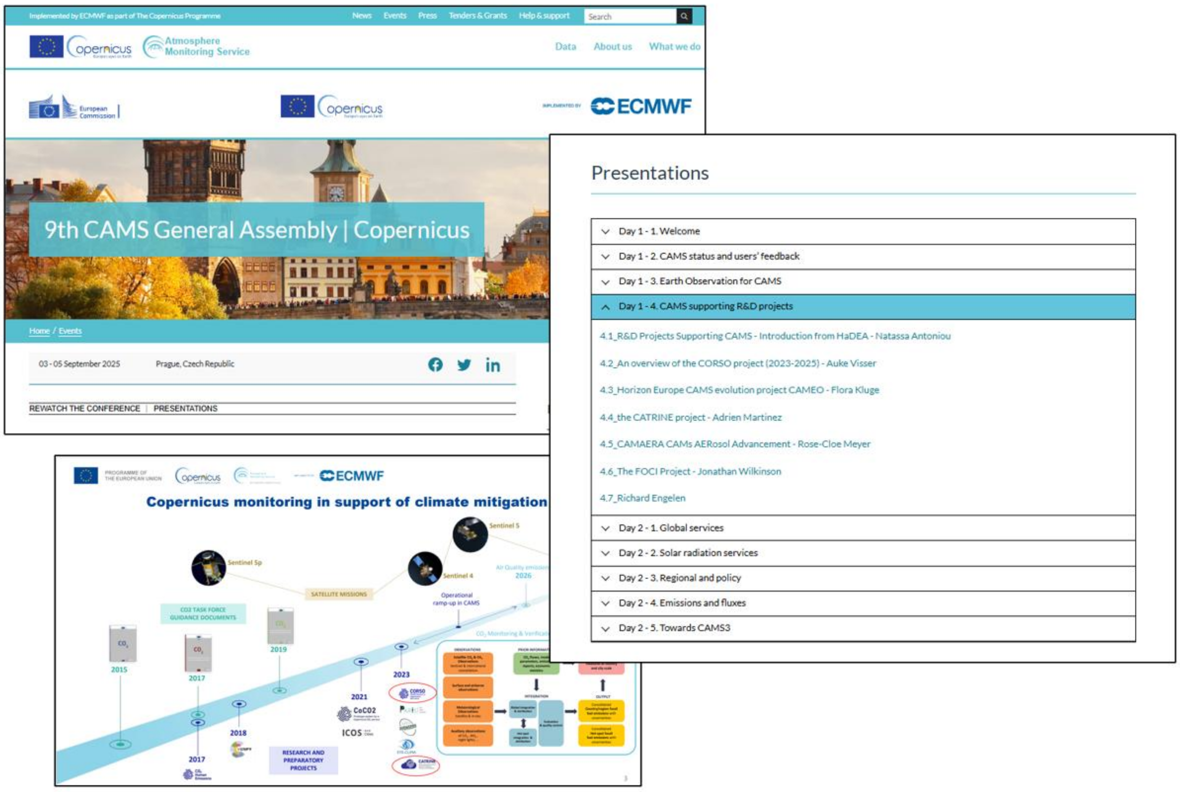


Figure 7: CORSO at 9th CAMS General Assembly

We have provided posters to support the DG DEFIS/ HaDEA stand at ESA Living Planet Symposium (LPS) 2025 and the EU at Euro GEO (Figure 8).

Figure 8: Clockwise from left, CORSO poster for DGDEFIS/ HaDEA at LPS; the poster on display at LPS, with EC Project Officer and visitors to the stand; and extract of poster for the EU area at the EURO GEO conference.

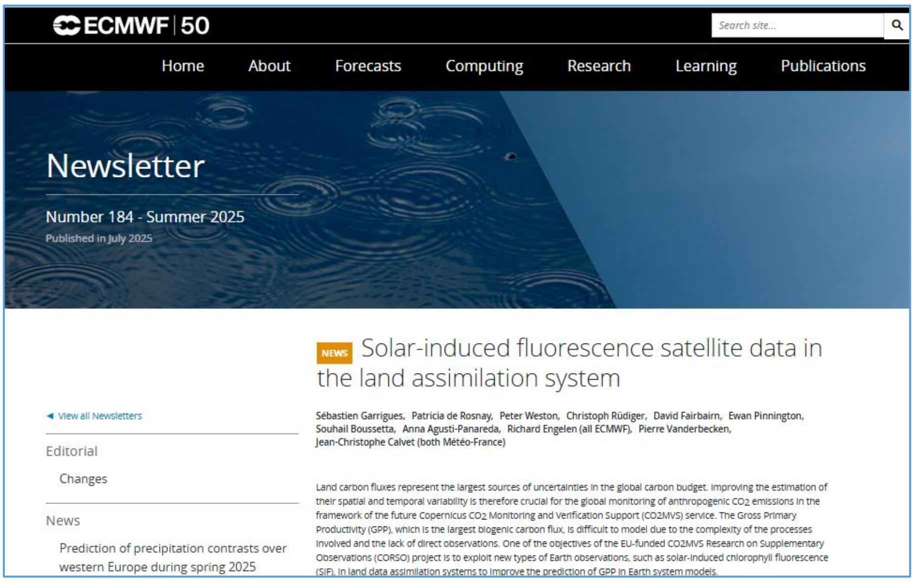


Figure 9: CORSO article in ECMWF Summer newsletter 2025

Google analytics has been used to collect and monitor traffic and users CORSO Website over the last 18 months.

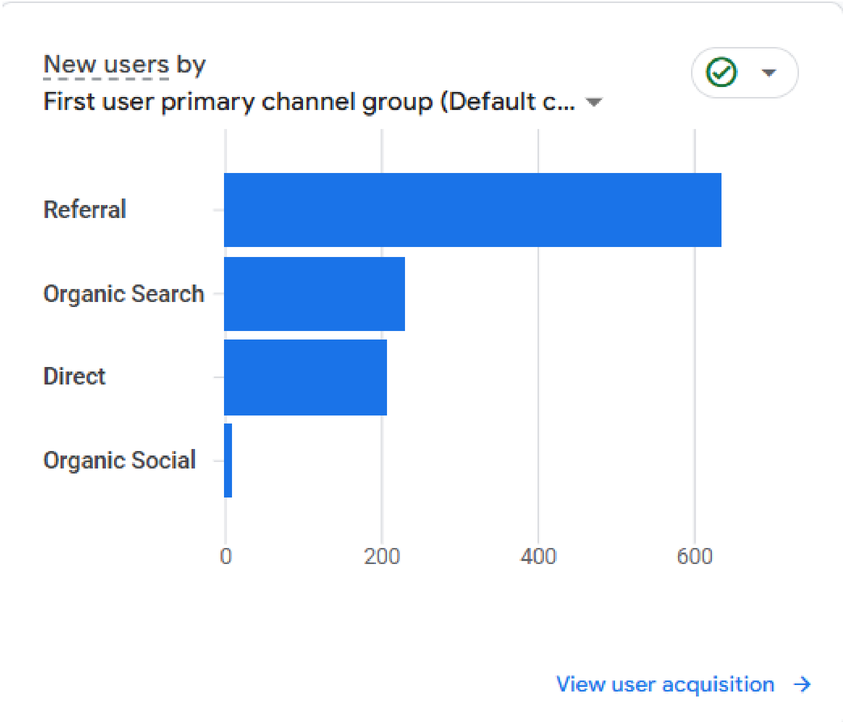


Figure 10: CORSO Website: Website acquisition,

The majority of users are accessing the website via Referral, followed by Organic search (Figure 10). Proving that the outreach has been successful and also that the website is easy to reach.

The stats show over 1.1K users with over 4.8K views (Figures 11, 12).

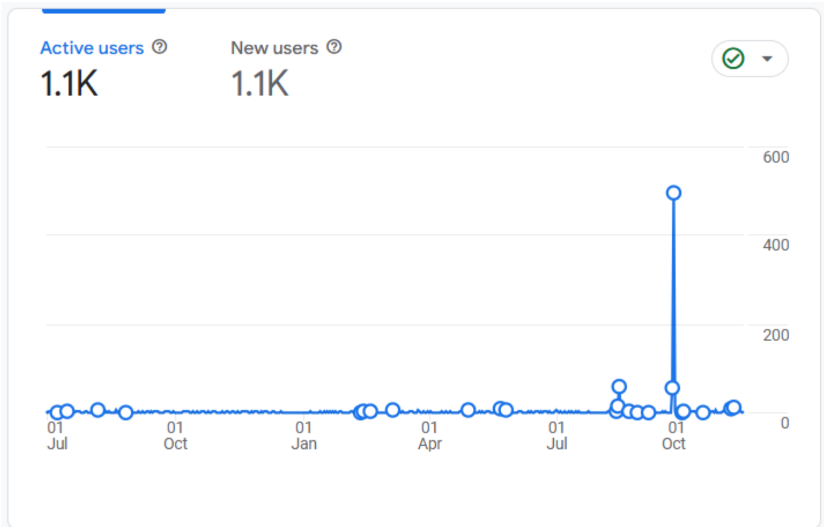


Figure 11: CORSO Website: Number of users

	Page title and screen class	Views	Active users
	Total	4,816 100% of total	1,099 100% of total
1	(not set)	2,190 (45.47%)	72 (6.55%)
2	Home | CORSO	1,577 (32.75%)	875 (79.62%)
3	Deliverables | CORSO	125 (2.6%)	60 (5.46%)
4	CORSO Data | CORSO	82 (1.7%)	53 (4.82%)
5	Objectives | CORSO	74 (1.54%)	53 (4.82%)
6	Events | CORSO	70 (1.45%)	45 (4.09%)
7	Team | CORSO	69 (1.43%)	60 (5.46%)
8	CORSO General Assembly - Agenda | CORSO	64 (1.33%)	23 (2.09%)
9	CORSO project - advancing the legacy of the CoCO2 project | CORSO	52 (1.08%)	29 (2.64%)
10	Consortium | CORSO	52 (1.08%)	44 (4%)

Figure 12: CORSO Website: Number of views and top pages accessed

The most views after the home page, are on the deliverables page, followed by the data page.

Figure 13 shows the users per country. Overall, there is good access from around the world, but the data shows that most are within the US and European continent.

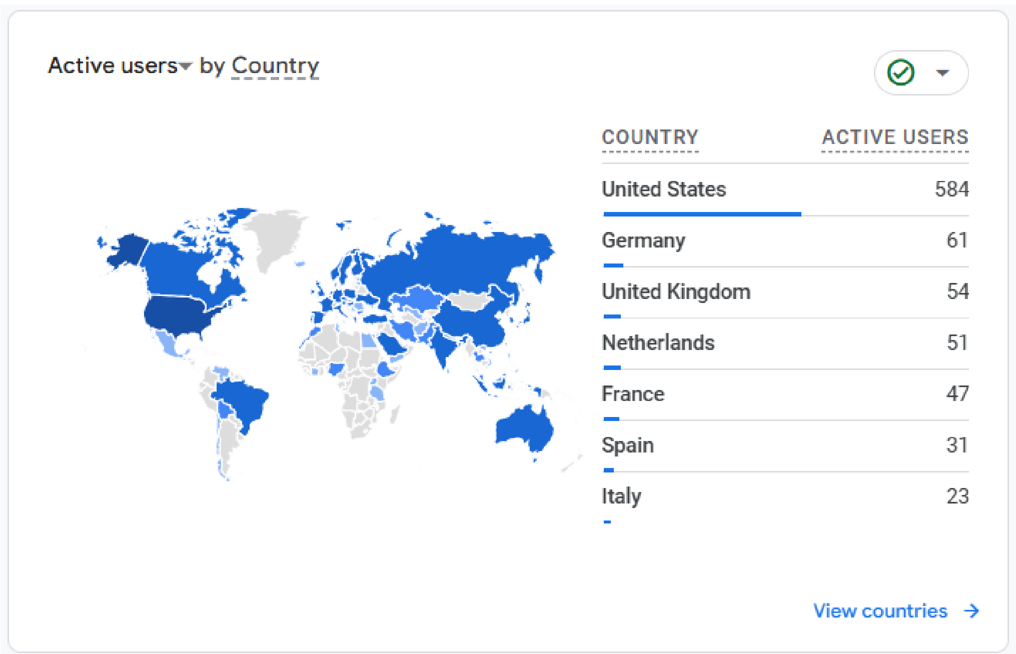


Figure 13: CORSO Website: Users per country.

5 Exploitation Plan

Deliverable D5.3 already outlined potential exploitation avenues, as per the table below.

Table: Summary of Exploitation Findings

Exploitable Products	• Global maps of CO_2, CO and NOx emission factors and their uncertainties per sector • Improved global point source emissions dataset • List of CO_2, NO_2 and CO hot spot locations for the year 2021 identified in satellite observations • Time series of NOx and CO emissions of hot spots in Africa, Europe and SE Asia • Software library for data-driven emission quantification of hot spots • A prototype for a simplified chemistry scheme to describe observed variations in NO_2 on spatial scales of ~25 km, suitable for global-scale models • Database of existing $^{14}CO_2$ measurements • Database of existing APO measurements • APO and $^{14}CO_2$ measurement datasets from the 1-year intensive observations in Western Europe • APO and $^{14}CO_2$ flux databases • Estimates of the annual fossil fuel CO_2 emissions at the continental to national scales over a decade, and specifically for 2024 in Europe • Improved land surface forward operators for SIF and low frequency MW data • Reports with recommendations for the implementation of the Copernicus CO2MVS
Exploitation Activities during the Project	• Any dataset that has been identified as public will be made available to external scientists. Several of these datasets are innovative and should create significant interest. • Project reports with recommendations will support uptake/implementation activities in CAMS, ICOS, and potentially other frameworks, already during the project.
Exploitation Activities after the end of the Project	• Any dataset that has been identified as public will be made available to external scientists. Several of these datasets are innovative and should create significant interest. • Project reports with recommendations will support uptake/implementation activities in CAMS, ICOS, and potentially other frameworks.
Consortium-wide/Joint Exploitation	• While outputs will be shared publicly as much as possible through documentation and peer-reviewed literature, the project will also support its consortium members to be better prepared for any upcoming CO2MVS implementation ITTs.

5.1 Update on the Exploitable Products at the end of the project

	How achieved (eg deliverable, milestone, dataset)	Status and availability
Global maps of $CO2$, CO and NOx emission factors and their uncertainties per sector (for the year 2021)	D1.1 document and dataset	Document on cordis/ website Dataset available at CORSO Zenodo site (https://zenodo.org/records/17488355)
Improved global point source emissions dataset	D1.2 document and dataset	Document on cordis/ website Dataset available at CORSO Zenodo site (https://zenodo.org/records/17206511)
List of CO2, NO2 and CO hot spot locations for the year 2021 identified in satellite observations	D2.1 document and dataset	Document on cordis/ website Dataset available at Zenodo.
Time series of NOx and CO emissions of hot spots in Africa, Europe and SE Asia	D2.2 document and dataset	Document on cordis/ website Dataset available at CORSO Zenodo site.
Software library for data-driven emission quantification of hot spots	D2.3	ddeq is an open-source Python library https://pypi.org/project/ddeq/
A prototype for a simplified chemistry scheme to describe observed variations in NO2 on spatial scales of ~25 km, suitable for global-scale models	D2.5	Document on cordis/ website.
Database of existing 14CO2 measurements	D3.1 document and dataset	Document on cordis/ website This dataset will be made available on the ICOS Carbon Portal, this is in progress.
Database of existing APO measurements	D3.2	This dataset will be made available on the ICOS Carbon Portal, also in progress.
APO and 14CO2 measurement datasets from the 1-year intensive observations in Western Europe	D3.3 document and dataset	Document on cordis/ website. Datasets are available on ICOS CP: https://meta.icos-cp.eu/collections/3BKIGVB6Vw3KKlMeYpDEMckb https://meta.icos-cp.eu/objects/Iq4N2vWXH8aUkmDxiCFL_qNR
APO and 14CO2 flux databases	D3.4 document and dataset	Document on cordis/ website Datasets produced during CORSO are on FTP and other links: TNO O2 product (Marya), Nuclear (Carlos/Hannah), Ocean radiocarbon (Hannah), terrestrial radiocarbon (Marko). We are working on transferring these to Zenodo.

	How achieved (eg deliverable, milestone, dataset)	Status and availability
Estimates of the annual fossil fuel CO2 emissions at the continental to national scales over a decade, and specifically for 2024 in Europe	D3.5	Due at M36, document will be available on website. This is a combined document of D3.5 and D3.6.
Improved land surface forward operators for SIF and low frequency MW data	D4.2 document	Document on cordis/ website
Reports with recommendations for the implementation of the Copernicus CO2MVS	***See section 5***	***See section 5***
*Collection of pollutant-dependent emission temporal profiles and associated uncertainties	M1 (WP1)	Document and Dataset available at CORSO Zenodo site (https://zenodo.org/records/17633162)
*Fluctuations of emission ratios in urban plumes	M2 (WP1)	Document and Dataset available at CORSO Zenodo site (https://zenodo.org/records/17633143)
*Public database to access all compiled emission factors	M3 (WP1)	Document and Dataset available at CORSO Zenodo site (https://zenodo.org/records/17397158)
*First 20-year global inversions assimilating APO and 14CO2	M7 (WP3)	Dataset available at CORSO Zenodo site https://doi.org/10.5281/zenodo.17397158

*Additional Exploitable product

5.2 Exploitation Activities during the Project

Any dataset that has been identified as public will be made available to external scientists. Several of these datasets are innovative and should create significant interest	Datasets were made available on FTP sites/ Zenodo and their locations were published in the deliverables.
Project reports with recommendations will support uptake/implementation activities in CAMS, ICOS, and potentially other frameworks, already during the project	Project reports contained recommendations where applicable.

5.3 Exploitation Activities after the end of the Project

Any dataset that has been identified as public will be made available to external scientists. Several of these datasets are innovative and should create significant interest.	Datasets were made available on FTP sites/ Zenodo and their locations were published in the deliverables
Project reports with recommendations will support uptake/implementation activities in CAMS, ICOS, and potentially other frameworks.	Project reports contained recommendations where applicable.

5.4 Consortium-wide/Joint Exploitation

While outputs will be shared publicly as much as possible through documentation and peer-reviewed literature, the project will also support its consortium members to be better prepared for any upcoming CO2MVS implementation ITTs.

The main outcome of the CORSO project are taken to be the foreseen (pre-)operational service in the Copernicus programme.

6 Recommendations for the implementation of the Copernicus CO2MVS

Overall recommendations from CORSO are presented in this section and grouped by WP following the structure

- Maturity of what each WP has produced
- Importance to CO2MVS
- Ease of Tx to operations
- Barriers or future research needed
- Gaps
- Where to go for further information, if available eg List of deliverable reports or milestones that contain more detailed recommendations

6.1 WP1

6.1.1 Maturity of what WP1 has produced

A total of 4 prior emission products were produced under CORSO WP1, including:

1. Gridded global maps of CO_2, CO and NO_x emission factors (EF) and their uncertainties per sector
2. Improved global bottom-up emission point source catalogue
3. Prior uncertainties in CO_2 fossil fuel emissions (including correlations in space and time) based on the FFDAS model
4. Prior CO_2:CO:NO_X gridded error correlations

Different levels of maturity were achieved depending on the product. The gridded global maps of EFs and uncertainties were developed from scratch under CORSO. The final database covers a selection of CO_2 fossil fuel sectors, including power plants, residential combustion and road transport, while other relevant sources such as manufacturing industry are currently not covered due to its complexity. On the other hand, the global point source catalogue, prior emission uncertainties and error correlations developed under CORSO represent improved and refined versions of the works previously performed under the CoCO2 project. As part of CORSO, the further improved global point source catalogue was used as input to the FFDAS model and evaluated through comparisons against independent TROPOMI-based NO_x emission estimates, overall finding a good agreement, while the prior uncertainties and error correlations were adapted to the input requirements of the IFS-based CO2MVS prototype system and tested as part of WP2. The prior uncertainties in CO_2 from FFDAS can provide high ensemble size (a total of 300 members were provided as part of CORSO); which can be samples to produce any summary covariance statistics (in time, space) needed as input to the CO2MVS.

6.1.2 Importance to CO2MVS

The improved global bottom-up emission point source catalogue allows covering the need of high-quality, spatially and temporally explicit prior information as input to the CO2MVS to properly monitor the so-called industrial 'hot spots'. The prior uncertainties in CO_2 fossil fuel emissions and CO_2:CO:NO_X error correlations are also critical inputs for the development of the prior emission error covariance (B matrix) of the global IFS-based CO2MVS prototype system. The gridded global maps of EF and associated uncertainties could be used for CO_2 emission monitoring through emission ratio conversion of NOx TROPOMI-based estimates to CO_2.

6.1.3 Ease of Tx to operations

Overall, the bottom-up global point source catalogue and prior emission uncertainty information developed under CORSO hold promise for implementation into the operational CAMS CO2MVS in the coming years, as both products have already been tested as input to the IFS. Concerning the gridded global maps of EF and associated uncertainties, the product provides reliable information for operational calculations of CO_2 emissions using inverse modelling, but coordination with ECWMF is needed to assess how the current dataset could be used as part of the IFS-based CO2MVS prototype.

For the global point source catalogue, which currently reports emissions for 2021, regular updates of the reference year will be needed under an operational framework to properly reflect structural (e.g., building of new power plants or retirement of existing power plants) and technological changes (e.g., implementation of new pollution aftertreatment systems, which has a direct impact on the emission ratios) as well as the impact of energy transition (e.g., moving from fossil fuel to biofuel combustion plants). The integration of the catalogue with the existing CAMS global anthropogenic emission product (CAMS-GLOB-ANT), which reports emissions not only from industrial sources but also from area, mobile and diffuse sources, will require allocating additional effort to avoid complications on double counting and/or underreporting.

Prior uncertainties in CO_2 fossil fuel emissions and the covariance structure of the CO_2:CO:NO_X error correlations are unlikely to change a lot over time, so these two products have less need for regular updates. However, the implementation of these prior uncertainties in the B matrix is challenging and continuous interaction between product developers and the IFS team will be needed beyond CORSO.

6.1.4 Barriers or future research needed

The following barriers and future research needs were identified for each one of the products developed as part of CORSO:

1. Gridded global maps of EF and their uncertainties: A lack of information and details on EF and activity data has been identified in many countries, especially for Latin America, the Middle East and Africa. Additional efforts should be placed to connect with key national and local emission compilers from these regions to obtain detailed information. Future work should also focus on improving the completeness of the current database by including EF and associated uncertainties for missing sectors such as manufacturing industry. The EF uncertainties are currently estimated considering the influence of fuels (power plants and residential combustion) and general vehicle categories (road transport), but do not account for the impact of differences in technologies (e.g., EURO categories for road transport, types of coal-fired boilers) which may artificially increase the scatter in the resulting EF. Finally, increasing the spatial resolution at which the EF and uncertainty information is currently provided (e.g., from country-level to region or grid cell level) is also relevant to increase its usability.

2. Improved global bottom-up emission point source catalogue: The comparison against TROPOMI-based hotspot locations revealed the need to add additional industrial sources that are currently missing in the bottom-up catalogue, namely refineries and combustion sources linked to mining sites, such as copper smelters or cobalt refineries. The estimation of bottom-up emissions from these types of facilities will come with challenges associated to the characterization of multiple combustion and process-related sources in the cases of refineries and the collection of activity factors and emissions factors and emission ratios in the case of mining-related activities, since most of these sources are occurring in developing regions such as Latin America or Africa, where we have a lack of bottom-up information. Further research will also be needed to understand the discrepancies

between bottom-up and TROPOMI-based CO estimates for iron and steel plants identified under CORSO. Explicit information about stack parameters (e.g., stack height and diameter, exit velocity and exit temperature of the efluent) should be included in future versions of the catalogue to support high resolution plume rise characterisation efforts. Finally, the current catalogue focusses on major CO_2 emitting activities, not major CH_4 sources. While the uncertainty in CH_4 bottom-up emissions is typically very large (i.e., undesired/uncontrolled leaks that remain unaccounted in the activity factors/emission factors), having a complete CH_4 point source database could be useful to ensure a better spatially explicit prior and to classify the monitored satellite plumes into specific categories or cluster of sources located nearby (e.g., landfills, wastewater treatment plants, oil/gas facilities, coal mine, biogas/biomethane plants, farms)

3. Prior uncertainties in CO_2 fossil fuel emissions: The sectoral models considered in the FFDAS model and associated input data could be refined to improve the accuracy of the emissions and uncertainty results. This includes, for instance, the use of a more refined proxy for the spatial distribution of the aviation emissions or the assimilation of emissions and energy balances reported on a finer scale than at the country-level. The approach considered for the estimation of CO_2 prior uncertainties could be extended to NO_x and CO to provide consistent uncertainty correlation in time, space and between species. This extension could also be implemented for CH_4 emissions. The high temporal correlation in the CO_2 emission uncertainty derived by FFDAS and the role of the underlying ensembles of temporal considered as input should be further investigated. The CCFFDAS model could be used to deliver uncertainty correlations for natural CO_2 fluxes at high spatial and temporal resolution and uncertainty correlation with fossil fuel CO_2 fluxes. Finally, as a member in a multi-scale, multi-model assimilation mode of the CO2MVS, CCFFDAS could be operated at regional or global scale to provide posterior sectoral fossil emissions and natural fluxes consistent with atmospheric observations.

4. Prior CO_2:CO:NO_X gridded error correlations: The correlation coefficient between CO_2 and co-emitted CO or NOx species is currently provided as a function of the uncertainty in activity data and the EF of CO/NOx. To include more detail in the calculation of the error correlations, further investigation on the impact of geometry shapes and diversity in sub-sector activities is needed. Moreover, the global gridded uncertainties in CO_2 emissions estimated from uncertainties in activity data and emission factors were compared against the CO_2 gridded uncertainties from the FFDAS ensemble, which reveal interesting discrepancies that should be studied in more detail to improve the gridded uncertainties in the future.

6.1.5 Gaps

N/A

6.1.6 List of deliverable reports or milestones that contain more detailed recommendations

The following CORSO deliverable reports and milestones contain more detailed recommendations: D1.1, D1,2, D1.3, D1.4 and D1.5.

6.2 WP2

The recommendations from WP2 have been ordered by WP task:

- Task 2.1: Develop and apply data-driven methods to detect and quantify CO and NOx emissions of hot spots in satellite measurement
- Task 2.2: Simplified NOx chemistry schemes in data assimilation systems
- Task 2.3: Modeling and testing of the IFS prior error covariance matrix
- Task 2.4: Quantify annual CO2 emissions of hot spots

6.2.1 Task 2.1: Develop and apply data-driven methods to detect and quantify CO and NO_x emissions of hot spots in satellite measurement

CORSO advanced methods for detecting and quantifying emissions of hot spots. Hot spot locations were obtained from TROPOMI and GEMS NO_2 measurements, making it possible to identify missing sources in the CORSO point source database. CO and NO_x emissions were estimated from TROPOMI CO and NO_2 observations (Deliverable 2.2 and 2.3). They were used for evaluating the CORSO point source database (Deliverable 1.3).

6.2.1.1 Maturity of what WP2/Task 2.1 has produced

Hot spot locations: Two methods were developed to retrieve hot spot locations from NO_2 satellite observations: Annual NO_2 satellite maps to identify hot spots (Deliverable 2.2) and the divergence method combining NO_2 satellite maps and ERA5 wind fields.

Quantification of CO and NO_x emissions of hot spots:

- **Annual emissions:** TROPOMI was used to quantify CO emissions of cities and iron & steel plants and NO_x emissions of power plants.
- **Emissions at satellite overpass:** Cross-sectional flux method was used to quantify NO_x from power plants at TROPOMI overpass times.

6.2.1.2 Importance to CO2MVS

Accurate hot spot locations required for data assimilation in CO2MVS.

Annual emissions required for validating annual emissions outside data assimilation system.

Emission estimates at satellite overpass required for data assimilation of hot spots.

Co-emitted species provide valuable information about CO2 emissions with relatively high CO emissions for iron & steel plants and high NOx emissions for power plants.

6.2.1.3 Ease of Transfer to Operations

Hot spot locations: High ease for transfer to operations.

Annual emissions: Medium ease for transfer to operations due to some barriers.

Emissions at overpass: Low ease for transfer due to high uncertainties.

6.2.1.4 Barriers or Future Research Needed

Hot spot locations: Annual NO_2 maps have limited spatial resolution with challenges to identify individual sources in hot spots with many sources. Divergence method is better suited for resolving neighbouring sources, but method has artefacts in mountainous regions because ERA-5 wind fields have lower resolution than TROPOMI images. Future research needed to reduce artefacts by developing correction terms or by providing global wind fields at <2 km resolution.

Annual emissions: Further research is needed to provide reliable annual CO and NOx emission estimates.

Emissions at overpass: NO_x emissions at overpass have high uncertainties due to high uncertainty in wind fields and NO_x chemistry (see Task 2.2). In addition, CO emissions are not feasible at satellite overpass due to high uncertainty in the current satellite product. Finally, it is necessary to develop methods to flag satellite images where emission quantification fails because emissions are below the detection limit.

All methods still require substantial expert knowledge for quality control and are therefore labour intensive. Future research needed for improvement especially for hot spots with several neighbouring sources.

6.2.2 Task 2.2: Simplified NO_x chemistry schemes in data assimilation systems

CORSO developed surrogate models for NO_x chemistry to enable the assimilation of NO_2 satellite observations into ECMWF's Integrated Forecasting System (IFS), which cannot run full atmospheric chemistry schemes due to the high computational costs. These models are essential for assimilating NO_2 satellite observations and in the data assimilation for quantifying CO_2 emissions through NO_x:CO_2 emission ratios.

6.2.2.1 Maturity of what WP2/Task 2.2 has produced

Surrogate NOx chemistry models for global scale: A prototype system for Europe was developed using a Random Forest regression model trained on GEOS-Chem outputs (Deliverable 2.5; Schooling et al., 2025). https://doi.org/10.5194/acp-25-15631-2025

The model was subsequently expanded to global scale and validated using IFS input variables, demonstrating robust performance.

NO_x chemistry approach for hot spots: An initial methodology was developed using plume-resolving MicroHH simulations from the CoCO2 project and tested for four facilities in Germany, Poland, Russia and South Africa (Meier et al., 2024). https://doi.org/10.5194/acp-24-7667-2024

The method was also tested for 6 European and 12 U.S. power plants (Kuhlmann et al., 2025, in prep.). The tests indicate good generalization, but simulations were limited to 48 hours at the four facilities.

6.2.2.2 Importance to CO2MVS

Surrogate models are critical for integrating NO_2 observations into IFS, enabling improved NO_x emission estimates without full chemistry schemes.

Plume-scale modelling is important for hotspot quantification, particularly for power plants and industrial sources, but currently less mature.

6.2.2.3 Ease of Transfer to Operations

Surrogate models: High ease of transfer, as they are computationally efficient and compatible with IFS input variables.

Plume-scale approach: Low ease of transfer at present due to limited simulation coverage and complexity.

6.2.2.4 Barriers or Future Research Needed

Surrogate models: Minor tuning for global operational deployment.

Plume-scale approach requires plume-resolving simulations with chemistry for a global dataset of hotspots to address dependency of NOx chemistry on local meteorological conditions, chemical regimes and emissions.

6.2.3 Task 2.3: Modelling and testing of the IFS prior error covariance matrix

CORSO advanced our understanding of prior error covariance matrix (**B**) parameters of surface fluxes of greenhouse gases and co-emitted air pollutants. Ensembles of biogenic and anthropogenic CO_2 fluxes and their residuals were used to estimate prior uncertainties and their spatial, temporal and cross-species correlations. This information is already used to construct the IFS **B** matrix, but these parameters must be further evaluated, and tuned where necessary, to obtain a robust inversion system.

6.2.3.1 Maturity of what WP2/Task2.3 has produced

WP2 has developed ensemble-based methods to derive **B** parameters for surface fluxes and this resulted in a first set of these parameters that were already implemented in IFS or are ready for implementation (deliverable D2.6). These methods can be run routinely to derive **B** parameters in case of updates to input datasets or model updates for online-simulated fluxes (e.g., as part of IFS cycle upgrades).

6.2.3.2 Importance to CO2MVS

The **B** matrix is of critical importance to the CO2MVS, as it propagates observational information in space, time and across species within the IFS global inversion system.

6.2.3.3 Ease of Transfer to Operations

The derived **B** parameters are ready for testing in IFS in a pre-operational context.

Accounting for anisotropic spatial error correlation for anthropogenic emissions needs more work, which will be conducted as part of ongoing and future CAMS activities.

6.2.3.4 Barriers or Future Research Needed

We suggest investigating the use of observations and Observing System Simulation Experiments (OSSEs) to evaluate and tune the IFS prior error covariance matrix for surface fluxes:

Observation-based evaluation: observations provide useful (in)direct constraints on **B** parameters. We recommend using maximum-likelihood optimization of B parameters based on atmospheric observations:

- Use concentration observations for indirectly evaluating prior uncertainties (and their spatial and temporal correlations) in (single-species) inversion experiments. The initial focus should be on compounds with good observational coverage from space and dense surface observation networks (NOx, CO, possibly CH4, and later CO2).
- Evaluate the cross-species emission error correlation by focusing on NOx, CO and CO2 concentration observations in/near urban regions with dense observation networks, such as ICOS-Cities and CO2-USA for CO2.
- Where possible, use measurements from targeted campaigns linking concentration and flux measurements for GHGs and co-emitted species across spatial scales.

OSSE-based evaluation and sensitivity analysis: Controlled experiments such as OSSEs enable further evaluation of the system. In that framework synthetic observations are generated from simulated concentrations and subsequently used in the global IFS inversion system. Such approaches allow, in particular, to perform sensitivity analyses by testing the impact of changes in different components of the inversion system on the optimized fluxes. Preliminary work and testing using the EDA system developed at ECMWF has been carried out and should be pursued in the coming years. We recommend using this framework to conduct the following analyses:

- Ensemble-based (i.e., Monte-Carlo) quantification of posterior uncertainty in the optimized fluxes.
- Quantification of the impact of uncertainties in the **B** matrix parameters on the inverted fluxes.
- Assessment of the performance of methods to tune the **B** matrix parameters based on observed concentrations (e.g., posterior diagnostic using chi-squared criteria).

6.2.4 Task 2.4: Quantify annual CO_2 emissions of hotspots.

6.2.4.1 Maturity of what WP2/Task2.4 has produced

Ensemble Kalman Filter inversion: The EnKF-based NOx emission inversion using a lightweight NOx model within GEOS-Chem has been finalised. The system assimilates TROPOMI NO_2 data to update NOx emissions, which are then converted to fossil-fuel CO_2 using TNO emission ratios and cross-species error correlations.

IFS hotspot assimilation: First tests using the posterior hotspot assimilation algorithm have been carried out. It consists of using the IFS flux ensemble generated by an EDA as prior and update each member based on an ensemble Kalman filter method that assimilates hotspot emission estimates. This algorithm has been tested in an OSSE framework and applied to assimilate hotspot emission estimates from task T2.1 into an IFS CO2 emission ensemble for two months in 2021. A prior error tuning approach based on posterior statistic diagnostics has also been tested and demonstrated its ability to improve the inversion results.

6.2.4.2 Importance to CO2MVS

Ensemble Kalman Filter inversion: The use of a surrogate model for the NOx chemistry is key to provide a computationally tractable approach to perform operational long-window IFS inversions that exploit satellite NO2 observations. The ensemble Kalman filter results obtained as part of T2.4 provide a proof-of-concept of the feasibility of the approach in an inversion framework similar to that of the future IFS global CO2MVS. It could also be used to benchmark the results obtained from the future IFS global CO2MVS.

IFS hotspot assimilation: The assimilation of posterior flux products generated by other, higher resolution inversion systems will allow to build a multi-scale inversion capability within the global IFS system, tackling scales from point source to regional emissions.

6.2.4.3 Ease of Transfer to Operations

Ensemble Kalman Filter inversion: remains to be determined.

IFS hotspot assimilation: the framework needed to assimilate the hotspots within the IFS inversion system is being implemented and transfer to operations will be done in the coming years, without any foreseen difficulty.

6.2.4.4 Barriers or Future Research Needed

Ensemble Kalman Filter inversion: the feasibility of frequent provisions of inversions to benchmark the future IFS global CO2MVS will be considered in the coming years.

IFS hotspot assimilation: the prior error tuning approach, as well as the generalisation of the method to the assimilation of regional inversion products will, be the subject of further investigations in the coming years.

6.3 WP3

6.3.1 Maturity of what WP3 has produced

In connection with ICOS we have achieved a higher measurement capacity for 14CO2. Furthermore, we have expanded the continuous O2 monitoring stations from 2 to 3 in North-West Europe, and an additional site will soon be coming online through the Horizon Europe PARIS project. These O2 and 14CO2 observing frameworks are now fully mature. Flask sampling and analysis is operational at Class 1 sites of the ICOS network, and the newly developed graphitisation system is transitioning from testing to operational use. The continuous O2 measurements at Cabauw has been interrupted due to maintenance, but they should be resumed soon.

In parallel, CORSO WP3 has launched the development of a set of advanced global and regional CO2/14C/O2 inversion frameworks. Preliminary results have been obtained, and configurations will be further refined after the end of CORSO (for the full 14CO2/O2/CO2 modelling to increase accuracy). Current systems have resulted in reference inversions using precomputed FFCO2 data from the 14C/O2/CO2 observations.

6.3.2 Importance to CO2MVS

The results in WP3 raised indications that 14C and O2 can add useful information to global and regional scale CO2 and thus to the main CO2MVS multiscale inversions or to benchmarking inversions. This applies not only for the estimate of fossil fuel emissions, but also for CO2 natural sinks, even though there are large uncertainties in isotopic / O2 signatures from CO2 natural sinks. However, the modelling work so far is still exploratory compared to other on-going developments in CO2MVS and further work is needed on potential biases to fully quantify the added value of these tracers (e.g., uncertainties in disequilibrium fluxes for interpreting 14CO2, or the influence of the biosphere and ocean exchange on FFCO2 derived from O2 and CO2).

6.3.3 Ease of Tx to operations

For the implementation of 14C and O2 in CO2MVS, the ingestion of the inputs and the tracer transport of 14C and O2 should be straightforward. The implementation of off-line inversions using precomputed FFCO2 observations should also be relatively straightforward, but this specific approach has a limited range of applications for the CO2MVS and the impact of potential biases in the derived FFCO2 still need to be characterised. Increasing and splitting the control vector in a full CO2, 14C and O2 inverse modelling framework will raise more complexity e.g. if solving for gross instead of net fluxes and will require further research.

6.3.4 Barriers or future research needed/ gaps

We strongly advocate for continuation of the high frequency measurements of 14C from the ICOS flask network, and continuous O2 measurements, as well as expanding the network further. For the modelling, further research should focus on improving the prior estimates of the isotopic / O2 signature of natural fluxes and better characterize their uncertainties (incl. spatial / temporal correlations). There is also a need to gain more experience with CO2/14C/O2 inversions solving for the full 14CO2/O2/CO2 system

6.3.5 Further recommendations

Deliverables 3.3, 3.4 and 3.5.

6.4 WP4

6.4.1 Maturity of what WP4 has produced

In CORSO, observation operators have been developed for several types of satellite observations: solar induced fluorescence (SIF), low frequency microwave brightness temperatures and backscatter coefficients.

These developments have led to mature forward operators openly available and shared with the scientific community.

In the IFS system, used for CAMS, developments related to ASCAT backscatter data assimilation have been demonstrated in operational environment (TRL7) in the IFS system, with targeted implementation in the future IFS cycle 51r1 or 52r1.

Furthermore, exploratory research on Above Ground Biomass data assimilation was conducted using physics-based land surface models representing carbon pools. This work will guide further developments that need to be conducted in the IFS ecLand surface model to enable the exploitation of biomass observations in the future.

6.4.2 Importance to CO2MVS

Data assimilation results conducted in research environments based on machine learning and physics-based systems demonstrated the relevance of SIF data assimilation for the CO2MVS.

SIF data assimilation improves LAI, especially over croplands, while mixed results were shown in terms of GPP impact. These results support future developments required towards operational implementation (D4.2).

Advanced Scatterometer (ASCAT) backscatter data assimilation results showed to be highly relevant to analyse root zone soil moisture with potential for joint analysis of soil moisture and leaf area index in the IFS. These results are highly relevant to CO2MVS and NWP applications.

CORSO WP4 demonstrated that the co-assimilation of SIF and LAI in the ISBA model is beneficial for GPP representation, while co-assimilation of SIF and GPP benefits physics-based ORCHIDEE fluxes representation.

Passive microwave data assimilation results from ISBA highlight the importance of these observations to represent LAI.

Results from WP4 using physics-based land surface models such as ORCHIDEE and D&B showed that simulating realistic biomass pools and forest demography is key to estimates fluxes, which is in particular important for estimating fluxes related to LULUCF. The combination of multiple satellite observations (VOD, SIF, FAPAR, SMOS) and data assimilation scheme provides a powerful tool for assessing carbon fluxes and stocks. Taking a simpler approach to simulating above-ground biomass (AGB), as in ISBA, enables the sequential assimilation of AGB observations using a Kalman filtering approach. In Task 4.4, results showed that resolution matters for minimising biases in plume detection.

These results based on ecLand and land surface models of various degrees of complexity are important for CO2MVS to guide corresponding future developments of the ecLand system.

6.4.3 Ease of Tx to operations

ASCAT data assimilation developments conducted in the IFS have reached high TRL level at the end of the project with clear pathway towards operational implementation.

SIF data assimilation work demonstrated potential in the IFS which motivates further developments in operational like environments. This will require developments to interface observations in the IFS using a dedicated Observation DataBase.

AGB data assimilation in the IFS is currently not possible as the ecLand surface model does not represent carbon pools.

6.4.4 Barriers or future research needed

Data assimilation results in ecLand/IFS showed promising results to constrain GPP, LAI and soil moisture. However, the impact was limited by the fact that ecLand currently uses prescribed LAI. Results using models of diverse complexity showed that moving to a prognostic LAI representation in ecLand is key to fully exploit surface sensitive satellite observations in the CO2MVS.

Similarly, AGB data assimilation investigations require carbon pool representation which is not currently available in ecLand.

6.4.5 Gaps

CORSO has investigated the potential of ML observation operators to exploit land observations into a coupled water and carbon cycle land data assimilation system in the IFS

It is also needed to exploit surface observations in purely data-driven systems such as AI-DOP.

6.4.6 Further recommendations

D4.3 "Report on SIF data assimilation method and preliminary testing in the IFS"

D4.4 "Report on multivariate coupled land data assimilation impact on water and carbon cycle representation in the IFS"

D4.5 "Report providing recommendations for the ECLand and IFS evolution to constrain biomass and biospheric fluxes over forests, and the required IFS evolution in CO2MVS at city-scale based on the ICON-ART simulations"

6.5 Uptake by CAMS

As presented above, CORSO has significantly improved the various methodologies that could potentially be used by the CO2MVS within the CAMS programme. Some of the developments that were directly done within the ECMWFD IFS environment will logically flow into the global CO2MVS monitoring system. Other activities have already been adopted in CAMS Invitation To Tenders (ITTs), most notable the following:

- A directly negotiated contract to support ICOS ERIC, which includes the continuation of 14CO2 analyses every 3 days from ICOS flasks, for the next 2 years.
- An ITT[1] to implement a regional emission estimation benchmark system within Europe based on ICOS observations that can be used to evaluate the global CO2MVS system
- Continuation of the global point source catalogue developments as part of the ITT[2] on bottom-up emission estimates.

It is also expected that the CORSO activities in WP1 and WP2 will be used to guide new ITTs on hotspot emission monitoring for CO2, NOx, and CO.

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[1] https://atmosphere.copernicus.eu/cams284b-development-regional-benchmark-system-greenhouse-gas-observation-based-emissions

[2] https://atmosphere.copernicus.eu/cams261bis-global-and-european-emission-inventories

As shown in Figure 1 results from all CORSO work packages are expected to contribute to the implementation of the CO2MVS.

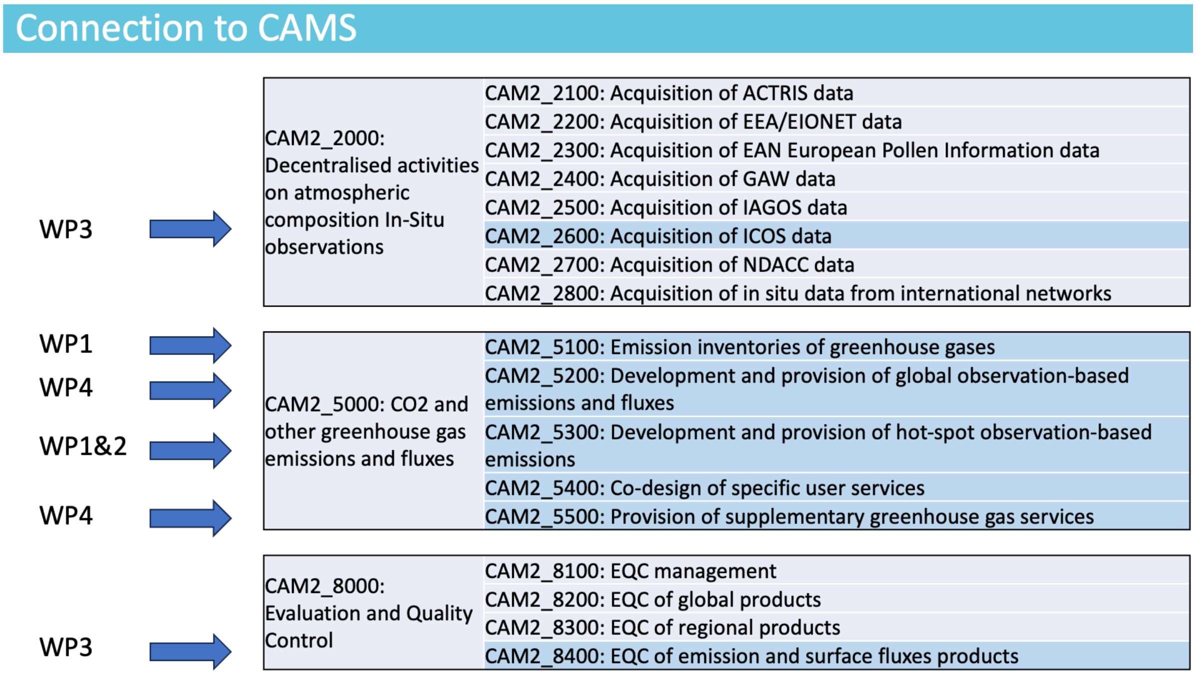

Figure 1 Expected contributions of CORSO activities to the CAMS CO2MVS service development.

7 Conclusion

This deliverable, D5.9 has provided an update of the dissemination and exploitation activities at the end of the project.

For the dissemination we have achieved our aims to disseminate via a set of identified instruments namely a website, news items, scientific conferences, workshops and committee/board meetings and scientific papers.

Exploitation updates were solicited from all partners and represents the status at the end of the project. The exploitable products have been listed along with their availability and access.

Finally, the project recommendations for the CO2MVS have been listed and the uptake of CORSO results in the ramp-up of the CO2MVS have been described.

Document History

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1.0	Tanya Warnaars	15/12/2025	Final version addressing comments

Internal Review History

Internal Reviewers	Date	Comments
Tanya Warnaars	11/12/2025	Minor formatting edits
Richard Engelen	12/12/2025	Various edits throughout the document.