CoCO2
Prototype system for a Copernicus CO_2 service

7.6 Gap analysis report of the current *in situ* measurement capacity

Sindu Raj Parampil

Co-ordinated by ECMWF

D7.6 Gap analysis report of the current *in situ* measurement capacity

Dissemination Level:	Public
Author(s):	Sindu Raj Parampil Ville Kasurinen Elena Saltikoff
Date:	30/06/2023
Version:	1
Contractual Delivery Date:	30/06/2023
Work Package/ Task:	WP7/ T7.3
Document Owner:	ICOS ERIC
Contributors:	DLR, ULUND, FMI, input from across the project
Status:	Final

CoCO2: Prototype system for a Copernicus CO_2 service

Coordination and Support Action (CSA)
H2020-IBA-SPACE-CHE2-2019 Copernicus evolution – Research activities in support of a European operational monitoring support capacity for fossil CO_2 emissions

Project Start Date: 01/01/2021
Project Duration: 36 months

Published by the CoCO2 Consortium

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

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

Table of Contents

Figures

Tables

1 Executive Summary

The gaps described in this report are reflecting the needs of modellers and model development based on previous CoCO2 deliverables D7.1, D7.2 and D7.4. When confronting the *in situ* data needs of the prototype Copernicus CO_2 service with the currently available measurements, a relatively small mismatch was observed. This discrepancy is assessed based of five parameters:

1) Georaphic coverage
2) Timeliness
3) Quality control
4) Access
5) Continuity

The main coverage gaps are found in the tropics, where satellite data are also sparse due to persistent cloudiness. Timeliness is connected to quality control, as manual quality assessment is the most common factor delaying data releases. For many data streams, the situation has been improving recently. Access remains an issue, especially for more research-oriented datasets. For continuity, the goal of 10 years time series can not be reached with campaign-based datasets, a problem often occurring in undersampled regions.

Entirely missing data streams, representing scales and variables that are currently not observed at all, were not identified. However, further development of monitoring and modelling systems might reveal new needs for data that is covered in this report - (pre-)operational systems tend to orient themselves to data streams that exist, or are expected to exist in the near future.

2 Introduction

2.1 Background

The prototype CO_2 Monitoring & Verification Support (MVS) capacity being developed within the CoCO2 project aims to extract information about anthropogenic greenhouse gas emissions from satellite measurements provided by the planned CO2M constellation. These satellites will provide imager-type column-integrated measurements of atmospheric CO_2, CH_4, and NO_2 at ~2 km x 2 km resolution with a swath ~250 km wide, enabling the imaging of emission plumes from point sources and hot spots associated with anthropogenic activities, and global coverage to constrain emissions and biogenic fluxes on national scales. While these satellites are being developed with this application in mind, such an integrated system will require extensive *in situ* and ancillary observations in order to achieve its proposed objectives.

WP7, “Observations”, is focusing on the in situ and ancillary observations, mapping what is needed, what is available, what could be added, and how it should be made available.

In the proposed structure of CoCO2, WP7 oversees surface and airborne observations and the auxiliary observations. During the project work it has become logical also to discuss some aspects which go to the box “priors” namely the CO_2 fluxes from ecosystem and oceans.

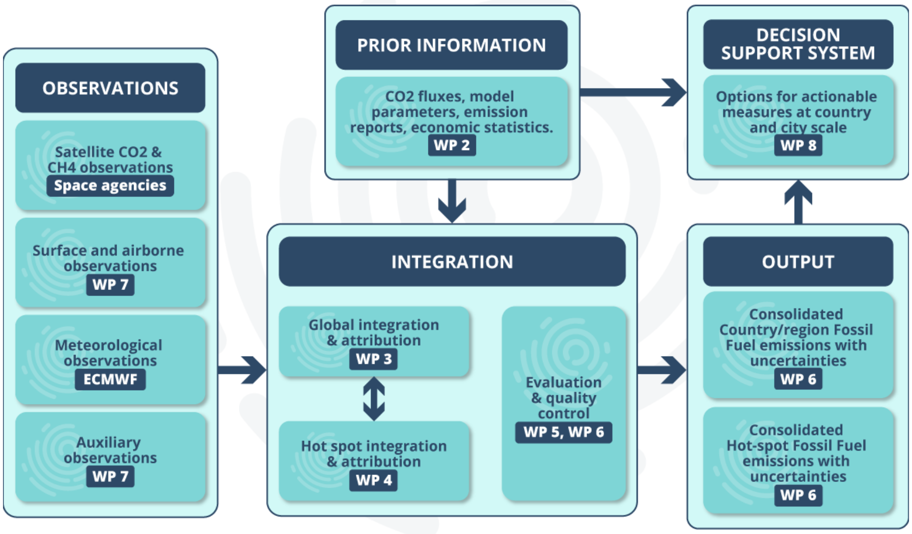

Figure 1. Structure of CoCO2

2.2 Scope of this deliverable

2.2.1 Objectives of this deliverable

This deliverable aims at confronting the data needs documented in Task 7.1 with the currently available data streams documented in Task 7.2. This discrepancy is assessed on the basis of five parameters: measurement coverage (or geographical extent), factors related to timeliness and/or quality control of the data, accessibility to or openness of the data in terms of its use in an operational context and lastly, the continuity of the data. The last parameter is often important in the case of satellite data or when the measurements are funded by short-term projects with a duration of only a few years.

These gaps are documented for each data stream for which they occur, following the structure laid out in the deliverables D7.1, D7.2 and D7.4. For each data stream, only those parameters where gaps are identified are discussed. Thus, parameters for which no gaps are identified are not discussed.

Recommendations for improvement concerning organisational, administrative, and financial aspects are included in the Conclusions, and identified gaps in the current methodology and/or technology are discussed in Chapter 5.

The documentation of these gaps will also feed into Task 7.5, providing guidance on the work to be carried out there. This will link directly to the design studies in Task 5.5, which will be documented in D5.5.

2.2.2 Work performed in this deliverable

The basis of the data collection was the survey and interviews organized together with Task 7.1, complemented with deeper discussions and literature reviews.

In the first year of the project, information was collected via an online survey. To make the data collection more efficient, and reduce the uncertainty of the respondents, we decided to carry out interviews in the second year of the project, separated by work package. The information collected and the categories considered were essentially the same, but collecting the information from several participants in parallel led to informative discussions. (A detailed description of the survey design and testing is included in Deliverable 7.1., and the interviews in Deliverable 7.2)

In order to get a deeper understanding and to verify initial observations, several other experts were interviewed and recent literature was reviewed. We want to mention discussions with Guillaume Monteil and Marko Scholze (ULUND), Ute Karstens (ICOS CP at ULUND), Arjo

Segers (TNO), Anna Agusti-Panareda (ECMWF), Simone Kotthaus (IPSL), Niku Kivekäs (FMI / ACTRIS) Ewan O'Connor (FMI) and Minna Huuskonen (FMI).

2.2.3 Deviations and counter measures

A risk of overlap with the content of D7.5 has been observed, and we suggest that a new version of this deliverable should be submitted together with D7.5 in September.

3 In situ data needs

3.1 Eddy covariance flux data

3.1.1 Geographical extent

Continuous Eddy covariance measurements in different type of ecosystem have become the most common methodology to derive annual carbon balance estimates (NEE, GPP and RECO). Global data collections like FLUXNET (Pastorello et al, 2015) or regional collections like ICOS Drought 2018, Warm winter 2020 and COVID-19 lockdown (Nicolini et al. 2022) releases compile and harmonize measurements from several stations into one data collection that can be then distributed to researchers and data users. Despite developments following the first workshop held in 1995 in La Thuile the latest global FLUXNET release is from the year 2015. Eddy covariance data from several locations around the world can be found from regional measurement networks, as described below.

In the survey, the need for more data from the Tropics and the Iberian Peninsula was expressed.

The following specific geographical areas are targeted by the measurement networks listed below:

Global: FLUXNET 2015 contains more than 2000 site years of data from over 200 sites (North and South America, Asia, Europe and Australia

Europe:

- ICOS
- European Eddy Fluxes Database Cluster (contains past EU-funded research projects) Europe, Africa, Russia, Greenland and North and South America

Americas (North, Central & South):

- AmeriFlux; 562 PI-managed sites measuring CO_2, water & energy fluxes
- US: NEON 47 EC flux data (CO_2, latent & sensible heat, NEE, terrestrial sites + 34 fresh water sites

Australian & New Zealand: OZ Flux (Program) & TERN (Network of sites)

Asia:

- AsiaFlux (Japan, China, Korea, Malaysia, Thailand, Taiwan, India)
- ChinaFlux (China)

Arctic: Arctic Eddy Covariance

Some of the bigbigbiggestbig geographical gaps are in Africa and the Tropics in general. However, we want to point out that ICOS has 2 ecosystem stations in the Tropics, in the Democratic Republic of the Congo (station CD-Ygb) and in French Guyana. (station GF-Guy).. The data from these locations are ICOS data and therefore, consistent with the FAIR (Findable, Accessible, Interoperable and Reusable) data use policy.

3.1.2 Timeliness.

In the survey made for D7.2, change from annual releases towards near real time data was mentioned. At the time of writing this deliverable, the FLUXCOM team has started to use the NRT data from Europe via ICOS.

The latest release of FLUXNET global dataset is from 2015. Access to more recent data is depending on personal contacts. Australian and US programmes are expected to be moving to annual data releases soon, and ICOS has been exploring data releases three times a year, rather than the current annual data releases. In Europe, datasets of “Drought 2018” and “Warm winter 2020” have been published by ICOS and are widely used. However, ICOS measurements lack global coverage. The next FLUXNET release is currently in preparation, and the community has a general meeting in July 2023.

3.1.3 Access

The majority of FLUXNET data are provided with a CC-BY-4.0 license, which specifies that the data user is free to Share (copy and redistribute the material in any medium or format) and/or Adapt (remix, transform, and build upon the material) for any purpose. Data use should follow attribution guidelines for CC-BY-4.0

Six additional sites are classified as Tier 2 data (RU-Sam, RU-SkP, RU-Tks, RU-Vrk, SE-St1, ZA-Kru), and are available only for scientific and educational purposes. Under this policy, data producers must have opportunities to collaborate and consult with data users. Substantive contributions from data producers result in co-authorship.

Many regional networks like ICOS, AmeriFlux, NEON, OZ Flux & TERN follow the FAIR data policy.

Other regional networks do not have FAIR data policy. For example:

- AsiaFlux (Japan, China, Korea, Malaysia, Thailand, Taiwan, India): Data are available from AsiaFlux DB on request
- ChinaFlux Data may be available on request (unconfirmed)

3.1.4 Quality Control

FLUXNET Data Processing – FLUXNET Unified, standardized data quality control and gap-filling methodologies are typically applied for global data collections (FLUXNET) as well as some geographically specific networks like ICOS in Europe or NEON in the United States. These quality-control procedures are described briefly below. Outside of these networks, there are several hundred measurement sites around the world, including both continuous and campaign-type measurements, for which the data are post-processed and quality-controlled based on decisions made by the site PI. This lack of standardization can be challenging for data users: Before product generation starts, data for each site goes through quality assurance / quality control (QA/QC) steps tailored to the generation of these derived data products (e.g., gap-filling or uncertainty estimation). A few of these QA/QC steps are described in *Pastorello et al. 2014 (eScience)*. Quality checks are done over single variables (e.g., overall trends at multiple temporal resolutions), multiple/combined variables (e.g., variables that should vary comparably), or can include more specialized tests (e.g., comparing measured radiation to the maximum, top of the atmosphere radiation expected for a given location).

ICOS: Data are obtained from ICOS-recommended sensors at validated ICOS stations. The measurements are standardised due to protocols mutually agreed upon. The protocols have been published in *International Agrophysics (Franz et al, 2018).* Before stations are included in the ICOS Ecosystem station network they go through a labelling process, where the Ecosystem Thematic Center (ETC) evaluates the quality of the stations. The ETC performs centralised data processing and quality control and provides technical assistance to the stations. ICOS data are available in Levels 0, 1, 2 and 3, where the numbers describe increasing level of processing from raw data (0), to automatic QC (1), manual QC (2) and data fusion (3).

For ecosystem data, the non-continuous information, including general station description, metadata about the sensors and set up, maintenance and disturbance events, biological and ecological data that characterize the ecosystem etc., are submitted using the Biological, Ancillary, Disturbance and Metadata (BADM) system. The BADM protocol is standardized across the FLUXNET networks, in particular, between the AmeriFlux and European Networks. In the context of ICOS, specific variables designed for the characteristics of the ICOS data (raw data processing, standardized protocols, instructions etc.) have been created following the same BADM structure and logic. All the ICOS-BADM variables are fully compatible with the standard BADM.

NEON: QA/QC methods are applied throughout the entire life cycle of the data. Quality assurance methods check data quality early on, during collection and before they are ingested into the data system. Quality control methods are inserted at several points along the processing and publication chains.

3.1.5 Continuity

The last official data release of the global FLUXNET dataset was FLUXNET2015. The next FLUXNET data release will happen shortly but there no official release date yet. Regular, operationalized data releases are not foreseen yet.

Two unique long-term datasets with homogeneous historic CO_2 flux and concentration data are available in ICOS Carbon ortal. For the ecosystem data, these have been compiled from 52 stations ICOS & non-ICOS stations. The ecosystem CO_2 flux data goes back to 1995 from some stations and was the effort of Drought-2018 analysis team and ICOS Ecosystem Thematic Centre. The data is named Drought-2018 ecosystem eddy covariance flux product.

3.2 In situ CO_2 measurements

3.2.1 Geographical coverage

In the survey, the need for more data in the Tropics and in Iberian Peninsula was mentioned.

In additional interviews, one researcher raised the question of small-scale topographical effects. Especially, stations in a complex topographic environment (in a valley or on a slope) can be difficult to simulate by transport models which use topographic information at a much coarser resolution. Stations in a flat plain or mountain tops are therefore preferred. The position of influences can be represented by a transport model

An overview of the geographical coverage of stations measuring CO_2 is available from the WMO OSCAR database, which includes metadata for stations measuring a given parameter. The number of stations listed there has increased since Deliverable 7.4. was written, but is still not considered to be an exhaustive list of all existing stations around the world.

The development of OSCAR started from defining quantitative user-defined requirements for observation of physical variables in application areas of WMO (i.e. related to weather, water and climate). OSCAR also provides detailed information on all earth observation satellites and instruments, and expert analyses of space-based capabilities.

If the upcoming WMO Global Greenhouse Gases initiative wants to use OSCAR, the following challenges are foreseen:

- Motivating national meteorological Services to update and complete it, as many of the GHG stations are not operated by the same organizations as the weather, water, and climate observations. For example, in France, Meteo-France is the contact to OSCAR, but 13 different organizations operate the ICOS stations[1]. (*see comment below)

- Motivating modellers to use it, and interact with it regularly. Most weather prediction models take the station metadata from a lookup table, which has been written in early phases of model development. Even if more stations are added to OSCAR, or critical metadata such as station location is changed in OSCAR, the change is not always reflected in the model.
- Clearly defining what a "station" is (e.g., should stations equipped with low-cost sensors with poorer accuracy and/or precision be included)

Table 1. In situ CO_2 observations according to OSCAR

Area	Africa	Antarctica	Asia	Europe	North + Central America, Caribbean	South America	SW Pacific	total
Feb 2022	13	9	27	64	45	7	18	186
May 2023	13	10	35	75	68	8	18	227

As a response to observed gaps of coverage, especially in the Tropics, the implementation of low-cost sensor networks has been suggested.

Research-quality GHG sensors have costs on order of 50 000 - 100 000 euros. This has raised interest in low-cost GHG sensors (<1 k€) e.g., based on non-dispersive infrared (NDIR) and open path technology. Müller et al (2019) integrated and evaluated more than 300 low-cost sensors in Switzerland. Their accuracy during 19 to 25 months deployment was between 8 to 12 ppm. This level of accuracy was achieved careful sensor calibration prior to deployment, continuous monitoring of the sensors, efficient data filtering, and a procedure to correct drifts and jumps in the sensor signal during operation. They concluded that the sensors used are not suitable for the detection of small regional gradients and long-term trends. However, with careful data processing, the sensors can resolve CO_2 changes and differences with a magnitude larger than about 20 ppm. Thereby, they conclude that the sensor can resolve the site-specific CO_2 signal at most locations in Switzerland.

It should also be noted that, even though the sensor itself is a major investment, the infrastructure and running costs of a station often surpass the initial investment, especially in areas where electricity, data connections and the availability of skilled maintenance personnel are a challenge. Unfortunately, this applies to many areas where gaps in observation network have been identified.

[1] An interviewee from a national weather service mentioned that even though she knows they are, in principle, responsible of bringing the weather stations of other bodies (in her case, the national road authority) to OSCAR, they have not yet done that. This means that even for weather parameters such as temperature, there are many more observations available than the number of stations in OSCAR indicates.

During the first year of the ICOS Cities project (originally PAUL - Pilot Application in Urban Landscapes - Towards integrated city observatories for greenhouse gases, GA Nr 101037319) we have also learned that getting permissions for operating a new observation station in an urban area is a major effort, which can significantly slow down project work.

The CO2 measurements data are available from the data repository World Data Centre for Greenhouse Gases (WDCGG). WDCGG collects, archives and distributes data provided by contributors on greenhouse gases (such as CO_2, CH_4, CFCs, N_2O) and related gases (such as CO) in the atmosphere and elsewhere. Other data repositories containing measurements from specific (regional) networks are also available.

The geographical coverage of the largest data repositories is as follows:

Global: World Data Centre for Greenhouse Gases WDCGG (https://gaw.kishou.go.jp/)

Global: NOAA Obspack (https://gml.noaa.gov/ccgg/obspack/)

Europe: ICOS Carbon Portal (https://www.icos-cp.eu/data-products/atmosphere-release)

(Note that ICOS has also two atmosphere stations outside Europe: La Réunion and Canary Islands).

Figure 2.. Global distribution of sites measuring atmospheric CO_2 from the WDCGG

3.2.2 Timeliness

ICOS is providing CO_2 concentration data in two releases: The NRT time series files are growing daily with data from the past 24 hours. The annual releases (L2) include fully quality-controlled data.

NOAA's ObsPack is released approximately annually, and all datasets with more frequent updates are called "NRT". The biggest concerns modelers had with the use of these data are the limited coverage and temporal delays, although these delays (particularly with ObsPack) have decreased in recent years as the demand for timely data has increased. The sparsity of measurements in the Tropics is seen as a major limitation for global data coverage.

ICOS has now started to release ObsPack Europe, and aims to increase its frequency to monthly releases. The dataset is in ObsPack format, and consists of three time series: old pre-ICOS data, manually quality-controlled L2 data until the date of latest release and in the end, and near-real-time data which has been through automatic quality control only.

3.2.3 Access

Data released by ICOS and NOAA are released under a CC-BY-4.0 License. The uncalibrated raw data from ICOS stations is available from the PI upon request; this part of data policy will be discussed again for the next funding period of ICOS (after 2025).

The content of the WDCGG Data Archive is free and unrestricted. GAW data policy: "For Scientific purposes, access to these data is unlimited and provided without charge. By their use you accept that an offer of co-authorship will be made through personal contact with the data providers or owners whenever substantial use is made of their data. In all cases, an acknowledgement must be made to the data providers or owners and to the data centre when these data are used within a publication."

3.2.4 Quality control

In the survey and interviews, most modelers were using quality-controlled data, but there was also one user of raw data.

Quality control and timeliness are tightly connected. As for ICOS data and European ObsPack, the L2 data releases include a thorough manual quality control where the station PI and ICOS thematic centre work together to QC the data. The PI flags the data based on their knowledge of the sources of disturbances, such as people working near the sensor. This type of information cannot be easily achieved with purely automatic QC.

For the global ObsPack products, the process varies. Metadata describing each ObsPack data set include the location, sampling strategy, calibration and quality assurance history as well as contact of the data providers (Masarie et al, 2014).

.

3.2.5 Continuity

The longest widely available dataset, the ObsPack GlobalView Plus product, includes data for the period 1957-2021 where available. The European dataset, e.g., in ObsPack Europe, starts

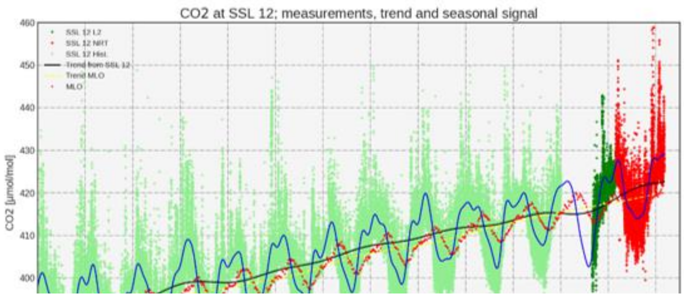

Figure 3. European Obspack compilation of atmospheric carbon dioxide data from ICOS and non-ICOS European stations for the period 2010-2023. Pre-ICOS data (light green), ICOS L2 releases (dark green) and NRT data (red).

from 1972. At the other end of the continuity spectrum, some modelers have expressed the usefulness of campaign-based datasets, especially for model evaluation

A unique long-term dataset with homogeneous historic atmospheric CO_2 concentration data was compiled from 48 stations, both those belonging to ICOSand non-ICOS stations. The atmosphere CO_2 flux data goes back to 1971 from some stations and was compiled by the Drought-2018 analysis team and ICOS Atmosphere Thematic Centre. The data are referred to as Drought-2018 atmospheric CO_2 mole fraction product and are available in the ICOS Carbon Portal (doi:10.18160/ERE9-9D85).

3.3 In situ CH_4 measurements

The users of methane data are a subset of CO_2 data, and data repositories are, by and large, the same as reported above in 3.2.

3.3.1 Geographical coverage

See comments in section 3.2 about completeness of the metadata below.

Table 2. Geographical distribution of stations measuring CH_4

according to WMO OSCAR database

	Africa	Antarctica	Asia	Europe	North + Central America, Caribbean	South America	SW Pacific	Sum
Feb 2022	11	10	21	61	49	6	18	177
May 2023	11	12	24	68	69	6	19	209

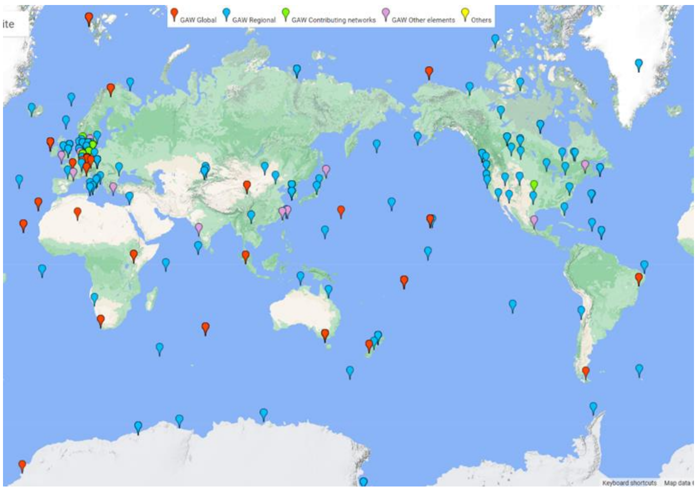

Figure 5. Global distribution of Methane from WDCGG

3.3.2 Timeliness

ObsPack and ICOS have releases of methane data, annually and in near real time. The ObsPack near-real time releases have been so far less frequent that those of CO_2.

3.3.3 Quality control

ICOS Near Real-Time (NRT, Level 1) data are generated using only completely automated quality control procedures. These NRT time series are generated within 24 hours after measurement and will not be updated later using improved information or become completed with missing data. The final completely quality-controlled and flagged (Level 2) data are released with a delay between 6-12 months, and include all corrections and maximum completion of missing data.

3.3.4 Continuity

NOAA began measurements of atmospheric CH_4 from discrete air samples collected in its existing Cooperative Global Air Sampling Network in 1983. Since 1998, $\delta^{13}C_{CH4}$ has been measured in a subset of the same air samples by the Institute of Arctic and Alpine Research (INSTAAR), at the University of Colorado. Currently, many laboratories around the world monitor atmospheric CH_4 abundance and a few measure $\delta^{13}C_{CH4}$. To help ensure the availability of comparable, high-quality observations for global CH_4 budget studies, these efforts are organized under the umbrella of the World Meteorological Organization (WMO) Global Atmosphere Watch (GAW) program, and data are reported to the World Data Center (WDCGG) for Greenhouse Gases hosted by the Japan Meteorological Agency.

Even with this structure in place, there are still 'ease of use' issues; not all laboratories report data in a timely fashion, they report data on different standard scales without providing conversion to the WMO GAW CH_4 mole fraction scale, uncertainties are not reported, etc. Isotopic data are further hindered by a lack of CH_4-in-air reference materials and different methods of tracing $\delta^{13}C_{CH4}$ (Lan et al, 2021)

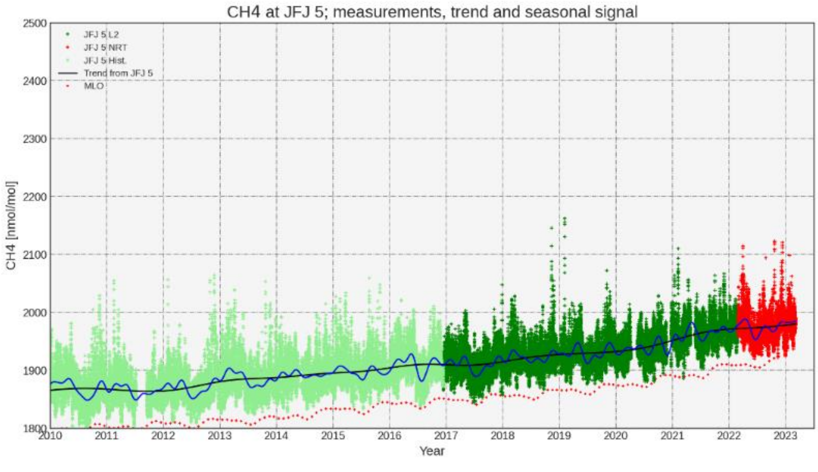

Figure 6. Obspack Europe for Methane data from ICOS and non-ICOS European stations for the period 2010-2023. Pre-ICOS data (light green), ICOS L2 releases (dark green) and NRT data (red).

3.4 In situ measurements of co-emitted species

Among co-emitted species NO_x is one of the most important gases, but is often missing in different places and for different purpoces (air quality in urban areas) than CO2. The focus in emission inventories and modelling is going from concentrations to sectors (like transport, residential heating, agriculture etc). The ratio of these species to that of CO_2 enables sector identification. As policy makers think in terms of sectors sector identification is very important.

Another important Co-emitted species is CO.

The CORSO project will focus on co-emitted species, yet, there is still the need to identify the sectors. Emission experts have stated the need for observations of co-emitted species co-located with CO_2 and CH_4; the measurements of these species need to be done very close in time and space. For e.g., ethane measurements together with methane measurements would be beneficial in calculating fossil fuel contributions. As the distance between the measurements increases, so do the uncertainties.

3.4.1 Geographical extent

In Europe, the gaps in data are mainly in regions like Bulgaria and Romania, to name a few. However globally the gaps are bigger: Africa and Southeast Asia are regions where no time series data exist, and trends based on *in situ* data are unavailable. Nevertheless, these are crucial regions as changes occur rapidly there. These are potential areas of interest and it is worth examining the changes that could take place there soon, for instance by 2040.

3.4.2 Timeliness & Quality Control

Often the data obtained from bookkeeping done by farmers or citizen scientist are of poor quality. It is therefore imperative that the paid agencies be given the responsibility to gather the data. This would invariably improve the quality of the data and thus be more useful.

3.4.3 Accessibility

Use of non-standard data, for example, from campaigns (mainly activity datasets) would be beneficial to have, but at least until the organizers of the campaign have published their results, the data often stays in their repositories.

3.5 Measurements from urban networks

In the survey, some modelers reported use of data from urban air quality networks. Concentration of CO_2, CO, NO_2, NO were used for emission inventories and plume modelling.

Interest of urban fluxes was indicated, but data had not been accessed yet. For the urban fluxes WP3 has a deliverable due in September in WP3 to describe the modelling of anthropogenic emissions in the IFS, including the urban residential heating degree day model. A manuscript of a paper is in the planning phase, using the EC data from Crete to do the evaluation of the residential emission fluxes in the IFS.

Urban areas and landscapes account for a small but growing fraction of terrestrial land area. Globally or even locally, urban landscapes are not well monitored using eddy covariance-based techniques. The AmeriFlux Urban Fluxes committee white paper (Biraud et al, 2021) describes well the challenges related to urban measurements. These are also discussed in Chapter 5 of this deliverable.

Urban areas are typically hot spots of CO_2 emissions due to high population density and industrial activities including industrial production of goods, traffic, energy production and other human activities. Urban or city scale emissions can be estimated based on emission inventories following for example the GPC guidelines. Inventories are based on locally derived estimates from six main sectors: stationary energy, transportation, waste, industrial processes, agriculture, forestry and other land use and any other emissions occurring outside the geographic boundary as a result of city activities. Emission inventories are typically bottom-up tool used to estimate emissions in city scale.

Urban eddy covariance measurements would be helpful in order to understand the influence of natural or managed ecosystems on urban scale CO_2 dynamics. For example, Nordbo et al. (2012) showed that the fraction of natural area can be used as a main predictor of net emissions from cities. Such top-down estimates and measurement data would increase our current understanding of urban and city scale carbon emission and sink dynamics. Urban measurements can also locally be used together with models to determine if local emission reduction activities are effective or not. Urban areas are important also for CO_2 monitoring and verification activities.

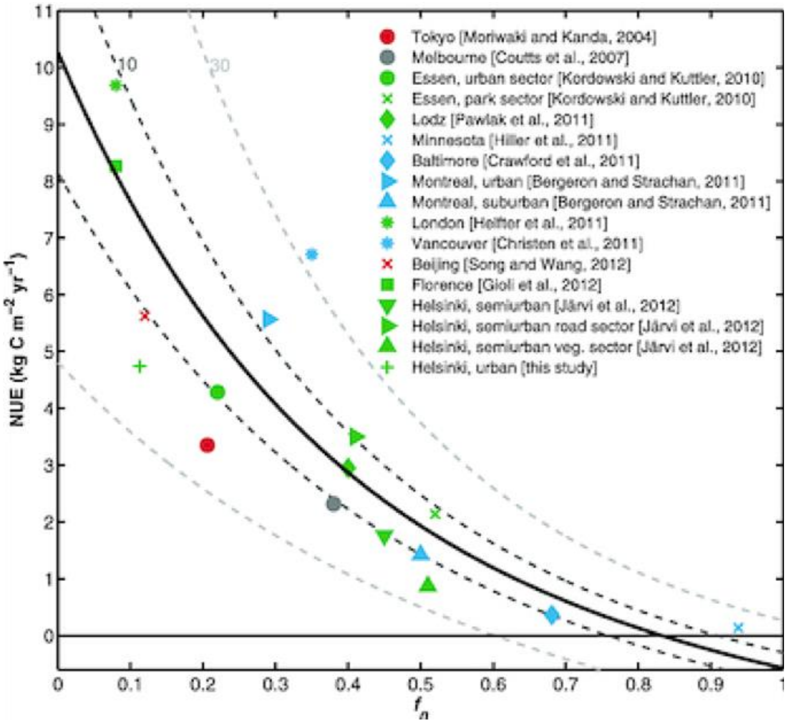

Figure 7. Fraction of natural area as main predictor of net CO_2 emissions

from cities (Nordbo et al., 2012)

As part of CoCO2 WP7, measurements in urban areas have been performed in Krakow Poland and Heraklion Greece. Results will be reported in deliverables D7.9 "Dataset of atmospheric observations from Krakow, Poland" (09/2023) and D7.10 "New measurement and modelling methodologies for high resolution monitoring of urban anthropogenic and biogenic CO_2 fluxes" (09/2023). First results, shown in figure 7 show that the fluxes in high emission busy urban zone and in low emission zone (park) differ significantly, and that a station in a seemingly urban environment can still experience conditions more typical for rural environment depending on the prevailing wind direction.

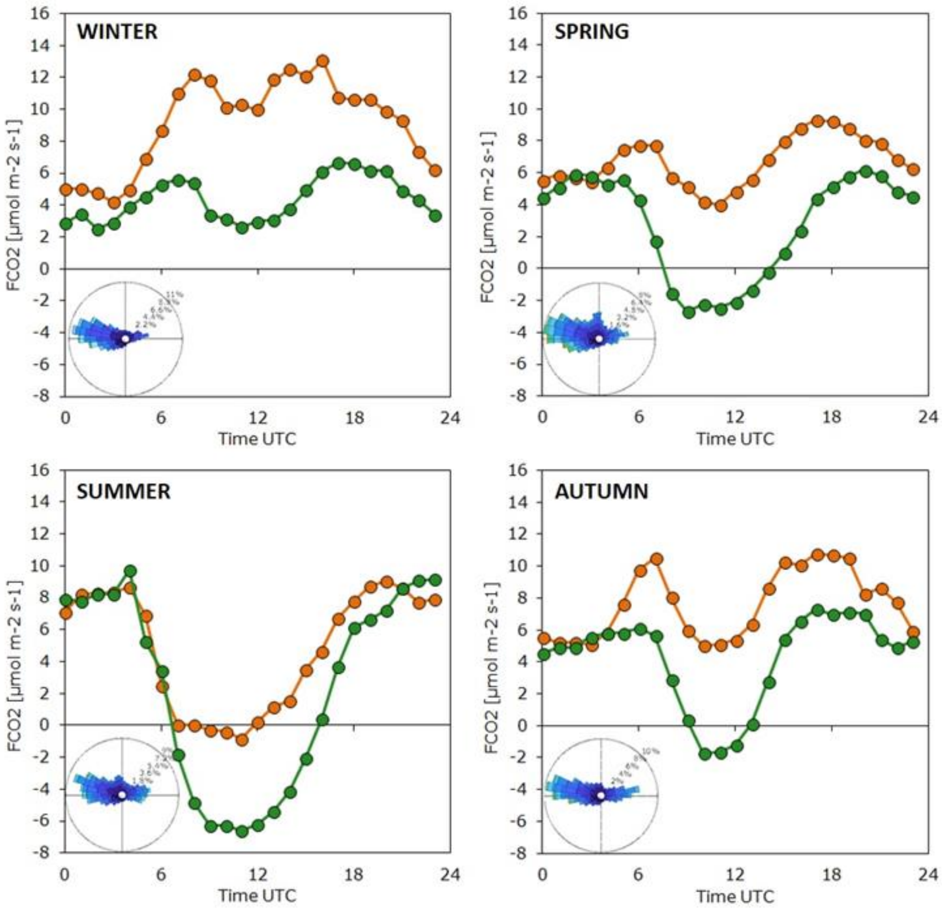

Figure 8. Measurements from an urban station in Krakow: Diurnal changes of net CO_2 flux measured in high emission zone (orange dots) and low emission zone (green dots) in different seasons. Insets are seasonal windroses.

3.6 Ocean fluxes/partial pressures

Interest was expressed in an exploratory manner. Results of first nature run (Agusti-Panareda 2022) show their significance as source of uncertainty. The reason being that there are gaps in several levels: in the geographical extent of the data, in knowledge and in the timeliness of the data.

Global data:

1 The Surface Ocean CO_2 Atlas (SOCAT) is a global surface fCO_2 data set, in a common format, all publicly available for the surface oceans. The fugacity of carbon dioxide, or fCO_2, is the partial pressure of CO_2 (pCO_2) corrected for non-ideal behaviour of the gas. SOCAT data serves a wide range of user communities. Two distinct data products are available:

- 2nd level quality controlled global surface ocean fCO_2 data set,

- Gridded SOCAT product of monthly surface water fCO_2 i.e., on a 1° x 1° grid with no temporal or spatial interpolation.

2 Global Surface pCO_2 (LDEO) Database V2019: Global Ocean Surface Water Partial Pressure of CO_2 Database: Measurements Performed During 1957-2019. This is another dataset of ocean surface CO_2 (Takahashi et al., 2017)

It is important to note that most data in the LDEO, especially from the North Atlantic Ocean and European seas, is available in SOCAT.

3.6.1 Geographical extent

Despite being a global dataset, SOCAT has many regions where there is no data (see Figure 8). Coastal regions are generally under sampled regions of uncertainty, arising from their dynamic nature, for which more measurements are needed. Also, in the last years SOCAT has seen a shift from open ocean measurements towards more coastal ones. But that leaves large gaps in the open ocean as the total number of measurements is not increasing

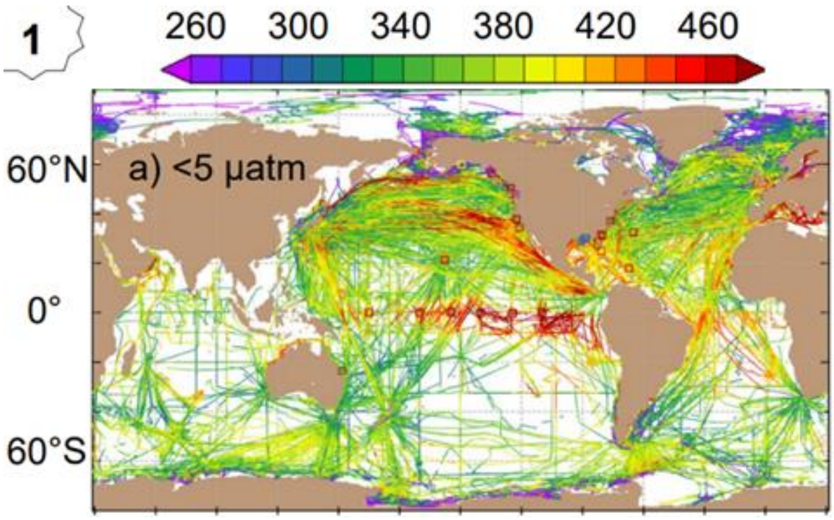

Figure 9. *In situ* surface ocean fCO_2 values (µatm) with an estimated accuracy of >5 µatm in SOCAT version 2022. The main synthesis and gridded products contain values shown here. The fCO_2 values with accuracy 5-10 µatm are available separately.

For ocean fluxes, these fCO_2 observations are interpolated in space and time using different interpolation schemes (e.g., Rödenbeck et al., 2013, Landschützer et al., 2020). From these fCO_2 fields the fluxes are calculated using global wind fields, atmospheric xCO_2 and a parameterization for the gas transfer velocity.

Insufficient sampling has given rise to strong biases in the trend of the ocean carbon sink in the pCO_2 products. According to a recent paper by Hauck et al (2023) the estimates of the ocean CO_2 uptake are improved from a sampling scheme that mimics present-day sampling to an ideal sampling scheme with 1000 evenly distributed sites. The overestimation of the CO_2 flux trend by 20–35% globally and 50–130% in the Southern Ocean with the present-day sampling is reduced to less than 15% with the ideal sampling scheme. A substantial overestimation of the decadal variability of the Southern Ocean carbon sink occurs in one product and appears related to a skewed data distribution in pCO_2 space. With the ideal sampling, the bias in the mean CO_2 flux is reduced from 9–12% to 2–9% globally and from 14–26% to 5–17% in the Southern Ocean. On top of that, discrepancies of about 0.4 PgC yr−1 (15%) persist due to uncertainties in the gas-exchange calculation.

3.6.2 Timeliness

SOCAT data are released once annually, in June after quality control. Its release is connected intricately to the 'value chain' from measurements to mapped data products to modelling forecasting and ultimately, to scientific assessments and synthesis reporting. SOCAT data are used by the models of the Global Carbon Project to produce the annual Global Carbon Budget.

Closely connected to, but not part of, SOCAT is the NOAA atmosphere CO_2 fluxes, where the SOCAT fCO2 data and NOAA atmospheric pCO_2 are used for estimating CO_2 fluxes. Understandably, these flux data are released after the SOCAT release. https://gml.noaa.gov/ccgg/mbl/index.html

The LDEO partial pressure of CO_2 (pCO_2) is a static dataset available from 1957 to 2019. It is no longer updated.

3.6.3 Access

Both the SOCAT and LDEO 2019 datasets are public access

3.6.4 Continuity

SOCAT fCO2 data are updated annually and are released in June**.** Most data in the LDEO from the North Atlantic and European seas is available in SOCAT. However, there is fCO_2 from other regions of the world which are in the LDEO dataset, but are not in SOCAT. Therefore, despite being static, parts of the LDEO data, which are not in SOCAT, can be used for parameter estimation, a need expressed by a survey respondent (from Task 4.4)

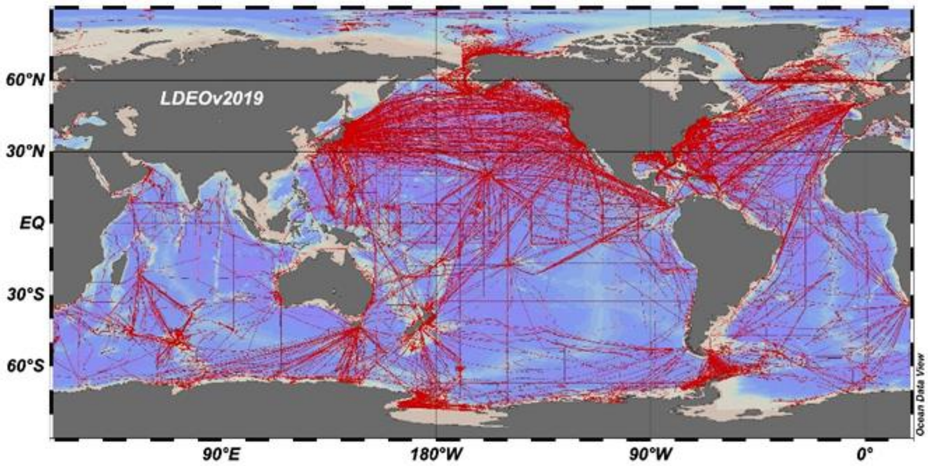

Figure 10. Geographical extent of the LDEO Version 2019 CO_2 data

Gaps in knowledge:

Besides the observation-based flux products described above, also forced ocean biogeochemistry models are used to estimate global carbon fluxes (Friedlingstein et al 2022). In the ongoing RECCAP2 project, the outgassing river carbon was identified as one major uncertainty when comparing observations-based flux products and modelled estimates (e.g. Perez et al, under review). Most models do not, or do not completely, account for this outgassing. There is a large river carbon flux (via outgassing) to the ocean. The values can be quite large for the North Atlantic (0.27 PgC/yr compared to annual fluxes of 0.37-0.47 pgC/yr (Perez et al, under review)). Thus, omitting or not accounting for this entire process in the nature run models for the CoCO2 prototype can lead to large uncertainties.

Studies have also reported large seasonal differences between the modelled and observed CO_2 flux or pCO_2, mainly in the sub-polar region (Rodgers et al, under review). For example, the subpolar North Atlantic is a large source of CO_2 in the winter i.e., the ocean is outgassing or releasing CO_2 to the atmosphere. This is not captured by many global biogeochemistry models. It is therefore, important that global climate models are able to model a realistic seasonal cycle for ocean CO_2.

3.7 Radiocarbon

Radiocarbon is measured at all ICOS Class1 stations as integrated 14-day samples. According to modeler's experiences, in areas of low anthropogenic/biological CO_2 ratios such as Scandinavia, the integrated data are of lesser value, as they often represent emissions transported for long distances. Hence radiocarbon measurements from both time scales: integrated and instantaneous, are needed. The project CORSO (CO2MVS Research on Supplementary Observations, Grant agreement ID: 101082194 until 31 December 2025) is temporarily increasing the sampling rate by a factor of 5 at ICOS stations.

3.7.1 Geographical extent

Long time series for background information from across the globe are available as listed in D7.4. There are 15 stations in China as per Zhou et al (2020); the accessibility of the data is unknown and may be available on request.

3.7.2 Timeliness

ICOS Class 1 stations continue to provide the radiocarbon data as per FAIR principles and they are available from the ICOS Carbon Portal.

3.7.3 Accessibility

The data from 15-station network in China may be available upon request to the Principal Investigator and author of Zhou et al. (2020).

3.8 Atmospheric mixing ratios of other species

Modelers mentioned use of radon and carbonyl sulphide, but the latter was not aiming for operational use at least in scope of CoCO2. As these tracers can be used to evaluate/benchmark atmospheric inversion systems / atm transport models, timeliness is less relevant.

Timeliness and access of radon data has improved recently, as NRT radon data timeseries are now available from 6 ICOS stations in France, the Netherlands, Switzerland, and the UK via the ICOS Carbon Portal. The radon data still need full QA/QC and proper calibration, which was started in the EMPIR project 19ENV01 traceRadon. Limited coverage of these measurements remains the most serious limitation to their use.

3.9 Ground-based remote sensing (e.g., TCCON)

Two types of measurements are discussed in this category: Total-column measurements (TCCON, EM27) and profiles of GHG concentration (aircraft, AirCore). Boundary layer height, which is also collected with ground-based remote sensing such as LIDAR, is discussed under "other meteorological variables".

3.9.1 Geographical coverage

Survey respondents have reported limited coverage as a significant limitation in the use of total column data. Most of them used TCCON data, some of them COCCON (EM27) data. Raising the access and technical readiness of the EM27 may improve the coverage of total column data.

Ongoing and proposed activities within ICOS community may improve the accessibility and timeliness of the data.

The optimal cal/val for GHG satellite is provided by ground-based Fourier Transform (FTIR) Spectrometers, which also measure total column concentrations of GHG but are more accurate as they are not affected by the back-scattered solar radiation and are regularly calibrated. The standard FTIR network for spaceborne GHG measurements is currently Total Carbon Column Observing Network (TCCON). This network of approximately 20 stations covers mostly the mid-latitudes of the northern hemisphere. The recent development of lower resolution and transportable FTIR, so called EM27/SUN, complements the current TCCON network at the cost of slightly lower precision, but with the benefit of increasing the measurement density.

These instruments exist and are used, but the data management is heterogeneous. Data retrieval of EM27/SUN raw spectra is currently performed via existing open access bricks of software developed and maintained by the Karlsruhe Institute of Technology in Germany.

Regular profiles on board civil aircraft at some airports are provided through the Japanese CONTRAIL programme, and have been recently added to the suite of IAGOS measurements as well. Plans are underway to expand such sampling to regional airlines in the United States. Of course, these measurements provide coverage only in the vicinity of airports at which participating airlines operate.”

The National Oceanic and Atmospheric Administration (NOAA)/Earth System Research Laboratory’s (ESRL’s) airborne flask network contains now 14 active sites in North America. Their sites on other continents have been discontinued.

3.9.2 Timeliness

Temporal delays were the other significant limitation in use of this data. As such, it is used for model evaluation only. TCCON data in netCDF format are publicly available no later than one year after the spectra are recorded; many sites release their data earlier. Network-wide data releases have been published 2009, 2012, 2014 and 2020.

3.9.3 Access

TCCON has its own data licence policy. The license grants you a perpetual, royalty-free, non-exclusive, and non-assignable license to use the Data subject to the terms and restrictions set forth herein. Individual datasets or parts of individual datasets might be licensed under a less restrictive license. If datasets with different licenses are used, the more restrictive license applies. All Data are assigned a digital object identifier (DOI). Use of these data to support a published work must include a citation that includes the Data DOI.

Those who use E27 have received data directly from PIs. This is a gap in its potential use in an operational setting.

Profiles from AirCore and airplane measurements are very useful for model development and model validation exercises. However, in many areas the data are mainly campaign-based and access to it relies on personal contacts. The expanding network of profiles on board civil aircraft should help address this.

3.9.4 Quality control

Individual TCCON sites are responsible for processing their collected interferograms in a standardized procedure to ensure consistency across the network. Standard processing should use the current release versions of the relevant software packages and requires:

- transformation of interferograms to spectra using defined software, which computes spectra using standardized phase correction, Fourier transformation and DC correction algorithms, and writes OPUS-format spectra and

- fitting of spectra using a suite of tools created by JPL to retrieve total column amounts and derived output data. The results are delivered in a *.eof.csv file is which specifies the site, date, and current version of the software is indicated in a standardized manner.

3.9.5 Continuity

The first TCCON instrument was installed in 2004 in Park Falls, WI; USA. By 2014, the network consisted of 23 instruments. (Wunch et al, 2015)

Light weight and relatively low cost of EM27 has made it popular for campaigns and projects.

AirCore has been patented in 2006, and it is used in campaigns.

The National Oceanic and Atmospheric Administration (NOAA)/Earth System Research Laboratory's (ESRL's) airborne flask network has been used for regularly sampled vertical profiles. The NOAA/ESRL/GML CCGG cooperative air sampling network effort began in 1967.

Many aircraft measurements have been part of various intensive campaigns on a continental or regional scale as well. Karion et al. (2010) provides a list of these from years 2002-2010. Regular greenhouse gas sampling from commercial aircraft has provided another valuable dataset (Machida et al, 2008).

3.10 Site-level ecosystem parameters

Site-level ecosystem parameters and activity data are variables such as harvest, Leaf Area Index (LAI) and Fraction of absorbed Photosynthetically Available Radiation (FAPAR): lack of comparable, widespread data is the primary reason why such measurements are not currently being incorporated into upscaling approaches. Nevertheless, modelers agree that input data like LAI, FAPAR and SIF are important variables for priors in inverse modelling.

Direct estimation of site-level parameters like LAI can be invasive and labour and time-intensive. However, in the past, EU projects like RINGO (Readiness of ICOS for necessities of Global Integrated Observations, Horizon Europe, GA no 730944) have been successfully measured and documented these parameters from several ICOS forest stations. The parameter, using Terrestrial Laser Scanning (TLS), which produces extremely accurate 3D images of sites which are then fed into models which estimated was above-ground biomass (AGB). More about the work is reported in Demol et al, 2022.

3.11 Site-level management and lateral fluxes

In the survey, no modeler reported they were using thisthisthesethis data, but they still mentioned it is an important parameter. We are aware of such data used on station level research projects, outside of CoCO2, e.g., Korkiakoski et. al studied effects of partial cutting of a boreal forest at ICOS station Lettosuo (Korkiakoski 2023) so we can forecast that there will be needs in parameter development. In a wider scale, much of what is said about activity data applies here: many datasets are project-based or pro bono, thus in heterogenous formats, difficult to find, access and reuse, and as such do not conform to FAIR principles.

3.12 In situ soil moisture

It has been mentioned that it would be useful to look at soil moisture measurements when using radon to assess transport models. Soil moisture data are collected widely for use in forest fire prevention, but those data are concentrating on the surface layer of forest, while the radon modelers would prefer information from deeper layers.

Also the international Soil Moisture Network concentrates in soil moisture in the uppermost soil layer for validation of satellite retrievals. Soil moisture measurements are conducted at ICOS ecosystem stations at several depths but only available with sufficient metadata (e.g. measurement depth) as soon as they are labelled. Historic time series in the ICOS Drought 2018 and Warm winter 2020 releases are without metadata for soil moisture.

3.13 In situ meteorological measurements

One of the modelers mentioned that boundary layer height (BLH) would be nice for verification purposes. Ideally, the BLH should be co-located, but information from some distance would also be useful.

The oldest method for determination of BLH is radio sounding. The network consists 1300 instruments worldwide and the typical temporal sampling of twice a day, which is too low for model verification purposes. Remote sensing technology, including wind profile radars based on microwaves or longer wavelengths and lidar Barlow et al. (2011) are, widely used for measuring BLH (Wang et al, 2016). Kotthaus et al (2023) have provided a good overview, which is summarized in table 3 below and figure 8.

Now, the most advanced tool for automatic boundary level height detection is based on aerosol backscatter profiles observed with automatic lidars and ceilometers (ALC) which is already close to operational implementation. A tool for height detection from Doppler lidar turbulence observations is at earlier stages of implementation.

The EUMETNET E-PROFILE network collects automatic aerosol lidar data from > 400 stations in Europe. ACTRIS cloud remote sensing sites (39 sites, 5 more planned 2024-2025) should all have a Doppler lidar, microwave radiometer and an ALC. Also, ICOS is aiming to operate automatic aerosol lidars (ALC) at more and more stations.

Table 3. Profiling instruments suitable for BLH observations

Abbreviation	Instrument	Amount	Note
RS	Radiosonde	985	Non-continuous measurement
MWR	Microwave radar	100 in MWRnet,	Probably not up-to date number. 46 in Europe
RWP	Radar wind profiler	223	
ALC	Automatic lidars and ceilometers	400 in real time and increasing	ACTRIS, ICOS, E-PROFILE and many others
DWL	Doppler wind lidar	ARM has 15	used for meteorology, aerosols (ACTRIS) and wind energy applications

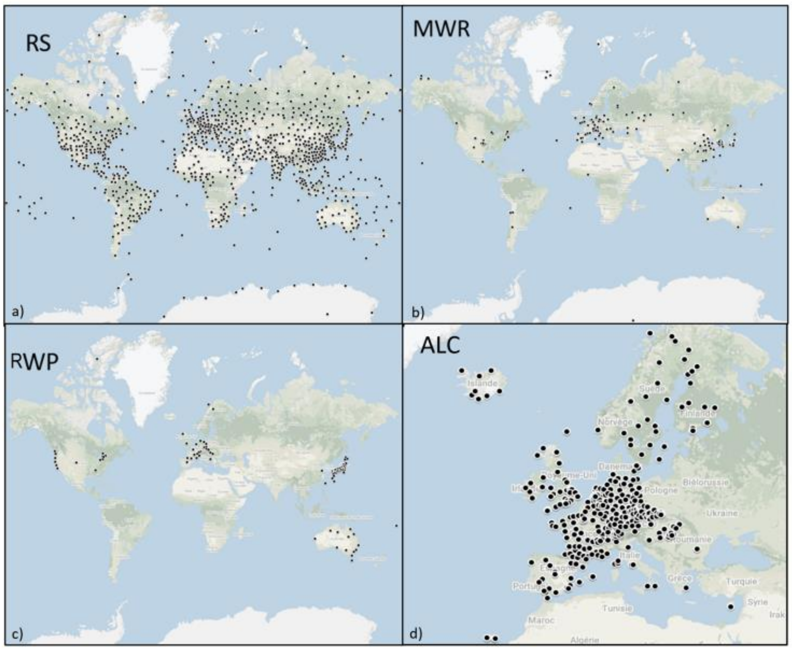

Figure 11. Operational networks of selected stations providing information about boundary layer height: radio sounding (RS), microwave radar (MWR) radar wind profilers (RWP) and automatic lidars and ceilometers (ALC). (Kotthaus et al, 2023)

4 Ancillary/Auxiliary data needs

4.1 Meteorological model fields

In this report we concentrate mainly on the gaps in the current in situ measurements, so will not be discussing concentration fields from models.

4.2 Nightlights

4.2.1 Timeliness

A respondent from Task 3.2 reported in the survey that they use data from other years for parameter estimation. The datasets identified in the CoCO2 Deliverable “Report on data providers and long-term data availability” (D7.4 V1): VIIRS DNB available from 2012-2020 and DMSP-OLS from 1992-2013 can be used for the purpose of parameter estimation.

4.2.2 Accessibility

The static datasets listed above are accessible via Google Earth Engine software but they do not follow FAIR principles.

4.3 Activity data

An emission modeler interviewed for this task mentioned that there are more data than they have time to use. However, these data are typically patchy, and longer time series would be of great value. Even if the data is coming from a regular source such as farming or traffic statistics, collection and preprocessing the data is typically done either pro bono or by a PhD student. with project-based funding. Collecting and QC of such data cannot be pro bono activity. To get meaningful datasets (geographical coverage and length of time series) professional operational activities are needed. Someone has to be paid to collect, QC and deliver these data.

4.4 Satellite-based indices

Surface reflectance from satellites is post-processed to yield higher-level indices, such as Normalised Difference Vegetation Index (NDVI), Enhanced vegetation Index (EVI), and Land Surface Water Index (LSWI) for use in diagnostic biosphere models and for machine-learning-based flux tower upscaling approaches.

4.4.1 Accessibility

Working groups have reported in D7.2 that despite the strong dependence on MODIS, they have been generally dissatisfied with the lack of data FAIR-ness. Part of this is related to the use of platforms to easily use the data, turning to private applications like Google Earth Engine. Also, groups working with satellite reflectances, report that they find NASA data products such as MODIS and VIIRS easier to access than those from ESA, such as Sentinel-2. Here the download speed is a substantial issue, as well as the lack of availability of public platforms on which data can be processed online, without the need for massive downloads.

4.4.2 Continuity

Most modelers in WPs 2-5 use MODIS reflectance for calculating these indices. However, as MODIS will be decommissioned in 2023, they are looking for similar products, from both NASA and ESA; products from the Sentinels and VIIRS may provide an appropriate replacement. These teams These teams VIIRS was foreseen as the natural successor to MODIS, but the spectral bands are slightly different, meaning that the models and algorithms have to be adjusted accordingly (e.g. using EVI2 rather than EVI). Some were also considering passive microwave data as these provide additional information, but till now their approach has been focussed on optical sensors like the MODIS and Sentinel series.

4.5 Satellite measurement of SIF

Space-borne sun-induced fluorescence (SIF) data is used in the CoCO2 project mainly for comparing with the site-level simulations and for evaluating the upscaled GPP product by the FLUXCOM team. Timeliness requirement is comparatively less stringent as the need for the data is mainly for the current year of simulation and not Near Real Time.

4.6 Other satellite-based measurements

This mainly concerns measurements of atmospheric composition and satellite-based indices, like LAI and Fraction of Absorbed Photosynthetically Active Radiation (FAPAR), which have been covered in Section 3.10. No gaps were identified here.

Indirect LAI are available from the global assimilation MERRA 2. MERRA-2 is the first long-term global reanalysis to assimilate space-based observations of aerosols and represent their interactions with other physical processes in the climate system. The spatial resolution is 50 km latitudinally, temporal coverage is 1980-01-01 to present. Data are available at https://disc.gsfc.nasa.gov/datasets?project=MERRA-2

FAPAR and LAI are available from the MODIS instrument onboard the Terra and Aqua satellites. These Level-4 data products and their level of validation are given in Table 4. As these products are based on the MODIS sensors, the same continuity issues as for the reflectance-based indices in Section 4.4 apply.

Table 4. Satellite-based data for Leaf Area Index (LAI) and Fraction of Absorbed Photosynthetically Active Radiation (FAPAR)

Product name	Terra	Aqua	Combined Terra Aqua
Leaf Area Index/ FPAR 8-Day L4 Global 500m	MOD15A2H* 8-day 2000-02-18 to 2023-02-10	MYD15A2H 8-day 2022-03-17 to 2023-02-18	MCD15A2H** 8-day 2002-07-04 and 2023-02-10
Leaf Area Index/ FPAR 4-Day L4 Global 500m			MCD15A3H** 4-day 2002-07-04 to 2023-02-14

*Validated Stage 2: Accuracy has been assessed over a widely distributed set of locations and time periods via several ground-truth and validation efforts.

**Validated Stage 1: Accuracy has been estimated using a small number of independent measurements obtained from selected locations and time periods and ground-truth/field program efforts.

4.7 Land cover maps

Most land cover maps used by the respondents were from satellite (e.g.. ESA-CCI land cover product) or from the static, built-in land surface schemes of their models.

These maps are rather important for the biosphere modelling.

4.7.1 Timeliness

One of the biggest gaps in land cover maps is the timeliness. While some users updated their land use models regularly, many simply use the (outdated) land surface map that is distributed with their model, or do not update it in a regular, operational matter.

4.7.2 Quality control

Misqualification of land cover types is a serious issue. Modelers have discovered many errors in both Copernicus and CCI maps, and there is no organized way forward on how to improve these maps.

4.8 Concentration fields from global models

In this report we concentrate mainly on the gaps in the current in situ measurements, so will not be discussing concentration fields from models. (This section is to keep numbering a par with other deliverables in the same WP, and the summary tables.)

5 Gaps in technology and methodology

5.1 Gap-filling of ecosystem fluxes

Ecosystem fluxes data are always gap-filled; the gap-filled data can be up to 80% of the provided data. For example, in the global FLUXNET2015 data set, with 1532 site-years of data, on average 68% of the half-hourly CO_2 fluxes are missing. Even if the site-years that have gaps longer than two months are excluded, the mean data coverage is 40%. Only 50 site-years have a coverage higher than 60% and only 5 site-years a coverage higher than 70%. The gap-filling methods are not always applicable to different environments, as seen in a recent article by Vekuri et al (2023). They showed that the commonly used gap-filling method MDS causes significant carbon balance errors for northern ecosystems (latitude > 60 °N) sites. MDS systematically overestimates the CO_2 emissions through respiration and underestimates the sequestration of carbon by the biospheric sink. They developed methods to substantially reduce the northern site bias.

5.2 Urban eddy covariance data

The EU-funded project PAUL (ICOS Cities, 2021-2025 Grant agreement ID: 101037319) coordinated by ICOS ERIC, is developing and evaluating innovative greenhouse gas measurement technologies and observatories for urban environment. The aim is to provide unique data sets feeding diverse models and scientific studies, while testing the feasibility of modelling approaches in various areas PAUL aims to extend the two established ICOS core technologies of high-precision concentration measurements and eddy covariance flux measurements and combine them with large networks of mid- and low-cost sensors at roof and street-level as well as ground-based remote sensing technologies with the objective of urban emission monitoring. It will also provide additional observations to specifically improve the representation of urban biogenic fluxes and transport processes in models.

The main challenge of applying the eddy covariance technology to measure fluxes of CO_2 from a city is that the surface sampled (i.e., the turbulent flux source areas) changes constantly with wind direction and atmospheric stability, and is further modified by the heterogeneity of urban topography (Auvinen et al., 2017). While changing sampled source areas are not a problem in the case of extensive and spatially uniform natural ecosystems or crops, this becomes a challenge due to the inherent heterogeneity of both sources, sinks and roughness elements in a city. Therefore, fluxes aggregated through the EC method in cities are greatly depending on constantly changing flux footprint. As a result, different emission strengths and contributing sectors are aggregated by EC measurements. A second challenge is that EC systems must measure in the inertial sublayer of the urban atmosphere in order to directly couple surface emissions to fluxes by means of turbulent eddies (Grimmond et al, 1999). As such, the maximum size of turbulent flux source areas of tall towers reaches a few km^2 under typical daytime conditions. Thus, for larger cities, a single tall-tower EC system is not suitable for monitoring city-scale emissions across hundreds to thousands of km^2 - EC will provide data for only a small portion of a city at a given time. Nevertheless, for future urban observatories, those challenges will be turned into opportunities by combining turbulent flux source area models with urban EC towers to statistically disentangle fluxes and provide highly valuable, possibly sector-specific datasets on the temporal signature of urban emissions. These opportunities are studied in the ICOS Cities project.

6 Conclusion

6.1 Conclusion

Entirely missing data streams, representing scales and variables that are currently not observed, were not identified. A summary of identified gaps in geographical coverage, timeliness, access, quality control and continuity of the datasets in in Fig 11. Note that different modelers have different needs, and as they were asked what they use for now, the view given here is somewhat restricted and the view is subjective.

To improve the availability of data, the low-hanging fruit would be to organize access to campaign datasets of surface-based profiling and total column instruments, such as AirCore, EM27 and airplane campaigns as well as boundary layer height data. Their use in assimilation is not that urgent, but they are crucial for model evaluation and development. The ongoing project AtmoACCESS has a task with limited resources for “homeless datasets”, but for long-term applications these datasets could be of interest to an existing permanent body such as CAMS or EUMETSAT.

Another clearly identified need would be to improve the organization, curation and “technical readiness level” of activity data, from campaign and project-based endeavours to more operational level. The heterogeneity of activity data from different sectors and spatial scales (e.g. countries, sub-national regions, cities) remains a challenge.

	Parameter	Coverage	Timeliness	FAIR	QC	Cont.	Note
3.1	Eddy covariance flux data	4	3	4	3	3	Heterogenous QC between networks
3.2	In situ CO_2 measurements	4	4	4	4	5	
3.3	In situ CH_4 measurements	4	4	4	5	4	
3.4	In situ measurements of co-emitted species	3	4	4	7	7	
3.5	Measurements from urban networks	6	6	3	7	3	
3.6	Ocean fluxes/partial pressures	2	2	5	5	3	
3.7	Radiocarbon	2	3	4	5	5	
3.8	Other tracers (e.g. radon)	2	2	3	5	7	Used for transport model development
3.9	Ground-based remote sensing (e.g. TCCON)	1	1	5	5	5	Used for model evaluation as coverage and timeliness not suitable for operational use
3.10	Site-level ecosystem parameters	6	6	3	7	2	Used for parameter development
3.11	Site-level management and lateral fluxes	6	6	7	7	7	Used for parameter development
3.12	In situ soil moisture	1	6	7	7	7	Used for transport model development
3.13	Met in situ: Boundary layer height	3	6	7	7	7	
4.1	Met. Model fields	5	5	5	5	5	
4.2	Nightlights	5	5	5	5	5	
4.3	Activity data	5	5	2	7	2	
4.4	Satellite-based indices	6	6	2	7	3	From MODIS to Sentinel
4.5	SIF	6	6	2	7	3	
4.6	Other satellite-based measurements	6	6	2	7	3	
4.7	Land cover maps	6	6				
4.8	Concentration from global models						

Figure 11. Summary of gaps identified in different data streams. (Note this is highly subjective, and a new version after feedback from modelers will be provided in the September update of this deliverable).

Legend

1	Showstopper
2	Bad

3	Not good
4	Bearable
5	Sufficient
6	Not relevant
7	Unknown

6.2 Future perspectives

The World Meteorological Organization (WMO) has endorsed plans for a new Global Greenhouse Gas Monitoring Infrastructure. It seeks to build on WMO's experience in coordination international collaboration in weather prediction and climate analysis and on long-standing activities in greenhouse gas monitoring, research, and provision of related services under the auspices of the Global Atmosphere Watch established in 1989 and its Integrated Global Greenhouse Gas Information System (IG3IS).

According to this resolution, WMO would coordinate efforts within a collaborative international framework, to leverage all existing greenhouse gas monitoring capabilities – space-based and surface-based observing systems, and all relevant modelling and data assimilation capabilities – in an integrated, operational framework.

Many of the existing international and national activities dealing with greenhouse gases are supported mainly by the research community. At present, there is no comprehensive, timely international exchange of surface- and space-based greenhouse gas observations or modelling products.

In its initial configuration, it is envisaged that the Greenhouse Gas Monitoring Infrastructure will include as one of its main components a comprehensive sustained, global set of surface-based and satellite-based observations of CO_2, CH_4 and N_2O concentrations, total column amounts, partial column amounts, vertical profiles, and fluxes and of supporting meteorological, oceanic, and terrestrial variables, internationally exchanged as rapidly as possible, pending capabilities and agreements with the system operators.

As an output the infrastructure will be gridded net monthly fluxes of CO_2, CH_4 and N_2O at the spatial resolution of 100 km by 100 km, with the minimum possible delay. These outputs can drive multiple applications from contribution to the global stocktake to assessment of the fluxes from individual facilities or landscapes. (WMO, 2023)

It is likely that implementation of this initiative will on the one hand increase the motivation of public institutions such as national weather services and the World Bank to establish new monitoring stations in under-observed areas, especially in the Tropics, and to share the data openly. On the other hand, this will increase the demand for mid-cost instrumentation, and require the development of standardized data and metadata formats, quality assessment and quality control.

7 References

Agusti-Panareda, Anna (2022) CoCO2 global nature run as an evaluation tool of the integrated earth system model to support the monitoring of greenhouse gas emissions. ICOS Science conference (a manuscript in preparation)

Auvinen, M., Järvi, L., Hellsten, A., Rannik, Ü., & Vesala, T. (2017). Numerical framework for the computation of urban flux footprints employing large-eddy simulation and Lagrangian stochastic modeling. *Geoscientific Model Development*, *10*(11), 4187-420

Biraud, S., & Chen, J. (2021). Eddy Covariance Measurements in Urban Environments White paper prepared by the AmeriFlux Urban Fluxes ad hoc committee. Available online at https://ameriflux.lbl.gov/wp-content/uploads/2021/09/EC-in-Urban-Environment-2021-07-31-Final.pdf

Demol, M., Verbeeck, H., Gielen, B., Armston, J., Burt, A., Disney, M., ... & Calders, K. (2022). Estimating forest above-ground biomass with terrestrial laser scanning: Current status and future directions. *Methods in Ecology and Evolution*, *13*(8), 1628-1639.

Fiz F. Perez, M. Becker, N. Goris, M. Gehlen, M. Lopez-Mozos, J. Tjiputra, A. Olsen, J.D. Müller, I. E. Huertas T. T. T. Chau, V. Cainzos, A. Velo, G. Benard, J. Hauck N. Gruber and Rik Wanninkhof. An assessment of CO_2 storage and sea-air fluxes for the Atlantic Ocean and 1 Mediterranean Sea between 1985 and 2018. Under review for Global Biogeochemical Cycles

Franz, D., Acosta, M., Altimir, N., Arriga, N., Arrouays, D., Aubinet, M., ... & Vesala, T. (2018). Towards long-term standardised carbon and greenhouse gas observations for monitoring Europe’s terrestrial ecosystems: a review. *International Agrophysics*, *32*(4), 439-455.

Friedlingstein, P., Jones, M. W., O'Sullivan, M., Andrew, R. M., Bakker, D. C., Hauck, J., ... & Zeng, J. (2022). Global carbon budget 2021. Earth System Science Data, 14(4), 1917-2005.

Grimmond, C. S. B., and T. R. Oke, 1999: Aerodynamic Properties of Urban Areas Derived from Analysis of Surface Form. *J. Appl. Meteor. Climatol.*, **38**, 1262–1292, https://doi.org/10.1175/1520-0450(1999)038<1262:APOUAD>2.0.CO;2.

Hauck Judith, Nissen Cara, Landschützer Peter, Rödenbeck Christian, Bushinsky Seth and Olsen Are 2023: Sparse observations induce large biases in estimates of the global ocean CO2 sink: an ocean model subsampling experiment *Phil. Trans. R. Soc.* A.3812022006320220063

Korkiakoski, M., Ojanen, P., Tuovinen, J. P., Minkkinen, K., Nevalainen, O., Penttilä, T., ... & Lohila, A. (2023). Partial cutting of a boreal nutrient-rich peatland forest causes radically less short-term on-site CO2 emissions than clear-cutting. *Agricultural and Forest Meteorology*, *332*, 109361.

Kotthaus, S., Bravo-Aranda, J. A., Collaud Coen, M., Guerrero-Rascado, J. L., Costa, M. J., Cimini, D., ... & Haeffelin, M. (2023). Atmospheric boundary layer height from ground-based remote sensing: a review of capabilities and limitations. *Atmospheric Measurement Techniques*, *16*(2), 433-479.

Lan, X., Nisbet, E. G., Dlugokencky, E. J., & Michel, S. E. (2021). What do we know about the global methane budget? Results from four decades of atmospheric CH4 observations and the way forward. *Philosophical Transactions of the Royal Society A*, *379*(2210), 20200440.

Landschützer, P., Laruelle, G. G., Roobaert, A., & Regnier, P. (2020). A uniform pCO 2 climatology combining open and coastal oceans. Earth System Science Data, 12(4), 2537-2553.

Machida, T., and Coauthors, 2008: Worldwide measurements of atmospheric CO2 and other trace gas species using commercial airlines. *J. Atmos. Oceanic Technol.*, **25 ,** 1744–1754.

Masarie, K. & Peters, W. & Jacobson, A. & Tans, P.. (2014). ObsPack: a framework for the preparation, delivery, and attribution of atmospheric greenhouse gas measurements. Earth System Science Data. 6. 10.5194/essd-6-375-2014.

Müller, M., Graf, P., Meyer, J., Pentina, A., Brunner, D., Perez-Cruz, F., Hüglin, C., and Emmenegger, L (2020). Integration and calibration of non-dispersive infrared (NDIR) CO2 low-cost sensors and their operation in a sensor network covering Switzerland, Atmos. Meas. Tech., 13, 3815–3834, https://doi.org/10.5194/amt-13-3815-2020,.

Nicolini, G., Antoniella, G., Carotenuto, F., Christen, A., Ciais, P., Feigenwinter, C., Gioli, B., Stagakis, S., Velasco, E., Vogt, R., Ward, H. C., Barlow, J., Chrysoulakis, N., Duce, P., Graus, M., Helfter, C., Heusinkveld, B., Järvi, L., Karl, T., … Papale, D. (2022). Direct observations of CO2 emission reductions due to COVID-19 lockdown across European urban districts. Science of The Total Environment, 830, 154662. doi: https://doi.org/10.1016/j.scitotenv.2022.154662

Nordbo, A., Järvi, L., Haapanala, S., Wood, C. R., & Vesala, T. (2012). Fraction of natural area as main predictor of net CO2 emissions from cities. *Geophysical Research Letters*, *39*(20).

Pastorello, G., Trotta, C., Canfora, E., Chu, H., Christianson, D., Cheah, Y. W., ... & Law, B. (2020). The FLUXNET2015 dataset and the ONEFlux processing pipeline for eddy covariance data. Nature *Scientific data*, *7*(1), 1-27.

Rodgers, K., Jörg, S., Fassbender, A., et al. (2023). Seasonal variability of the surface ocean carbon cycle: a synthesis. ESS Open Archive, Manuscript under review. DOI: 10.22541/essoar.168167394.47800179/v1

Rödenbeck, C., Keeling, R. F., Bakker, D. C., Metzl, N., Olsen, A., Sabine, C., & Heimann, M. (2013). Global surface-ocean p CO_2 and sea–air CO_2 flux variability from an observation-driven ocean mixed-layer scheme. Ocean Science, 9(2), 193-216.

Takahashi, Taro; Sutherland, Stewart C.; Kozyr, Alex (2017). LDEO Database (Version 2019): Global Ocean Surface Water Partial Pressure of CO2 Database: Measurements Performed During 1957-2019 (NCEI Accession 0160492). [indicate subset used]. NOAA National Centers for Environmental Information. Dataset. https://doi.org/10.3334/cdiac/otg.ndp088(v2015).).

Wang, C., Shi, H., Jin, L., Chen, H., & Wen, H. (2016). Measuring boundary-layer height under clear and cloudy conditions using three instruments. *Particuology*, *28*, 15-21.

Vekuri, H., Tuovinen, J. P., Kulmala, L., Papale, D., Kolari, P., Aurela, M., ... & Lohila, A. (2023). A widely-used eddy covariance gap-filling method creates systematic bias in carbon balance estimates. *Nature Scientific Reports*, *13*(1), 1720.

WMO 2023. World Meteorological Congress approves Global Greenhouse Gas Watch. (*Press release*) https://public.wmo.int/en/media/press-release/world-meteorological-congress-approves-global-greenhouse-gas-watch

Wunch, D., Toon, G. C., Sherlock, V., Deutscher, N. M., Liu, C., Feist, D. G., & Wennberg, P. O. (2015). Documentation for the 2014 TCCON Data Release (GGG2014.R0). CaltechDATA. https://doi.org/10.14291/TCCON.GGG2014.DOCUMENTATION.R0/1221662

8 Annex: List of acronyms

ACTRIS	Aerosol, Clouds and Trace Gases Research Infrastructure
ALC	Automatic lidars and ceilometers
AmeriFLUX	Network of ecosystem flux sites in N, C and S America (1996 -)
BADM	Biological, Ancillary, Disturbance and Metadata (BADM) system
BLH	Boundary layer Height
COCCON	collaborative carbon column observing network
CORSO	CO2MVS Research on Supplementary Observations
DMSP-OLS	Defence Meteorological Satellite Program - Operational Linescan System
ESA	European Space Agency
EUMETSAT	Europe's meteorological satellite agency
FAIR	Findable, Accessible, Interoperable and Reusable
FAPAR	Fraction of Absorbed Photosynthetically Available Radiation
fCO_2	fractional carbon dioxide
FLUXCOM	An initiative to upscale biosphere-atmosphere fluxes from FLUXNET sites to continental and global scales
FLUXNET	1) The data portal and 2) measurement site network.
FTIR	Fourier Transform infra-red
GAW	Global Atmospheric Watch programme
GCP	Global Carbon Project
GPP	Gross Primary Production
JPL	Jet Propulsion Laboratory
LAI	Leaf Area Index
LDEO	Lamont-Doherty Earth Observatory *(Columbia University)*
LIDAR	Laser Imaging Detection and Ranging
LSWI	Land Surface Water Index
MERRA	Modern-Era Retrospective analysis for Research and Applications
MODIS	Moderate Resolution Imaging Spectroradiometer
MVS	Monitoring & Verification Support
NASA	National Aeronautics and Space Administration.
NDIR	Non Dispersive Infrared
NDVI	Normalised Difference Vegetation Index
NEE	Net Ecosystem Exchange - NPP minus the heterotrophic respiration
NEON	National Ecological Observatory Network
NOAA	U.S. National Ocean and Atmosphere Administration
NRT	Near-Real-Time
NUBICOS	New Users for Better ICOS
ObsPack	Observation Package
OSCAR	Observing Systems Capability and review Tool
OZ Flux	Australian & New Zealand ecosystem research network, part of FLUXNET
RECO	Ecosystem respiration
SIF	Solar Induced Fluorescence
SOCAT	Surface Ocean CO_2 Atlas

TCCON	Total Carbon Column Observing Network
TERN	Terrestrial Ecosystem Research Network (Australia)
VIIRS DNB	Visible Infrared Imaging Radiometer Suite, day/night band
VPRM	Vegetation Photosynthesis Respiration Model
WDCGG	World Data Centre for Greenhouse Gases
WMO	World Meteorological Organisation
WP	Work Package

Document History

Version	Author(s)	Date	Changes
For review	Sindu Raj Parampil	19/06/2023	
After review	Ville Kasurinen	30/06/2023	Merged comments, solved some
Submission	Elena Saltikoff	03/07/2023	Solved more comments

Internal Review History

Internal Reviewers	Date	Comments
Konstantinos Politakos (FORTH)	27/06/2023	Minor changes
Julia Marshall (DLR)	27/06/2023	Some comments to be implemented in September update
Marko Scholtze (ULUND)	27/06/2023	Some comments to be implemented in September update
Hugo Denier van der Gon (TNO)	27/06/2023	Some comments to be implemented in September update

Estimated Effort Contribution per Partner

Partner	Effort
Organisation	effort in person month
Total	0