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An Operational Anthropogenic CO_2 Emissions Monitoring & Verification Support Capacity

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An Operational Anthropogenic CO_2 Emissions Monitoring & Verification Support Capacity

Needs and High Level Requirements for *in situu* Measurements

Report from the CO_2 Monitoring Task Force

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Legal Notice

Preamble

This report describes the needs and high level requirements of *in situ* measurements to help establish an operational Monitoring & Verification Support (MVS) capacity to quantify anthropogenic CO_2 emissions. The analysis addresses these needs for all core elements of the envisaged integrated system with a particular focus on the impact of *in situ* measurements in achieving the proposed objectives. The specific needs for the validation of products delivered by the space component – that is, the Copernicus Sentinels CO_2 monitoring constellation – are addressed as an additional prerequisite for the success of the CO_2 support capacity. The resulting European asset will represent a significant contribution to the virtual international constellation proposed by the Committee on Earth Observation Satellites (CEOS) and complementary requirements are elaborated in that international context.

The report acknowledges that, suitably high measurement standards are already present within existing networks such as the Integrated Carbon Observation System (ICOS) but explains why these are not adequate for an operational system whose primary purpose is to quantify anthropogenic CO_2 emissions. Apart from the sustained need for world-wide *in situ* measurements to lower retrieval uncertainties, a fundamental prerequisite is also to have a good geographical coverage over Europe with sufficient temporal and spatial resolution to evaluate the data assimilation and modeling system over a wide variety of environmental conditions such as, for instance: urban areas, industrial complexes and other intense fossil fuel emission areas in addition to rural regions currently sampled for the purpose to quantify natural CO_2 fluxes. Consequently, the *in situ* measurements need to be extended under a coordinated European lead with dedicated infrastructure and targeted, additional and sustained long-term funding.

This report aims to motivate those agencies and organisations that have the capability and mandate to contribute to advance the current situation. A set of key recommendations and concrete next steps are proposed in order to leverage the material presented in this report in advancing the MVS capacity definition and implementation. A more in-depth analysis of the various needs, e.g., to consolidate research-based networks, to extend existing networks and to develop new networks, and the elaboration of practical solutions on a case-by-case basis require urgent actions. Complimenting the outcomes of the current report, specific actions and options for the sustained implementation of these elements, as well as critical partnerships required with international stakeholders will be addressed in an additional report addressing the “Implementation Framework” which is also ongoing in the current phase of the CO_2 Monitoring Task Force’s activities.

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Executive Summary

Multiple input data streams of *in situ*[1] measurements are required for the Copernicus CO_2 Monitoring & Verification Support (MVS) capacity. These data streams include measurements of greenhouse gases fluxes from the ground and greenhouse gases concentrations collected with air samples from tall towers, atmospheric soundings from the ground, air samples collected by aircraft as well as ground-based remote sensing of the atmospheric composition. *In situ* measurements are required to:

- calibrate and validate the space component of the MVS capacity,
- assimilate data in the models and to integrate information in the core MVS capacity,
- validate and further improve physical models that govern the evolution of CO_2 in computer simulations, and
- evaluate the output generated by the MVS capacity for its end users.

It is now recognized that the sparseness of current *in situ* atmospheric CO_2 measurement networks does not sufficiently constrain estimates of fossil anthropogenic emissions. Enhancing these observation networks with ^{14}C[2] and fossil fuel CO_2 co-emitted species measurements across major fossil fuel CO_2 emitting regions is important for estimating national emission budgets, because it will provide complementary information to satellites for quantifying emissions from hot-spots. As such, well-coordinated and inter-operable urban and ^{14}C and CO_2 co-emitted networks, beyond the current capabilities of the Integrated Carbon Observation System (ICOS) network must be developed in Europe.

The current status of existing networks may be the source of large uncertainties in anthropogenic CO_2 emission estimates as well as of limited capability in meeting the requirements for country, large city and point source scale assessments. This conclusion results from an analysis of four scenarios: 1) maintaining the *status quo,* 2) assuring sustained funding for the *status quo*, 3) enhancing network capabilities at European scale with sustained funding and 4) with a significantly improved *in situ* infrastructure in Europe and beyond.

The availability of sustained *in situ* networks is currently a significant factor of risk that needs to be mitigated to establish a European CO_2 support capacity which is fit-for-purpose.

It is imperative to ensure that the required *in situ* measurement system is in place in terms of observational capability with appropriate geographical coverage and with sufficient temporal and spatial resolution. A baseline system could be built upon the existing networks, specifically the Total Carbon Column Observing Network (TCCON) supplemented by the COllaborative Carbon Column Observing Network (COCCON), the AErosol RObotic NETwork (AeroNet) and Aircore observations. However, these networks, as they are today, do not meet all operational requirements for the European CO_2 support capacity and therefore may carry important risks in achieving all its objectives.

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[1] *In situ* observations from the Copernicus Regulation: 'Copernicus *in situ* data' means measurements collected by ground borne, seaborne or airborne sensors, as well as reference and ancillary data licensed or provided for use in Copernicus.

[2] Measuring ^{14}C (radiocarbon) concentrations in atmospheric CO_2 is the best approach identified so far for separating fossil CO_2 in the atmosphere from the signal of natural fluxes. Fossil fuels do not contain radiocarbon and their combustion releases CO_2 that is diluted with other CO_2 sources that actually contain ^{14}C. This dilution induces a measurable depletion of the ^{14}C isotope.

These capabilities should therefore be further expanded in order to meet the full requirements of the foreseen Copernicus CO_2 MVS capacity. The highest priority is to ensure coordinated governance and sustained operational funding. Sound governance minimizes duplication of effort thereby maximises the return on financial investment. Coordination naturally facilitates centralised data access in a standard format, which minimizes effort for both the data provider and data user. Without an adequate international and European-level coordination mechanism to sustain the operational system there is an increased risk of underperformance of the whole system.

The foreseen applications for the Copernicus CO_2 MVS capacity span a range of scales, from point sources to city and country scales. This is adding additional requirements on the ground-based network in terms of coverage and availability:

- Regional and country-scale applications can be addressed with an extended TCCON network supplemented the COCCON facilities. There should also be a strong buy in from other countries which requires international coordination and dialogue.
- For urban-scale and large industrial infrastructures, there is a need to validate the gradients up and downwind of the emitting sources. This can be achieved using portable instruments together with other longer-term installations around selected areas.

It has been clearly understood from the onset that the international dimension of the European CO_2 support capacity would be critical and that these aspects should be developed in parallel to, and in synergy with the definition and implementation of a European contributing system to the globally coordinated efforts, e.g. the one by the World Meteorlogical Organization that coordinates the global observations of greenhouse gases since 1975. It was also understood that this international dimension had strategic, policy-relevant and technical dimensions and the Commission and the relevant European institutional partners have started since several years to engage both bilaterally and multilaterally with the relevant stakeholders and counterparts to develop these relations. Specifically, the Committee on Earth Observation Satellites (CEOS) will undertake, over the next few years, dedicated preparatory work in a coordinated international context, to provide cumulative added value to the specific programmatic activities of their member agencies. Concerted efforts have already taken place in the context of the European Commission's Chairmanship of CEOS in 2018.

It is recognized in the context of the European efforts, and increasingly by our international counterparts that a broad and holistic system approach is required to address the requirements which are represented by the climate policy, of which the satellite component, whilst important, cannot effectively be developed in isolation. This system indeed includes the satellite observing capability but in addition, the required modelling component and data integration elements, prior information, ancillary data and *in situ* measureements delivered by essential dedicated networks.

Acknowledging the need for an efficient coordination and standardisation at international level (for instance via the Global Atmosphere Watch programme of the World Meteorological Organisation) is a key towards a successful implementation of appropriate actions to ensure the sustainability of essential networks, to enhance current network capabilities with new measurements and to propose adequate governance schemes. Such actions to mitigate current network limitations are deemed critical to implementing the Copernicus CO_2 Monitoring & Verification Support capacity in its full strength.

The analysis of key challenges due to current limitations of main *in situ* networks requires dedicated actions on three complementary fronts:

- to ensure the sustainability of essential networks such as the TCCON and others,
- to enhance existing network capabilities to include new observations such as ^{14}C and co-emitted species from fossil fuel burning[3],
- to propose adequate governance schemes to be coordinated at the international level given the global dimension of issues at stake.

Additionally, well-coordinated, inter-operable, and optimally designed large city scale networks, to measure ^{14}C nearby strong emitting sources for example, must be designed and implemented. The CO_2 monitoring Task Force set-up and chaired by the European Commission shall promote the following actions:

- to propose viable and sustainable governance options and to evaluate appropriate funding schemes at the European level and with the support of the European countries,
- to suggest one or more strategies to establish a dialogue and to engage with other institutions, organizations and agencies contributing to the same objectives and with an established mandate at the international level,
- to evaluate quantitatively the impact on the Copernicus CO_2 Monitoring & Verification Support capacity of the current limitations due to essential networks,
- to design a framework and to generate a roadmap for designing and developing observation networks of ^{14}C and co-emitted species from fossil fuel burning enabling us to assess the impact of emission reduction policies.

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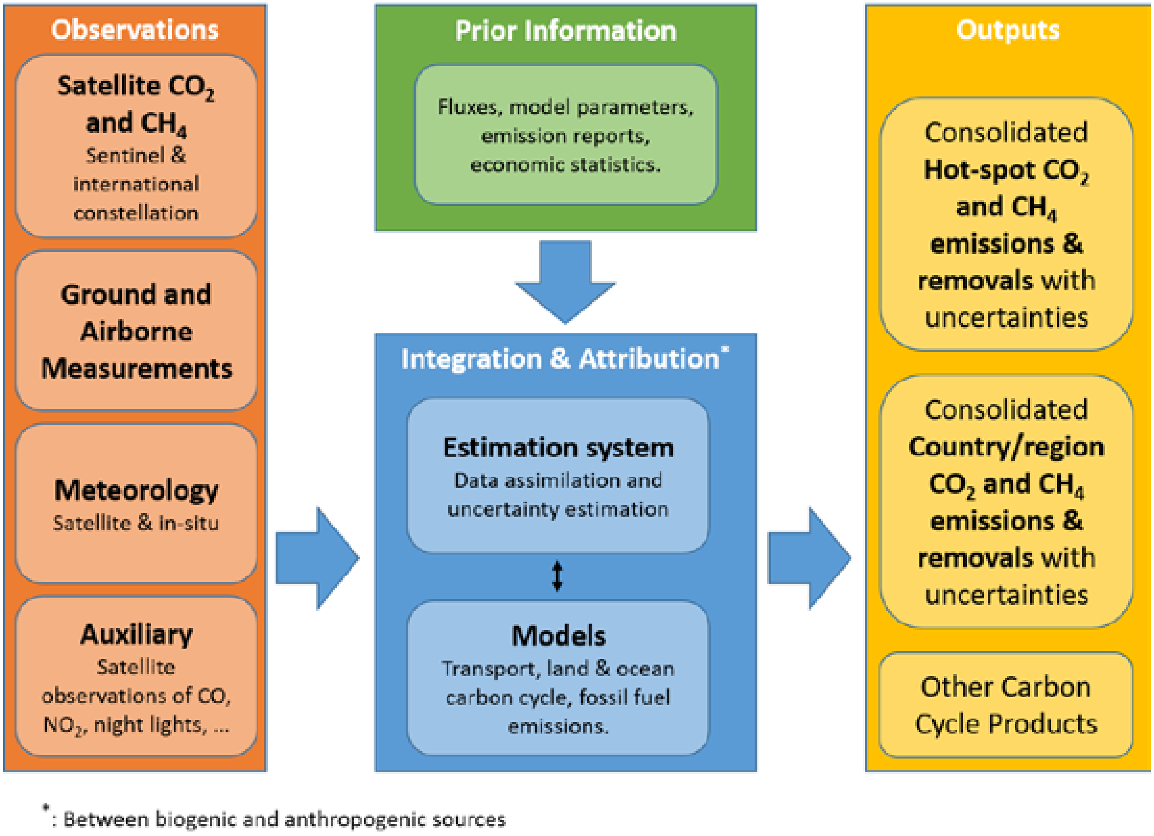
[3] In concrete terms, this enhancement is likely in the range of 50 to 80 stations to cover the main emitting hot spots in Europe.

1. Background & Rationale

The objective of this report is to provide a comprehensive assessment of the needs and high level requirements for *in situ*[4] measurements to form part of an operational system capable of monitoring and providing support to verify anthropogenic CO_2 emissions. Previous reports[5,6] describe the overarching goal, baseline requirements, functional architecture and system elements needed to implement such an operational capacity. The European Commission has adopted a holistic approach toward implementation which is based on optimal use of all relevant information and knowledge, including observations, statistical data, models of the Earth system, as well as fossil fuel emission models. The core elements of the foreseen Copernicus CO_2 Monitoring & Verification Support (MVS) capacity are displayed below (adapted from[3]).



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[4] *In situ* observations from the Copernicus Regulation: 'Copernicus in situ data' means measurements collected by ground borne, seaborne or airborne sensors, as well as reference and ancillary data licensed or provided for use in Copernicus.

[5] Ciais, P., D. Crisp, H. Denier Van Der Gon, R. Engelen, M. Heimann, G. Janssens-Maenhout, P. Rayner and M. Scholze (2015): **Towards a European Operational Observing System to Monitor Fossil CO_2 emissions**, European Commission Joint Research Centre – ISBN 978-92-79-53482-9; doi:10.2788/350433.

[6] Pinty B., G. Janssens-Maenhout, M. Dowell, H. Zunker, T. Brunhes, P. Ciais, D. Dee, H. Denier van der Gon, H. Dolman, M. Drinkwater, R. Engelen, M. Heimann, K. Holmlund, R. Husband, A. Kentarchos, Y. Meijer, P. Palmer and M. Scholze (2017): **An Operational Anthropogenic CO_2 Emissions Monitoring & Verification Support capacity: Baseline Requirements, Model Components and Functional Architecture,** European Commission Joint Research Centre - ISBN 978-92-79-72100-7;doi: 10.2760/39384.

Successful implementation of the operational system critically depends on achieving a significant increase of high-quality satellite observations related to atmospheric CO_2 concentration[7].

A proposal for implementing the space-based component addressing an operational CO_2 mission with dedicated space borne sensors is under development and is described in detail in a Mission Requirements Document (MRD)[8]. The MRD describes a measurement system that increases the number of CO_2 satellite observations to an unprecedented capacity. It also describes its broader integration with the Committee on Earth Observation Satellites (CEOS) virtual satellite constellation, which also exploits the capabilities of the Coordination Group Of Meteorological Satellites (CGMS), designed to estimate greenhouse gas concentrations, including contributions from anthropogenic sources[9]. This system also contributes to the implementation of the 2040 vision for the World Meteorological Organization (WMO) Integrated Global Observing System (WIGOS)[10].

The functional design of the operational end-to-end system[11] of the MVS capacity conceived by the European Commission crucially relies on sustained access to high-quality *in situ* observations of CO_2 concentrations and relevant tracers. Accurate local information on CO_2 concentrations is needed in various elements of an operational end-to-end system. *In situ* observations are required for calibration and validation of the space component, for assimilation in models that are used to integrate information in the core of the system –as illustrated above-, to validate and further improve physical models that govern the evolution of CO_2 in computer simulations, and for evaluating the output generated by the system for its end users. Significant and continual efforts are required to ensure the quality and sustainability of the *in situ* component and reduce the risk of underperformance of the system as a whole, as we describe below.

The present report describes in detail the role of the *in situ* component in the MVS capacity, and exposes various risks associated with inadequate access to sustainable, high quality, regional and global networks of *in situ* measurements. Mitigating these risks requires efforts on resolving complex issues relating to data policy, governance, access and availability, standards, sustainability, as well as data distribution and archiving. The issues are especially challenging since the existing *in situ* networks are heterogeneous in terms of their governance, sustainability and funding mechanisms. An in-depth analysis of the current state of play and foreseeable developments is clearly needed needed in view of meeting the specific requirements of the MVS capacity. Such an analysis will help to develop a viable implementation strategy together with WMO, through the Global Atmosphere Watch (GAW) and the Integrated Global Greenhouse Gas Information System (IG3IS), as well as with other entities responsible for coordination of *in situ* observation networks.

Furthermore, the European Commission has recognised from the outset that its efforts on the CO_2 emissions initiative should not be undertaken in isolation. There is added value in both bilateral partnerships and multi-lateral coordination in implementing a number of system elements. The emerging CEOS Greenhouse Gas virtual constellation, mentioned above, is one important aspect of this. The current report therefore also considers specific *in situ* data requirements for the implementation of the virtual constellation, to which the European Commission should contribute, as well as for which the external partnerships should be prioritized.

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[7] The report focuses on the monitoring of atmospheric CO_2 concentration in relation with the anthropogenic emissions. The functional architecture and technical concepts envisaged for the ground-based infrastructure as well as for the space component will, in addition and as a secondary objective for the operational system, support the monitoring of methane at high resolution and worldwide.

[8] 'The MRD is an evolving document. The latest version is available from ESA upon request and can also be found online at https://www.esa.int/Our_Activities/Observing_the_Earth/Copernicus'

[9] http://ceos.org/document_management/Virtual_Constellations/ACC/Documents/CEOS_AC-VC_GHG_White_Paper_Version_1_20181009.pdf.

[10] http://www.wmo.int/pages/prog/www/WIGOS-WIS/meetings/ICG-WIGOS-8/ICG-WIGOS-8.html

[11] In the context of this report, the end-to-end system designates the ensemble of the core elements contributing to the integrated system (see illustration on the previous page).

Chapter 2 below describes the main requirements of the MVS capacity regarding *in situ* observations aligned with three main topics: Validation of input data and prior information, use of *in situ* observations in the integration system, and validation of the system outputs. Chapter 3 then summarizes how *in situ* observations are currently used to estimate biogenic and to some extent anthropogenic CO_2 fluxes from global to local scales and how these estimation systems could further develop to contribute to the future CO_2 system. Chapter 4 describes the role of and the high level requirements for *in situ* observations in the validation of the space-based observations. The *in situ* observation requirements regarding the CEOS virtual constellation are addressed in Chapter 5. Chapter 6 discussed series of challenges associated with current limitations of *in situ* networks while a series of key recommendations are listed in Chapter 7.

This report presents the outcomes of discussions by experts of the CO_2 Task Force on requirements for *in situ* measurements and observation networks that must be met in order to make the European Commission initiative on anthropogenic CO_2 emissions a success. To this end, the report provides a synthesis of identified gaps and gives recommendations on the way forward, addressing critical aspects of the *in situ* observation component underpinning the operational CO_2 Monitoring & Verification Support capacity. The recommendations provided in this report should be considered by the European Commission and its main partners as a basis for developing a the roadmap detailing further actions on this topic in the coming years.

2. *In situ* measurement needs for the CO_2 MVS capacity

The purpose of this chapter is to clarify the essential role of *in situ* observations in an integrated system that combines measurements from space-based and *in situ* instruments with information from models together with various types of proxy data on emissions. Such a system requires accurate *in situ* measurements of atmospheric CO_2 to be able to identify and to reduce instrument-dependent biases in space-based observations. *In situ* data are also needed to estimate unknown parameters in the model components of the system, and similarly to optimize the use of proxy data on anthropogenic emissions. **Finally, a meaningful quality assessment of the system as a whole, including its emission products, requires independent *in situ* measurements of all key variables involved in the processing chain**.

In situ measurements are an essential component of any observing system aiming at monitoring fossil fuel CO_2 emissions. The iconic *in situ* measurements from Mauna Loa and the South Pole by the Scripps Institution of Oceanography network over the past 60 years are a testimony to this. Even after a few years of measurements, it was clear that the steady increase in CO_2 concentrations modulated by the seasonal cycle reflected a human influence on the global atmosphere from burning fossil fuels and an important role for the land biosphere. These data continue to draw worldwide attention to a global problem that causes changes in Earth's climate systems.

In situ observations provide precise and accurate measurements mainly at high temporal frequency in all weather conditions (except for flask samples which record an integrated signal over a week or even longer time periods). Many *in situ* observations are made in the planetary and surface boundary layers and therefore differ fundamentally from column-averaged observations of CO_2 concentrations provided by current space instruments (Pinty et al., 2017). CO_2 variability due to surface fluxes is largest in the boundary layer and therefore easier to detect in measured CO_2 gradients between surface stations than in satellite soundings of column-averaged CO_2 concentrations. However, quantification of the heterogeneity of surface fluxes requires a high spatial and temporal coverage, which makes the sustainment of a global network of *in situ* observations very challenging. In addition, ground-based remotely-sensed observations of total column CO_2 can be used to make the link between space-based observations and the well-calibrated surface network observations.

2.1. Validation of satellite observations and prior information

Box 1

Satellite observations and supplementary emission inventory data are the input data needed by the CO_2 Monitoring & Verification Support capacity. *In situ* observations are key to validate these input data and assure independent quality control.

2.1.1 Observations

Satellite-based observations of CO_2 column concentration and related species will form the backbone of the foreseen observation-based CO_2 MVS capacity. It is therefore critical that these satellite-based observations are well-calibrated and well-characterised over the lifetimes of the various satellite missions.

This MVS capacity must be resilient to changes in instrument performance and therefore requires continuous evaluation of instrument status and validation of product quality. Routine and continuous monitoring and reporting is essential to facilitate early detection of product processing and delivery issues. In order to support this activity, it is necessary to ensure the routine availability of ground-based or other validation data sets. These data sets are also required to be made available in a timely, traceable and controlled manner. They should cover a wide range of environmental conditions and be internally consistent. This implies the need for long-term continuity of resources and regular benchmarks to support the provision of such validation data to ensure a sustained satellite product quality, as will be further described in Chapter 4.

2.1.2 Temporal variability of prior emissions

While bottom-up emission inventories are typically constructed from annual statistics, monthly emissions data are required as an input for models that use monthly averaged proxy data. Further increases of the temporal resolution, for instance to reach hourly profiles, require additional proxy data and assumptions on their representativeness which can be incorporated within the models. The air quality community has been developing temporal emission profiles for more than two decades either in their pollutant emissions models (see e.g., Lenhart and Friedrich, 1995; Baldasano et al., 2008) or sometimes embedded in air quality modeling systems (see e.g., Schaap et al., 2008; Simpson et al., 2012). Over the last decade modeling of the temporal distribution of carbon emissions has also received some attention (see e.g., Nassar et al., 2013; Thiruchittampalam, 2014). Validation requires careful comparison of the modeled and *in situ* measured atmospheric concentrations (see e.g., Galmarini and Solazzo, 2015). Often sites are selected such that the total concentration of a typical air pollutant, with reasonably understood loss rates (for instance, nitrogen oxides, $NOx=NO_2+NO$) and with well-known decay, is mainly determined by a few activity sectors (e.g., transport, electricity, residential or manufacturing) for which the temporal profiles are known. It might be more challenging to identify these in the case of greenhouse gas (GHG) emissions, especially for non-combustion sources or sinks.

A range of reactive trace gases are emitted from activity sectors relevant to GHGs. Many of these affect surface air pollution and human health and are therefore monitored in many countries across the world. Most of the automated roadside monitoring sensors are located within (peri) urban areas, with much fewer sites located in rural areas. While they can provide information about the temporal variation of individual activity sectors, such as public and private transportation, they might not be representative on regional scales by virtue of their location (less than 2m above the ground close to roads). These automated sites vary in measurement coverage but will typically include a range of hydrocarbons (for example, alkenes, alkanes, aromatics), nitrogen dioxide, ozone, carbon monoxide and ammonia. These *in situ* data can be used indirectly as a proxy for diurnal variations of GHGs from individual activity sectors (e.g., ammonia for agriculture) or potentially used directly where there are coincident measurements of GHGs and reactive trace gases to understand emission factors. A similar range of data is available on a global scale via the WMO/GAW program but coordinated calibration of data has proved to be challenging.

The temporal (diurnal) and spatial variations of emissions from the transport sector could potentially also be inferred from systems such as Google Traffic, which use Global Positioning System locations transmitted by mobile phone users. This application is now available for most major cities around the world. Translating this into GHG emissions would require knowledge of emissions associated with the composition of the fleet, including for example idling during congestion.

2.2 Use of *in situ* observations in the CO_2 MVS capacity

Box 2

The CO_2 Monitoring & Verification Support capacity requires accurate *in situ* observations in addition to the satellite observations to reliably estimate anthropogenic emissions. The *in situ* data are also needed to minimize any systematic discrepancies between the various input data streams and the model components.

2.2.1 Direct estimation of fossil fuel emissions and natural fluxes

Observations of atmospheric CO_2 concentrations provide a means to estimate the distribution of net CO_2 fluxes between the land or ocean on the one hand and the atmosphere on the other hand. This is done through processes called data assimilation or inverse modelling, that use transport models simulating atmospheric motions to infer from the observed concentrations of CO_2 the net CO_2 fluxes at the Earth's surface (see e.g., Bergamaschi et al., 2018). By accurately modelling the winds, vertical diffusion, and convection in the global atmosphere, the observed concentrations of CO_2 are used to infer the surface fluxes at various spatial and temporal scales. While the majority of observations for the CO_2 MVS capacity will come from satellite-based sensors, *in situ* data provide complementary information to better constrain and separate the required fossil fuel emissions and natural fluxes. While limited in amount, *in situ* observations can record on a continuous basis CO_2 concentrations in the atmospheric boundary layer, which in turn are sensitive to changes in the local underlying fluxes and emissions. *In situ* observations also include measurements of constituents that are not directly observable from space, such as ^{14}C, a tracer to separate fossil fuel CO_2 from biospheric or oceanic CO_2. Furthermore, *in situ* observations can more easily be calibrated against internationally agreed reference standards than space-based observations. It is for these reasons that in situ observations should form an elemental and indispensable part of the MVS capacity.

2.2.2 Estimation of process-based model parameters

A further development for estimating CO_2 fluxes from *in situ* observations is the so-called Carbon Cycle Data Assimilation (CCDAS) method. Rayner et al. (2005) performed one of the first data assimilation studies that introduced this methodology. They demonstrated that high precision *in situ* data combined with a process-based model and a variational assimilation algorithm achieve a significant uncertainty reduction in parameter values as well as in the modelled net ecosystem productivity.

The same approach can be applied for estimating fossil fuel emissions in a so-called Fossil Fuel Data Assimilation System (FFDAS), where the interpretation of the data provided by a fossil fuel observing system relies on a process model capable of simulating fossil fuel CO_2 emissions. In that sense, an FFDAS does not directly solve the spatio-temporal distribution of fossil emissions; rather it optimizes unknown parameters in an emission model in order to minimize the mismatch between the model output and the observations.

As such, CCDAS and FFDAS are able to extract and to extrapolate information from a wider range of observations (*in situ* and space-based) than traditional transport inversion methods do. Also, by relying on the process-based models this approach includes additional information in the form of the process knowledge contained in the underlying models. However, any approximations in the process description or even missing processes would be reflected in the inferred parameter values, which makes the use of a wide range of *in situ* observations essential.

2.2.3 Calibration of the integration model

A data assimilation or an inversion system aims to combine the information from various observational data sets with information from prior knowledge (e.g., model forecast or climatology) by minimizing a cost function that takes the uncertainties of all the data sets into account. However, such a system generally minimizes the differences between the observations and the model simulations weighted by their respective uncertainties assuming unbiased input data. In reality, data sets often have systematic differences (biases) between them, which means that the data assimilation system will find a solution that is optimal in terms of minimal root mean square errors, but is sub-optimal in terms of the mean. It is therefore important to account for any remaining biases between the observations and the prior in order to derive a mean state that is as close to reality as possible. To achieve this, high-quality *in situ* data is a key input.

Biases in satellite data sets can result from the assumptions in the retrieval process, errors in the on-line calibration and drifts of the specific orbits, among others. Additional biases can come from errors in the atmospheric transport model or incorrect assumptions about elements of the anthropogenic and natural carbon cycle and associated fluxes. In the case of satellite observations, great care is taken in the calibration and validation of the observations because even sub-ppm biases result in disproportionately large biases in flux estimates (see chapter 3). A data assimilation system requires consistency between all input data sets that requests significant coordination between all data providers.

In addition, it is possible to include a bias correction within the data assimilation system itself. This is already common practice in numerical weather prediction and described in detail in for instance Dee (2005) and Dee and Uppala (2008). The various input data streams are bias corrected to a common baseline, which ideally is defined by a data set with high accuracy and precision. Here again, high-quality *in situ* data play a crucial role.

The most important requirement for *in situ* data for the above-described purposes is to have observations with high accuracy or low bias. The observations should sample the atmosphere as fully as possible. While vertical profiles such as provided by lidar systems, would be ideal in this respect, total column ground-based observations could be a significant step forward. In terms of horizontal coverage, the data should sample as much of the global variability as possible, but there is no strict requirement for a very dense network. Both vertical and horizontal sampling should be assessed within the framework of the integrated data assimilation system. It is clear that the ground-based observations of the concentration or mole fraction can provide the highest accuracy and stability, but not the required horizontal and vertical coverage. At the same time, column observations sample the full vertical extent of the atmosphere, but lack somewhat in accuracy relative to the flask measurements.

2.3 Validation of the outputs of the CO_2 MVS capacity

Box 3

Quality assessment of the outputs of the CO_2 Monitoring & Verification Support capacity are required in support of the uncertainty estimation of the end-to-end system. Enhanced *in situ* infrastructure for measuring CO_2 fluxes and concentrations and related atmospheric species is required in a few key urban areas to enable the validation of the outputs of the MVS capacity.

It is not only the generation of the satellite derived CO_2 observations that requires a dedicated validation programme relying on *in situ* data availability but also the end-to-end system for monitoring fossil fuel CO_2 emissions. As with any other data assimilation or inversion system there is also the need to assess, by independent means, the quality of the data products derived from the system that is, validating the outputs of the MVS capacity against independent data that are not used in the assimilation. This is another aspect where *in situ* data will play a pivotal role.

Undoubtedly, the envisaged system will use more than one data source in the assimilation and systematic differences between these data products will have to be evaluated with great care. Unbiased, or bias-corrected data are key to the performance of any data assimilation system, and it is particularly important in the case of CO_2, for which small systematic errors can lead to very significant errors in the flux results. Validation and inter-comparison between the assimilated observations therefore constitutes a crucial part of the operational processing chain and relies on the availability of *in situ* observations covering ideally the whole spectrum of observables.

Another aspect is that for a complex modelling system with a large number of unknowns (as represented by the control vector consisting of initial and boundary conditions, model parameters and state variables) not all elements of the control vector can be constrained by the assimilation. There may well be unobserved sub-spaces in the total control vector space which can possibly lead to the detoriation of some system variables / outputs. Therefore, the end-to-end system should not only be evaluated against its main output but as widely as possible given the quantities the system is capable of simulating and making use of *in situ* observations in addition to CO_2 concentrations. This is especially relevant for the estimation of process-based model parameters.

Direct micrometeorological *in situ* observations of the exchange fluxes of CO_2 between the Earth surface and the atmosphere as provided by for instance the FLUXNET network can in principle be used as independent information for the evaluation. FLUXNET is a global network of eddy covariance measurements of carbon dioxide and water vapor exchange fluxes between the Earth and the atmosphere. These FLUXNET measurement sites are organized through regional networks across the world. However, these measurements have footprints of the order of 100-2000 m and typically represent smaller areas than the outcomes of the inverse modelling systems do. About 40 micrometeorological tower sites, included in the FLUXNET infrastructure, are measuring CO_2 emissions in urban areas.

Furthermore, it is clear that the MVS capacity is required to also deliver uncertainty estimates of the outputs in order to be used and interpreted correctly (see e.g., Smith et al., 2014). It is therefore important to include an uncertainty estimation mechanism that takes into account the uncertainties in the inputs (e.g., the obervations and the prior information) and the uncertainties in the integration step (e.g., the model components and the data assimilation scheme). However, with a complex system as is envisioned, formally combining the uncertainties of all inputs and system elements into a final uncertainty estimate is far from straightforward. Often, approximations have to be made in this process. It is therefore crucial to validate the intrinsic uncertainty estimates with independent observations.

The main issue with the above is that accurate observations of emissions at the high spatial and temporal time scales required do not exist. It is however possible to establish dense *in situ* atmospheric CO_2 networks around a few key urban areas (cities and/or large emitting hotspots) that can be used with inverse modeling to establish a budget including the anthropogenic emissions. Stack monitoring near high emission plants also provide accurate information. Interpretation of data from urban *in situ* atmospheric CO_2 networks are subject to the uncertainties introduced through inverse modelling approaches but they are additionally subject to the contamination by very local sources nearby each station. An important aspect for the interpretation of the data from such networks is the internal consistency as any biases among the networks sampling sites will reflect on the inferred emissions. These networks could still act for selected large cities as a baseline for the MVS capacity which relies much more on satellite data to obtain global coverage.

In parallel, *in situ* data of CO_2 as well as related species such as carbon monoxide and nitrogen dioxide (both are co-emitted species from fossil fuel burning) can be used to assess the modelled atmospheric concentrations of these species from the MVS capacity. An inversion system that correctly estimates the underlying emissions should also provide accurate atmospheric concentrations which can be verified by *in situ* networks as long as these observations have not been used in the inversion itself. This asks for a careful assessment of which *in situ* observations are used for which part of the MVS capacity.

Finally, any integrated data assimilation modelling system will only optimize processes and parameters that are explicitly built in its model structure. Emissions from unexpected sources will lead to concentration signals, that might be attributed to wrong built-in model processes in the optimization. Both satellite and *in situ* observations will therefore be needed to identify missing sources, either within or outside the data assimilation system, in order to adapt the MVS capacity accordingly.

3. Estimation of CO_2 fluxes from global to urban scale based on existing *in situ* surface networks

Existing *in situ* networks were designed to evaluate the main patterns and trends of natural CO_2 fluxes at large scales, and have been enhanced during the last decade to constrain sub-continental natural CO_2 budgets. Such atmospheric CO_2 and co-emitted species networks are essential components of an end-to-end system for monitoring fossil fuel CO_2 emissions. These networks must be consolidated with additional targeted measurements and new stations to enable us to separate the contributions of fossil fuel CO_2 emissions from natural fluxes in atmospheric CO_2 concentrations must be added. Sustainability of the *in situ* networks must be reinforced. It is now recognized that the sparseness of the current networks does not sufficiently constrain estimates of fossil anthropogenic emissions. Enhancing networks with ^{14}C and fossil CO_2 co-emitted species observations across major fossil fuel CO_2 emitting regions is important for estimating fossil fuel emissions budgets, because this will provide complementary information to satellites for estimating anthropogenic emissions from hot-spots. Well-coordinated and inter-operable city and ^{14}C and tracers observation networks, beyond the current capabilities of the ICOS network must be developed in Europe. **Sustained availability of such *in situ*** observations reduces the risks **to operation and increases performance of the European CO_2 MVS capacity. This requires consideration of issues such as governance and enhancement of network sustainability.**

In this chapter, we summarize the capabilities achieved to date by current surface *in situ* networks with respect to natural CO_2 fluxes and wherever relevant to fossil fuel CO_2 emissions as well. As summarized in chapter 2, different methodologies exist. Section 3.1 to 3.4 describe in more detail the current status and *in situ* data requirements of direct flux/emission estimation systems at different spatial scales, while section 3.5 goes into more detail for the process-based model parameter estimation approach. In terms of *in situ* data requirements there is no significant difference between direct flux estimation and process-based model parameter estimation. The global CO_2 growth rate, which can be measured very accurately, monitors changes in the sum of global fossil fuel emissions and natural fluxes including enhanced ocean and land sinks. Estimation of one of these two fluxes requires knowledge and information on the other and clearly both estimates are intimately linked.

3.1 Global surface network to estimate large scale natural CO_2 fluxes

Box 4

The sparseness of the global *in situ* network does not provide sufficient constraints for estimating fossil fuel emissions related to anthropogenic activities.

Observations from the current global *in situ* networks provide a means to quantify the large-scale distribution of net CO_2 fluxes between the land and ocean on the one hand and the atmosphere on the other. This is done through atmospheric CO_2 inversions, which use global transport models of the atmosphere to link the observed concentrations of CO_2 to the net fluxes at the Earth's surface. By correctly modelling the atmospheric flow, vertical diffusion, and convection in the global atmosphere, observed surface *in situ* concentrations of CO_2 have to be used to infer the net surface-atmosphere fluxes at large spatial scales for the last four decades or so. CO_2 emissions calculated from statistics of fossil fuel combustion are typically prescribed in the inversion or subtracted from the net fluxes in order to estimate the natural CO_2 budgets of large scale terrestrial ecosystems.

The Global Greenhouse Reference Network (GGRN) consists of about 150 sites (of which more than 80 sites are active in 2019) operated by different institutions with the NOAA ESRL network being the largest contributing network (https://www.esrl.noaa.gov/gmd/ccgg/ggrn.php) (see also Annex 1). The observations can be grouped into flask air samples collected about once a week and analyzed at a central laboratory, and continuous measurements collected by on-site gas analyzers. The continuous measurement sites contain more information about sources and sinks than flask data, by virtue of their data density, but flasks have the advantage that they can be analyzed off-site for a variety of different radioactive and neutral compounds. The majority of stations are located in the marine boundary layer in the western Northern Hemisphere. Important regions, where natural CO_2 fluxes are likely sensitive to future climate changes are significantly under sampled. This severely hinders the ability of global inversions to infer robust natural CO_2 flux estimates over regions such as the Southern Ocean, tropical South America, tropical Africa, Siberia and the Arctic.

Nonetheless, global atmospheric inversions constrained by data from the global surface *in situ* networks provided key information about natural large-scale natural CO_2 fluxes, such as the existence of a northern terrestrial sink and the role of the tropical land in modulating inter-annual variability (Bousquet et al., 2000). Uncertainties on the budget of natural CO_2 fluxes, however remain too large, even at coarse continental scale, typically on the order to 50 to 100% of the mean.

Within the Copernicus programme, the Atmosphere Monitoring Service (CAMS) already provides estimates of global net CO_2 fluxes using observations from global and European networks. These flux estimates currently span the period between 1979 and 2017 and are updated on an annual basis.

3.2 Regional networks to estimate sub-continental natural fluxes

A relatively high density of continuous surface *in situ* stations has been realized during the last decade over the US, western Europe and China. High-frequency CO_2 variations recorded by such regional networks reflect smaller-scale features in surface CO_2 fluxes. Based on transport models with resolutions higher than those applied to global inversions (see e.g., Pillai et al., 2010; Kountouris et al., 2016a), regional inversions allow us to constrain the patterns of natural CO_2 fluxes at sub-continental scale, (see e.g., Broquet et al., 2011; Kountouris et al., 2016b ; Peters et al. 2007) in Western Europe and (Gourdji et al., 2012) in North America, and to evaluate the performance of ecosystem models (Fang et al., 2014). CO_2 fluxes have also been inferred over even smaller regions with very dense networks (see e.g., Schuh et al., 2013; Lauvaux et al., 2016). One study from Kadygrov et al. (2015), on the performance of networks of tall tower stations over Western Europe based on simulated observations, indicated that uncertainty reductions on natural CO_2 fluxes of up to 60% could be reached in large European countries where the stations coverage is the densest. However, these inversions of *in situ* CO_2 data from dense regional networks have been obtained in an idealized setting, where it is assumed that the space and time patterns of fossil fuel CO_2 emissions are perfectly known as *a priori* information, and that the only unknown fluxes are natural CO_2 fluxes.

In Europe, the Integrated Carbon Observation System (ICOS) Research Infrastructure (https://www.icos-ri.eu) (see also Annex 2) is a pan-European research infrastructure providing long-term, continuous observations of concentrations and fluxes of the greenhouse gases (GHGs) carbon dioxide, methane, nitrous oxide, and water vapour since 2017. The ICOS research infrastructure coordinates a network of 33 atmospheric stations (including 16 stations to be labelled during 2019). The ICOS Atmospheric Thematic Center is consistently processing all data using the same operational algorithms and ensuring full traceability to the WMO standards. Other networks in various European countries provide additional continuous CO_2 concentration data from about 30 sites. In addition ICOS operates eddy covariance measurements of CO_2 exchange fluxes between the atmosphere and the surface at around 70 sites.

Systematic airborne *in situ* observations derived from flask sampling or continuous analyzers on-board regular passenger aircraft provide high-frequency coverage of the troposphere and lower stratosphere. The In-service Aircraft for a Global Observing System (IAGOS) (https://www.iagos.org/) (see also Annex 3), a European research infrastructure, deploys newly developed high-technology instruments for regular in situ measurements of atmospheric chemical species (O_3, CO, CO_2, CH_4, NO_x, H_2O), aerosols and cloud particles. Airborne measurements of CO_2, CO, and CH_4 proposed in the context of IAGOS can provide profiles from take-off and landing of airliners near major metropolitan areas which are useful for understanding the impact of assumed vertical profiles (Boschetti et al., 2018).

In the same vein, the Comprehensive Observation Network for Trace gases by Air-liner (CONTRAIL) from Japan (http://www.cger.nies.go.jp/contrail/contrail.html) (see also Annex 4) provides a powerful observational platform for obtaining tropospheric CO_2 systematically for long periods of time over a large geographical space. *in situ* CO_2 measurements have been installed on several Boeing aircraft operated by Japan Airlines (JAL) with regular flights from Japan to Australia, Europe, East, South and Southeast Asia, Hawaii, and North America, providing large spatial data coverage, particularly in the Northern Hemisphere (Matsueda et al. 2002; Machida et al., 2008).

3.3 Regional surface networks to estimate sub-continental/ national fossil fuel CO_2 emission fluxes

Box 5

Enhancing the network with ^{14}C observations and providing the network for the incorporation of future continuous ^{14}C monitoring instrumentation present an important opportunity for determination of fossil fuel related emissions versus natural CO_2 exchanges and cycles.

Measuring ^{14}C concentrations in atmospheric CO_2 (radiocarbon) is the best approach identified so far for separating fossil CO_2 in the atmosphere from the signal of natural fluxes and hence for inversions to constrain fossil fuel CO_2 emissions (see e.g., Levin et al., 2003; Turnbull et al., 2006). Fossil fuels do not contain radiocarbon and their combustion releases CO_2 that is diluted with other CO_2 sources that actually contain ^{14}C. This dilution induces a measurable depletion of the ^{14}C isotope. The potential to monitor fossil fuel emissions of the Unites States using ^{14}C and CO_2 measurements was found to be very significant (NRC, 2010), even with a somewhat limited network of measurement locations (Ray et al., 2014). With current sampling of $^{14}CO_2$ measurements available in 2010 over North America (969 measurements per year) annual (monthly) means of these emissions were found to be constrained up to a precision of about 1% (5%) according to Basu et al. (2016).

With current technology, $^{14}CO_2$ measurements are performed *in situ* by collecting flask air samples, which are then analyzed in the laboratory mainly by Accelerator Mass Spectrometer (AMS). The ICOS infrastructure provides 2-week integrated samples of $^{14}CO_2$ measurements at about 19 stations with long term plans to increase similar measurements at 40 stations, soon to be supplemented by flask sampling of targeted source areas. In the future, a breakthrough may be achieved by new *in situ* spectrometers (Fleisher et al., 2017) capable to measure ^{14}C in CO_2 on a continuous basis. If the instrumental precision and accuracy are sufficiently high, those instruments would greatly alleviate the cost of flask sampling and AMS analysis.

The assimilation of and inversion against $^{14}CO_2$ measurements is complicated by the emissions from nuclear facilities (see e.g., Kuderer et al., 2018) and, for trends, by soil respiration from "old" carbon sources that bear a ^{14}C signature different from the contemporary atmosphere. Nuclear emissions are not so well known and may contaminate regional measurement stations, causing a bias in the retrieval of fossil fuel CO_2 emissions.

The current regional CO_2 monitoring networks may constrain regional /national budgets but will not provide information on emissions and emission trends from specific hotspots such as cities, industrial sites and power plants. Indeed these hot-spots generate plumes of CO_2 that are mixed by transport with natural CO_2 fluxes within distances (10 to 50 km) shorter than the current mesh of regional networks established in Europe, United States or China. The requirement to capture emissions from hotspots has prompted the development of urban CO_2 networks as summarized below.

3.4 Urban networks to estimate city-scale fossil fuel CO_2 emissions

Box 6

Enhancing the *in situ* network around cities presents an important opportunity for Europe to make progress in estimating city scale emissions.

Urban areas contribute a significant fraction of CO_2 emissions from fossil fuel burning and are expected to further grow in importance in the future (see e.g., IEA, 2008, Dhakal, 2009, IPCC-WG3, 2014), so that it is important that we collect surface *in situ* CO_2 measurements around and within large cities. This should go together with the development of high-resolution inversions to constrain urban emissions using atmospheric transport models. The performance of such urban inversion systems primarily depends on the quality of local emission inventories and density of atmospheric observations, emission models as well as the skill of urban-scale atmospheric transport models that link emissions to atmospheric signals. A number of cities have already established urban networks supported by research projects such as in Indianapolis, Boston, Los Angeles, Toronto, Paris, Berlin and Rotterdam (Duren and Miller, 2012; Gurney et al., 2015; Shusterman et al., 2016; Hase et al., 2015; Super et al., 2017a and b; Zhao et al., 2019). Current urban inversions rely on high-resolution inventories of carbon emission at hour- and kilometre-scale resolution, high-precision measurements of atmospheric carbon dioxide and modelling of mesoscale atmospheric transport (Bréon et al., 2015; Lauvaux et al., 2016; Staufer et al., 2016). The uncertainty in monthly inventory emission estimates could be reduced by up to 50% by integrating information from atmospheric observations with *a priori* knowledge of emissions in the inversion procedure. With about 10 high-precision sensors in the city of Indianapolis, the inferring system suggested possible omission in inventories, a default scarcely to be traced beforehand while compiling carbon emissions for dozens of activity sectors of urban activities (Lauvaux et al., 2016; Gurney et al., 2017). While it is difficult to distinguish anthropogenic emissions from natural flux variations at regional and global scales, at the city scale, the atmospheric signals are large enough (typically 5-15 ppm) to shed light on separating the anthropogenic from biogenic sources.

Typically, these urban networks implement high-precision *in situ* observations. Various observing systems have been tested in some cities, for example, ground-based total column (in Boston, Berlin and Paris), continuous carbon stable isotope measurements (in Toronto) and lower-cost sensors (in San Francisco). Observing System Simulation Experiments (OSSE's) have also been conducted to demonstrate the value of such novel (dense) networks (Wu et al. 2016; Lopez-Coto et al. 2017), when attempting to quantify emissions for specific activity sectors. Other studies have used observations of co-emitted species or carbon isotopes to quantify activity sector contributions (see e.g., Turnbull et al. 2016; Lopez et al. 2013; Vardag et al., 2016; Pugliese et al. 2017; Super et al., 2017b). As this field continues to grow, the WMO established a dedicated working group to promote and coordinate these efforts within the Integrated Global Greenhouse Gas Information System (IG3IS) (https://ig3is.wmo.int/).

Some countries also have started to foster collaboration across their cities, for example within the CO_2 Urban Synthesis and Analysis (CO_2-USA) network (http://sites.bu.edu/co2usa/). A key deliverable of such collaborative programs is to establish best practices and to help transform research successes into solutions relevant for stakeholders. No such "inter-city" coordinated urban atmospheric CO_2 program exists in Europe, although the implementation plan of IG3IS has a specific action about urban CO_2 networks and the private sector shows interest for mapping urban CO_2 emissions with very high-resolution data down to building and road scale.

3.5 Process-model parameter estimation at all scales

Box 7

Employing models that calculate CO_2 fluxes is an alternative approach to the direct flux estimation. This approach makes use of additional process information as included in the model and needs to be calibrated using a range of *in situ* and remote sensing observations.

In contrast to the direct estimation of fluxes/emissions by transport inversions, process-model parameter estimation is less dependent on the spatial scales because of the underlying process model. This has, for instance, been demonstrated by Wu et al. (2018) who estimated process parameters with a CCDAS at site scale and then used these parameters for global scale simulations with a process model. As noted above, however, any data assimilation modelling system will only optimize model parameters of processes that are explicitly built in its model structure. Emissions from unexpected sources will lead to concentration signals, that might be attributed to wrong built-in model processes in the optimization. Both satellite and *in situ* measurements will therefore be needed to identify missing sources, either within or outside the data assimilation system, in order to adapt the MVS capacity accordingly.

In the context of process model parameter estimation for the natural terrestrial biosphere GHG fluxes, data assimilation systems such as CCDAS are capable of assimilating, in addition to atmospheric CO_2 observations, other independent data such as eddy-covariance measurements of exchange fluxes between the Earth's surface and the atmosphere provided by regional infrastructures such as the European ICOS or the global FLUXNET network. Various studies have shown the potential of assimilating observations of either CO_2 or energy surface atmosphere exchange fluxes from eddy covariance measurements in constraining model parameters (see e.g., Knorr and Kattge, 2005; Williams et al., 2005; Kato et al., 2013; Xiao et al., 2014). Other examples for multiple data assimilation include the combination of *in situ* eddy covariance flux observations and ecological observations (such as Leaf Area Index, litterfall and carbon stocks; e.g. Richardson et al., 2010; Keenan et al., 2012) or eddy covariance flux observations and biomass inventory observations (Thum et al., 2017).

In the context of process model parameter estimation for fossil fuel emissons Rayner et al. (2010) have developed a FFDAS based on national statistics of fossil fuel CO_2 consumption and other census data to estimate fossil fuel CO_2 emissions based on the Kaya identity (Kaya, 1990; Nakicenovic, 2004), which relates CO_2 emissions from human sources to population density, per capita economic activity, energy intensity of the economy, and carbon intensity of energy. As observations, they used remotely sensed nightlights and *in situ* data for population density, per capita gross domestic productivity and energy intensity of the economic productivity. Nightlights data correlate with fossil fuel emissions (Doll et al., 2000) and are assumed to be proportional to the real density of energy consumption (Raupach et al., 2010), which can be expressed as the product between population density, per capita gross domestic product and energy intensity.

This system can be further refined by estimating the emissions processes per activity sector as shown by Asefi-Najafabady et al. (2014) who separated the emission processes into a power generation and an 'other' sector and by doing so requiring an additional pointwise *in situ* database of global power plant emissions with improved information and individual power plant uncertainties. In principle, further sectors can be addressed such as the transport sector, which requires additional *in situ* observations of major roads provided by detailed global road atlases as well as other traffic information mentioned above.

3.6 Gap analysis

3.6.1 Current situation

Box 8

Existing global and regional atmospheric CO_2 networks are essential components of the CO_2 Monitoring & Verification Support capacity. These networks must be consolidated with addition of other relevant measurements and more stations and their sustainability must be reinforced.

As outlined in the previous chapter, *in situ* observations will play a crucial role in any inversion system that is focused on anthropogenic emissions of CO_2 and the global carbon cycle. While satellite observations can provide global coverage over cloud-free regions, they lack the capability to provide information about the vertical distribution of atmospheric CO_2 and especially about near-surface concentrations, which are most sensitive to changes in emissions. It is therefore recommended to exploit all existing relevant *in situ* capabilities and extend them as appropriate.

In situ observations are supported by a diversity of funding mechanisms. This had led to a skewed distribution of *in situ* observations that is biased towards the most developed/industrial countries such as USA, Western Europe and China. This is not necessarily a bad thing, since these countries also currently contribute most of the global fossil fuel CO_2 emissions and *in situ* regional network infrastructure are already in place to monitor natural CO_2 fluxes. However, the focus of these networks has been mostly on obtaining a better understanding of the natural carbon cycle and locations of individual stations are therefore selected to a large extent to cover this aim. In addition, many important regions of the world such as the tropics are largely undersampled. Apart from a few limited studies there has not been any focus on creating *in situ* networks around specific emission hot spot areas. They should thus also be extended towards monitoring in emerging economies such as India, Brazil and in Africa.

The investment costs of a full atmospheric station is around 450 thousand Euros (ICOS Handbook, 19 May 2019) with the possibility of a reduced setup costing about 60% of that. On top of the investment cost are operating costs which may amount to 9 person months of service per year. Flux sites vary more in their cost, depending over which surface they cover: a forest site would amount to 570 thousand Euros, with a grassland site up to 380 thousand Euros. Again a reduced setup would be around 60% and also person power for maintenance comes in at an annual additional costs. Installing an additional 50 atmospheric sites would require an investment budget of around 22.5 million Euro (excluding annual maintenance, which may be estimated at 3 million Euros per year).

In situ observation networks to monitor pollutants for air quality purposes and regulations provide information on emitted species such as NO_2 and aerosols. These urban networks already operate to some extent in operational frameworks and are part of countries' efforts to mitigate air quality problems which are highly relevant for the mitigation of CO_2 emissions as well.

These observations can therefore be exploited through partially known correlations between co-emitted species and CO_2. Capabilities of global networks set up to monitor the impacts of the Montreal Protocol and the Comprehensive Test Ban Treaty Organisation, measuring series of anthropogenic chemicals, e.g. the global network for F-gases of the Advanced Global Atmospheric Gases Experiment (AGAGE) (https://agage.mit.edu/global-network) could also be extended to include additional measurements relevant for supporting the MVS capacity.

Global collaboration efforts on *in situ* observations and networks (e.g., via WMO-GAW and in particular its IG3IS program) aim to favor the development of regional networks, and the densification of networks to diagnose CO_2 fluxes from sub-continental scale down to national scale, such as achieved in few countries. However, this relies on national contributions from countries in these areas or support from other countries. The lack of sustained funding for essential *in situ* observation networks is in contrast with the set-up of a large scale activity to monitor anthropogenic CO_2 emissions in the context of an operational program.

3.6.2 Missing elements

Box 9

Well-coordinated networks in the vicinity of intense emission areas , beyond the plans to increase the current capabilities of the ICOS network, must be developed in Europe to accurately monitor radiocarbon (^{14}C).

Improving the capability of the system to detect fossil fuel emissions from city and point sources requires a rethink and replanning of the existing networks. For this purpose the ICOS network needs to be upgraded with an estimated 40 to 80 radiocarbon measurement stations that preferably should be colocated with the current ICOS regional network and perform bi-weekly integrated measurement frequency (see also section 3.3). Such a network extension for Europe is indeed currently being planned in ICOS.

Preliminary, often campaign-based, studies have shown the potential for using enhanced *in situ* networks around cities to determine fossil fuel CO_2 emissions annual budgets. To achieve this and provide sustained access to such data several additional measures are needed. Urban *in situ* networks for selected large cities or urban areas in Europe, based on existing efforts and networks in the cities such as those of Berlin, Rotterdam, Paris should be installed. These data should be available in a form that can be readily assimilated in high-resolution inversions and thus provide an independent evaluation of satellite-based city emissions. This requires improved intra-European coordination with an “inter-city” programme to develop robust and scalable methodologies for inter-comparison, evaluation and improvement of urban CO_2 inversion methods. Such a programme could involve the private sector and would be a very useful component of the IG3IS initiative, while providing data exchange from different countries and regions and inter-operability.

In the medium term, preparing for the second and third stock take of the Paris agreement, a further refinement of the *in situ* network is foreseen. Here we envisage about 80 radiocarbon measurement stations, with progressively more stations located in the vicinity of regions with intense and frequent emissions. If the development of online ^{14}C measurement has continued to a level that the instrumentation can be deployed routinely, a considerable increase in temporal sampling can be achieved at these sites. Relevant trace gases measurements, including some reactive gases like CO and NOx can be used to further constrain fossil fuel CO_2 emissions. This requires taking stock of existing and future Air Quality networks and infrastructures and, where possible, collocating these with the newly planned stations.

Europe could, by implementing these measures in the medium term, develop urban *in situ* networks for a much larger number of cities or urban areas in Europe, preferably for say, the 20 largest emitting urban areas in the EU. Well-characterized low cost CO_2 sensors may help to extend the high quality urban CO_2 measurements when they are collocated with current Air Quality stations in cities and part of the system design.

4. *In situ* observation requirements for the Copernicus space component of the CO_2 MVS capacity

A main challenge of the Copernicus CO_2 Monitoring & Verification Support capacity is meeting the stringent overall end-to-end performance, including the calibration and validation of the space-based system. In-orbit verification of the space component, which will be composed of several satellites and traceability to on-ground calibration and characterisation is key.

It is therefore imperative to ensure that the required *in situ* observation system is in place in terms of observational capability with appropriate temporal and geographical coverage. For the relevant precursor greenhouse gas missions, *in situ* validation has been an integral part of the missions and their success. A baseline system could be built upon the existing networks, specifically TCCON (Total Carbon Column Observing Network) supplemented by COCCON (COllaborative Carbon Column Observing Network), AeroNet (AErosol RObotic NETwork) and Aircore observations. However, these networks as available today do not meet all operational requirements for the European CO_2 support capacity and therefore may imply important risks in achieving all its objectives. These capabilities should therefore be further expanded in order to meet the full requirements of the foreseen system. **The highest priority is to ensure coordinated governance and sustained operational funding.**

4.1 The European Copernicus Sentinel CO_2 monitoring constellation

Achieving the overarching goal of monitoring anthropogenic CO_2 emissions implies that the observing capabilities for atmospheric concentrations of CO_2 need to be expanded. Dense and frequent measurements from space-borne instruments will become an essential component of the proposed operational support capacity for monitoring anthropogenic CO_2 emissions (Ciais et al., 2015; Pinty et al., 2017).

The space-borne sensors will routinely acquire observations with global coverage under clear-sky conditions with a density and a periodicity adequate to resolve both natural and anthropogenic emissions. The requirements for the space-borne elements of a CO_2 monitoring constellation include high resolution imagers - of dry air column-averaged mole fractions of CO_2 (denoted as XCO_2)- with high spatial resolution (4 km^2), individual sounding precision of 0.7 ppm and absolute bias of less than 0.5 ppm. The objective is to acquire global operational images of XCO_2 and XCH_4 distributions at daily to weekly intervals –revisiting period within 2 to 3 days as a minimum at mid-latitudes- implying a deployment of at least 3 medium-swath (300-400 km) imagers in Low Earth Orbit (LEO). It should be noted that the number of usable measurements will be less than the revisit time due to clouds, and poor illumination at high latitudes in winter. Planned auxiliary instruments on the same satellite platforms as the CO_2 imager target NO_2 measurements for locating plumes from point source and city emissions where NO_2 is co-emitted with CO_2. Furthermore, measurements of aerosol parameters are required to retrieve XCO_2 with the required accuracy and to identify areas with low to medium aerosol loading, and a cloud imager to filter out measurements contaminated by low clouds and high altitude cirrus. The technical specifications associated with these observations for the Copernicus CO_2 monitoring (identified as CO2M in some documents) mission are provided in the Mission Requirements Document[12].

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[12] 'The MRD is an evolving document. The latest version is available from ESA upon request and can also be found online at https://www.esa.int/Our_Activities/Observing_the_Earth/Copernicus'

The mission objectives and the scientific and technical specifications push the need for highly accurate space-borne observations – as the case for any other greenhouse gas space-based mission-, which in turn push the requirements for their calibration and validation (cal/val) to a quite demanding level. Methods to achieve and maintain high accuracy to traceable fiducial standards are therefore key drivers in the implementation and operation strategies for pre-launch and on-orbit calibration, retrieval algorithm development, and data product validation approaches.

This chapter focuses on the needs and requirements for the in-orbit calibration monitoring and the validation of the main products, i.e. column-averaged CO_2 (XCO_2) in ppm and column-averaged CH_4 (XCH_4) in ppb, as well as the auxiliary and ancillary by-products.

4.2 Requirements analysis

4.2.1 CO_2 and CH_4 retrievals

Retrieval algorithms for XCO_2 and XCH_4 require highly accurate radiance and irradiance spectra. Directly after launch, it is imperative to trace the in-orbit calibration to the pre-flight calibration and to verify the stability requirements. This necessitates deployment of extensive in-orbit calibration systems, calibration campaigns and routine comparisons using vicarious calibration methods together with radiometric reference sites (e.g., Kuze et al., 2014; Crisp et al. 2017). The requirements of the planned Copernicus CO_2 monitoring (CO2M) mission are expected to be of similar nature as heritage missions such as Orbiting Carbon Observatory-2&3 (OCO-2&3), Greenhouse Gases Observing Satellite (GOSAT) and the Chinese Carbon Dioxide Observation Satellite Mission (Tansat) but with higher precision and better coverage and will need to be secured and implemented on an operational basis.

It should also be mentioned that as long-term monitoring of the mission is critical, measurement precision (repeatability) becomes crucial. As vicarious calibration using surface targets is required, it will not be sufficient to characterize the reference sites at a single moment in time, but the seasonal / annual behaviour will also have to be addressed.

In terms of XCO_2 and XCH_4 product validation, the data can be grouped along two lines. The larger scale applications require less precision from an imaging mission but strongly rely on data with very low bias. The smaller scale applications require imaging capability with very high precision but in this case the larger temporal and spatial resolution biases have a small impact. In polluted areas and areas with high emissions, the data quality will depend on the capability of the retrieval algorithm to simulate the actual situation including the vertical distribution of the trace gases and aerosols.

Dependency parameters impacting the retrievals and those correlating with the plumes need to be subjected to frequent validation in both background and polluted sites. This becomes further evident when these measurements are then combined with collocated satellite-based measurements where significant error contributions come from inaccurate knowledge of the Bidirectional Reflectance Factors (BRFs) (Kataoka et al, 2017). At such stage the pointing and geolocation accuracy of the space based observations also becomes critical, particularly in areas with strong variability in the local topography and surface properties like the surface albedo and the BRF as shown in Wunch et al. (2017).

4.2.2 NO_2 retrievals

The Copernicus Sentinel-5 Precursor mission is currently measuring NO_2 at a spatial resolution of approximately 25 km^2 providing first insights in associated plumes. Several other missions measuring NO_2 are planned, including the geostationary Copernicus Sentinel-4 and the low Earth orbit Sentinel-5 missions hosted on EUMETSAT (European Organisation for the Exploitation of Meteorological Satellites) satellites. Within that context, extensive calibration and validation plans are under preparation and can also be exploited for the Copernicus CO_2 mission. The dedicated validation activities for these missions will rely on airborne sensors and ground-based spectrometers, sun-photometer and lidar measurements. They further rely on meteorological imagers and ground based ceilometers for observations on cloud fraction, optical depth and height, in order to assess the impact of clouds and/or to enable cloud-free observations. The use of these validation activities can be explored for the Copernicus CO_2 mission. The primary objective for measuring NO_2 for the Copernicus CO_2 mission is to locate the CO_2 plumes and to separate them from the CO_2 high-level background. This application is rather straightforward given that, by contrast with the fossil fuel CO_2 emissions, the enhanced NO_2 levels are high with respect to the background. The NO_2 product can also be extremely useful in itself for air quality applications or can potentially be exploited for CO_2 by investigating emission ratios. Depending on these secondary objectives, the absolute quality of the NO_2 data product becomes relevant.

4.2.3 Aerosols correction and sub-pixel cloud identification

The multi-angle polarimeter and the cloud imager currently planned to be on board the Copernicus CO_2 mission provide vital information to obtain highly accurate XCO_2 and XCH_4 data. There is heritage in missions like Polder and Parasol, and the upcoming 3MI (Multi-viewing Multi-channel Multi-polarization Imaging) mission on EUMETSAT Polar Satellite Second Generation (EPS-SG) will require very similar product validation requirements as for the Copernicus CO_2 mission. For clouds and aerosols the required data sets can be analysed, building around other existing initiatives like the Coordination Group for Meteorological Satellites (CGMS) International Cloud Working Group (ICWG) having extensive access to various data sets and performing regular algorithm and product inter-comparisons and quality assessments. Furthermore, there is an opportunity to capitalise on the observations performed for the NO_2 retrievals for clouds and aerosol. For aerosol, in addition to coordinating activities for algorithm development and inter-comparison, the activities should also build on the approaches to be prepared for EPS-SG 3MI. Specifically there is a need to combine ground-based column instruments with coincident aerosol sensors to allow validating XCO_2 in the presence of aerosol information.

4.2.4 Ancillary retrievals

The rigorous validation of satellite-derived Sun Induced Fluorescence (SIF) is challenging due to the lack of *in situ* datasets enabling us to perform direct comparison exercises. It is however possible, as a surrogate, to take advantage of the linear relationship observed at coarse spatial and relevant temporal scales between the SIF and the terrestrial Gross Primary Production (GPP). This allows us to evaluate the consistency between SIF retrievals and ground-based GPP observations (see e.g., Frankenberg and Berry, 2018; Koffi et al., 2015, Madani et al., 2017). Although this relationship depends on vegetation stress conditions (Wieneke et al., 2018), this check helps assessing the confidence in the consistency between space and flux tower derived information. For all practical purposes, GPP estimated from flux tower measurements are available worldwide thanks to Fluxnet (see e.g., Sanders et al., 2016).

It must be noted that O2-A band based SIF observations are possible from drones and aircraft as well. Both platforms can provide data over relevant spatial scales but most likely under a viewing geometry that differs from the space-based observations. Ground-based O2-A band based SIF measurements are currently carried out at a number of places including in conjunction with tower observations. This approach could thus provide an additional resource for SIF validation.

4.3 Gap analysis

4.3.1 Current situation

Box 10

The TCCON and AERONET networks, the COCCON and the AirCore instrumentation are essential components to achieve the calibration and validation of observations and products delivered by the space component of the Copernicus CO_2 Monitoring & Verification Support capacity.

Here we present the current situation regarding available observation networks for calibration and validation of the main satellite derived products. A short description of each network is provided below and summarized in Annexes 5 , 6 and 7 of the current report.

The main contributing network used for heritage missions is the **Total Carbon Column Observing Network (TCCON)** (see Annex 5). TCCON (Wunch et. al., 2011) is a global-network of ground-based Fourier Transform Spectrometers (FTS) that provide column-averaged measurements of XCO_2, XCO, XCH_4, XN_2O under clear-sky conditions and other molecules that absorb in the near infrared. As of 2018, TCCON consists of 24 stations in North America, Europe, South East Asia, Australia/ New Zealand and some islands in the Atlantic and Indian Ocean. There are only 5 stations in the Southern Hemisphere while South America, Africa and Central Asia are currently not covered. New sites are admitted into the network after site investigators have demonstrated that they use the required hardware, follow the data processing procedures and pass all quality checks. Uniformity is maintained across the network by using the same FTS model and the same retrieval software. The TCCON instruments are calibrated against the WMO GHG *in situ* scale maintained by NOAA by taking airborne *in situ* profiles above the stations whenever possible (Messerschmidt et al., 2011). The TCCON activities in North America and Australia are mostly funded by NASA (National Aeronautics and Space Administration) as part of the OCO-2 mission. Many sites in Asia are funded through the Japanese GOSAT mission. However, in Europe most TCCON stations depend on institutional and competitive external funding.

The **COllaborative Carbon Column Observing Network (COCCON)** (Frey et al., 2018) instrumentation provides careful testing of and operational procedures for spectrometers using common quality assurance measures (see Annex 6). Applying common quality assurance measures and based on a long-term inter-comparison of column-averaged greenhouse gas abundances, Frey et al. (2018) concluded that the EM27/SUN spectrometer offers highly stable instrument characteristics on timescales of several years. The favourable instrument stability which is preserved even during transport events and operation under ambient conditions suggests that the EM27/SUN spectrometer is well suited for campaign use and long-term deployment at very remote locations as a supplement for the existing TCCON network in remote areas. However, long-term operations in remote areas have not really been demonstrated yet and cannot be expected to be much easier than running a TCCON station. Most TCCON stations are fully automated while COCCON instruments typically require an operator. Getting COCCON instruments to a similar level of automation and autonomy will likely be a comparable effort. Whilst current COCCON activities that provided inter-comparisons of 30 instruments have been supported by the European Space Agency (ESA) and the aim is to have an operational implementation, it is still a research network for which long-term sustained funding is to date not secured.

The **AirCore system** (see Annex 7) (Karion et al., 2010) stems from an idea originally developed by Tans (2009) in using a long tube descending from a high altitude with one end open and the other closed to retain a mole fraction profile of a gas to be analysed at a later stage (see annex 7). The current AirCore evacuates to ambient pressure as it ascends to approximately 30 km. As the AirCore descends through the atmosphere under a balloon or a parachute, surrounding air flows into the AirCore tube to maintain equal pressure with the air outside. In order to fully validate the retrieved total column at the level of precision required by carbon cycle studies, it is necessary to use independent *in situ* measurements of GHG profiles, especially in the upper troposphere and lower stratosphere regions and above. As AirCore samples the vertical profiles of CO_2 and CH_4, it will also be very useful in the validation assumptions made in the airmass factor in the retrieval algorithm. AirCore deployment has limited global coverage and is frequently related to specific scientific campaigns, which currently rates it as a research activity. In order to optimise the benefits regular AirCore ascents should be performed at a significant number of reference stations such as those implemented in the framework of TCCON and COCCON.

Whilst the existing networks, primarily TCCON, COCON and AirCore provide significant support for ground-based validation activities for column integrated products such as XCO_2 and XCH_4, it should however be noted that there is only a limited number of stations and these stations are not covering all climate or environmental regimes. It is therefore important to span the full dynamic range from bright deserts to dark vegetation/ocean, and cover different aerosol regimes as well in order to develop accurate retrieval algorithms that provide full traceability from the observed reflectances to the retrieved geophysical products. Due to station-to-station variation within TCCON, it is mandatory to inter-calibrate the instruments at reference sites, which could be achieved using portable calibration instruments and approaches as proposed with COCCON, and to maintain a traceability to the WMO GHG scale by aircraft vertical profiles plus Aircore profiles over selected sites.

The aerosol by-product information required to enhance the accuracy of the XCO_2 and XCH_4 retrievals can be partly validated using the **AErosol RObotic NETwork (AERONET)** (see Annex 8). AERONET is a federation of ground-based remote sensing aerosol networks established by NASA and PHOTONS (PHOtométrie pour le Traitement Opérationnel de Normalisation Satellitaire; Univ. of Lille 1, CNES, and CNRS-INSU) and is greatly expanded by other networks and collaborators from national agencies, institutes, universities, individual scientists, and partners. For more than 25 years, the project has provided long-term, continuous and readily accessible public domain database of aerosol optical, microphysical and radiative properties for aerosol research and characterization, validation of satellite retrievals, and synergism with other databases. The network imposes standardization of instruments, calibration, processing and distribution. AERONET collaboration provides globally distributed observations of spectral aerosol optical depth, inversion products, and precipitable water in diverse aerosol regimes. The (WMO) GAW Aerosol Lidar Observation Network (GALION)[13] offers a coordinated complementary database for aerosols.

4.3.2 Missing elements

Box 11

The existing TCCON network must be geographically expanded to cover a wide range of environmental and ambient conditions. In addition, routine COCCON and monthly AirCore measurements must be performed at some selected sites including the TCCON stations.

Validation approaches rely on highly accurate ground-based observations. As noted by Rayner and O'Brien (2001) and confirmed by ESA (2016) a precision of 0.25% or better is required to improve the understanding of the carbon cycle, however a precision down to 0.1% is required to assess the Northern Hemisphere carbon sink (Olsen and Randerson, 2004). Whilst TCCON has taken these requirements on board (the XCO_2 measurement precision varies from site to site but is generally less than 0.25% (which is close to 1-sigma) for single measurements and solar zenith angles less than 82 degrees), it is to be confirmed whether it is sufficient for the Copernicus CO_2 mission. It is therefore mandatory to inter-calibrate the instruments at reference sites, which could be achieved using portable calibration instruments and approaches as adopted in COCCON. The COCCON instruments have good long-term stability and may, in addition, to be used for inter-calibration purposes as well as to complement the TCCON network (Frey et al., 2018).

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[13] https://www.wmo.int/pages/prog/arep/gaw/documents/gaw178-galion-27-Oct.pdf)

The measurements at validation sites should, as much as possible, be complemented by aircraft and balloon measurements, like those delivered by CONTRAIL and IAGOS for instance and from AirCore, respectively. There is also a need to analyze the required temporal frequency and geographical coverage (in terms of reference stations) required to satisfy the validation needs of the Copernicus CO_2 mission. Furthermore, the characterization of the environment of reference stations like the TCCON stations is critical.

As shown for GOSAT and OCO-2, the approach to fiducial reference radiometric standards was key for the current success of these missions (Rosenberg et al., 2018) and these standards will have to be taken a step further, including on-ground instrument cross-calibration of the full constellation of the Copernicus CO_2 mission. Therefore, in order to ensure high-quality laboratory measurements of the instruments, characterization of line-shape and intercalibration of instruments, further improvements in spectroscopy and radiative transfer modelling are required as well as close links with the metrology community.

The foreseen applications for the Copernicus CO_2 mission span a range of scales, from point sources to country scales. This is adding extra requirements on the ground-based network in terms of coverage and availability:

- Regional and country-scale applications can be addressed with an extended TCCON network. There should also be a strong buy in from other countries which requires international coordination and dialogue;
- For city-scale and large industrial infrastructures, there is a need to validate the gradients up and downwind of the emitting sources. This can be achieved using portable instruments together with other longer-term installations around selected areas. For this application the mapping capability is crucial and this requires the support of airborne mapping instruments, like ACADIA (Airborne CArbon Dioxide Imager for. Atmosphere), MAMAP-2D (Methane Airborne MAPper – 2D), AirSpex (Airborne Spectropolarimeter for Planetary Exploration) or AirMAP (Atmospheric Investigation, Regional Modeling, Analysis and Prediction);
- Point sources such as power stations might be best sampled with aircraft campaigns.

Further research studies are required for assessing the suitability of the TCCON instruments *per se* as well as the geographical distribution of the stations in order to increase the capacity of the network to represent a diversity of geophysical conditions. Dedicated activities related to calibration of different instruments to be used at reference stations must also be conducted.

5. *In situ* observation requirements regarding the CEOS virtual constellation

In the context of the envisaged Copernicus CO_2 monitoring & verification support capacity it has been clearly understood (see Ciais et al., 2015) that the international dimension of the initiative would be critical and that this aspect should be developed in parallel to, and in synergy with the definition and implementation of an eventual European system.

It was also understood from early on that this international dimension had both strategic, policy relevant and technical dimensions and the Commission and the relevant European institutional partners have started since several years to engage both bilaterally and multilaterally with the relevant stakeholders and counterparts to develop these relations.

This is particularly true in the context of the Space Agency coordination activities where the European Commission acting as Chair of CEOS in 2018 has advanced the **coordination of GHG monitoring as a priority** and has led the creation of a longer-term coordination mechanism amongst agencies on these topics. This included the successful completion of a whitepaper on requirements of a GHG monitoring constellation at global scale, which provides the blueprint for international coordination activities going forward.

In the context of the current report this envisaged international engagement aims to mitigate several areas of risk identified in earlier chapters and to add efficiencies and redundancies in the realization of the overall system.

Some key areas where this is relevant include: the need for relevant *in situ* data for the required sensor inter-comparison and inter-calibration activities, the necessary non-EU *in situ* data needed for the integration sub-system and data assimilation and finally data required for the use of third party mission calibration and validation both in the system prototyping and pre-operational phase, that is before the launch of the dedicated Sentinels.

The risks on the international dimension itself are primarily in the implementation mechanisms adopted and the success of the necessary international coordination. Careful attention will have to be placed on the types of agreement made, the key partners identified and the leading role that European institutions are able to play within the international coordination frameworks where possible, in order to ensure the accessibility and operational delivery of the required *in situ* datasets.

5.1 Global *in situ* infrastructure coordination

Recognizing the need for a coordinated global system to monitor the carbon cycle's response to both human activities and the changing climate, the Group on Earth Observations (GEO) commissioned the *GEO Carbon Strategy* (Ciais et al., 2010). This report called for an Integrated Global Carbon Observing system (IGCO) within GEO and the Global Climate Observing System (GCOS) that would incorporate advanced ground- and space-based observations to meet the increasingly pressing needs for policy-relevant scientific information. The Committee on Earth Observation Satellites (CEOS) responded to the GEO Carbon Strategy report by convening a Carbon Task Force (CTF), which compiled the *CEOS Strategy for Carbon Observations from Space* (hereinafter, CEOS Carbon Strategy). The CEOS Carbon Strategy report documents the state of knowledge and measurement requirements for the atmospheric, oceanic, and terrestrial domains and their interfaces, and identifies several actions to be completed by its member agencies.

Given the recent progress with SCIAMACHY, GOSAT, and OCO-2, in 2017 the Chair of CEOS recognized that high-quality observations of atmospheric CO_2 and CH_4 could be an essential component of an integrated global carbon observing system, such as that advocated by the World Meteorological Organization (WMO) through the Integrated Global Greenhouse Gas Information System (IG^3IS). In such systems, the space-based XCO_2 and XCH_4 estimates complement the spatial resolution and coverage of the ground-based and airborne *in situ* measurements. If the ground-based, airborne, and space-based datasets can be harmonized, they can be assimilated into atmospheric inverse systems to yield top-down global inventories of CO_2 and CH_4 fluxes with the accuracy, precision, resolution and coverage needed to serve as a complementary system for estimating trends reflecting implementation of the Nationally Determined Contributions (NDCs). In addition, if these atmospheric data products were distributed freely and openly, in compliance with the CEOS data policy, they could support the transparency framework designed in the Paris Agreement.

5.2 Inter-calibration and inter-comparison

Over the last decade and a half, research missions have provided considerable insight into instrument calibration, validation and the broader aspects of uncertainty quantification and quality control. In the short-term, these lessons represent best practices that should be extracted and generalised by the CEOS/CGMS Working Group on Calibration and Validation (WGCV) and the Global Space-based Intercalibration System (GSICS) so that they are available as Calibration-Validation strategy protocols for space agencies that are now preparing missions.

The strategy for cross-calibrating the GOSAT and OCO-2 instruments has employed common standards, including observations of the sun, moon, and surface vicarious calibration sites, such as Railroad Valley, Nevada, U.S.A. Additional efforts by WGCV and GSICS is needed to maintain and improve the quality of these standards to better address the calibration needs of space-based CO_2 and CH_4 sensors.

TCCON (see Annex 5) has provided the primary transfer standard to relate space-based XCO_2 and XCH_4 estimates to the ground-based in situ standards maintained by the WMO GAW network. The insights gained through studies on GOSAT and OCO-2 has underlined that this network must be maintained and augmented using portable, ground-based remote sensing instruments (e.g., EM27/SUN), in situ sensors on fixed-wing of commercial aircraft (as the case with measurements provided by CONTRAIL (see Annex 4) and IAGOS (see Annex 3) and balloons (e.g., AirCore ; see Annex 7), and airborne remote sensing instruments (MAMAP, CHARM-F and others) to provide a robust and accurate operational validation approach.

To identify, characterize, and mitigate the impact of instrument, geophysical, or methodological biases in the space-based XCO_2 and XCH_4 estimates, both internationally recognized validation standards and validation protocols are needed. The ground-based and aircraft-based in situ CO_2 and CH_4 measurements available through the WMO GAW program play a critical role in this activity, but they cannot be used directly because they describe the concentrations of the species at a single point location or along a horizontal or vertical flight path, while the space-based results refer to an atmospheric optical path that extends from the top of the atmosphere to the surface and back to the spacecraft. The ground-based XCO_2 and XCH_4 estimates retrieved from the measurements collected by the TCCON or COCCON FTS instruments (see Annex 5) provide a transfer standard between the space-based estimates and the WMO GAW standards.

Retrievals of XCO_2 and XCH_4 from satellites are validated by closely comparing values retrieved from upward-looking TCCON Fourier Transform spectrometers. Biases between the TCCON and space-based XCO_2 and XCH_4 estimates are continuing to decrease as the quality of the space-based measurements and retrieval algorithms have improved. By applying simple parametric corrections, the agreement is now better than 1 ppm for XCO_2 (Wunch et al., 2011; 2017; Buchwitz et al., 2015; Hedelius et al., 2017; O'Dell et al., 2018) and 6 ppb for XCH_4 (Yoshida et al., 2011) across the TCCON network.

5.3 Cross-calibrating the sensors deployed across the constellation

To integrate the measurements collected by instruments deployed on a constellation of satellites into a single consistent climate data record, these instruments must be cross-calibrated against common standards to characterize the precision, accuracy and information content of their measurements. The XCO_2 and XCH_4 estimates retrieved from these measurements must then be validated against common standards before they can be combined in atmospheric inversion systems to estimate CO_2 and CH_4 fluxes. Both of these efforts pose challenges for a virtual constellation that employs multiple instrument types that observe from different vantage points and must meet unprecedented accuracy and precision requirements. Fortunately, the GOSAT and OCO-2 teams pioneered methods for addressing these challenges.

As part of their pre-launch testing programs, the GOSAT and OCO teams visited each other's test facilities and cross-calibrated their radiometric standards (Sakuma et al., 2010). These measurements benefited both teams by identifying subtle errors and uncertainties in their pre-launch calibration hardware and testing procedures. Many of the lessons learned from the OCO-GOSAT pre-launch calibration were adopted as parts of the OCO-2, OCO-3, and GOSAT-2 pre-launch calibration programs.

The OCO-2 and OCO-3 teams took a further step by enlisting the direct participation of the National Institute of Standards and Technology in the pre-launch radiometric calibration process (Rosenberg et al., 2018). Similar methods and instruments can be adopted across the constellation to radiometrically calibrate high-spectral-resolution NIR and SWIR spectrometers. It was not possible to directly cross-calibrate the geometric, spectroscopic or polarimetric performance of the OCO/OCO-2/OCO-3 and GOSAT/GOSAT-2 instrument families prior to launch, but the teams exchanged information on experience and best practices in each of these areas. The information provided a basis for diagnosing and correcting trends in performance of these instruments discovered after launch. Currently, there are no programs supporting the cross-calibration of radiometric standards used in pre-launch testing of CO_2 and CH_4 sensors.

Once GOSAT was successfully launched, the GOSAT team worked closely with the OCO-2 teams to develop the Railroad Valley Vicarious Calibration site (Nevada, USA), and then incorporate observations of this site into both GOSAT and OCO-2 in-flight calibration programs (Kuze et al., 2014). Earlier missions had used this site to monitor the radiometric calibration of broadband radiometers (for instance using the MISR and the MODIS instruments) that were designed to measure surface reflectance in spectral regions with little or no atmospheric absorption. To monitor the radiometric performance of the GOSAT and OCO-2 instruments, which were designed to measure high-resolution spectral radiances at wavelengths occupied by O_2, CO_2, and CH_4 bands, the vicarious calibration strategy used for those earlier missions had to be updated with additional atmospheric measurements.

The routine surface reflectance and atmospheric aerosol measurements were augmented with radiosonde profiles of pressure, temperature, and water vapor and with up-looking XCO2 and XCH4 measurements from ground-based instruments such as TCCON. These data provided a much more comprehensive description of the atmospheric extinction above the site, and allowed a comprehensive assessment of the spectrally-dependent radiances throughout each of the spectral bands of interest. Railroad Valley observations then provided a spectroscopic as well as a radiometric standard. If the ground-based measurement campaigns initiated by the GOSAT and OCO-2 teams can be maintained, this site can be used by future CO_2 and CH_4 missions. Similar sites in the Asian/Oceania and Europe/African domains would be needed to cross calibrate in addition the GEO orbiters operating over these areas.

CEOS and CGMS should play an important role in coordinating the development of these sites and distributing ground-based calibration data collected during calibration campaigns. In the short term, lessons learnt from the GOSAT and OCO-2 missions represent best practices that should be extracted and generalized by the CEOS Working Group on Calibration and Validation (WGCV) through the Atmospheric Composition Subgroup (ACSG) and the Global Space-based Intercalibration System (GSICS) under its newly re-established Reflective Solar Spectrometers Subgroup (UVSG). In addition, the strategy for cross-calibrating the GOSAT and OCO-2 instruments has employed common standards, including observations of the sun, Moon, and vicarious calibration from surface sites. Additional efforts by WGCV and GSICS (see section 5.5) are needed to maintain and to improve the quality of these standards to better address the calibration needs of the constellation of space-based CO_2 and CH_4 sensors.

5.4 Cross-validating XCO_2 and XCH_4 estimates across the constellation

To cross-validate the XCO_2 estimates from GOSAT and OCO-2, the science teams from both missions worked closely with the TCCON consortium and aircraft programs to develop internationally recognized standards for validating space-based XCO_2 and XCH_4 estimates. The TCCON network now provides the primary method for relating the space-based XCO_2 and XCH_4 measurements to the ground-based in situ standards maintained by the WMO GAW network. This validation approach involves two steps (Wunch et al., 2011). First, XCO_2 and XCH_4 estimates derived from measurements obtained at individual TCCON stations are validated against vertical profiles of in situ measurements obtained by high altitude aircraft flying above the stations. Data collected by both high-altitude fixed-wing aircraft and also balloon-borne systems are being used for this application. XCO_2 and XCH_4 estimates from coincident space-based and TCCON measurements are then compared to relate these remote sensing results.

The TCCON network is currently providing a cross-validation standard with accuracies near 0.1% (~0.4 ppm) (Wunch et al., 2017). The network is adequate for identifying and correcting biases on regional to hemispheric scales, but a much denser network may be needed to support a constellation designed to quantify anthropogenic CO_2 fluxes at regional scales. In particular, the current network, whose stations are primarily located in North America, Western Europe, Japan, and Oceania (Australia, New Zealand, Philippines) will have to be expanded to Africa, South America, and China to also support the GEO elements of the constellation.

The TCCON network is now managed as a loose confederation of individual Principal Investigators, most of whom are funded from year to year from a variety of sources to operate the stations, archive and distribute their data. This funding model has limited the number and geographic distribution of TCCON stations and does not provide the resilience needed to support an operational space-based CO_2 and CH_4 constellation. Given the importance of this network to any future constellation, CEOS should strongly encourage its member agencies to identify a more coordinated and sustainable method for supporting and expanding the TCCON network and the distribution of its products.

As the CO_2 constellation grows, we anticipate that spacecraft-to-spacecraft validation opportunities will become more common. For example, as mentioned above, cross validation of XCO_2 and XCH_4 estimates from coincident observations from LEO and GEO platforms should be strongly encouraged. Also, if the broad-swath imaging CO_2 spectrometers on one or more of the LEO platforms could be combined with an active CO_2 and/or CH_4 Lidar, the Lidar would then serve two purposes. First, as noted above, it would provide some coverage of the night side hemisphere and Polar Regions during polar night. XCO_2 or XCH_4 measurements retrieved from a selected footprint of the passive spectrometer could be compared to Lidar observations boresighted with that footprint to identify persistent systematic biases in both instruments, since passive solar and active Lidar instruments are affected differently by uncertainties in clouds, aerosols, and other sources of bias. CEOS and CGMS should encourage their member agencies and partners to support these and other cross-platform validation activities.

Concerted efforts have already begun in the context of 2018 during the European Commission's Chairmanship of CEOS. These included a number of activities which resulted in discussions on the needs across CEOS (and CGMS) agencies for *in situ* data both in finalising the GHG Constellation whitepaper[14] itself as well as in the context of a dedicated workshop hosted by the European Commission to address interfaces between the space agencies and their partner agencies in the *in situ*, modelling and inventory communities – thus ensuring the overall system approach to problem at hand.

Based on these and other discussions a forward looking coordination mechanism is now being put in place to define and implement an internationally agreed roadmap that will allow the GHG constellation to be implemented on timescales for it to be effective to address the international policy requirements. Within this international coordination framework there are elements addressing the *in situ* aspects in the broader context of calibration, inter-calibration and validation. These are foreseen to be addressed through two existing (but re-enforced) groups covering both research and operational elements. These are the CEOS Working Group on Calibration and Validation (WGCV) through the Atmospheric Composition Subgroup (ACSG) and the Global Space-based Intercalibration System (GSICS) under its newly re-established Reflective Solar Spectrometers Subgroup (UVSG). GSICS, in particular, is an international collaborative effort initiated in 2005 by the WMO and CGMS to monitor, to improve and to harmonize the quality of observations from operational weather and environmental satellites of the Global Observing System (GOS). GSICS aims at ensuring consistent accuracy among space-based observations worldwide for climate monitoring, weather forecasting, and environmental applications. This is achieved through a comprehensive calibration strategy which involves:

- monitoring instrument performances;
- operational inter-calibration of satellite instruments;
- tying the measurements to absolute references and standards;
- re-calibration of archived data.

GSICS contributes to the integration of satellite data within the WMO Integrated Global Observing Systems (WIGOS) and within the Global Earth Observation System of Systems (GEOSS) of the Group on Earth Observations (GEO) in particular through the subgroup addressing spectrometers operating in the UV –SWIR range, with the following focus areas:

- Pre-launch calibration and characterisation is a major focus area, for all but particularly for GHG missions;
- Solar calibration including interactions with the solar community which have already been initiated;
- Lunar calibration where the focus will be on UV and spectrally resolved data, contributing to other lunar calibration activities;
- Polarization (also for lunar calibration where possible);
- Inter-calibration and development of common methods for use of pseudo-invariant targets and vicarious calibration sites (with a homogeneous surface over a sufficiently large area) will be further developed, noting that the focus is on the atmospheric absorption.

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[14] http://ceos.org/document_management/Virtual_Constellations/ACC/Documents/CEOS_AC-VC_GHG_White_Paper_Version_1_20181009.pdf.

This renewed emphasis in GSICS will be complemented with an enhanced effort in WGCV/ACSG which will address the following activities in the short-term:

1. Address existing CEOS Action by Q1 2020 on "Greenhouse gas reference standards for interoperability – Develop list of reference standards for CO_2 and CH_4 products that are suitable for use in inter-comparison of multiple missions;
2. Identify the current shortcomings/gaps/sustainability in GHG calibration and validation, and formulate recommendations on the medium- to long-term way forward, that is with a specific focus on GHG Fiducial Reference Measurement (FRM).

And on the medium to long-term,

1. Address improvements/gaps in the inter-calibration of sensors (cooperation with GSICS) and the level-2 validation infrastructures (ground-based algorithm inter-comparisons and geographical/geophysical gaps for FRM);
2. Identify long-term validation needs from 2025 onwards and potential process study needs;
3. Work towards an operational reporting on the quality of space-borne GHG measurements and the underlying calibration and validation infrastructure.

6. Known challenges

We have identified three major categories of challenges associated with current limitations in the existing *in situ* networks (which translate into uncertainties on the inferred CO_2 fluxes) that may prevent the Copernicus CO_2 Monitoring & Verification Support capacity from fully delivering the expected information:

1. **Sustained and coordinated governance**

   Sound governance is key to support and develop a complex and globally coordinated monitoring system. First, it is critical to ensure that the *in situ* networks uniformly meet well-defined requirements for the quantification of fossil fuel CO_2 emissions[15]. Sound governance also ensures the long-term technical, scientific and financial support required to deliver operationally *in situ* observations across the network and to maintain and expand the network. Sound governance minimizes duplication of effort thereby maximises the return on financial investment. Coordination naturally facilitates centralised data access and standardisation of data format, which minimizes effort for both the data provider and data user. Without an adequate international and European-level coordination mechanism to sustain the operational system there is an increased risk of underperformance for the whole system. Shortcomings in the *in situ* system and in the interoperability of data collected by different regional networks, will critically affect the performance of the overall measurement network. For the inverse modelling at all spatial scales it is critical that there is a high level of consistency across the various measurement networks..

2. **Sustained funding at current infrastructure level**

   Existing essential networks are mainly supported through national research initiatives, grants and individual contributions. The current funding mechanism of *in situ* networks in Europe, both through ICOS, IAGOS and national, regional and urban networks is diverse, mostly, if not exclusively, based at country level and sometimes short-term research projects, or prone to shifts in political and national priorities. Maintaining the *status quo* implies that all funding continues as it is with the system as a whole remaining volatile and susceptible to changes in the funding, consequently jeopardizing the goals at all levels. It is not immediately obvious that external operational funding would be the ideal substitute for meeting any shortfall in funding from research institutes. It is likely that some tailor made funding system to repair sudden national shortfall in funding needs to be developed. Long-term acquisition of high-quality data and its sustained availability is required for the CO_2 Monitoring & Verification Support capacity to provide the appropriate support for ongoing science and policy objective. Any data gaps, temporally or regionally, will severely affect the performance of inversion systems and may introduce hindering biases. Sustainable funding provides the long-term security of the operational MVS capacity.

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[15] These requirements shall be defined from accuracy targets, taking into consideration spatial and temporal resolutions for the final product such as, for instance, fossil fuel CO_2 emission budgets and their trends, and translated into a list of species to be measured, the required measurement accuracy, the frequency of the measurements, and optimal number of stations.

3. **Sustained extendable funding/initial investments**

   Meeting all the objectives of the CO_2 Monitoring & Verification Support capacity requires significant additional funding to consolidate some essential networks such as TCCON and COCCON and to support evaluation and validation campaigns, as appropriate. In addition, networks such as ICOS, need to be extended to better address the requirements of the CO_2 Monitoring & Verification Support capacity such as, for instance, measurements of CO_2 and ^{14}C around urban environments. Without significant investments, a too high level of uncertainty from the space component may remain in the inferred CO_2 fluxes and anthropogenic emission assessments, particularly those that relate to monitoring city and point sources of fossil fuels. This extended funding requires *inter alia* strong international collaboration.

The table below lists the plausible impact of reducing observations uncertainties and enhancing network sustainability for different funding scenarios. It is appropriate to stress again that the *in situ* networks and their proposed enhancements are fundamental to the performance of the overall MVS capacity. Possibilities to achieve assessments are given from the global assessments of GHG budgets and fluxes to the point source estimates. They are formulated for four scenarios: maintaining the *status quo,* assuring sustained funding for the *status quo*, and two situations with enhanced network capabilities at European scale with sustained funding and global scale, respectively, and with a significantly improved *in situ* infrastructure in Europe and beyond.

Table 1. Possibilities identified for different funding and *in situ* networks enhancement scenarios from point source to global scale assessment of CO_2 emission estimates.

	Status Quo	***Status Quo* with sustained funding**	**Enhanced network capabilities & densities with sustained funding in EU countries**	**Enhanced network capabilities & densities with sustained funding in EU countries including coordination with non-EU assets**
Objective #1 &2 **(related to city & point source emissions)** Detection of emitting hot spots such as megacities, medium-size cities or power plants. Monitoring the hot spot emissions to assess emission reductions/increase of the activities.	Fossil flux estimates with **high uncertainty** limited to the **very few cities** equipped with some limited and ***ad hoc*** *in situ* monitoring networks	**Systematic** fossil flux estimates with **high uncertainty** limited to the **very few cities** equipped with limited but **perennial** *in situ* monitoring networks	Systematic fossil flux estimates with **low uncertainty** limited to the **large cities** adequately sampled by the networks	Systematic fossil flux estimates possible for many **large cities around the world** with **low uncertainty**
Objective #3 **(related to national & regional)** Assessing emission changes against local reduction targets to monitor impacts of the NDCs.	Information on fossil fuel CO_2 fluxes with **high uncertainty**	**Long term** provision of information on fossil fuel CO_2 fluxes with **high uncertainty**	Long term provision of information fossil fuel CO_2 fluxes with **moderate uncertainty** over regions with adequate sampling networks	Long term provision of information fossil fuel CO_2 fluxes and **budgets** with **moderate uncertainty**
Objective #4 **(related to global and national)** Assessing the national emissions and changes in 5-year time steps to estimate the global stock take.	Information on fossil fuel CO_2 fluxes with **high uncertainty**	**Long term** provision of information on fossil fuel CO_2 fluxes with **high uncertainty**	Long term provision of information fossil fuel CO_2 fluxes with **moderate uncertainty** over countries with adequate sampling networks	Long term provision of information fossil fuel CO_2 fluxes with **moderate uncertainty**

Note:

1. High uncertainty corresponds approximately to values larger than 50% of the mean flux while these uncertainty values should decrease to 10% or less for low uncertainty estimates. These low uncertainties are in a range enabling us to add significant information to the bottom-up inventories;
2. The enhancement in network capabilities may for example correspond to collocated observations of fluxes and ^{14}C, respectively;
3. The enhancement in network densities may correspond to a doubling of the current number of observation sites in Europe.

7. Conclusions and recommendations

This report presents the needs and high level requirements for *in situ* observations in the core elements of the foreseen Copernicus CO_2 Monitoring & Verification Support capacity. In particular, *in situ* observations are required for calibration and validation of the space component, for assimilation in models that are used to integrate information in the core of the system, for model improvements, and for evaluating the output generated by the system for its end users.

A broad and holistic system approach is required to address the requirements which are represented by the climate policy, of which the satellite component, whilst important, cannot effectively be developed in isolation. *In situ* component is crucial for deriving reliable information from the MVS capacity and solutions to enhance the current networks performance must be proposed. Whenever and wherever appropriate these solutions should build upon existing infrastructures and may include the extension of current capabilities at the European and global scales. Additionally, well-coordinated, inter-operable, and optimally designed large city scale networks, to measure ^{14}C nearby strong emitting sources for example, must be designed and implemented.

The analysis of the major challenges associated with current limitations of key *in situ* networks requires dedicated actions on three complementary fronts:

- to ensure the sustainability of essential networks such as the TCCON and others,
- to enhance existing network capabilities to include new observations such as ^{14}C and co-emitted species from fossil fuel burning[16],
- to propose in the appropriate time frame adequate governance schemes to be coordinated at the international level given the global dimension of issues at stake.

Each of the above items calls for an in-depth analysis of the current observing capabilities with respect to the requirements of the MVS capacity, and the elaboration of solutions that are sound, well documented and fit for purpose, and can be implemented at the horizon 2025. Whenever and wherever appropriate these solutions should build upon existing infrastructures such as ICOS for instance and may include the extension of current capabilities. Additionally, well-coordinated, inter-operable, and optimally designed large urban scale networks, to measure ^{14}C nearby strong emitting sources for example, must be designed and implemented.

The CO_2 monitoring Task Force set-up and chaired by the European Commission shall promote the following actions:

1. **To propose viable and sustainable governance options** and to evaluate appropriate funding schemes for providing essential networks with the proper resources including with regard to the foreseen evolutions at the European level and with the support of the European countries. Of particular concern are the networks developed on research grants and initiatives, which have proven successful in setting up the standards and delivering key contributions to the monitoring of greenhouse gases.

2. **To suggest one or more strategies to establish a dialogue and to engage** with other institutions, organizations and agencies contributing to the same objectives and with an established mandate at the international level. The key towards success includes agreeing on best practices and standards for data acquisition, fostering data exchange and harmonization and promoting the sharing of the information among all contributing partners. The latter is of utmost importance given the global dimension of the impacts associated with long-lived greenhouse gases emissions.

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[16] In concrete terms, this enhancement is likely in the range of 50 to 80 stations to cover the main emitting hot spots in Europe.

3. **To evaluate quantitatively the impact** on the Copernicus CO_2 Monitoring & Verification Support capacity of the current limitations in essential dedicated networks, e.g., TCCON, for the validation of the space products and to demonstrate the benefits from enhancing current capacities and for deploying more observation sites that help to fill gaps in current geographical measurement coverage. Each proposed evolution of the current measurement capacity must be justified by significant contributions to the overall performance and satisfying the requirements of the CO_2 Monitoring & Verification Support capacity. Specifically, the CO_2 Human Emissions (CHE)[17] Coordination and Support Action and its follow-on may offer an appropriate vehicle for conducting such science studies.

4. **To design a framework and to generate a roadmap** for designing and developing observation networks of ^{14}C and fossil CO_2 co-emitted species enabling us to assess the impact of emission reduction policies and to validate some deliveries of CO_2 Monitoring & Verification Support capacity. These networks should be designed in a way that the concentrations both away and nearby large emitting sources are monitored. Measurement protocols have to be investigated in view of the collection and analysis of a large number of samples and best practices must be defined ahead of time. An example of such a practice are the Carbon Dioxide, Other Greenhouse Gases, and Related Measurement Techniques (GGMT) meetings organised by WMO/IAEA to review the scientific understanding of greenhouse gas sources and sinks, to evaluate the network development, to review the best practices for quality assurance and quality control, and to examine data quality objectives and measurement techniques. Interoperability, synergies with existing networks, European coordination and networking are of paramount importance to ease the sharing of the efforts and the data exchanges.

Access to the necessary *in situ* data in an operational context will be a determining factor in the successful implementation of the MVS capacity, and consequentially for the substantial investment envisaged for the space-component. It is beyond doubt that further efforts and discussions will be required in the coming years to prepare for these aspects in the overall implementation of the pre-operational system.

These efforts point at technical and scientific aspects that need to be addressed as well as issues involving programmatics and governance that need to be considered. A major and recurrent message from this report is the diversity and fragmentation in the different communities and networks currently involved in the provision of the *in situ* observations and the various levels of maturity and mandates from research to operational mode.

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[17] https://che-project.eu/node/135

In order to leverage the material presented here, the following concrete steps are proposed on short term:

1. In the coming year, the Copernicus Programme should initiate a dialogue within the Commission services to understand the continued and/or enhanced support through existing research infrastructures such as ICOS and to ensure systematic access to *in situ* observations in an operational context, acknowledging the potential contribution from the European Environmental Agency.

2. The Commission should consult and collect feedbacks from the EU Member states through the Copernicus Programme Committee's and User Forum and in particular about their views regarding the support from national funding to the implementation of the necessary *in situ* elements.

3. By mid-2020, the institutional partners, specifically EUMETSAT, ESA and ECMWF, should elaborate a first version of a detailed plan for the calibration and validation of the space component and the full MVS capacity, from which *in situ* measurement requirements will be derived.

4. The Commission and institutional partners should advocate a central international repository or multiple complementary inter-operable repositories, for the relevant necessary *in situ* data and inter-calibrated satellite products.

5. By establishing a formal working relation with WMO on Copernicus, the Commission should emphasize the role for WMO on coordinating the global *in situ* data provision for GHG atmospheric concentration data, establishing and maintaining measurement standards and protocols.

6. The Commission, through the relevant and existing research funding mechanisms should consider whether there is need for additional technology innovation investments.

7. Budgets should be defined to support *in situ* data to be partly resourced through the Copernicus Programme. These budgets should also include resources required to ensure the operational access to datasets funded by and through third parties external to the Programme.

8. The Commission and institutional partners should continue to play active and leading roles in relevant activities at the international level (for instance through CEOS and CGMS, WMO and IG3IS, GEO) and should contribute to resourcing relevant research activities required for the *in situ* contributions to the roadmap for the MVS capacity.

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List of Abbreviations and Definitions

A

anthropogenic	Used here to designate fossil fuel CO_2 emissions
ACADIA	Airborne CArbon Dioxide Imager for Atmosphere
ACSG	CEOS Atmospheric Composition Subgroup
AGAGE	Advanced Global Atmospheric Gases Experiment
AeroNet	AErosol RObotic NETwork
AirCore	A sampling device that is usually released from the lower stratosphere by a balloon
AirMAP	Atmospheric Investigation, Regional Modeling, Analysis and Prediction
AirSpex	Airborne Spectropolarimeter for Planetary Exploration

B

bottom-up	Used for emission inventories obtained by aggregating statistical data from relevant economic sectors at a given terrestrial scale relevant for mitigation policy
BRF	Bidirectional Reflectance Factor

C

calibration	The process of quantitatively defining the space-based sensor outputs to reference standard of known accuracy It is a key process for further use of space-derived observations in a variety of applications where sensor biases must be absolutely avoided, e.g., climate change impact detection.
CAMS	Copernicus Atmospheric Monitoring Service
CCDAS	Carbon Cycle Data Assimilation System
CHARM-F	DLR’s airborne Integral Path Differential Absorption lidar for simultaneous measurements of CO_2 and CH_4
CH_4	Methane
CEOS	Committee on Earth Observation Satellites
CFC	Chlorofluorocarbons, artificially produced greenhouse gases
CGMS	Coordination Group for Meteorological Satellites
COPxx	UNFCCC Conference of Parties Session No. xx

COCCON	COllaborative Carbon Column Observing Network
CO	Carbon monoxide, an air pollutant and a tracer when incomplete combustion occurs
CO_2	Carbon dioxide
CO2M	Copernicus CO_2 monitoring
C3S	Copernicus Climate Change Service
CONTRAIL	Comprehensive Observation Network for Trace gases by Air-liner
^{14}C	Radiocarbon, a radioactive carbon isotope with 6 protons and 8 neutrons

D

data assimilation	A process by which observations of the actual system are incorporated into the model state of a numerical model of that system
DG CLIMA	Directorate General Climate Action of the European Commission

E

EC	European Commission
ECMWF	European Centre for Medium-Range Weather Forecasts
EDGAR	Emission Database for Global Atmospheric Research
EEA	European Environmental Agency
EPS-SG 3MI	EUMETSAT Polar Satellite Second Generation Multi-viewing Multi-channel Multi-polarization Imaging
ESA	European Space Agency
ESFRI	European Strategy Forum on Research Infrastructures
ESRL	NOAA Earth System Research Laboratory
EU	European Union
EUMETSAT	European Organisation for the Exploitation of Meteorological Satellites

F

FFDAS	Fossil Fuel Data Assimilation System
FLUXNET	A network of regional networks to coordinate regional and global analysis of observations from micrometeorological tower sites. (http://fluxnet.fluxdata.org/)
FP6	6th framework programme of the European Union for funding research
FP7	7th framework programme of the European Union for funding research

FRM	Fiducial Reference Measurement
FTS	Fourier Transform Spectrometer

G

GALION	GAW Aerosol Lidar Observation Network(https://www.wmo.int/pages/prog/arep/gaw/documents/gaw178-galion-27-Oct.pdf)
GeoCarb	Geostationary satellite from USA – planned - (https://www.nasa.gov/press-release/nasa-announces-first-geostationary-vegetation-atmospheric-carbon-mission)
GAW	Global Atmosphere Watch programme of the World Meteorological Organization
GCP	Global Carbon Project
GEO	Group on Earth Observations
GEOSS	Global Earth Observation System of Systems
GHG	Greenhouse gas
GOS	Global Observing System
GPP	Gross Primary Productivity
GGRN	Global Greenhouse Research Network
GOSAT	greenhouse Gas Observing SATellite from Japan (JAXA) - in operation
GSICS	Global Space-based Intercalibration System

H

I

IAEA	International Atomic Energy Agency
IAGOS	In-service Aircraft for a Global Observing System
ICOS	Integrated Carbon Observation System, a research infrastructure of the EU
IEA	International Energy Agency
IG3IS	Integrated Global Greenhouse Gas Information System
IPCC	Intergovernmental Panel on Climate Change

J

JRC	Joint Research Centre of the European Commission

K

kton	Kilotonnes

L

LEO	Low Earth Orbit
LULUCF	Land Use, Land-Use Change and Forestry

M

MAMAP-2D	Methane Airborne MAPper – 2D
MISR	Satellite from USA (NASA) - in operation - (https://terra.nasa.gov/about/terra-instruments/misr)
MODIS	Satellite from USA (NASA) - in operation - (https://terra.nasa.gov/about/terra-instruments/modis)
Mton	Megatonnes
MRD	Mission Requirements Document
MRV	Measuring-Reporting-Verifying framework of the UNFCCC
MVS	Monitoring & Verification Support capacity of the Copernicus programme

N

NDC	Nationally Determined Contribution (national emission mitigation action plan under the Paris Agreement)
NASA	National Aeronautics and Space Administration of the USA
NOAA	U.S. National Oceanic and Atmospheric Administration NOAA/NCDC U.S. National Oceanic and Atmospheric Administration/National Climatic Data Centre
N_2O	Nitrous Oxide, a greenhouse gas
NOx	Nitrogen oxides, the sum of nitric oxide (NO, reactive product oxidizing quickly to NO_2) and nitrogen dioxide (NO_2), acidifying and eutrophying air pollutants
NRT	Near-Real Time
NWP	Numerical Weather Prediction

O

OCO-2	Orbiting Carbon Observatory from USA (NASA) - in operation
OSSE	Observing System Simulation Experiments

P

ppb	Parts per billion 10^{-9}
ppm	Parts per million 10^{-6}

Q

QA/QC	Quality assessment/Quality control

R

S

SIF	Sun (Solar)-Induced Fluorescence
SOCAT	A collection of surface ocean CO_2 quality controlled observations (from IOCCP) - (http://www.socat.info/)
SWIR	Shortwave Infrared

T

top-down	refers to the approach to determine sources and sinks of greenhouse gases from observations of the atmospheric concentration variations of these gases
TanSAT	Mini satellite for CO_2 detection and monitoring from China (MOST) - in operation - (https://directory.eoportal.org/web/eoportal/satellite-missions/t/tansat)
TCCON	Total Carbon Column Observing Network
TNO	The Netherlands Organisation for applied scientific research
TROPOMI	The TROPOspheric Monitoring Instrument (TROPOMI) is the satellite instrument on board the Copernicus Sentinel-5 Precursor satellite.

U

UN	United Nations
UNFCCC	United Nations Framework Convention on Climate Change
UNEP	United Nations Environment Programme
UVSG	GSICS UV subgroup
UV	Ultraviolet

V

validation	The process of assessing by independent measurements the quality of the data-products derived from the space-based sensor outputs

W

WIGOS	WMO Integrated Global Observing System
WGCV	CEOS Working Group on Calibration and Validation
WMO	World Meteorological Organization

X

XCO_2	Column-weighted CO_2 mixing ratio estimated from satellite
XCH_4	Column-weighted CH_4 mixing ratio estimated from satellite

Y

Z

Annexes

Annex 1 NOAA Greenhouse Gas Reference Network – GGRN

https://www.esrl.noaa.gov/gmd/ccgg/ggrn.php

Purpose

Primary: Measurement of atmospheric distribution and trends of CO_2 and CH_4 and other GHGs.

Secondary: Main observation inputs used in data assimilation mode by inverse models to estimate surface fluxes.

Type of measurements

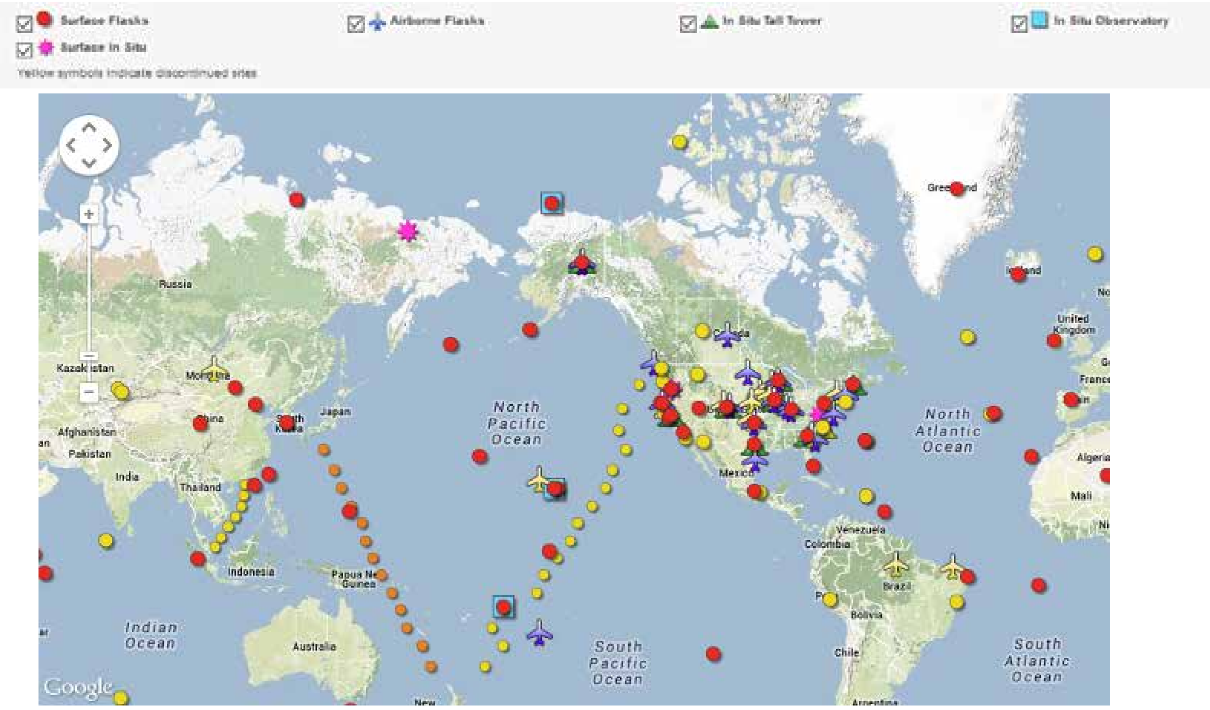
GGRN includes 4 baseline observatories and 8 tall towers, air samples collected by volunteers at more than 50 sites, and air samples collected regularly from small aircraft mostly in North America and the AirCore sampling system.

Funding

GGRN is a part of NOAA's Earth System Research Laboratory (USA). The network is an international effort, which also includes regular discrete samples from cooperative fixed sites, and commercial ships. GGRN maintains the WMO international calibration scales for CO_2 and CH_4. GGRN contributes to the WMO-GAW network.

Site map

Worldwide distribution of the stations contributing to the network.



Annex 2 European Integrated Carbon Observation System – ICOS – and national networks

https://www.icos-ri.eu/

Purpose

Primary: Long-term production of standardised high precision data on GHG (including CO_2 and CH_4) atmospheric concentrations and terrestrial and oceanic fluxes over Europe and key regions of European interest.

Secondary: ICOS and other GHG data are used in data assimilation mode by inverse models for generating elaborated products such as GHG flux maps.

Type of measurements

The ICOS stations operate a continuous gas analyser as well as collect air samples at weekly interval using automated samplers into glass flasks for additional parameter measurements including carbon isotopes at 17 sites. ICOS operates eddy-covariance measurements at 70 ecosystem stations. In addition to ICOS, a number of national networks and projects in Europe support high precision GHG continuous atmospheric measurements across Europe (light blue dots) and in different regions of the world.

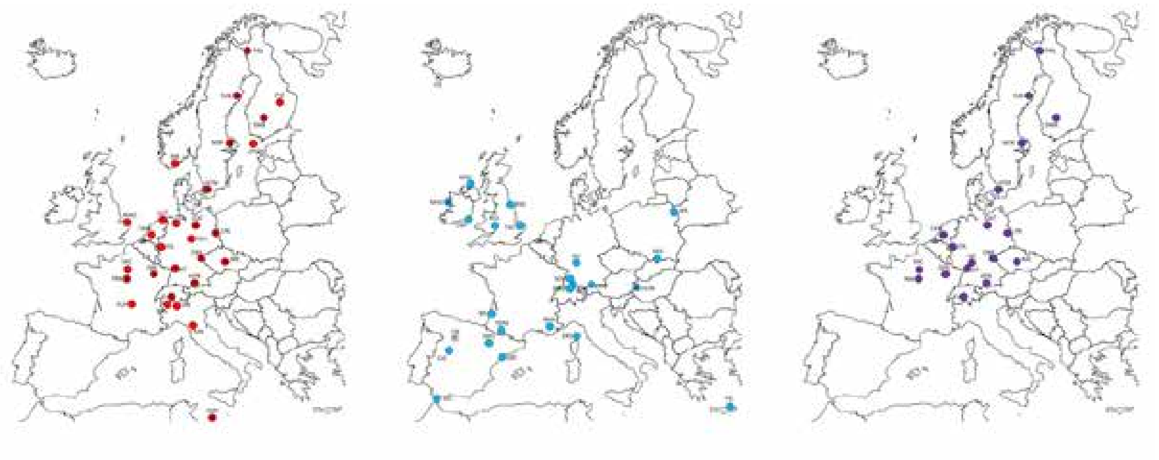
Funding

ICOS is a Research Infrastructure of the European Union and ICOS of the strategic European Strategy Forum on Research Infrastructures (ESFRI) list. The ICOS stations are operated and funded by national funding agencies, institutes and universities. ICOS central facilities are funded by membership fees and contributions from their hosting countries.

Additional measurement stations in Europe in non-membership ICOS countries delivering data to the WMO-GAW programme are funded through research or long-term monitoring projects.

Site map

European distribution of the network stations: continuous CO_2, CH_4, CO measurements stations in ICOS Research Infrastructure (red dots, left hand map), continuous GHG measurements stations in other national / research networks (blue dots, middle map), ICOS sites equipped with flask air sampling to measure radiocarbon in atmospheric CO_2 (purple dots, right hand map).



Annex 3 In-service Aircraft for a Global Observing System – IAGOS

https://www.iagos.org/

Purpose

Primary: Provision of essential data on GHGs including CO_2 and CH_4 and air quality at a global scale.

Secondary: The IAGOS data can be used in data assimilation mode by inverse models.

Type of measurements

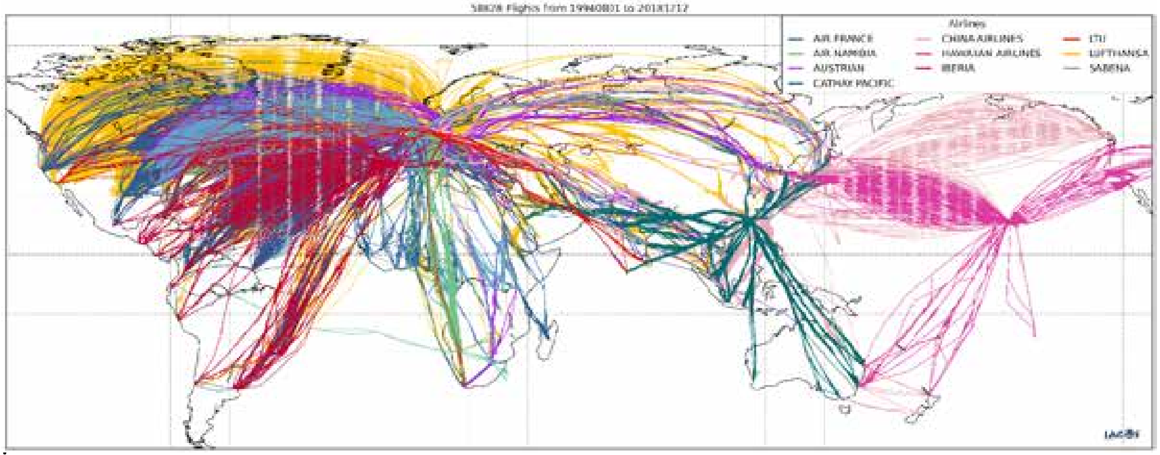
Air samples from regular passenger aircraft such as AIRBUS A330 and A340-600 based on a commercial analyser developed by Picarro Inc. that is designed for autonomous deployment.

Funding

IAGOS is organized as an International not for profit Association (IAGOS-AISBL) and it is a research infrastructure part of ESFRI. Members are leading research organizations, universities and weather services from Germany, France and the U.K. IAGOS builds on the experience gained within the research projects MOZAIC which was funded by the EC under FP 4 and FP 5, and CARIBIC. IAGOS contributes to the WMO-GAW network.

Site map

Geographical distribution of the IAGOS flights measuring CO, ozone and aerosols



Geographical distribution of the IAGOS Lufthansa A330 flights measuring GHGs (soon available).

Annex 4 Comprehensive Observation Network for Trace gases by Air-liner – CONTRAIL and other aircraft measurements

http://www.cger.nies.go.jp/contrail/contrail.html

Purpose

Primary: Provision of essential data on GHGs (including CO_2 and CH_4 and air quality at a global scale) vertical profiles during aircraft take-off and landing and upper air measurements at cruising altitude. In addition to CONTRAIL, research aircraft flights have been collecting vertical profiles using flask air samples or continuous CO_2 instruments, part of the NOAA program in USA, the NIES program in Japan, various research laboratories in Western Europe and in Brazil.

Secondary: The CONTRAIL data can be used in data assimilation mode by inverse models.

Type of measurements

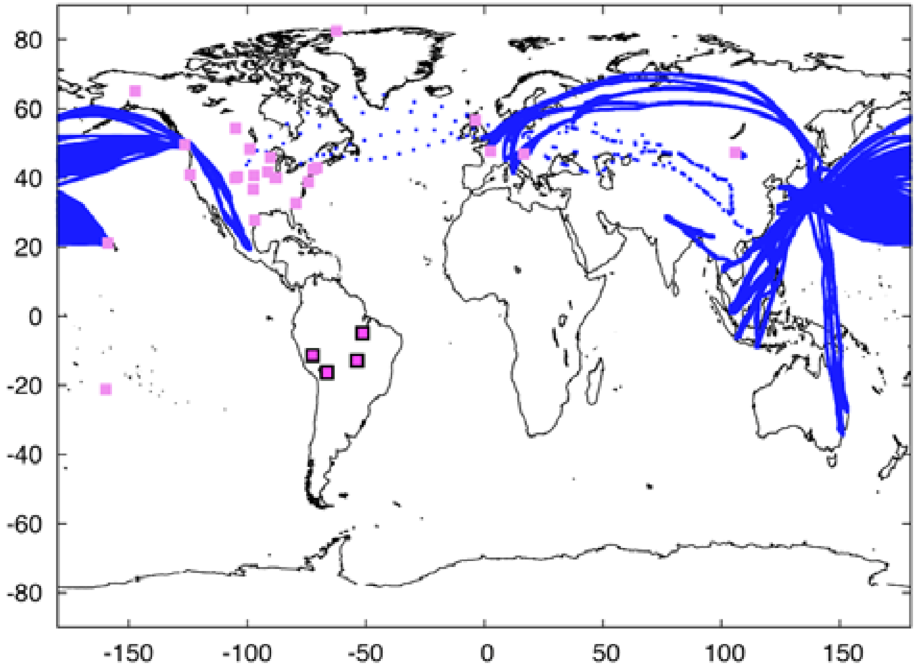
Flask air sampling with an automatic control based on the real-time monitoring of the flight navigation data and manual sampling. The aircraft currently used for atmospheric observation is 777-200ER configured for international flights. Data are made available via the World Data Centre for Greenhouse Gases (WDCGG) is a World Data Centre (WDC) operated by the Japan Meteorological Agency (JMA) under the Global Atmosphere Watch (GAW) programme of the World Meteorological Organization (WMO).

Funding

The CONTRAIL project is jointly conducted by the National Institute for Environmental Studies (NIES), the Meteorological Research Institute (MRI), Japan Airlines (JAL), JAMCO corporation (JAMCO) and JAL Foundation (JAL-F).

Site map

Map of contrail passenger flights (blue lines) and of regular research aircraft vertical profiles (pink squares).



Annex 5 Total Carbon Column Observing Network – TCCON

http://tccon.caltech.edu/

Purpose

Primary: Validation of the major column -averaged Greenhouse gases including CO_2 and CH_4 retrieved from satellite observations.

Secondary: The TCCON data can be used in data assimilation mode by inverse models.

Type of measurements

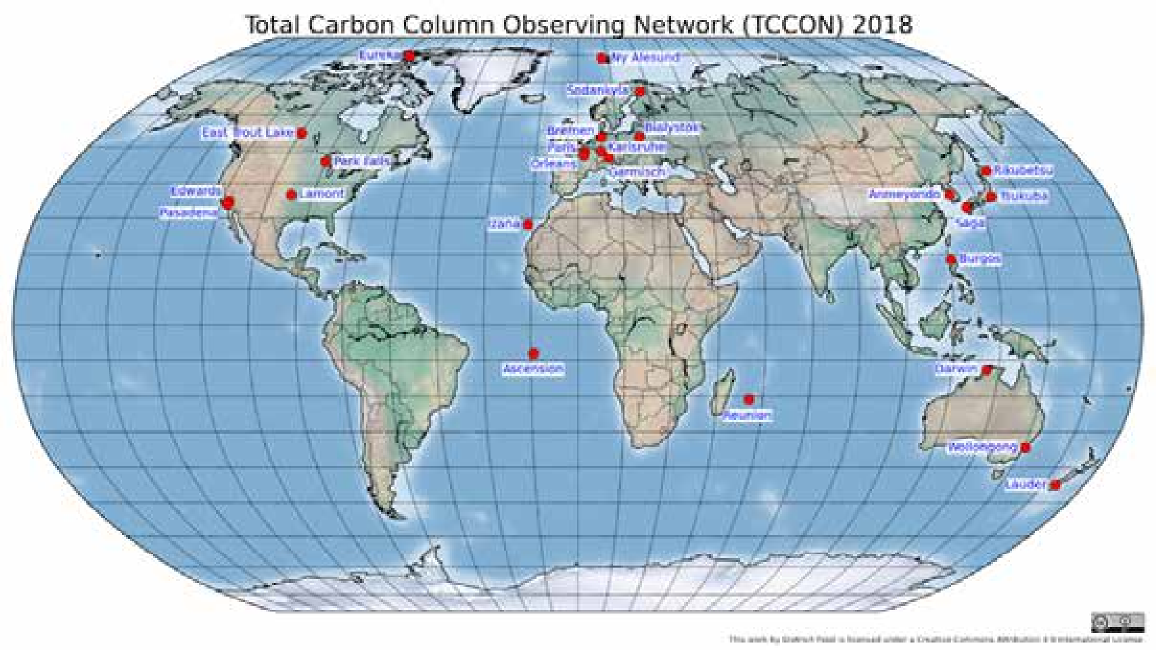
TCCON is a network of ground-based Fourier Transform Spectrometers recording direct solar spectra in the near-infrared spectral region.

Funding

Support for the network is provided in part by NASA through grants made to the California Institute of Technology. Several stations are funded through specific programs. Support for analysis and operations at the individual sites are described on the site pages. TTCON contributes to the WMO-GAW network.

Site map

Worldwide but irregular distribution of the network stations.


Total Carbon Column Observing Network (TCCON) 2018

Annex 6 COllaborative Carbon Column Observing Network - COCCON

https://www.imk-asf.kit.edu/english/3221.php

Purpose

Primary: Validation of the major column -averaged Greenhouse gases including CO$_2$ and CH$_4$ retrieved from satellite observations as a supplement to TCCON.

Secondary: The COCCON data can be used in data assimilation mode by inverse models.

Type of measurements

COCCON is an infrastructure of portable and non-autonomous ground-based Fourier Transform Spectrometers recording solar spectra in the near-infrared spectral region.

Funding

The European Space Agency (ESA) has provided support for about 30 devices for this research infrastructure.

Site map

COCCON devices can be deployed anywhere and especially in remote areas during measurement campaigns.

Instrumentation

COCCON devices are portable Fourier Transform Spectrometers.

Annex 7 AirCore

https://www.esrl.noaa.gov/gmd/ccgg/aircore/
http://ara.abct.lmd.polytechnique.fr/index.php?page=aircore

Purpose

Primary: Direct measurement of the vertical profiles of CO_2, CO, and CH4. These profiles can extend from the surface up to about 30 km, providing a way to validate satellite and ground-based (TCCON) retrievals of the full or partial column of CO2, CO and CH4.

Secondary: The AirCore data can be used for atmospheric chemistry-transport model developments.

Type of measurements

The device is made of a long tube that collects a sample of the ambient air as it descends, after a balloon-borne ascent. It is sealed upon recovery and measured with a continuous analyser for trace gas mole fraction.

Funding

The Aircore community is still at an early stage of development and funding for measurement campaigns remains national (e.g., space or meteorological agencies). H2020 project “RINGO” supports further Aircore development and works towards community integration.

Site map

AirCore is a sampling device that is usually released from the lower stratosphere by a balloon. It can be deployed anywhere in principle, but the tube has to be collected rapidly after it has hit the Earth’s surface. This may happen quite far from the launch location, depending on the wind. This prevents operating over the ocean, above very uneven terrain or with high and dense vegetation.

Instrumentation

Aircore is only a tube that samples air. The air is then analysed on ground by a gas analyser. “Active” Aircore versions under development can be operated with controllable platforms like Unmanned Aerial Vehicles (UAVs) to sample in preferential locations.

Annex 8 AErosol RObotic NETwork – AERONET

https://aeronet.gsfc.nasa.gov/

Purpose

Primary: Validation of aerosol optical, microphysical and radiative properties retrieved from satellite based platforms.

Secondary: Prior knowledge of global distribution of major spectral aerosol optical properties and types.

Type of measurements

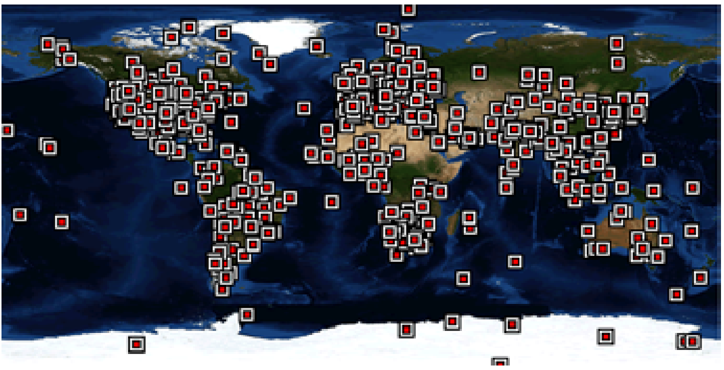
Multiband sun photometers that perform measurements of spectral sun irradiance and sky radiances.

Funding

Federation of ground-based remote sensing aerosol networks established by NASA. Collaborators include RIMA (University of Valladolid, Spain), AeroSpan (Australian Network), AEROCAN (University of Sherbrooke and Meteorological Service of Canada, Canada), CARSNET (China Meteorological Administration, China). The organizations involved are NASA Goddard Space Flight Center (USA), Centre National De La Recherche Scientifique (France), Centre National d'Etudes Spatiales (France), Network for the Detection of Atmospheric Change (USA), Aerosols, Clouds, and Trace gases Research InfraStructure Network (European Union), Long Term Ecological Research (LTER) National Science Foundation (USA), Commonwealth Scientific and Industrial Research Organisation (Australia), Atmospheric Radiation Measurement Program (USA), CEILAP -CITEFA-CONICET (Argentina) and Joint Research Centre (European Union).

Site map

Worldwide distribution of the network stations.



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