CO_2 Human Emissions

Final report on service elements for CO_2 Earth observation integration

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1 Executive Summary

The present chapter puts relevant information from the Copernicus CO_2 Monitoring Mission Requirements Document and from the three reports of the Copernicus Expert group and of the Task forces in perspective in the context of the prototype system which is being designed in CHE. It successively discusses the satellite CO_2 retrievals, the satellite non-CO_2 observations, the ground-based remote sensing observations, the in situ and flask-sampling observations, and near-real-time activity data. It highlights the large research needs for the identification of the role of each relevant Earth observation type in the Copernicus CO_2 support capacity system and for the modelling capability associated to the main ones.

2 Introduction

2.1 Background

The CHE prototype aims at building a system to monitor the exchange of CO_2 and potentially other important man-made greenhouse gases like CH_4 between the Earth surface and the atmosphere with the use of observations (mostly in the atmosphere), models and prior information including the specification of their uncertainties. The system is designed to support the Paris Agreement and follows the directive of the EC as described by Task Forces on CO_2[1]. The general rationale and strategy for the CHE prototype is provided in D5.9, stemming from the discussions in the first WP5 workshop (Reading, 25-26 September 2019). The main challenges will be explored with the following recommendations:

- **Multi-scale** approach to monitor emission from point sources (power stations or industrial facilities), cities and countries using different model domains from global, regional to local and model resolutions (e.g. from 25 km to 100 m).
- **Multi-species** approach to detect and attribute the observed atmospheric signal to specific sources/sinks (e.g. natural and anthropogenic emissions with sectoral distribution).
- **Multi-stream** approach to support different applications and users with a near-real time stream focusing on shorter synoptic timescales designed to provide early warnings and give feedback to data producers, and a re-analysis stream that uses consolidated quality-controlled data, products and models with their associated uncertainties to estimate trends.

Earth observation, the topic of this chapter, is the gathering of information about the physical, chemical and biological systems of the Earth by natural- and man-made- environment monitoring[2]. The exploitation of Earth observations about atmospheric CO_2 will bring the primary added value of the Copernicus CO_2 support capacity compared to existing national greenhouse gas emission inventories that traditionally rely on national activity data only. Helped in particular by unprecedented satellite imagery means, the CO_2 support capacity for anthropogenic CO_2 emissions aims to supply extra evidence on the emissions levels and trends (Pinty et al., 2017, p. 7) that will be merged or contrasted with existing knowledge. Its

[1] https://www.copernicus.eu/en/news/news/new-co2-green-report-2019-published
[2] https://www.earthobservations.org/g_faq.html

scope will not be limited to CO_2 satellite imagery and will cover many types of Earth observations that are related to CO_2 emissions or to CO_2 dispersion in the atmosphere. Together, the various Earth observation types will drive and support a complex emission-estimation process at various spatial scales from the very local one (a few hectares) to the global one: the list of potentially-useful data is exceptionally long. CHE is currently exploring a relatively small number of ways to complete CO_2 observations with other types of Earth observations: radiocarbon, NO_2, oxygen, solar-induced fluorescence, carbonyl sulfide, night-light intensity and fraction of absorbed photosynthetically active radiation in the plant canopy. However, at this early stage of development of an operational CO_2 support capacity with unprecedented ambition, it is important to keep many more strategies open, at least as second choices. In the end, they may all play some role in the operational system but some of them will be directly assimilated in the CO_2 system while some will only be used at the pre- or post-processing stage to better guide the Copernicus CO_2 support capacity or to characterize its skill. Weather observations form a typical example of this dilemma. Resolving it implies making choices on the modelling of uncertainty in the estimation problem (e.g., strong-constraint formulation vs. weak-constraint or coupled formulation of the data assimilation) that may dramatically affect the skill of the operational system.

The needs and requirements for Earth Observations in the future European CO_2 support capacity for anthropogenic CO_2 emissions have already been extensively discussed in a series of documents:

- The Copernicus CO_2 Monitoring Mission Requirements Document (Meijer et al., 2019)
- The three reports of the Copernicus Expert group and of the Task forces[3]

The present chapter does not aim at replacing or even paraphrasing those documents, but rather at putting their relevant information in perspective in the context of the prototype system which is being designed in CHE. It successively discusses the satellite CO_2 retrievals, the satellite non-CO_2 observations, the ground-based remote sensing observations, the in situ and flask-sampling observations, and the near-real-time activity data.

2.2 Scope of this deliverable

2.2.1 Objectives of this deliverable

In this report we aim at reviewing and assessing the options of available observations for the CHE prototype.

2.2.2 Work performed in this deliverable

Synthesis of work performed in CHE WP1, WP3 and WP4, ESA MRD and Task Force CO_2 reports.

2.2.3 Deviations and counter measures

Not applicable

[3] https://www.copernicus.eu/en/news/news/new-co2-green-report-2019-published

3 Earth Observation System components

5.1 Satellite CO_2 observations

A Copernicus CO_2 monitoring (CO2M) constellation with imaging capability as described in Pinty et al. (2017) is considered a prerequisite for the success of the CO_2 support capacity (Pinty et al. 2019, p. 3) within various limitations (see, e.g., Chevallier et al., 2020; Ciais et al., 2020), while the need for a strong ground-based infrastructure comes in addition to the Copernicus constellation (Meijer et al., 2019, p. 11). This chapter is therefore built with the assumption that this Copernicus constellation will be deployed in orbit. Otherwise, the emphasis on the various observation types would be different.

Compared to existing satellite missions, an extensive CO_2 plume imaging capacity in cloud-free areas will be the best asset of the future Copernicus CO_2 monitoring constellation for the monitoring of CO_2 anthropogenic emissions. It will be extensive spatially because of the large swath of each space-borne instrument (better than 250 km, requirement S7MR-OBS-010 in Meijer et al., 2019) joined with its high spatial resolution (better than 4 km^2, requirement S7MR-OBS-020 in Meijer et al., 2019). It will be extensive temporally too because the observing system will include copies of the same instrument deployed on satellites with different orbital characteristics.

The CO_2 plume imaging capacity will rely on the near-contiguous sampling of backscattered solar light in selected spectral bands within the swath of the instrument and along the track of the satellite. When observation conditions are favourable (which mainly means enough insolation with low cloud and aerosol contamination), the column average dry-air mole fraction of CO_2 (and associated vertical averaging kernel) will be retrieved at each viewing location with low systematic and random errors (requirements S7MR-DAT-010 and S7MR-DAT-050 in Meijer et al., 2019). This will allow for resolving CO_2 plumes from emission hot spots and their surroundings. The necessity to restrict the quality-assured column retrievals to almost cloud-free areas remains a limiting factor because it will prevent from identifying some of the changes in CO_2 emissions, as was the case during the first months of the coronavirus recession in 2020 (Chevallier et al., 2020). Together with some other challenges (e.g., Ciais et al., 2020), it motivates the inclusion of other Earth observation types, as described in the following sections, in the Copernicus CO_2 support capacity system.

The wealth of high-quality column retrievals will also allow constraining large-scale carbon budgets over the globe to an unprecedented level.

The Sentinel CO_2 constellation will be operated within a larger constellation of CO_2 sounders of various types and operated by several agencies (CEOS Atmospheric Composition Virtual Constellation Greenhouse Gas Team, 2018), which can help filling gaps between Sentinel orbits and characterizing the actual Sentinel CO_2 retrieval noise over time.

5.2 Satellite non-CO2 observations

Satisfying the ambitious objectives of the European CO_2 support capacity for anthropogenic CO_2 emissions implies exploiting complementary Earth observations, including some from satellites.

Meijer et al. (2019) plan for aerosol and cloud information to be provided by different types of radiometers on-board the same platform and at the same location as the Sentinel CO_2 column retrievals. Such data will both help disentangling the CO_2 signal from the cloud and aerosol signals in the measured spectra, and help excluding the pixels where the signal remains too ambiguous.

Further in the data flow, NO_2 retrievals that are spatially and temporally co-located with the Sentinel CO_2 retrievals will allow some tagging of the CO_2 plumes with respect to cleaner "background" scenes to identify the CO_2 source and to characterize the plume direction and the local wind speed (Meijer et al., 2019, p. 24). NO_2 was chosen because it is co-emitted with CO_2 when fossil fuel is burnt; but, on the downside, CO_2 and NO_2 plumes may not always overlap, even close to the plume origin, because NO_2 has a lifetime of the order of hours while CO_2 does not have any defined lifetime.

Information about wind direction from NO_2 plumes will be restricted to the vicinity of NO_2 emission hot spots. It will have to be complemented by information about wind speed at the same location and by information about the 3D structure of wind over the whole globe when inferring large-scale CO_2 budgets. This information can come from wind-dedicated satellites in particular and from a much larger range of weather observations assimilated in Numerical Weather Prediction systems in general.

Many satellite observations can also provide some valuable information related to CO_2 sources and sinks in vegetated areas (solar-induced fluorescence, green fraction of absorbed photosynthetically active radiation in the plant canopy, vegetation biomass, …) or about CO_2 anthropogenic emissions (NO_2[4], CO, …). Some other satellite observations can serve as proxies for the spatial and temporal variations of CO_2 emissions (data from the Global Positioning System, night light imagery, …).

5.3 Ground-based remote sensing observations

The above-mentioned satellite retrievals of CO_2 and NO_2 columns and of aerosol properties are traditionally tuned[5] with the help of ground-based radiometers that also observe vertically-integrated quantities. Reference retrievals from such devices are organized in international networks, like the Total Carbon Column Observing Network (TCCON, Wunch et al., 2011) and the Collaborative Carbon Column Observing Network (COCCON, Frey et al., 2019) for CO_2 or the Aerosol Robotic Network (AERONET, Holben et al., 1998) for aerosols. The importance of atmospheric plume monitoring in the CHE prototype implies a need to characterize the metrological resolution[6] of the satellite retrievals or of local averages of satellite retrievals. TCCON and COCCON can address it as long as their ability to identify XCO_2 variations of a few tenths of ppm only is further improved.

5.4 In situ and flask-sampling observation

Article 3 of the Copernicus regulation[7] defines "in situ data" as all Earth observation data and ancillary ones that are not made from space. We choose the standard English definition here: "in the original or correct place"[8], that excludes ground-based remote-sensing and flask samples analysed in distant laboratories. We therefore distinguish between in situ

[4] NO_2 was mentioned above for plume tagging. Here, we mention its use for data assimilation.
[5] Following the definition of BIPM (https://www.bipm.org/fr/publications/guides/vim.html), we do not use the word "calibrated" here that implies controlled conditions that are not possible in the open air.
[6] "smallest change in a quantity being measured that causes a perceptible change in the corresponding indication" (https://www.bipm.org/fr/publications/guides/vim.html).
[7] https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32014R0377
[8] https://www.oxfordlearnersdictionaries.com/definition/english/in-situ

observations and flask-sampling observations in this section and we separate this section from the previous one about ground-based remote-sensing observations.

Relevant observations for the European CO_2 support capacity obviously include observations of the target quantities that can be used at the minimum for validation: local flux observations from micrometeorological towers in urban or other environments (like the Urban Flux Network or FluxNet), or from stack emission monitoring systems. They also cover local observations that either can be directly assimilated, or can inform about the quality of the assimilated data, or can help numerical models used in the data assimilation process. The more observation types and model types involved in the European CO_2 support capacity, the more Earth observations will be needed to support them. For example, satellite retrievals need observations for tuning; any additional tracer observation that is assimilated needs information about its sources and sinks and about how it relates to CO_2 emissions; any numerical model used in the assimilation process requires uncertainty quantification. It is important to note that there will be nuisance variables (i.e. knowledge gaps that are not limited to the target variables of the Copernicus support capacity) for all atmospheric tracers, even for the most obvious ones here like radiocarbon (Wang, 2016).

Given the emphasis put on atmospheric dispersion in the European CO_2 support capacity for anthropogenic CO_2 emissions, it is natural to quote in situ and flask-sampling tracer observations first. They are made close to the Earth's surface or higher in the atmosphere by aircraft, balloons or from free-fall tubes. They include observations of the main tracers mentioned so far in this chapter (CO_2, NO_2, CO), but also of isotopic measurements like radiocarbon, for other tracers that are related to CO_2 sources and sinks (e.g., oxygen and carbonyl sulfide) or to atmospheric transport (e.g., radon and SF_6). Reference measurements of that kind are maintained within programmes coordinated by the Global Atmospheric Watch Programme of the World Meteorological Organization (like those of the European Integrated Carbon Observation System, or of the National Oceanic and Atmospheric Administration Greenhouse Gas Reference Network, or the long-term aircraft programmes Comprehensive Observation Network for TRace gases by AirLiner and In-service Aircraft for a Global Observing System). Urban networks of lower-cost medium precision sensors for greenhouse gases may also be deployed in the future (e.g., Wu et al., 2016). Some data are available from air quality networks. Some come with delays that are not fit for near-real-time data assimilation and leaving them suitable for post-processing (e.g., validation) or re-analyses. Aircore measurements of the CO_2 mole fraction profile (Tans, 2009) have a special role in this domain because they are the only calibrated measurements of the CO_2 column per se and therefore come with very small systematic errors. However, they cannot be operated in an urban (i.e. inhabited) environment for security reasons. We also mention here again the need for accurate information about atmospheric winds when inferring emissions from mole fraction gradients, and the interest of exploiting proxy observations for the spatial and temporal variations of CO_2 emissions, like road traffic or temperature data. In terms of emission model support, the main need will likely be for observations informing about emission factors or emission ratios which vary much in space and time (e.g., Ammoura et al., 2014).

In situ and flask-sampling observation all have heterogeneous spatial coverage, in particular outside developed countries. They therefore do not sample the natural variability of their target variables well.

5.5 Near-real-time activity data

Annual national inventories of energy and fuel use that are traditionally used to assess CO_2 emissions rely on economic statistics and are available at least one year after reality. The first report of the Copernicus Expert group already highlighted the potential of near-real-time activity data, like mobility data or electricity management data, to offer spatial and temporal detail rapidly (Ciais et al. 2015, p. 16). This potential has been realized within the first months of the coronavirus recession, when such activity data allowed converging estimates of the changes in on-going CO_2 emissions, initially over China (Myllyvirta, 2020) and then over the whole globe (Le Quéré et al., 2020; Liu et al., 2020; http://carbonmonitor.org). Some of the activity data originate from the private sector and had to be purchased. In general, there is no commitment from the various activity data providers across the globe to sustain their data flow in the same conditions. Actually, the visibility offered by their use for CO_2 emission estimation increases their strategic value and, for some of them, may change their price or even call their public availability into question. Identifying appropriate data providers across the globe, characterizing the relationship between their data and CO_2 emissions, and sustaining the data flow with the providers represent both a remarkable new opportunity for the CHE prototype and a difficult challenge.

4 Recommendations for operational prototype

As explained in the introduction, it is still too early to define the role of each Earth observation stream in the operational prototype. Only the data from the CO2M mission have a clear position in the system, as assimilated data. The measurement systems or measurement networks for the other data that will be given a key role will likely need to be developed, but this is not addressed here.

The above-mentioned Earth observations can be summarised in the following form.

Table 1: Implementation priorities linked to the domain (global, regional, local) and stream for application in the prototype: Near Real Time (NRT) and re-analysis (RA). An estimate of the effort required is given in person months.

Component	Domain	Stream	Recommendation	Estimated effort (Person Months)
Satellite XCO_2 retrievals (Atmospheric Composition Virtual Constellation with or without the CO2M mission)	Global, regional	NRT, RA	Timeliness, accuracy	60
Satellite retrievals of column-average non-CO_2 tracers related to CO_2 anthropogenic emissions (NO_2, CO, …),	Global, regional	NRT, RA	Timeliness, accuracy	60
Satellite retrievals related to CO_2 sources and sinks in vegetated areas	Global, regional	NRT, RA	Timeliness, accuracy	60

(SIF, FAPAR, vegetation biomass, …)				
Satellite observations related to the spatial and temporal variations of CO_2 emissions (data from the GPS, night-light imagery, …).	Global, regional	NRT, RA	Timeliness, accuracy	36
Ground-based remote sensing observations (TCCON, COCCON, AERONET)	Global, regional	RA	Metrological resolution (higher than current for XCO_2)	6
In situ and flask-sampling observations of tracers that are related to CO_2 sources and sinks or to atmospheric transport (WMO/GAW including ICOS, NOAA, IAGOS, CONTRAIL; air-quality networks and some lower-cost medium precision sensor urban networks)	Global, regional	NRT, RA	Timeliness, accuracy	36
Flux observations (FluxNet, the Urban Flux Network, …)	Global, regional	RA	Accuracy	6
Wind observations from satellites or from the surface	Global, regional	NRT, RA	Timeliness, accuracy	60
Observations about sources and sinks of any non-CO_2 tracer used and about how this tracer relates to CO_2 emissions (e.g.,	Global, regional	NRT, RA	Timeliness, accuracy	60

OH concentrations).				
Near-real-time activity data	Global, regional	NRT, RA	Timeliness, operational data flow	60

5 Research priorities

The assimilation of Earth observations in an atmospheric chemistry-transport model, possibly coupled with emission and absorption process models, to monitor anthropogenic CO_2 emissions is a new promising research area. However, the ambition of the Copernicus CO_2 support capacity to reach enough accuracy in this domain for the provision of extra evidence on the anthropogenic emissions levels and trends within the framework of the Paris Agreement is particularly challenging. A large research effort is needed to identify the role of each relevant Earth observation type in such a system and to develop the modelling capability associated to the main ones. The priorities are summarised in the following table.

Table 2: Research priorities linked to the domain (global, regional, local) and stream for application in the prototype: Near Real Time (NRT) and re-analysis (RA). An estimate of the effort required is given in person months.

Component	Domain	Stream	Recommendation	Estimated effort (Person Months)
Data assimilation system	Global	NRT, RA	Identify contributions from direct or indirect observations of anthropogenic activity (co-emitted tracers, activity data, …) for the separation between fossil fuel and non-fossil fuel fluxes and possibly for some sectoral attribution	60
Data assimilation system	Global	NRT, RA	Identify contributions from direct or indirect observations of vegetation activity (SIF, COS, …) for the separation between fossil fuel and non-fossil fuel fluxes	60
Transport model	Global	NRT, RA	Identify contributions from direct or indirect observations of atmospheric transport	60

			(plume orientation in the CO2M mission images, wind vector retrievals, measurements of radon, …) for the improvement of transport simulation	
Observation operator	Global	NRT, RA	Develop a realistic modelling framework for each new observation (radiocarbon, NO_2, etc.), including corresponding error statistics	60

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