The Integrated Carbon Observation System in Europe

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Abstract

Since 1750, land use change and fossil fuel combustion has led to a 46 % increase in the atmospheric carbon dioxide (CO_2) concentrations, causing global warming with substantial societal consequences. The Paris Agreement aims to limiting global temperature increases to well below 2°C above pre-industrial levels. Increasing levels of CO_2 and other greenhouse gases (GHGs), such as methane (CH_4) and nitrous oxide (N_2O), in the atmosphere are the primary cause of climate change. Approximately half of the carbon emissions to the atmosphere is sequestered by ocean and land sinks, leading to ocean acidification but also slowing the rate of global warming. However, there are significant uncertainties in the future global warming scenarios due to uncertainties in the size, nature and stability of these sinks. Quantifying and monitoring the size and timing of natural sinks and the impact of climate change on ecosystems are important information to guide policy-makers' decisions and strategies on reductions in emissions. Continuous, long-term observations are required to quantify GHG emissions, sinks, and their impacts on Earth systems. The Integrated Carbon Observation System (ICOS) was designed as the European *in situ* observation and information system to support science and society in their efforts to mitigate climate change. It provides standardized and open data currently from over 140 measurement stations across 12 European countries. The stations observe GHG concentrations in the atmosphere and carbon and GHG fluxes between the atmosphere, land surface and the oceans. This article describes how ICOS fulfills its mission to harmonize these observations, ensure the related long-term financial commitments, provide easy access to well-documented and reproducible high-quality data and related protocols and

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tools for scientific studies, and deliver information and GHG-related products to stakeholders in society and policy.

Capsule

ICOS is a distributed Research Infrastructure conducting standardized, high-precision and long-term observations and facilitating research to understand the carbon cycle and to provide necessary information on greenhouse gases.

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Introduction

Since the industrial revolution the combination of land use change and fossil fuel combustion has led to a 46 % increase in the atmospheric CO_2 concentrations totaling to a buildup of 2200 +/- 320 $GtCO_2$ in the atmosphere (Friedlingstein et al. 2020; Rogelj et al. 2018). Consensus is that this has led to a significant warming of the atmosphere and increased heat storage of the upper ocean with subsequent effects of considerable societal importance. Human-induced increase in atmospheric concentrations of carbon dioxide (CO_2) and other greenhouse gases (GHGs), such as methane (CH_4) and nitrous oxide (N_2O), are the primary cause of the ongoing climate warming (IPCC 2018). The atmospheric buildup of CO_2 would have been about twice as large had approximately half of the carbon emitted to the atmosphere not been sequestered by ocean and land sinks, leading to the rate of warming being reduced (Friedlingstein et al. 2020). However, the size, nature and stability of these sinks are uncertain, which together with the uncertainty of the speed of release of the heat stored in the ocean surfaces leads to large uncertainties in the projected global climate warming with different GHG mitigation scenarios (Ma et al. 2020; Rhein et al. 2013). Improving the quantification and reducing the uncertainty of these projections is important to support policy-making and the size and timing of reductions in global emissions. There are uncertainties in the emission sources but the largest cause for uncertainty in the global carbon budget estimates are likely due to the lack of understanding of land and ocean sinks (Friedlingstein et al. 2020). Understanding of these sinks, sources, and the related processes can only be achieved with research based on spatially and temporally comprehensive and precise data. This is ever more important now that a specific goal has been set at limiting average global surface temperature increases to well below 2°C above pre-industrial levels (The Paris Agreement (United Nations 2015a) ratified by 189 countries to guide the actions to combat climate change).

Anthropogenic emissions of GHGs to the atmosphere are superimposed on with the much larger natural GHG exchange fluxes between the atmosphere and the terrestrial ecosystems and ocean, which are further affected by ongoing climate warming. Quantifying the anthropogenic perturbation therefore depends on quantifying both natural and anthropogenic emissions and sinks and understanding the drivers of feedback mechanisms over both.

The Integrated Carbon Observation System (ICOS), which currently includes over 140 stations, was designed as the European *in situ* observation and information system to support science and society in their efforts to mitigate climate change. ICOS is motivated by understanding the sources, sinks and cycling of greenhouse gases in the atmosphere-biosphere-hydrosphere continuum. The European Commission, Belgium, Finland, France, Germany, Italy, the Netherlands, Norway, Sweden, and Switzerland committed to this mission when the ICOS ERIC (European Research Infrastructure Consortium) was established in 2015.

Key aspects of climate science addressed by ICOS have been elaborated in earlier articles, with Schulze et al. (2009) emphasizing the importance of N_2O and CH_4 in the European greenhouse gas budget, Peters et al. (2010) quantifying European net terrestrial CO_2 exchange, Gielen et al. (2017) briefly summarizing the different components of the network, Franz et al. (2018) giving an overview on ICOS ecosystem observations, Steinhoff et al. (2019) describing the ocean network, and Levin et al. (2020) addressing the atmospheric network. This article provides a comprehensive overview of the ICOS Research Infrastructure (RI), including a historical overview, describing the structure, operations and financial sustainability of the ICOS RI, elaborating present and future scientific questions, and discussing lessons learned and challenges addressed by ICOS.

The rationale and path into Integrated Carbon Observation System

Even though the connection between human actions and climate change had been made by the end of the 20th century (IPCC 1992), many important questions were still open, such as how much CO_2 from fossil fuel burning remains in the atmosphere and how much was taken up by oceans and terrestrial ecosystems (Keeling 1978). A major obstacle in answering these questions was limited data availability and the use of different observational methods, units, and scales by different countries and sites. This required global harmonization of observations, first started in the atmosphere by the World Meteorological Organization Global Atmosphere Watch (WMO GAW) programme in 1989 (WMO 2014) and with the FLUXNET ecosystem global network in 1996 (Baldocchi et al. 2001).

Another obstacle was how to draw conclusions from various pieces of data and information. This called for a framework how to systematically provide scientific knowledge in global scale, giving birth to the Intergovernmental Panel on Climate Change (IPCC), established in the end of 1980s. Eyes turned next to land, where various methods had been developed to understand highly diverse and complex terrestrial ecosystems. This posed challenges to compare the results, and the Global Climate Observing System (GCOS) was established to harmonize terrestrial observations and to define a set of Essential Climate Variables (GCOS 1994, 2016; WMO 2009). Quantifying relatively small long-term trends in CO_2 and other GHG concentration and fluxes against a background of much larger short-term variations caused by the ‘natural’ carbon cycle requires highly precise and accurate observations. To decrease uncertainties by improving the quality of observations, and to draw general conclusions, research- and investigator-based European ecosystem networks, with foci on CO_2, energy and water exchange, emerged in the 1990s with the support of the European Commission funding programs (EuroFlux, CarboEurope IP and GHG Europe). During 1998-2002, the Euroflux network covered 30 stations mainly in forest ecosystems across Europe (Janssens et al. 2003), which later developed into the network of ecosystem stations within ICOS.

At the beginning of the 1990s, the Global Ocean Observing System (GOOS) was established to coordinate and harmonize ocean observations together with GCOS. The scientific community undertook the task to provide open access to global ocean surface CO_2 data via the Surface Ocean CO_2 Atlas, SOCAT (Pfeil et al. 2013). These data are essential to estimate ocean carbon budget and acidification. As a community effort, SOCAT depends heavily on voluntary data submission and secondary quality control, and the Ocean Carbon Data System of National Oceanic and Atmospheric Administration and ICOS support SOCAT and contribute significantly to its data operations and development.

The development of observation networks had been fragmented into various projects in Europe (see Fig. 1 in Franz et al. (2018)). By the beginning of the 2000s, it was possible to estimate the European terrestrial carbon budget by either using the few ecosystem network data available (e.g. Papale and Valentini 2003) or by methods using atmospheric network data, but these provided dissimilar and highly uncertain results (Janssens et al. 2003). The results suggested that increase in ecosystem representation and data would reduce the uncertainty in the bottom-up approach and that including more atmospheric stations would improve the accuracy of top-down estimates. The EU-funded CarboEurope Integrative Project (2004-2008), was a major step towards integrated studies, harmonized observations and data flows, covering atmosphere and ecosystem sciences (Schulze et al. 2009). In parallel, the CarboOcean IP conducted over 2005-2009 developed systematic ocean carbon observations and analysis across Europe. The observations collected in the context of these projects were an important example to demonstrate how a large and coordinated network could provide a unique dataset valuable for the modeling activities to estimate continental scale GHG fluxes (e.g. Luyssaert et al. 2010; Schulze et al. 2009; Vetter et al. 2008).

European countries have been at the forefront of setting-up the Paris Agreement to reduce emissions. Implementation of climate change mitigation is done by individual nations, but to effectively curb the increase of GHG concentrations in the future, a comprehensive strategy of emission reductions and natural sink conservation must be designed collectively. The success of the scientific projects showing capability of the scientific community to provide quantitative information at a European scale paved way for the political will to develop ICOS – an observation system that will narrow down future uncertainties and provide observational evidence of the current state of the carbon cycle perturbation. Throughout the development of ICOS, the policy-makers, funders and scientists have been in constant dialogue to improve the scientific foundation of decision-making and obtain the political and financial commitments across European countries.

ICOS foundation required negotiating the concept for such as system, with clear purpose and governance as well as financial structure and responsibilities of each participants, in which the countries could then commit. This was the purpose of ICOS preparatory phase project in 2008-2013 (reference, see also Appendix 1).

User-centric approach drove the development of a centralized data provision hub for all ICOS data, the Carbon Portal. The problem of different type of observations in atmosphere, ecosystem, and ocean stations was addressed by centralizing the quality control and data processing in three respective Thematic Centres with specific experience and knowledge. To allow measurements of required precision, the Central Analytical Laboratories was designed to provide calibration gases to atmospheric and ocean monitoring stations. The process for scientific development was planned on the interactions between these components and the Monitoring Station Assemblies (MSAs) which include all station Principal Investigators (PIs).

The financial challenges were tackled by acquiring commitments from various countries interested to build a national network of ICOS stations or propose a Central Facility. The host countries provide the majority of the financial support by direct governmental grants (ICOS Ecosystem Thematic Center is hosted by Italy, France, and Belgium, Atmosphere Thematic Center by France and Finland, Ocean Thematic Center by the Norway and the UK, the Central Analytical Laboratories by Germany, and the Carbon Portal by Sweden and the Netherlands). The stations are maintained by individual countries, and each country also contributes to the general costs for the upkeep of the RI. The principles for sharing the financial responsibilities were written in the ICOS financial rules.

With scientific, technical, and financial concepts in place, the last challenge was how to coordinate such an infrastructure across many countries. The solution was to establish a legal entity designed to manage Research Infrastructures and recognized in all European countries, called ICOS ERIC (European Research Infrastructure Consortium (https://ec.europa.eu/info/research-and-innovation/strategy/european-research-infrastructures/eric_en), hosted by Finland and France with participation from all member countries), to coordinate the whole research infrastructure and to report to and consult with the ministerial stakeholders.

The mission of ICOS is to harmonize European carbon and GHG observations, ensure the related long-term financial commitments, provide easy access to well-documented and reproducible high-quality data and related protocols and tools for scientific studies, and to deliver GHG-related products to stakeholders in society and policy. The first five years of ICOS from 2015-2019 focused on establishing an operational infrastructure, and as an acknowledgement of successful implementation, ICOS ERIC was included in the European Strategy Forum on Research Infrastructures' strategy as a Landmark infrastructure (ESFRI 2016). Since becoming operational in 2015, the Czech Republic, Denmark, the United Kingdom, and Spain have joined ICOS, and Poland has announced to join ICOS, considerably expanding the network, and negotiations are currently under way with Estonia, Greece, Hungary, Ireland, Portugal and Romania. The second phase of ICOS, described in the ICOS strategy published in 2019 (ICOS 2019), and its associated implementation plan, will place emphasis on the use of data and on enhancing the network's capability to analyze anthropogenic impacts on the carbon cycle. We foresee the new European Green Deal launched by EU Commission at the end of 2019 (https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en), designed to make Europe the first net-zero continent, will further strengthen ICOS' role in the forthcoming years.

Description of ICOS observations and data

ICOS provides the core network of highly accurate, long-term European *in situ* observations of carbon and GHGs (see Appendix 2 for full list of observed variables). The terrestrial network of over 100 stations ranges from Sweden (Latitude 68^{o}N in WGS84 coordinates) to the

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Mediterranean Sea (Lat 36^{o}N), from the UK (Longitude 3^{o}W) to Finland (Lon 30^{o}E), from the lowlands near sea level to alpine regions (2168 m a.s.l., Italy), with stations also outside of Europe (e.g. in French Guyana, Greenland and Democratic Republic of the Congo). The marine network of over 20 stations and vessels extends from polar areas to the equator and from coasts to open ocean.

The atmospheric network of tall towers, mountain, and coastal stations covers large parts of Europe with continuous measurements of CO_2 and CH_4 mole fractions. When coupled with an atmospheric model, these data provide an integrated view of all natural and anthropogenic fluxes. In fully equipped ICOS stations, meteorological variables, N_2O and ^{222}Radon are observed to link concentration variations to atmospheric mixing. In addition, N_2O, SF_6, H_2, and for CO_2 source apportionment CO, ^{13}C-CO_2, ^{14}C-CO_2, ^{18}O-CO_2, and O_2/N_2, are analyzed in air sampled by automated flask samplers at the most extensively equipped stations, called Class 1 stations (ICOS 2017a; Levin et al. 2020; Appendix 2).

GHG fluxes in different terrestrial ecosystems (forests, croplands, grasslands, mires, wetlands, shrublands, lakes, Mediterranean savannas, urban sites) are observed at comprehensively equipped stations to quantify the exchange of carbon, GHGs and energy between the atmosphere and the ecosystems (Franz et al. 2018), by using the eddy covariance technique (Rebmann et al. 2018). Biosphere-atmosphere exchange measurements at flux towers represent the only direct method to provide detailed data at ecosystem scale, and they are valuable also for different user communities: e.g. sensible and latent heat fluxes are important to understand the water cycle and to improve weather forecasts, turbulence data are used in studying boundary layer physics. In a subset of stations, fluxes of CH_4 and N_2O are observed (Nemitz et al. 2018). Complementary data comprise e.g. soil organic carbon content, Green Area Index, litterfall, aboveground biomass, records of disturbances, and vegetation properties such as leaf nutrients and phenological status, as well as management activities (Arrouays et al. 2018; Gielen et al. 2018; Hufkens et al. 2018; Loustau et al. 2018; Op de Beeck et al. 2018; Pavelka et al. 2018; Saunders et al. 2018). These various observations are used to estimate the contributions of different components of the ecosystem, such as soil or vegetation, to the seasonal and interannual variability of the carbon and GHG budget of the whole ecosystem, as well as when upscaling carbon fluxes to regional and global scales (Jung et al. 2020).

The ocean observations are conducted either on fixed platforms (e.g. moorings and surface buoys) or on ships operating predominantly in the North Atlantic, Nordic, Baltic and Mediterranean Seas, but occasionally also in Polar regions and equatorial Atlantic. Partial pressure of sea surface CO_2 is used in conjunction with other parameters (temperature, salinity, mixed layer depth) and satellite remote sensing products including wind fields and chlorophyll to calculate oceanic uptake of CO_2 (ICOS 2017b, 2020b; Steinhoff et al. 2019). Other carbon cycle parameters (pH, alkalinity, dissolved inorganic carbon) and related properties such as nutrients and oxygen are used to investigate ocean transports and controls over carbon uptake. This latter work involves collaboration across various elements of the European RI landscape and components of the Global Ocean Observing System (GOOS) including Euro-Argo (European consortium for operating Argo floats), EMSO (the European Multidisciplinary Seafloor and water column Observatory), and GO-SHIP (the Global Ocean Ship-based Hydrographic Investigations Program). While the main policy framework that ICOS contributes to is the Paris Agreement, also Agenda 2030 (United Nations 2015b) and its Sustainable Development Goal 14.3 is supported with monitoring of ocean acidification.

The variables and related costs for all ICOS observations are detailed in the ICOS Handbook, released every 2 years (ICOS 2020a). For example, to build one fully equipped atmosphere or ecosystem station (Class 1) costs between 0.5 and 1 M€ (not including personnel costs), whereas costs for stations having only a subset of observations (Class 2) can be between 0.1 and 0.3 M€. Maintenance requirements and collection of ancillary data are also provided, with the most significant component being person-power, ranging from 0.3 to 4 Full Time Equivalents per annum depending on the type of the station.

Quality Assurance and Control (QA/QC)

Within the CarboEurope IP project (Schulze et al. 2010) the challenges to achieve highly compatible atmospheric data became obvious. Large efforts were undertaken to assess the compatibility of atmospheric measurements done by different laboratories at different observational sites. Yet, results from these exercises repeatedly yielded evidence that the WMO compatibility goals were not met by all participants and for all tracers. Biases between laboratories could sometimes be of the same order of magnitude as the atmospheric signals that should be captured and it was not possible to define a network data compatibility. This was motivating the ICOS concept with highly standardized measurement approaches at the observatories (including aspects such as instrumentation, procedures to account for atmospheric humidity, and calibration procedures) and the establishment of central facilities that assess the adequate performance of all installed analyzers and assure transparent data processing (ATC), as well as the consistency of sample measurement results and reference gas assignments that are used within the monitoring network (CAL). To have the ability to make a defendable uncertainty assessment that is required for observational data (WMO 2020b) the following QA/QC approaches are applied that cover all levels of the observational system (stations as well as central facilities). To minimize uncertainties in both observations provided by single stations and studies using data from multiple stations, several steps are taken. The instruments themselves have strict requirements, they are systematically calibrated, their setup is based on stringent protocols, and the data are processed by the Thematic Centers with proven and standardized methodologies (Hazan et al. 2016; El Yazidi et al. 2018; Vitale et al. 2020).

Scientists in the ICOS atmosphere community, coordinated via the Atmospheric MSA, have defined and approved protocols for instrumentation setup and sampling strategies (ICOS 2017a, Levin et al. 2020) to ensure that atmospheric measurements comply with the compatibility goals set by the WMO for measurements of major GHGs and associated tracers (WMO 2020b). Stringent network compatibility within ICOS and with other networks is key when using the observations in concert with atmospheric transport models to quantify GHG sources and sinks. Calibration gases are prepared and calibrated centrally for the network by the Flask and Calibration Laboratory (FCL) of the Central Analytical Laboratories (CAL) that maintains tight links to the WMO Central Calibration Laboratory to ensure the traceability of ICOS data to internationally accepted WMO calibration scales by one unique path. To assess the accuracy of the implementation of these scales at the FCL maintains several ongoing round robin exercises with the NOAA laboratories as quality control. The FCL is also responsible for flask analyses except for ^{14}C-CO_2, which is analyzed by the Central Radiocarbon Laboratory of the CAL. The precision and stability of all GHG analyzers are tested at the Atmosphere Thematic Centre prior to deployment (Yver Kwok et al. 2015). A comprehensive overview of the optimization of the quality management as part of the labelling process of atmosphere stations is given in Yver-Kwok et al. (2021). For quality control of the continuous *in situ* measurements, automated QC figures are generated on a daily level by the ATC that summarize the statistics of the measurement precision (repeatability and target gas bias) which provide a basis to quantify the measurement uncertainty. Additional auditing is made with travelling instrumentation (ICOS Mobile Lab) operated at selected stations for a couple of weeks, and by ongoing comparison of flask results with *in situ* observations at Class 1 stations (Levin et al. 2020).

To ensure high quality of observations in diverse ecosystems, with various drivers influencing the carbon and GHG fluxes, the observation methods need careful attention. Since diverse observation methods were established for different climate regions and ecosystem types in the past decades, a community-driven effort was necessary to define key and ancillary components to be observed in each ecosystem type to analyze carbon and GHG fluxes. Also, much effort has been put into defining the specifications and methodology of observations by the community, together with the Ecosystem MSA and the Ecosystem Thematic Centre. Both optimal sets of variables and practical feasibility were considered when harmonizing the observations, which resulted in a compromise suitable for high quality and long-term continental scale observation system (Franz et al. 2018). Over 100 scientists' efforts were acknowledged in a set of publications describing the ecosystem measurement protocols in 2018 (International Agrophysics, vol. 32(4), 2018). Starting from the protocols, more practical and detailed Instruction documents were prepared and published by the ETC (http://www.icos-etc.eu/documents/instructions) that are revised and updated regularly, following the newest developments and know-how.

For the ocean observations, the major challenges are the complexity of the carbonate system, the often remote location of stations, and suitability of different observing methods for different types of stations. Tailored solutions are needed in order for each station to deliver the best possible data, and the ICOS ocean community, supported by the Ocean Thematic Centre, has adopted and adapted existing and proven best practice guidelines and protocols (Dickson et al. 2007) for observations made by different types of stations (Steinhoff et al. 2019). ICOS is the first multi-national entity within the marine community that has standardized CO_2 observations (Steinhoff et al. 2019). The Fixed Ocean Stations' maintenance and calibration are done during the visit by research vessels, ideally several times per year, whereas observations on Ships of Opportunity (SOOP) are calibrated even more frequently. Inclusion of marine towers with direct flux observations is currently under development (Steinhoff et al. 2019). CO_2 observations are calibrated with standards traceable to the WMO calibration scales (ICOS 2020b). Data quality, control and uniformity is also supported by a customized QuinCe tool developed by the OTC.

To guarantee the quality of observations, in all three network components (atmosphere, ecosystem, and ocean), it is necessary for a station to pass an ICOS station certification process. Here, the station characteristics are evaluated, its compliance with measurement protocols and standards is analyzed, and data transfer and quality are evaluated by the respective Thematic Centres during a test measurement period of a few months. After successfully completing this process which typically takes two to three years, the station receives the ICOS certificate. This means the station meets the high standards of the ICOS network and continuously provides ICOS data. Of the over 140 stations in the ICOS network, over 60 stations have been certified by the end of 2020.

Open data access

ICOS has addressed the major challenge of data access and simplification of data use (Fig. 2) thanks to the PI and Central Facilities work that agreed on a continuous data submission and adoption of an open data license (Creative Commons Attribution 4.0 International, which also allows commercial use). Additionally, the services provided to make data distribution easier and assignment of Digital Object Identifier (doi) to datasets are major advances to improve and promote open data.

To serve various user needs, different levels of the data are openly accessible with different level of processing and quality check. Much attention has been paid to the metadata that follow the specifications defined by the Carbon Portal in collaboration with the Thematic Centres, also considering existing international standards. All steps of data flows were designed based on the FAIR (Findable, Accessible, Interoperable, Reusable) principles (Wilkinson et al., 2016), giving the user sufficient tools to interpret the data (ICOS 2015).

Different levels of data are stored throughout the process, from raw sensor data (Level 0), to the automatically calibrated near-real-time data (Level 1; available within 24 hours of the measurement) to the final, quality-checked data (Level 2). All the data are passed on to the Carbon Portal, which provides free and open access to ICOS data. The data are minted with Persistent Identifiers to provide unique identification and citation of the datasets and their contributors (ICOS 2019). The Carbon Portal offers tailor-made tools and services (Fig. 3) and distributes products (Level 3) that are created by the scientific community based on ICOS data and possibly from other data sources (Fig. 4). The Carbon Portal has started to develop and provide tools for online analysis of data and model results (see e.g. ICOS 2020c). These enable transparent analyses of data by station PIs, interactive collaboration with the data users and utilization of cloud services as virtual working environments.

Major scientific questions and glimpse to the future

Many major scientific questions have guided the development of systematic, continental observations of carbon and GHG budgets. Scientists have been able to answer how much of emitted CO_2 from fossil fuels have accumulated in the atmosphere, oceans and terrestrial ecosystems (Friedlingstein et al. 2020). Many advancements have been made in defining how terrestrial ecosystems are affected by and how they feed back to climate change, e.g. by changes in evapotranspiration or albedo.

With the ICOS network reaching maturity via station certification, the compilation of the European carbon and GHG budget, which was previously possible as one-time effort (Schulze et al. 2009), can soon be produced annually at high spatial resolution and with reduced uncertainty. This is a significant step forward in assessing changes and trends on the continental scale. Advancements have been made in providing detailed information on the dominantly studied ecosystems, e.g. forests, grasslands and croplands, while we still have only rudimentary understanding of some other ecosystem types, e.g. lakes, rivers, peatlands, Mediterranean savannas and Arctic tundra (Baldocchi 2014; Schulze et al. 2010), or on urban systems. Mitigation capacity of urban areas as well as their adaptation capacity will need much deeper attention as the urban population is continuously growing and urban areas represent the major sources of GHGs in Europe and in most of the continents (Calfapietra et al. 2015).

ICOS data is widely used in publications from various scientific fields. The amount of ICOS-related publications per year have increased from 30 in 2012 to roughly 200 in 2020, and the citations from 600 to 11 000, respectively (https://www.icos-cp.eu/science-and-impact/society-impact/references). The publications are associated to almost 60 categories with the two largest being meteorology and atmospheric sciences (37% of all publications) and environmental sciences (34%) (ICOS 2021). The cross-domain integration in ICOS allows us to comprehensively address the biogeochemical fluxes of carbon and GHGs and to identify and study existing gaps in knowledge. A recent example are the 17 publications, based on data from more than 100 stations, following the drought in Europe in 2018. The drought was analyzed from how it was detectable in the atmospheric station network and how it affected ecosystem processes and GHG budgets, to regional assessments of its influences on ecosystem carbon exchange, and relations to major crops (Peters et al. 2020). ICOS made this rapid scientific response possible by building the foundation for fast action, by harmonizing observations and centralized data processing, by analyzing the data in near-real time to detect anomalies in drivers and ecosystem responses, by facilitating networking of scientists, and by providing virtual solutions for joint work. The results show that the drought affected more the productivity of crops and grasslands than forests, which protected themselves by reducing their evaporation and growth, leading to decreased uptake of carbon dioxide (Peters et al. 2020). In general, carbon sinks decreased by 18% in a study covering 56 ecosystem sites (Graf et al. 2020). The dry conditions even turned some mires from sinks into sources (Rinne et al. 2020). In some parts of Europe, winter 2018 was wet, leaving a lot of soil moisture in the ground, while spring was sunny and came early - this caused the vegetation to grow in spring more than average. In some places, this early spring growth was enough to offset the reduction of carbon uptake later in summer (e.g. Smith et al. 2020). Currently, there is a joint effort of similar magnitude under preparation analyzing the warm winter 2019-2020. The above mentioned are also reflected in the biennial ICOS Science Conference that brings scientists from different disciplines together to discuss besides science, also e.g.

methodological improvements and societal relevance of long-term observations of climate-related variables.

Now, with the Paris Agreement having clear processes to guide the nations with climate change mitigation, the pressure is increasing to provide robust information to support the review of the impact of these actions (Art 14.1 in the Paris Agreement). ICOS is actively engaged with GCOS to provide observations of Essential Climate Variables and to draft a suitable indicator representing terrestrial ecosystems. ICOS provides data and participates to the development of Global Carbon Budget to reduce the uncertainty of the global estimates and to build a solid foundation for some of the global data sources, such as SOCAT and FLUXNET, the global network of gas flux observations between ecosystems and the atmosphere (Papale 2020). ICOS is in active dialogue with UNFCCC Subsidiary Body for Scientific and Technological Advice to facilitate discussion between science and policy. ICOS is currently focusing on providing the needed information at national and regional levels with the separation of natural and anthropogenic fluxes. For example, VERIFY (H2020 project 776810) aims to improve national GHG inventories with top-down (atmospheric inversions) and bottom-up (inventories made with complementary methods and data than used by governmental authorities) scientific approaches (Petrescu et al. 2020).

The capability to disentangle the natural cycle and the anthropogenic disturbance has made progress, and consensus exists that the required next step is to link tightly *in situ* and remote sensing observations and modelling to more accurately quantify anthropogenic CO_2 emissions (Copernicus 2015, 2019). The calibration and verification of satellite products and models within this system aim to rely on the *in situ* ICOS network, including potential atmospheric vertical profiling of GHGs using AirCore (Karion et al. 2010) and collaboration with the Total

Carbon Column Observing Network (TCCON). This system is currently developed by scientists involved in ICOS and peers in the CoCO2 project (H2020 project 958927). Further developments could include the provision of more accurate observations of hot spots of human activities, mainly in urban areas (WMO 2019). The ^{14}C methodology is used for quantifying the CO_2 emissions from fossil fuel burning, as the fossil energy sources are void of ^{14}C. Their contribution can be derived from measurements of the $^{14}C/^{12}C$ ratio in atmospheric CO_2 (Basu et al. 2020; Levin et al. 2003, 2011). These observations are systematically made in ICOS but mostly in sparsely populated locations. The concept of an urban observatory has been tested in some European and US cities (Breon et al. 2015; Lauvaux et al. 2020) but more development, probably combining atmospheric observations and modelling with flux observations, is needed before the methodology is mature enough to be incorporated into a research infrastructure such as ICOS. This system for greenhouse gas measurements in urban areas is developed by ICOS in the H2020 project PAUL (Pilot Application in Urban Landscapes – towards integrated city observatories for greenhouse gases). Additionally, the flux towers are invaluable to provide data on carbon sinks over vegetated urban surfaces at neighborhood-scale (e.g. Nordbo et al. 2012).

Lack of sufficient geographical coverage of observations is a source of major uncertainty in most regions of the world (WMO 2020a). Even in Europe where the *in situ* observations of CO_2 and other GHGs were brought together by ICOS, large parts of Eastern Europe are still to join this network. The benefits are understood at the scientific level but as membership in a research infrastructure obliges sustained funding and commitments, the discussions must enter the political level. Currently, the discussions are ongoing with seven countries to join ICOS.

ICOS is collaborating with complementary networks in Europe and in other continents towards more harmonized standardization of observations and data processing, common data policies, and common data citation system. Examples are the Long-Term Ecosystem Research (eLTER), the European Research Infrastructure for the observation of Aerosol, Clouds and Trace Gases (ACTRIS), the AmeriFlux Management Project and the National Ecological Observatory Network (NEON) in the US and the US Carbon Cycle Science Program, the Chinese Ecosystem Research Network, the Terrestrial Ecosystem Research Network (TERN) in Australia, and the National Institute for Environmental Studies in Japan. ICOS also supports and develops the global data networks, such as WMO Global Atmosphere Watch and the World Data Centre of Greenhouse Gases for atmospheric observations, FLUXNET for ecosystem GHG fluxes, Surface Ocean CO_2 Atlas (SOCAT), and GLobal Ocean Data Analysis Project (GLODAP). ICOS contributes to the development of harmonized observations in Africa via design study and capacity building (Lopéz-Ballesteros et al. 2018).

Many global coordination frameworks are in place to address the global environmental challenges. However, there is a huge distance between global frameworks and local actions. Developments are needed on different scales to improve the observational capacity and to transform the data into information useful for local and national decision makers, non-governmental organizations and the private sector. Examples of the urgently needed developments are defining how changing climate affects the ability of natural terrestrial and ocean sink to sequester carbon, supporting the verification of national GHG inventories, and understanding and validating the efficacy of mitigation actions. ICOS provides the European *in situ* observations of CO_2 and other GHGs, and is well positioned to coordinate the *in situ* component of a comprehensive system that caters to different information needs at different spatial and temporal scales (Copernicus 2019). Combatting climate change needs reliable information, and ICOS is here to deliver.

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Appendix

Appendix 1. ICOS Governance and Funding

Governance

The European Strategy Forum for Research Infrastructures (ESFRI) produced a roadmap of RIs in 2006, including the preparation of ICOS to cover European carbon dioxide and other GHG observations (ESFRI 2006). The ICOS Preparatory Phase Project (2008-2013) focused on integrating the already existing stations into a single network and establishing a model for sustained funding since the ICOS observations at the stations was usually limited to the lifetime of regular research projects. Besides harmonized observations, data management and archiving, this unprecedented effort covered also administrative, financial and legal aspects. ICOS ERIC (was established in 2015 with the member (Belgium, Finland, France, Germany, Italy, the Netherlands, Norway, Sweden) and observer (Switzerland) countries committing to the long-term funding of the RI.

The governance and operational structure of Integrated Carbon Observation System European Research Infrastructure Consortium (ICOS ERIC) and ICOS Research Infrastructure (RI) is shown in Appendix Fig. 1. The data are provided by the ICOS National Networks which are networks of stations operated at national level and form the backbone of ICOS RI. The Central Facilities receive, quality control and process the data measured at the ICOS stations. The Central Facilities are operated by one or several Host Institutions either at national or at multi-national level, and they include the Atmosphere Thematic Centre (ATC), Ecosystem Thematic Centre (ETC), Ocean Thematic Centre (OTC) and Central Analytical Laboratories (CAL). Monitoring Station Assemblies (MSAs) in atmosphere, ecosystem and ocean domains, gather together the ICOS Station Principal Investigators (PIs) to discuss technical and scientific

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topics. All data from raw, near-real time to final quality controlled data are stored and published through the ICOS Carbon Portal, part of ICOS ERIC.

The task sharing between ICOS ERIC and Central Facilities is clearly defined and agreed upon in ICOS ERIC - Central Facilities agreements. Furthermore, the basic management and internal distribution of the work is organized by the Central Facilities host institutions, and employment practices are carried out according to the respective institutional practices. Financial governance follows the similar approach: the host institutions have their own responsibility but have to comply with common rules and are monitored by ICOS ERIC.

The decision-making body in ICOS ERIC is the General Assembly consisting of delegates from all Member and Observer countries. The Research Infrastructure Committee, with representatives from the ICOS ERIC and Central Facilities and MSAs, advises the Director General and the General Assembly on scientific and organizational topics. Scientific Advisory Board and Ethical Advisory Boards are external bodies for giving strategic guidance for ICOS RI.

Funding

The national networks are funded mainly by the national funding agencies and respective ministries, with additional support by the host institutions of the measuring stations. A substantial part of the total costs of the Central Facilities and ICOS ERIC is covered by contributions of the hosting country/ies (host premium contribution) of the Central Facilities, Head Office and Carbon Portal.

Member and Observer countries of ICOS ERIC pays annual membership contributions. Total membership contributions are formed by the following elements: common basic contribution, common GNI based contribution, and number and type of stations. The latter part of the membership contribution is redistributed to the activities in the ICOS Central Facilities. The Central Facilities are also supported by the host organizations. ICOS ERIC seeks funding opportunities from European Commission and other sources.

Appendix 2. Observed Variables at ICOS Stations

All the observed variables at ICOS stations are presented in Appendix 2 tables 1-4.

References

Arrouays, D., and Coauthors, 2018: Soil sampling and preparation for monitoring soil carbon. *International Agrophysics*, **32**(4), 633–643, doi:10.1515/intag-2017-0047.

Baldocchi, D., 2014: Measuring fluxes of trace gases and energy between ecosystems and the atmosphere - the state and future of the eddy covariance method. *Global Change Biology,* **20**(12): 3600–3609, https://doi.org/https://doi.org/10.1111/gcb.12649.

Baldocchi, D., and Coauthors, 2001: FLUXNET: A New Tool to Study the Temporal and Spatial Variability of Ecosystem-Scale Carbon Dioxide, Water Vapor, and Energy Flux Densities. *Bulletin of the American Meteorological Society*, **82**(11), 2415-2434, https://doi.org/10.1175/1520-0477(2001)082<2415:FANTTS>2.3.CO;2.

Basu, S., and Coauthors, 2020: Estimating US fossil fuel CO_2 emissions from measurements of ^{14}C in atmospheric CO_2. *Proceedings of the National Academy of Sciences*, **117** (24), 13300-13307, DOI: 10.1073/pnas.1919032117

Breon, F. M., and Coauthors, 2015: An attempt at estimating Paris area CO_2 emissions from atmospheric concentration measurements. *Atmos. Chem. Phys.*, **15**, 1707–1724, www.atmos-chem-phys.net/15/1707/2015/.

Calfapietra C., Ü., Niinemets, and J. Peñuelas, 2015: Urban Plant Physiology: adaptation-mitigation strategies under permanent stress. *Trends in Plant Science*, **20**, 72-75.

Copernicus, 2015: Towards a European Operational Observing System to Monitor Fossil CO_2 emissions. https://edgar.jrc.ec.europa.eu/news_docs/CO2_report_22-10-2015.pdf.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-19-0364.1.

Copernicus, 2019: An Operational Anthropogenic CO$_2$ Emissions Monitoring & Verification Support Capacity – Needs and high level requirements for in situ measurements. https://doi.org/10.2760/182790.

Dickson, A. G., C. L. Sabine, and J. R. Christian (Eds.) 2007: Guide to Best Practices for Ocean CO$_2$ Measurements. PICES Special Publication 3, pp 191, ISSN: 1813-8519.

El Yazidi, A., and Coauthors, 2018: Identification of spikes associated with local sources in continuous time series of atmospheric CO, CO$_2$ and CH$_4$. *Atmospheric Measurement Techniques,* **11**(3), 1599-1614.

ESFRI, 2006: European Roadmap for Research Infrastructures. Report 2006. 84pp, https://www.esfri.eu/sites/default/files/esfri_roadmap_2006_en.pdf.

ESFRI, 2016: Strategy report on Research Infrastructures. 208pp, https://www.esfri.eu/sites/default/files/20160309_ROADMAP_browsable.pdf.

Franz, D. and Coauthors, 2018: Towards long-term standardised carbon and greenhouse gas observations for monitoring Europe's terrestrial ecosystems: A review. *International Agrophysics,* **32** (4), 439–55, https://doi.org/10.1515/intag-2017-0039.

Friedlingstein, P., and Coauthors, 2020: Global carbon budget 2020. *Earth System Science Data,* **12** , 3269–3340, https://doi.org/10.5194/essd-12-3269-2020.

GCOS, 1994: Report of the GCOS/GTOS Terrestrial Observation Panel. WMO/TD- No. 642; GCOS- No. 08. https://library.wmo.int/doc_num.php?explnum_id=3804.

GCOS, 2016: The Global Observing System for Climate: Implementation Needs. GCOS- No. 200. https://library.wmo.int/doc_num.php?explnum_id=3417.

Accepted for publication in *Bulletin of the American Meteorological Society.* DOI 10.1175/BAMS-D-19-0364.1.

Gielen, B., M. Op de Beeck, D. Loustau, R. Ceulemans, A. Jordan, and D. Papale, 2017: Integrated Carbon Observation System (ICOS): An Infrastructure to Monitor the European Greenhouse Gas Balance. In *Terrestrial Ecosystem Research Infrastructures: Challenges and Opportunities*, 1st edition, CRC Press, ISBN 9781498751315.

Gielen, B., and Coauthors, 2018: Ancillary data measurements at ICOS sites. *International Agrophysics*, **32**(4), 645-664, doi: https://doi.org/10.1515/intag-2017-0048.

Graf, A., and Coauthors, 2020: Altered energy partitioning across terrestrial ecosystems in the European drought year 2018. *Philosophical Transactions of the Royal Society B*, **375**, doi: 10.1098/rstb.2019.0524.

Hazan, L., J. Tarniewicz, M. Ramonet, O. Laurent, and A. Abbaris, 2016: Automatic processing of atmospheric CO_2 and CH_4 mole fractions at the ICOS Atmosphere Thematic Centre. *Atmospheric Measurement Techniques*, **9**(9), 4719-4736.

Hufkens, K., and Coauthors, 2018: Assimilating phenology datasets automatically across ICOS ecosystem stations. *Int. Agrophys.*, **32**(4), 677-687, doi: https://doi.org/10.1515/intag-2017-0050.

ICOS, 2015: ICOS RI Data Policy. *ICOS ERIC*, 11pp, https://www.icos-cp.eu/sites/default/files/cmis/ICOS%20RI%20Data%20Policy.pdf.

ICOS, 2017a: ICOS Atmospheric Station specifications, Version 1.3. *ICOS ATC*, 55pp, https://doi.org/10.18160/SDW6-BX90.

ICOS, 2017b: ICOS Marine Station Labelling Step 2. *ICOS OTC*, 23pp, https://otc.icos-cp.eu/sites/default/files/2018-05/ICOS%20Marine%20Station%20Labelling%20Step%202%20v4_crb.docx_.pdf.

ICOS, 2019: ICOS Strategy. *ICOS ERIC*, 44pp, https://doi.org/10.18160/TV1J-4XQY.

ICOS, 2020a: ICOS Handbook 2020. *ICOS ERIC*, 152pp, ISBN 978-952-69501-1-2.

ICOS, 2020b. ICOS Ocean Station Labelling Step 2. *ICOS OTC*, 20pp, doi: 10.18160/8SDC-K4FR.

ICOS, 2020c: Jupyter Notebook for ICOS Flask Sampling Strategy (Version 1.0). *ICOS ERIC*. https://doi.org/10.18160/FSS2-SH26.

ICOS, 2021: ICOS five year evaluation 2020. *ICOS ERIC*, 127pp, ISBN 978-952-69501-3-6.

International Agrophysics, vol. **32**(4), 2018. *Special Issue on ICOS Ecosystem Protocols*. http://www.international-agrophysics.org/Issue-4-2018,7048.

IPCC, 1992: Climate change 1992. The supplementary report to the IPCC scientific assessment. ISBN 0 521 43829 2.

IPCC, 2018: Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change, sustainable development, and efforts to eradicate poverty. Masson-Delmotte, V., P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P.R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J.B.R. Matthews, Y. Chen, X. Zhou, M.I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield, Eds., 630 pp, in press.

Janssens, I. and Coauthors, 2003: Europe's Terrestrial Biosphere Anthropogenic CO_2 Emissions. *Science*, **300**, 1538–42, https://doi.org/10.1126/science.1083592.

Jung, M. and Coauthors, 2020: Scaling carbon fluxes from eddy covariance sites to globe: synthesis and evaluation of the FLUXCOM approach. *Biogeosciences*, **17**, 1343-1365, https://doi.org/10.5194/bg-17-1343-2020.

Karion, A., C. Sweeney, P. Tans, and T. Newberger, 2010: AirCore: An innovative atmospheric sampling system. *Journal of Atmospheric and Oceanic Technology,* **27** (11), 1839–1853, doi: 10.1175/2010JTECHA1448.1.

Keeling, C. D., 1978: The influence of Mauna Loa Observatory on the development of atmospheric CO2 research. In *Mauna Loa Observatory. A 20th Anniversary Report*, J. Miller, Ed., 36–54. U.S. Department of Commerce.

Lauvaux, T. and Coauthors, 2020: Policy-Relevant Assessment of Urban CO_2 Emissions, *Environmental Science & Technology*, **54** (16), 10237-10245, doi: 10.1021/acs.est.0c00343.

Levin, I., S. Hammer, E. Eichelmann, and F. R. Vogel, 2011: Verification of greenhouse gas emission reductions: The prospect of atmospheric monitoring in polluted areas. *Philosophical Transactions of the Royal Society A*, **369** (1943), 1906–1924, doi:10.1098/rsta.2010.0249.

Levin, I., B. Kromer, M. Schmidt, and H. Sartorius, 2003: A novel approach for independent budgeting of fossil fuel CO_2 over Europe by $^{14}CO_2$ observations. *Geophysical Research Letters,* **30** (23), 1–5, doi:10.1029/2003GL018477.

Levin, I., and Coauthors, 2020: A dedicated flask sampling strategy developed for ICOS stations based on CO_2 and CO measurements and STILT footprint modelling. *Atmospheric Chemistry and Physics Discussions*, 1–29, doi:10.5194/acp-2020-185.

López-Ballesteros, A., and Coauthors, 2018: Towards a feasible and representative pan-African research infrastructure network for GHG observations. *Environmental Research Letters*, **13** (8), doi:10.1088/1748-9326/aad66c.Loustau, D., and Coauthors, 2018: Sampling and collecting foliage elements for the determination of the foliar nutrients in ICOS ecosystem stations. *Int. Agrophys.*, **32**(4), 665-676, doi: https://doi.org/10.1515/intag-2017-0038.

Luyssaert, S., and Coauthors, 2010: The European carbon balance. Part 3: Forests. *Global Change Biology*, **16,** 1429-1450, doi: 10.1111/j.1365-2486.2009.02056.x.

Ma, X., W. Liu, R. J. Allen, G. Huang, and X. Li, 2020: Dependence of regional ocean heat uptake on anthropogenic warming scenarios. *Science Advances*, **6**(45), eabc0303, doi:10.1126/sciadv.abc0303.

Nemitz, E., and Coauthors, 2018: Standardisation of eddy-covariance flux measurements of methane and nitrous oxide. *International Agrophysics*, **32** (4), 517–549, doi:10.1515/intag-2017-0042.

Nordbo, A., L. Järvi, S. Haapanala, C. R. Wood, and T. Vesala, 2012: Fraction of natural area as main predictor of net CO_2 emissions from cities. *Geophysical Research Letters*, **39** (20), 1–5, doi:10.1029/2012GL053087.

Op de Beeck, M., and Coauthors, 2018. Soil-meteorological measurements at ICOS monitoring stations in terrestrial ecosystems. *International Agrophysics*, **32**(4), 619-631, https://doi.org/10.1515/intag-2017-0041.

Papale, D., 2020: Ideas and perspectives: enhancing the impact of the FLUXNET network of eddy covariance sites. *Biogeosciences*, **17**, 5587-5598, doi: 10.5194/bg-17-5587-2020.

Papale, D., and R. Valentini, 2003: A new assessment of European forests carbon exchanges by eddy fluxes and artificial neural network spatialization. *Global Change Biology*, **9**, 525-535, https://doi.org/10.1046/j.1365-2486.2003.00609.x.

Pavelka, M., and Coauthors, 2018: Standardisation of chamber technique for CO_2, N_2O and CH_4 fluxes measurements from terrestrial ecosystems. *International Agrophysics*, **32** (4), 569–587, doi:10.1515/intag-2017-0045.

Peters, W., and Coauthors, 2010: Seven years of recent European net terrestrial carbon dioxide exchange constrained by atmospheric observations. *Global Change Biology*, **16** (4), 1317–1337, doi:https://doi.org/10.1111/j.1365-2486.2009.02078.x.

Peters, W., Bastos, A., Ciais, P., Vermeulen, A., and Kutsch, W. (eds.), 2020: Impacts of the 2018 severe drought and heatwave in Europe: from site to continental scale. Special issue in *Philosophical Transactions of the Royal Society B*, https://royalsocietypublishing.org/toc/rstb/375/1810.

Petrescu, A. M. R., and Coauthors, 2020: The consolidated European synthesis of CH_4 and N_2O emissions for EU27 and UK: 1990-2018, *Earth System Science Data Discussion*. preprint in review, https://doi.org/10.5194/essd-2020-367.

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-19-0364.1.

Pfeil, B., and Coauthors, 2013: A uniform, quality controlled Surface Ocean CO_2 Atlas (SOCAT). *Earth System Science Data*, **5**, 125-143, doi:10.5194/essd-5-125-2013.

Rebmann, C., and Coauthors, 2018: ICOS eddy covariance flux-station site setup: a review. *International Agrophysics,* **32**, 471-494, doi: 10.1515/intag-2017-0044.

Rhein, M., and Coauthors, 2013: Observations: ocean. *Climate Change 2013: The Physical Science Basis*. T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P. M. Midgley, Eds., 60 pp, Cambridge University Press, Cambridge.

Rinne, J., and Coauthors, 2020: Effect of the 2018 European drought on methane and carbon dioxide exchange of northern mire ecosystems. *Philosophical Transactions of the Royal Society B*, **375**, doi:10.1098/rstb.2019.0517.

Rogelj, J., and Coauthors, 2018: Mitigation Pathways Compatible with 1.5°C in the Context of Sustainable Development. *Global Warming of 1.5°C. An IPCC Special Report on the impacts of global warming of 1.5°C above pre-industrial levels and related global greenhouse gas emission pathways, in the context of strengthening the global response to the threat of climate change*, *sustainable development, and efforts to eradicate poverty*, V. Masson-Delmotte, P. Zhai, H.-O. Pörtner, D. Roberts, J. Skea, P. R. Shukla, A. Pirani, W. Moufouma-Okia, C. Péan, R. Pidcock, S. Connors, J. B. R. Matthews, Y. Chen, X. Zhou, M. I. Gomis, E. Lonnoy, T. Maycock, M. Tignor, and T. Waterfield, Eds., 82 pp. In press.

Saunders, M., and Coauthors, 2018: Importance of reporting ancillary site characteristics, and management and disturbance information at ICOS stations. *International Agrophysics*, **32** (4), 457–469, doi:10.1515/intag-2017-0040.

Schulze, E. D., and Coauthors, 2009: Importance of methane and nitrous oxide for Europe's terrestrial greenhouse-gas balance. *Nature Geoscience*, **2**, 842–850.

Schulze, E. D., and Coauthors, 2010: The European carbon balance. Part 4: Integration of carbon and other trace-gas fluxes. *Global Change Biology,* **16**, 1451–69, https://doi.org/10.1111/j.1365-2486.2010.02215.x.

Smith, N. E., and Coauthors, 2020: Spring enhancement and summer reduction in carbon uptake during the 2018 drought in northwestern Europe. *Philosophical Transactions of the Royal Society B*, **375**, doi:10.1098/rstb.2019.0509.

Steinhoff, T., and Coauthors, 2019: Constraining the Oceanic Uptake and Fluxes of Greenhouse Gases by Building an Ocean Network of Certified Stations: The Ocean Component of the Integrated Carbon Observation System, ICOS-Oceans. *Frontiers in Marine Science*, **6**, 1–15, https://doi.org/10.3389/fmars.2019.00544.

Thompson, R., Broquet, G., Gerbig, C., Monteil, G., Lang, M. and Koch, F.-T., 2019: Drought-2018 ensemble of inversion results for 2009–2018, doi:10.18160/YQ8P-P7CF.

Thompson R. L., Broquet G., Gerbig C., Koch T., Lang M., Monteil G., Munassar S., Nickless A., Scholze M., Ramonet M., Karstens U., van Schaik E., Wu Z. and Rödenbeck C., 2020: Changes in net ecosystem exchange over Europe during the 2018 drought based on atmospheric observations. *Philosophical Transactions of the Royal Society B*, **375**:20190512, http://doi.org/10.1098/rstb.2019.0512.

United Nations, 2015a: Paris Agreement. https://unfccc.int/files/meetings/paris_nov_2015/application/pdf/paris_agreement_english_.pdf.

United Nations, 2015b: Transforming our world: the 2030 Agenda for Sustainable Development. https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_RES_70_1_E.pdf

Vetter, M., and Coauthors, 2008: Analyzing the causes and spatial pattern of the European 2003 carbon flux anomaly using seven models. *Biogeosciences*, **5**, 561-583, https://doi.org/10.5194/bg-5-561-2008.

Wilkinson, M. D., and Coauthors, 2016: The FAIR Guiding Principles for scientific data management and stewardship. *Scientific Data*, 3:160018, doi: 10.1038/sdata.2016.18.

Vitale, D., Fratini, G., Bilancia, M., Nicolini, G., Sabbatini, S., and D. Papale, 2020: A robust data cleaning procedure for eddy covariance flux measurements. *Biogeosciences*, **17**, 1367-1391, doi: 10.5194/bg-17-1367-2020.

WMO, 2009: A history of climate activities. *WMO Bulletin,* **58** (3), 141, https://library.wmo.int/doc_num.php?explnum_id=6945.

WMO, 2014: The Global Atmosphere Watch Programme: 25 Years of Global Coordinated Atmospheric Composition Observations and Analyses. *WMO-No. 1143*, https://library.wmo.int/doc_num.php?explnum_id=7886

WMO, 2019: An Integrated Global Greenhouse Gas Information System (IG3IS) Science Implementation Plan. *GAW Report*, 245, https://library.wmo.int/doc_num.php?explnum_id=10034.

WMO, 2020a: WMO WDCGG Data summary. *WDCGG* No. 44, https://gaw.kishou.go.jp/static/publications/summary/sum44/sum44.pdf

Accepted for publication in *Bulletin of the American Meteorological Society*. DOI 10.1175/BAMS-D-19-0364.1.

WMO, 2020b: 20th WMO/IAEA Meeting on Carbon Dioxide, Other Greenhouse Gases and Related Measurement Techniques (GGMT-2019). GAW Report 255, 19-23. https://library.wmo.int/doc_num.php?explnum_id=10353

Yver Kwok, C., and Coauthors, 2015: Comprehensive laboratory and field testing of cavity ring-down spectroscopy analyzers measuring H_2O, CO_2, CH_4 and CO. *Atmospheric Measurement Techniques,* **8**(9), 3867-3892.

Yver-Kwok, C., and Coauthors, 2021: Evaluation and optimization of ICOS atmosphere station data as part of the labeling process. *Atmospheric Measurement Techniques*, **14**, 89–116, https://doi.org/10.5194/amt-14-89-2021.

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Tables

Appendix Table 1. List of variables observed at ICOS Atmosphere stations.

Category	Gases, continuous sampling	Gases, periodical sampling	Meteorology, continuous	Eddy Fluxes
Class 1 Mandatory parameters	● CO_2, CH_4, CO: at each sampling height	● CO_2, CH_4, N_2O, SF_6, CO, H_2, ^{13}C and ^{18}O in CO_2: weekly sampled at highest sampling height ● ^{14}C (radiocarbon integrated samples): at highest sampling height	● Air temperature, relative humidity, wind direction, wind speed: at highest and lowest sampling height* ● Atmospheric Pressure ● Planetary Boundary Layer Height**	
Class 2 Mandatory parameters	● CO_2, CH_4: at each sampling height		● Air temperature, relative humidity, wind direction, wind speed: at highest and lowest sampling height* ● Atmospheric Pressure	
Recommended parameters***	● ^{222}Rn, N_2O, O_2/N_2 ratio ● CO for Class 2 stations	● CH_4 stable isotopes, O_2/N_2 ratio for class 1 stations: weekly sampled at highest		● CO_2: at one sampling height

		sampling height		

* Atmospheric temperature and relative humidity recommended at all sampling heights

** Only required for continental stations

*** Recommended for its scientific value but support from ATC in terms of protocols, database, spare analyser will not be ensured as long as the parameters are not mandatory

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Appendix Table 2. List of variables observed at ICOS Ecosystem Stations, with numbers indicatingClass 1 and 2 stations.

Variables	Forest	Grassland	Cropland	Wetland*	Marine**	Lakes**
CO_2, H_2O and H fluxes (eddy covariance, including profile for storage)	1 & 2	1 & 2	1 & 2	1 & 2	1 & 2	1 & 2
CH_4 and N_2O fluxes (eddy covariance, including profile for storage)	1	1	1	1	1	1
Air H_2O concentration	1	1	1	1	1	1
Incoming, Outgoing and Net SW and LW radiations	1 & 2	1 & 2	1 & 2	1 & 2	1	1
Incoming SW radiation (high quality)	Fac	Fac	Fac	Fac	Fac	Fac
Incoming PPFD	1 & 2	1 & 2	1 & 2	1 & 2	1 & 2	1 & 2
PPFD below canopy + ground reflected	Fac	Fac	Fac	N.R.	N.R.	N.R.
Outgoing PPFD	1 & 2	1 & 2	1 & 2	1 & 2	Fac	Fac
Diffuse PPFD and/or SW radiation	1	1	1	1	Fac	Fac
Spectral reflectance	Fac	Fac	Fac	Fac	Fac	Fac
Soil Heat flux	1 & 2	1 & 2	1 & 2	1 & 2	N.R.	N.R.
Air Temperature and Humidity profile	1 & 2	1 & 2	1 & 2	1 & 2	Fac	Fac
Backup meteo station (TA, RH, SW_IN, Precipitation)	1 & 2	1 & 2	1 & 2	1 & 2	1 & 2	1 & 2
Total high accuracy precipitation	1 & 2	1 & 2	1 & 2	1 & 2	1 & 2	1 & 2
Snow height	1 & 2	1 & 2	1 & 2	1 & 2	Fac	Fac
Soil Water Content profile	1 & 2	1 & 2	1 & 2	1 & 2	N.R.	N.R.
Soil Temperature profile	1 & 2	1 & 2	1 & 2	1 & 2	N.R.	N.R.

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Air Pressure	1 & 2	1 & 2	1 & 2	1 & 2	1 & 2	1 & 2
Trunk and branches temperature	Fac	N.R.	N.R.	N.R.	N.R.	N.R.
Water Table Depth	1 & 2	1 & 2	1 & 2	1 & 2	N.R.	N.R.
Tree diameter (continuous)	1	N.R.	N.R.	N.R.	N.R.	N.R.
Phenology/camera	1	1	1	1	N.R.	N.R.
Soil CO_2 automatic chambers	1	1	1	1	1	1
CH_4 and N_2O fluxes by automatic chambers	1	1	1	1	1	1
Wind speed and wind direction (additional to 3D sonic)	1	1	1	1	1	1
GAI	1 & 2	1 & 2	1 & 2	1 & 2	N.R.	N.R.
Above Ground Biomass	1 & 2	1 & 2	1 & 2	1 & 2	N.R.	N.R.
Soil carbon content	1 & 2	1 & 2	1 & 2	1 & 2	N.R.	N.R.
Litterfall	1	1	1	1	N.R.	N.R.
Leaf nutrients content	1 & 2	1 & 2	1 & 2	1 & 2	N.R.	N.R.
Soil water N content	Fac	Fac	Fac	Fac	N.R.	N.R.
DOC concentration	Fac	Fac	Fac	Fac	N.R.	N.R.
C and N import/export by management	1 & 2	1 & 2	1 & 2	1 & 2	N.R.	N.R.
Oxygen and pCO_2 surface concentration	N.R.	N.R.	N.R.	Fac	2	2
Oxygen, pCO_2 and pN_2O concentration profile	N.R.	N.R.	N.R.	Fac	1	1
Salinity	N.R.	N.R.	N.R.	N.R.	1 & 2	N.R.
Wave properties	N.R.	N.R.	N.R.	N.R.	Fac	Fac
Water temperature profile	N.R.	N.R.	N.R.	N.R.	1	1
Management and disturbances information	1 & 2	1 & 2	1 & 2	1 & 2	1 & 2	1 & 2

Fac = Facultative variable; N.R. = Not Relevant for the ecosystem
* Wetland includes all different water inundated or saturated ecosystems according to Joosten and Clark 2002
** List of variables for Lake, Marine and Urban sites under discussion

Appendix Table 3. List of variables measured at ICOS Ships of Opportunity.

VARIABLE	**FREQUENCY**	**ACCURACY**	**REQUIRED FOR CLASS**
Sea surface *f*CO_2	Quasi-continuous	± 2 µatm	1 & 2
Intake temperature (SST)	Continuous	± 0.05 °C	1 & 2
Equilibrator temperature	Continuous	± 0.05 °C	1 & 2
ΔT (Intake/Equilibrator temperature difference)	Continuous	< 1.5 °C (normal) < 3 °C (ice-edge)	1 & 2
Water vapour pressure*	Continuous	± 0.5 mbar	1 & 2
Equilibrator pressure	Continuous	± 2.0 mbar	1 & 2
Atmospheric pressure/sea level pressure	Continuous	± 1.0 mbar	1 & 2
Sea surface salinity (SSS)	Continuous	± 0.1 PSU	1 & 2
Dissolved oxygen	Continuous	± 2%	1
Total alkalinity (TA)**	***	± 10 µmol kg^{-1}	1
Dissolved inorganic carbon (DIC)**	***	± 5 µmol kg^{-1}	1

*If the analysed headspace gas is not dried completely prior to measurement.

** At least one of these variables must be provided.

*** The frequency of these additional variables will be decided on during the labelling process based on the area where the station is operating.

Appendix Table 4. List of variables measured at ICOS Fixed Ocean Stations.

VARIABLE	**FREQUENCY**	**ACCURACY**	**REQUIRED FOR CLASS**
Sea surface pCO_2	> 1/day (open ocean) > 3/day (coastal)	± 10 µatm	1 & 2
Sea surface temperature	> 1/day (open ocean) > 3/day (coastal)	± 0.02 °C	1 & 2
Sea surface salinity	> 1/day (open ocean) > 3/day (coastal)	± 0.1 PSU	1 & 2
Pressure (depth)	> 1/day (open ocean) > 3/day (coastal)	± 3 dbar	1 & 2
Dissolved oxygen	> 1/day (open ocean) > 3/day (coastal)	± 2%	1 & 2
Total alkalinity (TA)*	**	± 4 µmol kg^{-1}	1 & 2
Dissolved inorganic carbon (DIC)*	**	± 2 µmol kg^{-1}	1 & 2
pH***	**	± 0.003	1 & 2
Dissolved nutrients ****	**	± 1-3%****	1

* At least one of these variables must be provided.

** The frequency of these additional variables will be decided on during the labelling process based on the area where the station is operating.

*** pH (together with TA or DIC) is ONLY required for validation of the pCO_2 data. pH should NOT be used together with pCO_2 to calculate the full carbonate system due to high resulting uncertainty.

**** At least two out of the three dissolved nutrients nitrate (NO_3), phosphate (PO_4), and silicate ($Si(OH)_4$) must be provided.

***** The accuracy refers to samples without conservation. If conservation is used (freezing is the most used method) the accuracy might increase.

Figures

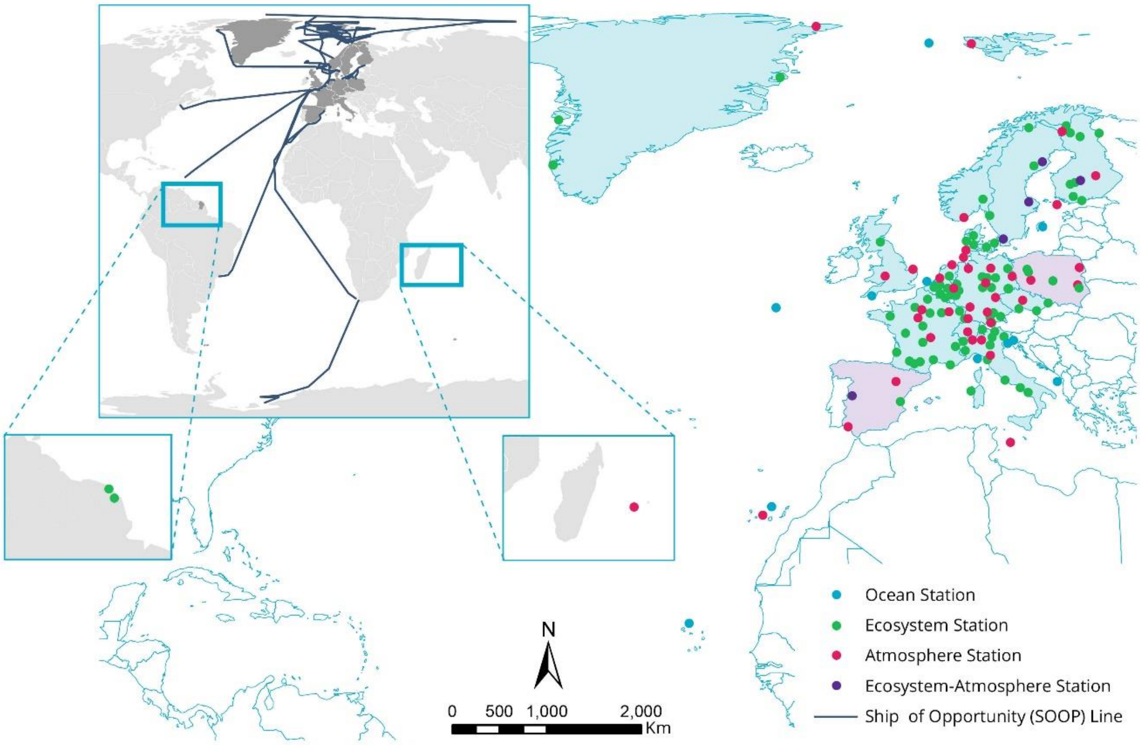

Figure 1. Map of ICOS stations. The dots represent fixed stations in different domains (ocean, ecosystem, atmosphere) and lines the Ships of Opportunities. Up-to-date details (e.g. station class, contact info, data) from each station can be found from https://www.icos-cp.eu/observations/station-network.

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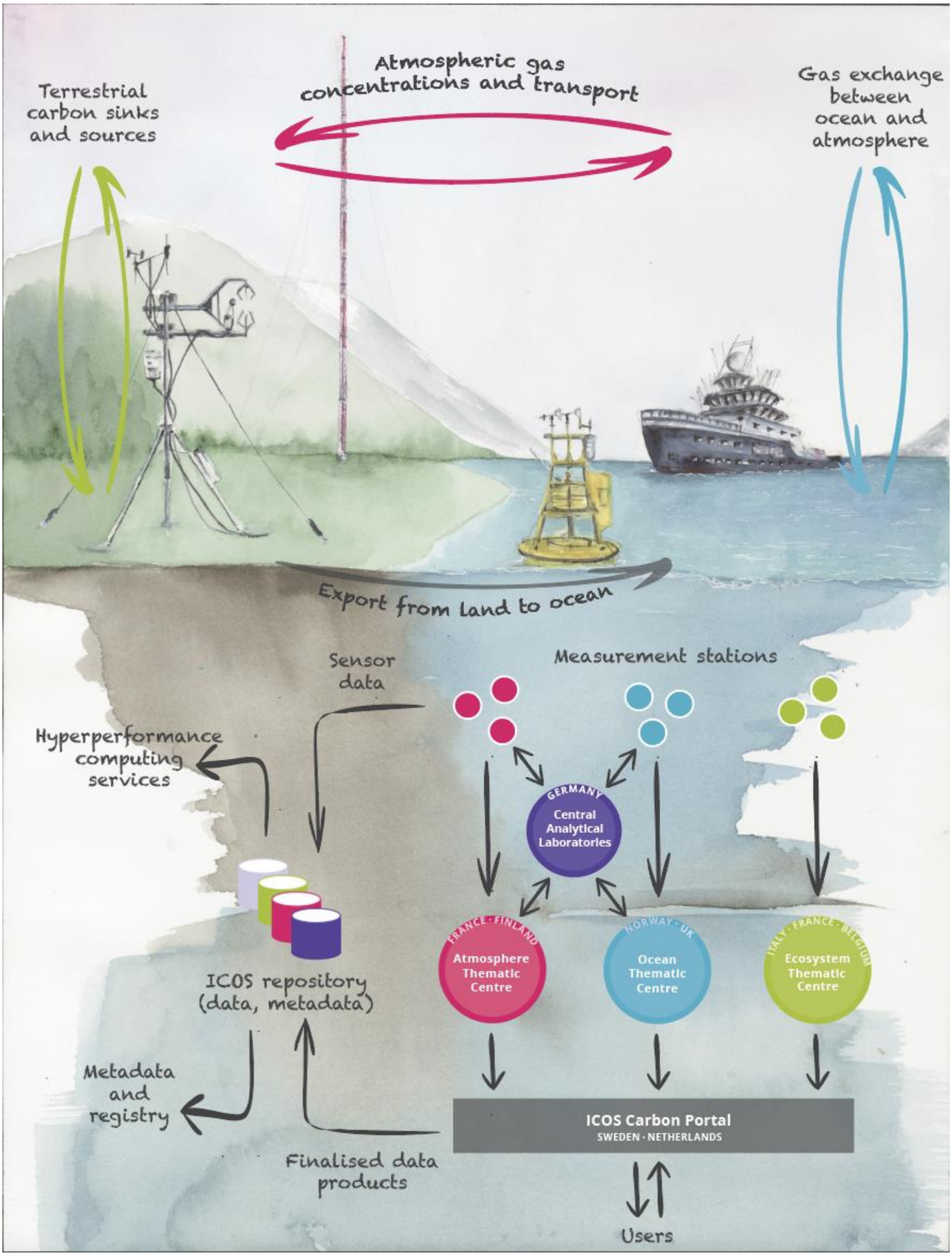
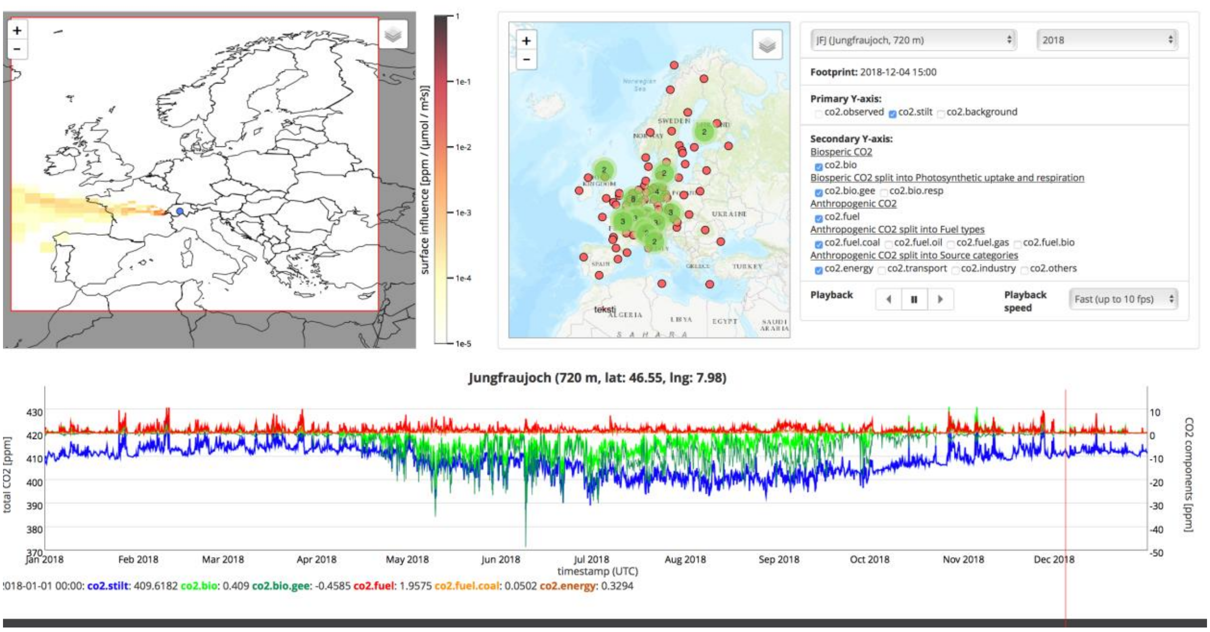


Figure 2. Schematic figure of the carbon cycle and related data collection process and user access to all the data via the Carbon Portal. The color-coding links the areas of the biogeochemical carbon cycle to the respective stations and Thematic Centres. The green

color indicates the exchange of carbon, GHGs and energy between the atmosphere and ecosystems (vertical arrows), the red color the atmospheric gas concentrations, chemistry and transport processes (horizontal arrows), and the blue color the ocean-atmosphere gas exchange (vertical arrows), observed within the ICOS stations of respective domains (dots in the lower part and also in Fig. 1). The observations are centrally processed within the Thematic Centres and the data stored to ICOS repository, with Carbon Portal serving as one-stop-shop for all ICOS data products.



JFJ (Jungfraujoch, 720 m) ⇕ 2018 ⇕

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Primary Y-axis:
☐ co2.observed ☑ co2.stilt ☐ co2.background

Secondary Y-axis:
Biosperic CO2
☑ co2.bio
Biosperic CO2 split into Photosynthetic uptake and respiration
☑ co2.bio.gee ☐ co2.bio.resp
Anthropogenic CO2
☑ co2.fuel
Anthropogenic CO2 split into Fuel types
☑ co2.fuel.coal ☐ co2.fuel.oil ☐ co2.fuel.gas ☐ co2.fuel.bio
Anthropogenic CO2 split into Source categories
☑ co2.energy ☐ co2.transport ☐ co2.industry ☐ co2.others

Playback ◀ ⏸ ▶ **Playback speed** Fast (up to 10 fps) ⇕

:018-01-01 00:00: **co2.stilt**: 409.6182 **co2.bio**: 0.409 **co2.bio.gee**: -0.4585 **co2.fuel**: 1.9575 **co2.fuel.coal**: 0.0502 **co2.energy**: 0.3294

Figure 3. An example of ICOS tool to analyze the potential impact of natural and anthropogenic emissions to the CO_2 concentrations in the atmosphere, based on model simulation of Lagrangian transport model STILT (Stochastic Time Inverted Lagrangian Transport; Lin et al 2013) together with emission-sector and fuel-type specific emissions from a pre-release of the EDGARv4.3 inventory (EC-JRC/PBL, 2015). Figure shows results for the ICOS Class 1 Jungfraujoch station in Switzerland, including biospheric and anthropogenic carbon emissions. Panel A) shows modelled footprint and wind directions influencing the measurement tower signal; panel B) shows selected towers, location of atmospheric tower in Europe and variables that are available for interactive visualization; while panel C) shows the time series of a selected variable, including measured and modelled concentrations.

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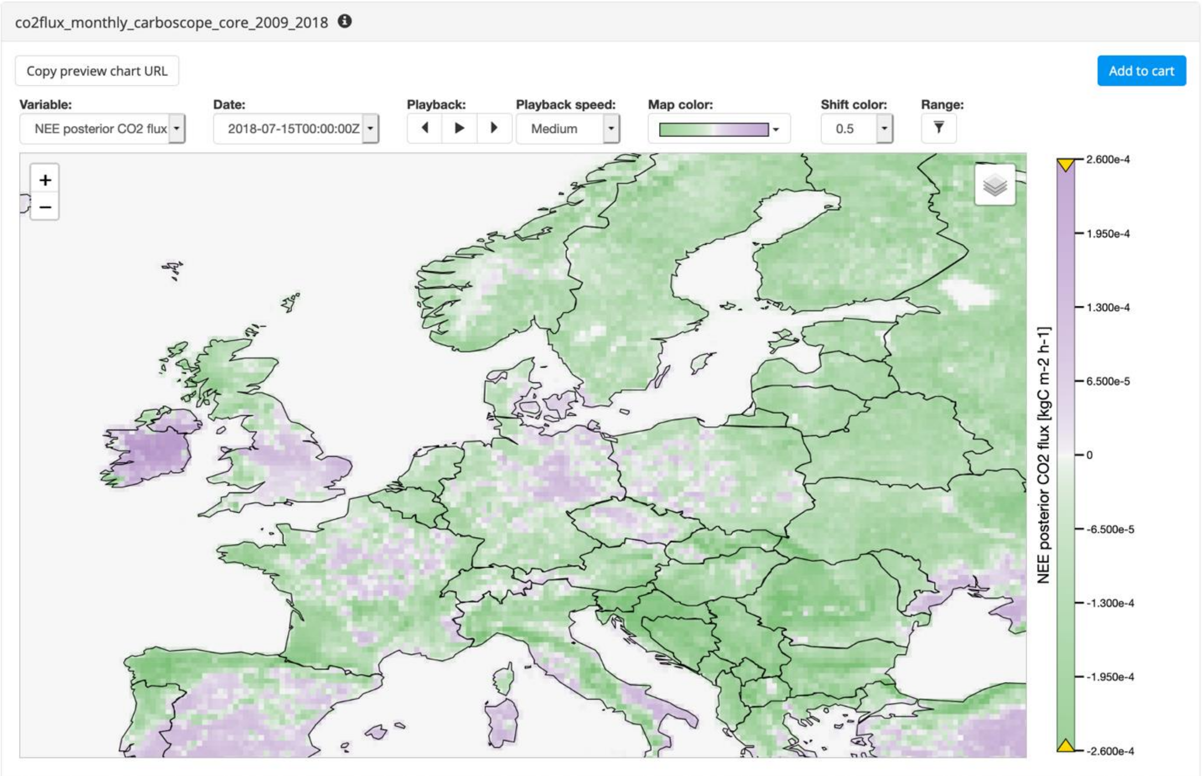

co2flux_monthly_carboscope_core_2009_2018

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Figure 4. Example of a regional-scale atmospheric inversion result, estimating the net ecosystem exchange (NEE) based on atmospheric observations from ICOS and other stations. The presented example is part of a multi-model ensemble of atmospheric inversions, available at Carbon Portal (Thompson et al, 2019), that was used to estimate the effect of the 2018 drought on net ecosystem exchange over Europe (Thompson et al., 2020).

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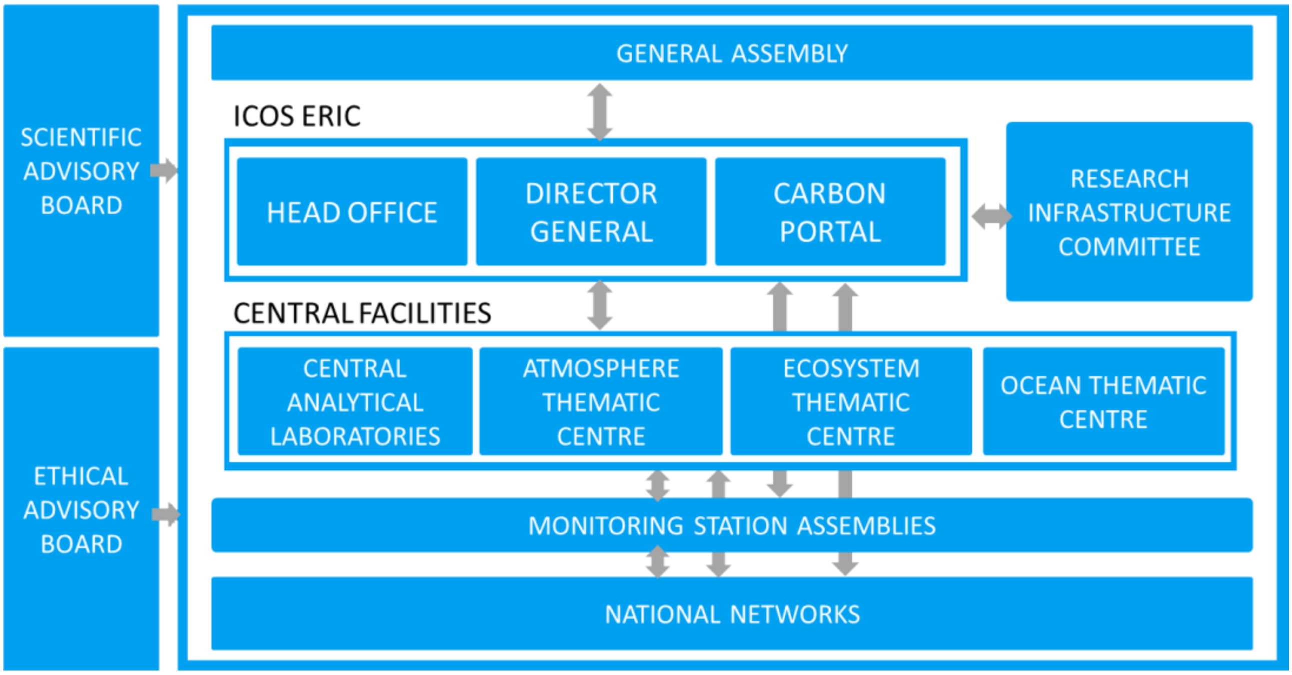

Appendix 1 Figure 1. The governance structure of ICOS.

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