ICOS strategy

ICOS
INTEGRATED CARBON OBSERVATION SYSTEM

Contents

Executive Summary

The Integrated Carbon Observation System (ICOS) is a distributed pan-European research infrastructure producing high-quality data on greenhouse gas concentrations in the atmosphere, as well as on carbon fluxes between the atmosphere, the land surface and the oceans. It was listed on the first Roadmap for European Research Infrastructures in 2006, reaching its final legal status (ICOS ERIC) in 2015.

The research infrastructure became fully operational towards the end of the first five-year period of ICOS ERIC, and this milestone seems to be the right time to reflect and orient further developments. The framework in which ICOS is operating has been dynamic during the past years; Earth observation is increasingly an integration of increasing in-situ observations and remote sensing, supported by big data applications that have recently become available. The high quality data and related products provided by ICOS are becoming part of a global system of science and observation that supports the

political processes following the Paris Agreement, which came into force in 2016. When the mechanisms of the Paris Agreement are fully implemented, the supporting monitoring and verification systems must also be at full capacity and able to confirm the intended emission reductions in Europe.

This strategy report analyses the background and framework of ICOS within the context of the UN-driven Global Climate Observation System (GCOS), and as a core element of the European Copernicus system. It draws conclusions for the further development of the research infrastructure and provides a vision beyond the next decade that includes:

- A denser and better spatial coverage of the fully operational ICOS greenhouse gas observation network with fully equipped stations covering atmosphere, terrestrial ecosystems and oceans, which are delivering high quality data that fulfils the requirements of the expanding user base.
- A vibrant scientific user community that ICOS supports by offering a powerful platform that brings together observational data and analysis products to advance science.
- Increased societal impact of ICOS through the dissemination of scientific results that fulfill the knowledge needs of Climate Policy.
- Well-developed interoperability with the remote sensing community, as well as the scientific communities and agencies working on national inventories of anthropogenic emissions and the global stocktake developed in the framework of the Paris Agreement.
- Trustful cooperation within the community of European environmental research infrastructures (ENVRI) and globally with fellow research infrastructures in other regions. The goal being for ICOS to be recognized around the world as an excellent model for an in situ observation system on greenhouse gases (GHG), and as the European pillar of the Global GHG Observation system.

This strategy identifies scientific trends that will influence the future development of the ICOS observations and require future investments in initiatives such as city observatories, understanding the drivers in land and ocean sinks, and terrestrial ecosystem management. The summary of the strategy is presented in a visual format in Figure 1, on the next page.

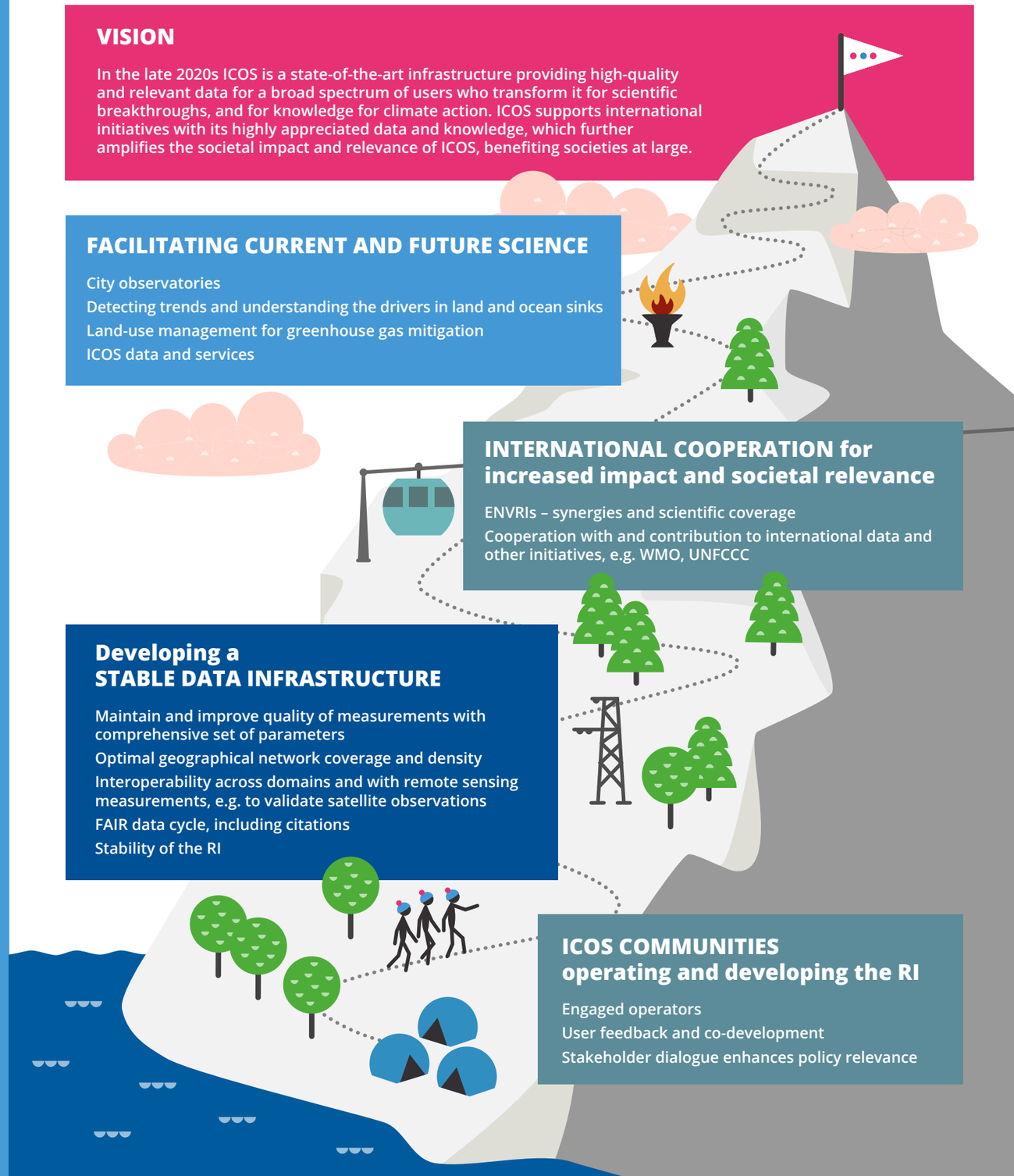
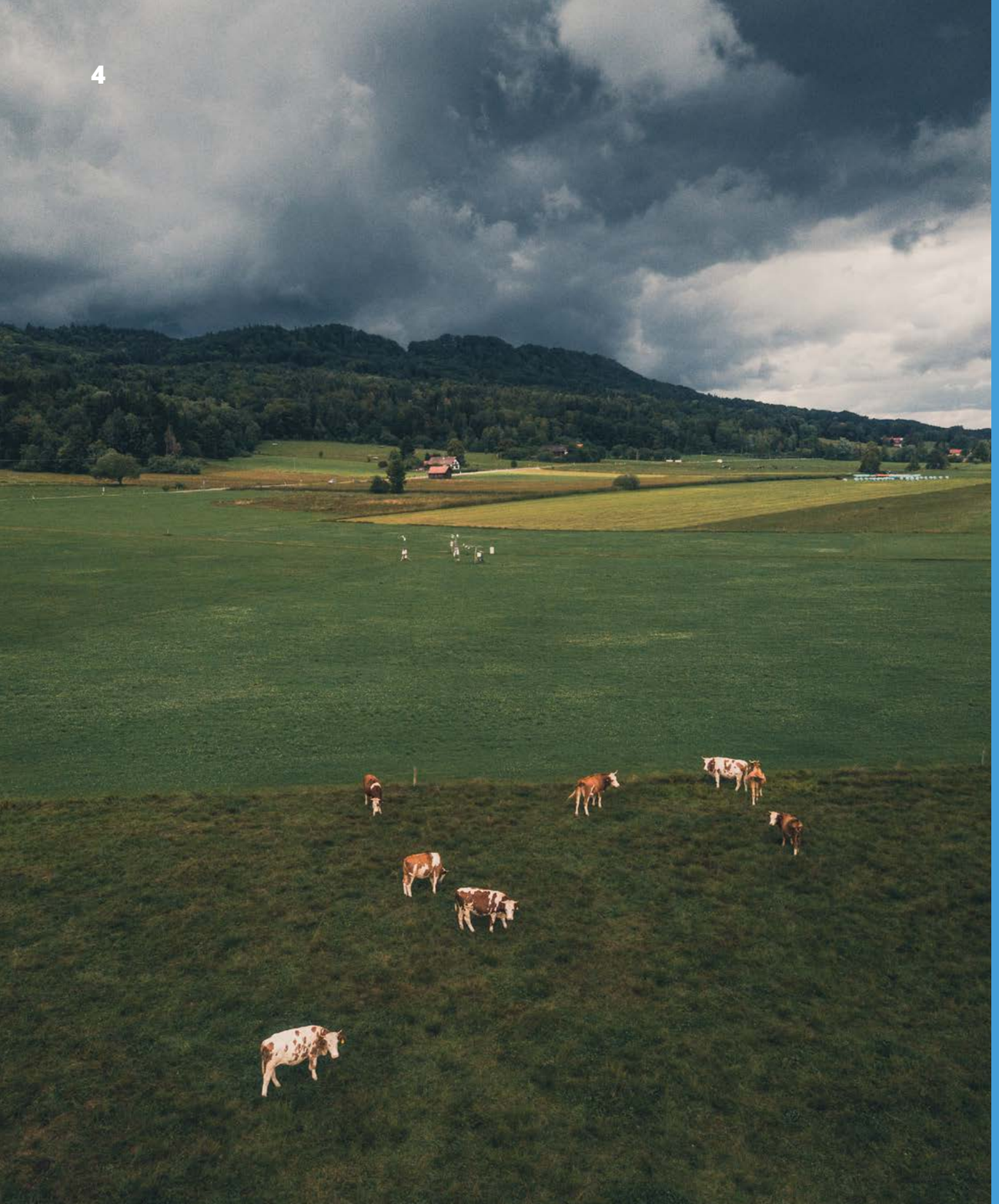


Figure 1. *A summary of ICOS vision and of the steps needed to climb towards this goal, as described in this strategy. The official vision text, approved by the ICOS General Assembly, starts on page 15.*



A strategy is a 'plan of action designed to achieve a long-term or overall aim', according to Oxford Dictionaries[1]. Furthermore, as Richard Chapman writes[2], it is the basis of intentional (purposeful), collaborative, and coherent action based on an assessment of

i. the current situation ('as is'),
ii. the preferred future ('to be') and
iii. the next steps / action plan ('to do').

This document is part of a collection of four documents that together outline the current status and the strategy for future development of ICOS. The current situation is described by a progress report[3] and an impact analysis[4] of ICOS. These documents are only briefly referred to here. This document focuses on the long-term, overall aim or preferred future. The next steps are outlined in a separate document, the five-year action plan 2020–2024.

ICOS has a complex financial structure. The revenues for the observational stations are organised in the National Networks with a mosaic of funding from national funding agencies and host institutions. The Central Facilities and the ERIC institutions (Head Office and Carbon Portal) receive revenues through host premium contributions and ERIC contributions. Investments in the further development of ICOS that go beyond the maintenance of the currently implemented operations need thorough planning and decision making on a case-by-case basis. The financial aspects of further development of ICOS are therefore only mentioned briefly in this strategy but articulated fully in the five-year plan(s). Notwithstanding, perspectives to broaden the financial basis of ICOS beyond public funding are strategically useful and will be explored during the upcoming years.

Background

The mission of ICOS

The Integrated Carbon Observation System (ICOS) is a distributed research infrastructure operating standardized, high-precision, and long-term observations, facilitating research to understand the carbon cycle, providing necessary information on greenhouse gases. ICOS-based knowledge supports policy- and decision-making to combat climate change and its impacts. ICOS is the European pillar of a global GHG observation system. It promotes technological developments and demonstrations related to GHGs by the linking of research, education and innovation.

The structure of ICOS

The ICOS Research Infrastructure is coordinated by the Integrated Carbon Observation System European Research Infrastructure Consortium (ICOS ERIC) established on 23 November 2015 by nine European member states on the basis of a regulation of the Council of the European Union (EC/723/2009) and a decision of the European Commission (Official Journal of the European Union 2015: L303/19[5]). The Finnish Parliament has provided a Finnish law about legal personality and partial tax-exempt status in Finland according to which ICOS ERIC is a legal entity with legal capacity in Finland. ICOS ERIC has its registered Head Office in Helsinki. The number of participating countries at the time of writing is 12 (11 members and 1 observer). ICOS aims to enlarge its observational capacity by attracting more member countries.

ICOS is a research infrastructure that integrates highly standardized networks from multiple domains (atmosphere, terrestrial ecosystems, and oceans) and connects different carbon reservoirs. All stations provide high-quality observations using state-of-the-art technologies. In the first standardisation phase during the ICOS Preparatory and Interim Phase (2008 – 2015), protocols to build stations were developed. Once standards were achieved, stations were ingested into the network through the labelling process to ensure compliance to the quality requirements and robustness. The measurement stations are run in National Networks. Central Facilities provide services and data integration for the networks. ICOS ERIC operates the ICOS Carbon Portal, the central information portal through which all data and higher-level products produced by ICOS and related data products are available in an open and transparent way (according to the FAIR principles of the FORCE11[6] group). ICOS ERIC acts in cooperation with, amongst others, end-users of data and research results, industry, policy-makers, and the media. The structure described here is illustrated in Figure 2.

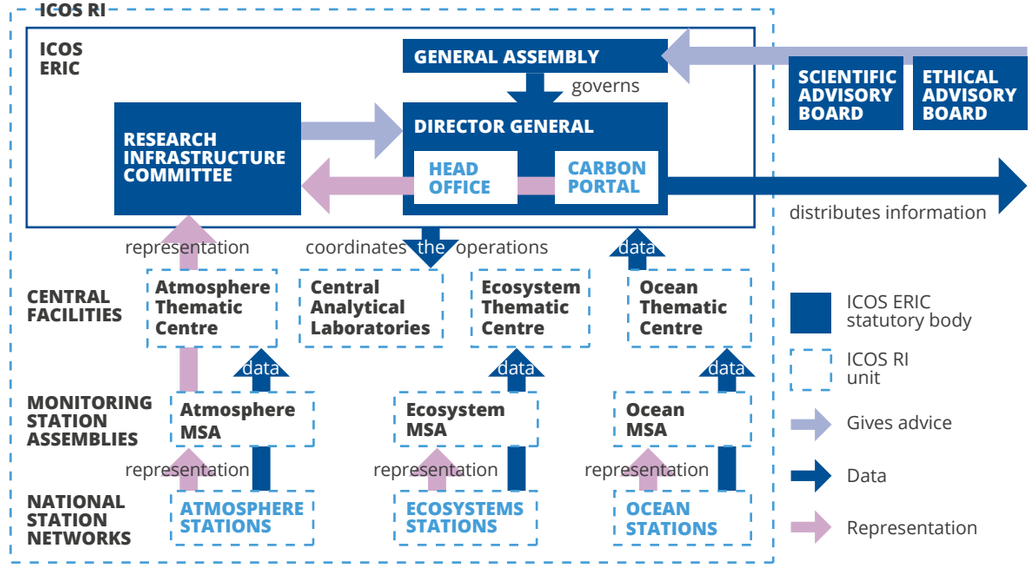


Figure 2. *ICOS governance and structure.*

This strategy for further developing the ICOS research infrastructure is constrained by two simultaneous challenges: while the achieved observational networks have to be sustained, essential enhancements defined by novel requirements arising, e.g., from the Paris Agreement, need to be stepwise developed and ingested. This strategy explores perspectives for the future design of ICOS and possible ways to achieve them. The required change management will be based on an agile system throughout the whole ICOS research infrastructure. Task forces with contributions from the different bodies will be set up for each extension. The coordination and the supporting resources will be discussed in the Research Infrastructure Committee and decided case by case. Each enhancement will undergo scientific and technical feasibility studies. At the end of respective research phases, operational standards will be developed and a formal decision about the extension presented to the General Assembly.

Framework

The strategy of ICOS is embedded into a multi-dimensional framework that includes, on one hand, the overall European strategy on research infrastructures as recently formulated in the 2018 ESFRI Roadmap[7] and, on the other hand, global and European strategies on knowledge-based climate change mitigation, which are targeting societal impact of research infrastructures. In order to better understand how the two goals, scientific excellence and societal impact, are combined within the ICOS strategy, it is important to describe the global and European frameworks for observation and research to provide knowledge for climate change mitigation.

Scientific excellence: ICOS as an ESFRI Landmark

By being an ESFRI Landmark, ICOS is an important contribution to the European Research Area and part of the European portfolio of long-term undertakings in excellent science and innovation. The ICOS strategy has been developed closely along the ESFRI principles for long-term sustainability as outlined in the 2018 Roadmap. Excellent science is best encouraged by providing easily accessible and high-quality data in a timely manner. Thus, it is the key priority of ICOS to further develop its services based on ICOS data. ICOS will provide tools for interactive analysis of data and model results, thereby securing reproducibility by using web-based technologies and direct access to ICOS data and elaborated products. With that ICOS will enable transparent analyses, interactive collaboration of modellers and data providers, and connections to computing resources in the European Open Science Cloud.

ICOS will thoroughly monitor and support scientific developments and adapt to the demands of its scientific community. The ICOS science case has a primary focus on understanding carbon cycle feedbacks and possible tipping points. ICOS also has a strong technological innovation potential to support excellent science on quantifying fossil fuel emissions from systematic in-situ observations. It will follow and support this science, will co-design a respective system during the upcoming years and will thereafter suggest implementation pathways.

Societal impact: the role of ICOS in the Paris Agreement

ICOS provides data for the science to understand the Earth system. Scientific knowledge on carbon emissions, sinks, and trends advances the fulfilment of the UN Sustainable Development Goals (Goal 13: Take urgent action to combat climate change and its impacts[8], Goal 14: minimize and address the impacts of ocean acidification[9]) and EU Societal Challenges (Climate Action – Informed decisions for a climate-resilient low-carbon society). The mission of ICOS (to understand the carbon cycle and to provide necessary information on greenhouse gases) places ICOS into a framework of international climate activities. The knowledge generated by the use of ICOS data supports efforts to comply with the Paris Agreement[10] resolutions within the United Nations Framework Convention on Climate Change (UNFCCC). ICOS responds to the international goal of establishing global standards for observations as well as open, accessible, and interoperable data in order to ensure optimal services for societies in their efforts to mitigate climate change.

The Paris Agreement has brought in a new paradigm for the relationship between science and policy. It has been formulated as “science driving policy” and “policy driving science”. The Science & Review Team at UNFCCC secretariat has described information transfer from science

to policy stepwise from 'observations' to 'research' to 'assessment' (Figure 3). The feedback mechanisms from policy to science are coordinated by the Subsidiary Body for Scientific and Technical Advice (SBSTA) that formulates requests on knowledge gaps. Climate services are currently mainly located at the World Meteorological Organization (WMO) and related national weather services and support adaptation e.g. through climate scenarios and weather forecasts on extreme events. It can be expected that climate services will also include services to support mitigation efforts in the future.

ICOS locates itself in this scheme with a primary focus on 'observations' and connections towards 'research' and 'services'. This does not necessarily mean that ICOS conducts research and services by itself, but facilitates them and gathers information that steers the further development of ICOS observations. In this context, it is important to note that ICOS consists of contributions from about 70 research institutions which all have their own scientific profiles and are themselves evaluated for their scientific performance and their societal impact independently of ICOS. ICOS can represent them in processes and bodies where not all of them can be, and act as a translator and mediator within the "science driving policy" and "policy driving science" paradigm.

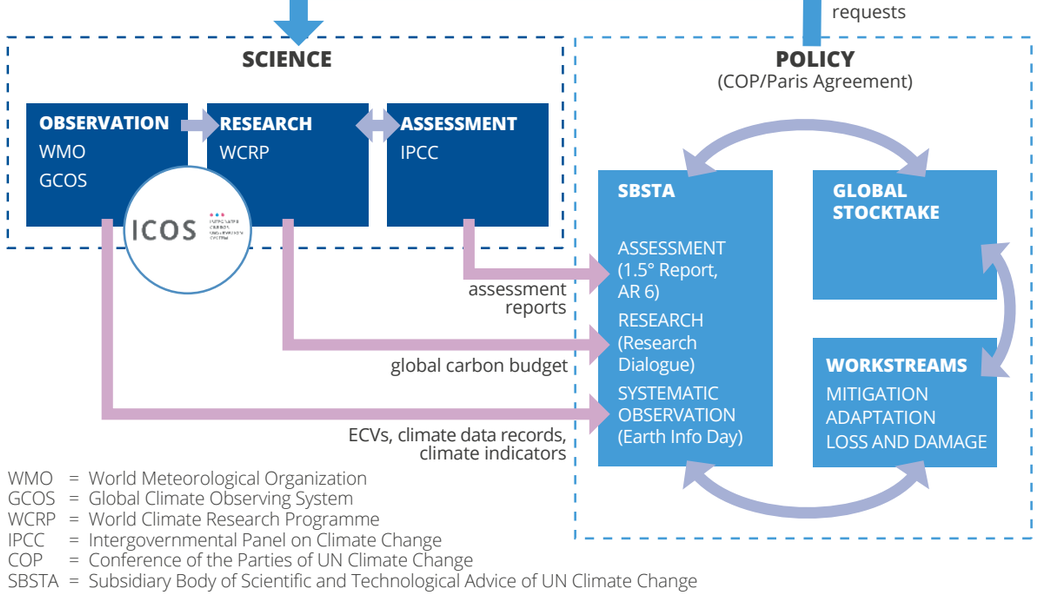


Figure 3. *The "Science driving policy" and "Policy driving science" paradigm resulting from the Paris Agreement: Steps from observations via research to assessment mark the Science sphere. In there, ICOS represents observations, but reaches out towards science. In the Policy spehere, SABSTA acts as an interface between the Science sphere and the other two COP bodies. (Simplified graph based on a picture by the Science & Review Team at UNFCCC secretariat.)*

ICOS as part of the Global Climate Observation System (GCOS)

ICOS is a science-based research infrastructure directly addressing the "Essential Climate Variables" (ECVs) developed under the United Nations Framework Convention on Climate Change (UNFCCC), with strong inputs by the World Meteorological Organization (WMO), the UN Food and Agriculture Organization (FAO), the Committee on Earth Observation Satellites (CEOS), and the Group on Earth Observations (GEO). The ECVs are documented in the Implementation Plan of the Global Climate Observation System[11] (GCOS). ICOS has been co-designed with GCOS from the beginning. In the atmosphere domain, coordinated through the Global Atmosphere Watch (GAW) programme, ICOS provides observations on two ECVs on atmospheric composition ('carbon dioxide' and 'methane, other long-lived greenhouse gases'). In the ocean domain, coordinated through IOC UNESCO's Global Ocean Observing System (GOOS) and its framework of ocean observations (FOO) with associated essential ocean variables (EOVs), ICOS is related to the biogeochemical ECVs and EOVs 'inorganic carbon' and 'oxygen'. In the terrestrial ecosystem domain, ICOS provides observations towards the ECV anthropogenic GHG fluxes, mainly related to land use. However, natural carbon dioxide and methane fluxes are currently not identified as ECVs while other parameters measured at ICOS ecosystem sites, such as albedo, leaf area index (LAI), aboveground biomass and soil carbon, are. The Global Terrestrial Observation System (GTOS) is currently not functional and under re-construction. The role of ICOS in observing the Essential Climate Variables (ECV's), shown in relation to a proposed fossil fuel emission inversion system, is presented in Figure 4.

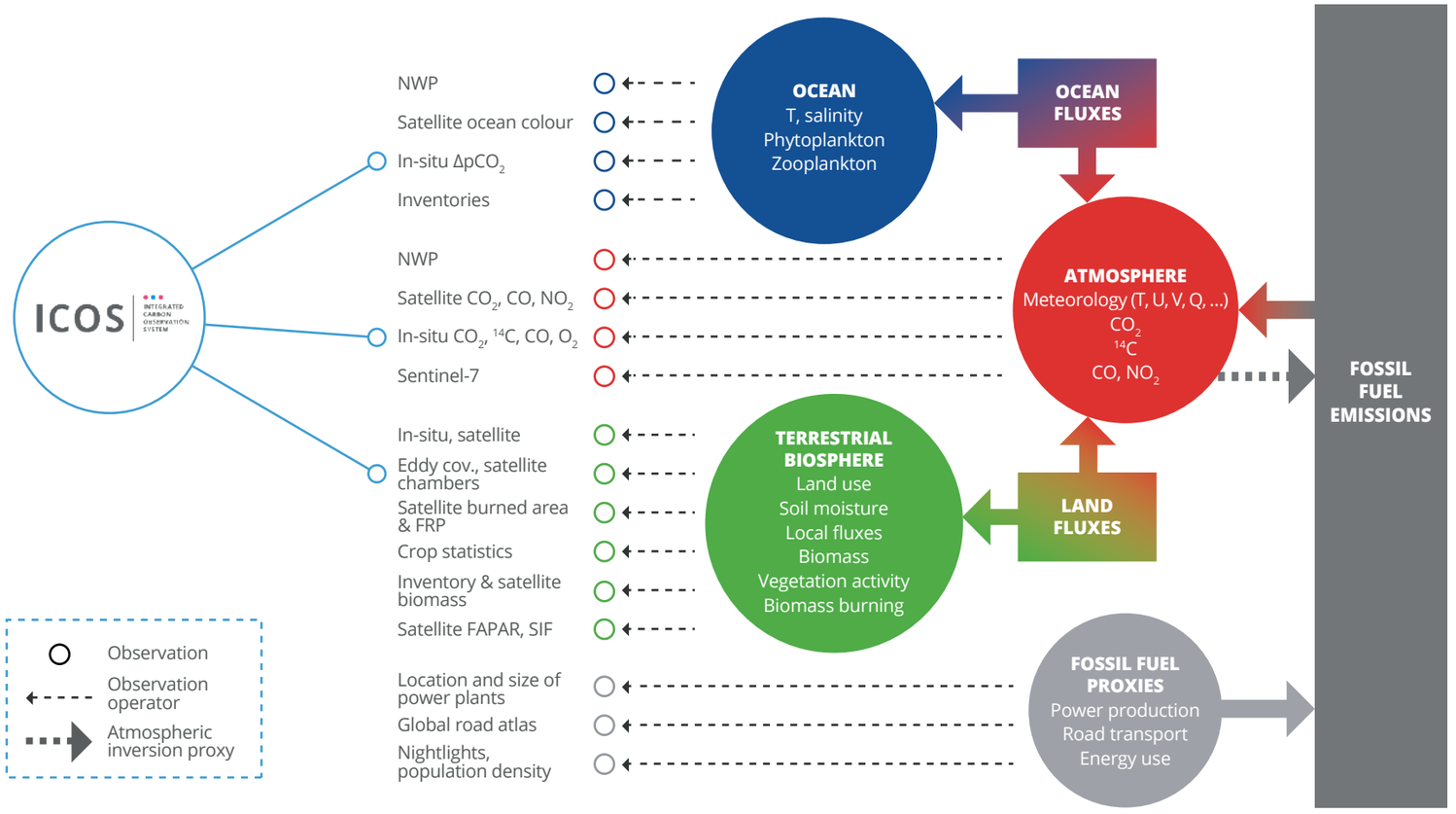


Figure 4. *ICOS observations related to the schematic overview of a fossil fuel emission inversion system showing the various required model blocks as well as the potential observations that can be used to constrain the system. (From Pinty et al., Copernicus 2017 CO_2 Report)*

ICOS in the European Framework (COPERNICUS)

In the respective Copernicus 2015[12] and 2017[13] CO_2 Reports, ICOS has been identified as a building block of a European monitoring and verification support capacity. The concept – which can be partly seen as the European contribution to GCOS – unites space and in situ infrastructure, data assimilation and modelling infrastructure and inventory data as necessary elements of a decision support system that aims to enable independent verification of emissions, improved UNFCCC reporting, assessment of effectiveness of voluntary emission reductions and carbon management. ICOS, which is already providing near real time (NRT) atmospheric data to the Copernicus Atmospheric Monitoring System (CAMS) and will provide data streams to the Copernicus Land and Ocean Services, can be clearly identified as observation operator in this concept.

The framework locates ICOS as the European in-situ operational part of GCOS and as core element of the Copernicus system. The following vision describes the desired development and the envisaged position of ICOS within its multi-dimensional framework. It is timed beyond the next decade when the mechanisms of the Paris Agreement will be fully functional, the monitoring and verification support will be at full capacity and able to confirm the intended emission reductions in Europe[14].

A vision of ICOS beyond the next decade

This vision refers to a time up to twenty years after the implementation of ICOS ERIC in 2015. It assumes that ICOS has attracted more countries and is supported with stable and sufficient resources to sustain the observations built up in the first implementation phase (till 2019) and with the necessary investments to further develop the observations towards the requirements of the late 2020s to early 2030s.

At this time, ICOS provides robust observation-based data for science on the carbon cycle and for quantifying greenhouse gas emissions and sinks including their uncertainties. This includes in situ observational networks to separately quantify fossil-fuel related emissions and sources and sinks in the land-use sector (‘anthropogenic fluxes’) from other fluxes of greenhouse gases (‘natural fluxes’). The high precision ICOS

data products have proven their utility for detecting the temporal and spatial variations of the greenhouse gases exchanges between the three earth reservoirs and to understand their drivers with unprecedented acuteness.

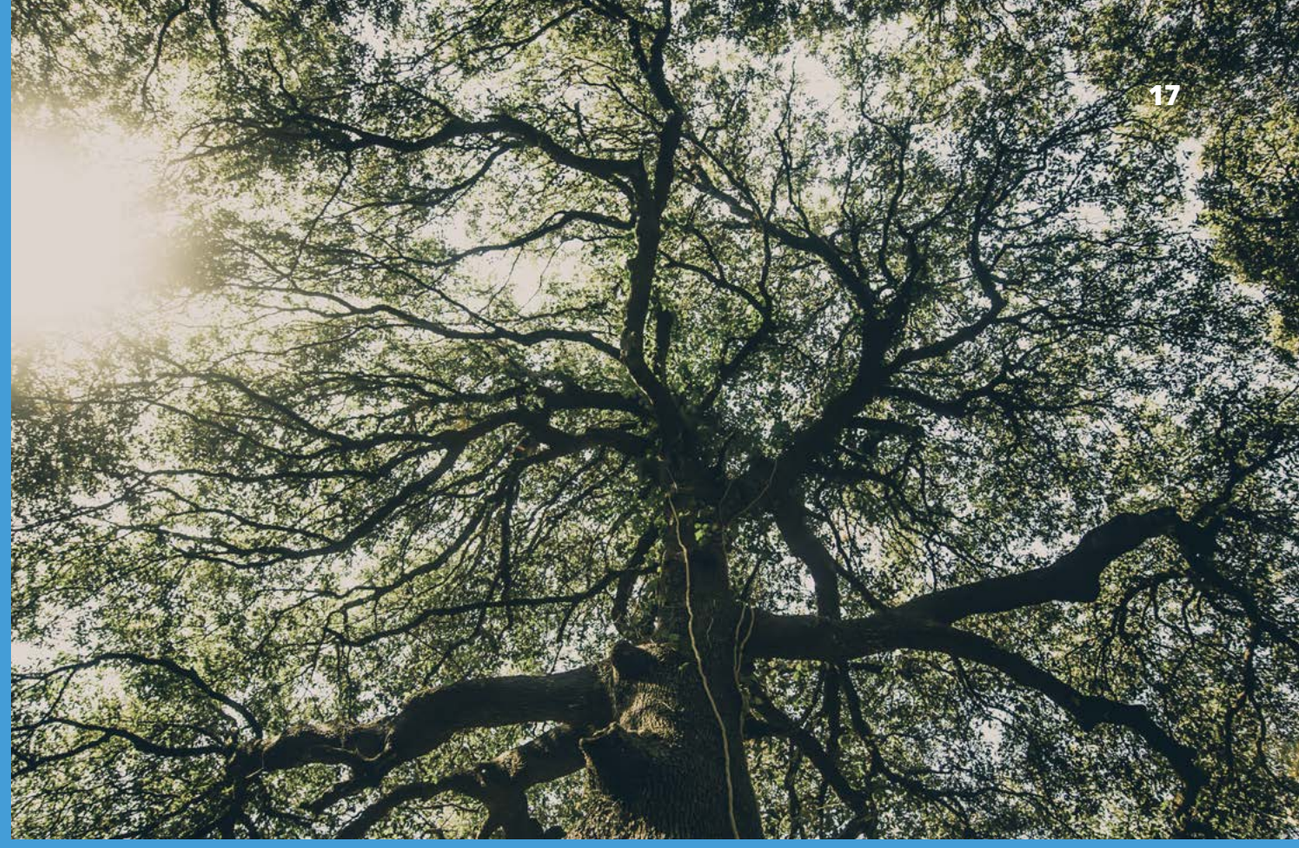
During the past two decades, ICOS data have been used by a broad spectrum of individuals and organizations who transformed ICOS data with scientific excellence into knowledge for climate action. The services to support and integrate research on ICOS data have been adopted by the scientific user community and beyond. ICOS data have been keystones for major scientific breakthroughs. In return, the vivid user community has provided many impulses to further develop the observations. ICOS facilitates a permanent dialog with its users to optimize its data provision and the relevance of the measured parameters. As a result, spatial density, representativeness, set of measured parameters and their precision and accuracy are state-of-the-art and enable multiple services towards science and society.

ICOS has a well-integrated data life cycle that ensures data integrity and is fully compliant with the FAIR principles. Near-real time data from sensors are available within 24 hours through the Carbon Portal. Quality-controlled higher-level data are published through the Carbon Portal in frequencies defined with the scientific users. The work on metadata has resulted in a representation of ICOS data in major global data systems within the World Meteorological Organization (WMO), the Intergovernmental Oceanographic Commission (IOC-UNESCO) and the Group on Earth Observations (GEO). The data usage is documented through download and data usage tracking via citable digital object identifiers. A global data citation system provides station principle investigators, host institutions, and funding organisations with citation statistics that show that the ICOS data has an enormous impact on science and beyond.

The ICOS observations meet the requirements for the United Nations Societal Development Goals (SDGs) and the Paris Agreement, namely the GCOS Climate Monitoring Principles[15] defined by the Global Climate Observation System (GCOS) and those of the European monitoring and verification system coordinated by Copernicus. The resulting scientific publications and products (e.g. integrated flux maps) have been established as important sources for IPCC and UNFCCC.

ICOS has become a mediator between the scientific community working on greenhouse gases on one hand and the agencies that work on national inventories and the global stocktake in the framework of the Paris Agreement, Parties at the UNFCCC, and the European Commission in its climate actions on the other. The ICOS Science Conferences have established themselves as a market place to present outcomes and impacts of ICOS observations, to advertise observational and scientific priorities, to further develop the Monitoring, Reporting and Verification (MRV) system and to translate requirements that are formulated in the political sphere (e.g. at COPs or SBSTA meetings) into scientific and observational approaches. In this role, ICOS is representing a strong European community of institutions investing in in situ observations and has established itself as an organisation where relevant stakeholders including national and European funding organisations seek advice.

International cooperation has established a global environmental research infrastructure that covers the essential variables related to the



UN Societal Development Goals as well as the Convention on Climate Change and the Convention on Biological Diversity. Within the ensemble of European Environmental Research Infrastructures (ENVRIs), ICOS is a strong European building block of this global research infrastructure providing observations and data on long-lived GHG and the carbon cycle. The close cooperation between the ENVRIs has strengthened the European Research Area since ENVRIs act united and in close cooperation with the European Commission and the national governments towards GCOS and global organisations. Data from ICOS sites are well integrated into global data networks such as FLUXNET, SOCAT, GLODAP, and GAW. ICOS Thematic Centres have established as centres of excellence in their domains, reference points at European and international level and provide stable support for these networks in close cooperation with research infrastructures on other continents.

ICOS has become a ‘catalyst’ of technical developments since it combines scientific and engineering competences with access to a platform of observational sites and laboratories in a unique way. ICOS drives technical developments in order to improve analytical capacities. It is an ideal place for translating scientific questions into technical requirements and supports specific technical developments by industry partners in response to its high-quality observational needs.

Activities towards our vision

Developing the infrastructure

Quality of measurements

ICOS aims to optimize its network quality. The already achieved observational standardisation and centralized data processing by the CFs will be continuously improved within the established participative approach. The labelling process to ensure compliance, high quality and robustness for new stations will be continued to be improved and optimized. The next steps will be the implementation of international metrological standards and external certification. Through development and implementation of network quality measures, ICOS will furthermore deepen the cooperation with industry partners, mainly manufacturers of instruments.

Network coverage

Network quality also includes geographical coverage and density of the networks. ICOS' remote strategic aim is to cover the full European continent with denser networks to reduce current uncertainties and to explore potential hotspots areas such as the permafrost, megacities, land surface exposed by glacier retirement, Mediterranean area and other areas subject to strong pressures. Enhancing the network coverage will be concerted in close cooperation with GCOS and its domain-related sub-programs and the Copernicus services. Improvements to network coverage will be guided by, among other factors, Observing System Simulation Experiments (OSSEs) that make it possible to assess the improved constraint on GHG fluxes made possible by proposed changes to the network, and thereby to guide the optimization of the observational network. OSSEs are often used in developmental work conducted in European research projects and the WMO IG^{3}IS framework.

Comprehensive set of parameters

The list of parameters observed in ICOS will be regularly re-evaluated. They will be related to the needs of scientific users (see below "Feedback from scientific users of ICOS data") and to the further development of the ECVs. Achieving comprehensive observations of all three major greenhouse gases (carbon dioxide, methane, nitrous oxide) across all three domains is one important next step towards full operability of ICOS.

Interoperability

The integrated design of ICOS as a Research Infrastructure with observations encompassing atmosphere, terrestrial ecosystems and oceans requires internal cross-domain interoperability. This has partly been achieved by technically harmonizing the data life cycles and by developing common approaches like e.g. high-precision atmosphere observations on ships or coastal flux stations, and will be further developed. ICOS will specifically initiate and support scientific activities that integrate ICOS data across domains e.g. for better understanding the European carbon cycle response to extreme events or changes in land use and land management or to reduce uncertainties in the European greenhouse gas balances.

The interoperability between ICOS in situ data with satellite data is strongly enhancing the scientific value of an integrated global greenhouse gas information system. A number of satellite sensors for GHG observations that overlap partially in time are planned for

the next decade. Satellites designed to measure the total column concentrations, deliver information at high spatial resolution all over the globe but with low time resolution, only at low cloudiness, with relatively coarse precision and potential biases. Furthermore, they can be single points of failure. The stable and consistent network of ground observations provided by ICOS, complemented by observations along the vertical dimension as provided by the ESFRI RI IAGOS, is therefore indispensable as an independent data stream for an integrated information system, but also offers calibration and validation for satellites. The integration of the European Total Carbon Column Observing Network (TCCON) and the co-location with atmospheric stations is a concrete option to foster this. Furthermore, ICOS observations will support research on proxies for fossil fuel CO_2 emissions (CO, NO_x) that can also be observed from satellites, but also require in situ observations for specific calibration and coverage of areas and periods with clouds or without enough sunlight. This will partly be achieved through co-location with the ESFRI RI ACTRIS networks to avoid doubling up on efforts.

It is expected that future information systems on greenhouse gases, e.g., those that combine improved atmospheric transport models, dynamic vegetation models, and inversion frameworks, will use the high-quality ICOS time series from all domains. This is an area where ICOS will work closely with its scientific user community in order to optimise the match between the scientific capabilities of the observational system and the scientific analysis systems and open a path towards a network of even higher spatial density than the current ICOS network.

The Ecosystem station network is also offering calibration and validation capabilities for a variety of remotely sensed variables through constantly monitored uniform areas around each station. The Ecosystem stations are currently monitoring the terrestrial photosynthesis and respiration processes, energy exchanges between ecosystems and the atmosphere and additional variables such as the LAI, standing biomass, foliage nutrient ratios, soil organic carbon, nitrogen and soil moisture, disturbances and vegetation phenology and life cycle. Due to their accuracy, temporal consistency and standardisation these data are being increasingly used for calibrating satellite proxies such as fraction of absorbed solar radiation (FAPAR), photochemical reflectance index (PRI) or fluorescence (solar induced fluorescence, SIF) and validate other remote sensing products (soil moisture, canopy radiative temperature, standing biomass). Furthermore, the Ecosystem network offers a considerable potential for hosting additional measurements fully interoperable with satellite-borne measurements. As such, it will play a critical and unique role along the next 20 years and beyond in documenting and online monitoring the impacts of environmental drivers on terrestrial ecosystems and their GHG balance at high temporal and – through interoperability with satellite products – spatial resolution.

Ocean scientists need satellite information to support the calculation of ocean fluxes from inorganic carbon concentration measurements in the surface ocean as provided by ICOS. Accurate calculation requires the use of satellite estimates of surface temperature (SST), surface microlayer effects, wave state and wind speeds, in order to provide the best estimates of fluxes. Retrieval of

the satellite data will be further developed within the ICOS OTC as a means of integrating such calculations into ICOS, with the aim of making these calculations operational in NRT within ICOS.

Interoperability between ICOS, the related scientific communities and agencies working on national inventories and the global stocktake in the framework of the Paris Agreement requires an established communication and translation process with parties at the UNFCCC and the European Commission in its climate actions. Observation and research are important inputs to further develop the Monitoring, Reporting and Verification (MRV) system. Interoperability will be established in twofold ways. Atmospheric observations will supplement national inventories as currently developed in the IPCC guidelines while ecosystem data will also be helpful in improving calculation of carbon stocks and annual net carbon uptake where data are limited, or Tier 3 calculations of emissions e.g. from land-use. Interoperability will also be used as a tool for quality enhancement. Co-locating measurements from other networks, e.g. NOAA flask samples at ICOS atmosphere stations or a flux tower from another network close to an ICOS station will provide valuable information on uncertainties.

Realizing a reliable data life cycle from sensors to users

Through the access to high-quality, well documented and traceable data documenting continuously the GHG cycle in the earth system, ICOS is about to become one of the main data providers for the entire biogeoscience community in this area. This objective is at the heart of the ICOS objective, but it has still to be proven and strengthened. This will constitute the main operational challenge for the next 5 years with the establishment of the data acquisition and processing of more than a hundred ICOS labelled stations.

The general principles on handling and distribution of ICOS data products were agreed on very early in the planning phase. In practice, the FAIR principle means giving the user sufficient tools to understand the meaning and quality of the data before and after downloading it. It also makes the machine-to-machine communication of data possible. Metadata and other descriptions are visible, and the user should be able to preview the data before downloading. It also means highest standards in data curation (provenance, curation, archiving).

Usage tracking

Data usage is a key indicator for the success of ICOS. Data citation is a prerequisite of open data policies. ICOS will further develop data usage tracking by archiving all data downloads and following the subsequent usage via citable digital object identifiers (pids and dois) and with that support the development of a comprehensive data citation system according the Data Citation Principles of the Force11[16] group. This will include data citation services provided by the Carbon Portal and the connection of ICOS data to a data citation index under development.

Stability

Consolidated networks for long-term in situ observations require stable and sustainable funding. As a prerequisite, ICOS ERIC will coordinate the resource management within the research infrastructure at highest business standards and in compliance with the underlying financial rules and principles. Perspectives to broaden the financial basis will be further developed in the five-year plan(s) that refer to this strategy. It is anticipated to broaden the financial basis beyond public funding. Particularly for the new elements of network (city observatories or MRV services, see below), new financial cooperation models with cities and agencies or through private-public partnerships for the provision of elaborated products and services to the commercial sector will be explored.

Sustaining and developing the network requires a specific human resources policy guaranteeing the necessary competences throughout the whole infrastructure. Operational, technical and scientific skills are necessary within the entire ICOS research infrastructure for connectivity between ICOS and scientific studies using the site data or for the usage of the sites as platforms for additional scientific studies. These skills will be indispensable at the Central Facilities and National Networks for driving further technical developments in any part of the observational networks. Minimizing risks of dysfunction due to personnel fluctuation will be achieved by career path planning and skill development of key personnel, by education and integration of young scientists and increases in skill redundancy wherever necessary.

Current and future science

ICOS has been developed and is used by a broad scientific community. This close connection is a very valuable asset for ICOS. In its strategic development, ICOS is continuously responding to the emerging needs from the scientific community which covers a broad spectrum from basic to applied questions and transforms ICOS data into knowledge for climate action.

Demands from science to improve ICOS observations and services

As a consequence of the Paris Agreement, the link between science and policy has become stronger than before, and even more relevant to policy-makers who should be guided by research and innovation advances, as stated by Ourbak & Tubljana (2017)[17]. ICOS observations will be an important source for scientists who investigate the possible consequences of the climate policies of the European countries, megacities and regions.

The ICOS observational network has been designed to enable multiple types of scientific studies around two major scientific questions:

1. How do carbon-climate feedbacks induced by the anthropogenic perturbation of the global carbon cycle change the natural carbon sinks and greenhouse gas emissions?
2. How can the primary agents of change be quantified, such as fossil fuel combustion and modifications of global vegetation through land use change (deforestation, forest degradation) and intensified land management?

ICOS has the necessary components to contribute to these scientific demands and will develop standard systems for integrating this information. The high quality ICOS data products have proven their utility for detecting temporal and spatial variations of the greenhouse gases exchanges between the three earth reservoirs and relating them to carbon-climate feedbacks and additional drivers (e.g. ozone and nitrogen depositions on land surface or nutrient imports into coastal oceans). The ICOS data should also make it feasible to detect tipping points in the Earth system or, even better, inform models that can predict tipping points so they can be avoided, and climate-carbon feedbacks that could result in major changes of the natural greenhouse gas fluxes.

Isotopic observations – particularly on ^{14}C that has a permanent abundance in atmospheric CO_2 but is absent in fossil fuels – constitute a bridge between the two major questions since they enable scientists to separate the imprint of natural and anthropogenic CO_2 fluxes in the atmosphere. The Central Radiocarbon Laboratory (CRL) of ICOS is prepared to measure long-term integrated $^{14}CO_2$ time series at ICOS class-1 atmospheric stations. It will provide an optimized sampling strategy as a result of the RINGO project that will serve both initial scientific questions and will thereafter be implemented as essential part of ICOS observations.

The following paragraphs will highlight some specific scientific aspects that may influence the further development of ICOS observational network in the next decade and therefore have to be closely followed.

Detecting trends and understanding the drivers in land and ocean sinks

In-depth scientific understanding of the global carbon cycle is an important element of efficient adaptation and mitigation strategies and key knowledge for future stocktaking in the Paris Agreement framework. One practical goal is to combine the comprehensive ICOS networks with technical and scientific improvements in land and ocean flux calculations towards operational flux calculation systems. The long term, high precision observations in the atmosphere and at the ocean and land surface will enable the assessment of regional greenhouse gas flux patterns, carbon-climate feedbacks, tipping-points and vulnerabilities.

City observatories

"Cities are where the climate battle will be won or lost" – *Patricia Espinosa, Executive Secretary of the U.N. Framework Convention on Climate Change (UNFCCC), in April 2018 during a conference of city and government officials in Germany.*

It is consensus that accurate and robust observation-based methods for quantifying GHG emissions and sinks in urban areas are important tools for policy and societal stakeholders. Policies in support of climate change mitigation through GHG emission reductions require estimates of emission baselines and changes. ICOS will further develop relevant methods for urban GHG measurement approaches, which are already applied as prototypes. The direct observation of CO_2 emissions from fossil fuels ($ffCO_2$) need to be optimised and further developed since continuous and precise ^{14}C analyses are costly and therefore have to be combined with other methods in an intelligent way. In this context, also methods currently applied in the Ecosystem component of ICOS may be adapted to some extent from natural ecosystems to urban areas. ICOS will provide support and access to scientists and projects who aim to further develop

and integrate technologies to detect urban GHG fluxes. Results from these scientific efforts could be standardized and implemented into the ICOS networks. ICOS wants to pave the way towards city observatories that directly support the development of climate-smart cities.

Terrestrial ecosystem management between food production, bioenergy and greenhouse gas mitigation

There exists a trade-off between different possibilities to manage ecosystems and use ecosystem services where scientific knowledge is highly required for political action. Regarding the ICOS-related questions on the global carbon cycle, forests can be managed as long-term carbon sinks. Whole trees have been proposed as a source of bioenergy under the assumption that it is carbon neutral, yet studies show bioenergy does not reduce emissions and can increase emissions. It requires full accounting of forest carbon, transport, use and losses from cradle to grave to assess net emissions. Therefore, the high profile of bioenergy within the EU's renewable energy mix needs to be justified, particularly when it is clear that other sources of renewable energy have much shorter carbon payback periods. Agricultural management practice has likewise strong demands for scientific knowledge that can be supported by ICOS data. The influence of management on soil carbon accumulation or loss is still unclear while large expectations for carbon storage are formulated in the political sphere e.g. by the 4 per 1000 initiative[18]. The ICOS network comprises already a multitude of ecosystem sites providing invaluable long-term data sets for supporting scientists to improve best practice guidelines for forest and agricultural management and to report and detect the possible unrevealed effects. In this context it is important to note that ICOS covers only a sub-set of variables for monitoring terrestrial ecosystems functioning and will stimulate partnerships with biodiversity, agronomy and forestry networks for an integrated assessment of terrestrial ecosystems across continents.

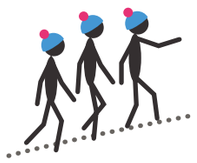
Services supporting science

The best way to encourage science is by providing easily accessible and high-quality data to scientists. As described in the previous chapter, the key priority of ICOS will always be that data is made available in the Carbon Portal with highest possible documented quality with the shortest possible delay from the time of collection. Requests from scientists will increase if the high-quality data is available quickly. By scientists using ICOS data, publishing papers, and communicating their findings, the importance of ICOS will be made clear to policy-makers and society.

To ensure optimized usage and support for scientists, the Carbon Portal has started to provide tools for interactive analysis of data and model results. They are based on web-based technologies and on direct access to ICOS data and elaborated products, and they enable transparent analyses, interactive collaboration of modellers and data providers and connections to computing resources in the European Open Science Cloud. These services will be further developed on demand.

ICOS will further develop its services based on ICOS data. The developments will be partly built on current and future EU and national funding by using the ICOS brand to foster participation of a broader scientific community for developing higher level products that thereafter can be accessed through the Carbon Portal once they have become standard products.

The ICOS communities



The ICOS impact assessment report[19] published in August 2018 clearly distinguishes between the mandated 'activities' of ICOS and the related 'output' (data, higher-level data products and services) and the 'outcomes' that are produced by the 'users' of ICOS and represent a first-order effect of ICOS. Societal or economic 'impact' e.g. in the framework of the Paris Agreement generated by scientific results is a second-order effect. The ICOS strategy distinguishes, consequently, between three roles:

- ICOS personnel employed at the host institutions of the National Networks and Central Facilities and at ICOS ERIC who are involved into ICOS activities and producing the ICOS output are called 'operators'
- Scientists who use ICOS data, publish papers, and communicate their findings are called 'users'
- People, organisations or groups that benefit from the impact of ICOS are called 'stakeholders'.

The ICOS Identity Study has shown that more than 50 % of the people involved in ICOS are 'scientists in a managerial and scientific role', in the above terminology 'operators and users in one person'. The host institutions of the National Networks seem to see this as the ideal solution and motivation for their engagement in ICOS. For ICOS RI as an organisation, the high number of participating scientists is definitely an asset. Nevertheless, this strategy document works along the roles and distinguishes between different engagement pathways even though they may partly target to the same group of people. The ultimate goal of feedback from operators, users and stakeholders is the permanent innovation of the observations.

Maintaining the engagement of the community of ICOS operators

ICOS will continuously develop ways to engage and motivate the people involved in the ICOS RI operations. This is important due to the nature of the distributed infrastructure: organizational structures, different priorities in people's tasks, geographical distances and different languages affect our ability to cooperate efficiently. Findings from an ICOS Identity Study[20] conducted show that people are driven by a variety of perceived purposes, motivations, and expectations on societal, professional and personal levels. Understanding and addressing these will help create a more inclusive culture within ICOS RI.

To improve the engagement and internal cooperation, ICOS will develop its ways of working, culture, and internal communications in order to have timely and correct information available, increase motivation and sense of belonging towards ICOS. This will, in turn, support strategy execution and enhance work efficiency. ICOS will, for example, further develop virtual platforms for internal two-way communications, increase sharing of news internally, and foster dialogue. ICOS will also implement other actions defined in a specific "ICOS Involvement plan", that will be created based on the results of the aforementioned Identity Study. The success of ICOS in this area will be measured periodically.

Feedback from users of ICOS data

ICOS needs to be agile and open to respond to new requirements and opportunities. Therefore, ICOS wants to have a permanent dialog with its users to optimize its observations and its data provision. Although the ICOS user community is very diverse, some core user groups ICOS users can be clearly identified. ICOS will actively follow the scientific developments and resulting observational needs of these identified user groups in common projects and in conferences and will make use of its own biannual science conference to optimise data streams towards users and network design. ICOS clearly aims also at user communities beyond Europe and will participate in respective conferences at other continents. ICOS will inform the users on the precision and the relevance of the measured parameters, and provide analyses of the data. User feedback will sharpen the strategic aims and provide novel ideas for the spatial distribution of observational sites as well as the applied methods. ICOS will be open for improvements in spatial density, representativeness, set of measured parameters, precision and accuracy.

New user groups may occur for ICOS data as well as for the stations themselves.

Recommendations for services and physical access for additional scientific projects and for industrial partners (e.g. for sensor development) will be developed in close cooperation with the respective users.

Dialog with stakeholders: societal impact of greenhouse gas observations

ICOS sets up a permanent dialogue process with stakeholders. The general objective of the dialogue is to gather participants with an insight in climate change related policies and identify their needs in terms of GHG data or services. The dialogue will be continuous. ICOS will, for example, participate in the annual Science Dialogue organized by the SBSTA of UNFCCC, promote stakeholder activities within IG^{3}IS and the GEO-C Initiative and use the biennial ICOS Science Conference to find new ways to interact with decision-makers. ICOS will translate questions from the policy sphere into further development of observations and research, and similarly transfer knowledge from observations to policy-making.

International cooperation

Cooperation among European Environmental Research Infrastructures

ICOS covers an important part of the European Research Area and provides core competences on the European GHG balance to the European Environmental Research Infrastructures (ENVRI community) which should not be made redundant by upcoming research infrastructures. Instead, ICOS strongly supports the consensus among European Environmental Research Infrastructures about synergies being a strategic goal within the established ENVRI framework. ICOS will continue to work on a consistent landscape where duplication and operational conflict (measuring the same variable with different methods or standards) can be avoided. As formulated in the ENVRIplus Whitepaper on “further integration of research infrastructures related to the terrestrial ecosystem research”, ICOS supports the in-depth cooperation of structurally independent entities under the subsidiarity principle. ICOS will closely follow the development of other ENVRIs in an open and cooperative manner and seek innovative synergies where possible, e.g. by seeking a common voice towards funding organisations, by promoting integrated scientific concepts, technical interoperability, co-location of sites as well as common administrative structures or external representation of the ENVRI community by one research infrastructure. This ENVRI integration implies a considerable effort in harmonisation, standardisation, inter-calibration, shared protocols and instructions, which is currently supported by H2020 cluster projects (ENVRI, ENVRIplus, ENVRIfair). ICOS will further support and lobby this approach.

In the atmospheric domain, ICOS is endorsed as contributing regional network in the Global Atmosphere Watch (GAW) Program coordinated by WMO and will steer further global cooperation in this framework by strong coordination with the respective European atmosphere research infrastructures (IAGOS and ACTRIS).

In the terrestrial ecosystem and biodiversity domain, ICOS will negotiate cooperation agreements with the respective European research infrastructures (namely eLTER RI and AnaEE). The aim is to coordinate and to develop the European contribution to a global terrestrial observation system based on commonly agreed variables, shared protocols, enhanced inter-operability and open data access. With DANUBIUS RI, a common protocol for GHG fluxes between lakes, rivers and streams and the atmosphere and for lateral carbon transport to the oceans will be developed.

In the ocean domain ICOS will closely cooperate with EMSO ERIC and EUROARGO ERIC to optimise the European contribution to the GOOS Biogeochemistry data streams. Together, the three research infrastructures cover the inorganic carbon system from the seafloor to the atmosphere, complementing each other and providing data and knowledge base for climate research, design of environmental policies, and education. ICOS and EMSO share a variety of observation platforms and mutually benefit by sharing technology and knowledge. Closer cooperation in the further development of their data life cycles namely in data quality assurance and control is of strategic importance.

Further development of international data initiatives

ICOS aims to continue and further develop the support for FLUXNET, SOCAT, GLODAP and GAW. These global data collation initiatives have already proven to be a precious data source for excellent and, at the same time, relevant science. They are facing a transition from single PI and project engagement to a global cooperation of research infrastructures such as NEON and Ameriflux (USA), CERN/Chinaflux (China), TERN/Ozflux (Australia) and NIES/Japanflux in (Japan) in the ecosystem domain. Each of these infrastructures has developed its own data life cycle, data license and data policy which will have implications on future cooperation within the global networks. ICOS will be a driving force in developing perspectives for future cooperation in the mentioned global data initiatives. The activities will comprise standardisation, common data policies, a common data citation system including developing recommendations for data citation of integrated data sets from different sources.

Involvement in international initiatives

As part of the stakeholder engagement (see above) and in its role as mediator between the spheres, ICOS is observing organisation to the UNFCCC and part of the SBSTA dialogues on research and systematic observation. ICOS will closely cooperate with WMO and contribute to the Integrated Global Greenhouse Gas Information System (IG^{3}IS) on the long-term goal of a more systematic operational approach. Since IG^{3}IS intends to build upon existing observations, ICOS will contribute to the further development of IG^{3}IS once the WMO has provided a clearer governance structure. ICOS is, furthermore, participating organisation in the Group on Earth Observations (GEO) and supports the GEO Carbon and GHG Initiative (GEO-C). The rationale behind the participation in international initiatives and programs is that the precise observation of emissions as well as natural fluxes require global cooperation in organisational frameworks. Only there, policy-relevant information systems can be established and further developed. The emerging partnership with the US Carbon Cycle Science Program will be further developed to increasingly advance carbon cycle science.

Active support for the construction of networks in less developed regions

ICOS will also support the construction of networks in less developed regions, where ICOS can contribute to design studies and be mentors in technical implementation and establishment of knowledge centres. Based on recent and upcoming design studies (e.g. in the H2020 project SEACRIFOG), ICOS will strongly support the implementation of a greenhouse gas monitoring system adapted to the needs of African countries. These activities will be further developed in an established cooperation framework with WMO, GCOS, European Union and African Union. The aim is a stepwise development from a comprehensive design study that will be finalized during 2020 towards stepwise implementation in the following years. ICOS National Networks and Central Facilities will have a crucial role in translating the design study into detailed technical requirements, contributing to capacity building and supporting the construction of sites. There are already success examples for these activities very often supported by national grants. ICOS ERIC can play an important role in connecting the nationally funded activities with each other and with globally coordination institutions such as WMO. Furthermore, it will use established international frameworks for fund raising.

Appendix 1: Abbreviations

^{14}C	Radiocarbon
$^{14}CO_2$	Carbon dioxide containing heavy isotope of carbon
ACTRIS	Aerosol, Clouds, and Trace gases Research Infrastructure
Ameriflux (USA)	A network of PI-managed sites measuring ecosystem CO_2, water, and energy fluxes in North, Central and South America.
AnaEE	Analysis and Experimentation on Ecosystems Research Infrastructure
AR6	Sixth IPCC Assessment Report
CEOS	Committee on Earth Observation Satellites
CERN/Chinaflux	Chinese Ecosystem Research Network/Chinese Flux Research Network
CFs	ICOS Central Facilites, i.e. Atmospheric Thematic Centre (ATC), Ecosystem Thematic Centre (ETC), Ocean Thematic Centre (OTC), Central Analytical Laboratory (CAL)
CGMS	The Coordination Group for Meteorological Satellites
CHE	H2020 CO_2 Human Emissions Project
CMA	Conference of the Parties serving as the meeting of the Parties to the Paris Agreement.
CO	Carbon monoxide
CO_2	Carbon dioxide
COP	Conference of the Parties to the United Nations Framework on Climate Change (UNFCCC)
COPERNICUS	Copernicus is the European Programme for the establishment of a European capacity for Earth Observation.
CRL	Central Radiocarbon Laboratory of ICOS Central Analytical Laboratory
DANUBIUS RI	The International Centre for Advanced Studies on River-Sea Systems Research Infrastructure
DOI	Digital Object Identifier
ECV	Essential Climate Variable
eLTER RI	European Long-Term Ecosystem Research Infrastructure
EMSO ERIC	The European Multidisciplinary Seafloor and water column Observatory European Research Infrastructure Consortium
ENVRI	Environmental Research Infrastructure
ENVRIfair	A Horizon 2020 project focusing on harmonisation between the infrastructures
ENVRIplus	a Horizon 2020 project bringing together Environmental and Earth System Research Infrastructures, projects and networks together with technical specialist partners to create a more coherent, interdisciplinary and interoperable cluster of Environmental Research Infrastructures across Europe.
EOSC	European Open Science Cloud
ERIC	European Research Infrastructure Consortium
ESFRI	European Strategy Forum on Research Infrastructures
EU	European Union
EUROARGO ERIC	European Research Infrastructure Consortium for Observing the Oceans
FAIR	A set of guiding principles to make data Findable, Accessible, Interoperable, and Reusable
FAO	United Nations Food and Agriculture Organization
$ffCO_2$	CO_2 emissions from fossil fuels
FLUXNET	A global network of micrometeorological tower sites that use eddy covariance methods to measure the exchanges of carbon dioxide, water vapor, and energy between terrestrial ecosystems and the atmosphere.
FORCE 11	FORCE11 is a community of scholars, librarians, archivists, publishers and research funders that has arisen organically to help facilitate the change toward improved knowledge creation and sharing.
Future Earth	A research initiative on global environmental change and global sustainability
GAW	Global Atmosphere Watch (World Meteorological Organisation Program)
GCOS	Global Climate Observing System
GEO	Group on Earth Observations

GEO-C	Group on Earth Observations Carbon and greenhouse gas initiative
GFCS	Global Framework for Climate Services
GHG	Greenhouse gas
GLODAP	Global Ocean Data Analysis Project
GOOS	Global Ocean Observing System
GTOS	Global Terrestrial Observation System
H2020	Horizon 2020 is an EU Research and Innovation programme
IAGOS	In-service Aircraft for a Global Observing System Research Infrastructure
ICOS	Integrated Carbon Observation System
ICOS ERIC	Integrated Carbon Observation System European Research Infrastructure Consortium
ICOS OTC	ICOS Ocean Thematic Centre
ICOS RI	Integrated Carbon Observation System Research Infrastructure
IG^{3}IS	Integrated Global Greenhouse Gas Information System
IOC UNESCO	The Intergovernmental Oceanographic Commission of UNESCO
IPCC	Intergovernmental Panel on Climate Change
Japan flux	Japanese ecosystem research network
LAI	Leaf area index
MRV	Monitoring, Reporting and Verification
N_2O	Nitrous oxide
NAP	The National Adaptation Plan
NC	National Communications
NDC	Nationally Determined Contributions
NEON	The National Ecological Observatory Network
NN	National Network

NOAA	National Oceanic and Atmospheric Administration of U.S. Department of Commerce
NOX	Nitrogen oxides
NRT	Near-Real-Time
OSSEs	Observing System Simulation Experiments
pid	persistent identifier for data objects
PRI	Photochemical reflectance index
RI COM	Research Infrastructure Committee
RINGO	H2020 project, Readiness of ICOS for Necessities of Integrated Global Observations
SBSTA	Subsidiary Body for Scientific and Technical Advice
SIF	Solar induced fluorescence
SOCAT	Surface Ocean CO_2 Atlas data set
SR	(IPCC) Special Report
SST	Sea surface temperature
TCCON	Total Carbon Column Observing Network
TERN/Ozflux	Terrestrial Ecosystem Research Network/Australian Flux Research Network
UN	United Nations
UNEP	United Nations Environment Programme
UNESCO	United Nations Educational, Scientific and Cultural Organization
UNFCCC	United Nations Framework Convention on Climate Change
VERIFY	H2020 project on Observation-based system for monitoring and verification of greenhouse gases
WCRP	World Climate Research Programme
WCSP	World Climate Services Programme
WMO	World Meteorological Organization

Appendix 2: Relevant documents

Constitutional documents

- **ICOS ERIC Statutes**:
  www.icos-ri.eu/sites/default/files/cmis/ICOS ERIC Statutes.pdf
- **Technical and scientific description of ICOS RI:**
  www.icos-ri.eu/sites/default/files/cmis/Technical and Scientific Description of ICOS RI.pdf

Finances

- **ICOS RI Internal Financial Rules:**
  www.icos-ri.eu/sites/default/files/cmis/ICOS Internal Financial Rules_Approved2016.pdf
- **ICOS RI Financial Report 2017:**
  www.icos-ri.eu/sites/default/files/cmis/ICOS RI Financial Report 2017.pdf

Operations

- **ICOS Handbook:**
  www.icos-ri.eu/sites/default/files/cmis/ICOS Handbook 2019.pdf
- **ICOS RI Data policy:**
  www.icos-ri.eu/sites/default/files/cmis/ICOS RI Data Policy.pdf
- **ICOS RI Progress Report 2015-2017:**
  www.icos-ri.eu/sites/default/files/cmis/ICOS Progress Report 2015-2017.pdf
- **ICOS Impact Assessment Report 2018:**
  www.icos-ri.eu/sites/default/files/cmis/ICOS Impact Assessment Report 2018.pdf
- **ICOS RI Annual Report 2017:**
  www.icos-ri.eu/sites/default/files/cmis/ICOS RI Annual Report 2017.pdf

Documentation of station labelling process

- **ICOS ATC station labelling Step 2:**
  www.icos-ri.eu/sites/default/files/cmis/ICOS Atmospheric Station Labelling STEP 2.pdf
- **ICOS ATC station specifications:**
  www.icos-ri.eu/sites/default/files/cmis/ICOS Atmospheric Station specifications Version 1.3 - November 2017.pdf
- **ICOS ETC station labelling Step 1:**
  www.icos-ri.eu/sites/default/files/cmis/Ecosystem stations labelling process document Step 1.pdf
- **ICOS ETC station labelling Step 2:**
  www.icos-ri.eu/sites/default/files/cmis/Ecosystem stations labelling process document Step 2.pdf
- **ICOS ETC station labelling Step 2 practical procedure:**
  www.icos-ri.eu/sites/default/files/cmis/Ecosystem stations labelling Step 2 practical procedure.pdf
- **Instructions for ICOS ETC Associated Stations:**
  www.icos-ri.eu/sites/default/files/cmis/Instructions for ICOS Ecosystem Associated Stations.pdf
- **ICOS ETC station specifications:**
  www.icos-etc.eu/variables
- **ICOS OTC station labelling Step 2:**
  https://otc.icos-cp.eu/sites/default/files/2017-11/ICOS Marine Station Labelling Stage 2 v3_crb_0.pdf

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