



HAL
open science

The Integrated Carbon Observation System in Europe

Jouni Heiskanen, Christian Brümmer, Nina Buchmann, Carlo Calfapietra,
Huilin Chen, Bert Gielen, Thanos Gkritzalis, Samuel Hammer, Susan
Hartman, Mathias Herbst, et al.

► **To cite this version:**

Jouni Heiskanen, Christian Brümmer, Nina Buchmann, Carlo Calfapietra, Huilin Chen, et al.. The Integrated Carbon Observation System in Europe. *Bulletin of the American Meteorological Society*, 2022, 103 (3), pp.E855-E872. 10.1175/bams-d-19-0364.1 . hal-03411211

HAL Id: hal-03411211

<https://hal.science/hal-03411211>

Submitted on 2 Nov 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



1 The Integrated Carbon Observation System in Europe

2 Authors

3 Jouni Heiskanen, Head Office, Integrated Carbon Observation System European Research
4 Infrastructure Consortium, Helsinki, Uusimaa, Finland, and Faculty of Biological and
5 Environmental Sciences, University of Helsinki, Helsinki, Uusimaa, Finland. Corresponding
6 author: email jouni.heiskanen@helsinki.fi

7 Christian Brümmer, Thünen Institute of Climate-Smart Agriculture, Braunschweig, Germany

8 Nina Buchmann, Department of Environmental Systems Science, ETH Zurich, Zurich,
9 Switzerland

10 Carlo Calfapietra, Institute of Research on Terrestrial Ecosystems, National Research
11 Council, Porano, Italy

12 Huilin Chen, Centre for Isotope Research, University of Groningen, Groningen, The
13 Netherlands

14 Bert Gielen, Department of Biology, University of Antwerp, Wilrijk, Belgium

15 Thanos Gkritzalis, Flanders Marine Institute, Ostend, Belgium

16 Samuel Hammer, Institut für Umweltphysik, Heidelberg University, Heidelberg, Germany

17 Susan Hartman, National Oceanography Centre, Southampton, United Kingdom

18 Mathias Herbst, Centre for Agrometeorological Research, German Meteorological Service,
19 Braunschweig, Germany

20 Ivan A. Janssens, Department of Biology, University of Antwerp, Wilrijk, Belgium

21 Armin Jordan, Max-Planck-Institute for Biogeochemistry, Jena, Germany

22 Eija Juurola, Institute for Atmospheric and Earth System Research, University of Helsinki,
23 Helsinki, Uusimaa, Finland

24 Ute Karstens, ICOS ERIC, Carbon Portal, Lund, Sweden

25 Ville Kasurinen, Head Office, Integrated Carbon Observation System European Research
26 Infrastructure Consortium, Helsinki, Uusimaa, Finland

27 Bart Kruijt, Department of Environmental Sciences, Wageningen University & Research,
28 Wageningen, the Netherlands

29 Harry Lankreijer, ICOS ERIC, Carbon Portal, Lund, Sweden

30 Ingeborg Levin, Institut für Umweltphysik, Heidelberg University, Heidelberg, Germany

Early Online Release: This preliminary version has been accepted for publication in *Bulletin of the American Meteorological Society*, may be fully cited, and has been assigned DOI 10.1175/BAMS-D-19-0364.1. The final typeset copyedited article will replace the EOR at the above DOI when it is published.

31 Maj-Lena Linderson, Department of Physical Geography and Ecosystem Science, Lund
32 University, Lund, Sweden

33 Denis Loustau, INRAE, ISPA, Villenave d'Ornon, France.

34 Lutz Merbold, Agroscope, Research Division Agroecology and Environment,
35 Reckenholzstrasse 191, 8046 Zurich, Switzerland – previously at Department of
36 Environmental Systems Science, ETH Zurich, Zurich, Switzerland

37 Cathrine Lund Myhre, Atmosphere and Climate Department, Norwegian Institute for Air
38 Research, Kjeller, Norway

39 Dario Papale, Department for Innovation in Biological Agro-food and Forest systems,
40 University of Tuscia, Viterbo, Italy and euroMediterranean Center on Climate Change
41 (CMCC), Lecce, Italy

42 Marian Pavelka, Department of Matter and Energy Fluxes, Global Change Research Institute,
43 CAS, Brno, Czech Republic

44 Kim Pilegaard, Department of Environmental Engineering, Technical University of Denmark,
45 2800 Kgs. Lyngby, Denmark

46 Michel Ramonet, Université Paris-Saclay, CEA, CNRS, UVSQ, Laboratoire des Sciences du
47 Climat et de l'Environnement (LSCE/IPSL), Gif-sur-Yvette, France

48 Corinna Rebmann, Helmholtz Centre for Environmental Research, GmbH – UFZ, Leipzig,
49 Germany

50 Janne Rinne, Department of Physical Geography and Ecosystem Science, Lund University,
51 Lund, Sweden

52 Léonard Rivier, ATC ICOS, Université Paris-Saclay, CEA, CNRS, UVSQ, Laboratoire des
53 Sciences du Climat et de l'Environnement (LSCE/IPSL), Gif-sur-Yvette, France

54 Elena Saltikoff, Head Office, Integrated Carbon Observation System European Research
55 Infrastructure Consortium, Helsinki, Uusimaa, Finland

56 Richard Sanders, Climate Department, Norwegian Research Centre, Bergen, Norway

57 Martin Steinbacher, Laboratory for Air Pollution / Environmental Technology, Empa,
58 Duebendorf, Switzerland

59 Tobias Steinhoff, Chemical Oceanography, GEOMAR Helmholtz Centre for Ocean Research
60 Kiel, Kiel, Germany and NORCE Norwegian research Centre AS, Bergen, Norway.

61 Andrew Watson, College of Life and Environmental Sciences, University of Exeter, Exeter,
62 United Kingdom

63 Alex T. Vermeulen, ICOS ERIC, Carbon Portal, Lund, Sweden

64 Timo Vesala, Institute For Atmosphere and Earth System Research/Physics, Faculty of
65 Science, University of Helsinki, Helsinki, Uusimaa, Finland, and Institute for Atmosphere and
66 Earth System Research/Forest Sciences, PO Box 27, Faculty of Agriculture and Forestry,

67 University of Helsinki, Helsinki, Uusimaa, Finland, and Yugra State University, 628012,
68 Khanty-Mansiysk, Russia
69 Gabriela Vítková, Global Change Research Institute of the Czech Academy of Sciences,
70 Bělidla 986/4°, Brno, Czech Republic
71 Werner Kutsch, Head Office, Integrated Carbon Observation System European Research
72 Infrastructure Consortium, Helsinki, Uusimaa, Finland
73

74 Abstract

75 Since 1750, land use change and fossil fuel combustion has led to a 46 % increase in the
76 atmospheric carbon dioxide (CO₂) concentrations, causing global warming with substantial
77 societal consequences. The Paris Agreement aims to limiting global temperature increases
78 to well below 2°C above pre-industrial levels. Increasing levels of CO₂ and other greenhouse
79 gases (GHGs), such as methane (CH₄) and nitrous oxide (N₂O), in the atmosphere are the
80 primary cause of climate change. Approximately half of the carbon emissions to the
81 atmosphere is sequestered by ocean and land sinks, leading to ocean acidification but also
82 slowing the rate of global warming. However, there are significant uncertainties in the
83 future global warming scenarios due to uncertainties in the size, nature and stability of
84 these sinks. Quantifying and monitoring the size and timing of natural sinks and the impact
85 of climate change on ecosystems are important information to guide policy-makers'
86 decisions and strategies on reductions in emissions. Continuous, long-term observations are
87 required to quantify GHG emissions, sinks, and their impacts on Earth systems. The
88 Integrated Carbon Observation System (ICOS) was designed as the European *in situ*
89 observation and information system to support science and society in their efforts to
90 mitigate climate change. It provides standardized and open data currently from over 140
91 measurement stations across 12 European countries. The stations observe GHG
92 concentrations in the atmosphere and carbon and GHG fluxes between the atmosphere,
93 land surface and the oceans. This article describes how ICOS fulfills its mission to harmonize
94 these observations, ensure the related long-term financial commitments, provide easy
95 access to well-documented and reproducible high-quality data and related protocols and

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

98

99 **Capsule**

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

103

104 Introduction

105 Since the industrial revolution the combination of land use change and fossil fuel combustion
106 has led to a 46 % increase in the atmospheric CO₂ concentrations totaling to a buildup of 2200
107 +/- 320 GtCO₂ in the atmosphere (Friedlingstein et al. 2020; Rogelj et al. 2018). Consensus is
108 that this has led to a significant warming of the atmosphere and increased heat storage of the
109 upper ocean with subsequent effects of considerable societal importance. Human-induced
110 increase in atmospheric concentrations of carbon dioxide (CO₂) and other greenhouse gases
111 (GHGs), such as methane (CH₄) and nitrous oxide (N₂O), are the primary cause of the ongoing
112 climate warming (IPCC 2018). The atmospheric buildup of CO₂ would have been about twice
113 as large had approximately half of the carbon emitted to the atmosphere not been
114 sequestered by ocean and land sinks, leading to the rate of warming being reduced
115 (Friedlingstein et al. 2020). However, the size, nature and stability of these sinks are uncertain,
116 which together with the uncertainty of the speed of release of the heat stored in the ocean
117 surfaces leads to large uncertainties in the projected global climate warming with different
118 GHG mitigation scenarios (Ma et al. 2020; Rhein et al. 2013). Improving the quantification and
119 reducing the uncertainty of these projections is important to support policy-making and the
120 size and timing of reductions in global emissions. There are uncertainties in the emission
121 sources but the largest cause for uncertainty in the global carbon budget estimates are likely
122 due to the lack of understanding of land and ocean sinks (Friedlingstein et al. 2020).
123 Understanding of these sinks, sources, and the related processes can only be achieved with
124 research based on spatially and temporally comprehensive and precise data. This is ever more
125 important now that a specific goal has been set at limiting average global surface temperature

126 increases to well below 2°C above pre-industrial levels (The Paris Agreement (United Nations
127 2015a) ratified by 189 countries to guide the actions to combat climate change).

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

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

141 Key aspects of climate science addressed by ICOS have been elaborated in earlier articles,
142 with Schulze et al. (2009) emphasizing the importance of N₂O and CH₄ in the European
143 greenhouse gas budget, Peters et al. (2010) quantifying European net terrestrial CO₂
144 exchange, Gielen et al. (2017) briefly summarizing the different components of the network,
145 Franz et al. (2018) giving an overview on ICOS ecosystem observations, Steinhoff et al. (2019)
146 describing the ocean network, and Levin et al. (2020) addressing the atmospheric network.
147 This article provides a comprehensive overview of the ICOS Research Infrastructure (RI),
148 including a historical overview, describing the structure, operations and financial

149 sustainability of the ICOS RI, elaborating present and future scientific questions, and
150 discussing lessons learned and challenges addressed by ICOS.

151 **The rationale and path into Integrated Carbon Observation System**

152 Even though the connection between human actions and climate change had been made by
153 the end of the 20th century (IPCC 1992), many important questions were still open, such as
154 how much CO₂ from fossil fuel burning remains in the atmosphere and how much was taken
155 up by oceans and terrestrial ecosystems (Keeling 1978). A major obstacle in answering these
156 questions was limited data availability and the use of different observational methods, units,
157 and scales by different countries and sites. This required global harmonization of
158 observations, first started in the atmosphere by the World Meteorological Organization
159 Global Atmosphere Watch (WMO GAW) programme in 1989 (WMO 2014) and with the
160 FLUXNET ecosystem global network in 1996 (Baldocchi et al. 2001).

161 Another obstacle was how to draw conclusions from various pieces of data and information.
162 This called for a framework how to systematically provide scientific knowledge in global scale,
163 giving birth to the Intergovernmental Panel on Climate Change (IPCC), established in the end
164 of 1980s. Eyes turned next to land, where various methods had been developed to
165 understand highly diverse and complex terrestrial ecosystems. This posed challenges to
166 compare the results, and the Global Climate Observing System (GCOS) was established to
167 harmonize terrestrial observations and to define a set of Essential Climate Variables (GCOS
168 1994, 2016; WMO 2009). Quantifying relatively small long-term trends in CO₂ and other GHG
169 concentration and fluxes against a background of much larger short-term variations caused
170 by the 'natural' carbon cycle requires highly precise and accurate observations. To decrease

171 uncertainties by improving the quality of observations, and to draw general conclusions,
172 research- and investigator-based European ecosystem networks, with foci on CO₂, energy and
173 water exchange, emerged in the 1990s with the support of the European Commission funding
174 programs (EuroFlux, CarboEurope IP and GHG Europe). During 1998-2002, the Euroflux
175 network covered 30 stations mainly in forest ecosystems across Europe (Janssens et al. 2003),
176 which later developed into the network of ecosystem stations within ICOS.

177 At the beginning of the 1990s, the Global Ocean Observing System (GOOS) was established to
178 coordinate and harmonize ocean observations together with GCOS. The scientific community
179 undertook the task to provide open access to global ocean surface CO₂ data via the Surface
180 Ocean CO₂ Atlas, SOCAT (Pfeil et al. 2013). These data are essential to estimate ocean carbon
181 budget and acidification. As a community effort, SOCAT depends heavily on voluntary data
182 submission and secondary quality control, and the Ocean Carbon Data System of National
183 Oceanic and Atmospheric Administration and ICOS support SOCAT and contribute
184 significantly to its data operations and development.

185 The development of observation networks had been fragmented into various projects in
186 Europe (see Fig. 1 in Franz et al. (2018)). By the beginning of the 2000s, it was possible to
187 estimate the European terrestrial carbon budget by either using the few ecosystem network
188 data available (e.g. Papale and Valentini 2003) or by methods using atmospheric network
189 data, but these provided dissimilar and highly uncertain results (Janssens et al. 2003). The
190 results suggested that increase in ecosystem representation and data would reduce the
191 uncertainty in the bottom-up approach and that including more atmospheric stations would
192 improve the accuracy of top-down estimates. The EU-funded CarboEurope Integrative Project
193 (2004-2008), was a major step towards integrated studies, harmonized observations and data

194 flows, covering atmosphere and ecosystem sciences (Schulze et al. 2009). In parallel, the
195 CarboOcean IP conducted over 2005-2009 developed systematic ocean carbon observations
196 and analysis across Europe. The observations collected in the context of these projects were
197 an important example to demonstrate how a large and coordinated network could provide a
198 unique dataset valuable for the modeling activities to estimate continental scale GHG fluxes
199 (e.g. Luyssaert et al. 2010; Schulze et al. 2009; Vetter et al. 2008).

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

211 ICOS foundation required negotiating the concept for such as system, with clear purpose and
212 governance as well as financial structure and responsibilities of each participants, in which
213 the countries could then commit. This was the purpose of ICOS preparatory phase project in
214 2008-2013 (reference, see also Appendix 1).

215 User-centric approach drove the development of a centralized data provision hub for all ICOS
216 data, the Carbon Portal. The problem of different type of observations in atmosphere,

217 ecosystem, and ocean stations was addressed by centralizing the quality control and data
218 processing in three respective Thematic Centres with specific experience and knowledge. To
219 allow measurements of required precision, the Central Analytical Laboratories was designed
220 to provide calibration gases to atmospheric and ocean monitoring stations. The process for
221 scientific development was planned on the interactions between these components and the
222 Monitoring Station Assemblies (MSAs) which include all station Principal Investigators (PIs).

223 The financial challenges were tackled by acquiring commitments from various countries
224 interested to build a national network of ICOS stations or propose a Central Facility. The host
225 countries provide the majority of the financial support by direct governmental grants (ICOS
226 Ecosystem Thematic Center is hosted by Italy, France, and Belgium, Atmosphere Thematic
227 Center by France and Finland, Ocean Thematic Center by the Norway and the UK, the Central
228 Analytical Laboratories by Germany, and the Carbon Portal by Sweden and the Netherlands).

229 The stations are maintained by individual countries, and each country also contributes to the
230 general costs for the upkeep of the RI. The principles for sharing the financial responsibilities
231 were written in the ICOS financial rules.

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

240 The mission of ICOS is to harmonize European carbon and GHG observations, ensure the
241 related long-term financial commitments, provide easy access to well-documented and
242 reproducible high-quality data and related protocols and tools for scientific studies, and to
243 deliver GHG-related products to stakeholders in society and policy. The first five years of ICOS
244 from 2015-2019 focused on establishing an operational infrastructure, and as an
245 acknowledgement of successful implementation, ICOS ERIC was included in the European
246 Strategy Forum on Research Infrastructures' strategy as a Landmark infrastructure (ESFRI
247 2016). Since becoming operational in 2015, the Czech Republic, Denmark, the United
248 Kingdom, and Spain have joined ICOS, and Poland has announced to join ICOS, considerably
249 expanding the network, and negotiations are currently under way with Estonia, Greece,
250 Hungary, Ireland, Portugal and Romania. The second phase of ICOS, described in the ICOS
251 strategy published in 2019 (ICOS 2019), and its associated implementation plan, will place
252 emphasis on the use of data and on enhancing the network's capability to analyze
253 anthropogenic impacts on the carbon cycle. We foresee the new European Green Deal
254 launched by EU Commission at the end of 2019
255 (https://ec.europa.eu/info/strategy/priorities-2019-2024/european-green-deal_en),
256 designed to make Europe the first net-zero continent, will further strengthen ICOS' role in the
257 forthcoming years.

258 **Description of ICOS observations and data**

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

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

267 The atmospheric network of tall towers, mountain, and coastal stations covers large parts of
268 Europe with continuous measurements of CO₂ and CH₄ mole fractions. When coupled with an
269 atmospheric model, these data provide an integrated view of all natural and anthropogenic
270 fluxes. In fully equipped ICOS stations, meteorological variables, N₂O and ²²²Radon are
271 observed to link concentration variations to atmospheric mixing. In addition, N₂O, SF₆, H₂, and
272 for CO₂ source apportionment CO, ¹³C-CO₂, ¹⁴C-CO₂, ¹⁸O-CO₂, and O₂/N₂, are analyzed in air
273 sampled by automated flask samplers at the most extensively equipped stations, called Class
274 1 stations (ICOS 2017a; Levin et al. 2020; Appendix 2).

275 GHG fluxes in different terrestrial ecosystems (forests, croplands, grasslands, mires, wetlands,
276 shrublands, lakes, Mediterranean savannas, urban sites) are observed at comprehensively
277 equipped stations to quantify the exchange of carbon, GHGs and energy between the
278 atmosphere and the ecosystems (Franz et al. 2018), by using the eddy covariance technique
279 (Rebmann et al. 2018). Biosphere-atmosphere exchange measurements at flux towers
280 represent the only direct method to provide detailed data at ecosystem scale, and they are
281 valuable also for different user communities: e.g. sensible and latent heat fluxes are
282 important to understand the water cycle and to improve weather forecasts, turbulence data
283 are used in studying boundary layer physics. In a subset of stations, fluxes of CH₄ and N₂O are
284 observed (Nemitz et al. 2018). Complementary data comprise e.g. soil organic carbon content,

285 Green Area Index, litterfall, aboveground biomass, records of disturbances, and vegetation
286 properties such as leaf nutrients and phenological status, as well as management activities
287 (Arrouays et al. 2018; Gielen et al. 2018; Hufkens et al. 2018; Loustau et al. 2018; Op de Beeck
288 et al. 2018; Pavelka et al. 2018; Saunders et al. 2018). These various observations are used to
289 estimate the contributions of different components of the ecosystem, such as soil or
290 vegetation, to the seasonal and interannual variability of the carbon and GHG budget of the
291 whole ecosystem, as well as when upscaling carbon fluxes to regional and global scales (Jung
292 et al. 2020).

293 The ocean observations are conducted either on fixed platforms (e.g. moorings and surface
294 buoys) or on ships operating predominantly in the North Atlantic, Nordic, Baltic and
295 Mediterranean Seas, but occasionally also in Polar regions and equatorial Atlantic. Partial
296 pressure of sea surface CO₂ is used in conjunction with other parameters (temperature,
297 salinity, mixed layer depth) and satellite remote sensing products including wind fields and
298 chlorophyll to calculate oceanic uptake of CO₂ (ICOS 2017b, 2020b; Steinhoff et al. 2019).
299 Other carbon cycle parameters (pH, alkalinity, dissolved inorganic carbon) and related
300 properties such as nutrients and oxygen are used to investigate ocean transports and controls
301 over carbon uptake. This latter work involves collaboration across various elements of the
302 European RI landscape and components of the Global Ocean Observing System (GOOS)
303 including Euro-Argo (European consortium for operating Argo floats), EMSO (the European
304 Multidisciplinary Seafloor and water column Observatory), and GO-SHIP (the Global Ocean
305 Ship-based Hydrographic Investigations Program). While the main policy framework that ICOS
306 contributes to is the Paris Agreement, also Agenda 2030 (United Nations 2015b) and its
307 Sustainable Development Goal 14.3 is supported with monitoring of ocean acidification.

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

315 **Quality Assurance and Control (QA/QC)**

316 Within the CarboEurope IP project (Schulze et al. 2010) the challenges to achieve highly
317 compatible atmospheric data became obvious. Large efforts were undertaken to assess the
318 compatibility of atmospheric measurements done by different laboratories at different
319 observational sites. Yet, results from these exercises repeatedly yielded evidence that the
320 WMO compatibility goals were not met by all participants and for all tracers. Biases between
321 laboratories could sometimes be of the same order of magnitude as the atmospheric signals
322 that should be captured and it was not possible to define a network data compatibility. This
323 was motivating the ICOS concept with highly standardized measurement approaches at the
324 observatories (including aspects such as instrumentation, procedures to account for
325 atmospheric humidity, and calibration procedures) and the establishment of central facilities
326 that assess the adequate performance of all installed analyzers and assure transparent data
327 processing (ATC), as well as the consistency of sample measurement results and reference
328 gas assignments that are used within the monitoring network (CAL). To have the ability to
329 make a defensible uncertainty assessment that is required for observational data (WMO
330 2020b) the following QA/QC approaches are applied that cover all levels of the observational

331 system (stations as well as central facilities). To minimize uncertainties in both observations
332 provided by single stations and studies using data from multiple stations, several steps are
333 taken. The instruments themselves have strict requirements, they are systematically
334 calibrated, their setup is based on stringent protocols, and the data are processed by the
335 Thematic Centers with proven and standardized methodologies (Hazan et al. 2016; El Yazidi
336 et al. 2018; Vitale et al. 2020).

337 Scientists in the ICOS atmosphere community, coordinated via the Atmospheric MSA, have
338 defined and approved protocols for instrumentation setup and sampling strategies (ICOS
339 2017a, Levin et al. 2020) to ensure that atmospheric measurements comply with the
340 compatibility goals set by the WMO for measurements of major GHGs and associated tracers
341 (WMO 2020b). Stringent network compatibility within ICOS and with other networks is key
342 when using the observations in concert with atmospheric transport models to quantify GHG
343 sources and sinks. Calibration gases are prepared and calibrated centrally for the network by
344 the Flask and Calibration Laboratory (FCL) of the Central Analytical Laboratories (CAL) that
345 maintains tight links to the WMO Central Calibration Laboratory to ensure the traceability of
346 ICOS data to internationally accepted WMO calibration scales by one unique path. To assess
347 the accuracy of the implementation of these scales at the FCL maintains several ongoing
348 round robin exercises with the NOAA laboratories as quality control. The FCL is also
349 responsible for flask analyses except for $^{14}\text{C-CO}_2$, which is analyzed by the Central Radiocarbon
350 Laboratory of the CAL. The precision and stability of all GHG analyzers are tested at the
351 Atmosphere Thematic Centre prior to deployment (Yver Kwok et al. 2015). A comprehensive
352 overview of the optimization of the quality management as part of the labelling process of
353 atmosphere stations is given in Yver-Kwok et al. (2021). For quality control of the continuous
354 *in situ* measurements, automated QC figures are generated on a daily level by the ATC that

355 summarize the statistics of the measurement precision (repeatability and target gas bias)
356 which provide a basis to quantify the measurement uncertainty. Additional auditing is made
357 with travelling instrumentation (ICOS Mobile Lab) operated at selected stations for a couple
358 of weeks, and by ongoing comparison of flask results with *in situ* observations at Class 1
359 stations (Levin et al. 2020).

360 To ensure high quality of observations in diverse ecosystems, with various drivers influencing
361 the carbon and GHG fluxes, the observation methods need careful attention. Since diverse
362 observation methods were established for different climate regions and ecosystem types in
363 the past decades, a community-driven effort was necessary to define key and ancillary
364 components to be observed in each ecosystem type to analyze carbon and GHG fluxes. Also,
365 much effort has been put into defining the specifications and methodology of observations
366 by the community, together with the Ecosystem MSA and the Ecosystem Thematic Centre.
367 Both optimal sets of variables and practical feasibility were considered when harmonizing the
368 observations, which resulted in a compromise suitable for high quality and long-term
369 continental scale observation system (Franz et al. 2018). Over 100 scientists' efforts were
370 acknowledged in a set of publications describing the ecosystem measurement protocols in
371 2018 (International Agrophysics, vol. 32(4), 2018). Starting from the protocols, more practical
372 and detailed Instruction documents were prepared and published by the ETC
373 (<http://www.icos-etc.eu/documents/instructions>) that are revised and updated regularly,
374 following the newest developments and know-how.

375 For the ocean observations, the major challenges are the complexity of the carbonate system,
376 the often remote location of stations, and suitability of different observing methods for
377 different types of stations. Tailored solutions are needed in order for each station to deliver

378 the best possible data, and the ICOS ocean community, supported by the Ocean Thematic
379 Centre, has adopted and adapted existing and proven best practice guidelines and protocols
380 (Dickson et al. 2007) for observations made by different types of stations (Steinhoff et al.
381 2019). ICOS is the first multi-national entity within the marine community that has
382 standardized CO₂ observations (Steinhoff et al. 2019). The Fixed Ocean Stations' maintenance
383 and calibration are done during the visit by research vessels, ideally several times per year,
384 whereas observations on Ships of Opportunity (SOOP) are calibrated even more frequently.
385 Inclusion of marine towers with direct flux observations is currently under development
386 (Steinhoff et al. 2019). CO₂ observations are calibrated with standards traceable to the WMO
387 calibration scales (ICOS 2020b). Data quality, control and uniformity is also supported by a
388 customized QuinCe tool developed by the OTC.

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

398 **Open data access**

399 ICOS has addressed the major challenge of data access and simplification of data use (Fig. 2)
400 thanks to the PI and Central Facilities work that agreed on a continuous data submission and

401 adoption of an open data license (Creative Commons Attribution 4.0 International, which also
402 allows commercial use). Additionally, the services provided to make data distribution easier
403 and assignment of Digital Object Identifier (doi) to datasets are major advances to improve
404 and promote open data.

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

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

422 Major scientific questions and glimpse to the future

423 Many major scientific questions have guided the development of systematic, continental
424 observations of carbon and GHG budgets. Scientists have been able to answer how much of
425 emitted CO₂ from fossil fuels have accumulated in the atmosphere, oceans and terrestrial
426 ecosystems (Friedlingstein et al. 2020). Many advancements have been made in defining how
427 terrestrial ecosystems are affected by and how they feed back to climate change, e.g. by
428 changes in evapotranspiration or albedo.

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

441 ICOS data is widely used in publications from various scientific fields. The amount of ICOS-
442 related publications per year have increased from 30 in 2012 to roughly 200 in 2020, and the
443 citations from 600 to 11 000, respectively ([https://www.icos-cp.eu/science-and-](https://www.icos-cp.eu/science-and-impact/society-impact/references)
444 [impact/society-impact/references](https://www.icos-cp.eu/science-and-impact/society-impact/references)). The publications are associated to almost 60 categories

445 with the two largest being meteorology and atmospheric sciences (37% of all publications)
446 and environmental sciences (34%) (ICOS 2021). The cross-domain integration in ICOS allows
447 us to comprehensively address the biogeochemical fluxes of carbon and GHGs and to identify
448 and study existing gaps in knowledge. A recent example are the 17 publications, based on
449 data from more than 100 stations, following the drought in Europe in 2018. The drought was
450 analyzed from how it was detectable in the atmospheric station network and how it affected
451 ecosystem processes and GHG budgets, to regional assessments of its influences on
452 ecosystem carbon exchange, and relations to major crops (Peters et al. 2020). ICOS made this
453 rapid scientific response possible by building the foundation for fast action, by harmonizing
454 observations and centralized data processing, by analyzing the data in near-real time to detect
455 anomalies in drivers and ecosystem responses, by facilitating networking of scientists, and by
456 providing virtual solutions for joint work. The results show that the drought affected more
457 the productivity of crops and grasslands than forests, which protected themselves by reducing
458 their evaporation and growth, leading to decreased uptake of carbon dioxide (Peters et al.
459 2020). In general, carbon sinks decreased by 18% in a study covering 56 ecosystem sites (Graf
460 et al. 2020). The dry conditions even turned some mires from sinks into sources (Rinne et al.
461 2020). In some parts of Europe, winter 2018 was wet, leaving a lot of soil moisture in the
462 ground, while spring was sunny and came early - this caused the vegetation to grow in spring
463 more than average. In some places, this early spring growth was enough to offset the
464 reduction of carbon uptake later in summer (e.g. Smith et al. 2020). Currently, there is a joint
465 effort of similar magnitude under preparation analyzing the warm winter 2019-2020. The
466 above mentioned are also reflected in the biennial ICOS Science Conference that brings
467 scientists from different disciplines together to discuss besides science, also e.g.

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

470 Now, with the Paris Agreement having clear processes to guide the nations with climate
471 change mitigation, the pressure is increasing to provide robust information to support the
472 review of the impact of these actions (Art 14.1 in the Paris Agreement). ICOS is actively
473 engaged with GCOS to provide observations of Essential Climate Variables and to draft a
474 suitable indicator representing terrestrial ecosystems. ICOS provides data and participates to
475 the development of Global Carbon Budget to reduce the uncertainty of the global estimates
476 and to build a solid foundation for some of the global data sources, such as SOCAT and
477 FLUXNET, the global network of gas flux observations between ecosystems and the
478 atmosphere (Papale 2020). ICOS is in active dialogue with UNFCCC Subsidiary Body for
479 Scientific and Technological Advice to facilitate discussion between science and policy. ICOS
480 is currently focusing on providing the needed information at national and regional levels with
481 the separation of natural and anthropogenic fluxes. For example, VERIFY (H2020 project
482 776810) aims to improve national GHG inventories with top-down (atmospheric inversions)
483 and bottom-up (inventories made with complementary methods and data than used by
484 governmental authorities) scientific approaches (Petrescu et al. 2020).

485 The capability to disentangle the natural cycle and the anthropogenic disturbance has made
486 progress, and consensus exists that the required next step is to link tightly *in situ* and remote
487 sensing observations and modelling to more accurately quantify anthropogenic CO₂ emissions
488 (Copernicus 2015, 2019). The calibration and verification of satellite products and models
489 within this system aim to rely on the *in situ* ICOS network, including potential atmospheric
490 vertical profiling of GHGs using AirCore (Karion et al. 2010) and collaboration with the Total

491 Carbon Column Observing Network (TCCON). This system is currently developed by scientists
492 involved in ICOS and peers in the CoCO₂ project (H2020 project 958927). Further
493 developments could include the provision of more accurate observations of hot spots of
494 human activities, mainly in urban areas (WMO 2019). The ¹⁴C methodology is used for
495 quantifying the CO₂ emissions from fossil fuel burning, as the fossil energy sources are void of
496 ¹⁴C. Their contribution can be derived from measurements of the ¹⁴C/¹²C ratio in atmospheric
497 CO₂ (Basu et al. 2020; Levin et al. 2003, 2011). These observations are systematically made in
498 ICOS but mostly in sparsely populated locations. The concept of an urban observatory has
499 been tested in some European and US cities (Breon et al. 2015; Lauvaux et al. 2020) but more
500 development, probably combining atmospheric observations and modelling with flux
501 observations, is needed before the methodology is mature enough to be incorporated into a
502 research infrastructure such as ICOS. This system for greenhouse gas measurements in urban
503 areas is developed by ICOS in the H2020 project PAUL (Pilot Application in Urban Landscapes
504 – towards integrated city observatories for greenhouse gases). Additionally, the flux towers
505 are invaluable to provide data on carbon sinks over vegetated urban surfaces at
506 neighborhood-scale (e.g. Nordbo et al. 2012).

507 Lack of sufficient geographical coverage of observations is a source of major uncertainty in
508 most regions of the world (WMO 2020a). Even in Europe where the *in situ* observations of
509 CO₂ and other GHGs were brought together by ICOS, large parts of Eastern Europe are still to
510 join this network. The benefits are understood at the scientific level but as membership in a
511 research infrastructure obliges sustained funding and commitments, the discussions must
512 enter the political level. Currently, the discussions are ongoing with seven countries to join
513 ICOS.

514 ICOS is collaborating with complementary networks in Europe and in other continents
515 towards more harmonized standardization of observations and data processing, common
516 data policies, and common data citation system. Examples are the Long-Term Ecosystem
517 Research (eLTER), the European Research Infrastructure for the observation of Aerosol,
518 Clouds and Trace Gases (ACTRIS), the AmeriFlux Management Project and the National
519 Ecological Observatory Network (NEON) in the US and the US Carbon Cycle Science Program,
520 the Chinese Ecosystem Research Network, the Terrestrial Ecosystem Research Network
521 (TERN) in Australia, and the National Institute for Environmental Studies in Japan. ICOS also
522 supports and develops the global data networks, such as WMO Global Atmosphere Watch
523 and the World Data Centre of Greenhouse Gases for atmospheric observations, FLUXNET for
524 ecosystem GHG fluxes, Surface Ocean CO₂ Atlas (SOCAT), and GLObal Ocean Data Analysis
525 Project (GLODAP). ICOS contributes to the development of harmonized observations in Africa
526 via design study and capacity building (López-Ballesteros et al. 2018).

527 Many global coordination frameworks are in place to address the global environmental
528 challenges. However, there is a huge distance between global frameworks and local actions.
529 Developments are needed on different scales to improve the observational capacity and to
530 transform the data into information useful for local and national decision makers, non-
531 governmental organizations and the private sector. Examples of the urgently needed
532 developments are defining how changing climate affects the ability of natural terrestrial and
533 ocean sink to sequester carbon, supporting the verification of national GHG inventories, and
534 understanding and validating the efficacy of mitigation actions. ICOS provides the European
535 *in situ* observations of CO₂ and other GHGs, and is well positioned to coordinate the *in situ*
536 component of a comprehensive system that caters to different information needs at different

537 spatial and temporal scales (Copernicus 2019). Combatting climate change needs reliable
538 information, and ICOS is here to deliver.

539 **Acknowledgements**

540 Academy of Finland (Grants nr 281255, 319871, 320124, 329221)., the Danish Agency for
541 Science and Higher Education, Danish Ministry of Energy, Utilities and Climate, EU (Grants nr
542 211574, 730944), Finnish Ministry of Transport and Communication, Flemish Fund for
543 Scientific Research (FWO Grant nr G0H3317), French Ministry of Research (MESRI), German
544 Ministry of Education and Research (BMBF), German Ministry of Transport and Digital
545 Infrastructure (BMVI), the Italian Ministry of Universities and Research, The Netherlands
546 Ministry of Education, Culture and Science, the Netherlands Organisation for Scientific
547 Research., the Ministry of Education, Youth and Sports of the Czech Republic, The Natural
548 Environment Research Council of the UK, Norwegian Environmental Agency, Norwegian
549 Ministry of Climate and Environment, Research Council of Norway, Swedish Research
550 Council (Grant nr 2019-00205), Swiss National Science Foundation (ICOS-CH Phase 1 and
551 Phase 2, 20FI21_148992 and 20FI20_173691) and the ETH domain.

552

553 **Appendix**

554 **Appendix 1. ICOS Governance and Funding**

555 **Governance**

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

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

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

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

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

590 **Funding**

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

596 Member and Observer countries of ICOS ERIC pays annual membership contributions. Total
597 membership contributions are formed by the following elements: common basic
598 contribution, common GNI based contribution, and number and type of stations. The latter

599 part of the membership contribution is redistributed to the activities in the ICOS Central
600 Facilities. The Central Facilities are also supported by the host organizations. ICOS ERIC seeks
601 funding opportunities from European Commission and other sources.

602 **Appendix 2. Observed Variables at ICOS Stations**

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

604

605 **References**

- 606 Arrouays, D., and Coauthors, 2018: Soil sampling and preparation for monitoring soil carbon.
607 *International Agrophysics*, **32**(4), 633–643, doi:10.1515/intag-2017-0047.
- 608 Baldocchi, D., 2014: Measuring fluxes of trace gases and energy between ecosystems and
609 the atmosphere - the state and future of the eddy covariance method. *Global Change*
610 *Biology*, **20**(12): 3600–3609, <https://doi.org/https://doi.org/10.1111/gcb.12649>.
- 611 Baldocchi, D., and Coauthors, 2001: FLUXNET: A New Tool to Study the Temporal and Spatial
612 Variability of Ecosystem-Scale Carbon Dioxide, Water Vapor, and Energy Flux Densities.
613 *Bulletin of the American Meteorological Society*, **82**(11), 2415-2434,
614 [https://doi.org/10.1175/1520-0477\(2001\)082<2415:FANTTS>2.3.CO;2](https://doi.org/10.1175/1520-0477(2001)082<2415:FANTTS>2.3.CO;2).
- 615 Basu, S., and Coauthors, 2020: Estimating US fossil fuel CO₂ emissions from measurements
616 of ¹⁴C in atmospheric CO₂. *Proceedings of the National Academy of Sciences*, **117** (24),
617 13300-13307, DOI: 10.1073/pnas.1919032117
- 618 Breon, F. M., and Coauthors, 2015: An attempt at estimating Paris area CO₂ emissions from
619 atmospheric concentration measurements. *Atmos. Chem. Phys.*, **15**, 1707–1724,
620 www.atmos-chem-phys.net/15/1707/2015/.
- 621 Calfapietra C., Ü., Niinemets, and J. Peñuelas, 2015: Urban Plant Physiology: adaptation-
622 mitigation strategies under permanent stress. *Trends in Plant Science*, **20**, 72-75.
- 623 Copernicus, 2015: Towards a European Operational Observing System to Monitor Fossil CO₂
624 emissions. https://edgar.jrc.ec.europa.eu/news_docs/CO2_report_22-10-2015.pdf.

625 Copernicus, 2019: An Operational Anthropogenic CO₂ Emissions Monitoring & Verification
626 Support Capacity – Needs and high level requirements for in situ measurements.
627 <https://doi.org/10.2760/182790>.

628 Dickson, A. G., C. L. Sabine, and J. R. Christian (Eds.) 2007: Guide to Best Practices for Ocean
629 CO₂ Measurements. PICES Special Publication 3, pp 191, ISSN: 1813-8519.

630 El Yazidi, A., and Coauthors, 2018: Identification of spikes associated with local sources in
631 continuous time series of atmospheric CO, CO₂ and CH₄. *Atmospheric Measurement*
632 *Techniques*, **11**(3), 1599-1614.

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

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

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

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

642 GCOS, 1994: Report of the GCOS/GTOS Terrestrial Observation Panel. [WMO/TD-](#) No.
643 642; [GCOS-](#) No. 08. https://library.wmo.int/doc_num.php?explnum_id=3804.

644 GCOS, 2016: The Global Observing System for Climate: Implementation Needs. [GCOS-](#) No.
645 200. https://library.wmo.int/doc_num.php?explnum_id=3417.

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

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

652 Graf, A., and Coauthors, 2020: Altered energy partitioning across terrestrial ecosystems in
653 the European drought year 2018. *Philosophical Transactions of the Royal Society B*, **375**, doi:
654 [10.1098/rstb.2019.0524](https://doi.org/10.1098/rstb.2019.0524).

655 Hazan, L., J. Tarniewicz, M. Ramonet, O. Laurent, and A. Abbaris, 2016: Automatic
656 processing of atmospheric CO₂ and CH₄ mole fractions at the ICOS Atmosphere Thematic
657 Centre. *Atmospheric Measurement Techniques*, **9**(9), 4719-4736.

658 Hufkens, K., and Coauthors, 2018: Assimilating phenology datasets automatically across
659 ICOS ecosystem stations. *Int. Agrophys.*, **32**(4), 677-687, doi: [https://doi.org/10.1515/intag-](https://doi.org/10.1515/intag-2017-0050)
660 [2017-0050](https://doi.org/10.1515/intag-2017-0050).

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

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

665 ICOS, 2017b: ICOS Marine Station Labelling Step 2. *ICOS OTC*, 23pp, [https://otc.icos-](https://otc.icos-cp.eu/sites/default/files/2018-05/ICOS%20Marine%20Station%20Labelling%20Step%202%20v4_crb.docx_.pdf)
666 [cp.eu/sites/default/files/2018-](https://otc.icos-cp.eu/sites/default/files/2018-05/ICOS%20Marine%20Station%20Labelling%20Step%202%20v4_crb.docx_.pdf)
667 [05/ICOS%20Marine%20Station%20Labelling%20Step%202%20v4_crb.docx_.pdf](https://otc.icos-cp.eu/sites/default/files/2018-05/ICOS%20Marine%20Station%20Labelling%20Step%202%20v4_crb.docx_.pdf).

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

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

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

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

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

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

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

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

686 Janssens, I. and Coauthors, 2003: Europe's Terrestrial Biosphere Anthropogenic CO₂
687 Emissions. *Science*, **300**, 1538–42, <https://doi.org/10.1126/science.1083592>.

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

691 Karion, A., C. Sweeney, P. Tans, and T. Newberger, 2010: AirCore: An innovative atmospheric
692 sampling system. *Journal of Atmospheric and Oceanic Technology*, **27** (11), 1839–1853, doi:
693 10.1175/2010JTECHA1448.1.

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

697 Lauvaux, T. and Coauthors, 2020: Policy-Relevant Assessment of Urban CO₂ Emissions,
698 *Environmental Science & Technology*, **54** (16), 10237-10245, doi: 10.1021/acs.est.0c00343.

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

703 Levin, I., B. Kromer, M. Schmidt, and H. Sartorius, 2003: A novel approach for independent
704 budgeting of fossil fuel CO₂ over Europe by ¹⁴CO₂ observations. *Geophysical Research*
705 *Letters*, **30** (23), 1–5, doi:10.1029/2003GL018477.

706 Levin, I., and Coauthors, 2020: A dedicated flask sampling strategy developed for ICOS
707 stations based on CO₂ and CO measurements and STILT footprint modelling. *Atmospheric*
708 *Chemistry and Physics Discussions*, 1–29, doi:10.5194/acp-2020-185.

709 López-Ballesteros, A., and Coauthors, 2018: Towards a feasible and representative pan-
710 African research infrastructure network for GHG observations. *Environmental Research*
711 *Letters*, **13** (8), doi:10.1088/1748-9326/aad66c.Loustau, D., and Coauthors, 2018: Sampling
712 and collecting foliage elements for the determination of the foliar nutrients in ICOS
713 ecosystem stations. *Int. Agrophys.*, **32**(4), 665-676, doi: [https://doi.org/10.1515/intag-2017-](https://doi.org/10.1515/intag-2017-0038)
714 0038.

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

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

720 Nemitz, E., and Coauthors, 2018: Standardisation of eddy-covariance flux measurements of
721 methane and nitrous oxide. *International Agrophysics*, **32** (4), 517–549, doi:10.1515/intag-
722 2017-0042.

723 Nordbo, A., L. Järvi, S. Haapanala, C. R. Wood, and T. Vesala, 2012: Fraction of natural area
724 as main predictor of net CO₂ emissions from cities. *Geophysical Research Letters*, **39** (20), 1–
725 5, doi:10.1029/2012GL053087.

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

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

731 Papale, D., and R. Valentini, 2003: A new assessment of European forests carbon exchanges
732 by eddy fluxes and artificial neural network spatialization. *Global Change Biology*, **9**, 525-
733 535, <https://doi.org/10.1046/j.1365-2486.2003.00609.x>.

734 Pavelka, M., and Coauthors, 2018: Standardisation of chamber technique for CO₂, N₂O and
735 CH₄ fluxes measurements from terrestrial ecosystems. *International Agrophysics*, **32** (4),
736 569–587, doi:10.1515/intag-2017-0045.

737 Peters, W., and Coauthors, 2010: Seven years of recent European net terrestrial carbon
738 dioxide exchange constrained by atmospheric observations. *Global Change Biology*, **16** (4),
739 1317–1337, doi:<https://doi.org/10.1111/j.1365-2486.2009.02078.x>.

740 Peters, W., Bastos, A., Ciais, P., Vermeulen, A., and Kutsch, W. (eds.), 2020: Impacts of the
741 2018 severe drought and heatwave in Europe: from site to continental scale. Special issue in
742 *Philosophical Transactions of the Royal Society B*,
743 <https://royalsocietypublishing.org/toc/rstb/375/1810>.

744 Petrescu, A. M. R., and Coauthors, 2020: The consolidated European synthesis of CH₄ and
745 N₂O emissions for EU27 and UK: 1990-2018, *Earth System Science Data Discussion*. preprint
746 in review, <https://doi.org/10.5194/essd-2020-367>.

747 Pfeil, B., and Coauthors, 2013: A uniform, quality controlled Surface Ocean CO₂ Atlas
748 (SOCAT). *Earth System Science Data*, **5**, 125-143, doi:10.5194/essd-5-125-2013.

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

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

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

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

766 Saunders, M., and Coauthors, 2018: Importance of reporting ancillary site characteristics,
767 and management and disturbance information at ICOS stations. *International Agrophysics*,
768 **32** (4), 457–469, doi:10.1515/intag-2017-0040.

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

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

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

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

781 Thompson, R., Broquet, G., Gerbig, C., Monteil, G., Lang, M. and Koch, F.-T., 2019: Drought-
782 2018 ensemble of inversion results for 2009–2018, doi:10.18160/YQ8P-P7CF.

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

788 United Nations, 2015a: Paris Agreement.
789 https://unfccc.int/files/meetings/paris_nov_2015/application/pdf/paris_agreement_english
790 [_pdf](#).

791 United Nations, 2015b: Transforming our world: the 2030 Agenda for Sustainable
792 Development.
793 [https://www.un.org/en/development/desa/population/migration/generalassembly/docs/gl](https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_RES_70_1_E.pdf)
794 [obalcompact/A_RES_70_1_E.pdf](https://www.un.org/en/development/desa/population/migration/generalassembly/docs/globalcompact/A_RES_70_1_E.pdf)

795 Vetter, M., and Coauthors, 2008: Analyzing the causes and spatial pattern of the European
796 2003 carbon flux anomaly using seven models. *Biogeosciences*, **5**, 561-583,
797 <https://doi.org/10.5194/bg-5-561-2008>.

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

800 Vitale, D., Fratini, G., Bilancia, M., Nicolini, G., Sabbatini, S., and D. Papale, 2020: A robust
801 data cleaning procedure for eddy covariance flux measurements. *Biogeosciences*, **17**, 1367-
802 1391, doi: 10.5194/bg-17-1367-2020.

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

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

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

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

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

816 Yver Kwok, C., and Coauthors, 2015: Comprehensive laboratory and field testing of cavity
817 ring-down spectroscopy analyzers measuring H₂O, CO₂, CH₄ and CO. *Atmospheric*
818 *Measurement Techniques*, **8**(9), 3867-3892.

819 Yver-Kwok, C., and Coauthors, 2021: Evaluation and optimization of ICOS atmosphere
820 station data as part of the labeling process. *Atmospheric Measurement Techniques*, **14**, 89–
821 116, <https://doi.org/10.5194/amt-14-89-2021>.

822 **Tables**

823 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	<ul style="list-style-type: none"> • CO₂, CH₄, CO: at each sampling height 	<ul style="list-style-type: none"> • CO₂, CH₄, N₂O, SF₆, CO, H₂, ¹³C and ¹⁸O in CO₂: weekly sampled at highest sampling height • ¹⁴C (radiocarbon integrated samples): at highest sampling height 	<ul style="list-style-type: none"> • Air temperature, relative humidity, wind direction, wind speed: at highest and lowest sampling height* • Atmospheric Pressure • Planetary Boundary Layer Height** 	
Class 2 Mandatory parameters	<ul style="list-style-type: none"> • CO₂, CH₄: at each sampling height 		<ul style="list-style-type: none"> • Air temperature, relative humidity, wind direction, wind speed: at highest and lowest sampling height* • Atmospheric Pressure 	
Recommended parameters** *	<ul style="list-style-type: none"> • ²²²Rn, N₂O, O₂/N₂ ratio • CO for Class 2 stations 	<ul style="list-style-type: none"> • CH₄ stable isotopes, O₂/N₂ ratio for class 1 stations: weekly sampled at highest 		<ul style="list-style-type: none"> • CO₂: at one sampling height

		sampling height		
--	--	--------------------	--	--

824
825
826
827
828
829

* 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

830 Appendix Table 2. List of variables observed at ICOS Ecosystem Stations, with numbers
 831 indicating Class 1 and 2 stations.

Variables	Forest	Grassland	Cropland	Wetland*	Marine**	Lakes**
CO ₂ , H ₂ O 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 ₂ O fluxes (eddy covariance, including profile for storage)	1	1	1	1	1	1
Air H ₂ O 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.

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 ₂ O 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 ₂ O 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

833 Fac = Facultative variable; N.R. = Not Relevant for the ecosystem
834 * Wetland includes all different water inundated or saturated ecosystems according to Joosten and Clark 2002
835 ** List of variables for Lake, Marine and Urban sites under discussion
836

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

VARIABLE	FREQUENCY	ACCURACY	REQUIRED FOR CLASS
Sea surface $f\text{CO}_2$	Quasi-continuous	$\pm 2 \mu\text{atm}$	1 & 2
Intake temperature (SST)	Continuous	$\pm 0.05 \text{ }^\circ\text{C}$	1 & 2
Equilibrator temperature	Continuous	$\pm 0.05 \text{ }^\circ\text{C}$	1 & 2
ΔT (Intake/Equilibrator temperature difference)	Continuous	$< 1.5 \text{ }^\circ\text{C}$ (normal) $< 3 \text{ }^\circ\text{C}$ (ice-edge)	1 & 2
Water vapour pressure*	Continuous	$\pm 0.5 \text{ mbar}$	1 & 2
Equilibrator pressure	Continuous	$\pm 2.0 \text{ mbar}$	1 & 2
Atmospheric pressure/sea level pressure	Continuous	$\pm 1.0 \text{ mbar}$	1 & 2
Sea surface salinity (SSS)	Continuous	$\pm 0.1 \text{ PSU}$	1 & 2
Dissolved oxygen	Continuous	$\pm 2\%$	1
Total alkalinity (TA)**	***	$\pm 10 \mu\text{mol kg}^{-1}$	1
Dissolved inorganic carbon (DIC)**	***	$\pm 5 \mu\text{mol kg}^{-1}$	1

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

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

840 *** The frequency of these additional variables will be decided on during the labelling process based
841 on the area where the station is operating.
842

843 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

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

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

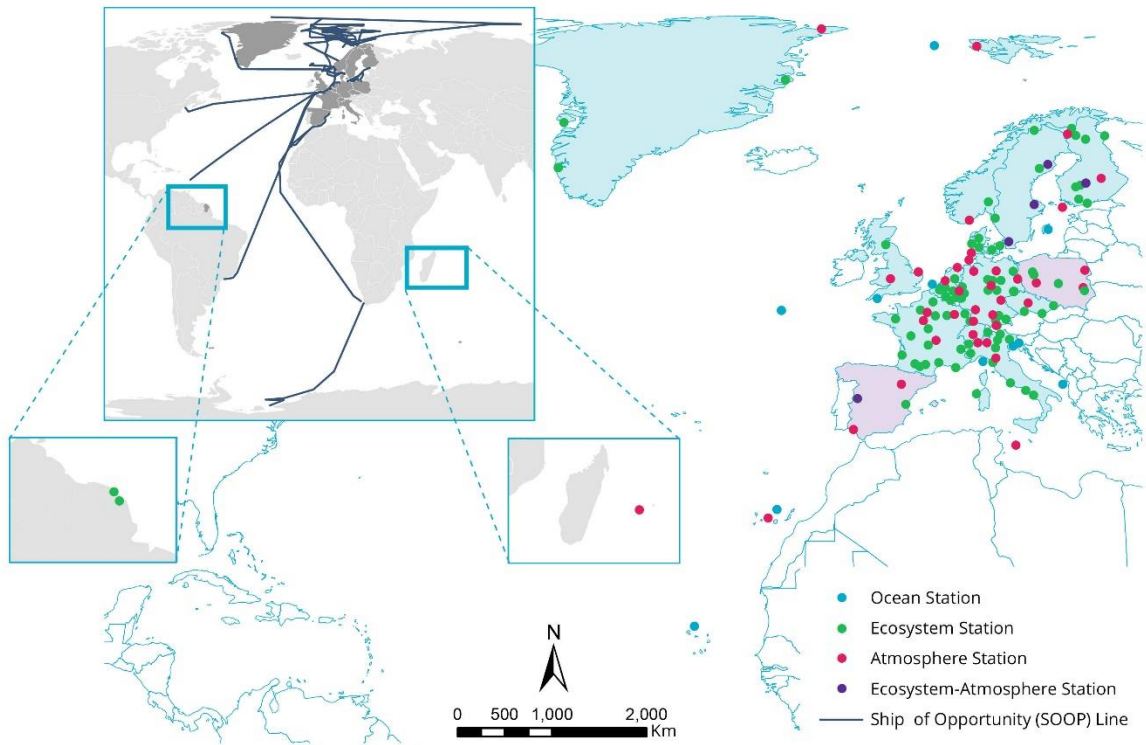
847 *** pH (together with TA or DIC) is ONLY required for validation of the pCO₂ data. pH should NOT be used
848 together with pCO₂ to calculate the full carbonate system due to high resulting uncertainty.

849 **** At least two out of the three dissolved nutrients nitrate (NO₃), phosphate (PO₄), and silicate (Si(OH)₄) must
850 be provided.

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

853

854 **Figures**



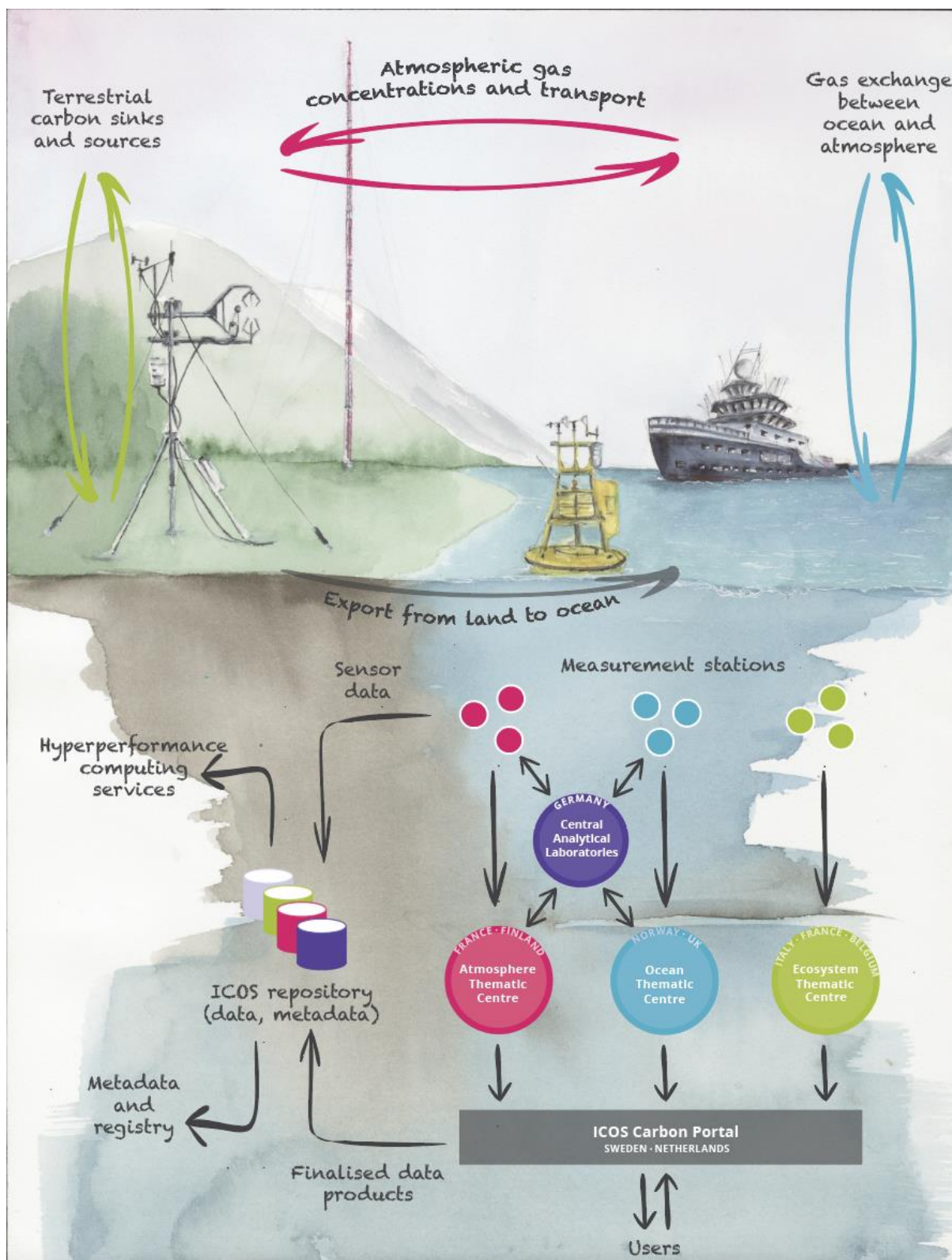
855

856 Figure 1. Map of ICOS stations. The dots represent fixed stations in different domains

857 (ocean, ecosystem, atmosphere) and lines the Ships of Opportunities. Up-to-date details

858 (e.g. station class, contact info, data) from each station can be found from

859 <https://www.icos-cp.eu/observations/station-network>.

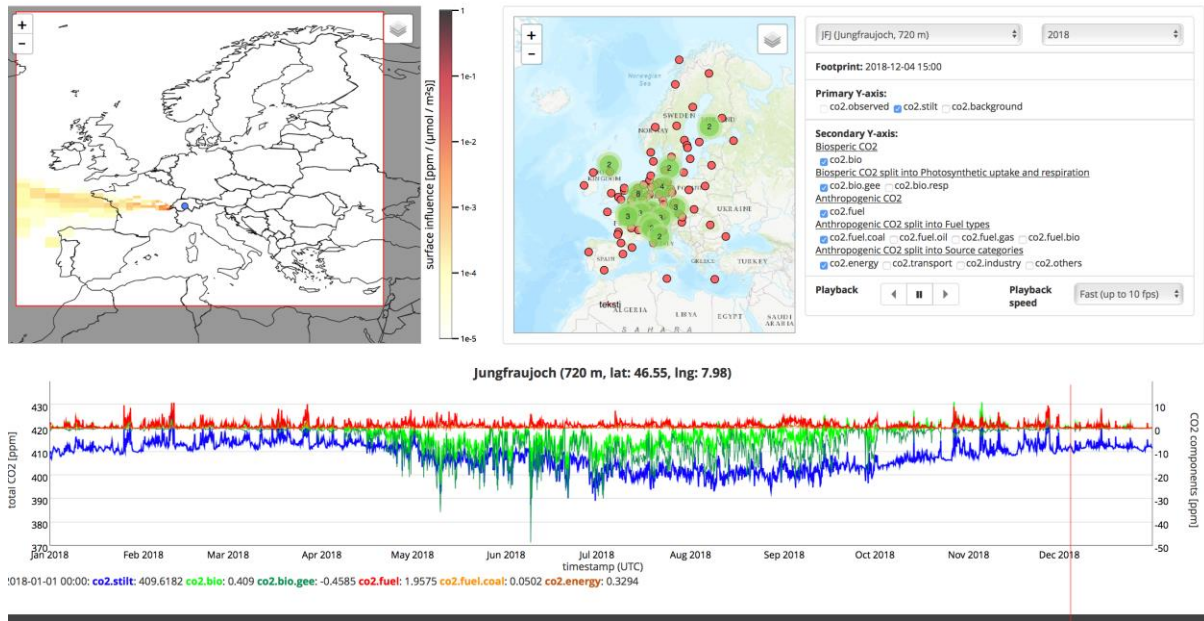


860

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

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

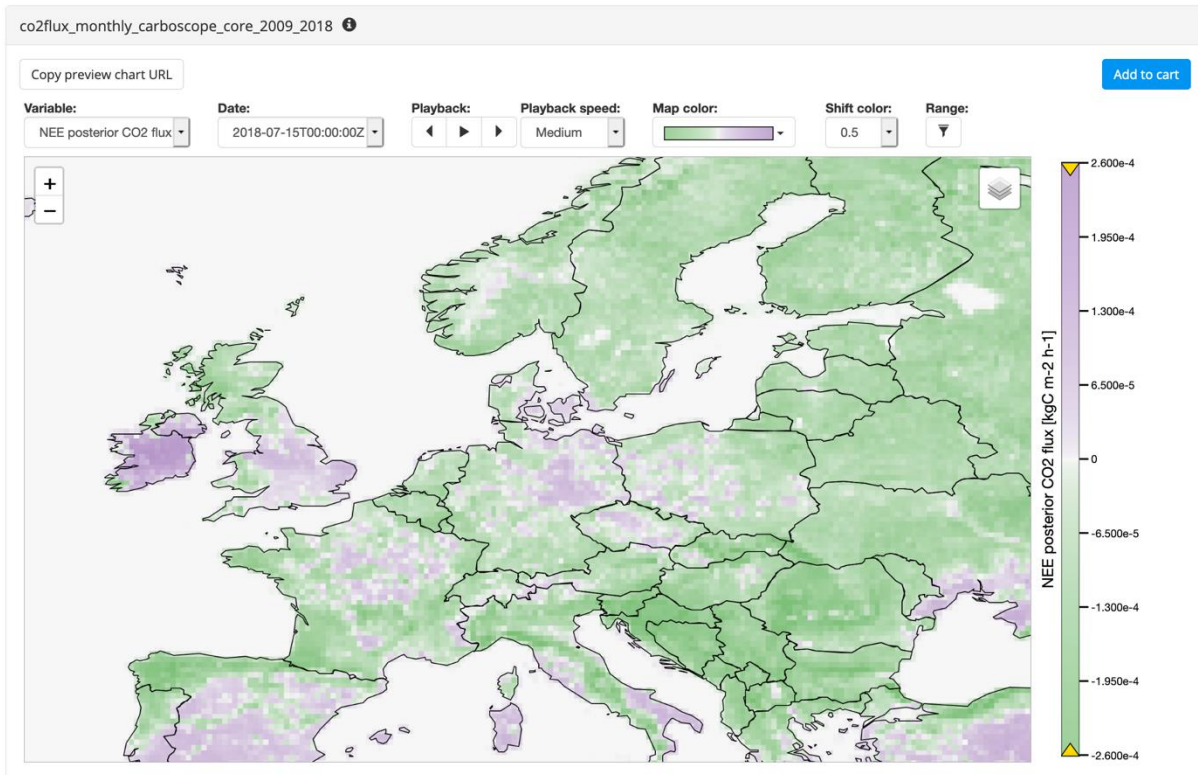
871



872

873 Figure 3. An example of ICOS tool to analyze the potential impact of natural and
 874 anthropogenic emissions to the CO₂ concentrations in the atmosphere, based on model
 875 simulation of Lagrangian transport model STILT (Stochastic Time Inverted Lagrangian
 876 Transport; Lin et al 2013) together with emission-sector and fuel-type specific emissions
 877 from a pre-release of the EDGARv4.3 inventory (EC-JRC/PBL, 2015). Figure shows results for
 878 the ICOS Class 1 Jungfraujoch station in Switzerland, including biospheric and anthropogenic
 879 carbon emissions. Panel A) shows modelled footprint and wind directions influencing the
 880 measurement tower signal; panel B) shows selected towers, location of atmospheric tower
 881 in Europe and variables that are available for interactive visualization; while panel C) shows
 882 the time series of a selected variable, including measured and modelled concentrations.

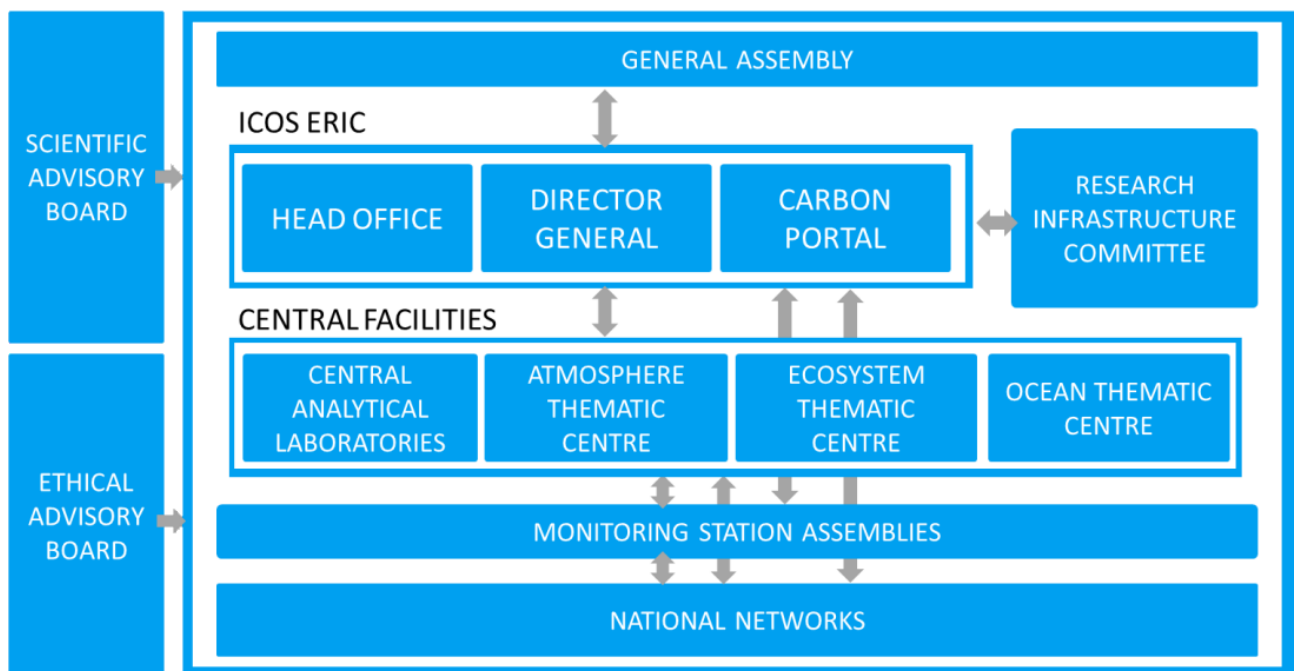
883



884

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

890



891
892

Appendix 1 Figure 1. The governance structure of ICOS.