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State of Europe's surface ocean CO_2 observations

Audit 2026

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The audit is aligned with the activities of the Integrated Carbon Observation System ERIC (ICOS ERIC), in particular its Ocean Thematic Centre, which coordinates and supports long-term ocean carbon observations across Europe. ICOS currently covers 16 European countries.

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Design: Isabel Caballero (JPI Oceans)

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Executive summary

The ocean absorbs around 30% of human-caused CO_2 emissions each year. Accurate and up-to-date estimates of ocean carbon uptake are therefore essential for effective policies on climate mitigation, adaptation, and carbon management. Current knowledge of this uptake is derived from estimates that integrate surface ocean CO_2 observations from regional seas and the open ocean worldwide. This audit provides a first assessment of Europe's contribution to global ocean carbon monitoring and assessment, covering the observational, data synthesis, analytical, and modelling roles. It shows that European biogeochemical models and data products are the primary engines driving the Global Carbon Budget and international climate assessments. However, the audit identifies a critical "leadership mismatch": Europe's excellent capacity in modelling and data products rests on a fragile and declining observational foundation and weak data stewardship capacity. Addressing this imbalance is essential for Europe's strategic autonomy and for meeting its European Ocean Pact goals and Paris Agreement commitments.

Key findings

- **European leadership:** Europe leads globally in ocean carbon modelling and data products; its outputs are the gold standard for tracking changes in the global ocean carbon sinks.
- **Measurement-model mismatch**: Europe's advanced modelling and data product capacity increasingly depends on surface ocean CO_2 observations provided by a shrinking number of countries.
- **Regional blind spots:** Severe and persistent gaps in observations remain around Europe in the Black Sea and the Mediterranean Sea, as well as in the climatically important Southern Ocean.
- **Stewardship risks:** The absence of an operational European SOCAT (Surface Ocean CO_2 Atlas) data synthesis hub creates a global single point of failure for the quality and continuity of data stewardship across the value chain from observations to policy-relevant information.

Metrics Matrix

			
Global metrics		Number of surface ocean *f*CO_2 measurements	Number of monthly gridded surface ocean *f*CO_2 data cells
		Mean difference between observation-based and model-based ocean CO_2 sink estimates	Standard deviation among Global Carbon Budget ocean CO_2 uptake estimates
European metrics	Number of European ocean data products contributing to the Global Carbon Budget	Presence or absence of a European SOCAT hub	
	Number of European ocean models contributing to the Global Carbon Budget		
Regional Seas metrics	Number of surface ocean *f*CO_2 measurements in the Baltic Sea & North-East Atlantic		Number of surface ocean *f*CO_2 measurements in the Black Sea, Mediterranean Sea & Southern Ocean
Country metrics			Number of European countries reporting surface ocean *f*CO_2 measurements

Table 1: Overview of assessed metrics and their corresponding traffic-light ratings in this audit.

Recommendations

Invest in under-observed and strategically critical regions

Address the severe surface ocean CO_2 data gaps in the Mediterranean Sea and the Black Sea. In parallel, strengthen Europe's engagement in two globally critical carbon uptake regions: the North-East Atlantic and the Southern Ocean. These regions should be made priority areas for new activities within the EU Ocean Observation Initiative. Cost-sharing models at the European level could support participation by smaller nations in these regions and maximise the use of existing European infrastructure and capacity.

Expand Europe's surface ocean CO_2 observing capability

Increase the number of high-accuracy surface ocean CO_2 systems deployed across the full spectrum of European observing platforms, including research vessels, ships of opportunity, commercial fleets, autonomous surface vehicles and fixed installations such as moorings. Strengthen calibration facilities, technical training and instrument development capacity to ensure measurement quality and interoperability across platforms. A stronger observational backbone will boost Europe's contributions to major global synthesis products, such as SOCAT, the Global Carbon Budget, the World Meteorological Organization's Global Greenhouse Gas Watch and assessments of the Intergovernmental Panel on Climate Change.

Secure continuous and timely surface ocean CO_2 data flows

Put incentives (funding and regulatory measures) in place to ensure sustained surface ocean CO_2 measurements and timely data reporting. Encourage the continued maintenance of measurements across all operational platforms equipped with CO_2 systems, and integrate them as a routine component of maritime operations rather than short-term research activities. Provide sustained support for maintenance, calibration and data management to maintain consistent and reliable data flows to SOCAT.

Re-establish a European SOCAT coordination hub

Reinstate a SOCAT data synthesis hub in Europe by embedding it within existing European Ocean Observing infrastructure. This would secure long-term data stewardship, improve quality control, and link surface ocean CO_2 observations directly to major European ocean initiatives.

Maintain leadership in data products and modelling

Support European teams developing ocean CO_2 data products and ocean biogeochemical models. Invest in modelling centres and intercomparison efforts to keep Europe at the forefront of global carbon cycle science.

Institutionalise an annual European ocean CO_2 monitoring audit

Establish this audit as a yearly, transparent review of Europe's ocean carbon observing and modelling capacity. This process should be refined to incorporate new metrics and include other critical regions, such as the Arctic, ensuring the audit evolves alongside Europe's strategic climate priorities.

Embed ocean CO_2 knowledge in European climate and ocean policy

Connect ocean CO_2 observations directly to European climate strategies and ocean governance frameworks. Emphasise the diplomatic value of measurements by using Europe's observational strengths as part of its climate leadership narrative. Recognise high-accuracy ocean data and Europe-built instrumentation and calibration standards as a strategic investment in Europe's scientific and geopolitical capital.

Rationale

High-accuracy in situ surface ocean CO_2 measurements are critical for understanding and managing ocean-climate interactions. As Europe advances major efforts under its European Ocean Pact[1], such as the Ocean Observation Initiative and the European Digital Twin of the Ocean, reliable ocean carbon observations provide the scientific foundation for Europe's capacity for political leadership, support for global partnerships, and shaping emerging standards in ocean governance. Investing in high-quality data collection today will enable these initiatives to become powerful instruments of European science diplomacy tomorrow.

This strategic need is grounded in the fundamental role the ocean plays in the global carbon cycle. The ocean takes up around 30% of the CO_2 emissions from human activities. Ocean CO_2 uptake slows down climate change, while also changing the ocean's chemistry, a process known as *ocean acidification*. Annual estimates of ocean CO_2 uptake come from the Global Carbon Budget (GCB), which combines observation-based data products with Earth system models, drawing on contributions from many countries worldwide. These measurements and estimates are essential for CO_2 management strategies and are expected to play a central role in the delivery of the World Meteorological Organization's Global Greenhouse Gas Watch (WMO G3W) programme.[2]

__SOCAT__ (Surface Ocean CO_2 Atlas) is a global data product providing a community-driven, quality-controlled synthesis of surface-ocean CO_2 observations from ships, moorings, autonomous surface platforms and sailing yachts worldwide. Updated annually, it serves as the primary surface-ocean carbon data source for the Global Carbon Budget and other major carbon cycle assessments. SOCAT is endorsed by the Global Ocean Observing System (GOOS).

The surface ocean carbon value chain connects measurements of CO_2 at the ocean surface and brings them together in the Surface Ocean

CO_2 Atlas (SOCAT, www.socat.info). These data are then used in data products to estimate how much CO_2 the ocean absorbs each year. The resulting information supports annual assessments for the Global Carbon Budget and the Intergovernmental Panel on Climate Change (IPCC) and ultimately informs international climate policy discussions under the UN Framework Convention on Climate Change (UNFCCC). The reliability of this chain depends directly on the quality, continuity and geographical as well as temporal coverage of the underlying observations.[3] Recent analysis shows that reduced data availability increases uncertainty and bias in estimates of ocean CO_2 uptake.[4] In response to ever-increasing demands for ocean carbon data and information to support climate policy and mitigation, the international ocean carbon community, through the International Ocean Carbon Coordination Project (IOCCP), has called for a stronger and better-coordinated operational value chain.[5]

Europe's contribution to this global value chain and its capacity to independently observe and assess ocean CO_2 dynamics both globally and in the seas surrounding Europe have not been previously assessed in a structured manner. This has left uncertainties about the extent, quality, and coherence of European surface ocean CO_2 observations, as well as Europe's strategic autonomy in assessing the ocean's role in moderating climate change. With the closure of the SOCAT European regional hub in 2022 and the resulting reliance of the annual SOCAT release on a single operational hub based in the United States, this challenge has increased.[6] In particular, it raises questions about Europe's dependence on non-European infrastructures for data collection, data stewardship and assessment, even for observations collected in European waters. This report, therefore, offers a first assessment of Europe's contribution to the surface ocean carbon value chain, focusing on its ability to observe its own seas, as well as the Southern Ocean as a globally important ocean carbon sink, and outlines opportunities and recommendations to strengthen this capacity in line with the ambitions of the European Ocean Pact.

Methodology

In this audit, Europe refers to all member states of the Council of Europe.[7] Our data sources are the latest versions of SOCAT (2025)[8] and the Global Carbon Budget (2025)[9].

The audit examines surface ocean fCO_2 observations and related contributions at four levels: global, European, regional seas, and country. For ease of reference, each metric is assigned a code reflecting its level of assessment (G = global, E = European, RS = regional seas, C = country).

***fCO_2**, or fugacity of CO_2, is a measure of how much CO_2 is dissolved in seawater. It indicates whether the ocean is absorbing or releasing CO_2.*

Global metrics. Number of monthly gridded surface ocean fCO_2 data cells (G1); number of surface ocean fCO_2 measurements (G2); standard deviation among Global Carbon Budget ocean CO_2 uptake estimates (G3); and mean difference between observation-based and model-based ocean CO_2 sink estimates (G4).

European metrics. Presence or absence of a European SOCAT hub in 2025 (E1); number of European ocean data products contributing to the Global Carbon Budget (E2); and number of European ocean models contributing to the Global Carbon Budget (E3).

Regional-seas metrics. Number of surface ocean fCO_2 measurements in each region (RS). The regional seas considered are those governed by the regional sea conventions around Europe, covering the North-East Atlantic, Baltic Sea, Black Sea, and Mediterranean Sea. The Southern Ocean area is additionally included, as it represents the most significant oceanic carbon sink globally.

Country metrics. Number of European countries reporting surface ocean fCO_2 measurements (C1)

Unless otherwise specified, metrics compare 2022–23 with the reference period 2015–19. Here 2020–21 are excluded for COVID-related disruptions and 2024 for reporting delays. The 2015–19 period was selected as a pragmatic multi-year pre-pandemic benchmark, which reduces sensitivity to interannual variability and supports a pre-/post-COVID comparison. Although data collection was relatively strong in some individual years within 2015–19,[10] the period was not necessarily adequate to meet the ambitions of the Global Climate Observing System (GCOS) or the future Global Greenhouse Gas Watch (G3W).[11]

For each metric, we assign a traffic light depending on whether the situation has improved (green), remained stable (amber) or worsened (red), with thresholds defined individually for each metric.

Note on data quality: SOCAT classifies surface ocean fCO_2 observations using quality flags (A–E) reflecting estimated measurement uncertainty. Consistent with the Global Carbon Budget methodology, this audit only includes SOCAT data with flags A–D (estimated uncertainty ≤5 µatm), while measurements flagged E are excluded due to their high uncertainty.

µatm (micro-atmospheres), *A unit of pressure used for CO_2 measurements, in air or seawater.*

Analysis of metrics

Focus Global

Traffic light definition: For the metrics focusing on surface ocean fCO_2 observations (G1, G2), we compare the years 2022-23 to the 5-year reference period from 2015 to 2019. Metrics assessing constraints on ocean CO_2 uptake (G3, G4) are evaluated over the most recent five-year period (2020–24) relative to the reference period (2015-19).

AMBER indicates broadly stable conditions, defined as changes within +/- 10% of the reference period. **GREEN** indicates an improvement of 10% or more, while **RED** indicates a worsening of 10% or more relative to the reference period.

Ocean Data Products provide global estimates of surface ocean CO_2 and air–sea CO_2 exchange based on real-world measurements. They use data from SOCAT and combine these observations with environmental information from satellites and other sources (such as temperature and salinity) using statistical or machine-learning methods to produce globally complete fields.

They are measurement-based estimates of how much carbon the ocean is absorbing

Ocean Biogeochemical Models simulate the circulation of the ocean and the biological and chemical processes that control the ocean carbon cycle. Using mathematical equations, they calculate how carbon moves through the ocean and how CO_2 is exchanged with the atmosphere.

They are used to understand how the system works and to assess past and future changes in ocean carbon uptake.

G1. Number of monthly gridded surface ocean fCO_2 data cells

This metric counts the number of monthly gridded cells with surface ocean *f*CO_2 measurements per year for the global ocean and coastal seas.

The number of such cells with measurements declined by 24% in 2022 and 2023 (average of 12,821 grid cells) relative to the 2015-19 baseline (average of 16,980 grid cells). In other words, the overall number of grid cells was much lower in 2022-23 than in 2015-19, due to fewer open ocean measurements. A **RED** light is therefore assigned. We note this metric is global; it does not isolate Europe's share.

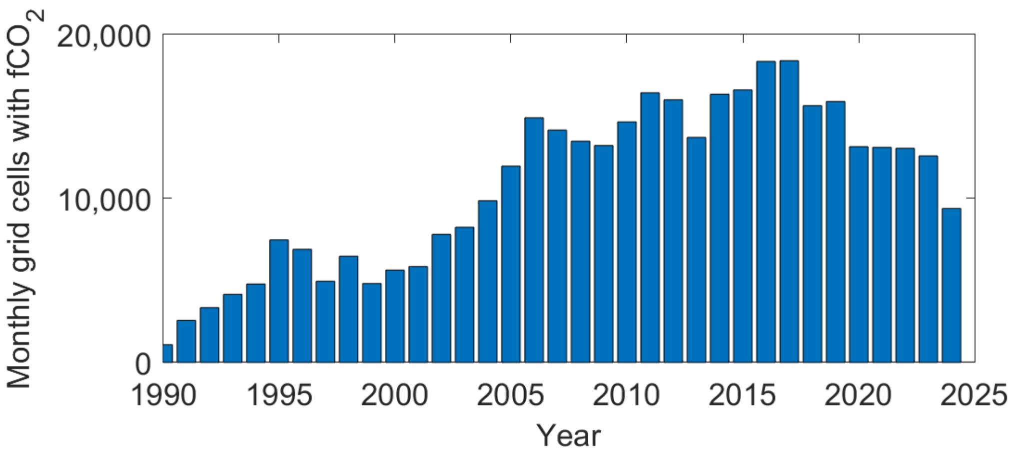
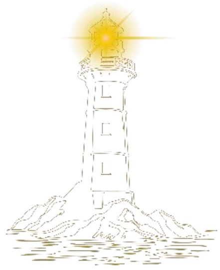


Figure 1. Number of monthly, 1° x 1° grid cells with *f*CO_2 measurements for the global ocean and coastal seas by year in SOCAT version 2025.[12]

Policy interpretation: The red light indicates a substantial decline in the representation of the global ocean in the record of surface ocean CO_2 observations in 2022–23 than during the reference period. Fewer regions were sampled regularly, reducing the completeness of the observational record and increasing the uncertainty in assessments of how much CO_2 the ocean absorbs each year.

G2. Number of surface ocean fCO_2 measurements

This metric counts the total number of *f*CO_2 measurements by year, globally and within the defined regions (2022–23 vs. baseline).



Globally, the total number of *f*CO_2 measurements remained roughly stable, showing little change (4% increase) from 2015–19 to 2022-23 (from average of 2,304,430 to 2,396,781). Hence, we assign an **AMBER** light. A comparison of Figures 1 and 2 shows that the 24% reduction in the open ocean data collection effort observed in the number of monthly gridded data cells (Figure 1) is not evident in the total number of *f*CO_2 measurements (Figure 2). This suggests that reporting frequency (every minute versus every second) or locations (from open ocean to coastal waters) may have changed, while the number of *f*CO_2 measurements was stable.

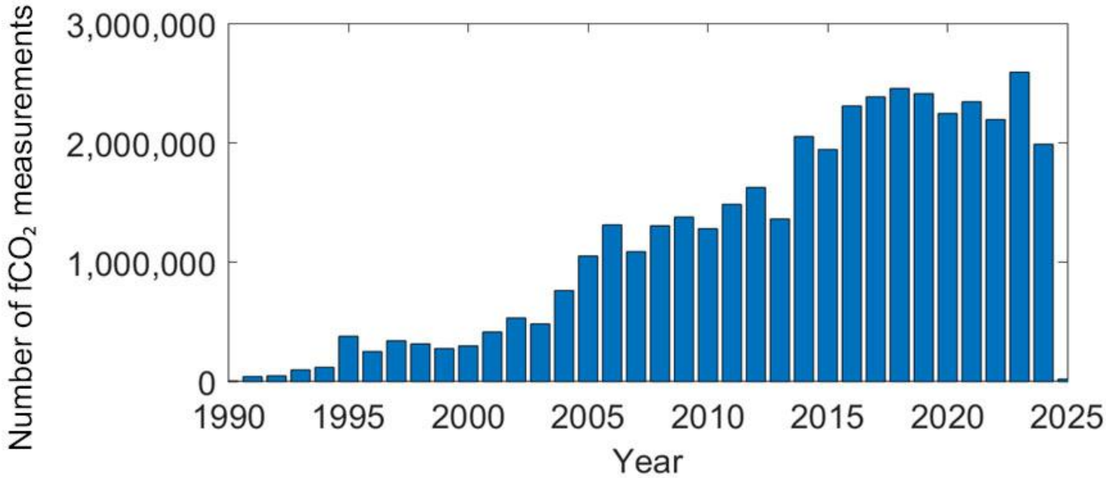


Figure 2, from SOCAT version 2025.[13]

Policy interpretation: The amber light reflects that overall observation volumes have been maintained but masks a shift in where measurements are taken. While numerical stability supports continuity in global assessments, reduced open-ocean coverage risks weakening the representativeness of large-scale ocean carbon sink estimates.

G3. Standard deviation among Global Carbon Budget ocean CO_2 uptake estimates

This metric measures the standard deviation of ocean CO_2 uptake estimates from observation-based data products over the last five years in the Global Carbon Budget relative to the baseline period.

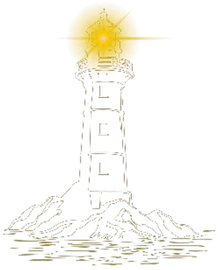
The average standard deviation of the air-sea CO_2 flux estimates of the final five years of the Global Carbon Budget 2025 timeseries has increased relative to the baseline period (2015-19) from 0.30 PgC / yr to 0.46 PgC / yr.[14] While some more spread is expected in the data products in the last year of the timeseries, the difference in the spread exceeds 10% of the likely better constrained baseline period and is thus assigned a **RED** traffic light.

PgC / yr*, Petagrams of carbon per year. A unit used to express the size of global CO_2 sources and sinks. 1 PgC = 1 billion tonnes of carbon.*

Policy interpretation: The red light signals that disagreement among ocean CO_2 uptake estimates has grown. This reduces confidence in the precision of the ocean carbon sink reported in the Global Carbon Budget, suggesting that weaker data coverage is affecting consistency of uptake estimates.

G4. Mean difference between observation-based and model-based ocean CO_2 sink estimates

This metric compares the average annual ocean CO_2 uptake estimated from observation-driven data products with the uptake estimated by ocean biogeochemical models over five-year periods during the last ten years.



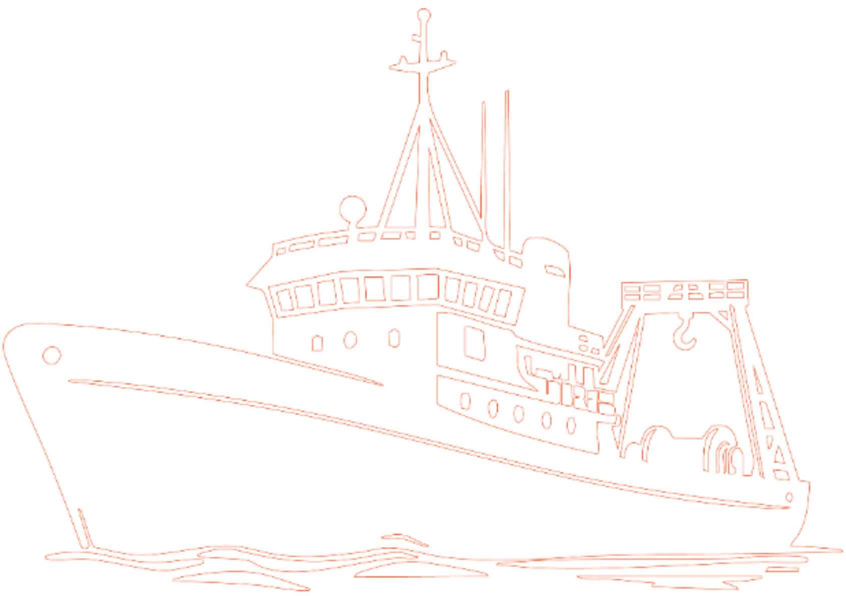
There is an increase in the difference between ocean fCO_2 product-derived air-sea CO_2 fluxes and ocean biogeochemical models in the last five years of the timeseries in GCB 2025 relative to the reference period 2015-19. While the difference between fCO_2-products and models was on average 0.61 PgC / yr in the GCB2025, it slightly increased relative to the reference period, where the difference was 0.57 PgC / yr.[15] While we expect some more variance in the final year of the timeseries, we assign it an **AMBER** flag as the increase relative to the reference period does not exceed 10%.

Policy interpretation: The amber light reflects a modest but emerging divergence between observation-based and model-based estimates of ocean CO_2 uptake. Although differences remain limited, this highlights the policy relevance of sustained co-ordination between ocean observations, data product development and modelling to maintain consistent and reliable ocean carbon sink assessments.

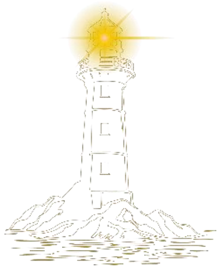
Focus Europe

Traffic light definition: For metric E1, the situation in 2025 is compared with the reference period 2015–19. A **GREEN** light is assigned when a European SOCAT hub is operational with sustained funding in 2025; an **AMBER** light when the hub is not operational but active efforts toward its re-establishment are underway; and a **RED** light when no hub exists and no concrete plans are in place.

For metrics E2 and E3, the number of European data products and models submitted to the Global Carbon Budget 2025 is compared with that of the 2015 edition. We assign a **GREEN** light if the number of data-products and models submitted to the GCB from Europe remains stable (+/- 1 submission as some variation may occur) or increases, an **AMBER** light if the number drops by 2 and a **RED** light if the number drops by 3 or more.



E1. European contribution to SOCAT via a European SOCAT hub



This metric assesses the European contribution to SOCAT through the presence or absence of a European SOCAT hub in 2025, compared to the baseline period.

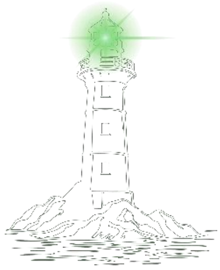
A European SOCAT hub existed from 2007 to 2022, but not afterwards. Steps are now being taken to re-establish the hub at the Flanders Marine Institute (VLIZ), where recruitment for a two-year SOCAT data engineer position started in 2025.[16] In addition, the EU-funded TRICUSO project includes, among its objectives, the development of a governance structure for the Surface Ocean CO_2 Atlas.[17] Hence, an **AMBER** light.

Policy interpretation: The amber light indicates that no European SOCAT hub is currently operational, but that concrete steps toward its re-establishment are underway. While recent developments are positive, the absence of a fully operational and sustainably funded hub limits Europe's capacity to coordinate and deliver SOCAT data efficiently. Securing long-term funding for a European SOCAT hub remains a priority to ensure a stable European contribution to global ocean CO_2 data products.

E2. Number of European ocean data products in the Global Carbon Budget

This metric counts how many of the ocean CO_2 data products used in the Global Carbon Budget originate from Europe.

There has been a strong increase in the number of European data products used in the GCB. While a decade ago, in the Global Carbon Budget 2015, two data products, originating from Europe were included in the GCB, in the latest release five of the nine (56 % of total) ocean data products originating from Europe are included. Hence, a **GREEN** light.



Product	Institute	Country
CMEMS-LSCE-FFNNv2	Laboratoire des Sciences du Climat de l'Environment (via Copernicus Marine Environment Monitoring Service)	FR (EU)
Jena-MLS	Max Planck Institut for Biogeochemistry	DE
OceanSODA-ETHZv2	ETH Zürich	CH
UExP-FNN-U	University of Exeter	UK
VLIZ-SOMFFN	Flanders Marine Institute	BE
CSIR-ML6	Council for Scientific and Industrial Research	ZA
JMA-MLR	Japan Meteorological Agency	JP
LDEO-HPD	Lamont-Doherty Earth Observatory	US
NIES-ML3	National Institute for Environmental Studies	JP

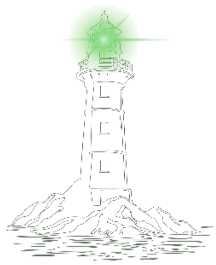
Table 2. Ocean data products for the Global Carbon Budget 2025 (European products in blue).[18]

Policy interpretation: The green light here reflects Europe's strong global leadership in developing ocean CO_2 data products. European products now represent a substantial share of the global set of ocean CO_2 data products, supporting robustness and continuity in ocean carbon sink estimates. Maintaining this leadership requires sustained investment in long-term observing programs, algorithm development, and data infrastructure.

E3. Number of European ocean models in the Global Carbon Budget

This metric counts the number of global ocean biogeochemical models in the Global Carbon Budget that are developed or led by European institutions.

Seven of the ten Global Ocean Biogeochemical Models (GOBM's) in the GCB2025 are delivered by European research institutions coming from France (2), Germany (2), Norway (1), Switzerland (1), and the United Kingdom (1). This is comparable to a decade ago, when six out of ten models were delivered by Europeans. Hence, we assign a **GREEN** light.



Model	Institute	Country
CESM-ETHZ	ETH Zürich (Center for Climate Systems Modelling)	CH
FESOM-2.1-REcoM3	Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research	DE
MICOM-HAMOCC	Bjerknes Centre for Climate Research / Norwegian Earth System Model	NO
MPIOM-HAMOCC6	Max Planck Institute for Meteorology	DE
NEMO3.6-PISCESv2-gas	Centre National de Recherches Météorologiques / Centre Européen de Recherche et de Formation Avancée en Calcul Scientifique	FR
NEMO4.2-PISCES	Institut Pierre-Simon Laplace	FR
NEMO-PlankTOM12	University of East Anglia	UK
ACCESS	Commonwealth Scientific and Industrial Research Organisation & Bureau of Meteorology	AU
MOM6-COBALTv3	Princeton University	US
MRI-ESM2-4	Meteorological Research Institute	JP

Table 3. Global Ocean Biochemistry Models used in the GCB2025 (European in blue).[19]

Policy interpretation: This strong model representation highlights Europe's scientific influence and technical capacity. To sustain this advantage, Europe should continue funding model development, high-performance computing, and intercomparison projects. Investing in next-generation modelling frameworks and linking them more tightly with European observing systems will further strengthen Europe's position in global climate assessment.

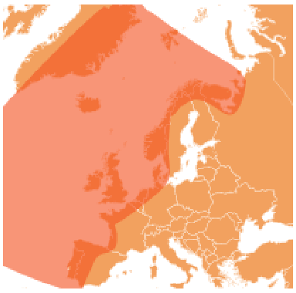
Focus Regional Seas

Traffic light definition. For the regional-level metrics, the traffic light assessment focuses on changes in the number of surface ocean *f*CO_2 observations between the reference period (2015–19) and the current period (2022–23).

AMBER indicates broadly stable conditions, defined as changes within +/- 10% in the total number of medium- to high-quality observations (SOCAT flags A–D). **GREEN** indicates a strengthening of the surface ocean CO_2 observing system, defined as an increase of more than 10% in total flag A–D observations. **RED** indicates a weakening of the ocean CO_2 observing system, defined as a decrease of more than 10% in total A–D observations.

For consistent area definitions, we use the spatial boundaries of the regional cooperation mechanisms for the five regional seas considered. This does not in itself imply that these mechanisms oversee or actively coordinate surface ocean CO_2 observations.

Sea Region	Regional Cooperation Mechanism
North-East Atlantic	OSPAR Commission for the Protection of the Marine Environment of the North-East Atlantic (OSPAR)
Baltic Sea	Baltic Marine Environment Protection Commission (HELCOM)
Black Sea	Commission on the Protection of the Black Sea Against Pollution (Black Sea Commission)
Mediterranean Sea	Mediterranean Action Plan of the United Nations Environment Programme (UNEP/MAP)
Southern Ocean	Commission for the Conservation of Antarctic Marine Living Resources (CCAMLR)



North-East Atlantic

Covered by OSPAR, established under the Oslo and Paris Conventions. Here, we refer to its maritime area before the 2025 enlargement.[20]

***RS(a). Number of surface ocean fCO_2 measurements* for the North-East Atlantic.**

Between 2022-23 and the 2015-19 reference period, the total number of surface ocean fCO_2 observations (SOCAT flags A-D) per year in the North-East Atlantic increased by 15% (from an average of 511,344 to 588,027 measurements per year).

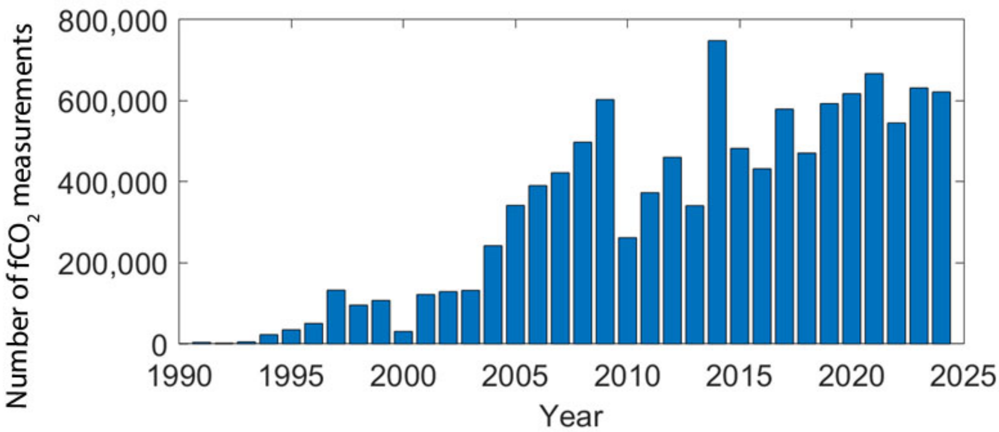
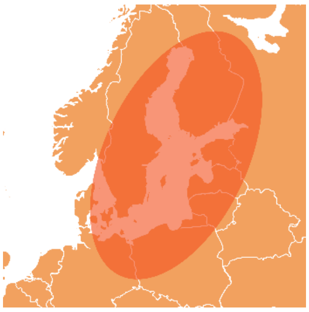


Figure 3. No. of surface ocean fCO_2 observations per year for SOCAT flags A to D in the North-East Atlantic.

Policy interpretation: The green traffic light reflects a positive trend in Europe's surface ocean fCO_2 observations in the North-East Atlantic. The increase in both, observation volume and data quality strengthens robust assessments of regional air-sea CO_2 exchange and the ocean carbon sink. Yet, closer inspection of the underlying data, beyond what is directly captured by this metric, indicates that part of this increase is driven by higher sampling frequency and a growing contribution from coastal observations. While enhanced coastal coverage is valuable, sustained and well-distributed open-ocean observations remain essential for reliably assessing large-scale ocean carbon uptake and long-term climate trends.

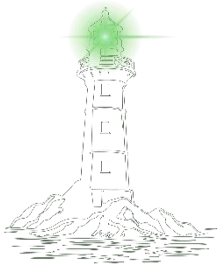


Baltic Sea

Covered by HELCOM, established under the Helsinki Commission.

RS (b). Number of surface ocean fCO_2 measurements for the Baltic Sea

The number of *f*CO_2 measurements (flags A-D) per year increased by 165% in the Baltic Sea in 2022 and 2023 relative to the 2015-19 baseline (from an average of 105,532 values to 279,757 values).



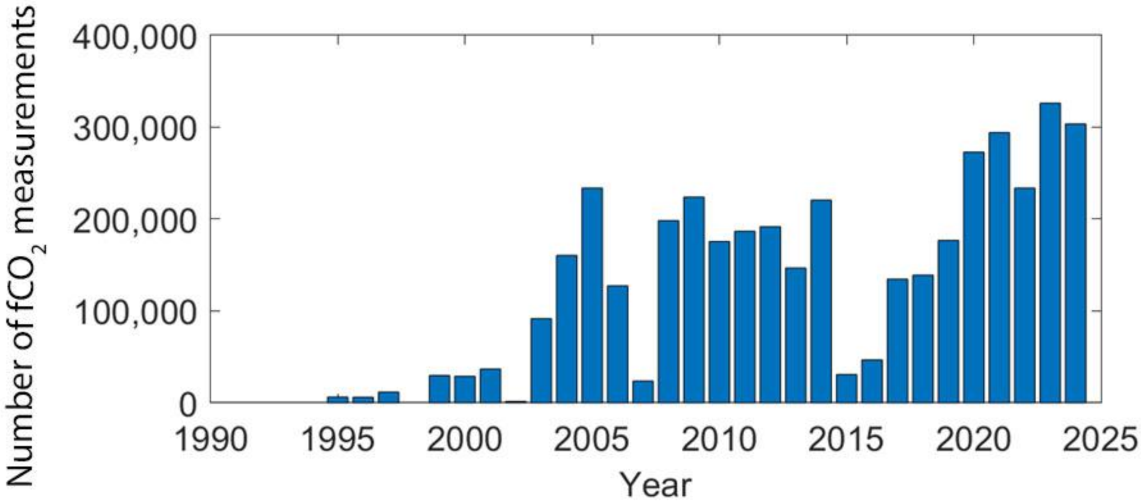
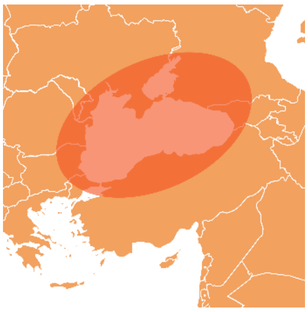


Figure 4. No. of surface ocean *f*CO_2 observations per year for SOCAT flags A to D in the Baltic Sea.

Policy interpretation: The green traffic light reflects a strong and promising positive trend in surface ocean *f*CO_2 observations in the Baltic Sea. The substantial increase in observation volume strengthens the basis for assessing regional air-sea CO_2 exchange and the the Baltic Sea's role in the ocean carbon cycle.



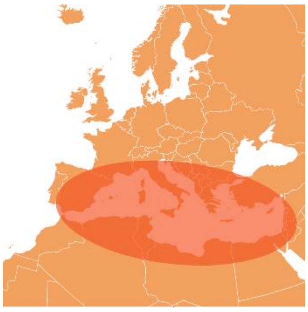
Black Sea

Covered by the Black Sea Commission, established under the Bucharest Convention.

RS(e). Number of surface ocean fCO_2 measurements in the Black Sea

No surface ocean fCO_2 measurements have been reported for the Black Sea after 2016.

Policy interpretation: The red traffic light reflects the complete absence of reported surface ocean fCO_2 observations in the Black Sea since 2016, preventing any assessment of regional air-sea CO_2 exchange or the basin's role in the ocean carbon cycle. This long-term data gap represents a critical blind spot in Europe's regional carbon observing system.



Mediterranean Sea

Covered by UNEP/MAP, implemented under the Barcelona Convention.

***RS(c). Number of surface ocean fCO₂ measurements* for the Mediterranean Sea**

The number of *f*CO_2 measurements per year reported for the Mediterranean Sea is extremely variable, with few high and medium quality (flags A-D) measurements made in 2017 and 2023. Overall, the Mediterranean is under-sampled.

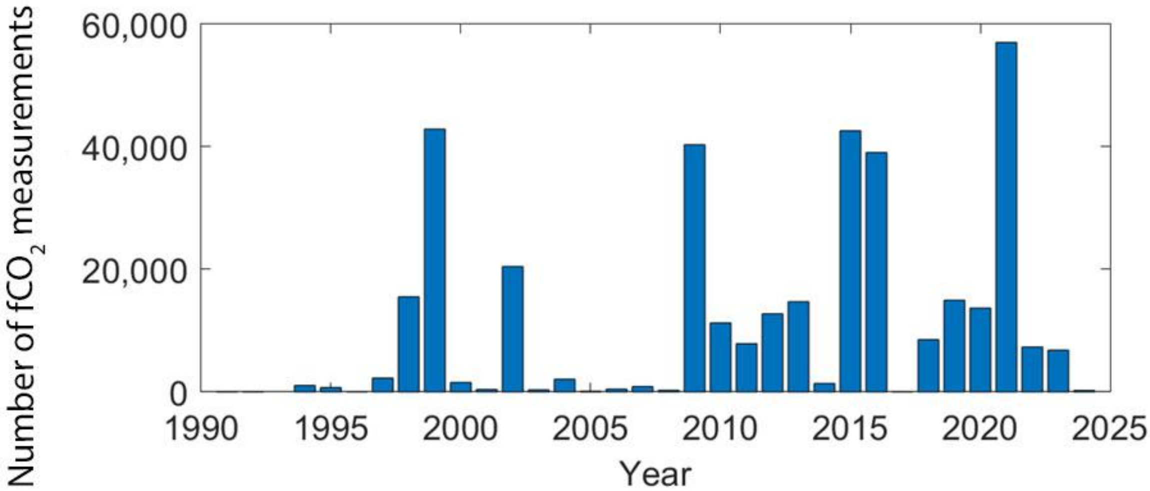
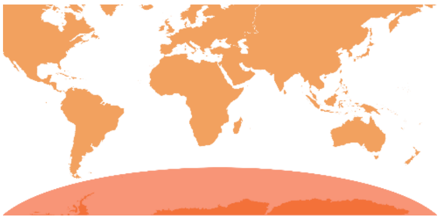


Figure 5. No. of surface ocean *f*CO_2 observations per year for SOCAT flags A to D in the Mediterranean Sea.

Policy interpretation: The red traffic light reflects persistent gaps in surface ocean *f*CO_2 observations in the Mediterranean Sea, limiting robust assessments of regional air-sea CO_2 exchange and the role of the basin in the ocean carbon cycle. Given the Mediterranean's active overturning circulation and its influence on carbon exchange with the Atlantic Ocean, these observational gaps are concerning.



Southern Ocean

Covered by CCAMLR, established under the Convention on the Conservation of Antarctic Marine Living Resources.

RS(d). Number of surface ocean fCO_2 measurements for the Southern Ocean

The number of fCO_2 observations (flag A-D) per year halved in the Southern Ocean CCAMLR region in 2022 and 2023 relative to the 2015-19 baseline (from an average of 337,895 to 159,584 measurements per year, a 53% reduction).

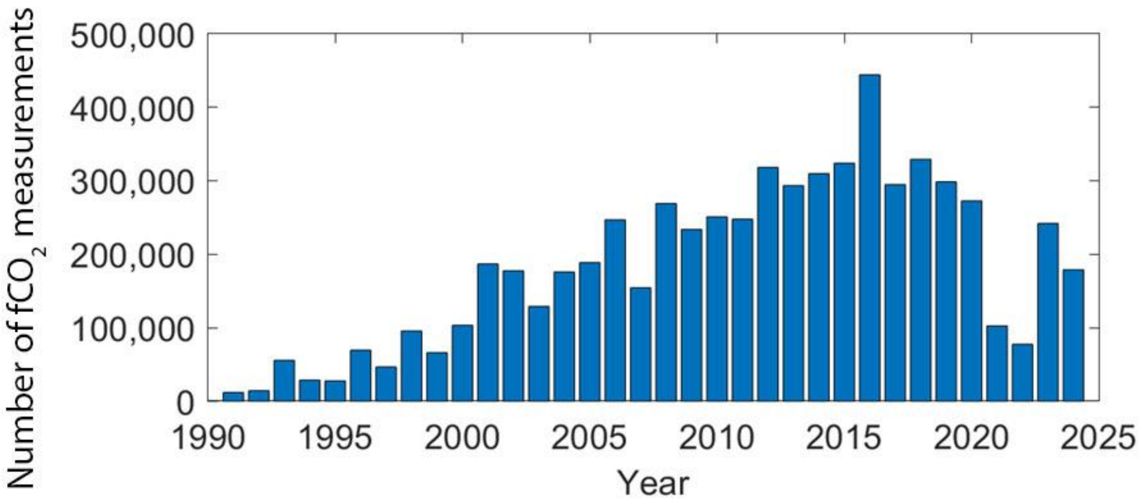


Figure 6. No. of surface ocean fCO_2 observations by year for SOCAT flags A to D in the Southern Ocean.

Policy interpretation: The red light indicates a large decline in Southern Ocean observations. This reduction is particularly concerning given the region's critical role in the global carbon cycle. The drop in data makes it harder to accurately determine the Southern Ocean's contribution to global carbon uptake.

Focus European countries

Traffic light definition: With regards to metric C1, we assign a **GREEN** light if the number of European countries reporting fCO_2 measurements increases, an **AMBER** light if the number remains stable (+/-1) and a **RED** light if the number drops by two or more.

Metric C1: Number of European countries reporting surface ocean fCO_2 measurements

This metric compares the number of countries reporting surface ocean fCO_2 observations to the Global Carbon Budget in 2022–23 with the baseline period of 2015–19. Further below, deeper insights into the four regional seas are provided by showcasing the cumulative number of days per year with fCO_2 measurements (flags A–D) for each European country and for other non-European countries.

While nine European countries reported surface ocean fCO_2 values in 2015–19, this number dropped to five countries in 2022–23. Hence, we assign a **RED** light. It is worth noting that some countries report Flag E data; however, as these flag E data are not included in the Global Carbon Budget, they are not considered in this audit.

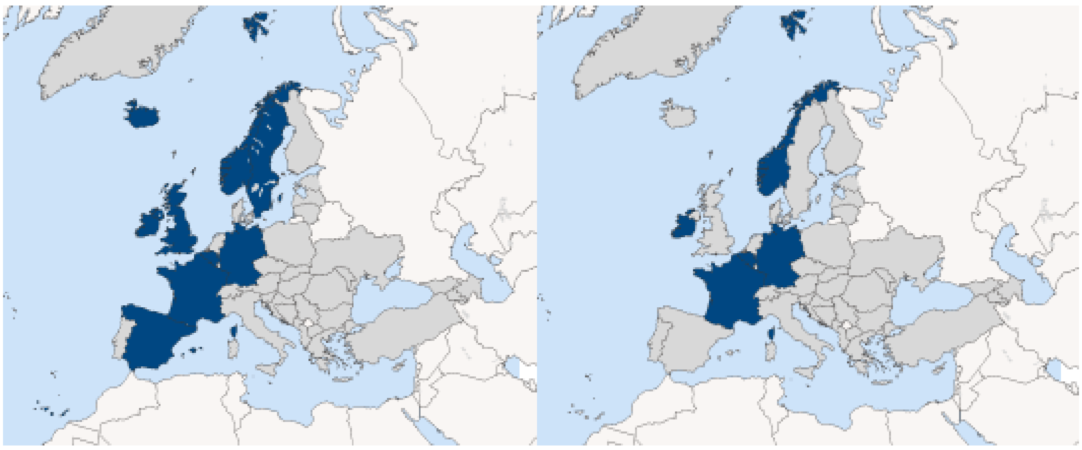


Figure 8. Comparison of European countries that contributed data in the 2015-19 period (left) vs 2022-23 (right).

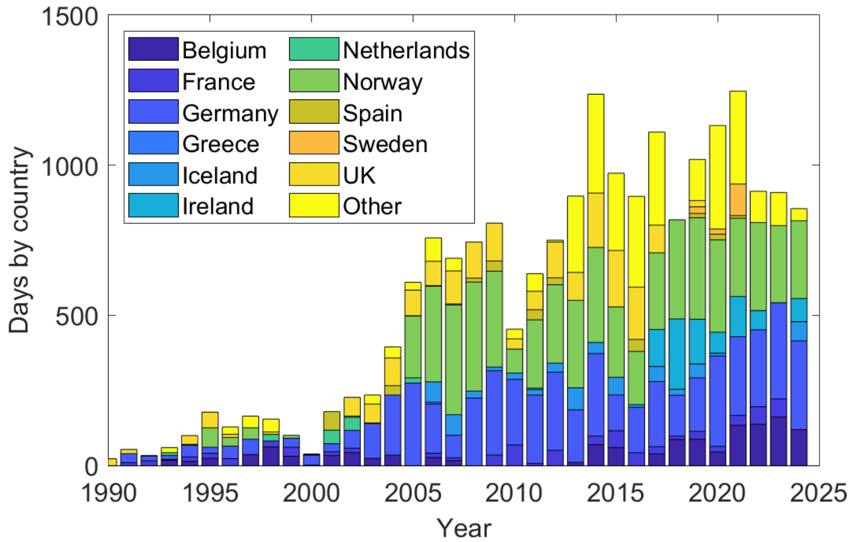


Figure 9. The cumulative number of days per year with *f*CO_2 measurements (flags A-D) for each European country and for other, non-European, countries for the North-East Atlantic.

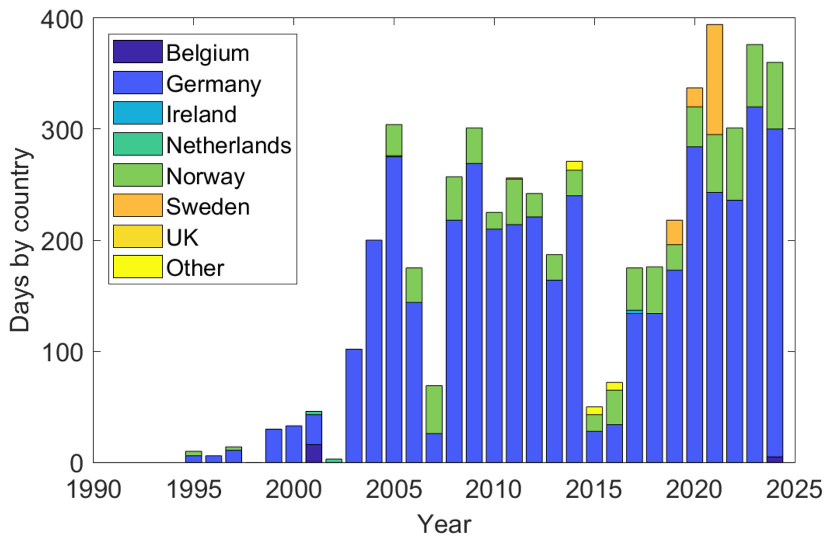


Figure 10. Annual cumulative *f*CO2 measurement days, Baltic Sea.

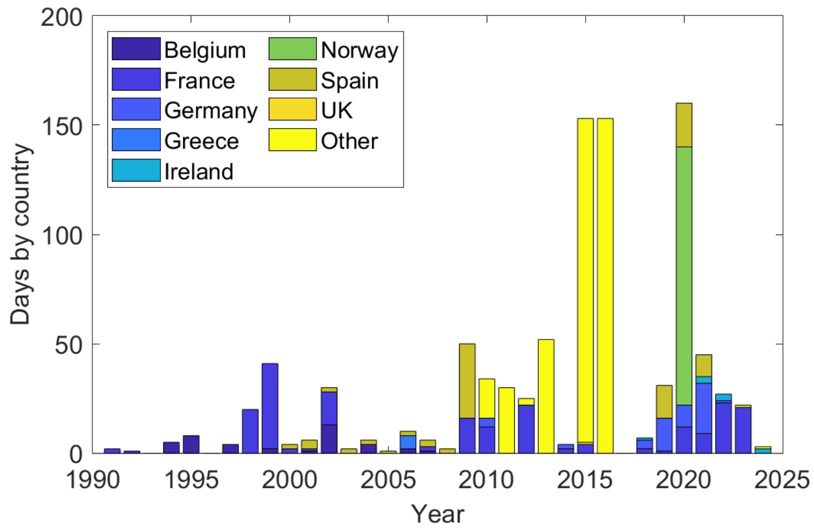


Figure 11. Annual cumulative *f*CO2 measurement days, Mediterranean Sea.

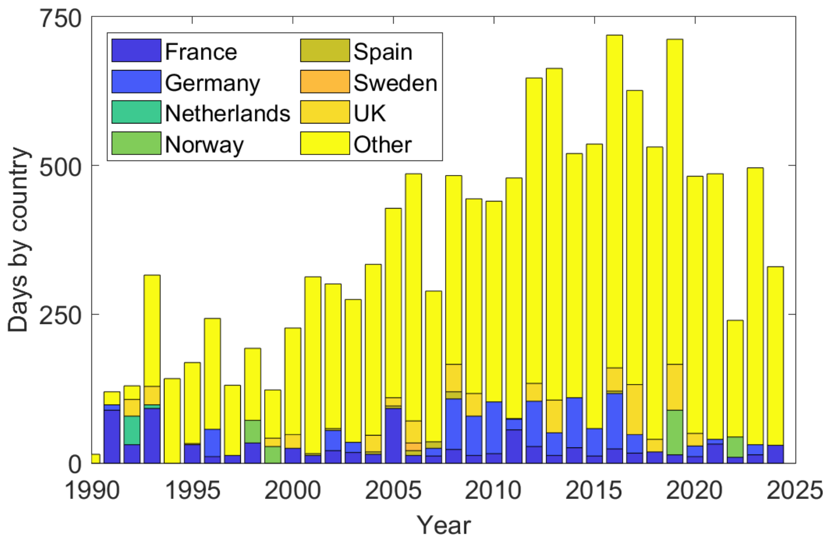


Figure 12. Annual cumulative fCO_2 measurement days Southern Ocean.

Policy interpretation: The red light here indicates that the number of reporting countries has nearly halved compared with the baseline period, which is highly concerning as it shifts the observational burden to only a few European nations. Efforts remain uneven across sea regions. Particularly positive are the strong contributions from Belgium, France, Germany and Norway. In the Southern Ocean, European observations represent only a small share of the total, increasing reliance on non-European partners. This combination of declining participation and external dependence risks undermining the continuity, robustness and strategic autonomy of Europe’s ocean carbon knowledge.

Overall assessment

Against the backdrop of a call by the International Ocean Carbon Coordination Project (IOCCP) to strengthen and operationalise the surface ocean carbon value chain, this audit shows that, at the global scale, surface ocean fCO_2 coverage has declined in recent years compared with the comparatively strong observation period of 2015–19. Even for that earlier phase, however, observational coverage has been considered to be below the level of ambition envisaged for the Global Climate Observing System. This reflects shifts across the international observing landscape rather than actions by Europe or any other single actor. However, it directly affects the reliability of the global datasets and synthesis products on which Europe's ocean carbon assessments and policy-relevant information depend, thereby shaping the context in which Europe's contributions must be interpreted.

Within this context, Europe holds a globally leading position in the development of surface ocean CO_2 data products and ocean biogeochemical models. This leadership underpins Europe's influence in global carbon cycle assessments, making the strength, continuity, and credibility of the observational foundation a critical consideration for sustaining that role.

However, the observational metrics assessed here show that this foundation is uneven, with contrasting patterns emerging at the regional level. The North-East Atlantic and the Baltic Sea show strengthened observational coverage, with the Baltic Sea providing a particularly positive example of how sustained and coordinated efforts can improve regional data availability. By contrast, surface ocean fCO_2 observations by European countries in the Southern Ocean have declined sharply, which is of particular concern given its central role in global ocean carbon uptake. In addition, the persistently under-observed Mediterranean Sea and the complete absence of recent surface ocean fCO_2 observations in the Black Sea raise questions about Europe's capacity to assess CO_2 dynamics across its bordering regional seas.

These regional imbalances are reinforced at the country level. Surface ocean CO_2 observations are increasingly concentrated in a small number of European countries. In particular, Belgium, France, Germany and Norway continue to provide strong and sustained contributions. However, the overall number of countries contributing medium- to high-quality data has fallen substantially. The absence of a fully operational European SOCAT coordination hub in recent years has further constrained Europe's capacity for data stewardship, quality control, and timely integration of observations into global synthesis products.

Taken together, the audit indicates that Europe's globally leading modelling and analytical capacity in the ocean carbon cycle is not yet supported by a consistently strong, geographically balanced, and strategically coordinated observational foundation. In a period of increasing reliance on ocean carbon information for climate assessment, policy, and diplomacy, addressing this imbalance is essential if Europe is to sustain and extend its leadership and to realise its ambition, under the European Ocean Pact, to take a leading international role in ocean observation and to contribute to the completion of a global ocean observing system that is fit for purpose.

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FAQ

What is surface ocean CO_2 and why is it relevant to measure it?
Surface ocean CO_2 is the carbon dioxide dissolved in the ocean's upper layer, where exchange with the atmosphere occurs. Measuring it shows how much CO_2 the ocean absorbs from the atmosphere and releases back into it. These measurements are essential for climate models, carbon budgets, and understanding climate change.

What is SOCAT and why is it essential?
SOCAT (Surface Ocean CO_2 Atlas, socat.info) is the global database of surface ocean CO_2 measurements for the open ocean and coastal seas. It brings together data from research ships, commercial vessels, yachts, moorings, buoys, and autonomous surface platforms into standardised data products. SOCAT underpins the Global Carbon Budget, IPCC assessments, and UNFCCC processes. Without SOCAT, reliable estimates of how much CO_2 the ocean absorbs would not be possible.

Why is broad geographic and good seasonal coverage so important?
Air–sea CO_2 exchange varies strongly across regions and seasons. If measurements are limited to a small number of shipping routes or mooring sites, large areas remain poorly constrained, increasing uncertainty. Broader coverage improves global carbon budgets, reduces uncertainty, and strengthens confidence in climate assessments.

How large is a 1° × 1° grid cell?
A 1° × 1° grid cell is defined as one degree of latitude by one degree of longitude. Because the Earth is curved, its area varies with latitude: at mid-latitudes it is approximately 100 km × 100 km (about 8,000–12,000 km^2), becoming smaller toward the poles and larger toward the tropics.

What does it mean when more grid cells are filled in a given year?
It means that surface ocean CO_2 measurements were made over a larger area of the ocean that year. A monthly grid cell is counted only if it contains at least one good- to medium-quality SOCAT fCO_2 measurement (flags A–D) during that month. More filled cells indicate broader spatial and temporal coverage and generally lower uncertainty.

How are surface ocean CO_2 measurements typically undertaken?
Most surface ocean fCO_2 measurements come from underway systems on ships. These typically consist of box-sized instruments installed inside the vessel, with seawater pumped continuously from below the hull and a CO_2 analyser measuring fCO_2 in near-real time. Smaller, but less accurate, sensors exist for moorings, surface vehicles, buoys, and sailing yachts.

Why do some ocean regions have few or no CO_2 measurements?
Measurements depend strongly on ship routes, national investment, and the ability to reach remote areas. Factors like harsh weather, sea ice, and political access also create observational “blind spots”. These gaps highlight where targeted investment could most effectively reduce uncertainty.

What is the surface ocean carbon value chain and why does it matter?
It describes the full system that turns in situ surface ocean CO_2 measurements into trusted climate information. It includes technology development, data collection, quality control, mapping, modelling, global climate reporting and policy making. A weakness at any step increases uncertainty in climate assessments.

Glossary

Air-sea CO_2 flux
The net exchange of CO_2 between ocean and atmosphere. Negative = ocean absorbs. Positive = ocean emits.

***f*CO_2**
Means fugacity of CO_2, which is a gas-corrected measure of CO_2 in seawater that indicates whether the ocean is absorbing or releasing CO_2.

G3W (Global Greenhouse Gas Watch)
A programme led by the World Meteorological Organization (WMO) that coordinates and integrates global greenhouse gas observations. It is being developed to provide up-to-date, observation-based information on greenhouse gas concentrations and surface–atmosphere fluxes over land and ocean.

GCB (Global Carbon Budget)
An annual assessment quantifying CO_2 emissions and natural sinks. Used by the Intergovernmental Panel on Climate Change (IPCC), the United Nations Framework Convention on Climate Change (UNFCCC), and national climate planners.

Gridded product
A spatial dataset created by combining individual observations into a regular, evenly spaced map, enabling analyses from regional to global scales.

ICOS (Integrated Carbon Observation System)
This European Research Infrastructure (ERIC) provides standardised measurements of CO_2 and other greenhouse gases across the ocean, the atmosphere and land-based ecosystems.

IOCCP (International Ocean Carbon Coordination Project)

This international coordination programme supports sustained global ocean carbon observations and assessments. It operates under the Intergovernmental Oceanographic Commission of UNESCO and the Scientific Committee on Oceanic Research.

μatm

Micro-atmospheres. A unit of pressure commonly used to express CO_2 levels in air or seawater.

Ocean carbon sink

The ocean's net uptake of CO_2 from the atmosphere. A stronger sink means more CO_2 absorbed and less remains in the air.

PgC / yr

Petagrams of carbon per year. A unit used to express the size of global CO_2 sources and sinks. 1 PgC = 1 billion tonnes of carbon.

Platform

Any system collecting in situ surface ocean CO_2 data, including ships, commercial vessels, sailing yachts, buoys, moorings, autonomous (uncrewed) surface vehicles.

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