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ARTICLE

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From Individual Observations to Global Assessments: Tracing the Marine Carbon Knowledge Value Chain

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Abstract

Marine carbon observations (MCOs) provide essential data to trace historical and current changes in marine carbon storage and fluxes that ultimately feed into the Global Carbon Budget and the Intergovernmental Panel on Climate Change report. Therefore, MCOs play a key role in informing global climate policy as well as ocean governance. However, they only achieve this potential if multiple sources of observations are combined and analyzed jointly. This implies an immense coordination effort by the international MCO community which developed, e.g., joint standards for the collection of (meta-)data, quality control processes, data platforms, etc. This article traces the value chain of MCOs, concretely for CO_2, from data collection to the Intergovernmental Panel on Climate Change report. Based on an interdisciplinary research project, the study illuminates which structures and practices the marine carbon community has developed to integrate different observations and measurement technologies, starting from German research institutes and agencies and expanding to the European and international networks to which they contribute. Combining a social network analysis with qualitative insights from in-depth interviews, the article identifies key information providers and brokers and pinpoints systemic vulnerabilities, e.g., where connections between observation networks or data platforms are maintained based on personal relationships or ad-hoc interactions rather than automated data submissions, or where temporally limited third party funding threatens the continued existence of the observation network.

The article concludes with recommendations on how the MCO network can be maintained and improved as an exemplary achievement of bottom-up coordination in scientific knowledge production.

Keywords
integrated knowledge production; marine carbon cycle; marine carbon observations; marine CO_2; ocean and climate

1. Introduction

The ocean absorbs roughly one-fourth of annual global CO_2 emissions (Friedlingstein et al., 2023; Global Carbon Project, 2023). Next to the atmosphere, which takes up 47%, forests, grass, and wetlands, which together make up 36%, fulfill an essential function in regulating the global climate and in buffering the human perturbation of the global carbon cycle. However, the latest iteration of the Global Carbon Budget (GCB; Friedlingstein et al., 2023) has shown that the effects of climate change are compromising both the ocean's and the land sinks' capacity to take up greenhouse gases. Increasingly, the ocean has also become a focus of carbon dioxide removal strategies, which include plans for the enhanced capture and storage of carbon dioxide, e.g., under the seabed (e.g., Mengis et al., 2023).

Understanding the dynamics of the marine carbon cycle and how climate and other changes affect it, as well as observing the exchange of CO_2 between the atmosphere and the ocean (marine CO_2 fluxes), is therefore essential for informed climate policy at the national and international scale. However, these insights stand at the end of a value chain that starts with an extensive number of individual measurements of marine CO_2. Ensuring that these measurements can be combined and analyzed jointly, as well as aggregating and synthesizing them, requires a massive coordination effort on the part of the international scientific community.

Over the last 15–20 years, this community has organized itself in a bottom-up process (e.g., Steinhoff et al., 2019; Wanninkhof et al., 2019). Through dedicated scientific conferences, research networks, and data platforms, scientists have created a global knowledge production and transfer system that permits the continuous measurement of key parameters to characterize and analyze the oceanic inorganic carbon system, to which marine CO_2 belongs. However, this bottom-up organization is reaching its limits. Over the last few years, the global capacity to observe surface ocean carbon to determine CO_2 fluxes has diminished rather than increased (Bakker et al., 2024)—precisely at a time when this knowledge is needed more than ever to design policies and evaluate measures to tackle climate change.

This article investigates the knowledge network that has created and maintained the value chain of marine carbon observations (MCOs) from data collection to the Intergovernmental Panel on Climate Change (IPCC) report, illuminating how and where different observations and measurement technologies are integrated. It conducts a social network analysis (SNA; e.g., Borgatti et al., 2013; Hanneman & Riddle, 2005) to identify key information providers and brokers (i.e., actors that connect disparate parts of the network; Meyer, 2010) and complements this analysis with information from in-depth interviews and participant observation to understand where vulnerabilities in the knowledge system exist and how they could be addressed. In that manner, the article contributes to debates among researchers from the MCO community as well as to the social science fields interested in opening the black box of academic knowledge production (Latour, 1987). It is the result of and reflects the findings of a three-year-long, interdisciplinary research project comprising social scientists, oceanographers, and biogeochemists.

Our investigation starts from the German MCO network. From there, it extends to the inter and transnational networks in which researchers from German organizations are embedded and to which they contribute. While the German MCO network shares some characteristics with those of other European countries (e.g., a somewhat decentralized organization of research, and a split between atmospheric and oceanic measurements), national networks can also be organized differently, taking, for example, a centralized approach that integrates atmospheric and marine observations, like the USA's National Oceanic and Atmospheric Administration does.

The article starts with a brief introduction to the marine carbon cycle and the observation networks that have been built to understand and monitor it, providing some insights into its historical emergence and development. We then introduce our data collection and SNA in Section 3 before presenting our results in Section 4, drawing on SNA findings and interview data to interpret network characteristics. In Section 5, we dive more deeply into the dynamics of the scientific system, discussing strengths and vulnerabilities. We conclude with a summary of our findings and a set of policy recommendations in Section 6.

2. The Marine Carbon Cycle and the Observation Network

2.1. The Marine Carbon Cycle

Out of all the natural carbon sinks, the ocean contains the largest carbon pool, of which the majority is inorganic carbon (Figure 1; Friedlingstein et al., 2023; Global Carbon Project, 2023). The inorganic carbon pool is represented by the variable dissolved inorganic carbon (DIC), which summarizes the concentrations of all DIC species (CO_2, bicarbonate HCO_3^-, and carbonate CO_3^{2-}) in seawater. Via air-sea gas exchange, CO_2 is constantly transferred between the atmosphere and the ocean. With rising CO_2 levels in the atmosphere, CO_2 uptake at the ocean surface has also increased, resulting in higher levels of oceanic DIC. Anthropogenic CO_2 uptake in the ocean can thus be quantified by comparing DIC measurements over time.

For air-sea exchange processes, the partial pressure of CO_2 (pCO_2) at the sea surface is particularly important. Together with wind speed, the difference between atmospheric pCO_2 and sea surface pCO_2 determines the direction and magnitude of the air–sea CO_2 flux, i.e., whether and how much CO_2 the ocean takes up from the atmosphere or vice versa, which varies seasonally and spatially (Takahashi et al., 2009). The oceanic inorganic carbon system has four measurable parameters: pH, DIC, total alkalinity, and pCO_2. It is sufficient to measure two of any of these four parameters to be able to calculate all other parameters of the inorganic carbon system based on knowledge of the environmental and equilibrium conditions (S. Emerson & Hedges, 2008).

2.2. Current State of MCOs and Historical Embedding

MCOs have traditionally been based on water samples taken from a research vessel and analyzed in the laboratory, relying on high-accuracy laboratory methods tailored to the measurement of marine inorganic carbon parameters (Dickson et al., 2007). These protocols were coordinated globally for the first time in the

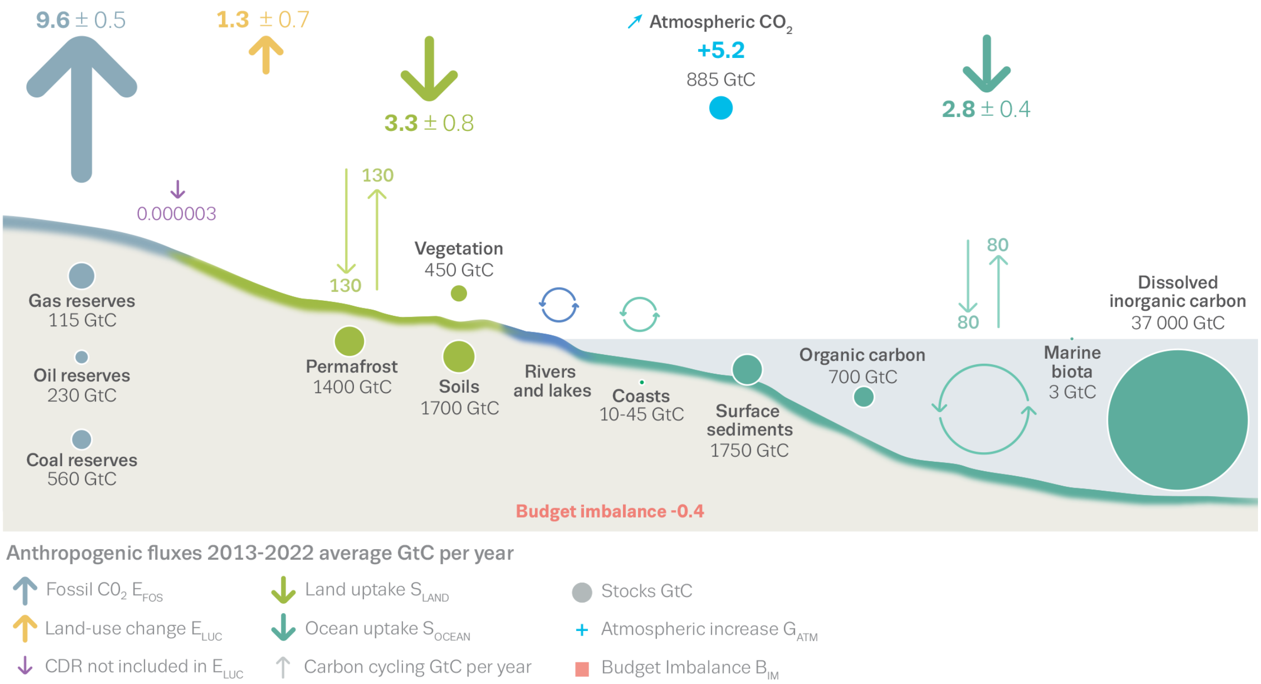

Figure 1. The global carbon cycle, including a quantification of different carbon sinks and anthropogenic fluxes from 2013–2022. Note: CDR is an acronym for Carbon Dioxide Removal. Source: Global Carbon Project (2023).

so-called GO-SHIP program, which emerged from the World Ocean Circulation Experiment in 1988–1998. The World Ocean Circulation Experiment collected research-vessel-based surveys of DIC on 40 basin-crossing transects, which, for the first time, allowed the tracing of anthropogenic CO_2 uptake and redistribution in the water column.

In the 1990s, improved and more automated instrumentation measuring surface ocean carbon to investigate CO_2 fluxes was established. This instrumentation permitted direct, high-accuracy measurements of pCO_2 from a seawater intake while the ship is underway thanks to additional reference gasses, and ancillary parameters like sea surface temperature and salinity (Pierrot et al., 2009). By installing such systems on commercial vessels, so-called Ships of Opportunity (SOOPs) were established, allowing commercial vessels to take continuous measurements along their regular routes and alleviating the need for a dedicated scientific ship and crew. This increased geographical and temporal coverage significantly. Given the increasing amount of pCO_2 data measured by different sources, participants at the UNESCO workshop Surface Ocean CO_2 Variability and Vulnerability agreed in 2007 that an effort was needed to make these data available on one single platform and in one common format. From this, the Surface Ocean CO_2 Atlas (SOCAT) emerged as a voluntary activity maintained by the global marine carbon community.

The early 2000s also saw an effort at the European level to establish a research infrastructure to integrate and coordinate carbon observations. Initially, these efforts focused on atmospheric and terrestrial observations but once the Integrated Carbon Observation System (ICOS) reached the preparatory stage, it expanded its scope to include MCOs as well. Today's ICOS marine observations rely on SOOP-based, underway observations as well as those on oceanic time series stations, which use submersible inorganic carbon sensors attached to moorings (Schuster et al., 2009) to continuously measure surface pCO_2 at a fixed location.

Such sensors are the most recent development in MCO methods, and techniques are continuously developed to improve their accuracy and stability. The development of small pH sensors allows the augmentation of SOOP-based observations with additional marine inorganic carbon system variables, as well as the expansion of carbon measurements to platforms such as the profiling Argo floats, which are autonomous, free-drifting platforms. Originating as a global program with over 30 member states in the 2000s, Argo floats revolutionized real-time data availability, providing synoptic global coverage of in-situ observations for the first time. While the original Argo program focused on temperature and salinity observations, the development of new sensors has allowed the program to include biogeochemical parameters as well (Roemmich et al., 2019), leading to the establishment of the biogeochemical Argo sub-program (BGC-Argo). Depending on the sensors attached, BGC-Argo floats either measure pCO_2 directly or parameters such as pH and dissolved oxygen, which can be used to calculate pCO_2. This can be done, for example, by drawing on pH values measured by the floats and estimates for total alkalinity based on regional relationships with salinity. Internationally, other efforts surrounding surface buoy data, coastal flux measurements, and non-surface observations beyond the Argo program also aim to refine and expand MCOs.

3. Concept and Methodology

Conducting science is an inherently social process (Latour, 1987) in which humans seek to understand their environment through the systematic collection and interpretation of information. Beyond the social practices of making meaning out of collected data shaped by specific sets of beliefs (Berger & Luckmann, 1966), science itself is also a social system with its operational logic and rules (e.g., regarding quality assurance, notions of good performance, etc.), communicative codes, forms of self-referencing, boundary creation, and auto-generation (Luhmann, 1984). As a social system, science and its respective sub-systems have a particular structural organization and functional differentiation, e.g., regarding funding streams, data collection, analysis, and provision, and the generation and dissemination of products. Therefore, understanding how scientific knowledge on marine CO_2 is produced—through the joint analysis of numerous instances of observation and various steps of aggregation and abstraction—and identifying potential path dependencies and vulnerabilities requires an analysis of the structural properties of this particular sub-system. This includes an analysis of the networks of actors that constitute it (Latour, 1987).

SNA is a useful method to do so, as it investigates social systems by looking at the relationships between different actors (see Borgatti et al., 2013; Hanneman & Riddle, 2005). It has been applied to various fields within the social sciences, including scientific collaborations and information exchange (e.g., Hatala & Lutta, 2009; Kardes et al., 2014; Long et al., 2015). It seeks to understand how actors ("nodes"), are connected and how an actor's characteristics ("attributes") influence their connections ("ties") or their position in the network, and vice versa. Ties can represent any type of relationship and they can be directed (e.g., when someone sends funds to someone else) or undirected, when two scientists collaborate on a publication, for example. Essential queries pertain to the network as a whole, e.g., to its so-called density, measuring how well actors are sharing information overall, or to the roles of specific actors. These can include gatekeeping or brokerage, i.e., when one actor connects two otherwise separate parts of the network ("betweenness" in SNA). In that position, the actor can either prevent the flow of information—serving as a gatekeeper—or support it and effectively link both parts of the network—serving as a knowledge broker (e.g., Behrend & Erwee, 2009; Cvitanovic et al., 2017). Other essential information gained from SNA pertains to the roles of sender vs. receiver in directed networks, measured by the number of outgoing or incoming ties, respectively.

As the MCO value chain requires extensive coordination among different actors and the exchange of various kinds of information, an SNA approach is useful to identify key players and potential bottlenecks. Combined with the information from in-depth interviews, this allows us to understand where the knowledge system is vulnerable and how the community has attempted to address these vulnerabilities.

In this article, SNA is used to assess how information flows between different actors engaged in MCOs and the associated science-policy interface. Nodes in the network represent organizations distinguished by kind (e.g., governmental agencies, research institutes, data platforms, etc.) and scale (e.g., rooted at the German national level, the European level, or the international level). Ties are directed and represent the sending or sharing of information (see data matrices in Supplementary Files). We conducted two separate analyses, one for the MCO knowledge network as a whole, and one for the sub-sample of the network that includes surface observations only. The former gives insight into the whole of MCO knowledge generation, while the latter illustrates whether there are specific characteristics for this smaller network, on which the MCO value chain has long relied, that might differ from the more extended picture.

Data for this article were collected between 2020 and 2023, in semi-structured interviews ($n = 26$) with scientists from Germany, Brazil, the UK, and Australia who contributed to different steps along the knowledge creation value chain (Mason, 2002). Interview questions included queries about (a) from whom actors received information related to MCO (data processing, interpolation, etc.) and (b) to whom they provided this kind of information. Data collection followed a purposive sampling process, deliberately selecting actors along the value chain, and included elements of snowball sampling, when interviewees pointed out other actors in the network (Jupp, 2006). Interviewees covered the entirety of the German MCO network and an illustrative sample of the international network into which this is embedded, covering essential actors along the value chain (e.g., ICOS and GCB). However, it did not manage to include actors engaged in the interpolation step of the value chain, which is therefore missing from the SNA. Next to SNA-specific questions, interviews primarily consisted of open-ended questions pursuing information on the tasks of different actors, and their perception and evaluation of the state of MCOs. Data collected also included various instances ($n = 8$) of participant observation during virtual and in-person meetings of organizations such as Argo, Argo Germany, ICOS, and ICOS Germany that were recorded in field notes (R. M. Emerson et al., 2001).

Interviews were transcribed and analyzed through a qualitative interpretative analysis (Heron, 1996), applying a bottom-up coding strategy and using the software Atlas.ti. For the SNA, qualitative information was translated into a two-dimensional matrix describing the flow of information between actors (see Supplementary Files). Weights from 1 to 4 were first assigned by the first author based on information reported in the interviews, evaluated by the co-authors, and then amended, in order to describe the intensity of information flow. 1 represents personal, ad-hoc information sharing, 2 represents institutionalized information sharing, 3 represents close ties and frequent exchanges, and 4 represents embodied links, i.e., when a person of one organization also works for another and thus unifies knowledge from both entities. The SNA was conducted with R Studio. Information on the specific software packages, queries, and their results are reported in the Supplementary Files.

4. MCOs as a Transnational Network

4.1. The Marine Carbon Value Chain and Its Contributors

Knowledge generation about the ocean as a dynamic carbon reservoir and sink starts with in-situ MCOs taken by fixed observation stations, research vessels, or SOOP lines. These data then undergo quality control to ensure that they are not subject to instrument failure or detectable measurement errors before they are submitted to SOCAT, where they are fed into the database and made available in two synthesis products: a global dataset of surface ocean pCO_2 and a gridded product of monthly surface water pCO_2 means.

Yet, combining data from different sources requires additional coordination as they need to be submitted in the same format and undergo the same quality control process to make them comparable, and to make claims regarding the accuracy of the final product. Scientists involved in SOCAT have created a protocol for sampling, quality control, and the submission process itself, which they update when the need arises, e.g., due to technological innovation, new scientific insights, or changes to the platform (Lauvset et al., 2018). This protocol includes the assignment of quality flags to communicate uncertainties transparently and a two-step quality control process where data are first controlled by the researcher submitting them but then also by another researcher from the community. The protocol and products are available via the SOCAT website, where contributions such as data submission or peer quality control are also recognized. Any researcher can contribute data to SOCAT as long as they fulfill the requirements laid out in these documents.

At the European level, in-situ surface MCOs are coordinated by ICOS, specifically the Ocean Thematic Center (ICOS-OTC). ICOS-OTC keeps an overview of carbon observations at the sea surface. It provides technical support to the individual measurement stations that are part of ICOS and coordinates the setting and implementation of joint standards for data collection that are developed in a bottom-up process, drawing on the experiences and expertise of the stations' principal investigators. Similarly, ICOS-OTC has coordinated the establishment of a protocol for subsequent quality control and provides an infrastructure for data management that is aligned with the SOCAT procedures to ensure usability and interoperability. Horizontal integration, i.e., coordination with terrestrial and atmospheric carbon observations, which also have dedicated thematic centers similar to the OTC, is provided by the national chapters of the member countries in the program, through an integrated data portal, and by the head office of ICOS. It is also at these levels that efforts are made to communicate the importance of these observations and to lobby for political attention and support, with national nodes doing so at the country level and representatives of the head office pursuing lobbying and communication efforts at the international scale, e.g., by participating at the Conference of the Parties (COP). ICOS as an entity is financed by the states that are members of it but the research infrastructure for MCOs themselves and the personnel conducting them is usually financed by individual agencies, research grants, etc.

To achieve the current quality and consistency of MCOs, the community has developed and provided seawater reference material for marine inorganic carbon analysis (Dickson et al., 2003), which assures that measurements are consistent across laboratories. It has also conducted intercomparison exercises to assess the level of accuracy achieved by various marine laboratories and systems and continues conducting them, for example, different instruments (Bockmon & Dickson, 2015; Körtzinger et al., 2000).

SOCAT gridded product is a synthesis product but one that does not interpolate, meaning that geographical and temporal gaps in the dataset remain as such. At the moment, these gaps are predominantly located in the Southern Ocean, South Pacific, South Atlantic, and Indian Ocean, where less commercial shipping activity and fewer research missions take place. Interpolated products use a variety of statistical and computational techniques to estimate values in unsampled areas, combining, e.g., machine learning and/or satellite data with SOCAT's observational data to create a product with continuous spatial fields that covers the ocean in its entirety (Gregg et al., 2003; Landschützer, 2016, 2020a, 2020b; Rödenbeck et al., 2013; Troupin et al., 2012). Interpolated maps are vital for climate models, which require complete data sets for boundary conditions and validation. They also allow researchers to calculate the carbon uptake of the ocean and quantify its function as a carbon sink. Doing so, and relating this value to other carbon sinks as well as anthropogenic CO_2 emissions is the task of the GCB. By estimating emissions from fossil fuel combustion and land use change, and balancing it against CO_2 uptake in the atmosphere, ocean, and on land, the GCB tracks how much carbon is entering the atmosphere due to human activity (Friedlingstein et al., 2023; Le Quéré et al., 2009). To do so, it draws directly on interpolated maps but also on SOCAT data, to assess the quality of model outputs. Its results are shared annually at the COP and data submission and quality control cycles of SOCAT are aligned with this schedule to ensure that updated data are available in time. The IPCC report, as the second final link in the value chain, refers directly to the GCB. Figure 2 shows the value chain and its respective components.

Various UN bodies report on oceanic observations related to CO_2 or try to coordinate them. The International Ocean Carbon Coordination Project provides coordination for the MCO community at the global scale, and serves as a bridge from the scientific community to policy-makers, a role that increasingly involves drawing attention to the importance of MCOs. The Global Ocean Observing System, which belongs to the UNESCO-IOC, seeks to coordinate ocean observations in general. To that end, it has established a list of essential ocean variables to be monitored globally, which includes all four variables of the marine inorganic carbon system. However, the IOC has no mandate to oblige member states to monitor these variables, thus drawing on its norm-setting power only. The Global Climate Observing System under the auspices of the World Meteorological Organization (WMO) coordinates observations of variables related to the global climate system and reports on marine carbon data as well.

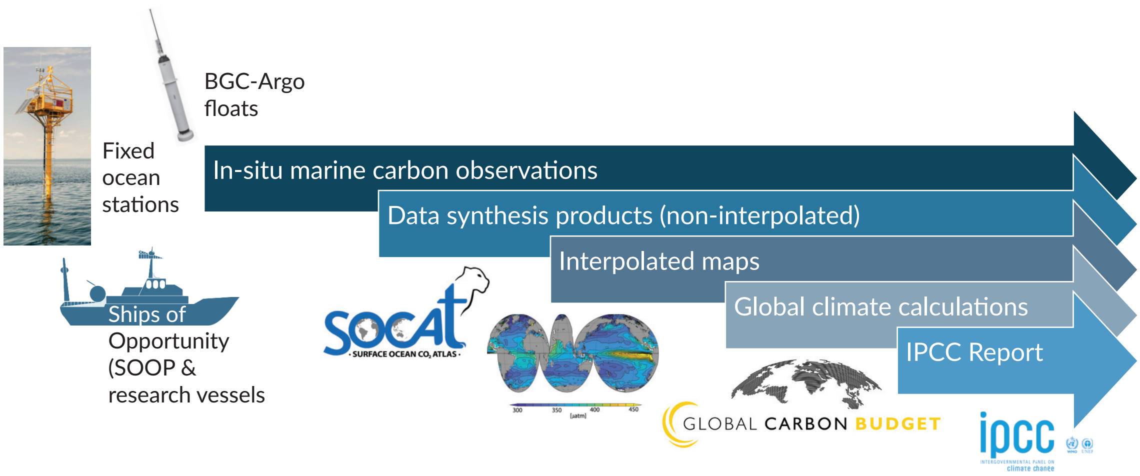

Figure 2. The value chain for MCOs.

To improve the understanding of the marine carbon cycle beyond the exchange of CO_2 at the ocean surface, to increase geographical coverage, and to extend measurements into the ocean interior, scientists have started to combine surface observations and observations of marine CO_2 across the ocean column collected by BGC-Argo floats, on top of other ongoing efforts mentioned in Section 2. However, integrating the measurements from floats is challenging as floats use different sensors from those generally used for surface observations. They are still comparatively new and target a different variable of the marine carbon system (pH vs. pCO_2). In addition, float sensors experience drift and need to be recalibrated against known standards. This can create issues regarding data accuracy and precision (Wimart-Rousseau et al., 2024). Integrating float data thus requires significant additional work, e.g., on the evaluation and improvement of pH sensor performance, the establishment of a new protocol that specifies requirements regarding accuracy, and the harmonization of data formats and metadata curation. At the moment, BGC sensors do not yet deliver data with sufficient accuracy to meet the requirements of SOCAT. Instead, they are submitted to the Global Argo Data Centers (Global DACs).

4.2. Analyzing the Flow of Information Across the Network

Various actors at the German, European, and international levels are involved in the MCO knowledge network. They provide, coordinate, or translate into policy advice scientific knowledge on marine CO_2 and thus fulfill different tasks at various points in the value chain. Table 1 provides an overview of those actors that were included in the SNA as part of the German MCO network and the European and international networks into which they are embedded. As data from BGC-Argo is not yet integrated into the MCO value chain, we ran two separate analyses, one focusing on the MCO knowledge network in its entirety (thus including BGC-Argo-related nodes and ties) and one with a sub-sample of the network focusing on surface observations only. Actors who are excluded from this second analysis are highlighted in blue. In addition to attributes like the scale and kind of the organization or program, Table 1 also indicates their core tasks concerning the MCO value chain, leaving aside the other work areas and related responsibilities. Some organizations are split into various entities located at different scales or with a slightly different focus. In these cases, we included the one most directly related to MCOs in the SNA and excluded the others, as indicated by the cells highlighted in grey. Due to limitations during data collection, actors related to the interpolation step in the value chain are missing from the analysis.

Table 1. Overview of German, European, and international actors involved in the MCO value chain and included as nodes in SNA.

Name	Kind	Scale	Core task in relation to marine CO_2
Alfred Wegener Institute (AWI), Helmholtz center for polar and marine research	Research institute	National	Conduct observations (focus on polar regions) and contribute to modeling for the GCB
BGC-Argo	Research program	International	Coordinate observations via Argo floats with BGC sensors and establish protocols
Argo-D		National	Coordinate the German contribution to Argo, e.g., float deployment and science communication
Euro-Argo		European	Coordinate the European contribution to Argo

Table 1. (Cont.) Overview of German, European, and international actors involved in the MCO value chain and included as nodes in SNA.

Name	Kind	Scale	Core task in relation to marine CO_2
Argo International		International	Coordinate the Argo program overall
Federal Ministry for Education and Research (BMBF)	Ministry	National	Fund research
Federal Ministry for Digit and Transport (BMDV)	Ministry	National	Fund infrastructure for, e.g., weather observations
Federal Maritime and Hydrographic Agency (BSH)	Agency	National	Coordinate German contribution to Argo and conduct observation with Argo floats
COP to UNFCCC	Part of the UN system	International	Climate policy-making
GCB	Research program	International	Calculate the GCB, including ocean sink
Global Climate Observing System (GCOS)	UN body	International	Coordinate global climate observations
GEOMAR Helmholtz Center for Ocean Research Kiel	Research institute	National	Conduct observations via research cruises, SOOP line in North Atlantic, and fixed ocean station in Cabo Verde
Global DAC	Data platform	International	Provide quality controlled data in a unified format
Global Ocean Observing System (GOOS)	UN body	International	Coordinate ocean research generally
Helmholtz Center Hereon	Research institute	National	Conduct observations via fixed ocean station at the German North Sea coast
ICOS-OTC	Research program	European	Coordinate observations from various sources at the European level
ICOS-Head Office	Research program	European	Coordinate carbon observations (including terrestrial and atmospheric) at the European level
ICOS Germany	Research program	National	Coordinate carbon observations (including terrestrial and atmospheric) at the national level
International Ocean Carbon Coordination Project (IOCCP)	Part of the UN system	International	Lobby for the importance of research on marine carbon
UNESCO-IOC	Part of the UN system	International	Science-policy interface for ocean research
Leibniz Institute for Baltic Sea Research Warnemünde	Research institute	National	Conduct observations with BGC Argo floats and SOOP line in the Baltic Sea
IPCC	Part of the UN system	International	Synthesize climate research
SOCAT	Data platform	International	Provide quality-controlled data in a unified format
WMO	Part of the UN system	International	Coordinate research on the global climate system

Note: Entities highlighted in grey are part of the same overarching organization.

In both the full transnational network through which knowledge on marine CO_2 is produced and its sub-sample for surface-only MCOs, more than 60% of the ties are reciprocated, which demonstrates that entities that send information to others also receive information in return. Knowledge generation on marine CO_2 is thus not a unidirectional process. Rather, it requires an exchange between those who compile or aggregate data from different sources and those who collect it in the first place, e.g., to set standards together and to ensure that they remain up to date, or to coordinate observations in order to maximize geographical coverage. Indeed, in-degree centrality (Borgatti et al., 2013), which measures how many incoming ties an entity has, and out-degree centrality, which measures out-going ties, are significantly correlated ($r = 0.787$, $p = 6.335\text{e-}05$). The correlation becomes even stronger when looking at the network related to surface observations only ($r = 0.825$, p-value $= 0.0001526$), indicating that information providers are nearly always also information recipients and vice versa.

Interestingly, actors that are higher up the value chain (such as the GCB or the IPCC) have fewer incoming ties than those further down (see Figure 3), which means that the integration of knowledge—in this case, of data points, and common measurement and submission standards, etc.—occurs beforehand. This is independent of whether we assess the entire network or its surface-only part. They also have fewer ties

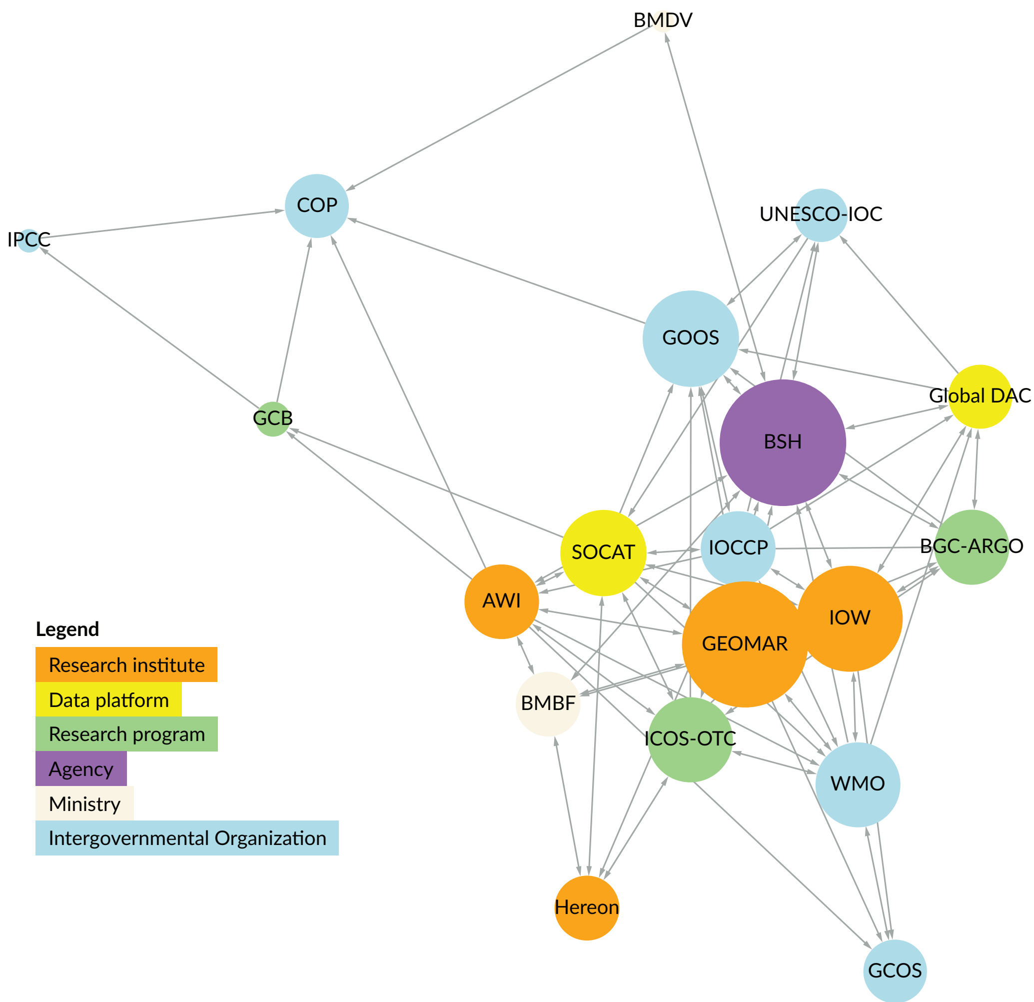

Figure 3. Full marine CO_2 knowledge network. Notes: Size of nodes according to the number of incoming ties; size of arrows according to the intensity of information sharing.

overall. This links to the comparatively low-density values of 0.35 and 0.32 that we find for the entire network and its surface-only sub-sample (Borgatti et al., 2013). In both, less than half of all connections that could, theoretically, be established between different actors are actually established and used to share information. Considering the notion of the value chain and the information supplied in the interviews, these measures reflect the successful division of labor: As knowledge is aggregated and shifted up along the value chain, there is less need for actors such as the GCB or the IPCC to draw information directly from actors engaged in MCOs. It also reflects the linear nature of the value chain where the IPCC and the COP are considered the endpoints, whose audience lies outside of the network assessed here.

As Figure 4 shows, the betweenness values in the full MCO network, which show the extent to which an entity connects disparate parts of the network (Borgatti et al., 2013), are comparatively high for research institutes such as GEOMAR and AWI and for the German maritime agency BSH (exact values are reported in the Supplementary Files). These actors thus have the capacity to act as knowledge brokers and, based on information provided in the interviews, effectively seek out information exchange across the network.

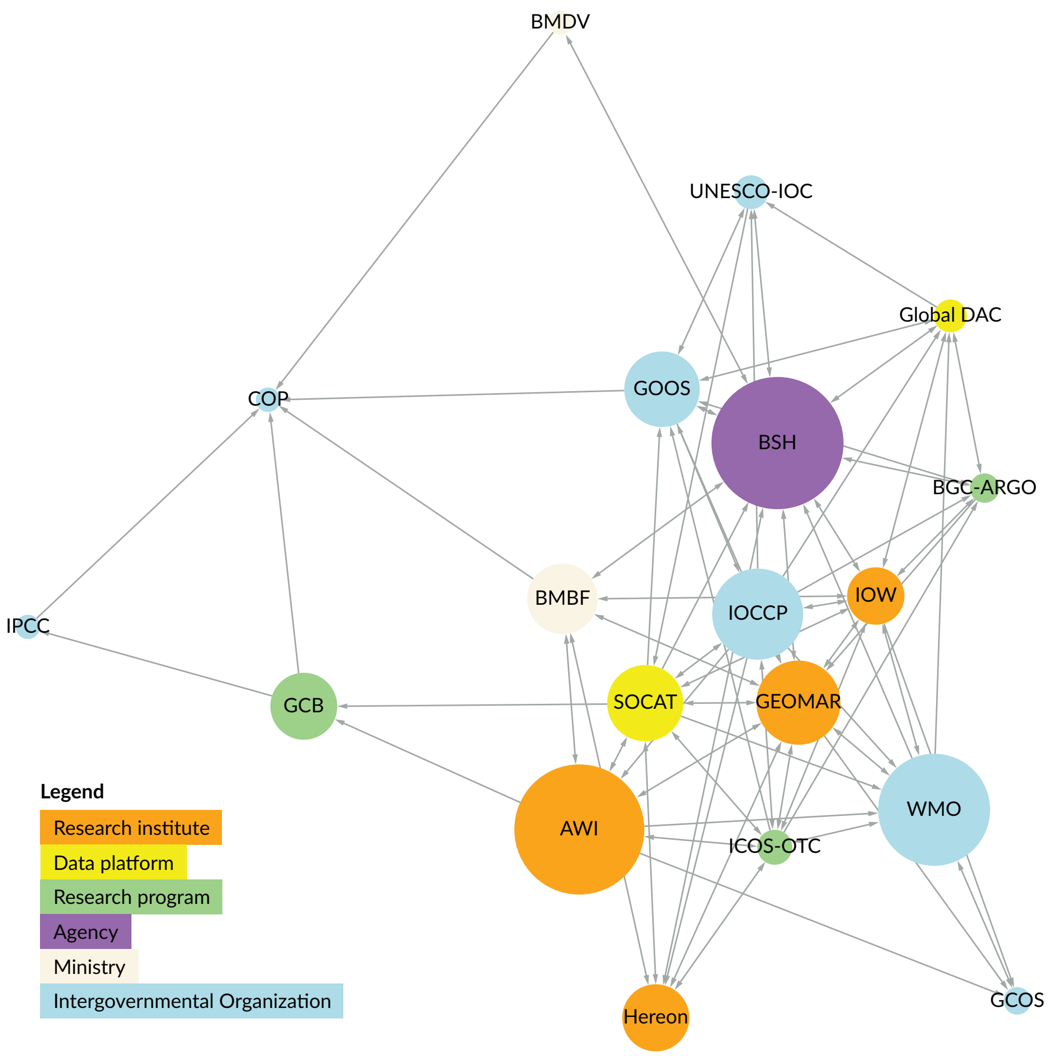

Figure 4. Full marine CO2 knowledge network. Notes: Size of nodes according to the betweenness values; size of arrows according to the intensity of information exchange.

For example, researchers from GEOMAR, Leibniz Institute for Baltic Sea Research Warnemünde, and BSH are the ones driving forward the integration of MCOs taken at the surface with measurements taken across the ocean column by Argo floats. Similarly, researchers from AWI are involved in marine carbon measurements as well as in modeling activities related to the GCB, connecting actors across the value chain. BSH, as the dedicated marine federal agency of Germany, has strong links to the research community across different observation networks but also to both ministries with tasks and interests related to ocean observations, and to intergovernmental entities such as the IOC where it represents Germany.

The WMO also has a comparatively high betweenness value. This can be explained by its recent initiative to establish a Global Greenhouse Gas Watch monitoring system, of which marine carbon is to be a part, and which led to increasing information exchange with actors in the MCO network. Until now, WMO has mostly been concerned with atmospheric measurements of CO_2, leaving marine measurements largely under the auspices of UNESCO-IOC, although marine carbon parameters are also reported to the Global Climate Observing System. Pushing for a holistic understanding and measurement of the global carbon cycle through one single initiative under the auspices of the WMO points to the fact that roles between WMO and IOC are shifting and that knowledge from the oceanic system is increasingly recognized as directly relevant to questions related to meteorology and climate.

The other body from the UN system with relatively high betweenness values is the International Ocean Carbon Coordination Project as the dedicated coordination and outreach entity for MCOs, connecting to actors conducting and compiling observation data and linking them to the UN system as well. It also has a large number of outgoing ties, illustrating that rather than fulfilling its role by receiving and compiling information, it operates as an entity that spreads news and engages proactively across its connections that succeed in bridging different parts of the network, which our interview data supports. When looking at the network of surface ocean carbon observations only, SOCAT becomes one of the entities with the largest betweenness values, demonstrating its importance for this part of the value chain in connecting individual data points to more aggregated, policy-oriented products (Figure 5).

When assessing homophily in the network, i.e., the extent to which actors are more likely to form ties within a group than across groups, it becomes evident that there are even more connections across different kinds of entities (e.g., research institutes, data platforms, ministries, etc.) than among them. The odds-ratio test returns a value of 1 for equal likelihood, a value between 0 and 1 for a higher likelihood of across-group ties, and a value higher than 1 to infinite for a higher likelihood of within-group ties (Bojanowski & Corten, 2014). For the different kinds of entities in the entire MCO network, the test returns a value of 0.78, and for the surface-only network one of 0.74. This shows that, next to information sharing between entities that likely have similar expertise (e.g., among research institutes), the majority of links tie actors to those that likely have different concerns and priorities (e.g., research institutes to UN bodies, data platforms, research programs, and vice versa) and that subsequently bring different stocks of knowledge to the table, e.g., related to funding priorities and opportunities, political developments at the international stage, etc. The slight heterophily of the network (i.e., the higher likelihood of ties across actor groups rather than within them) also speaks to its ability to move information along the value chain rather than circulating it back and forth within one particular group. When looking at scales (i.e., German, EU, and international) rather than kinds of entities, ties within and across groups are almost evenly split (odds-ratio test result: 1.15 for the entire network and 1.05 for the surface observation only). This demonstrates that actors overall are about as likely to share information with

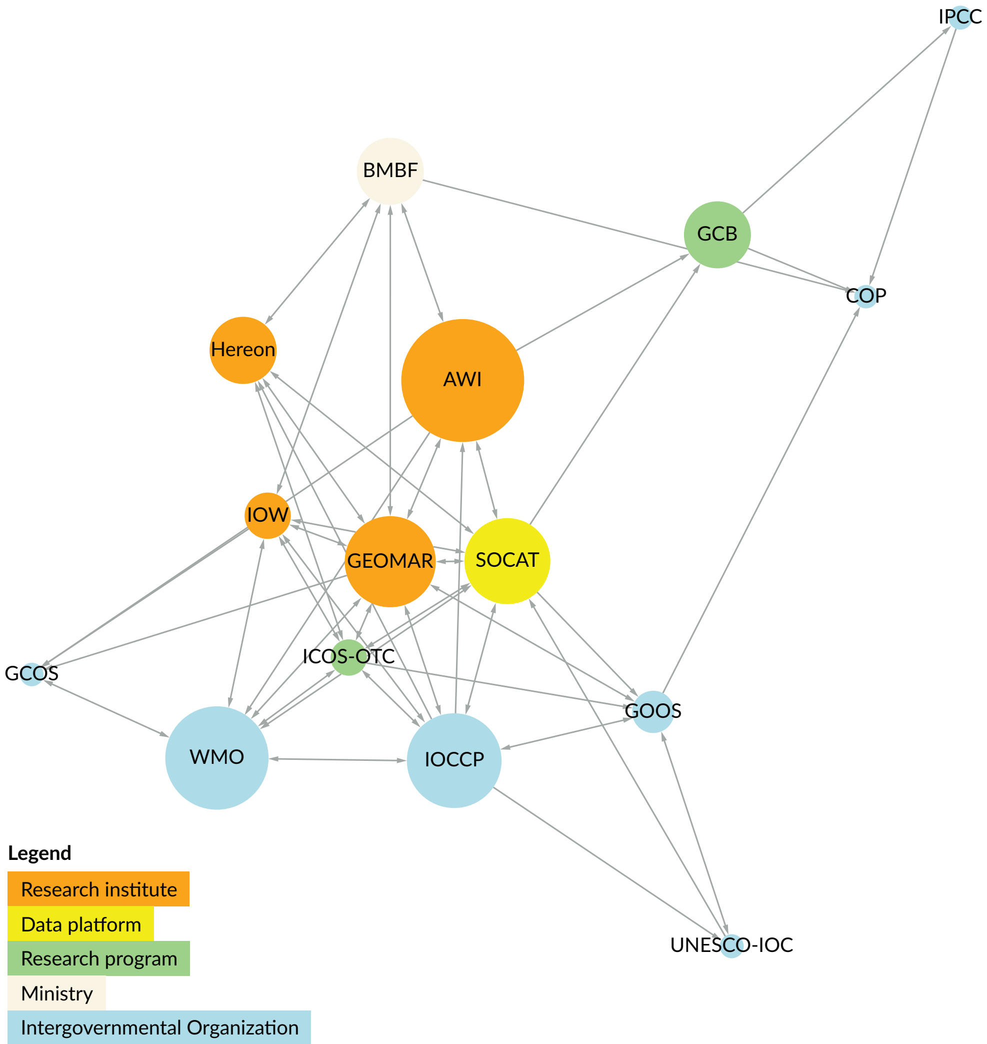

Figure 5. Marine CO_2 knowledge network for surface observation only. Notes: Size of nodes according to the betweenness values; size of arrows according to the intensity of information exchange.

others that are located at the same scale (i.e., that also form part of the German national science system) as they are with entities at the European or the international level, with a very slight tendency towards sharing information within the same scale if we look at the network in its entirety.

5. Strengths and Vulnerabilities of the Network

Looking at the structural properties of the system in which knowledge on marine CO_2 is produced demonstrates the large extent to which entities across spatial scales and focus areas are engaged in a mutual exchange of information, answering to the coordination challenges posed by a field of study that requires the synthesis of large amounts of single data points collected with various instruments and in diverse geographies. Contrary to the mental image provided by a value chain where information flows in one direction only, knowledge on marine CO_2 is created by a continuous back and forth between the entities located at different stages to ensure that the information provided fulfills the needs of the next aggregation step.

Interviewees unanimously agree that the close ties that actors maintain to others are the clear strength of the network, allowing researchers to minimize transaction costs by coordinating processes (e.g., aligning ICOS data submission requirements and timeline with those of SOCAT), to have an overview of the state of research and new technological developments in their field, and to ensure that the necessary knowledge for international climate policy-making reaches the policy sphere reliably.

However, several interviewees pointed out that the coordination effort that is required remains largely invisible, as standard-setting procedures, intercomparisons of instruments, data quality control, etc., are not, themselves, part of the final products to which they contribute. This lack of visibility is often tied to a lack of dedicated funding. SOCAT, for example, relies almost exclusively on voluntary contributions for its peer-review process of data. It receives no institutional funding, even though the 37.3 million individual measurements that it includes provide the backbone for global assessments of the ocean's function and capacity as a carbon sink. "A lot of it relies on personal conviction," says one researcher (Interview 3), describing how information flow across the network is maintained. Similarly, data management (i.e., the storage of data, its provision in adequate formats, the collection and provision of metadata, etc.), which is essential so that information collected by one entity can be found and used by another, is rarely given sufficient attention by funding organizations or recognition in academic performance metrics (Interview 3, Interview 12, and Observation 3).

As it is rather small, most researchers within the MCO community in Germany have well-established relationships with each other as well as with the representatives of international organizations and, sometimes, even their counterparts at the ministries. Many of the people engaged in the MCO value chain have actively shaped it and therefore also have knowledge about the functioning and operational requirements of other entities. Similarly, people are often affiliated with several entities at once. On the one hand, this eases the flow of information across the network and helps to keep it functional despite the lack of funding for key tasks and entities, as personal ties are often leveraged to solicit voluntary support (Interview 3, Interview 8, and Interview 12).

On the other hand, it also makes the system vulnerable to an extensive loss of institutional knowledge and an increase in transaction costs when people retire, fall ill, etc. (Interview 1, Interview 3, and Interview 11). As a generational change is approaching in many entities, this might pose a significant challenge in the coming years, especially because tasks for which no or very limited funds are available are often taken up by tenured professors whose positions don't rely on the acquisition of research projects (Interview 11 and Interview 12). "Maybe it's our own mistake that we have kept it going like this for so long, giving the impression that it's going well, when really, it is not," one meeting participant says, referring to the extent of voluntary work that goes into maintaining the existing MCO system and value chain (Observation 3). The personal conviction and intrinsic interest of actors within the network to facilitate the flow of information required to maintain the MCO value chain also explains why entities with high betweenness values overwhelmingly use their position to serve as knowledge brokers, as interviews and participant observation demonstrate, rather than as gatekeepers.

As significant and often voluntary effort goes into maintaining data collection and provision in the first place, little resources are left to evaluate and improve the value chain itself. For example, over the last years, the discrepancy between modeled marine carbon uptake and calculations based on data products has increased (Interview 11 and Interview 15). The research community has responded with a bottom-up process to improve the knowledge about the global carbon sources and sinks on regional levels to support the GCP (see RECCAP2-ocean, n.d.). Yet, the exact causes of the discrepancy and how to resolve it remain unclear as resources to deepen the endeavor are lacking—RECCAP-2 was another largely voluntary effort—and so is international steering (Interview 11).

The reliance on research funding for data collection represents another vulnerability. While technological innovations for measuring instruments satisfy the novelty requirement of research funding, the existing observation system mostly fulfills the purpose of monitoring marine carbon. This requires routine, standardized observations over time and is thus, by its very nature, ill-suited for research funding lines (Interview 4 and Interview 11). Having grown out of novel research and technology at the time, MCOs in Germany and many other parts of Europe are still linked to research funding rather than institutionalized climate monitoring systems. Partly due to this inconsistency, the existing network of SOOP lines maintained by European researchers has shrunk over the last years despite increasing recognition of the importance of integrated carbon observations and the fact that overall coverage of the global ocean surface by MCOs only extends to 2% (Interview 8 and Interview 11).

The positioning of MCOs between monitoring and research with the associated lack of funding security and academic recognition for key tasks also makes it challenging to recruit academic talent. As one senior researcher phrases it: “How can I advise my PhD students to pursue this? Or to put hours of their time into curating data for SOCAT when they have to write publications?” (Interview 12).

The Global Greenhouse Gas Watch initiative and the associated emergence of the WMO as a broker organization is therefore a promising development as, contrary to the UNESCO-IOC, it has the capacity to make binding decisions for its member states, e.g., on the establishment of monitoring networks. Including marine carbon in this initiative potentially represents an important step in shifting MCOs from research funding lines towards institutional ones and in making a steering effort at the international level. Symbolically, it also integrates MCOs more firmly into the climate observation community.

6. Conclusion

This article is the result of an interdisciplinary project aiming to understand how knowledge of MCOs is produced and made available for global policy-making. Starting from the German MCO network, and expanding to the European and international networks into which this is embedded, it provides an innovative perspective on the internal processes through which data from various sources are collected, made comparable, and turned into useful information for the policy process. It demonstrates the large extent of mutual information exchange that occurs within this knowledge system across entities at different scales and with different foci, and the immense and largely invisible coordination effort that it requires. It finds that, to a large part, this coordination effort is borne by entities at the bottom of the value chain, executing and coordinating measurement and data processing procedures so that data from multiple sources and geographies can be integrated and provided in a common format, in one location.

However, our analysis also shows that the knowledge system is vulnerable to fluctuations in funding, especially at the levels of data collection, data provision, and data management. It demonstrates that long-standing relationships facilitate the exchange of knowledge as well as the provision of voluntary support necessary to cope with, e.g., staff shortages or other systemic bottlenecks. These vulnerabilities have raised acute concerns about the sustainability of the knowledge system in its current form. Policy-makers engaged in the fields of science and/or climate policy thus need to (a) recognize the importance of coordination by ensuring the continued existence of coordination platforms and programs and providing them with sufficient resources, (b) resolve the institutional insecurity of MCOs by supporting the integration of marine carbon into a global greenhouse gas monitoring system, and (c) recognize the importance of data management and provision as a key task, adapting metrics for academic performance and ensuring that sufficient funds are available.

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Conflict of Interests

The authors declare no conflict of interests.

Data Availability

Data collected for this research can be made available upon request with some modifications to guarantee anonymity.

Supplementary Material

Supplementary material for this article is available online in the format provided by the author (unedited).

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