DISCOVER-C: DIagnoSis of Carbon in the Ocean: Variability, uncERtainty and the Coasts

Working Group proposal submitted to SCOR April 2019

Co-Chairs:

Peter Landschützer
Max Planck Institute for Meteorology, Hamburg, Germany
peter.landschuetzer@mpimet.mpg.de

Galen A. McKinley
Lamont Doherty Earth Observatory and Columbia University, NY, USA
mckinley@ldeo.columbia.edu

1. Summary

A number of recent studies have applied novel statistical and machine-learning methods to *in situ* surface ocean carbon dioxide (CO_2) observations to estimate the ocean carbon sink with unprecedented spatio-temporal resolution. These studies suggest that the oceanic CO_2 sink for carbon dioxide is more variable on multiyear timescales than previously estimated from biogeochemical model simulations. This newly-identified variability challenges our model-based mechanistic understanding, and puts into question our projections of the future ocean carbon sink. These observation-based estimates, however, rely on extensive interpolation of limited observations, and thus their reliability is unclear, particularly in data-sparse regions and seasons. Furthermore, inconsistencies regarding the ocean area covered by open and coastal ocean estimates hampers our ability to constrain CO_2 fluxes across the full aquatic continuum. The goal of this working group will be to assess critical uncertainties in existing data-based products, determine how best to integrate observation-based open ocean and coastal ocean estimates of CO_2 air-sea fluxes, and evaluate the impacts of CO_2 release associated with river discharge. These efforts will lead to better constraints on the contemporary ocean carbon sink and its variability. The results of this SCOR Working Group will assist the global carbon community in informing the 5-yearly global update of progress toward fulfilling the UNFCCC Paris Agreement, and thus contribute to sustainable development goal (SDG) 13. It will also provide guidance where we lack essential knowledge to assess the rate of ocean acidification and the saturation states of aragonite and calcite, which are direct indicators (SDG 14.3.1) for the wellbeing of marine life, related to SDG 14.

2. Scientific Background and Rationale

Global assessments suggest that, in the past decade, the ocean has annually taken up about 25% of the CO_2 emitted by human activities (Le Quéré et al. 2018) which, in turn, leads to ocean acidification harmful for entire ecosystems. Despite the ocean's crucial role, we still lack essential knowledge regarding variability of ocean carbon uptake in time and space. Without building up this knowledge towards the first UN stocktake in 2023, where the collective progress of all countries in reducing emissions will be established, we might be unable to measure the success of the Paris Agreement (Peters et al. 2017).

For many years, the strength of the ocean CO_2 sink has been estimated using ocean forward models that have been tuned to match a variety of observational estimates for the 1990s and the cumulative uptake over the industrial period. These models reproduce the increase in the surface ocean partial pressure of CO_2 (pCO_2) that is expected from the increase in anthropogenic CO_2 in the atmosphere and indicate only small to moderate climate variability around the anthropogenic trend. If this is the case, then the observed variations in the atmospheric growth rate of CO_2 must be due almost exclusively to variability in the land sink. Recently, the Global Carbon Project reported that we are unable to balance the global carbon budget, finding a residual term of ~0.5 PgC yr^{-1} (or roughly 5% of current fossil fuel emissions) remains (Le Quéré et al. 2018). Despite the fact that the ocean sink is better constrained than the land sink, we cannot exclude the ocean as a possible source for this substantial discrepancy.

Over the past decade, the number of publicly available surface ocean CO_2 observations has increased rapidly from 6 million in the first release of the Surface Ocean CO2 Atlas (SOCAT) database (Pfeil et al. 2013, Bakker et al. 2014, Bakker et al. 2016) in 2011 to 23 million data in 2018. These valuable observations and synthesis effort have enabled scientists around the world to create a variety of new observation-based estimates of the ocean carbon sink, taking advantage of novel data-interpolation techniques based on statistics and machine-learning to fill observational gaps. These studies suggest much stronger variability on interannual to decadal timescales than earlier model estimates (Rödenbeck et al. 2015, Landschützer et al. 2016, Gregor et al. 2018, Le Quéré et al. 2018), calling into question both the mechanistic understanding gained from ocean models, and our ability to precisely predict the future ocean carbon sink (Figure 1). These surface ocean CO_2-based estimates, however, suffer from heterogeneous data distribution and large ocean regions with little data coverage. A study by Rödenbeck et al. (2015) highlights that substantial differences of up to 1 PgC yr^{-1} occur between methods, i.e. twice the current carbon budget imbalance, highlighting the need to better constrain observation-based air-sea CO_2 fluxes.

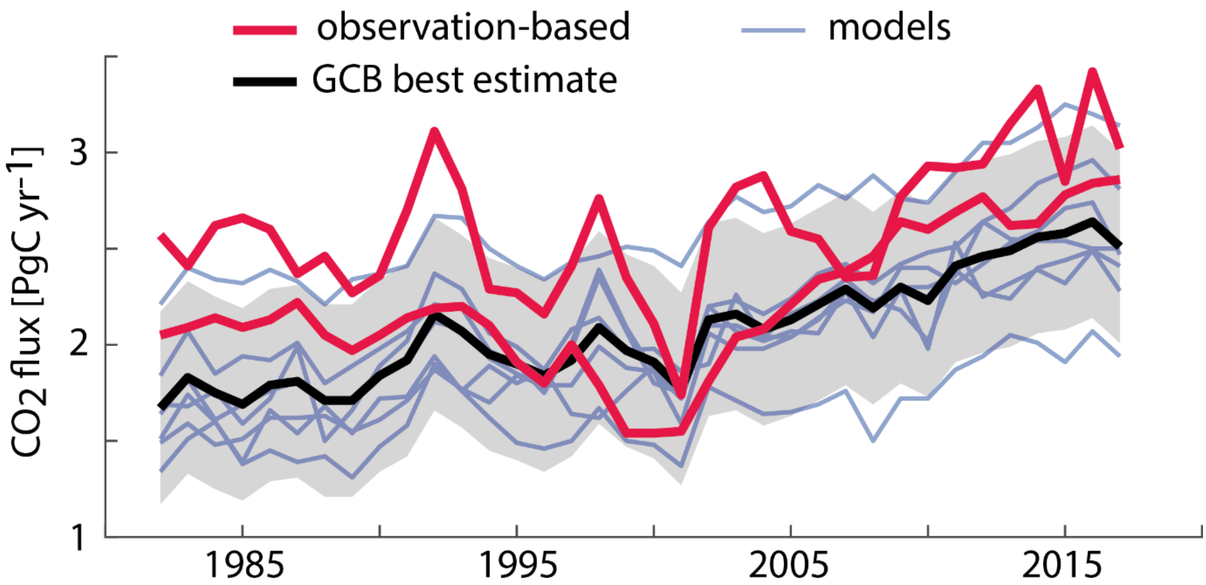

Figure 1: Air-sea CO2 exchange and its difference between different methods from Le Quéré et al. (2018). Observation-based estimates are highlighted in red, model-based estimates are in grey and the Global Carbon Budget best estimate with uncertainty shading is highlighted in black.

Substantial discrepancies do not only exist between observation-based estimates due to methodological differences (see e.g. Figure 1), but further as a result of differences in the ocean regions covered by observation-based estimates (Rödenbeck et al 2015). The majority of surface ocean CO_2 measurement-based methods do not include significant carbon sinks such as the Arctic Ocean and coastal waters. Yet, the polar oceans as well as the Eastern Boundary upwelling systems (Gruber et al. 2012) will be among the first ocean regions to experience critical declines in ocean pH. We are in desperate need to close this gap and investigate the role of these regions before we can compare products and provide a best global ocean carbon sink constraint. While there have been recent developments in constraining the coastal ocean CO_2 fluxes (Laruelle et al. 2017) and Arctic Ocean CO_2 fluxes (Yasunaka et al. 2016), these have not yet been integrated with the global ocean flux products.

Another issue is that the area of the ocean represented in the different approaches varies significantly. Based on the 1^{o} x 1^{o} global ocean mask of RECCAP (Canadell et al. 2011), ocean models cover 89-99% of the total ocean area. The data-based products include only 77-87%, often leaving out much of the Southern Ocean, a region of significant carbon uptake (Gruber et al. 2019). These differences alone lead to global mean flux discrepancies of up to 0.5 PgC yr^{-1}. The Global Carbon Budget (Le Quéré et al. 2018) has not addressed these masking issues, instead attribute mean differences between modelled and observation-based estimates to riverine inputs of natural carbon from 0.45 to 0.78 PgC yr^{-1} (Jacobson et al. 2007, Resplandy et al. 2018).

In summary, there are a wide range of issues – coastal, riverine, masking - that need to be resolved. All these issues impact the quality of our current estimates of the ocean carbon sink, both of its mean and its variability. These issues require expert attention and the development of clear recommendations that can support more reliable diagnoses in the years to come.

There are currently several active efforts to assess recent ocean carbon fluxes and placing these in context with the global anthropogenic carbon cycle, such as the REgional Carbon Cycle Assessment and Processes phase 2 (RECCAP2) (https://www.reccap2-gotemba2019.org), the Global Carbon Project's annual Global Carbon Budget (Le Quéré et al. 2018), and the IPCC AR6 assessment. As the primary goal of these ongoing assessments is to integrate ocean fluxes into a global carbon cycle meta-analyses, these projects will have the time to put focused attention on accounting for inconsistencies between ocean flux estimates. This is why this effort is needed. This working group will support these other efforts by understanding and remedying methodological discrepancies and quantifying the resulting uncertainty.

As we improve our diagnosis of ocean carbon fluxes based on models and existing data, new data streams based on autonomous measuring devices (such as Biogeochemical Argo (BGC-Argo) floats) have emerged. There is great potential from these data, but better understanding of the impacts of adding new data with different error statistics is required for robust product development. Further, discrepancies between open-ocean and coastal ocean estimates that this WG identifies will provide important direction for future field campaigns.

The United Nations has presented 17 sustainable development goals (SDG) from which SDG14 (Life below water) and SDG 13 (Climate action) will directly benefit from this working group. We will better constrain the representation of internal or forced variability based on the to-date most reliable air-sea CO_2 flux estimates from observations and models. These estimates are critical to assessing how changes in anthropogenic emissions are impacting atmospheric CO_2 concentration and thus are a critical component of the 5-yearly global stocktake under article 14 of the UNFCCC Paris Agreement with the first stocktake in 2023. For climate pledges to be renewed and strengthened, it is important that the global carbon science community be able to quantify natural carbon sources and sinks accurately.

Better quantification of past, present and future carbon fluxes will also improve estimates of trends in ocean acidification and the saturation states of aragonite and calcite, which are direct indicators (SDG 14.3.1) for the wellbeing of marine life. Combining available air-sea CO_2 flux estimates from models, open ocean, coastal and marginal sea products to enhance our ability to monitor the changing carbon state of the ocean is the only way to monitor our progress toward this critical development goal.

In this SCOR Working Group (WG) we will 1) compare monthly estimates of ocean carbon uptake and estimate uncertainties, 2) determine how to integrate coastal and open ocean air-sea CO2 fluxes, 3) make recommendations for improving estimates of global ocean carbon uptake (Section 3).

3. Terms of Reference

Objective 1: Compare air-sea CO_2 fluxes standardized at monthly temporal and 1° x 1° spatial resolution and estimate uncertainties. We will:

1. Gather and compare publicly available estimates of global and regional air-sea CO_2 fluxes based on *in situ* surface ocean observations and numerical models
2. Identify differences in ocean mask, riverine carbon input, treatment of ice-covered regions and resolution and the effect of these on CO_2 air-sea flux estimates
3. Assess uncertainty based on the spread across these estimates, and recommend more sophisticated approaches for formal uncertainty quantification

Objective 2: Determine how to integrate CO_2 air-sea flux estimates for the coastal seas, Arctic Ocean and open oceans. We will discuss the following issues that complicate integration of coastal fluxes with open ocean fluxes, and determine an optimal approach.

1. Coastal and Arctic Ocean flux estimates overlap in space with open ocean estimates in some areas, while there are gaps elsewhere.
2. Coastal flux estimates do not include variability beyond the seasonal cycle, while open ocean fluxes also have interannual variability.

Objective 3: Recommend a path forward to improve air-sea CO_2 flux estimates. We will:

1. Identify the regions and seasons where additional observations will most improve regional and global flux estimates
2. Make recommendations with respect to integration of BGC-Argo floats into a surface ocean CO_2 monitoring system
3. Combine observation-based CO_2 flux estimates with model output to improve our mechanistic understanding regarding the air-sea flux variability in time

4. Working Plan

Expected start: January 2020

Month 1 until month 6: In order to deliver the 3 objectives, the working group will contact representatives of the Global Carbon Project, RECCAP2, the large modelling centres and the providers of observation-based air-sea flux estimates (e.g., via the Surface Ocean CO_2 Mapping project (SOCOM), but also newer estimates that are not yet included in SOCOM) to gather the most up to date air-sea CO_2 flux estimates. Full Members of this proposed WG are directly involved with each of these projects, and thus we don't expect this process to take more than 6 months.

During the data-gathering phase, we will hold the first working group meeting, bringing together representatives from the measurement, modelling, and global carbon budget analysis communities. We propose to organize this meeting during the Ocean Sciences meeting in February 2020 in San Diego, USA, and to discuss the following issues:

- The current availability and methodologies implemented to create the suite of data-based products and the suite of hindcast models. Each participant will be asked to lead discussion for one or more data-based products or models.

- Masking issues, riverine carbon inputs and coastal CO_2 fluxes, and other pressing first steps in comparing flux estimates globally and regionally.

The main goal of the meeting is for the community to understand and discuss the methodological discrepancies between data-based open ocean and coastal ocean CO_2 flux products as well as model output in order to **fulfill Objective 1 of the working group**.

Month 6 until month 18:

After the data gathering phase, the working group will **proceed to examine Objective 2**. A detailed plan will be developed to best integrate data-based flux estimates for the open ocean, coastal ocean and other regions, such as the Arctic Ocean. Bi-monthly, i.e. every two months, teleconferences will be held in order to work towards common metrics to combine and evaluate these estimates.

The group will establish ways to best represent uncertainties of the air-sea CO_2 flux, e.g. based on random subsampling or bootstrapping approaches, using synthetic data from internally consistent output from ocean model simulations and by examining the spread between the different observational data interpolation approaches. Furthermore, the working group will discuss ways to best incorporate shipboard measurements in combination with sensor data from autonomous platforms such as BGC Argo floats. We further plan to make these merged best-estimate products based on measurements available to the public and directly transfer our results to intercomparison studies such as RECCAP2 and global budget analyses such as the GCB. Furthermore, a revised observation-based air-sea CO_2 flux estimate including open ocean, coastal ocean and Arctic Ocean, will be submitted to an open-access peer-reviewed journal, **completing Objective 2 of the working group**.

Month 18 until month 30:

Following the first working group meeting in San Diego, two additional key conferences will be identified, to which the majority of working group members are planning to travel. We suggest combining the working group meetings with other conferences to keep our carbon footprint as low as possible. The 11th International Carbon Dioxide Conference (ICDC11) in late 2021 is a possible venue for the next second WG meeting. The location of ICDC11 is not yet determined, and as our goal is to spread the meetings geographically, we will have to determine if this is the best choice once the location is announced.

A side-event will be organized at the 11th International Carbon Dioxide Conference meeting in late 2021 (or at the alternative venue) for the second working group meeting, where the revised observation-based air-sea flux, including the uncertainty estimates, will be presented. We further plan to liaise with IOCCP to co-host a hands-on workshop that will introduce other scientists to the methodologies being used to upscale sea surface pCO_2 observations. This will provide them with hands-on experience in the creation and best use of available air-sea CO_2 flux estimates. We further intend to provide tools for analysis of the suite as well as their uncertainty calculation.

Once we have established a set of merged observation-based air-sea CO_2 flux estimates that cover a consistent global ocean area, the working group will continue to combine these with state-of-the-art biogeochemical models in order to identify remaining regional and temporal discrepancies that were not originally linked to area differences, **so as to address Objective 3**. The working group will establish where these differences occur on the regional level and whether these differences can be linked to data paucity. At this stage, we will start and subsample process model output to perform Observing System Simulation Experiments (OSSEs) using the available mapping methods in order to identify key regions where observations are essential to reduce the uncertainty in our best air-sea flux estimate. Bi-monthly teleconferences will be held to coordinate this effort.

Month 30 until Month 42:

The working group will meet for its 3rd and last time at a conference in the Asia/Oceania region. We aim to organise a conference session, where the results of the observation-based CO_2 flux and model CO_2 flux intercomparison study will be presented. We will also present the revised best marine carbon sink estimate and we will communicate where the observing system simulations identified the need to further collect surface ocean CO_2 measurements. Using the revised air-sea flux estimate we will further examine the remaining global carbon budget imbalance.

As a last step, **to fulfil Objective 3**, the working group will examine the temporal variability of the air-sea exchange using both the new consistent global observation-based flux estimates and a suite of ocean biogeochemical models. The new combined observation-based estimates will allow a fair comparison between data and models. The working group will focus on the amplitude of the interannual-to-decadal variability in the air-sea CO_2 exchange. Furthermore, combining both observations and models, the working group will investigate the drivers of the dominant modes of variability, providing a realistic estimate of the expected variations in the ocean carbon sink on top of the anthropogenic forcing for the UN stocktake period. Bi-monthly teleconferences will be held to coordinate this effort.

Month 42 until month 48:

The results of the observing system simulations and data-model comparison study will be submitted to an open access journal. This article will also serve as a new standard for data-model intercomparison and its results will be directly communicated to the GCP and RECCAP2.

5. Deliverables

The discussions of this working group will be critical to the development of several key open-access scientific publications from the WG members and their collaborators. These publications are well-aligned with the individual research directions of the WG members, which will support their timely completion. The fact that this WG will allow for a broader engagement of the community than would otherwise be possible will enhance their scope. These publications will be comprehensive guidelines that can push forward our community's efforts in diagnosis of the ocean carbon sink and its variability. These publications will:

1. Identify the impacts of differences in ocean mask, riverine carbon input, treatment of ice-covered regions on CO_2 air-sea flux estimates; assess uncertainty based on the spread across estimates; and recommend standard operational procedures (SOPs) for the integration and formal uncertainty quantification of observation-based air-sea CO_2 flux estimates.
2. Integrate open ocean with Arctic Ocean and coastal ocean air-sea CO_2 fluxes and create a first fully global observation-based air-sea flux estimate.

3. Use model experiments to locate ocean regions where large flux discrepancies are driven by data paucity, and thus illustrate where additional CO_2 measurements are essential to better constrain the ocean carbon uptake. The role for BGC-Argo floats in filling these holes will be addressed.
4. Constrain the origin and magnitude of interannual air-sea CO_2 flux variability and work towards reducing the global carbon budget imbalance.

6. Capacity Building

The working group will **provide standard operational procedures (SOPs)** combining observation-based estimates from various sources (open ocean, coast, Arctic Ocean) providing the baseline for a representative global air-sea CO_2 flux product. This will provide the baseline for future intercomparison studies such as RECCAP2, the global carbon budget and future studies to come.

At our second meeting, we will host a 1-day training workshop for early-career scientists and others that will introduce the range of methodologies being used to interpolate sparse in situ pCO_2 data to full coverage estimates. IOCCP will be asked to assist in this activity. Uncertainty estimation will be discussed. We will provide basic analysis scripts and provide time for discussion on important directions for detailed analyses. This workshop will increase the community of scientists who are knowledgeable about how these data-based products are created, but so that they can become more knowledgeable users and also so they can apply these techniques to their own data sets.

This first fully global observation-based air-sea CO_2 flux product provides the **baseline for ocean acidification studies** as the surface ocean pH can be directly inferred from the surface ocean pCO_2 in combination with salinity-based total alkalinity estimates (Lauvset et al. 2015). This is highly **relevant for the UN SDG 14** and for monitoring trends in marine ecosystem stressors.

Combining observation-based estimates with process model output will **provide valuable insight into the drivers and magnitude** of the interannual to decadal variability. This will **directly benefit the WCRP grand challenge on Carbon Feedbacks in the Climate System** and will build towards improved future CO_2 flux predictions.

The working group efforts are further well-aligned with the first stages of the UN Decade for the Ocean Science for Sustainable Development (2021-2030) and will **build toward** a more better constrained ocean carbon sink, which is a necessary requirement **for the UN stocktake periods** and monitoring the success of the Paris climate accord.

7. Working Group Composition

7.1 Full Members (chairs are highlighted in bold letters)

Name	Gender	Place of Work	Expertise
1 Peter Landschützer	**M**	**Max Planck Institute for Meteorology, Hamburg, Germany**	**Expert in observation-based air-sea flux estimates, open ocean carbon cycle and its variability**

2 Galen A. McKinley	**F**	**LDEO and Columbia University, New York, USA**	**Expert in mechanisms of air-sea CO_2 flux variability; models and data**
3 Dorothee C. E. Bakker	F	UEA, Norwich, United Kingdom	Lead-scientist in the Surface Ocean CO_2 Atlas (SOCAT) data synthesis effort
4 Shin-ichiro Nakaoka	M	NIES, Tsukuba, Japan	Expert in CO_2 observations, CO_2 mapping and marine carbon cycle
5 Sara Mikaloff Fletcher	F	National Institute of Water and Atmospheric research, Wellington, New Zealand	Global biogeochemical cycles of CO_2 and other trace gases as well as ocean acidification
6 Pedro Monteiro	M	Southern Ocean Carbon-Climate Observatory (SOCCO), CSIR, Cape Town, South Africa	Expert in observing, modelling and assessing variability and trends of surface ocean CO_2 fluxes through the seasonal cycle
7 Raphaëlle Sauzède	F	Laboratory of Oceanography of Villefranche, Villefranche-Sur-Mer, France	Expert in interpreting biogeochemical Argo data, global data analysis and synthesis
8 Goulven G. Laruelle	M	Université Libre de Bruxelles, Bruxelles, Belgium	Expert in observation-based coastal ocean CO_2 mapping and the coastal ocean carbon cycle
9 Leticia Cotrim da Cunha	F	Universidade do Estado do Rio de Janeiro Faculdade de Oceanografia, Rio de Janiero, Brazil	Coastal and open ocean biogeochemistry, CO_2 observations
10 Laure Resplandy	F	Princeton University, USA	Expert in Ocean carbon modelling and biophysical processes; eddy-scale to global scale variability.

7.2 Associate Member

Name	Gender	Place of Work	Expertise
1 Christian Rödenbeck	M	Max Planck Institute for Biogeochemistry, Jena, Germany	Surface Ocean CO_2 mapping (SOCOM) lead-scientist, atmospheric inverse estimates
2 Brendan Carter	M	NOAA Pacific Marine Environmental Laboratory, USA	Analysis of ocean carbonate system data, data-model intercomparison
3 Geun-Ha Park	F	East Sea Research Institute, Korea Institute of Ocean Science and Technology, Uljin, Korea	CO_2 mapping and marine carbon cycle
4 Sayaka Yasunaka	F	Japan Agency for Marine-Earth Science Technology, Japan	Arctic Ocean carbon cycle, CO_2 mapping
5 Siv K. Lauvset	F	NORCE Norwegian Research Centre, Norway	Surface ocean and interior ocean carbon measurements, data analysis and synthesis
6 Tatiana Ilyina	F	Max Planck Institute for Meteorology, Hamburg, Germany	Ocean modelling CO_2 projections and decadal CO_2 predictions, WCRP grand challenge co-chair
7 Kim Currie	F	National Institute of Water and Atmospheric research, Wellington, New Zealand	Measurements of ocean pCO_2 and carbonates in the coastal and open ocean, marine chemistry, ocean acidification
8 Nicolas Gruber	M	ETH, Zürich, Switzerland	Observation based CO_2 estimates from surface and interior, Ocean Modelling, RECCAP2 ocean leader
9 Nicole Lovenduski	F	University of Boulder, Colorado, USA	Ocean Modelling, CO_2 projections

10 Yosuke Iida	M	Japanese Meteorological Agency, Tokyo, Japan	CO_2 mapping based on surface ocean CO2 observations and marine carbon cycle

8. Working Group Contributions

The working group will:

- Combine data-based open ocean with coastal ocean and Arctic Ocean estimates and provide SOPs for the future. This will add to our estimates regions that include some of the most vulnerable ecosystems to climate change.
- Identify key ocean areas where data collection is a high priority and future field campaigns should set their focus
- Provide an improved baseline for model validation, e.g. within the CMIP6 effort and thereby contribute towards a data-driven global carbon budget
- Contribute to Sustainable Development Goal 13 by supporting the 5-yearly global stocktake under article 14 of the UNFCCC Paris Agreement
- Advance ocean acidification studies in order to achieve the United Nations Sustainable Development Goal 14
- Reduce the working group's carbon footprint by planning working group meetings in combination with conferences
- Combine these meetings with a training event that will broaden the user base of these products and advance the careers of the next generation of scientists

During the working group meetings, the working group chairs will identify group members to lead the tasks above.

9. Expertise

Peter Landschützer is an expert in ocean pCO_2 mapping using machine-learning algorithms and is an expert in the analysis of the decadal variability of the global ocean uptake of CO_2.

Galen A. McKinley is an expert in assessment of the mechanisms of variability and long-term change of CO_2 fluxes using pCO_2 observations and ocean biogeochemical models.

Dorothee C. E. Bakker is expert in the collection and synthesis of CO_2 observations and she is carrying a lead role in the SOCAT effort.

Shi-Ichiro Nakaoka is an expert in collecting surface ocean CO_2 observations, their analysis and interpretation through advanced statistical methods.

Sara Mikaloff Fletcher is an expert in modelling atmospheric CO_2 and other gases that are linked to ocean biogeochemistry. She serves on the WMO IG^3IS Scientific Advisory Panel, and is an Editor for the journal *Global Biogeochemical Cycles*.

Pedro Monteiro is an expert in understanding the role of climate variability in the ocean carbon cycle based on numerical models with a special focus on the Southern Ocean.

Raphaëlle Sauzède is an expert in the synthesis of BGC-Argo data for 4-dimensional reconstructions of biogeochemical parameters using machine learning-based methods.

Goulven G. Laruelle is expert in coastal ocean biogeochemistry and in mapping the exchange of CO_2 in coastal regions based on observations and models.

Leticia Cotrim da Cunha is an expert in marine biogeochemistry observations, and is at present part of the Reference Group for GLODAP (Global Ocean Data Analysis Project).

Laure Resplandy is an expert in the analysis and modeling of bio-physical interactions controlling CO_2 air-sea fluxes, and the use of oceanic and atmospheric data to constrain the global carbon cycle.

10. Relationship to other International Programs

We will interact with many international projects, analysis and synthesis efforts. In particular, the working group sets out to provide guidance for the air-sea CO_2 flux comparison in assessment studies by the **Global Carbon Project**, namely the **Global Carbon Budget** and **RECCAP2**. The Global Carbon Project provides annual updates of the global sources and sinks of carbon and the results of the working group will help to provide the best marine air-sea flux constraint and its variability in time.

Furthermore, we will closely collaborate with the existing surface ocean CO_2 data collection efforts, in particular the **Surface Ocean CO_2 Reference Observing Network (SOCONET),** the **Surface Ocean CO_2 Atlas (SOCAT),** and the **Biogeochemical ARGO** projects. In particular, we will provide recommendations where additional observations will help to reduce future uncertainties.

We will collaborate with the **International Ocean Carbon Coordination Project (IOCCP)**, in particular relaying information on critical gaps in the existing pCO_2 network, to ensure that appropriate actions can be taken to improve this. We will also enlist IOCCP help in the planned training workshop.

We will communicate our findings and recommendations to the **Integrated Global Greenhouse Gas Information System (IG^3IS)**, which is a **World Meteorological Organisation** program that provides a bridge between science and policy for greenhouse gas monitoring and emissions. This will ensure uptake by relevant global, regional, and national research projects that seek to improve CO_2 emission and uptake estimates using atmospheric observations.

Providing crucial information regarding trends and variability of the ocean carbon as well as ocean pH content, in addition to progress in integrating CO_2 synthesis, will serve towards the achievement of both **United Nations Sustainable Development Goals 13 (Climate action) 14 (Life below water).**

We will be in direct interaction with the **WCRP grand challenge on Carbon Feedbacks in the Climate System.** Our Associate Member Tatiana Ilyina is co-lead of this WCRP project.

We will provide essential information in the area of “Constraining ocean carbon uptake and storage”, highlighted in **CLIVAR**’s 2018 Science and Implementation Plan as a key component of its overarching goal: “Understanding the ocean’s role in climate variability, change, and transient sensitivity”.

Finally, we will work closely with global modelling groups to help improve future carbon cycle projections and decadal CO_2 predictions by adding the observation-based uncertainty, but also by providing an observation-based reference for model intercomparison projects such as **CMIP6**.

11. Key References

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Other references cited in the text are found in the next section.

12. Appendix

Full Member 5 Key Publications:

Peter Landschützer:

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Landschützer, P., Gruber, N., Bakker, D. C. E., Schuster, U., Nakaoka, S., Payne, M. R., Sasse, T., and Zeng, J.: A neural network-based estimate of the seasonal to inter-annual variability of the Atlantic Ocean carbon sink, Biogeosciences, 10, 7793-7815, doi:10.5194/bg-10-7793-2013, 2013

Galen A. McKinley:

McKinley, G. A., Fay, A. R., Lovenduski, N. S. and Pilcher, D. J.: Natural Variability and Anthropogenic Trends in the Ocean Carbon Sink. Annu. Rev. Marine. Sci. 9, 125–150, 2017

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