OCB Working Group Proposal:

Filling the gaps in observation-based estimates of air–sea carbon fluxes

Galen McKinley, Jessica Cross, Tim DeVries, Peter Landschützer,
Goulven G. Laruelle, Nicole Lovenduski, Pedro Monteiro, Ray Najjar,
Laure Resplandy, Adrienne Sutton, Rik Wanninkhof, and Nancy Williams

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 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 area covered by open and coastal ocean estimates hampers our ability to constrain CO_2 fluxes across the full marine continuum (i.e., all tidal waters). The goal of this working group will be to assess critical uncertainties in existing observation-based products, determine how best to integrate observation-based open-ocean and coastal-ocean CO_2 air–sea fluxes, and quantify uncertainties in the natural (pre-industrial) outgassing of CO_2. These efforts will lead to better constraints on the contemporary ocean carbon sink and its variability. The results of this OCB Working Group will assist the global carbon community in understanding the state of the global carbon cycle so as to contribute to international efforts to address climate change.

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 in climate, 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 two decades, the strength of the ocean CO_2 sink has been estimated using ocean forward models that are consistent with observational estimates for the 1990s fluxes and the cumulative uptake over the industrial period, estimated from interior data. 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 Pg C 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 CO_2 Atlas (SOCAT) database (Pfeil et al. 2013, Bakker et al. 2014, Bakker et al. 2016) in 2011 to 26 million in 2019. These valuable observations and synthesis efforts 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 (Wanninkhof et al., 2013; 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. Rödenbeck et al. (2015) highlight that substantial differences of up to 1 Pg C 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.

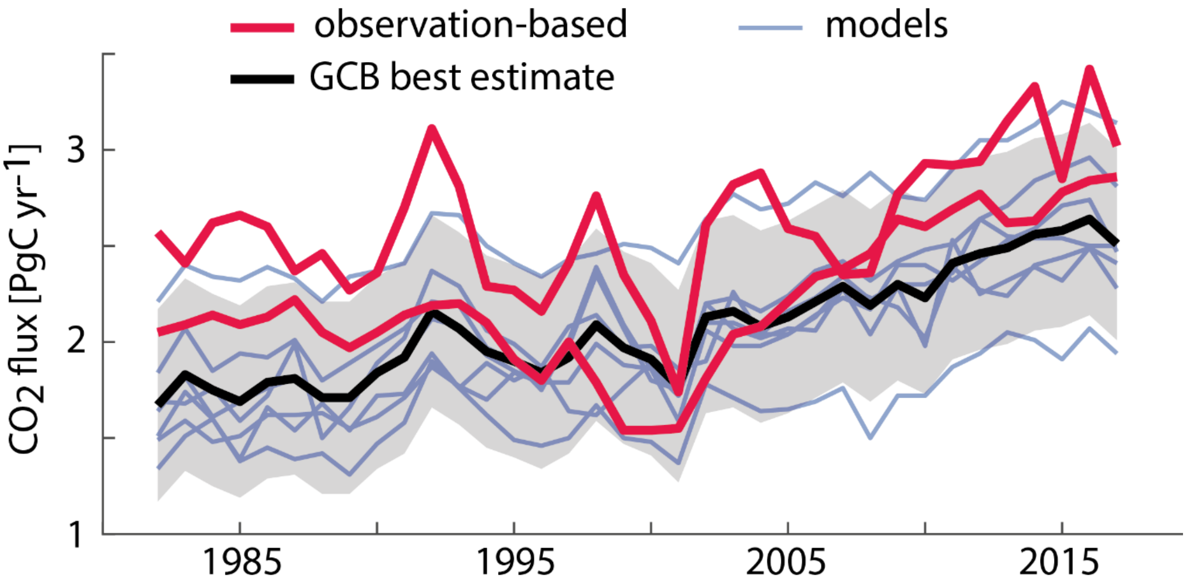

Figure 1: Air–sea CO_2 exchange and its difference between different methods from Le Quéré et al. (2018). Observation-based estimates are highlighted in red, model-based estimates are in grey and the Global Carbon Budget best estimate with uncertainty shading is highlighted in black.

Substantial discrepancies do not only exist between observation-based estimates due to methodological differences (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 regions of CO_2 exchange with the atmosphere, such as the Arctic Ocean and coastal waters, including estuaries and tidal wetlands. These regions are important and highly sensitive to anthropogenic perturbations, such as declines in ocean pH and saturation states of carbonate minerals in the polar regions and eastern boundary upwelling systems (Gruber et al. 2012) and eutrophication and sea-level rise in tidal wetlands and estuaries. We 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, Schuster et al. 2013) these have not yet been fully integrated with the set of available open ocean flux products. Furthermore, the global area of tidal wetlands and estuaries is very poorly constrained (Najjar et al. 2018).

Another issue is that the area of the ocean represented in the different approaches varies significantly. Based on the $1^{\circ} \times 1^{\circ}$ global ocean mask of RECCAP (Canadell et al. 2011), ocean models cover 89–99% of the total ocean area (Wanninkhof et al. 2013; supplement A).

Currently available data-based products include only 77–88%, often leaving out much of the Southern Ocean, a region of significant carbon uptake (Gruber et al. 2019). These differences lead to global mean flux discrepancies of up to 0.5 Pg C yr^{-1} in the data-based products (Fay and McKinley, in prep). To date, the Global Carbon Budget (Le Quéré et al. 2018) has not addressed these masking issues. Mean differences between modelled and observation-based estimates have been attributed to highly uncertain estimates of the natural (pre-industrial) outgassing of CO_2 (sometimes referred to as the "river loop") of 0.45 to 0.78 Pg C yr^{-1} (Jacobson et al. 2007, Resplandy et al. 2018). This natural outgassing of CO_2 is the result of several processes, including riverine input, biological transformations within the ocean (such as photosynthesis and respiration), and burial. There is likely some need for a natural outgassing adjustment once masking issues are addressed, but the path forward to determine the appropriate magnitude is not yet clear. Moreover, the magnitude of the river-loop has likely changed over the anthropocene.

In summary, there are a wide range of issues—coastal, natural outgassing, and 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 uncertainties also have major implications for the global carbon budget. 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 place them in the context of 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 global carbon cycle meta-analyses, these projects will not have the time to put focused attention on accounting for inconsistencies between ocean flux estimates. This is why our working group effort is needed. **This working group will support these other efforts by understanding and remedying methodological discrepancies, quantifying the resulting uncertainty where possible, and recommending needed research where it is not.**

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, saildrones, and gliders, have emerged. There is great potential from these data, but better understanding of the impacts of adding new data with different quality and error statistics is required for robust product development. Further, discrepancies between open-ocean and coastal ocean estimates that this working group identifies will provide important direction for future field campaigns.

In this OCB Working Group, our objectives will be to 1) determine how to integrate open-ocean, coastal, and natural outgassing fluxes to scale up to global air–sea CO_2 fluxes and 2) make recommendations for future improvements in estimates of global ocean carbon uptake.

3. Objectives

Objective 1: Determine how to integrate open-ocean CO_2 air–sea flux with fluxes from the coastal ocean, the Arctic Ocean, and natural outgassing. We will discuss the following issues that complicate this integration, and propose an optimal approach.

1. The coverage of existing observationally based products for the open ocean do not generally cover coastal zones, the Arctic Ocean and marginal seas, and in some cases, much of the Southern Ocean. The community needs to agree on how to best address these coverage gaps.
2. Existing coastal and Arctic Ocean flux estimates overlap in space with open-ocean estimates in some areas, while there are gaps elsewhere.

3. Global coastal flux estimates generally do not include estuaries and tidal wetlands.
4. Global coastal flux estimates do not include variability beyond the seasonal cycle, while open ocean fluxes also have interannual variability.
5. The natural outgassing flux has been estimated primarily by the difference from surface fluxes of contemporary carbon and interior ocean anthropogenic carbon uptake estimates, but much uncertainty remains, particularly in the various processes that contribute to this outgassing and how this might be changing.

Objective 2: Recommend a path forward for improvements of air–sea CO_2 flux estimates over the coming decades. We will:

1. Identify the regions and seasons where additional observations will most improve regional and global flux estimates.
2. Make recommendations on integration of calculated pCO_2 data from BGC-Argo floats and other autonomous platforms into a surface-ocean CO_2 monitoring system.
3. Assess approaches that make use of both data-based CO_2 flux estimates and ocean models to improve our mechanistic understanding of air–sea flux variability in time.

4. Work Plan

Year 1: At Lamont Doherty Earth Observatory in spring 2020, we will meet to critically review the latest flux estimates for the open ocean, coastal ocean, Arctic Ocean, and natural outgassing. A detailed plan will be developed to integrate data-based flux estimates for the open ocean, coastal ocean, the Arctic Ocean, and natural outgassing. Preliminary findings and our proposed path forward will be presented at the 2020 OCB summer workshop. Over the following year, teleconferences every two months will be held to work towards common metrics to combine and evaluate these estimates.

Year 2: In the days prior to the OCB meeting in summer 2021, we will hold a second 2-day meeting to focus on global and regional uncertainties, and how to reduce them. We will discuss and compare existing approaches to assess and represent uncertainties of the air–sea CO_2 flux, e.g. spread across ensembles, random subsampling or bootstrapping approaches, or using synthetic data from internally consistent output from ocean model simulations to evaluate data-based gap-filled estimates. We will consider strategies that use ocean model output to test gap-filling methods and quantify uncertainties. This approach can also be used to identify the key regions where observations are most needed to reduce uncertainty. The working group will discuss ways to best improve observing systems, including how to use shipboard measurements in combination with sensor data from autonomous platforms such as BGC-Argo floats. Our findings to date will be presented at the 2021 OCB summer workshop, and summarized in a Working Group report.

5. Advancing OCB Priorities and Benefiting the Broader OCB Community

This working group will accelerate our ability to quantify air–sea carbon fluxes and thus will directly address two of OCB's currently identified priorities: (1) ***Ocean carbon uptake and storage, including processes from the air–sea interface to the deep ocean*** and (2) ***Carbon cycling and associated biogeochemical fluxes and exchanges along the aquatic continuum, from rivers to the coastal ocean***.

The work of the working group is also well-aligned with the individual research directions of the its members, which will support the timely completion of the tasks. The working group will allow for a sustained engagement of our community, something that would not otherwise be possible. This will enhance outcomes. Our WG report and the publications that come directly from the working group, and those from its members that will be informed by our collaboration, will push forward our community's efforts in diagnosis of the ocean carbon sink and its variability. Our report and publications will:

- Identify the impacts of differences in ocean mask, natural outgassing, 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 uncertainty quantification of observation-based air–sea CO_2 flux estimates.
- Integrate open ocean with Arctic Ocean and coastal ocean air–sea CO_2 fluxes and create a first fully global observation-based air–sea interannual flux estimate.
- Use model experiments to locate ocean regions where large flux discrepancies are driven by data paucity. How BGC-Argo floats and other autonomous platforms can be integrated with ship-based observations to fill these holes will be discussed.
- Improve understanding of the origin and magnitude of interannual air–sea CO_2 flux variability and work towards reducing the global carbon budget imbalance.

We will interact with a variety of international observing, 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 annual Global Carbon Budget and RECCAP2. We will collaborate with the existing surface-ocean CO_2 data collection efforts, in particular the Surface Ocean CO_2 Reference Observing Network (SOCONET), SOCAT, and the BGC-Argo projects. In particular, we will provide recommendations where additional observations will help to reduce future uncertainties. We will inform 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 development and intercomparison. This work also supports OCB's partner program, CLIVAR. We will provide essential information in the area of *Constraining ocean carbon uptake and storage*, highlighted in CLIVAR's 2018 Science and Implementation Plan.

6. Members

The working group will be led by Galen McKinley (LDEO/Columbia). Members with expertise in ocean observations from ships and autonomous platforms are Cross, Sutton, Wanninkhof, and Williams. Members with expertise in creating observation-based products are Landschützer, McKinley, Monteiro, and Wanninkhof. Experts in Arctic Ocean, coastal ocean and natural outgassing are Cross, Laruelle, Lovenduski, Najjar, and Resplandy. Modeling expertise will come from DeVries, Lovenduski, McKinley, Najjar, and Resplandy.

7. Budget and Justification

BUDGET	Cost	# Person	Per meeting	2 meetings	Total
Domestic Travel	$550	8 (Y1) 9 (Y2)	1	17	$9,350
International Travel	$1,000	3	1	6	$6,000
Hotel	$150	11(Y1) 12(Y2)	2	46	$6,900
Per diem / catering	$50	12	2	48	$2,400
Room costs at WHOI	$250			2	$500
Publications	$1,500			2	$3,000
Total					**$28,150**

Requested funds will cover travel to Lamont Doherty Earth Observatory (LDEO) in 2020 and to Woods Hole in 2021. Nine participants are domestic, and three are international. We request eight domestic airfares ($550) and 3 international airfares ($1000) for travel to Lamont in year 1, and 11 rooms for 2 nights. For year 2, we request nine domestic and 3 international airfares and 12 rooms for 2 nights in Woods Hole. We request catering for the meetings ($50 per person). At WHOI, we request meeting room costs of $250 / day; there is no charge at LDEO. We request also funding to cover 2 publications at $1500 each. Our total request is $28,150.

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