Ocean Carbon from Space

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Introduction

Quantifying the ocean carbon budget and understanding how it is responding to anthropogenic forcing is a major goal in climate research. It is widely accepted that the ocean has absorbed around a quarter of CO_2 emissions released anthropogenically, and that the ocean uptake of carbon has increased in proportion to increasing CO_2 emissions. Yet, our understanding of the pools of carbon in the ocean, the processes that modulate them, and how they interact with the land and atmosphere, is not satisfactory enough to make confident predictions of how the ocean carbon budget is changing. Improving our understanding requires a holistic and integrated approach to ocean carbon cycle research, with monitoring systems capable of filling the gaps in our understanding. Satellite observations can play a major role in this.

The breakout workshop at IOCS formed part of the second 'Ocean Carbon from Space' workshop, and we addressed three key questions that emerged from the online component of this workshop:

1) What are the critical gaps in our current satellite observing capabilities that prevent us from accurately quantifying the ocean carbon cycle, and how can we prioritise filling these gaps?
2) How can we improve our understanding of the physical, chemical and biological processes that govern the ocean carbon cycle, and assess how climate change affects carbon flow through marine ecosystems?
3) What specific, actionable steps should the international research community and space agencies take to ensure satellite-derived ocean carbon data can effectively inform climate model evaluation and policy decisions?

Participants of the breakout workshop were asked to examine these key questions at the short (1-5 years), medium (5-10 years) and long-term (10-20 years) with a focus on actionable recommendations to the community, agencies and/or IOCCG.

Session Summary

The breakout workshop was introduced with a summary of the outcomes from the online component of the second Ocean Carbon from Space workshop, with highlights from keynote and oral presentations and discussions sessions. Outcomes of the subsequent in-person plenary session (keynote and panel discussion) at IOCS were also briefly highlighted. The roughly 80 participants of

the breakout workshop were then split into three groups to discuss one of three key questions (see 'Introduction') with the help of two co-chairs and one rapporteur. After 20 minutes, chairs rotated to a new group and the next question was discussed, and this was repeated once more to cover all three key questions. The group discussions were captured by the chairs and rapporteurs using flip charts for each key question and participants were able to provide additional inputs through post-its. Parallel to the in-person discussions at IOCS, a small group discussed the three key questions with two co-chairs online. After a break, the co-chairs then summarised the discussions for each key question and a plenary discussion was held to formulate recommendations to the community, space agencies and IOCCG. Overall, participants were highly engaged and provided valuable input to address the posed key questions and formulate recommendations on the topic of ocean carbon from space.

Review of Existing IOCS Recommendations

One existing IOCS recommendation that is relevant to the topic of ocean carbon from space is recommendation 2023.08.3:

> "Space agencies and distribution services (in collaboration with the ocean colour and metrology communities) need to prioritise calculating and distributing uncertainties associated with all products (pixel-based and composite), and including propagation through AC and algorithms following metrological practices."

The estimation of uncertainties was an important topic highlighted in the online component of the second Ocean Carbon from Space workshop as well as the plenary session and breakout workshop at IOCS. While some progress is being made to estimate pixel-by-pixel uncertainties for ocean carbon pools and fluxes, more work is needed to fully understand and reduce uncertainties in satellite-based ocean carbon products.

New IOCS Recommendation(s)

The new IOCS recommendation(s) related to observing the ocean carbon cycle from space are listed below. Recommendations are provided for the short (1-5 years), medium (5-10 years) and long-term (10-20 years)

Recommendation	Actor(s)
At the short term, the research community should resolve carbon pools and fluxes at the **regional scale** across key environments, including tropical, polar and coastal regions, inland waters (lakes) and in the deep ocean, using integrated observations, models and synthesis approaches. Ocean carbon budget assessments should explicitly include Blue Carbon components (e.g., mangroves, seagrasses, salt marshes). Progress should be assessed by tracking	Community

the number and proportion of peer-reviewed publications on regional ocean carbon assessments.	
At the short term, the research community should develop and validate tools to detect **change and the rate of change** in the ocean carbon cycle, enabling identification of potential tipping points. Progress should be measured by the number of peer-reviewed publications and publicly released datasets demonstrating the use of these tools, including documented methodologies and case studies showing detection of significant change events or trends.	Community
At the short term, space agencies should support efforts to generate robust evidence on the impact and effectiveness of **marine Carbon Dioxide Removal (mCDR)**. Progress should be measured by funding projects that specifically target mCDR from satellite observations (or integrate observations with models), with publicly accessible datasets and methodologies to inform timely decision-making.	Agency
At the long term, space agencies should continue to maintain and improve the accuracy and stability of **primary observables** needed for ocean carbon research by sustaining robust calibration and validation (cal/val) activities and implementing advances in atmospheric correction. Progress should be measured through regular, publicly reported assessments demonstrating reductions in calibration bias and uncertainty, and documented improvements in atmospheric correction performance across satellite data products.	Agency
At the short term, the IOCCG should promote the inclusion of ocean carbon from space in existing and new **training activities**. Progress can be tracked by noting the number of training events that incorporate ocean carbon topics, the participants engaged and the availability of openly accessible training materials and resources.	IOCCG
At the short term, the IOCCG is encouraged to assess and address the latency between **science and policy**, including evaluating the uptake of key ocean carbon research information in decision-making. The use of 'knowledge brokers' or knowledge hubs should be considered to bridge the gap between science and policy. Progress can be tracked through the preparation of a guidance document within the next few years.	IOCCG