**Support paper for CEOS plenary to explore**

**the development of an Aquatic Carbon From Space Roadmap**

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**Issues for Plenary Discussion and Decision**

* We ask the principals to decide at plenary whether they are willing to provide representation and resources going forward to support the development of a full CEOS Aquatic carbon Roadmap. This will support the global carbon assessments (e.g., annual global carbon assessments, future global carbon stocktakes), current and future ocean health assessments and mitigation (e.g., UN decade of ocean research) and will be used to guide the Intergovernmental Panel on Climate Change (IPCC) Guidelines and 2035+ vision.

1. **Vision and justification** 
   1. **Context**

Following the 2015 Paris Agreement, CEOS has issued in 2021 a Global Stocktake strategy paper (<https://ceos.org/observations/documents/GST_Strategy_Paper_V3.1.pdf>) to set out a way forward by which CEOS Agencies can coordinate their efforts to support the first (2023) and subsequent (every 5 years) Global Stocktake (GST). GST is a collective assessment process aiming at a) understanding how effective the combined efforts are in cutting GHG emissions over time, b) determining how close we are collectively to achieving its long-term temperature goals, and c) creating the momentum for countries to increase their ambitions in each new set of Nationally Determined Contributions (NDCs).The CEOS GST strategy paper covers the specific modalities of the GST and proposes where and how Agencies can support its implementation.

Significant effort has already been undertaken in the past years within CEOS to understand how Earth Observation data can best support the GST implementation. In particular, a White Paper entitled “A constellation architecture for monitoring carbon dioxide and methane from space”, was produced in 2018 by the Atmospheric Composition Virtual Composition (AC-VC) focusing on the provision of atmospheric GHG datasets to the GST process (Crisp et al., 2018). The white paper was followed in 2020 by the development of a comprehensive Roadmap (<https://ceos.org/observations/documents/CEOS_CGMS_GHG_Constellation_Roadmap_V2.3_cleaned.pdf>) for the implementation of the main recommendations of the GHG White Paper. This was followed in 2021 by the issue of a discussion Paper exploring the development of a CEOS AFOLU (Agriculture, Forestry and Other Land Uses) Roadmap in support of the GST process (<https://ceos.org/observations/documents/AFOLU%20Roadmap%20Discussion%20Paper%20v1-0.pdf>). The AFOLU roadmap was successfully developed and is being presented for endorsement at the CEOS plenary in November 2024.

* 1. **Rationale for an aquatic carbon roadmap to accompany the GHG and AFOLU roadmaps**

The ocean annually absorbs more than a quarter of all anthropogenic carbon dioxide (CO2), which has helped to slow the full impact of climate change, but this long-term absorption is fundamentally changing ocean chemistry and degrading ocean health. Its impact on the ocean ecosystem must be assessed and monitored, as well as the consequences for the services provided by the marine ecosystems.

The ocean, along with the atmosphere, are the two main observational constraints on global carbon assessments, and these assessments of regional and global carbon enable the impacts and risks associated with carbon uptake to be assessed (Shutler et al., 2020). Furthermore, all of the methods used to assess the land carbon sink (differencing methods, inversion models or dynamic vegetation models; e.g. Le Queré et al., 2016; Resplandly et al., 2018) rely upon accurate estimate of oceanic and aquatic carbon as a key constraint or input. Thus, using poor estimates of ocean carbon reduces the quality of land carbon estimates and that of the global carbon budget, which in turns erodes any guidance for emission targets. Conversely, improving the estimates of ocean carbon profoundly improves the strength of policy guidance resulting from these global carbon assessments.

As the ocean cover more than 70% of the Earth, these regional and global carbon assessments rely heavily on satellite observations, but their inclusion is often invisible or opaque to policy (Shutler et al., in-revision) and they tend to focus on ocean physics, largely overlooking biological controls which are critical for carbon uptake and sequestration. In addition, the biological response of the ocean is already changing in response to climate change and expected to continue to do so. Thus, renewed efforts to understand and include biology within these assessments are critical (Arico et al., 2021). Similarly, there is an increasing need to understand and map the impacts that ocean carbon uptake is having on ocean biology (e.g. ocean acidification) to support mitigation and management of ocean health (Shutler et al., in-revision).

Currently, global ocean carbon assessments are using satellite data in inconsistent and non-optimal ways; this has led to a lack of agreement between models and observation-based estimates of carbon uptake by the ocean, with large sources of errors and uncertainties within annual assessments. Furthermore, large uncertainties remain in our understanding of organic (e.g. biologically mediated) carbon fluxes in the ocean, notably primary production and export production, thus also undermining the potential of these global assessments and the policy advice that they underpin. This has resulted in substantial uncertainty for future climate projections. Changes of carbon fluxes in coastal blue carbon ecosystems (i.e. vegetated coastal and marine ecosystems storing carbon - mostly seagrasses, mangroves, and salt marshes –) remain to be characterized and constrained, and our knowledge gap in freshwater production and the flow of carbon between the land and ocean is even greater.

Finally, the change in the magnitude and regional distribution of organic carbon fluxes come from a variety of climate-related modifications to the marine environment (ocean acidification, storminess over the oceans, vertical stratification, changing temperature, increasing sea level, disappearing sea ice, and their combined impacts)*,* which still need to be better understood and assessed and will likely impact inorganic carbon pools (i.e. the estimates of the ocean carbon sink).

1. **Aquatic Carbon Roadmap Objectives**

In this context, the development of an Aquatic Carbon Roadmap, as the third component of the CEOS Carbon Strategy (following the GHG and AFOLU roadmaps), appears very timely and necessary.

The main objectives of such a roadmap would be:

* To provide a framework and serve as a guiding vision for long term (~ 15+ years) coordination of CEOS agency observing programmes in support of the science and policy needs for Aquatic carbon related information in the context of the CEOS carbon strategy.
* To characterize the needs, gaps and challenges, regarding the required data and products to support science, services and applications. Such products include (not exhaustive list):
  + - * + *Satellite-based aquatic carbon products and associated uncertainties to constrain models better, and through enhanced integration with field observations and models, to reduce uncertainties in carbon fluxes and in the global carbon budget.*
        + *Satellite-based mapping of the extent of blue carbon ecosystems at the global scale, and through enhanced integration with field observations, of blue carbon ecosystems carbon content and its dynamics.*
        + *Satellite-based Tools/Products/Indicators to support policy needs with a main focus on the needs and ambition cycle of the Global Stocktake of the Paris Climate Agreement.*
* To characterize the needs, gaps and challenges regarding the observing systems that can support the above developments, including the needs to plan for ground and space segments. This includes addressing basic observation continuity and the necessary agency coordination to achieve it.
* To serve as an effective means for communicating our intentions to society, UNFCCC, national inventory community

1. **Topics covered**

Both the GHG and AFOLU roadmap have a strong focus on the major milestones of GST1 (2023) and subsequently for GST2 (2028) and how remote sensing data can effectively support these by providing means to monitor carbon emissions and removals, based either on a top-down approach (GHG roadmap) or a bottom-up approach (AFOLU roadmap).

In order to address the objectives of the Aquatic Carbon roadmap, and effectively contribute to supporting the GST process, the Aquatic carbon roadmap not only will cover the specific topic of ocean carbon sink (air-sea CO2 exchange) monitoring, but the intent is, more widely, to:

* address all horizontal (from lakes to coastal and open oceans) and vertical dimensions, including the vertical transport of carbon from the surface to the deep ocean (building on the synergy with in-situ data (BGC-Argo) and models), and carbon fluxes across systems such as the exchange of CO2 with atmosphere, and the land to ocean aquatic continuum.
* address the linkages between organic and inorganic carbon and how they relate to each other and cover all the components of the Earth System from including the assessment of how long the open and coastal oceans will be able to keep up taking the current rate of anthropogenic CO2 uptake through to how this will affect the pH and biodiversity of the aquatic systems. Finally, it will also include aspects related to the understanding of how human’s action on land (deforestation, increasing nutrient input from rivers etc.) affect aquatic carbon.
* clarify the importance, and elevate the profile and complexity of, remote sensing and satellite Earth observation that are already routinely used within carbon assessments. It will highlight how Earth observation has much more to offer beyond its current use. It will also improve and expand but explain how this can only be achieved if the use is underpinned by expert advice and guidance. The roadmap will drive the inclusion of inorganic and organic carbon in the ocean within global and regional carbon assessments.
* contribute to support the needs and ambition cycle of the Global Stocktake of the Paris Climate Agreement, by further constraining the global carbon budget and also by supporting countries reporting on their NDC by improving the estimation and monitoring the changes in CO2 fluxes from/to the Oceans at country level (within each country’s exclusive economic zone, EEZ). The roadmap will also address the needs for monitoring the extent and carbon stocks of major Blue Carbon coastal ecosystem extent and carbon stocks around the world.

1. **Timeline for completion**

The ever-increasing emission rates, which are not abating or even stalling, highlights the immediate need for improved constraints on global carbon assessments to further tighten policy advice which rely upon emissions assessments. Some net-zero and cumulative emission targets focus on horizons of 2030 or 2040 and so this highlights the need for urgent action and progress. Therefore, it is recommended that the roadmap be completed within 2 years of starting.

1. **Resources for completion**

The development of the Aquatic Carbon Roadmap is a complex task, which will need the commitment, contribution and coordination of many.

In particular, resources from IOCCG/CEOS OCR-VC agencies will be essential. Most of these agencies have carbon related activities on which the roadmap will build.

ESA is currently launching three aquatic carbon projects that will run over the next two years:

* One project dedicated to the development of Satellite-based observations of Carbon in the Ocean: Pools, fluxes and Exchanges (SCOPE)
* One project dedicated to strengthening the understanding and the value of EO Ocean Carbon within the climate context of the IPCC by introducing steps towards Ocean Carbon related ECVs and climate data records, establishing time series of ocean carbon fluxes, and monitor signs of change, regionally and temporally (Ocean Carbon For Climate)
* One project dedicated to the development of satellite-based observations of Coastal Blue Carbon stock assessment.

NASA has provided continued support for a number of activities under the Ocean Biology and Biogeochemistry program, the Carbon Monitoring Program, and the Carbon Cycle Science program. Relevant current and planned activities by NASA include:

* Scientific research, to be competitively solicited in 2024, that will refine our predictive understanding of the Ocean Biological Pump; this type of research builds on investments by NASA such as the EXport Processes in the Ocean from Remote Sensing (EXPORTS) and focuses on reducing uncertainties in contemporary and future assessments of primary production on regional to global scales. Such activities are anticipated to be executed over the next three years.
* Continued support of forward-looking initiatives designed to characterize, quantify, understand, and predict the evolution of global aquatic carbon sources, sinks, and fluxes, with particular emphasis on terrestrial-ocean carbon fluxes for accounting purposes, refinement and uncertainty reduction of blue carbon ecosystem stocks and fluxes, and research that bridges knowledge gaps related to risks and benefits of Nature Based Solutions and ocean-based Carbon Dioxide Removal approaches. These initiatives are ongoing and plan to be continued beyond the duration of the roadmap.
* Investments to improve and expand the use of Earth Observing data for aquatic carbon and biogeochemical model refinement, especially related to biological carbon cycling and export. Development of relevant blue carbon products responsive to various stakeholders which support research and conservation of these habitats. These activities are ongoing and plan to be continued over the next three years through competitive research solicited in 2024.

Consequently, significant contribution to the Aquatic Carbon Roadmap is expected from the scientific community through the different activities being supported by the CEOS member agencies.

In addition, ESA and NASA are jointly organizing a Coastal Blue Carbon From Space Forum (<https://eo4society.esa.int/event/blue-carbon-from-space-forum/>) on 14-17 May 2024 at the International Space Science Institute (Bern, Switzerland). Outcome of this forum will directly contribute to the writing of the Aquatic Carbon Roadmap.

Relevant activities are also ongoing within the International Ocean Colour Coordination Group: an IOCCG Aquatic Carbon from Space Task Force is being initiated (led by Jamie Shutler, University of Exeter, UK and Cecile Rousseaux, NASA GSFC, US) and a Working Group on Primary Production (chaired by Robert Brewin, University of Exeter, UK). Both activities will be running in parallel to the roadmap development and will strongly contribute to it.

Other contribution might come from other OCR-VC agencies (e.g. NOAA) and other CEOS VC and WG (e.g. SST-VC, OST-VC, OSVW-VC, COAST, and WGClimate).

Finally, Copernicus has also launched different carbon related projects through the Copernicus Marine Service Evolution projects (<https://marine.copernicus.eu/about/research-development-projects>)

1. **Aquatic Carbon roadmap core team**

Considering the above, the following core team is proposed:

**Coordinators**

Laura Lorenzoni (NASA, agreed but still to be confirmed by CEOS Principals at Plenary)

Marie-Helene Rio (ESA, agreed but still to be confirmed by CEOS Principals at Plenary)

Hiroshi Murakami (JAXA, agreed but still to be confirmed by CEOS Principals at Plenary)

**Scientific leaders**

Jamie Shutler (University of Exeter, agreed)

Bob Brewin (University of Exeter, agreed)

Cecile Rousseaux (NASA, agreed)

Kelsey Bisson (NASA, agreed)

1. **Aquatic Roadmap Outline (notional)**

1. Introduction (overview, purpose and scope)

- the role of aquatic systems in carbon uptake and cycling

- the ocean observational constraint on global carbon

- Evaluate the role of remote sensing to inform IPCC Guidelines and 2035+ vision

2. The critical need and opportunity (from Brewin et al., 2020;2023, Shutler et al., 2020; in-revision and other contributions from the Aquatic Carbon From Space Special Issue).

3. Overview of remote sensing and Earth observation capabilities (brief overview from Brewin et al., 2020;2023, Shutler et al., 2020; in-revision), including the necessary synergy with in-situ measurements and models.

4. Deployment of capabilities

- use existing capabilities to demonstrate strength of the ocean constraint on global carbon (from Shutler et al., in-revision)

- expand visibility of satellite derived data within international data and products portals (e.g. Copernicus)

5. Roadmap and perspective

6. Complementarities and linkages to other CEOS roadmaps (GHG and AFOLU))

7. Capacity building

- CEOS data portal

- Private or commercial (e.g., Planet).

- agencies or programmes (e.g., Copernicus).

8. Forward looking actions

- future satellite missions (from Brewin et al., 2023)

- demonstrations (how to use roadmap, or identify importance – from Shutler et al., in-revision)

- links to other carbon-based cycles (e.g. methane).

- future global stocktakes and updates

9. Summary and next steps

10. Recommendations coming out of this roadmap.

1. **References**

Arico S, Arietta JM, Bakker DCE, Boyd PW, Cotrim da Cunha L, Chai L, Dai F, Gruber N, Isensee K, Ishii N, et al., Integrated ocean carbon research: a summary of ocean carbon research, and vision of coordinated ocean carbon research and observations for the next decade. UNESCO and the IOC, online, UNESCO, Paris, 45 pages, (2021).

Brewin et al (2021) Sensing the ocean biological carbon pump from space: a review of capabilities, concepts, research gaps and future developments. Earth-Science Reviews, 217, 103604-103604

Brewin et al (2023) Ocean carbon from space: Current status and priorities for the next decade. Earth-Science Reviews, 240, 104386-104386

Le Quéré, C., Andrew, R. M., Canadell, J. G., Sitch, S., Ivar Korsbakken, J., Peters, G. P., et al. (2016). Global Carbon Budget 2016. Earth Syst. Sci. Data 8, 605–649. doi:10.5194/essd-8-605-2016.

Resplandy, L., Keeling, R. F., Rödenbeck, C., Stephens, B. B., Khatiwala, S., Rodgers, K. B., et al. (2018). Revision of global carbon fluxes based on a reassessment of oceanic and riverine carbon transport. Nat. Geosci. 11, 504–509. doi:10.1038/s41561-018-0151-3.

Shutler et al (in-revision) The increasing importance of satellite observations to assess the ocean carbons sink and ocean acidification, Earth-Science Reviews

Shutler et al. (2020) Satellites will address critical science priorities for quantifying ocean carbon. Frontiers in Ecology and the Environment, 18(1), 27-35