Committee on
Earth Observation
Satellites

AQUATIC CARBON ROADMAP

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1. Key messages and executive summary

Aquatic ecosystems contain and cycle the second largest, long-term store of carbon on Earth, second only to the Earth's core. As of 2025, the ocean is estimated to be absorbing roughly 3 Gt C per year and continues to act as a brake on anthropogenic-driven climate change; so far, it has collectively absorbed 25% of all anthropogenic emissions, and absorbed over 90% of all anthropogenic heat. Marine and freshwater systems underpin biodiversity, fisheries, national security, and coastal protection. Long-term carbon sequestration occurs via deep-ocean storage and sediment burial, representing substantial climate and economic value.

The understanding of the importance and power of aquatic carbon in climate mitigation and regulation, and economic benefits it brings, is significantly lagging its atmospheric and land counterparts; for example, aquatic systems are largely overlooked in the Global Stocktake despite collectively covering more than 70% of the Earth. Earth Observations (EO) are fundamental to assess, observe, and understand the carbon cycle at local, regional, and global levels; the synoptic view they provide, coupled with the high frequency of observations, make EO essential for taking stock of aquatic carbon across the Earth system. In addition, EO enables scalable monitoring of extent, condition, productivity, and carbon dynamics for science and policy.

This roadmap outlines how EO are critical for quantifying and monitoring carbon stocks and fluxes across aquatic systems—open ocean, shelf seas, coastal and blue-carbon ecosystems, and inland waters—and how these observations are needed to support climate assessments, national inventories, and global stocktakes. It provides a framework for advancing carbon accounting and provides guidance on how to better integrate the ocean in specific strategies that would support informed ocean-based climate measures. The recommendations in this Roadmap leverage the power of remote sensing, which provide the only sustained, global coverage observations for aquatic carbon, especially in remote open-ocean and dynamic coastal zones. It can be executed by public and private entities, with the coordination and support of the Committee on Earth Observation Satellites (CEOS). While this roadmap focuses on carbon accounting, it hinges on foundational science to advance critical applications. However, the roadmap does not go in depth into the science of aquatic carbon; such details can be found in other efforts, for example the Earth-Science Reviews special issue, which contains a collection of overarching critical reviews of the advances of the science.

This roadmap identifies priority areas and opportunities in the short, medium, and long term. They address the needs of a variety of stakeholders (see Table 1), to gauge progress in the different areas. Specific quantifiable metrics will be developed that will allow the assessment of success, or where areas may need improvement.

Key priority areas – short term

a. Continue support of and expand aquatic carbon basic research and advanced products

- Continue to encourage and support inter-disciplinary science that promotes integration of remote sensing into broader biological and chemical models (Sec. 4). Consider science that integrates EO, field data, and models to support carbon estimates, Monitoring, Reporting, and Verification (MRV) for markets, and forecasting risks to guide restoration (Sec. 4.2)
- Invest in science that will develop and validate tools to detect change and the rate of change in the ocean carbon cycle, enabling identification of potential tipping points and fund more science to understand carbon tipping points. Leverage activity-based ("bottom up" in situ efforts, e.g. Pangea, Arctic COLORS/FORTE) carbon quantification approaches that use atmospheric-based and oceanic-based approaches to enable carbon estimates to converge (Sec. 4.1 and 4.2; Sec. 6)
- Invest in science that includes indicators of bio- and functional diversity and the flow of carbon through the marine ecosystem into ocean carbon research to improve understanding of carbon flows and feedbacks. Consider the improvements of models to gain the ability to predict ecosystem responses to changes in the carbon cycle, and identify areas most vulnerable to loss or in need of restoration or mitigation actions (Sec. 4.1 and 4.2).
- Further develop and refine algorithms for retrieval of carbon concentrations or primary productivity in inland waters (sec. 4.3)
- Maintain and improve the accuracy and stability of primary observables needed for ocean carbon research by sustaining robust calibration and validation (cal/val) activities (Sec. 4.1, 4.2, and 4.3).
- Invest in science that generate robust evidence on the impact and effectiveness of marine Carbon Dioxide Removal (mCDR) (Sec. 4.2 and Sec. 5)
- Continue improvements and advances in atmospheric correction, especially in complex coastal waters, and develop a more robust science-based approach to reduce uncertainty and error in carbon estimates for coastal waters (sec. 4.2 and 4.3).

b. Leverage existing observational platforms and models to gap fill aquatic carbon flux priority areas

- Exploit multi-sensors (active/passive) and multi-platforms (satellite, in-situ) synergy to access the three dimensionality of the ocean and refine/develop improved carbon cycling estimates (Sec. 4.1, 4.3, and 4.3).
- Advance the estimation of ocean circulation to better constrain aquatic carbon pathways (sec. 4.1).
- Further develop and support dedicated in situ networks, drones, and CubeSats to provide high-resolution validation measurements (Sec. 4.1, 4.2, and 4.3)
- Build integrated modeling frameworks linking inland waters, coasts, and ocean. Research should focus on developing approaches that consider this land to ocean continuum, its heterogeneity and cascade of scales and the carbon flow within this, so linking inland waters, estuarine and coastal seas (Sec. 4.3, Sec. 5)
- Expand hyperspectral in situ measurements of inland water bodies to improve validation of EO (sec. 4.3)

c. Support science that will advance aquatic carbon markets
  - Strengthen cross-roadmap (Aquatic–GHG–AFOLU) coordination, synergies, and co-benefits through shared use cases (Sec. 6).
  - Further the development of blue carbon ecosystem accounting from EO, especially seagrasses (Sec. 5.2)
  - Explore ways in which EO data products developed align with IPCC inventory and stocktake requirements, which includes consistent definitions, comprehensive uncertainty characterization, and scalability from global to national levels. Of particular importance are efforts to reduce the uncertainties or combined uncertainties of independent methods to assess the ocean carbon sink. This will act to strengthen the ocean constraint on global carbon assessments and further enhance the importance of ocean estimates (Sec. 5).

Key priority areas – medium term

a. Coordinate and plan future observational needs that will address gaps in aquatic carbon flux estimates
  - Establish a plan to develop active space-based (lidar) systems that will improve the understanding of organic carbon cycling in deeper parts of the ocean ‘hidden’ from passive satellite ocean colour (sec. 4.1)
  - Develop geostationary missions for high frequency measurements of open and coastal zones (sec. 4.1 and 4.2)
  - Encourage the full assessment and exploitation of current novel sensing technologies in orbit to study carbon processes, and utilize those results to inform new satellite missions that are maximized for cross-roadmap carbon research (Roadmap-broad).
  - Improve the accuracy and spatial and temporal coverage of key physical observations (e.g., winds, surface turbulence, surface ocean circulation) needed for ocean carbon research through new and improved retrieval algorithms, better integration of satellite and in situ observations (Roadmap-broad).

b. Support science that will advance aquatic carbon markets
  - Support the development of EO data products that align with IPCC inventory and stocktake requirements, which includes consistent definitions, comprehensive uncertainty characterization, and scalability from global to national levels (Sec. 5).
  - Evaluate and address the latency between science advances and policy uptake, including evaluating the uptake of key ocean carbon research information into decision-making (Sec. 5).
  - Further the development of Tier 2 and 3 reporting from EO (Sec. 5.2)

c. Support community standards and capacity building
  - Encourage fiducial reference measurement networks that collect measurements relevant to multiple communities on the same platform or frameworks and support the development of science based standards for these measurements e.g., atmospheric (e.g. XCO_2) and oceanic (e.g. pCO_2) data (Sec. 6)
  - Increase global capacity, especially in the Global South, for EO data use and inventory support (Sec. 7).

Key priority areas – long term

a. Support and sustain the provision of satellite datasets for ocean carbon, and further develop satellite-based climate data records so that they may continue to be used in global carbon assessments (Roadmap-broad).

b. Equitably coordinate and support the fiducial in situ infrastructures and best practices that climate measurements require, so the tracking of changes in Earth's environmental health continues and further evaluation of the impact on the Environment of policy decisions (Roadmap-broad).

c. Invest in technology maturation and frontier research that furthers the information extracted from EO signals and the different carbon pools in aquatic systems, as well as process-based understanding of aquatic carbon cycling (Roadmap-broad).

Areas of opportunity

1. Collaborate with international groups (e.g., GHRSST, Global Carbon Budget, SOCAT, GLODAP etc.) to reduce latency, interoperability, and accessibility of ocean carbon assessments. (Sec. 7)
2. Continue to enable and support interactions between communities (e.g. space agencies and linked organisations or groups like IOCCG, GHRSST) involved in all types of carbon related observations (e.g., in situ, autonomous and EO) and modelling (Sec. 6 and Sec. 7). Success can be gauged by documenting outcomes that demonstrate improved alignment.
3. Encourage the promotion of integrated ocean carbon capabilities and training (that bridge all types of observations, space activities and modelling approaches) by international leading groups (e.g., IOCCG, GHRSST, IOCCP, SOLAS, CLIVAR, etc.). (Sec. 7)
4. Involve the broader community; citizen science is a very useful approach for enhancing or contributing to research activities and should be encouraged alongside full consideration of its potential. (Sec. 7)

Table 1: Stakeholders/benefits of the roadmap

Stakeholders	Variable of Interest	Product Needed	Users	Specifications
UNFCCC	Blue Carbon mitigation targets in Nationally Determined Contributions (NDCs) ***reporting blue carbon in national GHG Inventory is a prerequisite to include BC under NDC mitigation commitments. Not needed for adaptation. Baseline areas of seagrasses and tidal marshes in 1990 (minimum 30m spatial resolution)	Baseline areas of seagrasses and tidal marshes in 1990 (minimum 30m spatial resolution). Multitemporal area changes for seagrasses and tidal marshes (ideally annually starting 1990 and until now)	Blue carbon countries (support to reporting Blue Carbon in Nat GHG Inventories and mitigation targets)	Minimum 30-meter maps usable at local (municipal) level. Enough detail for jurisdictional nesting If different satellites/sensors are used, data harmonization is needed to make data consistent along time.
Global Carbon Budget	Global estimates of the main stocks and fluxes of aquatic carbon from space, for use to help quantify global carbon emissions and sinks.	Global products of key pools (particulate and dissolved, organic and inorganic), and fluxes (primary production, export production, air-sea flux, land-sea flux, calcification) of aquatic carbon, that can be derived from space measurements, over as long a duration as feasible.	Primary use to track emissions, evaluate models, and inform climate action. Key users include: scientists, policymakers, climate assessment bodies, NGOs, and private sector.	Carbon budget models are typically coarse (0.5–2°, monthly), motivating global satellite products of aquatic carbon stocks and fluxes at comparable resolution, at as long as duration as feasible (through use of climate data records). Openly available data products.
mCDR	Direct satellite observations of mCDR efficacy and impacts, including medium and high resolution hyperspectral biogeochemical and physical data, and data-driven, operational models of the ocean state to build twin models for assessing mCDR.	More accurate measurements of DOC (CDOM) and DIC from remote sensing. Canopy extent for seaweed and seagrass, blue carbon health and extent for above-water species.	Scientists, policymakers, climate assessment bodies, NGOs, and private sector.	Minimum 30-meter spatial resolution for blue carbon ecosystems; global hyperspectral capabilities for OAE, OIF experiments. Global SST, SSS, SSH data
Ocean Carbon Models	Data to improve understanding and parametrization of air-sea gas exchange, biological pump efficiency, deep ocean carbon transport, ocean acidification feedbacks. Data need to be collected and analyzed using standardized methodologies. and representative of diverse locations.	Carbon export and variables involved in the carbon cycle at various depth, diverse location, carbon exchange with atmosphere and land to ocean transfer.	Primary use to track emissions, evaluate models, and inform climate action. Key users include: scientists, policymakers, climate assessment bodies, NGOs, and private sector.	Ocean and land carbon models carry uncertainty ranges of 10–20% or more. Complex climate-carbon feedbacks (e.g., how warming affects ecosystem carbon uptake) are not fully understood.

2.0 Introduction

2.1 The role of aquatic systems in carbon uptake and cycling

Authors: Kelsey Bisson, Gemma Kulk

Water is the foundation of life as we know it. We live on a blue marble - over 70% of Earth's surface is covered by the ocean, providing over 95% of the habitable volume for life on Earth. Life is sustained and proliferated in aquatic ecosystems which maintain extraordinary biodiversity and contribute to one of the largest active reservoirs of carbon on the planet. Aquatic ecosystems also provide foundational services to humanity; the ocean absorbs over a quarter of all anthropogenic CO_2 emissions (Gruber et al., 2023), helping to slow the pace of climate change. This uptake has been estimated at ~3.4 ± 0.4 Gt C y^{-1}, with land biosphere at 1.9 ± 1.1 Gt C y^{-1} (Friedlingstein et al., 2025). Indeed, the ocean has consistently acted as a carbon sink in the past two centuries (Sabine et al., 2004) and is expected to continue to do so in the future (Orr et al., 2001; Zickfield et al., 2016), albeit the rate of atmospheric carbon uptake is likely to change. It has been estimated that the ocean's biosphere alone offsets the atmospheric CO_2 equivalent to several billion US dollars annually, even when a modest value is assigned to carbon (Boyd et al., 2019). All in all, the monetary worth of carbon removal by the ocean could run into several trillion US dollars globally (Constanza et al., 2014; Barange et al., 2017).

Sinking aquatic carbon in the ocean not only removes carbon from the atmosphere but also fuels the metabolism of deep-sea organisms, including commercially important species like squid and tuna. Numerous processes act together today to shuttle carbon around different ecosystems, with societal benefits ranging from coastline protection against storms to food and national security, to job and recreation opportunities. Clearly, functioning aquatic ecosystems are key to the human economy, health, and prosperity.

2.2 Elevating the awareness of the complete aquatic carbon cycle

Authors: Kelsey Bisson, Gemma Kulk

The aquatic carbon cycle comprises freshwater, brackish, and oceanic systems. While the ocean is often considered a single reservoir of carbon in global budget assessments (e.g. Friedlingstein et al., 2025), it is comprised of different carbon pools – dissolved and particulate, organic and inorganic, above ground and submerged - that are connected by processes and fluxes between them. Together, these interactions determine how carbon is stored, transformed and ultimately sequestered for long time scales in the deep ocean or sediments.

The largest carbon pool in the ocean is inorganic; the Dissolved Inorganic Carbon (DIC) pool comprises ~38,000 Gt C (Hedges, 1992). The DIC pool consists of dissolved CO_2, carbonic acid, bicarbonate and carbonate, and the balance (i.e., equilibrium) between these components is referred to as alkalinity (Shutler et al., 2024). Temperature is an important regulator of CO_2 solubility in aquatic environments which means that as the ocean and inland waters warm, their ability to uptake CO_2 will decrease (Wanninkhof et al., 2013; Woolf et al., 2016). The DIC pool, specifically the balance between carbonic acid and carbonate, plays an important role in regulating the pH of seawater (Feely et al., 2009). DIC is replenished by air-sea CO_2 gas exchange, the process through which carbon from the atmosphere moves into the ocean. On average, this flux removes between 1-3 Gt C y^{-1} from the atmosphere (Friedlingstein et al., 2025). The Particulate Inorganic Carbon (PIC), the smallest pool of carbon in the ocean, stores ~0.03 Gt C (Hopkins et al., 2019). PIC is created when organisms, such as calcifying phytoplankton and foraminifera, convert bicarbonate into calcium carbonate in particulate form (i.e., calcification; Schiebel, 2002; Feeley et al., 2004). While calcification locks carbon into solid particles, it also releases CO_2 and changes the alkalinity and pH of seawater.

The Dissolved Organic Carbon (DOC) pool, at ~662 Gt C (Hansell and Carlson, 2013), is chemically diverse, consisting of refractory, semi-labile and labile components, each having different turnover times (Hansell and Carlson, 2013; Hansell, 2013). The differences in reactivity of these components make the roles of DOC in the ocean carbon cycle varied. For example, the labile component of DOC is rapidly respired back into DIC by microbial communities (i.e., turnover of days), while the refractory components of DOC, considered a major sink of carbon in the ocean, can persist over decadal/centennial time scales (Sexton et al., 2011; Hansell and Carlson, 2013). The Particulate Organic Carbon (POC) pool is estimated to be between 1.1-3.9 Gt C (Stramska and Cieszunska, 2015; Kong et al. 2024). The POC pool consists of non-living components, such as detritus, and living components including phytoplankton, zooplankton and bacteria. Phytoplankton carbon is of specific interest because it is formed via photosynthetic fixation of atmospheric CO_2, i.e., marine primary production, which is the largest flux of carbon in the ocean at 50 Gt C y^{-1} (Kulk et al., 2020). The organic carbon produced by phytoplankton can move through the food web, through grazing by microzooplankton, larger zooplankton and fish. The ratio between primary (phytoplankton) and secondary production (zooplankton, fish, etc.) can be used to quantify the efficiency of the marine food web (Sigman and Hain, 2012). The downward flux of POC is termed export production and is estimated to be between 5-20 Gt C y^{-1} (Jönsson et al., 2023). This downward transfer to depth represents a key pathway for long-term carbon sequestration, as carbon that reaches the deep ocean (~>500m) can be stored away from the atmosphere for centuries or longer.

The transfer of carbon between pools, and especially from the surface to the deep, is driven by a set of processes known as carbon pumps. These pumps modulate how much carbon remains in circulation at the surface and how much is sequestered at depth where, in the case of the ocean, it is locked away over decadal and centennial scales. The solubility pump (or physical pump) transports DIC from the surface to the interior (Raven and Falkowski, 1999). It is based on the ability of colder water to absorb more CO_2 (Woolf et al., 2016). In the ocean, this happens at high latitudes; these cold, dense waters sink through thermohaline circulation and carry carbon into the deep ocean where it can remain isolated for centuries (Raven and Falkowski, 1999).

The biological carbon pump is the dominant mechanism for transporting particulate carbon from the surface to depth. Photosynthesis by phytoplankton removes CO_2 from the surface, converting it into organic matter. When this material sinks or is transported downward, it leads to a vertical gradient of inorganic carbon that enhances the capacity of aquatic systems to absorb atmospheric CO_2 (Raven and Falkowski, 1999). Without the ocean's biological carbon pump, for example, it is estimated that present-day CO_2 concentrations would be two-fold higher (Heinze et al., 2015). Various physical and biogeochemical processes make up the biological carbon pump, including the physical, gravitational and migrant pumps, which act at different spatial and temporal scales (Boyd et al., 2019). While some components of the biological carbon pump have been extensively studied, new research continues to reveal many overlooked contributions of different organisms and mechanisms, such as the mixing and eddy-subduction pumps, that carry particles like fecal pellets and aggregates downward, and the migrant pump by which carbon is transported by upward and downward migrating fish and zooplankton, that transport carbon from the surface to depths (Boyd et al., 2019; Siegel et al., 2023).

In addition to pelagic processes, coastal vegetated ecosystems—commonly referred to as Blue Carbon systems (e.g., mangroves, salt marshes, and seagrasses)—represent an important and distinct pathway within the aquatic carbon cycle. These systems are characterized by high rates of primary production and efficient trapping and burial of organic carbon in waterlogged, anoxic sediments. Unlike the open ocean, where long-term sequestration is largely driven by vertical export to the deep ocean, Blue Carbon ecosystems store carbon locally in sediments that can persist over centennial to millennial timescales. Importantly, these coastal systems are not isolated from pelagic processes: they exchange carbon with adjacent shelf and open-ocean waters through lateral transport of dissolved and particulate organic carbon, thereby contributing to offshore carbon cycling and, in some cases, fueling components of the biological carbon pump. They also play a key role in mediating carbon exchange between land, ocean, and atmosphere through tidal processes.While organic and inorganic carbon pools in freshwater and brackish systems are much smaller than in the ocean, the partitioning, transformation, processes, and fluxes function in a similar way as in the open ocean. It is important to recognize, however, that the ultimate sink of carbon in freshwater and brackish ecosystems is in the sediments, which, being at a much shallower depth, can be mobilized and remineralized more easily than in the deep sea.

2.3 Conceptual coverage of this roadmap and definitions

This roadmap outlines the critical role of Earth Observations (EO) in quantifying and monitoring carbon stocks and fluxes across various aquatic systems. It serves as a framework for advancing carbon accounting and provides guidance on integrating the ocean into climate strategies and ocean-based climate measures, in particular the global carbon stocktake. It is not an all-encompassing document that covers the science of aquatic carbon but provides the scientific foundation for the execution of priorities that will advance carbon quantification across aquatic environments.

The scope of the document includes the following key areas:

a. **Aquatic Systems:** The roadmap addresses carbon dynamics across a "land-to-ocean-aquatic-continuum" (LOAC), specifically focusing on:
  - Open Oceans and Shelf Seas: The largest aquatic environments, covering roughly 94% of the global aquatic area.
  - Coastal and Blue Carbon Ecosystems: Specifically coastal areas and ecosystems such as seagrasses, tidal marshes, and mangroves.
  - Inland Waters: Including lakes, reservoirs, and rivers.

b. **Technical and Scientific Focus:** The roadmap takes into consideration the following:
  - Earth Observation (EO) Capabilities: It examines the current state of remote sensing to monitor different, relevant carbon pools (dissolved, particulate, organic, and inorganic) and fluxes (such as air-sea gas exchange and exchange across systems).
  - Prioritization of Needs: The roadmap identifies specific priority areas and opportunities that could be executed across different timelines, leveraging existing and planned activities by the EO community.
  - Foundational Science: While the roadmap focuses on carbon accounting, it notes that this hinges on foundational science to advance critical applications, though it does not go into exhaustive scientific depth itself.
  - Global Assessments: The document aims to support the Global Stocktake, National Greenhouse Gas (GHG) Inventories, and IPCC assessments, amongst other activities.
  - Dissemination and Capacity Building: The roadmap includes considerations to increasing global capacity for EO data use and improving communication across communities.

Core Definitions used throughout the document

- **Aquatic Ecosystems:** An aquatic ecosystem is a specific type of ecosystem found within bodies of water, encompassing both the plants and animals that inhabit these areas. Covering approximately 70 percent of Earth's surface, aquatic ecosystems are classified into two main categories: saltwater and freshwater.
- **Aquatic Systems**: A broader term that can include the physical, chemical, and hydrological processes of the water body,
- **Land-to-Ocean-Aquatic-Continuum (LOAC):** The flow of carbon from land to ocean across various aquatic ecosystems, including coastal vegetation.
- **Blue Carbon Ecosystems:** Blue carbon ecosystems are coastal and marine habitats that sequester and store vast amounts of carbon in their soils and plants. Blue carbon ecosystems classically include mangroves, tidal marshes and seagrasses, but increasingly expand to include ecosystems such as tidal flats, macroalgal forests and shelf sediments.
- **Carbon Pools and Pathways**: A carbon pool is a reservoir or system that has the capacity to store, accumulate, or release carbon. Pathways are the processes, often referred to as fluxes, that move carbon from one pool to another.
- **DIC (Dissolved Inorganic Carbon):** The largest carbon pool, consisting of dissolved CO_2, carbonic acid, bicarbonate, and carbonate.
- **PIC (Particulate Inorganic Carbon)**: One of the major reservoirs of carbon in the ocean, it is inorganic carbon in particulate form that is too large to pass through the filter used to separate dissolved inorganic carbon. Most PIC is $CaCO_3$.
- **DOC (Dissolved Organic Carbon):** Fraction of organic matter in water that passes through a filter. It is characterized by its categorized by its bioavailability: labile, semi-labile, and refractory.
- **POC (Particulate Organic Carbon):** Fraction of organic carbon that includes living components like phytoplankton and non-living detritus.
- **Carbon Pumps**: The set of processes that transfer carbon between pools, particularly from the surface to the deep ocean. The include the Solubility Pump (the physical transport of DIC from the surface to the interior based on CO2 solubility), and the Biological Carbon Pump (mechanism for transporting particulate carbon to depth via photosynthesis and sinking of organic matter).
- **Export Production**: The specific downward flux of POC from the surface to the deep ocean.
- **Marine Carbon Dioxide Removal (mCDR)**: refers to intentional, human-driven activities and technologies designed to remove from the atmosphere and store it durably within the ocean or marine sediments.
- **MRV (Monitoring, Reporting, and Verification)**: Essential systems for carbon markets that ensure the consistency, transparency, and reliability of carbon claims.
- **Global Stocktake (GST)**: The process under the Paris Agreement for assessing collective progress toward climate goals.
- **Calibration and Validation:** calibration is the process of testing or checking an instrument against a known standard. Validation is the process of assessing by independent means the quality of the data products derived from the system outputs.
- **NbS**: Nature-based Solutions which are science-based interventions that use natural ecosystems as part of the solution to climate change and other societal challenges, delivering multiple environmental and social benefits.

3.0 Current satellite Earth observation capabilities for aquatic carbon

3.1 Why Earth observations matter for carbon assessments

Author: Cecile S. Rousseaux

Satellite Earth observations (EO) have become an indispensable component of global carbon cycle science, providing sustained, spatially extensive, and repeatable measurements that cannot be achieved through in situ observations alone (IPCC, 2021; GCOS, 2022). For aquatic systems in particular—where logistical constraints, jurisdictional complexity, and strong spatial heterogeneity limit traditional sampling—EO provides the most plausible means to achieve sustained global coverage (IOCCG, 2014; Groom et al., 2019). EO already plays a recognized role in IPCC assessments, the Global Carbon Budget (GCB), and related international syntheses by constraining key components of the ocean carbon sink, air–sea CO_2 fluxes, and ecosystem productivity (IPCC, 2019; Friedlingstein et al., 2023, see section 5). Satellite-derived estimates of ocean colour, sea surface temperature, sea level, salinity, and ice cover underpin many of the observational products and model–data syntheses that inform assessments of the global carbon cycle (Landschützer et al., 2016; Fay et al., 2021). These contributions have improved confidence in the magnitude, variability, and long-term trends of the open-ocean carbon sink, and have increasingly informed attribution of interannual to decadal variability driven by climate modes such as ENSO and the Southern Annular Mode (McKinley et al., 2020; IPCC, 2021). However, as global climate governance evolves toward regular global stocktakes, enhanced transparency frameworks, and more complete and accurate national greenhouse gas inventories, expectations on observational systems are changing (UNFCCC, 2023). EO is no longer required solely to support global-scale understanding; it must increasingly inform policy-relevant monitoring, reporting and verification, particularly for aquatic and coastal carbon processes and activities that remain underrepresented in current IPCC methodological guidance for blue carbon (IPCC, 2019; Oreskes et al., 2023).

3.2 EO for aquatic carbon in open-ocean and shelf-seas, including air-sea fluxes

Authors: Bob Brewin, Cecile Rousseaux, Kelsey Bisson, Lionel Arteaga, Joaquim Goes

The open ocean and shelf seas are the largest aquatic environments on Earth, covering roughly 85% and 9% of the global aquatic area, respectively (Laruelle et al., 2018). Together, these environments play a central role in the global cycling of carbon. They also encompass some of the most remote and inaccessible regions on the planet, areas that, in some cases, have only ever been monitored from space. Space-based ocean observations rely on electromagnetic radiation in the visible, thermal, microwave and radar wavelength ranges (Robinson, 2004). This information can be retrieved passively, by detecting energy from the sun reflected or emitted by the ocean surface, or actively, when the satellite sends out its own energy signal and measures the ocean's response. Different regions of the electromagnetic spectrum reveal distinct ocean properties (Figure 3.1): visible wavelengths provide information on ocean colour, thermal wavelengths on sea surface temperature, microwave wavelengths on surface temperature, salinity, topography and roughness. These primary observables, in turn, can yield insights into the major dissolved and particulate carbon pools in the ocean (DIC, DOC, POC, PIC; Figure 3.1) and their environmental context.

Satellite-derived primary observables also provide essential information for quantifying some of the fluxes of carbon between the different pools (Figure 3.1). For example, carbon dioxide quickly dissolves in seawater, and the air-sea concentration gradient or partial pressure gradient of a gas determines the air-sea exchange. Estimating the flux of CO_2 between the ocean and atmosphere requires knowledge of the physical structure of the surface ocean (e.g., temperature) and the gas transfer velocity, which is influenced by surface turbulence. Satellite thermal, microwave, and radar measurements contribute to these estimates (Shutler et al., 2024). Similarly, primary production by phytoplankton—the conversion of DIC into POC—depends on phytoplankton biomass, photosynthetic quantum efficiencies of the native phytoplankton populations, light availability, and light penetration through the water column. Satellite observations of ocean colour provide key variables such as chlorophyll-a concentration, photosynthetically available radiation, and the diffuse attenuation coefficient, all of which are needed to quantify primary production rates in the ocean (Skákala et al., 2025; Westberry et al., 2023). The conversion between DIC and PIC, through processes of calcification and decalcification, is influenced by ocean acidity, which in turn depends on the carbonate system. Aspects of this system can be observed from space (Land et al., 2015), and in research, there has been an increasing use of EO to study carbon dynamics (Brewin et al., 2023).

Satellite platforms and sensors have advanced significantly in recent years, opening exciting new avenues to measure aquatic carbon from space (see Table 2 of Brewin et al., 2023). Improvements in spectral resolution, exemplified by NASA's PACE mission, are enabling more detailed quantification of carbon components (Cetinić et al., 2024). In addition, the development of micro- and nanosatellites offers the potential for cost-effective deployment in large swarms, greatly increasing both spatial and temporal

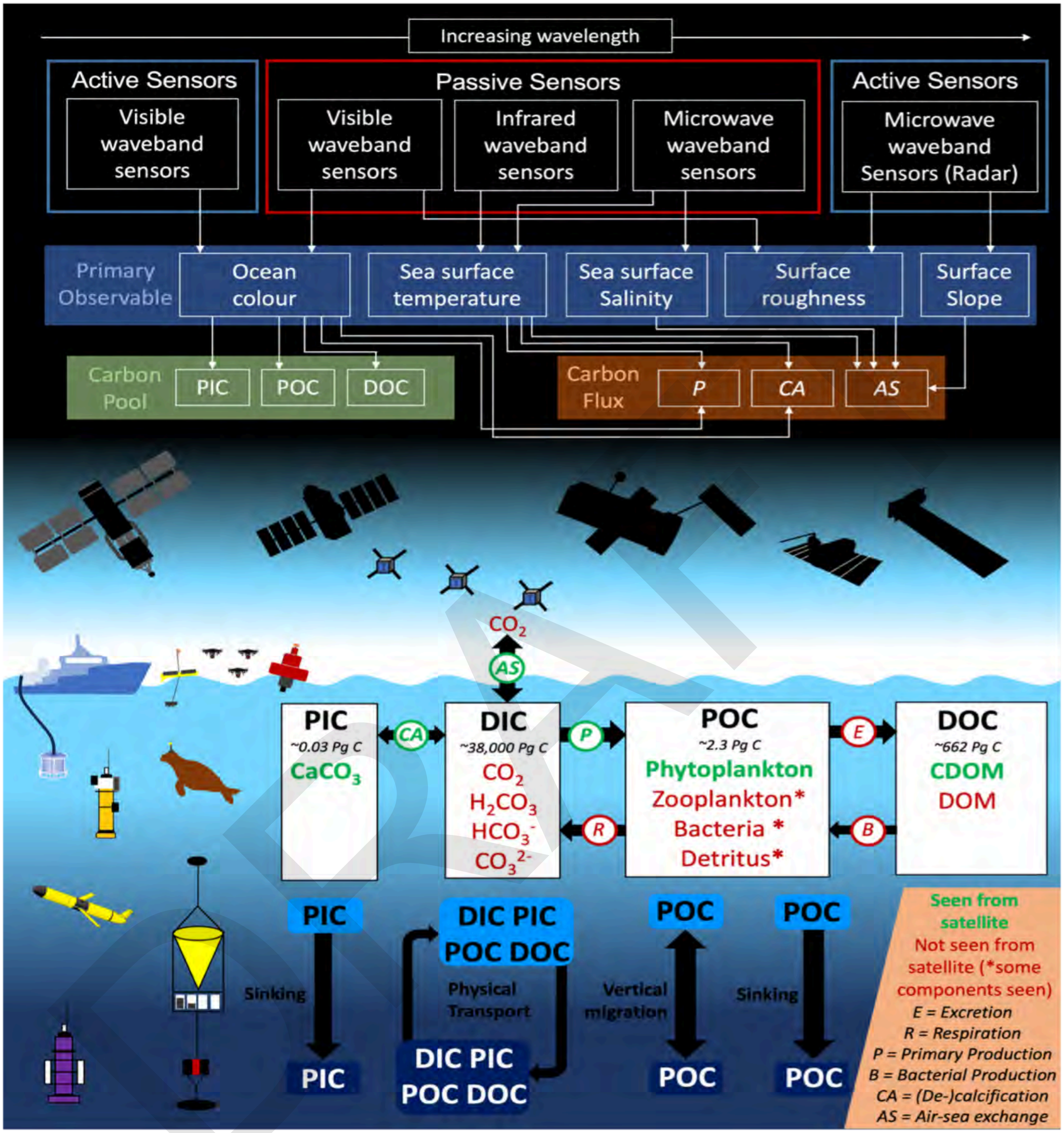

Figure 1 Capabilities of satellite Earth Observation for monitoring ocean and shelf carbon pools and fluxes. The top part of the figure illustrates the main regions of the electromagnetic spectrum used to observe the oceans from space, the primary observables that can be derived from these regions (note, with the exception of surface roughness, these are considered Essential Ocean Variables (EOVs) by the Global Ocean Observing System (GOOS)), and the key carbon pools and fluxes targeted by these measurements. This portion of the figure was inspired by and adapted from an earlier figure in Robinson (2004). DIC = dissolved inorganic carbon, DOC = dissolved organic carbon, PIC = particulate inorganic carbon, and POC = particulate organic carbon. The bottom part of the figure shows various satellite and in-situ technologies used to monitor ocean carbon, highlighting the key carbon pools and some of the important processes that control carbon fluxes between these pools, as well as exchanges with the deep ocean. Note the components of the pools shown in green reflect those that can be directly observed from space. This portion of the figure was inspired by and adapted from Brewin et al. (2021) and a figure in the 2014 CEOS Carbon Strategy report (https://ceos.org/home-2/the-ceos-carbon-strategy-space-satellites/).

resolution (Schueler and Holmes, 2016). The increasing number of commercial satellites being launched has potential to offer useful data for studying ocean carbon dynamics especially in areas which require higher spatial resolution. There is now continuous satellite data for many of the primary observables that exceeds 25 years, approaching the length needed to quantity longer-term climate trends (Cael et al., 2023a; Hollmann et al., 2013; Sathyendranath et al., 2019; Henson et al., 2017). While direct observations of pCO_2 in surface waters from remote sensing remains a challenge, space-based observations of the column-integrated CO_2 mole fraction, XCO_2, from missions such as the Orbiting Carbon Observatory 2 (OCO-2) are providing advances in observations of interannual variability in atmospheric CO_2 and can provide observations over the global ocean, improving the spatiotemporal information of ocean fluxes (Guan et al., 2024; Chatterjee et al., 2017; Shutler et al., 2019). Collectively, these advances suggest that EO will play an increasingly important role in quantifying and monitoring ocean and shelf sea carbon and will be able to support emerging initiatives looking to leverage the potential of aquatic systems for carbon sequestration, such as marine Carbon Dioxide Removal (mCDR) strategies, and supporting carbon accounting (e.g. Brewin et al., 2023). For a comprehensive review of the capabilities of satellites for monitoring carbon in the open ocean and shelf seas, readers are referred to Shutler et al. (2024) and Brewin et al. (2023).

3.3 EO for aquatic carbon in Coastal zones, including blue carbon ecosystems

Authors: Merrie Beth Neely, Dimitris Poursanidis, Aurelien Carbonniere, Christine Dupuy, Tiit Kutser, Antonio Mannino, Kesav Unnithan, Vincent Vantrepotte

The coastal zone hosts diverse habitats, including transitions from freshwater and brackish waters to seawater, mudflats, and rocky environments, most of which are influenced by tides. Blue carbon ecosystems – defined here as seagrasses, tidal marshes, and mangroves – capture and store vast amounts of carbon in both biomass and sediments, while providing co-benefits such as coastal protection, fisheries support, and biodiversity enhancement. Transitional waters systems, including lagoons, bays, and estuaries, are biodiversity hotspots and major carbon-cycling areas linking land, wetlands, and coastal seas. Assessing these ecosystems requires accounting for tidal dynamics, vegetation, hydrology, sediments, and carbon-cycle functioning across this gradient.

Carbon stocks in the coastal zone are distributed across three main pools, each of which offers specific measurement challenges from EO:

- Above-bottom living sessile biomass (herbaceous plants, seagrass, macroalgae, phytoplankton, microphytobenthos, oyster/worm/coral reefs);
- Below ground living sessile biomass (roots and rhizomes, infauna);
- Benthic sediment, which stores the largest and most stable carbon fraction through long-term sediment accumulation.

Nearshore waters exhibit high physical, biological, and biogeochemical variability over very small spatial scales (1–100 m) and short temporal scales (hours). In addition, coastal regions are interfaces where carbon from land exchanges with carbon from the ocean; these interchanges have impacts on coastal ecosystems and carbon cycling.

For example, land-derived DOC exported from catchments to coastal waters plays a major role in aquatic carbon cycling, light regulation, and nearshore ecosystem function. Tropical peat-draining rivers deliver extremely high concentrations of DOC and strongly absorbing chromophoric dissolved organic matter (CDOM), shaping the optical character and biogeochemical reactivity of receiving waters. For instance, DOC fluxes from Southeast Asian peatlands can exceed 50 mg L^{-1}, with clear land–sea gradients that reflect both hydrological connectivity and peatland disturbance intensity (ChunHock et al, 2020). Once delivered to the coast, CDOM dominates light attenuation, reducing underwater irradiance and constraining benthic primary production. This “coastal darkening” effect can have impacts on coastal primary production and carbon sequestration/export.

here is an intrinsic connection between coastal DOC–CDOM dynamics and upstream catchment condition, monsoon hydrology, and land-use trajectories. For example, catchment processes modify DOC quality and its bio-optical behaviour before reaching the coast (see also section 3.4). Studies of freshwater systems demonstrate that terrestrially derived DOM is often photoreactive and can transition from refractory to more labile pools under sunlight exposure, influencing carbon turnover and nearshore CO_2 outgassing (Kaushal et al, 2021; Reiman et al, 2019). Land-use change accelerates these dynamics by mobilising older peat carbon, increasing DOC loads, and altering the optical signature and degradability of exported DOM. For example, long-term satellite records indicate that DOC and CDOM in northwestern Borneo have risen steadily since 2002, driven by extensive peatland conversion (Sanwlani et al, 2022). Similar patterns have been documented in temperate systems, where increased terrestrial DOC has contributed to long-term browning of estuarine and coastal waters (Cherukuru et al, 2016; Urtizberea et al, 2013; Schroeder et al, 2012). Understanding and monitoring DOC and CDOM from catchments to coasts is therefore critical for regional carbon accounting, coastal ecosystem management, and anticipating climate-driven changes in aquatic light regimes and carbon fluxes.

Earth observations over the last decades have significantly advanced the quantification of carbon in coastal ecosystems (e.g. Campbell et al., 2022; Macreadie et al., 2019; 2022; Mannino et al. 2016; Signorini et al. 2019), including the characterization of carbon-relevant benthic and coastal communities (mangrove, marsh, seagrass and benthic microalgae, kelp and attached calcareous algae, nearshore hardbottom, oyster/mussel beds, worm- and coral-reefs). However, because of the biological and chemical complexity and scale of carbon processes in the coastal zone, field measurements remain essential for reliable carbon estimates and for validating fluxes and habitat maps derived from EO, along with carbon-distribution models (Poursanidis et al., 2025). Numerous methodological developments for deriving POC (Le et al., 2017; Tran et al., 2019; Loisel et al., 2023; Xue et al., 2025) and DOC (review by Fichot et al., 2023) from remote sensing measurements have been increasingly applied for coastal waters. Although moderate-resolution ocean colour missions with quasi-daily observations at 300m -1 km resolution can capture part of the variability observed in nearshore environments (Cao et al., 2018), their application becomes limited in highly heterogeneous and rapidly changing coastal zones. Satellite measurements capable of resolving small-scale variability (e.g. Cao and Tzortziou, 2021; Unnithan et al, 2025; Cherukuru et al, 2016) are therefore particularly useful, including the constellation of

Landsat-8/9 OLI and Sentinel-2A/B MSI sensors which provide observations at spatial resolutions of 10–30 m, and commercial satellite imagery (<10 m spatial resolution); however, the latter often lack the rigorous quality and cross-calibration assessments robust carbon measurements require.

When it comes to blue carbon ecosystems, EOs offer a cost-effective, scalable, and repeatable way to monitor the extent, condition, and carbon dynamics of these ecosystems. Mapping the areal extent of blue carbon ecosystems is fundamental for understanding their role in the global carbon cycle. EO technologies have allowed the reconstruction of historical and contemporary coverage of blue carbon ecosystems (Sunkur et al., 2023, Floyd et al., 2024). One of EO's strongest assets is its temporal coverage. Historical Landsat imagery has been extensively used to monitor changes in the areal extent of mangroves and tidal marshes over the past half century (Murray et al., 2022, Worthington et al., 2024). Similar approaches are increasingly applied to seagrass and macroalgae habitats, although challenges remain due to water-column effects and spectral similarity with other submerged habitats. Time-series analysis allows the detection of regrowth or restoration success, offering accountability for conservation interventions (Bunting et al., 2022). Today, high resolution sensors such as Sentinel-2, PlanetScope, and WorldView together with machine learning and artificial intelligence technologies enable more precise and automatized assessments of current areal extent (Kutser et al., 2020).

Estimating carbon stocks requires linking EO data with field measurements. Passive optical data provides proxies for aboveground biomass, while active sensors such as LiDAR and Radar can capture canopy height and structural complexity (Pham et al., 2020). Indeed, sub-bottom profilers and seismic-acoustic sensors allow estimating the several meter-thick soil carbon stores underneath blue carbon ecosystems (Lo Iacono et al., 2008). These inputs feed into machine learning and process-based models allow upscaling from site-level surveys to regional and global estimates. Efforts are underway to harmonize methods and reduce uncertainties, particularly in below-ground carbon pools where EO proxies are at its onset. Flux towers remain critical for measuring carbon exchange, but satellite data can complement and scale these insights. EO-derived productivity and biomass trends can be integrated into flux models to estimate carbon sequestration and emissions from degradation (Murdiyarso et al., 2023). Importantly, EO can help quantify fluxes associated with loss, conservation, or restoration, as well as lateral carbon transfers to coastal and deep-sea ecosystems (Liu et al., 2024).

Beyond areal extent, understanding the ecological status and composition of blue carbon ecosystems is critical as it dictates their ability to sequester carbon. Advances in time-series analysis of multi and hyperspectral satellite data are making it increasingly feasible to distinguish between major vegetation assemblages or dominant species. Hyperspectral data from current (ASI PRISMA, DLR EnMAP, Planet Tanager, PACE) and future satellite missions (NASA's EAGLE-VSWIR Copernicus S-2 Next Generation or Copernicus Expansion Mission CHIME) promise unprecedented capacity to resolve subtle spectral differences between vegetation types (Clarke et al., 2021). Satellite-derived indicators such as vegetation indices (NDVI, EVI, or water-adjusted indices), canopy height from LiDAR, and benthic cover from spectral analysis provide proxies for biomass, density, and canopy condition (Chandra et al., 2010). Blue carbon ecosystems exhibit significant intra-seasonal and inter-annual variability in productivity. EO platforms allow these dynamics to be monitored continuously. Seasonal peaks in tidal marsh and macroalgae productivity can be tracked, while seagrass meadows can be monitored for inter-annual shifts using specialized approaches to correct for water optical properties (Chen et al., 2024). Detecting such fluctuations is essential for understanding biomass production, resilience, and long-term carbon sequestration potential. Together, these measures enable broad assessments of ecosystem health and biodiversity, complementing field-based ecological surveys.

3.4 EO for inland aquatic carbon, including land to ocean fluxes

Authors: Antonio Mannino, Stefan Simis, Meghan Halabisky, Tiit Kutser, Dustin Carroll

Inland water bodies, including reservoirs, lakes, and rivers, amount to only ~4% of the Earth surface but play a prominent role in the regulation of terrestrial carbon, acting as net carbon sources or sinks. Inland waters are known to function as active pipes and reactors, transferring and transforming carbon and nutrients and account for significant sources and sinks of carbon at global scales (Cole et al. 2007; Tranvik et al. 2018). Specifically, inland waters receive 2.95 Pg C yr^{-1} from terrestrial ecosystems, outgas 1.85 Pg C yr^{-1} to the atmosphere, bury 0.15 Pg C yr^{-1}, and export 0.95 Pg C yr^{-1} to estuaries and tidal wetlands and ultimately to the coastal ocean (Regnier et al. 2022). Primary production takes place ubiquitously in inland water bodies, and macroalgae are also often found proliferating in locations that have been eutrophicated. Inland water bodies are also a critical connector to humans, often providing foundational ecosystem services that depend on their ability to cycle carbon.

Among the major pathways of carbon transport in the Earth system, the flow of carbon from land to ocean across aquatic ecosystems, including coastal vegetation, known as the Land-to-Ocean-Aquatic-Continuum (LOAC), has increased by 0.6 ± 0.4 Pg C yr^{-1} due to anthropogenic perturbations (Regnier et al., 2022). Sinks, sources, and transformation of carbon across the LOAC are dynamic, fine-scale processes, cover different ecosystems from inland waters to estuaries, wetlands, and finally to coastal ecosystems (tidal flats, mangroves, seagrass) and the open ocean, and are shaped by land disturbances.

Despite limitations in what biogeochemical information may be gleaned using remote sensing over lakes, reservoirs, and rivers, remote observations remain key to quantify aquatic carbon inland. Advances in satellite observations, such as SWOT, are also opening new avenues to quantify fluxes of carbon from land to ocean. Indeed, remote sensing observations of inland waters for water quality and carbon cycling studies have significantly expanded over the past three decades and pushed beyond initial efforts focused on remote sensing retrievals of chlorophyll-a, light attenuation, and suspended matter. With the availability of visible-NIR radiometric satellite instruments with additional spectral bands and sufficient sensitivity for ocean colour retrievals along with advances such as in atmospheric correction (Mishra et al. 2017; Palmer et al. 2016), remotely sensed parameters have expanded to inherent optical properties, in particular CDOM absorption (e.g., Fichot et al. 2023; Kutser et al. 2017; Li et al. 2018), dissolved organic carbon (e.g., Fichot et al. 2023; Harkort & Duan 2023; Kutser et al. 2016; Xu et al. 2025), particulate organic carbon (e.g., Duan et al. 2014; Jiang et al. 2019), partial pressure of carbon dioxide (e.g., Wen et al. 2021), primary productivity (e.g., Sayers et al. 2021), and phytoplankton community composition including harmful algal blooms (HABs) (e.g., Clark et al. 2017; Kutser 2009). Higher spatial resolution measurements from satellites are also opening the doors to monitoring the smaller, yet numerically dominant group of lakes and reservoirs; on the order of 2000 to 4000 lakes are globally monitored for Lakes essential climate variable (ECV) products (Carrea et al. 2024).

4.0 Critical challenges, gaps and opportunities

Authors: Cecile Rousseaux, Jamie Shutler, Kelsey Bisson, Gemma Kulk, Bob Brewin, Lionel Arteaga, Joaquim Goes

Quantifying aquatic carbon processes, including fluxes and storage, is complicated by the time scales in which they happen, and where they happen. The scales of variability of aquatic systems are much more rapid than those on land, making it more difficult to intuitively grasp the significance of different carbon transport pathways. Aquatic systems are constantly in motion, forcing carbon to be shuttled both vertically and laterally. For example, a carbon carrying particle in the ocean may sink 1 meter per day whereas it can be transferred laterally many 10s of kilometres during the same time. For this reason, quantifying the fate of aquatic carbon requires not only measuring its magnitude but also understanding how it flows through the ocean, accounting for important pathways of transport (such as gravitational sinking, physical transport and vertical migration, see Boyd et al. 2019 and Bellacicco et al 2025), but also processes related to flows of carbon through microbial ecosystems and higher trophic levels (e.g. Iversen, 2023). The speed at which changes in aquatic carbon processes are happening adds further complexity; sea ice melting in the Arctic is proceeding at rates four times as fast as other areas globally, which impacts physical circulation (that requires density gradients to propel water) and ecosystem stability. Acidification due to absorbed CO_2 influences the health of organisms requiring stable pH ranges for growing or maintaining carbonate bodies. Large uncertainties remain in permafrost thawing and release of dissolved organic carbon into the ocean, as well as the interplay between terrestrial plant biogeography and aquatic systems. Current in situ observational systems are not deployed broadly enough, nor rapidly enough, to capture the ongoing changes nor the scales of the fluxes at a global level. While remote sensing is advancing the required global observations, the spatial scales at which carbon fluxes often operate are not efficiently captured by current observational assets, though advances such as the PACE mission (see Section 3.2), and the planned EAGLE-VSWIR, CHIME and Sentinel Next Generation, are filling some of those gaps. Satellite observations are also constrained by the types of information that electromagnetic radiation can carry to the top of Earth's atmosphere - only certain signatures of carbon pools are observable from space (Figure 3). For instance, direct observation of DIC is not currently possible, and much of the DOC does not have an optical signature that can be seen from space. Parts of the particulate carbon pool also remain beyond direct detection (Brewin et al., 2021; Cael et al., 2023b). Many key carbon fluxes –such as respiration, excretion, bacterial production, and carbon export– cannot be directly measured from space. Derived carbon-based products are obtained through empirical or analytical algorithms linking remote sensing properties with biogeochemical observations, and error propagation suggests uncertainties in these products can be large.

Many aquatic carbon processes also take place in the interior of water bodies (e.g. lakes, rivers, estuaries, ocean), impervious to current passive satellite observations; passive ocean colour satellites detect signals representative of just the first optical depth (~10–30 m in most of the ocean). Passive thermal and microwave radiometry observe only the ocean's skin (on the order of sub-millimetre), and active radar is limited to mapping surface topography and roughness. As a result, much of the processes occurring below the surface remain invisible from space, and measuring these processes poses a significant challenge which is partly being overcome by process studies (ship-based), and autonomous platforms (e.g. floats), but are still ill characterized. Future active satellite missions, such as aquatic-optimized lidars which can penetrate deeper, up to potentially four optical depths (Behrenfeld et al., 2023), are expected to help address some of the existing shortcomings (see Section 3). There are important physical and biological processes that modulate the aquatic carbon cycle and that ultimately determine the strength of the carbon sink (e.g. for a review see Brewin et al., 2021 and Shutler et al., 2024) and overlooking these processes risks underestimating or mischaracterising the global carbon budget. Lastly, the high degree of connectivity across aquatic systems (e.g. rivers into estuaries and ocean) makes accounting for the lateral transport of carbon a must, though it remains a challenge because of inadequate observational capabilities at interfaces (e.g. land/ocean). Coordination among disciplines is critical for addressing this gap (see section 4.3).

The transition toward a comprehensive aquatic carbon roadmap requires addressing the persistent fragmentation between EO capabilities and requirements for various applications. While satellite remote sensing has revolutionized our understanding of surface dynamics, significant barriers remain in capturing the multi-dimensional complexity of the open ocean, the highly-variable shelf seas, and the challenging exchanges and interactions of inland aquatic environments. For example, reliance on single-satellite missions limits the temporal and spectral breadth of data needed to capture different processes that take place in aquatic ecosystems. Combining polar-orbiting ocean colour satellites with geostationary satellites and active measurements, such as lidars or synthetic aperture radar (SAR), will be necessary to increase the information density of surface-subsurface interactions (Muller-Karger et al., 2018). But overcoming these challenges will require not just improved observables that enable the acquisition of the data needed to quantify, within an acceptable uncertainty, the stocks and fluxes of carbon within and across systems, but a shift in perspective, where the continuum of carbon flows are recognized and duly characterized. Bridging the gap between the EO community and other disciplines remains difficult; inter-disciplinary misunderstandings regarding data uncertainties and spatial scales often hinder the integration of remote sensing into broader biological and chemical models (Bracher et al., 2017). This is aggravated by the sampling biases often present in oceanographic datasets. These biases are largely driven by the high costs associated with traditional research vessel expeditions, which often limit sampling to specific seasons or accessible geographic regions. These limitations, however, serve as opportunities for innovation as well as training the next generation of researchers. This will in turn improve predictions of how stocks and fluxes will change in the future, what kind of feedbacks may be expected from other systems (e.g., atmosphere and land), and how humanity should take stock of these changes so that we are better prepared for the upcoming changes.

4.1 Aquatic carbon in open-ocean and shelf-seas, including air-sea fluxes

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A primary challenge for assessing carbon stocks and fluxes in the open ocean and shelf seas lies in the limitations of current technology and expertise in combining the various dimensions of observations. This is especially acute in the "hidden" dimensions of the ocean, which lie beneath the surface, away from what current passive radiometric technology can reach. Prime examples are the Twilight Zone and Polar Regions; Twilight zone science (the mesopelagic layer) and under-sea ice regions remain "black boxes." The difficulty of signal penetration and physical access makes these areas critical frontiers for future exploration. Similarly, there is a lack of consistent, scalable data on higher trophic levels and biodiversity throughout the entire water column. While surface chlorophyll is well-mapped, the distribution of organisms from phytoplankton composition and zooplankton to top predators remains poorly integrated into EO frameworks.

Similar challenges arise determining the fluxes of carbon between the ocean and the atmosphere. Since the sea surface partial pressure of CO_2 (pCO_2) cannot be directly observed remotely, bottom-up estimates are obtained from indirect methods. For instance, the water partial pressure of CO_2 can be well constrained by physical, chemical and biological proxies that are remotely sensed. Thus, a common approach is to leverage sparse in-situ pCO_2 data from ships and buoys, and integrate them with satellite observations of ocean colour data and/or biogeochemical models to provide a bottom-up constraint on ocean-atmosphere carbon flux exchange (c.f. Landschützer et al., 2020; Ford et al., 2024). While this approach is considered reliable for global estimates, it is limited by the sparse spatial coverage of the in-situ data, with less than 2% of oceanic grid boxes sampled monthly (Bakker et al. 2016), and their density is insufficient to directly infer global gas exchange. The sampling is even more sparse over the Southern Ocean, which is thought to account for up to 40% of the ocean CO_2 sink (Hauck et al., 2023; Gruber et al., 2019). This makes this approach insufficient to monitor the response of air-sea fluxes with the precision, accuracy, resolution or coverage needed to track changes in the efficiency of the ocean CO_2 sink associated with reduced anthropogenic CO_2 emissions or climate change on policy-relevant spatial or temporal scales.

There is a major opportunity to incorporate multiple degrees of data in tandem leveraging both satellite and in situ data, such as merging physics (e.g. altimetry), biology (e.g. ocean colour), and chemistry (e.g. BGC-Argo floats). Indeed, to gain access to the three-dimensionality of the ocean, satellite-based products need to be complemented with in-situ measurements (e.g., Neukermans et al., 2023) and ocean biogeochemical models (Friedlingstein et al., 2025; Nowicki et al., 2022, Gregg 2008, Gregg et al., 2014). Autonomous in-situ platforms are playing an increasingly important role in monitoring both carbon pools and fluxes in the ocean (Chai et al., 2020; Claustre et al., 2021, 2020). For example, different research groups have developed machine learning algorithms building statistical relationships between remote sensing data, e.g. sea surface temperature and ocean colour products, and the sparse in-situ CO_2 measurements that are taken over the ocean. These relationships are then used to fill the in-situ observational gaps and provide globally interpolated ocean products of the sea surface partial pressure of CO_2 and the air-sea CO_2 flux. While a decade ago, only 2 methods were considered by the Global Carbon Budget (Le Quéré et al 2015), in its latest release 9 additional bottom-up air-sea CO_2 flux estimates were considered, with the majority relying on satellite missions and remote sensing data (Friedlingstein et al 2025). The satellite record of ocean-based products used in pCO_2 estimates extends back to the 1980s, allowing to investigate fluctuations in the air-sea CO_2 exchange from interannual to decadal timescales.

Perhaps the most promising technical frontier for EO is the advance in quantum sensing and Lidar. Lidar systems offer the ability to "see" further into the water column, bypassing the limitations of passive sensors that only see the surface layer (Jamet et al., 2019). Upcoming missions, such as the proposed Luce mission (Agenzial Spaziale Italiana), are expected to provide fresh insights into carbon-related processes (Behrenfeld et al., 2017, 2019). High-resolution quantum sensors could eventually provide unprecedented precision in measuring gravity anomalies and magnetic fields, further refining our understanding of ocean circulation. However, continued advancements in laboratory, field work, and mission planning remain essential to improve quality in space-based carbon products.

Shelf seas are particularly challenging for carbon retrievals as signal detection issues arise from saturated or "optically complex" waters where suspended sediments and dissolved organic matter interfere with standard algorithms. Current sampling frequencies are often insufficient to address near-coastal impacts in real-time. This presents a clear opportunity for geostationary satellites, which will enhance our ability to monitor diel carbon dynamics and improve spatial coverage (Dierssen et al., 2023; Groom et al., 2019; Salisbury et al., 2021), and provide the high-frequency observations necessary to monitor rapid events like harmful algal blooms or sediment plumes. It also highlights the importance and need for dedicated in situ networks, drones, and CubeSats to provide high-resolution validation (Duarte et al., 2021). Currently, some limitations can be overcome by using sensors in tandem, for example, by improving spatial coverage by merging satellite data (Sathyendranath et al., 2019), or improving accuracy in products by augmenting algorithms with independent ancillary observations (Bisson et al., 2023). The convergence of multi-sensor data and novel sensing hardware offers a transformative path for the characterization and advancement of carbon quantification across aquatic environments.

Recommendations to advance aquatic carbon stocks and fluxes in open-ocean and shelf-seas, including air-sea fluxes:

- *Rec-1: Exploit multi-sensors (active/passive) and multi-platforms (satellite, in-situ) synergy to access the three dimensionality of the ocean.*
- *Rec-2: Develop Lidar systems.*
- *Rec-3: Advance the estimation of ocean circulation.*
- *Rec-4: Develop geostationary missions for high frequency measurements*
- *Rec-5: Develop and validate tools to detect change and the rate of change in the ocean carbon cycle, enabling identification of potential tipping points and fund more science to understand carbon tipping points.*

Rec-6: Further develop and support dedicated in situ networks, drones, and CubeSats to provide high-resolution validation measurements.
Rec-7: Include indicators of bio- and functional diversity and the flow of carbon through the marine ecosystem into ocean carbon research to improve understanding of carbon flows and feedbacks.

4.2 Aquatic carbon in coastal zones, including blue carbon ecosystems

Authors: Merrie Beth Neely, Dimitris Poursanidis, Aurelien Carbonniere, Christine Dupuy, Tiit Kutser, Antonio Mannino, Kesav Unnithan, Vincent Vantrepotte, Kevin Kroeger.

Despite recent progress, major challenges remain for optically complex nearshore waters when it comes to the retrieval of in water properties, including carbon. Atmospheric and adjacency effects continue to pose significant difficulties, and these issues are especially critical for high-resolution sensors operating close to shorelines (IOCCG, 2010). Accurate quantification of particulate and dissolved matter from Rrs(λ) also remains to be improved in highly turbid environments, highlighting the need for better inversion techniques exploiting hyperspectral and UV information, and dedicated validation strategies in nearshore domains where strong spatial gradients and temporal dynamics occur.

To better resolve DOC and POC variability and drivers, observational efforts should aim for daily to sub-daily data acquisition at high spatial resolution (< 30 m) in nearshore waters to describe and capture the DOC and POC dynamics in response to episodic and extreme events, and hourly to bi-hourly acquisition at high-moderate spatial resolution (300 m or lower) improve estimates of cross-shelf DOC fluxes (Fichot et al., 2023; Dierssen et al., 2023).

Detailed vegetation mapping, especially for retro-littoral and salt marshes, remains insufficient, and more work is needed to improve habitat classification and map validation through field surveys and remote-sensing calibration.
Another pervasive challenge to measuring near-shore carbon remains a lack of openly available Calibration and Validation (Cal Val) data matchups which meet requirements. Data collection efforts are often only funded for short terms or in limited areas; networks, such as AERONET-OC, are relatively limited geographically and rely on support from space agencies or institutions which have no long-term certainty. Complementary in situ carbon chemistry instrumentation/measurements should also be considered in areas where consistent in situ coastal data collections are available to provide insight into processes and transformation of carbon that are occurring in these highly dynamic environments. Coastal carbon data collected by scientists outside the remote sensing community can be difficult to access, hindering the validation and improvements of remotely sensed measurements.

Regarding blue carbon ecosystems, satellite EO have transformed our ability to study these ecosystems – especially those above water like marshes and mangroves – and have provided unique insights into extent, condition, productivity, carbon dynamics, and biodiversity. This has enabled the possibility to establish baselines and project future risks for these important ecosystems. However, challenges remain; for example, subtidal seagrasses habitats are harder to observe from space (water column effects, turbidity). While optical remote sensing is already used to define baseline and large changes both through remote sensing (Floyd et al. 2024) and drones (Roe et al. 2020), EO often underestimates extent or misses below-water biomass without complementary methods. In addition, seasonal and yearly fluctuations in natural ranges further complicate seagrass mapping and monitoring. Soil carbon (vast in tidal marshes/mangroves, and where the bulk of sequestered carbon lies) still needs field cores for accurate stocks (Macreadie et al., 2021; Krause et al. 2025). Gaps also remain regarding the quantification of gas fluxes and the role of managed blue carbon ecosystems in CO_2 and CH_4 emissions and drawdowns. For instance, though some gas-flux data are openly available, expanding continuous CO_2 and CH_4 measurements (e.g., via eddy-covariance towers) in coastal areas is necessary to monitor greenhouse-gas exchanges at high resolution; the ICOS network (https://icos-france.fr/) provides an example. This remains a frontier in blue carbon research, requiring stronger integration of EO with in situ flux measurements and modelling (Dat Pham et al., 2019). EO have undoubtedly improved spatial and spectral resolution for blue carbon mapping, are reducing sampling costs by guiding where to sample, but cannot wholly replace in-situ measurement.

As blue carbon enters the carbon and nature repair markets embedded within climate policy frameworks, robust Monitoring, Reporting, and Verification (MRV) systems are essential (Dam et al., 2024). EO provides a scalable, transparent, and cost-effective foundation for MRV, reducing reliance on costly and complex field campaigns. By combining freely available global data streams with targeted high-resolution acquisitions, EO-based MRV can balance precision with affordability. The challenge is to ensure consistency, transparency, and stakeholder trust, particularly as MRV systems begin to underpin financial flows for conservation and restoration projects (Mengis et al., 2023).

Looking forward, EO can play a predictive role by integrating habitat distribution and suitability models with climate projections to forecast future shifts in distribution, and to identify areas most vulnerable to loss and in need of restoration actions (Erftemeijer et al., 2023). As sensor and machine learning capabilities expand and integration with field data improves, EO will play an even greater role in quantifying carbon stocks, monitoring fluxes, and enabling cost-effective MRV systems linked to the multiple ecosystem services provided by blue carbon ecosystems.

Lastly, organizations of global reach (e.g. GOOS, CEOS) could play a role facilitating open-source Cal Val data and ensuring access conforms to FAIR (Findable, Accessible, Interoperable and Reusable) principles so that EO measurements can be further validated and utilised for broad applications, from carbon budgets to MRV. Agreement on a science-based approach that adheres to community-vetted measurement protocols is also needed to reduce uncertainty and error in carbon estimates locally, nationally or regionally.

Recommendations to advance aquatic carbon stocks and fluxes in coastal zones, including blue carbon ecosystems:

- Rec-1: Develop geostationary mission for high frequency coastal measurements
- Rec-2: Exploit multisensor and multi-mission approaches to combine all types of surface and sub-surface observations that can characterize and constrain coastal carbon fluxes
- Rec-3: Integrate EO, together with relevant in situ data, with models to develop forecasting or evaluation approaches (digital twin element or Observing System Simulation Experiments) to identify areas most vulnerable to loss or in need of restoration or mitigation actions.
- Rec-4: Maintain and improve the accuracy and stability of primary observables needed for ocean carbon research by sustaining robust calibration and validation (cal/val) activities. Research communities should ensure all data are provided following FAIR practices.
- Rec-5: Continue improvements and advances in atmospheric correction, especially in complex coastal waters.
- Rec-6: Develop a more robust science-based approach to reduce uncertainty and error in carbon estimates for coastal waters.

4.3 Aquatic carbon in inland water bodies, including land to ocean fluxes

Authors: Dustin Carroll, Antonio Mannino, Stefan Simis, Meghan Halabisky, Tiit Kutser

A number of challenges remain for global-scale remote sensing observations of carbon in inland waters. For lakes and reservoirs, and some large rivers, algorithms are generally unique to the particular body of water for which they are developed. While progress has been made in creating development and implementation of global inland waters algorithms for chlorophyll-a, constituent absorption, total suspended sediments, cyanobacteria, and optical water type (e.g. CyAN), there are no global algorithms for retrieval of carbon concentrations or primary productivity. In addition, because of their size, challenges remain regarding adjacency effects, atmospheric correction, revisit frequency, spatial resolution (for smaller water bodies), and spectral information necessary to retrieve carbon properties. For example, the retrieval of CDOM in Lakes_cci using optical pre-classification remains challenging as algorithm sensitivity varies over concentration range, and has interference in phytoplankton dominated waters. Algorithms exist for products such as POC and DOC (e.g. Xu et al., 2020), but whether such algorithms are generally applicable for most lakes and other inland water bodies is not well known.

Building a unified, integrated framework for aquatic carbon quantification in inland waters, coupling knowledge from different disciplines (physics, biology, biogeochemistry, engineering) and thematics (atmospheric, land ecosystems, hydrological, blue carbon, solids and sediment diagenesis, coastal and ocean sciences) would help advance the field. Indeed, there are mechanisms altering or supplementing carbon in inland waters, especially when related to fluxes, that remain poorly constrained. Salinity gradients trigger flocculation and sorption that removes or transforms dissolved organic matter and metals through association with particulates

Sholkovitz, 1976). In addition, the source of the emission of organic carbon determines its availability for remineralization (labile, semi-refractory, refractory), which ultimately defines the magnitude of the remineralization across the LOAC and the associated respiration towards the atmosphere in terms of CO_2 and CH_4 fluxes (Lønborg et al., 2020). In some regions, riverine solutes and solids are supplemented by groundwater and subglacial discharge. Groundwater discharge delivers the equivalent of 23% of riverine DIC (Luijendijk et al., 2020). Subglacial upwelling can transport nutrients to the photic zone (Hopwood et al., 2018), and meltwater from ice sheets and icebergs provides reactive iron that supports high-latitude coastal ecosystems (Hawkings et al., 2014; Hopwood et al., 2020). Accounting for these gaps is pivotal to capture the sinks and sources of carbon across the LOAC and thus, the amount and nature of terrestrial carbon flowing into the ocean.

While the Global Carbon Budget (GCB) has exhaustively tracked global carbon emissions and sinks since 2012, the GCB and the global-ocean biogeochemistry models and dynamic global vegetation models it relies on do not properly account for the anthropogenic perturbation of the LOAC, leading to key uncertainties in quantifying the net land–ocean–atmosphere balance of carbon (Friedlingstein et al., 2024). To quantify carbon flow across the multi-dimensional, cross-domain, and highly-variable LOAC, model frameworks need to integrate data sets that are grounded in measurements to deliver actionable information that can be used by scientific communities, governments, land management, and users. This framework should leverage the complementary respective strengths of modelling, remote sensing, and in-situ measurements. This type of framework will also be of use to lakes and reservoirs that are impacted by changes in seasonal inflows, land use, and other processes that impact carbon production and transformation. When flowing through different systems, carbon is transformed through specific processes associated with the particular ecosystem (Ward et al., 2017). Thus, it is challenging to account for the regional complexity of the LOAC and to capture the coarse-to-fine-scale processes occurring within inland waters, sediments, estuaries, deltas, wetlands, coastal and open ocean, and at their mutual interfaces when accounting for sinks and sources of carbon. The speed of these processes (hourly, seasonal to decadal) adds to this intricacy, and these processes are also impacted by climate and anthropogenic perturbations both on land and in the ocean, which makes it even more challenging to disentangle natural, climate-perturbed, and anthropogenic variability when computing carbon budgets across the LOAC (Regnier et al., 2022).

Recent satellite missions are bridging key dimensional and intrinsic gaps in the remote sensing Earth observation system. PACE provides daily hyperspectral ocean colour to separate phytoplankton groups, coloured dissolved organic matter (CDOM), and particles. SWOT measures water level and surface dynamics in rivers, lakes, estuaries, and the coastal ocean to constrain exchange and routing. EAGLE-VSWIR and CHIME will connect land and water with imaging spectroscopy for soils, vegetation, and water quality. Geostationary ocean colour from GLIMR will capture diurnal coastal change and events. However, for smaller lakes, rivers, and reservoirs, airborne hyperspectral imaging spectroscopy (e.g., PRISM, AVIRIS) is needed to be able to develop algorithms for retrieval of carbon species. Nimble platforms, such as easy to deploy drones, should be considered. Existing integrated global databases of in situ optical and biogeochemical properties will be critical for algorithm development and evaluation;

the expansion of these databases with additional measurements will be needed to be able to capture the whole spectrum of biogeochemical conditions. Targeted field campaigns have the potential to provide the high-resolution measurements needed to validate and scale products, and autonomous in-situ observation platforms that provide high-frequency measurements that can be combined with models and remote sensing should be considered. More importantly, to capture gradients, measurements should cover the entire LOAC from inland waters to the open ocean. Most importantly, Earth System Models should seamlessly integrate estuaries and the coastal ocean when coupling land, ocean, and atmospheric models and adapt to account for sub-grid-scale processes (Ward et al., 2020).

By integrating models, satellites, and in-situ networks across the complete LOAC, key uncertainties can be reduced and the natural and human-driven change can be separated. This approach will deliver observation-constrained carbon budgets that inform management and improve estimates of the global carbon budget. The data-model framework's final products should be open-source, user-friendly, and accessible to any stakeholders.

Recommendations to advance aquatic carbon stocks and fluxes in inland water bodies, including land to ocean fluxes:

- Rec-1: Research should focus on developing approaches that consider the land to ocean continuum, its heterogeneity and cascade of scales and the carbon flow within this, so linking inland waters, estuarine and coastal seas. This will enable improved inclusion of inand regions within global budgets
- Rec-2: Expand hyperspectral in situ measurements of inland water bodies to improve validation of EO.
- Rec-3: Further develop and refine algorithms for retrieval of carbon concentrations or primary productivity in inland waters

5.0 Demonstrating the power of aquatic carbon Earth observation to inform diverse stakeholders

Author: Cecile S. Rousseaux, Rosa M. Roman-Cuesta

EOs are already enabling policy-relevant applications that link aquatic carbon dynamics with adaptation and mitigation objectives, especially when methodologies, governance, and capacity development align. In Guyana and Suriname, satellite observations have supported the planning and monitoring of green infrastructure approaches to sea-level rise, including the protection and restoration of mangroves. EO-derived data on coastal change, vegetation extent, and ecosystem condition have informed national adaptation strategies while simultaneously strengthening understanding of coastal carbon stocks and resilience co-benefits (GFOI, 2025; UNEP, 2022). Similarly, Australia, Japan, and the United States have advanced methodological frameworks for incorporating coastal blue carbon into national planning and reporting (e.g. Windham-Myers et al., 2018; Kroeger et al., 2017; Holmquist et al., 2018; GHGMMIS, 2023; Emmet-Booth et al., 2020; Blue Carbon Method, 2022; Japan's Plan for Global Warming Countermeasures; Basic Policy on Economic and Fiscal Management and Reform 2023). EO plays a central role in mapping ecosystem extent, tracking change, and supporting activity data required for inventory development, as documented in recent international guidance (Howard et al., 2017; GFOI, 2025).

Ocean carbon is embedded within IPCC Working Group I on 'The Physical Science Basis' and III on 'Mitigation of Climate Change' assessments and the GCB through a combination of satellite-constrained data products and model-data fusion approaches (IPCC, 2021; Friedlingstein et al., 2023). EO informs:

- Estimates of net ocean CO_2 uptake, via constraints on air-sea gas exchange, surface pCO_2 reconstructions, and biological productivity (Landschützer et al., 2016; Rödenbeck et al., 2022);
- Detection of interannual variability and trends in ocean carbon uptake associated with climate variability and long-term warming (McKinley et al., 2020; Fay et al., 2021);
- Characterization of cryosphere-ocean interactions, including sea ice extent and freshwater inputs that modulate carbon cycling at high latitudes (IPCC, 2019; Arrigo et al., 2020).

The contribution of EO to UNFCCC reporting and to the Global Stocktake is discussed in several publications (Bastos et al. 2022; Ochiai et al. 2023). For blue carbon ecosystems, EO has improved temporality and spatial coverage of these remote and hard to access ecosystems. It supplies spatially consistent, repeatable observations needed to (1) map coastal carbon-rich ecosystems at scale, (2) detect and track gains and losses over time, (3) feed national inventories and verification, and (4) inform ambition, finance and policy decisions.

Despite these advances in utilizing EO for aquatic carbon quantification and its incorporation in assessments, coverage remains uneven across aquatic domains. Open-ocean processes are comparatively well represented, while near-coastal waters, coastal blue carbon ecosystems, inland waters, and land–ocean fluxes remain weakly constrained or excluded from formal assessments as a result of the fragmentation and limited integration that exist across those aquatic domains (Regnier et al., 2013; Ciais et al., 2022). Methodological immaturity for inventory use of many EO aquatic carbon products also prevents their integration, as many are not yet designed to meet IPCC requirements for transparency, uncertainty reporting, and reproducibility (IPCC, 2019; GCOS, 2022). Institutional and assessment barriers, which limit systematic uptake of EO capabilities within IPCC and global stocktake workflows despite scientific readiness also constitute a significant hurdle (Oreskes et al., 2023; CEOS, 2023). These challenges and gaps propagate directly into global budgets and limit the ability of IPCC and GCB assessments to fully represent the aquatic carbon cycle. Coastal and inland aquatic systems are also where national policy relevance is highest, intersecting with adaptation planning, ecosystem services, and hazard mitigation. Yet their carbon dynamics are often treated qualitatively—or omitted entirely—from accounting frameworks (IPCC, 2019; UNEP, 2022). Addressing these challenges requires coordinated development across observation systems, assessment bodies, and national stakeholders.

5.1 Emerging needs: from global understanding to inventories and stocktakes

Author: Cecile S. Rousseaux

The transition towards the Enhanced Transparency Framework, and regular global stocktakes under the Paris Agreement introduces new opportunities for EO (UNFCCC, 2023):

1. Inventory relevance: Unlike in previous years, since 2024 all countries are now requested to report complete GHG Inventories of emissions and removals, using common reporting tables, and relying on the latest available IPCC Guidance for reporting (e.g. IPCC Guidelines 2006, IPCC Refinement 2019, IPCC Wetland Supplement 2013). For aquatic systems, this raises fundamental questions about how EO-derived information can support inventory development, particularly for:
   - Coastal blue carbon stocks and fluxes (Howard et al., 2017; IPCC, 2019);
   - Land–ocean carbon transfers (Regnier et al., 2013; Ciais et al., 2022);
   - Managed versus unmanaged aquatic systems relevant to national reporting.

2. Consistency across scales: EO products used in global assessments must be reconcilable with national and sub-national reporting in the application to determine activity data (AD) and emission factors (EF). Differences in goals, spatial resolution, ecosystem definitions, and uncertainty characterization currently hinder the operational use of EO in inventory workflows (GCOS, 2022; Oreskes et al., 2023).
3. Attribution and additionality: From a modeling perspective, there is growing demand to distinguish climate-driven variability from management-driven change—an essential requirement for credible reporting and claims of mitigation or adaptation benefits (Griscom et al., 2017; IPCC, 2019). EO can only do so much to separate attribution as observed variables; for example, NPP already integrates both aspects. The same limitation applies to country reporting, where ground data already integrate both effects (e.g., CO_2 fertilization, expanded growing seasons, and human management).

These needs align closely with the 2035+ vision for Earth observation, which emphasizes sustained observations, integrated land–ocean perspectives, and policy-ready information streams (NASA, 2024; CEOS, 2023; ESA, 2024).

5.2 Case studies

5.2.1 National Determined Contributions (NCDs) and blue carbon

Authors: Rosa M. Roman-Cuesta, Blake Clark, Miguel Cifuentes-Jara, Ben Poulter, Oscar Serrano

NDCs are the climate action plans that each Party to the Paris Agreement must prepare, communicate, and maintain (Decision 1/CP21, Katowice Climate Package). They set out what actions a country intends to take to reduce greenhouse gas (GHG) emissions (mitigation) and how it will adapt to the adverse impacts of climate change. Countries must also report on finance (requested/received support), capacity building and technological transfer. NDCs are updated every five years, and successive NDCs should represent progression and increasing ambition, following recommendations from the Global Stocktake assessment (see Section 5.1). Insufficient capacity and poor data on subtidal area changes are among the factors that hinder the accurate assessment of carbon emissions and removals, especially in lesser-studied ecosystems such as seagrasses (Arkema et al. 2023). For example, the Japanese Ministry of the Environment (MOE) has estimated and reported CO_2 removals from seagrass and seaweed beds in the inventory reported to the United Nations in April 2024, (https://www.env.go.jp/en/earth/ondanka/blue-carbon-en/initiatives.html). However, blue carbon–specific quantitative mitigation targets are not yet explicitly defined in the NDCs, and satellite data are only used to assess environmental condition for estimation of the seagrass and seaweed active areas. On a wider context, coastal and marine ecosystems are growing popular under NDCs as Nature Based Solutions, with almost half of the countries submitting their NDCs by 2023 mentioning their mitigation and adaptation services (Lecerf et al., 2023) (Figure 2).

Countries' commitments under their NDCs are not legally binding, but signatories of the Paris Agreement are expected to achieve or at least advance on their pledges. This means robust data on the spatial cover dynamics of land use categories are needed. Hence, to include blue carbon as part of a country's NDC adaptation target, baseline data on area and ecosystem status are needed to facilitate the tracking of their

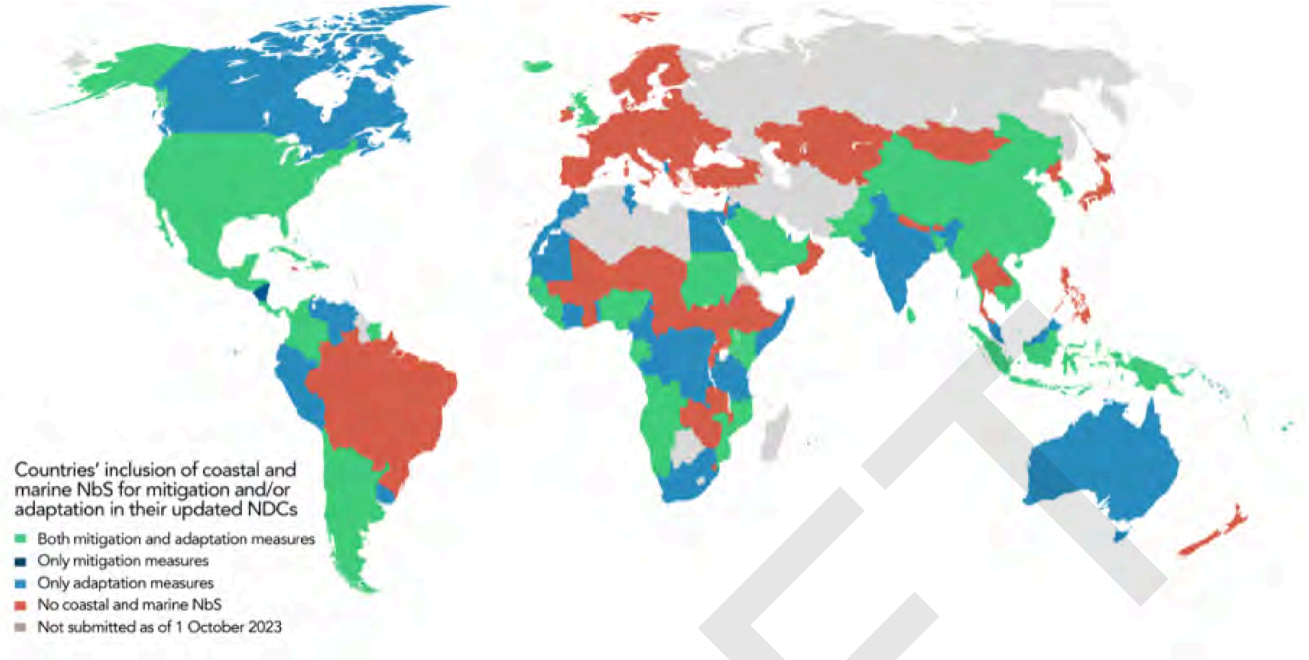

Figure 2: Countries' inclusion of coastal and marine NbS for mitigation and adaptation in their NDCs. Out of 148 countries that have submitted their NDCs as of 19 September 2023, 97 have included coastal and marine NbS. Among these, 61 countries included coastal and marine NbS for both mitigation and adaptation purposes, 1 for mitigation only and 35 for adaptation only. Source: (Lecerf et al. 2023).

achievements. For mitigation, countries willing to include blue carbon targets under their NDC's mitigation pledges need to have also reported blue carbon emissions and removals under their GHG Inventories.

Blue carbon ecosystems (BCEs; tidal marshes, mangroves, and seagrasses) are included in GHG Inventories as coastal wetlands (IPCC Wetland Supplement 2013), and as forests in the Land Use, Land Use Change and Forestry (LULUCF) category (IPCC 2006 Guidelines). Blue carbon is increasingly participating in countries' GHG inventory reporting and mitigation-adaptation commitments, making it more visible in the GST process (e.g. Decision 1/CMA.5 on the role of oceans). Reporting of blue carbon emissions and removals under National GHG Inventories is however not compulsory, as the use of the Wetland Supplement (2013) remains voluntary (e.g. Parties may choose to apply it if they want to include managed wetlands, drained/rewetted lands, mangroves, seagrass, etc., in their national inventories). Its absence in National GHG Inventories would prevent accountable mitigation commitments under countries Nationally Determined Contributions (NDCs) but would still allow its participation under adaptation planning and generic mitigation action through Nature Based Solutions (e.g., commitments to protect, restore and/or manage blue carbon ecosystems). At the moment this document was written, blue carbon is only enacted under the voluntary carbon market (VCM) with a range of standards and registries that enable cross-border purchase and sale of offsets for emissions (see also Sec. 6.5). The integrity of the VCM is being increasingly advanced by emerging bodies such as the Voluntary Carbon Market Integrity Initiative (VCMI) and the Integrity Council for the Voluntary Carbon Market (IC-VCM). An example of this is the J Blue Credit, which has been established and operated since 2020.

GHG reporting must follow all the available IPCC methodological guidance on blue carbon. These include the IPCC Wetland Supplement (2013), the LULUCF guidelines from IPCC (2006) on forest and grassland reporting, and the 2019 IPCC Refinement. As far as biases are avoided and minimized, countries can develop their own methodologies to report on blue carbon emissions/removals not covered yet by the IPCC. The appendix at the end of the document contains further information on particularities for blue carbon reporting under the UNFCCC.

EO data are used to measure and monitor blue carbon stocks, their threats and restoration opportunities (e.g., Arkema et al. 2023, Reiser et al. 2024). While changes in blue carbon biomass associated with different drivers (deforestation, degradation, restoration) can rely on standard Tier 1 factors for GHGI reporting (e.g. Emission Factors under the IPCC database), baseline data on BC extent and changes in their area are needed for reporting. EO can be used to quantify the latter, and can also provide proxy data on carbon losses and removals in these frequently remote and hard to access ecosystems. Moreover, EO can reduce monitoring expenses through repeated and consistent monitoring at a national scale (with increasing detail as technology and spatial resolution of EO continue to improve rapidly), and offer a consistent representation of ecosystems' extent and carbon fluxes over time, which are key requirements for reporting against climate targets.

Example - Blue carbon in Costa Rica's NDC

Coastal wetlands are a cross-cutting topic in Costa Rica's 2020 NDC (Costa Rica 2020), especially as they relate to people-centred and science-based sustainable management, restoration, protection, provision of ecosystem services, adaptation and resilience. The country focused its contributions on conserving 100% of its officially inventoried wetlands by 2025 and addressing the underlying causes for their loss to revert this process by 2030. In addition, it is committed to including adaptation measures in all its territorial, coastal and marine planning instruments by 2030. Including coastal blue carbon contributions in its NDCs (Costa Rica NDC 2020) allowed the country to springboard significant action towards coastal wetlands conservation.

Importantly, following its NDC, Costa Rica developed and launched the first-in-kind National Blue Carbon Strategy (SINAC 2023) and its supplementary Action Plan (2024). Rooted in scientific evidence and aligned with international commitments such as the Paris Agreement and the Ramsar Convention, the strategy recognizes blue carbon as a nature-based solution for both climate mitigation and adaptation. The strategy's main goal is to integrate actions for conserving and restoring blue carbon ecosystems to benefit both nature and coastal communities. It is guided by principles of ecosystem resilience, inclusive participation, fair benefit-sharing, and transparent markets, and is organized around five objectives: strengthening governance, conserving and monitoring ecosystems, creating financial mechanisms, empowering communities, and raising public awareness through education and communication. Based on its experience developing and implementing its National Blue Carbon Strategy, Costa Rica is offering international guidance on how to build similar policies (SINAC 2024a).
As a next step, Costa Rica accounted for mangrove blue carbon for the first time in its National GHG Inventory, using the 2013 IPCC Wetlands Supplement. Accounting for

emissions and removals from mangrove forests was done for the entire time series (1990-2021) and using recent (2013) maps of forest types. These new data show mangroves increased in area from 5499 ha in 1990 to 6100 ha in 2021 and removed CO_2e at a rate between 5 and 6 Mg CO_2e ha^{-1} yr^{-1} starting early on during that same period.

Next steps on blue carbon research under the UNFCCC/NDC that EO can help address

Identified gaps	Recommendations Action Short term	Recommendations Action long term
Subtidal Seagrass area monitoring remains challenging	Use remote sensing for shallow seagrasses under transparent water.	Promote diving and/or automated underwater rovers for monitoring activities to characterize area/area changes under different drivers and environmental conditions. Explore EO data combined with machine learning algorithms and ground-truthing to map and monitor changes in seagrass habitats
Tier 2 reporting is needed for mitigation commitments, and for improved reporting when blue carbon emissions or removals are key categories EF not included under the Wetland Supplement are needed, particularly for standing blue carbon ecosystems under conservation	Build a regional EF database that can be applied for similar conditions in countries without data. See Holmquist et al. (2024) for such an example of a coastal carbon data repository. Further research to estimate GHG gains and losses under different activities/EF: BCEs loss or restoration, rewetting, creation of new BCEs, etc as current activities under IPCC are limited	Promote ground sampling for more accurate Tier 2. Develop models (Tier 3) Promote ground sampling for more accurate Tier 2. Develop models (Tier 3)

5.2.2 Supporting and constraining global carbon assessments

Author: Daniel J. Ford, Neill Mackay, Jamie D. Shutler, Peter Landschutzer, Abhishek Chatterjee

As anthropogenic carbon emissions continue to increase, the ability to determine how these emissions are partitioned between the natural carbon sinks forms the global carbon budget. These natural sinks are (1) the accumulation within the atmosphere, (2) the ocean sink and (3) the land sink. Bottom-up air-sea carbon flux estimates are an essential part of the annual Global Carbon Budget analysis, as the atmosphere and oceans are the only two components which can be directly observed, and so they form the only two observational constraints within global carbon assessments (Shutler et al., 2020; Friedlingstein et al 2025). In contrast, the land sink is not observed but estimated using a range of modelling approaches. Tightening these two observational constraints will therefore improve the ability to quantify the redistribution of anthropogenic carbon within the Earth system.

A simple mass balance assessment can illustrate the constraint the ocean provides on balancing the changing nature of the global carbon budget. As the Earth system is largely closed, a change in one of the natural sinks (e.g. the ocean) must imply a change in the other (i.e. the land). Using the total carbon emissions within the latest global carbon budget assessment (Friedlingstein et al., 2025), alongside the observational constraints of the atmosphere and an EO-based ocean sink estimate, the land sink can be inferred (Figure 3; Mayot et al., 2024). The inferred land sink shows similar variability to the modelled estimates, but exercising the ocean constraint suggests that the land sink has largely stagnated over at least the last decade, with a trend of 0.11 Pg C yr $^{-1}$ dec^{-1}. This contrasts with the 0.43 Pg C yr^{-1} dec^{-1} trend for the period 1980 to 2023 estimated from the models (Friedlingstein et al., 2025). The simple analysis and result in Figure 3 are consistent with more advanced analyses that used the ocean as a constraint on the carbon budget (Mayot et al., 2024).

Clearly, this revision of the partitioning of carbon within the Earth system has urgent implications for policy. The result implies that efforts to enhance the land sink over the last decade appear to have been largely ineffective, calling into question their ability to mitigate against rising emissions. Whilst land policy and efforts to boost biodiversity and the land carbon sink are critically important for long-term climate stability; it would seem that they are unlikely to achieve any success in meeting the challenge of the climate emergency.

The ocean is now more effective at taking up anthropogenic carbon than the land sink (Friedlingstein et al., 2025) and is thus helping to slow the full impacts of climate change. But the ability of the ocean to continue this long-term absorption of carbon is unclear, as this same uptake is changing the ocean chemistry and reducing the ability of the ocean to absorb more. Moreover, the effects of potentially dramatic climate change-driven shifts and tipping points, such as a collapse in the Atlantic Meridional Overturning Circulation (AMOC), are not fully understood but are likely to be substantial. Policies need to focus on increasing protection and financial support to monitor ocean carbon if retaining this vital constraint on the global carbon budget is desired. Without it, it will be increasingly difficult to track progress related to carbon fluxes and detect any change in the service the ocean sink is providing.

Constraining the quantification of the ocean carbon sink remains critical. Estimates of the sink from ocean models have diverged from those from observational data products in recent years (Friedlingstein et al., 2025), raising the question as to whether the models may be deficient (Mayot et al., 2023; Terhaar et al., 2024) or whether insufficient observational coverage is biasing the data products' estimates (Hauck et al., 2023). To resolve these questions, monitoring of ocean carbon must continue, and in fact be boosted by utilising the latest technological advancements, including autonomous platforms and remote sensing, in conjunction with the gold-standard measurements achieved by more traditional means. In particular, the current suite of observational data products used to quantify the ocean carbon sink in the global carbon budget (Friedlingstein et al., 2025) builds its estimates using a database of observations of ocean surface fCO_2 that are mapped into global gridded products through their relationship to other variables, including sea surface temperature, sea surface salinity, and chlorophyll-a (which acts as a proxy for biological activity). These variables are only available with global coverage thanks to remote sensing infrastructure, which has therefore been instrumental in our ability to quantify and monitor the ocean carbon sink. Indeed, as a result of the increasing confidence in satellite-derived measurements and their importance, in its latest assessment cycle (AR6), the IPCC considered these bottom-up CO_2 flux estimates as reliable indicators of carbon sources and sinks over the ocean. Moreover, a total of 20 different data products combining ocean biogeochemistry models, in-situ measurements and remote sensing observations is currently used to inform the Global Carbon Budget (Friedlingstein et al., 2025) and will play a crucial role in the IPCC AR7 report. Essentially, without satellite Earth observation and concomitant in situ reference measurements, it would be impossible to assess and observe the ocean carbon sink (Shutler et al., 2024), removing a key constraint on global assessments and significantly degrading any resulting policy advice

Next steps that EO can help support and constrain global carbon assessments (see also Sec. 6)

Identified gaps	Recommendations Action Short term	Recommendations Action long term
Support near-real time release of remote sensing data to contribute to regular assessments of the ocean carbon sink	Ensure physical, chemical and biological proxy data from EO remains accessible to the community. Optimize validation of CO_2 data over open ocean and coastal areas	Ensure continuity of critical EO measurements (e.g. physical- sea surface temperature, salinity, sea surface height - chemical - atmospheric carbon dioxide- and biological - ocean colour) required to derive key parameters that contribute and constrain global carbon assessments
Further develop statistical and AI/ML approaches for improved estimations and reduce uncertainty of air-sea CO_2 fluxes leveraging EO and in situ measurements	Explore novel computational approaches to estimate air-sea CO2 fluxes at a variety of spatial and temporal scales; exploit novel platforms that are being launched in applications related to air-sea fluxes	Invest in future high-resolution remote sensing data (products) to support regional carbon budgets and climate interventions (e.g. marine carbon dioxide removal, mCDR)
Enhance monitoring of ocean carbon cycling	Leverage the latest technological advancements, including autonomous platforms and remote sensing, in conjunction with the gold-standard measurements achieved by more traditional means, to expand carbon flux observations. Invest in developing algorithms that exploit the information provided by XCO_2 measurements	Invest in purpose-built open ocean XCO_2 sensors designed to acquire high-spectral-resolution observations of the ocean. Further invest in upscaling air-sea CO_2 fluxes to estimate ocean carbon uptake and its variability at coarser global and very fine local scales

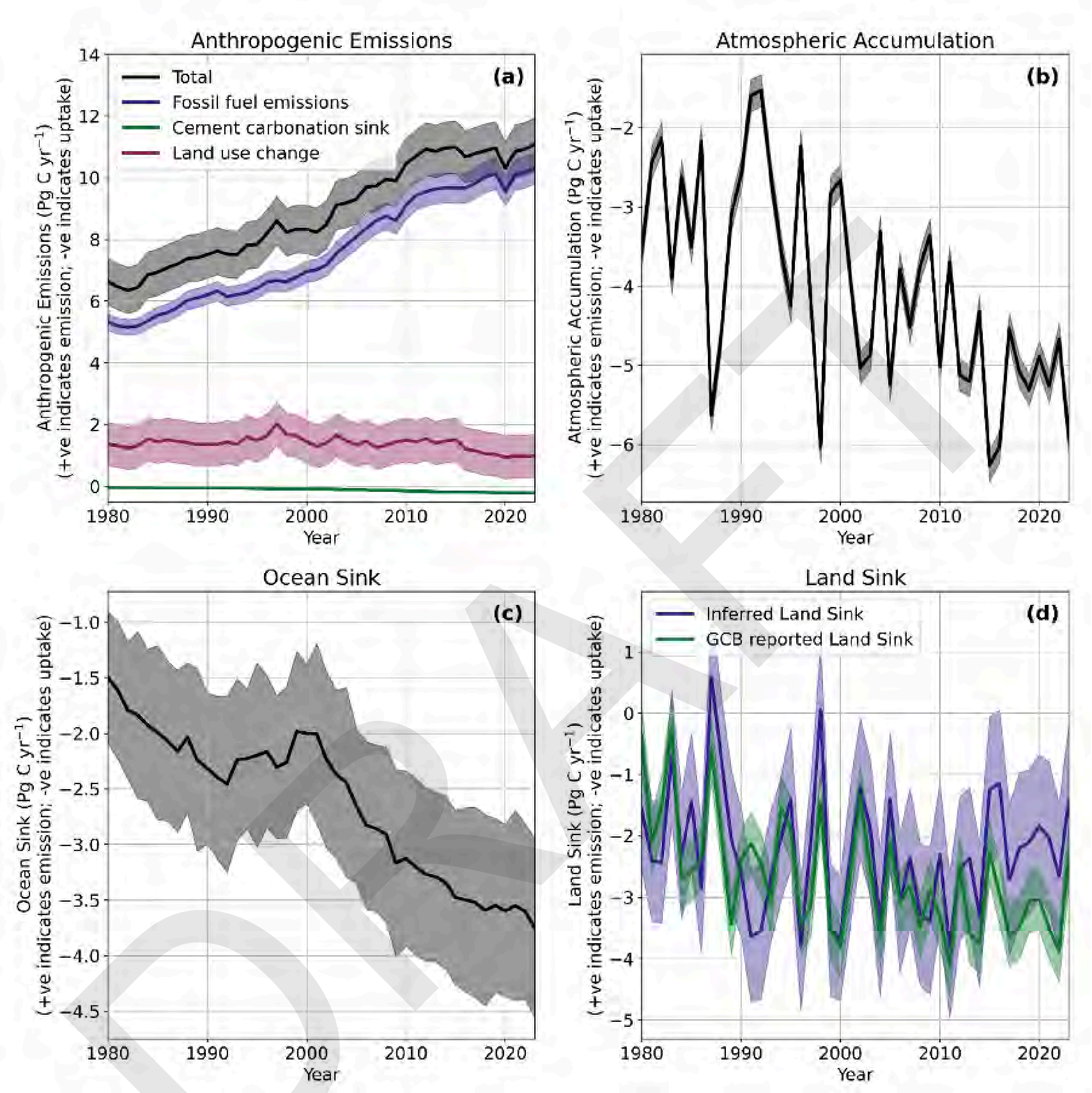

Figure 3: (a) Anthropogenic carbon emissions from fossil fuels and land use changes, alongside the cement carbonate sink as reported in the GCB2024. (b) Observational atmospheric accumulation of carbon as reported within the GCB2024. (c) Example observational assessment of the ocean carbon sink from the UExP-FNN-U, submitted to the Global Carbon Budget 2025 with uncertainty calculated following Ford et al. (2024). (d) The land sink inferred from the observational constraints compared to that reported by the modelled land sink within the GCB 2024. Uncertainty bounds in all plots indicate the 1 sigma (~67 %) confidence interval.

6.0 Complementarities and linkages to the GHG and AFOLU and other roadmaps

Authors: David Crisp, Abhishek Chatterjee, and Ben Poulter

The CEOS SIT recently initiated an effort to coordinate activities across the GHG, AFOLU, and Aquatic Carbon Roadmaps. One approach for implementing this coordination would be to define a series of use cases that require contributions across the individual roadmap communities but come together for solving a common problem plaguing all the communities.

In the context of the Aquatic Carbon Roadmap and its synergy with the GHG and AFOLU roadmaps, use cases can be identified. These are:

- Can space-based observations of CO_2, sea surface temperature, winds, salinity and ocean colour be combined with available in situ observations of ocean pCO_2 and dissolved carbon to create ocean carbon models that better exploit available in situ data to estimate air-sea fluxes?
- Can existing observational networks over the ocean be expanded to concurrently obtain both in situ observations of ocean pCO_2 and atmospheric CO_2, and total column CO_2 observations, to enable more robust validation of atmospheric GHG data over the open ocean?
- Can we reduce the uncertainties on the lateral transport of carbon among land ecosystems, ocean and atmospheric reservoirs? How is this lateral carbon flux changing due to human activity and climate change?
- Can we combine top-down and bottom-up methodologies with lateral transport to reconcile differences in net ecosystem exchange and provide a workflow for improved integration of atmospheric data within estimates of emissions and removals for the Agriculture, Forestry and Other Land Use sector?

6.1 Constraining air-sea fluxes from atmospheric GHG observations

A commonly overlooked approach for estimating air-sea fluxes is to use direct observations of atmospheric CO_2 within an inverse-modelling framework to provide a top-down constraint (Su et al., 2024; Byrne et al., 2023). However, a robust implementation of this top-down approach requires atmospheric column CO_2 observations with either high accuracy (over the open ocean), or high spatial resolution and high precision (over the coasts).

Over the open ocean, air-sea CO_2 fluxes are typically more than an order of magnitude smaller than those associated with anthropogenic emissions sources or sources and sinks in the land biosphere, and produce correspondingly smaller variations in XCO_2 (Byrne et al., 2023). In order to constrain such weak, spatially-extensive variations in the ocean fluxes, we require sensors with high accuracy (<0.2 ppm). This is extremely challenging to achieve with our current generation of dedicated, moderate-spatial resolution Global GHG Mappers, such as JAXA's GOSAT and GOSAT-2 and NASA's OCO-2 and OCO-3. These sensors now return XCO_2 estimates with precisions and accuracies of 0.25% (1 ppm). This level of precision and accuracy, combined with their near-global coverage, has revolutionized our understanding of surface-atmosphere CO_2 fluxes associated with anthropogenic emissions and the land biosphere. However, these space-based XCO_2 observations have provided much less insight into CO_2 fluxes over the ocean due to the presence of small (< 0.5 ppm) measurement biases that introduce systematic errors in flux inversion models. Even though recently launched Global GHG Mappers, such as MicroCarb and GOSAT-GW, or ESA's planned CO2M and China's TanSAT constellations will extend the spatial coverage and resolution of space-based XCO_2 datasets, these sensors were not optimized for quantifying CO_2 fluxes over the ocean. These missions, as designed, are therefore unlikely to return XCO_2 estimates with accuracies higher than 0.05% (0.2 ppm) over the ocean.

All existing space-based XCO_2 sensors have been optimized to monitor fluxes over land, where CO_2 sources and sinks are spatially heterogeneous. High spatial resolution and wall-to-wall coverage are critical for these applications.The need to collect samples at high spatial resolution from a spacecraft traveling at ~7 km/sec in low Earth orbit limits the exposure and integration time, and thus the signal-to-noise ratio (SNR) of each measurement. For example, the OCO-2 sensors were optimized to collect observations at a spatial resolution of ~2 km^2, yielding single-sounding random errors < 0.5 to 1 ppm (c.f., Das et al., 2025). Facility-scale hyperspectral plume mappers, such as PRISMA, EMIT or Carbon Mapper, have spatial resolutions of 30-50 m, but have correspondingly lower precision and accuracy (~10 ppm). Their measurements are ideal for monitoring intense CO_2 plumes from coal fired power plants and other large emitters, but not useful for monitoring weak, spatially extensive fluxes as is prevalent over the open ocean.

6.2 Purpose-built sensors for space-based XCO2 observations over the open ocean

No fundamentally new technologies are proposed to monitor ocean XCO_2 gradients on spatial scales of 10 to 1000 km with a much higher accuracy and precision, but existing technologies and sensor designs will have to be optimized to meet these needs. This should be possible because CO_2 sources and sinks over the open ocean are expected to have much less spatial variability than those over land. This will allow the use of much longer exposure times and larger surface footprints, yielding much greater SNR and much higher single sounding precisions. The primary factor limiting the exposure time and surface footprint size over the open ocean is the need for soundings that are completely free of clouds (or their reflections or shadows) to yield accurate XCO_2 estimates. This may require that dozens or hundreds of individual soundings be collected on spatial scales of 1°x1°, screened for clouds and then summed to maximize the SNR.

To maximize their precision and accuracy, purpose-built open ocean XCO_2 sensors should be designed to acquire high-spectral-resolution observations of the bright ocean glint, which can be highly polarized. Extremely stable instrument designs, combined with enhanced pre-launch and on-orbit calibration approaches are needed to ensure the accuracy of the reported, spectrally-dependent radiances. Also, following the CO2M example, these XCO_2 sensors should be co-manifested with co-bore-sighted sensors designed to detect and characterize the optical properties and distribution of thin clouds and aerosols, which are often the largest sources of systematic bias in space-based XCO_2 estimates (c.f., Nelson and O'Dell, 2019; Rusli et al., 2021).

Improved retrieval algorithms must also be developed to fully exploit the information provided by the combined XCO_2 and cloud/aerosol sensor suite. Advances in atmospheric inverse models are also needed to quantify weak ocean fluxes in the context of CO_2 outflows from land-based sources, which often dominate the XCO_2 variability over the ocean. Finally, a key requirement for optimizing the current technologies and retrieval algorithms to deliver more accurate CO_2 data over the ocean is the need for much more capable surface-based and airborne validation systems, as outlined in section 6.4.

6.3 Purpose-built sensors for space-based XCO2 observations over coastal regions

Unlike CO_2 fluxes over the open ocean, air-sea fluxes along the coastlines have larger variations in the magnitude of XCO_2, but are heavily influenced by the land signal that interferes with the large footprint of the retrieval (Lohrenz et al., 2018). Sensors optimized for this application ideally must combine small surface footprints and high precision to capture the high spatial and temporal heterogeneity in the fluxes.

In many cases, coastal fluxes could be suitably monitored using a combination of ground-based and novel airborne eddy flux measurements paired with satellite-based data, such as XCO_2, or surface reflectance, as has been recently demonstrated for the Everglades region in Florida, USA (Doughty et al, 2026). Retrieval algorithms and atmospheric inverse models will also have to be optimized to fully exploit this diverse range of data sources. Purpose-built observational networks and analysis systems, optimized to quantify CO_2 and CH_4 fluxes over wetlands, inland water bodies, and coastal oceans are not yet included in any agency's plans.

6.4 Validation of atmospheric GHG observations over the ocean

The accuracy of existing XCO_2 sensors over the ocean has been challenging to assess or improve in large part due to shortcomings of the existing, surface-based validation system. The design of the current system for validating space-based atmospheric GHG observations is largely focused on the validation of XCO_2 estimates over land (Wunch et al., 2011; Frey et al., 2019). This validation strategy has demonstrated accuracies better than 0.25% (~1 ppm). To produce meaningful space-based data on ocean carbon fluxes, the validation system's accuracy must be improved fivefold. This improvement does not require specific new technologies, but rather on strategically expanding and optimizing the validation network over open ocean and coastal areas, enhancing surface-based in situ and remote sensing data acquisition and analysis, and launching targeted validation campaigns. Key priorities that would enable a step change include:

1. adding more TCCON stations in regions that sample ocean environments,
2. routinely deploying portable, low-cost spectrometers (EM27/SUNs) on ships to take XCO_2 measurements over the open ocean (Klappenbech et al., 2015; Müller et al., 2021; Knapp et al., 2021),
3. Broader use of eddy covariance measurements for relating pCO_2 data to air-sea fluxes (Yang et al., 2022)
4. designing targeted validation campaigns to provide tiered observations from the ocean surface to the top of the atmosphere, i.e., combining pCO_2 measurements with atmospheric CO_2 flux correlation measurements and total column observations, and
5. deploying travelling standards to improve mutual consistency across and among various monitoring networks.

6.5 Crosscutting collaboration to improve assessment of blue carbon ecosystem contributions

Blue carbon ecosystems play multiple roles in national greenhouse gas accounting, the Global Stocktake, Voluntary Carbon Markets, and in closing the carbon budget. Within the Agriculture, Forestry and Other Land Use (AFOLU) category of national greenhouse gas inventories, blue carbon ecosystems bridge both ‘forest’ and ‘wetland’ categories depending on the type of wetland as well as its structural, i.e., height, characteristics. The Global Stocktake and blue carbon ecosystems intersect in policies related to Nationally Determined Contributions, where countries feature the management of blue carbon as part of their pathway toward net zero emissions. Voluntary carbon markets have established several methodologies where the management of blue carbon ecosystems can be associated with carbon credits that provide financial incentives.

In each of the above cases, data are critical for measurements and monitoring. Collecting field data in blue carbon ecosystems is challenging given their extent, remoteness and challenging conditions. Modeling of carbon stocks, sequestration, and developing baselines for carbon markets is also challenging given uncertainties in scaling, and in socio-economic dynamics. As such, ambition for using blue carbon as climate solutions is lagging the potential impact these systems could play in mitigating climate change.

Satellite data could play a key role in advancing how blue carbon ecosystems are represented in AFOLU and REDD+. While the CEOS AFOLU roadmap does not specifically refer to blue carbon ecosystems, it does include wetlands which, in addition to mangroves, also encompasses peatlands. The AFOLU roadmap suggests the improvement in current EO approaches that would allow for better detection of different wetland types in order to assess changes related to GHG estimation, with a focus on the terrestrial. Improved mapping and detection of mangroves is a common goal for both the Aquatic Carbon and AFOLU roadmap, and the expansion to coastal blue carbon in the Aquatic Carbon Roadmap will result in complementary work that will contribute to multiple mutual goals. By combining hyperspectral, radar and lidar data, carbon sequestration and stock uncertainties can be reduced to better support emissions and removal estimates using gain-loss, stock-change, and modeling studies associated with Tier 3 reporting.

The AFOLU Roadmap also includes a set of recommendations from testing mangrove maps that could be of use for implementation of both Roadmaps. EOs need to have fairly high spatial resolution to avoid cross contamination with vegetation and water, and use wavelengths that can retrieve information on canopy chemistry, vegetation health, vegetation structure, and be able to penetrate shallow surface waters to characterize aquatic biomass.

Lateral flows of carbon in blue carbon ecosystems are outside the scope of AFOLU, but provide great complementarity to that Roadmap. The quantification of lateral flows and carbon turnover from wetlands to estuaries to continental shelves is a key component in reconciling top-down and bottom-up carbon budgets used to understand the Earth system but also to make adjustments for national greenhouse gas inventories. While they remain challenging to quantify, this roadmap provides a path forward for closing that gap that is expected to provide benefits well beyond this current exercise.

7.0 Expanding visibility, utilisation and capacity development

7.1 Communicating the science of the changing marine carbon to policy makers

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Earth observation data are now fundamental for all global scale ocean carbon assessments that are used to guide policy decisions and those used to assess the carbonate health of the ocean e.g., all observation-based assessments within Friedlingstein et al. (2025) and its annual updates. But the use or critical reliance on Earth observation data is often opaque to policy makers (Shutler et al., 2024) and potential end users may not be aware of how to access or use these assessments. This section introduces two examples of how Earth observation-based assessments are being used to communicate the science and declining health of the oceans.

The ESA-OceanSODA project developed the OceanSODA-ETHZ product, an observation-based dataset that supports studies of ocean acidification (Gregor et al., 2021). To make these data accessible beyond the scientific community, the project also invested in tools that translate complex measurements into clear messages. Two communication products stand out. The OceanAcidificationStripes (Oastripes; Figure 4), inspired by the Warming Stripes, provide striking visual summaries of four decades of decline in surface ocean pH and aragonite saturation state. And, an online viewer further allows users to explore maps and regional statistics, offering tailored insights for stakeholders interested in specific areas.

These products were taken up by communities that bridge science and policy. The OAstripes in particular have been adopted by the GOA-ON community, and by the Ocean Acidification Alliance (OA Alliance). Their use has extended well beyond science communication into direct engagement with decision-makers.

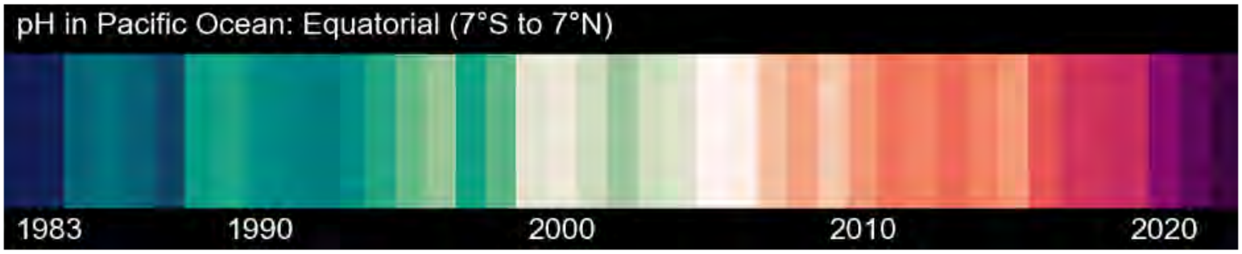

Figure 4 An adapted image of the Ocean Acidification Stripes for pH in the equatorial Pacific – a region of high interannual pH variability.

As a result, the OAstripes and related materials have gained visibility at major international events, including UNFCCC COP meetings (2022, 2023, 2024), the UN Ocean Conference in Lisbon (2022). At the 2025 UN Ocean Conference, the OA Alliance premiered Carbon in the Current, a 3D artistic animation that conveyed the threat of ocean acidification to wider audiences. OceanSODA data were also featured in high-profile outlets such as an Economist Impact article. The ESA OceanSODA project's success in reaching a wider audience does not come from compelling communication products alone. It has been rooted in the project's integration with a scientific community that actively engages with policy, and in direct connections with governmental and management stakeholders. Together, these elements have ensured that OceanSODA is not only a research product, but a platform for communicating the changing marine carbon system to those shaping decisions.

7.2 Utilisation and capacity development

Over the past decade, aquatic carbon has been viewed as a "background sink." However, this perception has been evolving as new technology and scientific approaches enable the measurement of its dynamic behaviour and composition, and its importance in the overall context of global carbon accounting and climate regulation. Indeed, the carbon stored in the ocean is roughly 50 times greater than what is currently in the atmosphere, and for it to be duly utilized in decision making and the blue economy, including planning, forecasting, geoengineering, mitigation, and carbon markets, it is necessary to obtain, with fit for purpose uncertainty, the type and permanence of different carbon pools, and their relative importance to the overall global carbon stocktake. For example, advancing the ability to derive robust estimations of carbon fluxes in blue carbon ecosystems using EO would enable the use of such data in carbon markets, including offsets and carbon credits.

The need to present scientific results in a manner that is useful for stakeholders and decision makers is not a new recommendation (e.g. GCOS 2016, CCSP 2010) but remains critical so that scientific findings are useful for planning and execution. Understanding the format and type of information, and uncertainty that needs to be associated with the products, remains high priority, and managers and decision makers have a clearer understanding of what they need; working hand in hand with scientists to achieve this goal is fundamental.

Various national and international agencies and organizations support capacity building for carbon flux estimation methodologies, including the use of compatible methods and translatable measurements (e.g. U.S. GHGMMIS, 2023); these are critical for advancing research and modeling, but current efforts are not enough. Capacity development for field and remote sensing measurements remains necessary, leveraging existing time-series networks and well-established groups. This is especially important for the Global South, where learning to utilize open source tools to process satellite data for region-specific applications, for example NDCs, is important to meet national priorities. It also remains important to account for the necessary IT-related infrastructure that enables the analysis of EO and in situ data, and support interoperability of new data (U.S. GHGMMIS, 2023).

Shared Socioeconomic Pathways (SSPs) scenarios predict that the ocean will continue to absorb carbon through 2050, current ocean models have uncertainty gaps of 10–20% for those predictions. Such uncertainties yield materially different outcomes with respect to target attainment and downstream impacts on aquatic systems. Specifically, shifts in ecosystem resilience – driven by climate variability – can alter a system's capacity for carbon sequestration, either amplifying or diminishing its effectiveness. Narrowing these model uncertainties would strengthen the reliability and applicability of predictive outputs, ultimately supporting more informed and robust scenario planning.

Ensuring that interdisciplinary and cross-disciplinary studies continue and expand remains just as critical to account for the different systems through which, and by which, aquatic carbon is transformed in the Earth system. Most importantly, however, is the addition of the human dimension to carbon cycle research. Social and political landscapes can impact the Earth system significantly, and added pressures from human expansion or purposeful management practices are expected to influence the distribution and health of important aquatic systems, such as blue carbon ecosystems. For example, Campbell et al. (2022) conducted a comprehensive salt marsh change analysis and found that anthropogenic marsh conversion varied globally; in countries where protection for salt marshes was effective, loss due to urbanization was low. The largest driver of marsh loss was climate change, with increased hurricane landfall and intensity, sea level rise, and coastal erosion. Warmer climates will also extend the range of mangroves (Enes Gramoso et al., 2026) poleward, encroaching into salt marsh ecosystems. While mangrove encroachment would increase carbon sequestration, the ecological implications of the ecosystem shift, and the impact to their services, are not well understood.

8.0 Forward look

This roadmap identifies key scientific priority areas that will help advance observations and quantification of aquatic carbon stocks and fluxes, critical in the understanding of the integrated Earth System and its elemental cycling. These priorities will also help ensure the services provided by aquatic ecosystems – economic growth, security, and safety - can continue to benefit humans for years to come. The roadmap underscores the important role of EOs, which afford a unique vantage point, and the only means, to observe aquatic ecosystem components globally, and provide powerful applications that help a varied suite of stakeholders at local, regional, and global levels. However, there is more to do.

Beyond the list of priority areas and areas of opportunity listed throughout the roadmap, there remain specific elements that are missing or need more attention in the future; they may be underdeveloped in this document because they are emerging, or the technology is not mature yet to address the topic, or because there are more urgent priorities that required the focus of the roadmap. However, this document is not meant to be a final statement, but rather the beginning of a journey.

Elements to be addressed in the future include the following, and are summarized in Table 2:

- Going beyond CO_2: The roadmap should be expanded to consider other greenhouse gases beyond CO_2, explicitly including methane (CH_4) and nitrous oxide (N_2O), particularly in inland, coastal, and wetland systems where uncertainties, and their importance as GHG contributors, remain high.
- Including ecosystem functioning: Future efforts must move beyond carbon stocks to better represent ecosystem function, including biodiversity, trophic dynamics, and carbon flow through aquatic systems. This is essential for understanding resilience, feedbacks, and long-term sequestration.
- Addressing the impact of extreme events on the aquatic carbon cycle: The impact of extreme (marine heatwaves, deoxygenation episodes, extreme runoff events) and transient (floods, droughts) events on aquatic carbon cycle needs to be further addressed, together with the development of early warning indicators of abrupt changes in carbon cycling.
- Investigating Cryosphere-aquatic interactions: Cryosphere–aquatic carbon interactions, including permafrost thaw, glacial meltwaters, and polar inland waters remain underexplored in this roadmap and would require targeted observational and modelling strategies.
- Other Aquatic Systems: Certain systems like flood plains, macroalgae such as Sargassum, and benthic ecosystems like reefs, were not included in the roadmap though their contributions towards the aquatic carbon cycle has been recognized and requires further evaluation.

- Leveraging Artificial Intelligence: The transformative role of artificial intelligence (AI) and machine learning (ML) needs to be leveraged. With rapidly increasing data volumes and complexity, AI will be critical to fuse heterogeneous datasets (satellite, in situ, models), retrieve complex or non-linear relationships between variables, detect anomalies, regime shifts, and early warning signals and quantify and propagate uncertainties in high-dimensional systems. Future efforts must also address explainability, reproducibility, and physical consistency of AI-driven approaches to ensure scientific credibility and policy trust.
- Marine carbon dioxide removal (mCDR): While marine carbon dioxide removal (mCDR) is mentioned in the current roadmap, it requires further attention especially as society develops and executes diverse mCDR approaches. These activities raise important ethical and governance questions that need to be addressed, and EO-based carbon information will be critical to evaluate scientific output, societal needs, and ethical/policy frameworks to validate safety and efficacy. Efforts should be focused on scientific understanding of the impact of mCDR on the marine environment and the aquatic carbon cycle itself.
- Including the human dimension: Increased attention should be given to the human dimensions influencing aquatic carbon dynamics. Future perspectives should consider impacts of land use, water management, aquaculture, and urbanization on aquatic carbon fluxes, socio-economic drivers of management or change in coastal and inland systems and how they impact aquatic carbon cycling. The integration of human activity data into Earth system analyses is particularly important for linking observations to mitigation and adaptation strategies.
- Societal alignment and Economic Valuation: Gaps persist between scientific results and stakeholders' needs for execution of activities related to carbon management. These needs are expected to continue to evolve in the future as society continues to grapple with mitigation of emissions and adaptation in a changing planet. Future roadmap activities must continue to address uncertainty of measures relevant to managers and decision-makers, and further activities that link aquatic carbon data to monetary or economic values so as to accelerate and improve incorporation of aquatic carbon into global, regional, and local priorities.
- Scalable Monitoring: A key future action will be aligning mature Earth Observation (EO) products that address aquatic carbon priorities with specific Global Stocktake (GST) requirements, including consistent definitions and scalability from national to global levels. This will require broadening the adoption of products and the incorporation of aquatic environments (e.g. the ocean) in the stocktake.

Table 2: overview of the different main priorities considered under the scope of the current roadmap, together with identified forward-looking priorities.

Category	Current Priorities (Roadmap Scope)	Identified Future Gaps / Forward-Looking Priorities
Carbon Species	Focus on DIC, DOC, POC, and PIC (Dissolved/Particulate Organic and Inorganic Carbon) and air-sea CO_2 flux	Methane (CH_4): Detailed treatment of the aquatic methane cycle is missing. Other cycles: Nitrogen
Ecosystems	Open oceans, shelf seas, and "Blue Carbon" (mangroves, seagrass, tidal marshes).	The LOAC Loop: Inclusion of floodplains and groundwater; deeper understanding of the "Twilight Zone" and under-ice regions
Methodology	Tier 1 IPCC reporting and establishing baseline Earth Observation (EO) capabilities.	Transitioning to Tier 2 and Tier 3 reporting; narrowing model uncertainties; and validating 3D ocean carbon storage.
Social and Economic	Scientific quantification of stocks and fluxes to support the Global Stocktake.	Human Dimension: Impact of urbanization and management; Economic Valuation: Linking carbon data to monetary value.
Climate Action	Initial framework for Monitoring, Reporting, and Verification (MRV).	mCDR: Dedicated focus on the safety, efficacy, and ethical frameworks of Marine Carbon Dioxide Removal technologies.
Policy and Data	Improving global data access and standardizing definitions for EO products.	Addressing "policy latency" (the speed at which science is adopted) and aligning products with specific legal/regulatory needs.

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