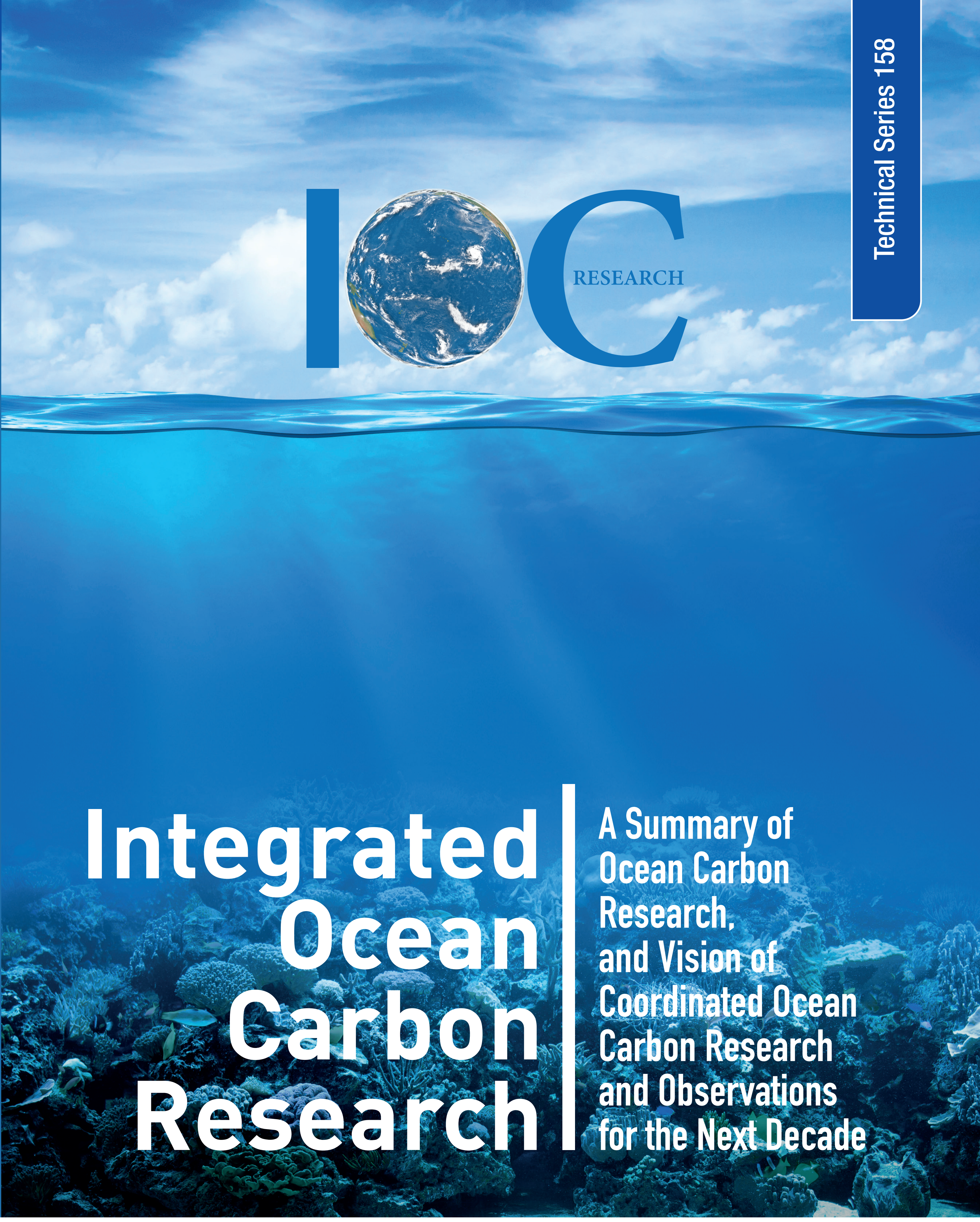

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Integrated Ocean Carbon Research

A Summary of Ocean Carbon Research, and Vision of Coordinated Ocean Carbon Research and Observations for the Next Decade

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Intergovernmental Oceanographic Commission

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Integrated Ocean Carbon Research

A Summary of Ocean Carbon Research, and Vision of Coordinated Ocean Carbon Research and Observations for the Next Decade

Editors

Rik Wanninkhof, National Oceanic and Atmospheric Administration, Miami, USA

Christopher Sabine, University of Hawaii, Honolulu, USA

Salvatore Aricò, Intergovernmental Oceanographic Commission, Paris, France

United Nations Educational, Scientific and Cultural Organization · Intergovernmental Oceanographic Commission

International Ocean Carbon Coordination Project IOCCP

IMBeR Integrated Marine Biosphere Research

surface ocean solas lower atmosphere study

CLIVAR

GLOBAL CARBON project

Contributors and Section Leads

This document is the result of deliberations at the inaugural Expert Workshop on Integrated Ocean Carbon Research at IOC headquarters in UNESCO, Paris, France on October 28-30, 2019 and subsequent interactions. Contributors to this document included participants and other experts in the community who generously shared their ideas and insights. In addition to the section leads, many scientists and managers provided important input as listed below.

Section leads

Salvatore Aricò, Intergovernmental Oceanographic Commission, France
Jesús M. Arrieta, Spanish Institute of Oceanography, Spain
Dorothee C. E. Bakker, University of East Anglia, United Kingdom
Philip W. Boyd, University of Tasmania, Australia
Leticia Cotrim da Cunha, Universidade do Estado do Rio de Janeiro, Brazil
Fei Chai, Second Institute of Oceanography, China
Minhan Dai, Xiamen University, China
Nicolas Gruber, ETH Zurich, Switzerland
Kirsten Isensee, Intergovernmental Oceanographic Commission, France
Masao Ishii, Japan Meteorological Agency, Japan
Nianzhi Jiao, Xiamen University, China
Siv K. Lauvset, NORCE, Norwegian Research Centre, Norway
Galen A. McKinley, Columbia University and Lamont Doherty Earth Observatory, United States
Pedro Monteiro, Council for Scientific and Industrial Research, South Africa
Carol Robinson, University of East Anglia, United Kingdom
Christopher Sabine, University of Hawaii, United States
Richard Sanders, Norwegian Research Centre and ICOS Ocean Thematic Centre, Norway
Katherina L. Schoo, Intergovernmental Oceanographic Commission, France
Ute Schuster, University of Exeter, United Kingdom
Jamie D. Shutler, University of Exeter, United Kingdom
Helmuth Thomas, Helmholtz Center Geesthacht, Germany
Rik Wanninkhof, National Oceanic and Atmospheric Administration, United States
Andrew J. Watson, University of Exeter, United Kingdom

Contributors

Laurent Bopp, Centre national de la recherche scientifique, France
Emmanuel Boss, University of Maine, United States
Annalisa Bracco, Georgia Institute of Technology, United States
Wenju Cai, Commonwealth Scientific and Industrial Research Organisation, Australia
Amanda Fay, Columbia University and Lamont Doherty Earth Observatory, United States
Richard A. Feely, National Oceanic and Atmospheric Administration, United States
Luke Gregor, ETH Zurich, Switzerland
Judith Hauck, Alfred Wegener Institute, Germany
Christoph Heinze, University of Bergen, Norway
Stephanie Henson, National Oceanography Centre, United Kingdom
Jeomshik Hwang, Integrated Marine Biosphere Research project (IMBeR) and Seoul National University, Republic of Korea
Joanna Post, United Nations Framework Convention on Climate Change, Germany
Parvadha Suntharalingam, University of East Anglia, United Kingdom
Maciej Telszewski, International Ocean Carbon Coordination Project, Poland
Bronte Tilbrook, Commonwealth Scientific and Industrial Research Organisation, Australia
Vinu Valsala, Indian Institute of Tropical Meteorology, India
Alejandro Rojas Aldana, Intergovernmental Oceanographic Commission, France

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Programmatic genesis of the Integrated Ocean Carbon Research programme (IOC-R)

The Integrated Ocean Carbon Research (IOC-R) programme is a formal working group of the Intergovernmental Oceanographic Commission (IOC) that was formed in 2018 in response to the United Nations (UN) Decade of Ocean Science for Sustainable Development (2021-2030), "the Decade." The IOC-R will contribute to the science elements of the overarching Implementation Plan for the Decade[1]. The Implementation Plan is a high-level framework to guide actions by which ocean science can more effectively deliver its contribution and co-development with other entities to achieve the societal outcomes outlined in the Decade plan and the sustainable development goals (SDGs) of the UN.

One of the major expectations from the Decade is a predicted ocean that relies on the integration of comprehensive modeling and sustainable ocean observing systems[2]. Specific to climate change and ocean carbon, the Implementation Plan contains dedicated Ocean Decade Challenge 5: "Enhance understanding of the ocean-climate nexus and use this understanding to generate solutions to mitigate, adapt and build resilience to the effects of climate change, and to improve services including improved predictions and forecasts for weather, climate, and the ocean."

The IOC-R addresses key issues in ocean carbon research through a combined strategy of research and observational goals. The research will be framed by four key questions that were formulated at the inaugural Expert Workshop on Integrated Ocean Carbon Research at IOC-UNESCO (UN Educational, Scientific and Cultural Organization) headquarters in Paris, France on October 28-30, 2019. The overarching questions that will be addressed by the IOC-R effort are:

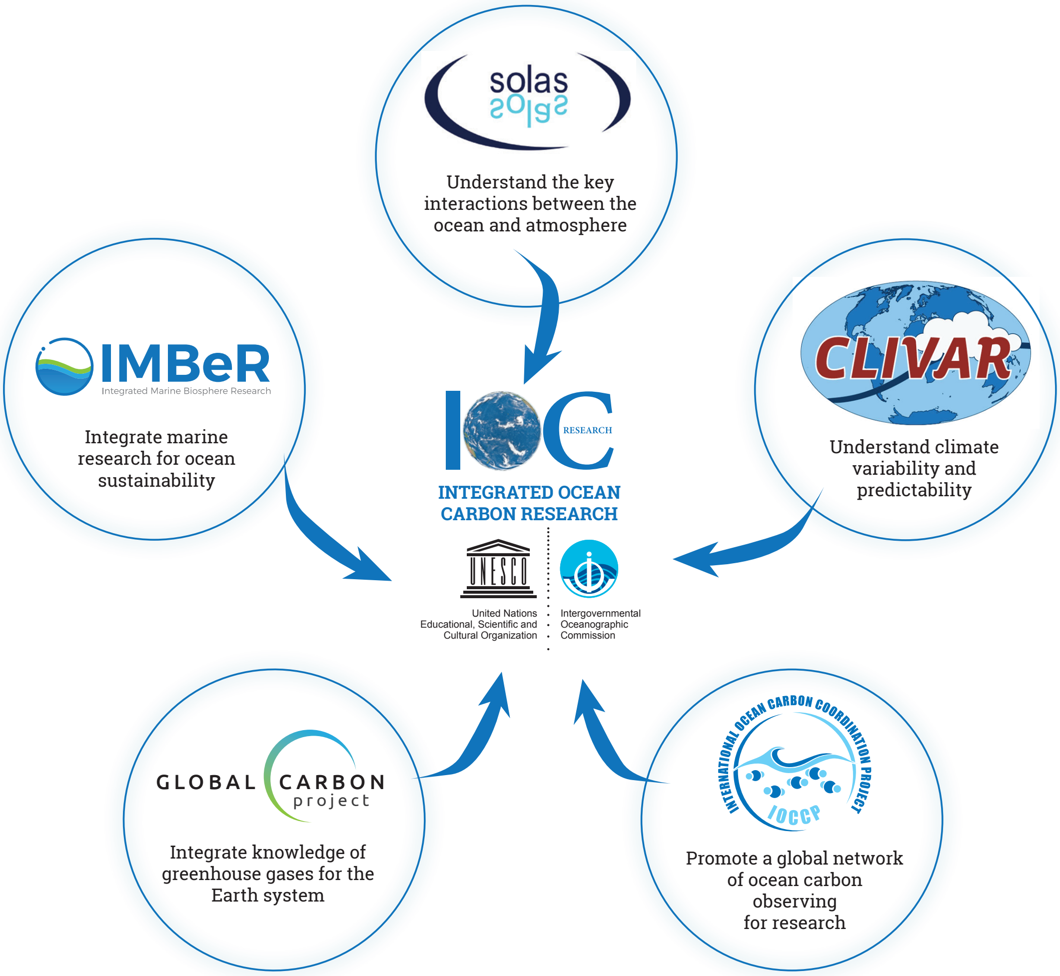

Figure 1. *The international global research and coordination programmes that contribute to IOC-R. Each programme has ocean carbon research, coordination, and assessment as part of its mission, and goals that will synergistically feed into IOC-R.*

- Will the ocean uptake of anthropogenic carbon dioxide (CO_2) continue as primarily an abiotic[a] process?
- What is the role of biology in the ocean carbon cycle, and how is it changing?
- What are the exchanges of carbon between the land-ocean-ice continuum and how are they evolving over time?
- How are humans altering the ocean carbon cycle and resulting feedbacks, including possible purposeful carbon dioxide removal (CDR) from the atmosphere?

The IOC-R was formed through a collaboration of several international programmes that include ocean carbon research in their purview. Each of the programmes, shown in Figure 1, addresses some of the key societal and environmental issues of the Decade's Implementation Plan, including those related to the ocean carbon cycle. By drawing on the diverse perspectives and expertise of these programmes in an integrative way, the emerging issues and cutting-edge approaches in observations, research, and modeling will effectively be addressed. Broadly speaking, the emerging issues related to carbon that are of paramount importance to our environment and society can be categorized as:

- The ocean as a [changing] sink for human-produced CO_2 and its climate change mitigation capacity.
- The vulnerability of ocean ecosystems to increasing CO_2 levels and our ability and need to adapt to changing ocean conditions.

a Abiotic refers to uptake due to chemical and physical processes, as opposed to biologically-mediated effects.

Integrated Ocean Carbon Research (IOC-R): A Vision of Coordinated Ocean Carbon Research and Observations for the Next Decade

I. Introduction

Knowledge of the ocean carbon cycle is critical in light of its role in sequestering CO_2 from the atmosphere and for meeting goals and targets such as the UN Framework Convention on Climate Change (UNFCCC) Paris Agreement, the UN 2030 Agenda for Sustainable Development, and the associated UN Decade of Ocean Science for Sustainable Development. Increasing levels of CO_2 in the ocean, predominantly due to human greenhouse gas emissions, and the partitioning of CO_2 into organic and inorganic species have fundamental impacts on ocean carbon cycling and ecosystem health. The Integrated Ocean Carbon Research (IOC-R) effort aims to address key issues in ocean carbon research through investigative and observational goals. It takes advantage of the appreciable knowledge gained from studies over the last four decades of the ocean carbon cycle and its perturbations. IOC-R addresses the clear and urgent need to better understand and quantify the ocean carbon cycle in an integrative fashion in light of the rapid changes that are currently occurring and will occur in the near future. IOC-R can make significant breakthroughs, capitalizing on advances in modeling, data assimilation, remote sensing, and new *in situ* observing technologies, including novel biological observing techniques, artificial intelligence, and the use of bioinformatics. This IOC-R vision reflects an increasing appreciation for the significant role the ocean carbon cycle has on global well-being now and in the future, and for the critical need to study and monitor it in a holistic fashion.

II. The Case for Integrated Ocean Carbon Cycle Research

a. The role of the ocean in the global carbon cycle (C. Sabine)

The global carbon cycle is an integral part of the Earth System (Figure 2). Of the land, atmosphere, and ocean components of the global carbon cycle that exchange carbon on the timescales of decades to centuries, the ocean contains greater than 90% of carbon contained in these reservoirs[3]. Since the beginning of

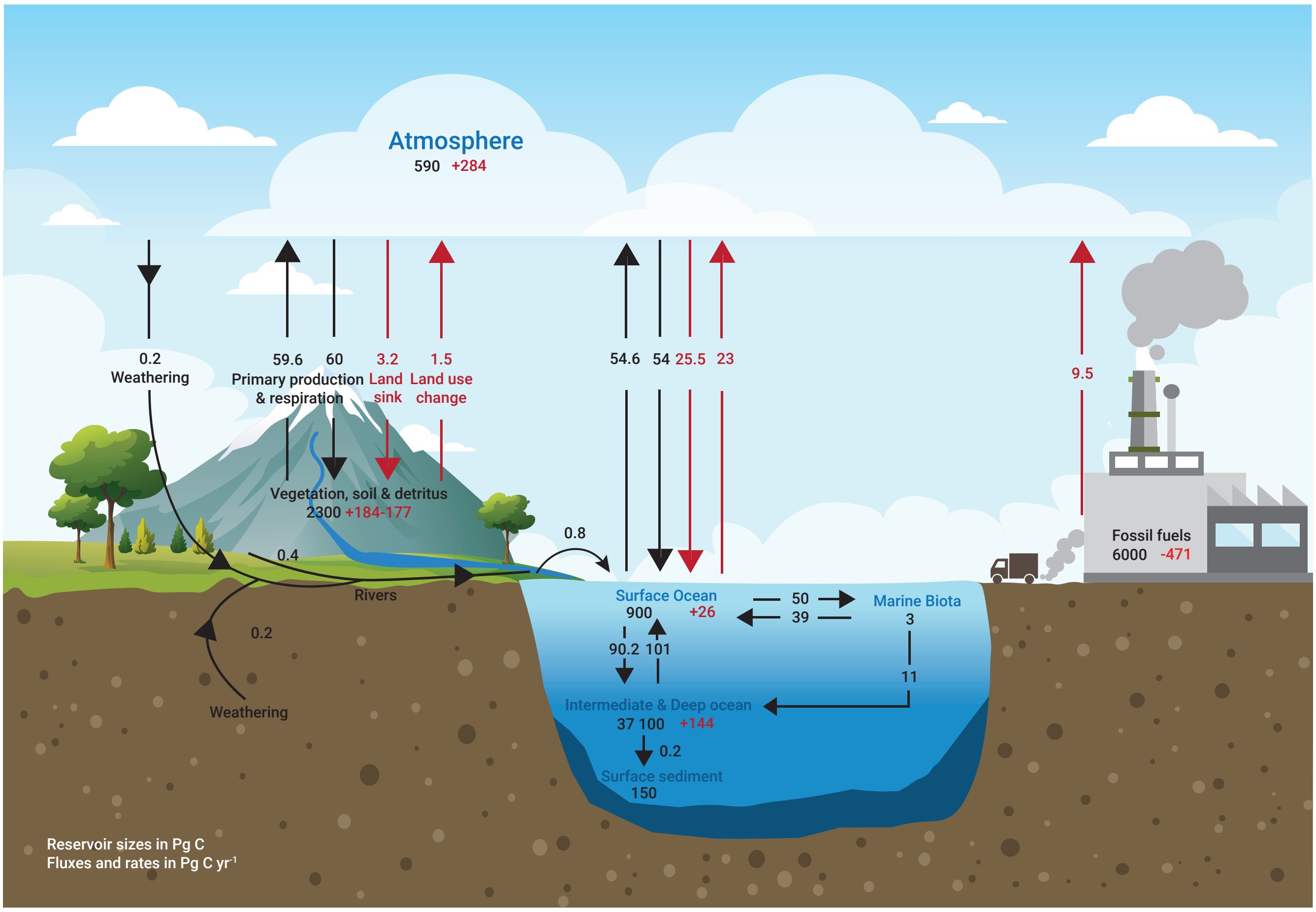

Figure 2. *Inventories of major carbon reservoirs and transport between the reservoirs of the global carbon cycle, estimated for the decade of 2010-2020. Black arrows and numbers indicate the natural carbon cycle and reservoirs, while red arrows and numbers indicate anthropogenic perturbations. The figure is adapted from Sarmiento and Gruber (2002)[3], with the permission of the American Institute of Physics, updated to the decade of 2009-2018 using values from Friedlingstein et al. (2019)[6]. Values outlined in light blue are updated values. Changes in natural fluxes between the ocean and atmosphere are based on a downward revision of the global gas average transfer velocity[7]. Uncertainties in values range from 10-50%.*

the Industrial Revolution (≈1750-1800 AD), humans have dramatically altered the carbon stocks and flows within the land-atmosphere-ocean system and have tapped into fossil carbon in the geological reservoir that would not have otherwise been a significant part of the carbon cycle on timescales relevant to modern society. Over time, the ocean has switched from a pre-industrial net annual source of carbon to the atmosphere of ~0.6 Pg C (1 Pg = 10^{15} g), balanced by uptake in the terrestrial biosphere and returned to the ocean via rivers, the riverine loop, to become a significant annual net carbon sink of ~1.9 Pg C through an anthropogenic carbon uptake of 2.5 Pg C (Figure 2).

The driver of the ocean's absorption of excess anthropogenic (human-derived) carbon, C_{anthro}, is the growth of atmospheric CO_2 levels due to human activities. The C_{anthro} sink observed over the industrial era is primarily an abiotic process that occurs as ocean surface waters work to maintain equilibrium with atmospheric CO_2 concentrations. This absorption of atmospheric CO_2 is superimposed on the large, steady-state natural exchanges of carbon into and out of the ocean (Figure 2). The large-scale ocean circulation slowly moves surface waters laden with C_{anthro} to depths where it can be stored for hundreds of years[4,5].

The accumulation of C_{anthro} in the ocean is altering seawater chemistry, commonly referred to as ocean acidification. These changes will impact the future role of the ocean as a sink for atmospheric CO_2 and will alter marine ecosystems in ways that are still under active investigation.

Significant advances have been made over the past four decades in understanding and quantifying the stocks and flows of carbon between the land, atmosphere, and ocean reservoirs. However, knowledge of the complex oceanic processes influencing the carbon cycle has been largely compartmentalized into physico-chemical and biological studies. The connections between coastal and open-ocean carbon processes have also been understudied. To fully appreciate the ocean carbon reservoir, and its anticipated changes in the future in response to climate change and other human pressures, a holistic and integrated approach to ocean carbon cycle research is needed. A greater quantitative understanding of how biological processes interact with carbon chemistry in the open ocean and in coastal waters is also needed. Moreover, the carbon cycle needs to be understood in the current socio-economic context and large societal changes anticipated in the coming decades.

b. Framework for a science-policy enabling environment (P. Monteiro, K. L. Schoo, K. Isensee)

The decadal vision for the IOC-R is framed by the priorities of a 'top-down' policy and political bodies, and 'bottom-up' science coordination programmes and projects (Figure 3). Both link through UN agencies (e.g. IOC[b] and WMO on ocean science and meteorological investigations, respectively, supporting climate science), non-governmental organizations such as the ISC (ISC is, along with WMO and IOC, a co-sponsor of the World Climate Research Programme), and towards the goal of avoiding dangerous climate change through the Intergovernmental Panel on Climate Change (IPCC) and UNFCCC.

IOC-R acts in concert with these different frameworks by engaging in different parts of the carbon cycle science-society value chain (Figure 3). IOC is the agency appointed by the UN General Assembly to play an enabling and coordinating role for the IOC-R community towards the ambitions and goals of the UN Decade of Ocean Science for Sustainable Development, and in doing so, to contribute to the UN 2030 Agenda for Sustainable Development. The protection of the ocean is the focus of a range of high-level political frameworks that have been established and strengthened over the past decades to frame the needed actions. The UN General Assembly has noted the importance of understanding the impacts of climate change on the ocean and the necessity for more research on ocean processes, as well as for investments in education and capacity building. This is reflected in the 2030 Agenda for Sustainable Development and its SDGs, especially SDG 14: "Conserve and sustainably use the oceans, seas, and marine resources for sustainable development."

IPCC reports, in particular, the most recent special reports on *Global Warming of 1.5°C*[8] and *Ocean and Cryosphere in a Changing Climate*[9] provide sound scientific evidence that underscores the role of ocean carbon in climate. These reports also emphasize the urgency to minimize further damage to the global ocean, as well as maintain key ocean services that are directly threatened by ocean acidification, deoxygenation, and warming. The SROCC also focuses on governance arrangements (e.g., management systems, marine protected areas and marine spatial plans) that are often too fragmented across administrative boundaries and sectors to provide integrated responses to the increasing and cascading risks from climate-related changes in the ocean. The Subsidiary Body for Scientific and Technological Advice (SBSTA), following decision 1/CP.25 of the Conference of the Parties (COP) at its 25th session, convened the Ocean and Climate Change Dialogue[c] at the session in December 2020. Participants considered how to strengthen mitigation and adaptation actions in the context of efforts by the COP to highlight the importance of the ocean, included as an integral part of the Earth's climate system, and to ensure the integrity of ocean and coastal ecosystems in the context of climate change.

IPCC reports [...] provide sound scientific evidence that underscores the role of ocean carbon in climate. These reports also emphasize the urgency to minimize further damage to the global ocean, as well as maintain key ocean services that are directly threatened by ocean acidification, deoxygenation, and warming.

b Acronyms and associated websites are listed in Appendix A.

c Ocean and Climate Change Dialogue: unfccc.int/event/ocean-and-climate-change-dialogue-to-consider-how-to-strengthen-adaptation-and-mitigation-action

SCIENCE - SOCIETY FRAMEWORK FOR IOC-R

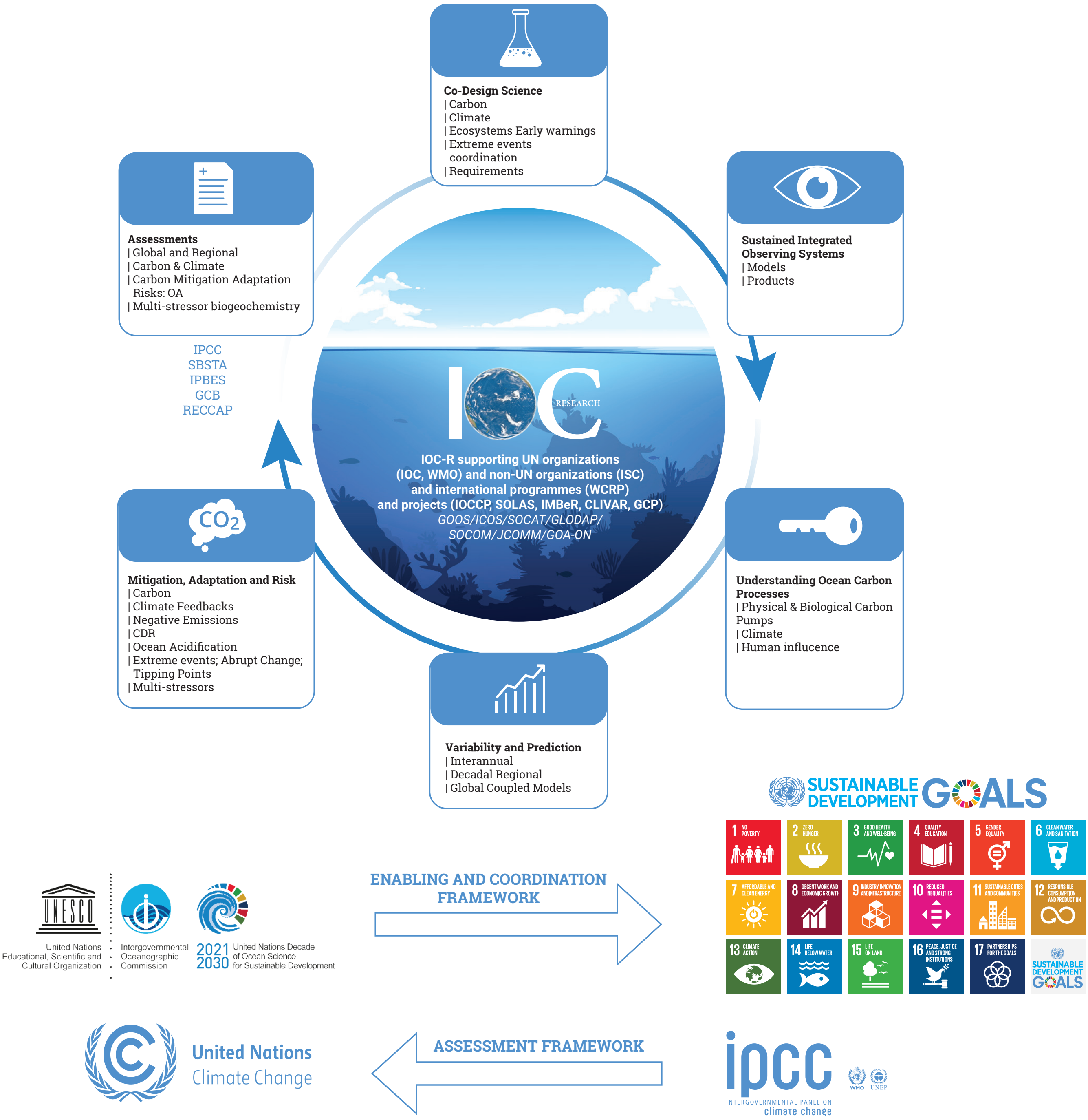

Figure 3. *Key elements that make up the science-society framework context for IOC-R, including its three main elements: The 'top-down' (blue arrows) Carbon-Climate Science to Society (via WMO, ISC and IOC) to UNFCCC global climate political processes through IPCC assessments and towards the SDGs of the UN Agenda 2030 through SDG 14 and the UN Decade of the Ocean for Sustainable Development. The 'bottom-up' ocean carbon science and climate science coordination programmes and projects also managed through the support and coordination of the WMO, ISC and IOC and partner programmes (central core). The IOC-R science-society value chain is set out between the 'top-down' and 'bottom-up' elements of the framework to show that the SDG and Climate aspects engage different parts of the value chain in a complementary way. The UN Ocean Decade provides enabling and coordinating support to the IOC-R that starts with co-designing globally- and regionally-integrated initiatives for observations and modeling that make it possible to work towards the achievement of the SDGs by 2030 but also strengthen the confidence level of science assessments made by the IPCC towards supporting climate negotiations.*

The 6th Assessment Report of the IPCC, currently underway, through Working Groups WG1 (Physical Science), WG2 (Adaptation and Ecosystem Services) and WG3 (Mitigation Policies) assesses the role of ocean carbon both in relation to climate, ecosystems and mitigation policy implications[d].

Looking forward, the UN Decade of Ocean Science for Sustainable Development (2021-2030)[1] presents a unique opportunity to convene regional and global stakeholders around common scientific priorities that can generate knowledge, applications, services, and tools to strengthen mitigation and adaptation actions related to the changing ocean carbon cycle. The Decade aims to provide an enabling framework for ocean science that is co-designed and co-delivered by a diverse range of actors to result in stronger uptake and use of ocean science for action and innovation. When the scientific community, national governments, UN agencies and intergovernmental organizations, business and industry, non-governmental organizations (NGOs), and philanthropic and corporate foundations work together, transformative and innovative pathways will be developed to ensure that future generations can rely on a healthy ocean for their well-being.

c. Brief historical overview of ocean carbon research (R. Wanninkhof, M. Ishii)

The role of CO_2 as a greenhouse gas was first reported at the turn of the 20th century. The influence of the ocean in modulating atmospheric changes was based on basic chemical principles, and the first estimates of ocean uptake capacity for CO_2 were made during this time. Arrhenius[10] provided the foundation for understanding and foresight of the role of the ocean in sequestering excess CO_2: "Although the sea, by absorbing carbonic acid[e] acts as a regulator of huge capacity, which takes up about five-sixths of the produced carbonic acid, we yet recognize that the slight percentage of carbonic acid in the atmosphere may, by the advances of industry, be changed to a noticeable degree in the course of a few centuries." Increased knowledge of the ocean carbon system occurred after the Second World War, including an improved understanding of the speciation of inorganic carbon in seawater, which led to the quantification of the buffering capacity of seawater commonly referred to as the Revelle factor[11,12]. Understanding the exchange of CO_2 between the ocean and atmosphere and ventilation of the oceans was greatly aided by the use of natural radioisotopes and isotopes produced by nuclear bomb testing in the 1950s and 1960s[13,14].

The verification of theories and full quantification was not possible on regional and global scales until the ability to accurately measure CO_2 in the air and ocean was accomplished at appropriate spatial coverage. Systematic and accurate atmospheric measurements started in the late 1950s by Charles David Keeling at Mauna Loa, Hawaii[15]; for the ocean, such measurements commenced several decades later. Global systematic ocean observations of geochemical parameters started with an exploratory programme, the Geochemical Ocean Sections Study (GEOSECS), that covered all major ocean basins in the late 1970s and early 1980s, and led to an estimate of the ocean carbon inventory, but inorganic carbon measurements lacked the accuracy needed to quantify anthropogenic change[16]. A baseline of the physical and geochemical state of the ocean was obtained by the oceanographic World Ocean Circulation Experiment/World Hydrographic Program (WOCE/WHP) survey with measurements of sufficient accuracy and standardization that led to the first observation-based estimate of anthropogenic CO_2[5]. This effort was followed by a survey of reduced density to investigate decadal variability under the Climate and Ocean-Variability, Predictability and Change (CLIVAR) project, and subsequently, a sustained effort, the Global Ocean Ship-based Hydrographic Investigations Program (GO-SHIP), focused on decadal changes and trends in carbon, water, and heat content.

Measurements of a variety of Essential Ocean Variables (EOVs)[f] and Essential Climate Variables (ECVs)[g], including inorganic carbon, have been made at full water column depths from research vessels over basin-wide sections and at time series stations. They provide high-quality data sets, and thereby, evidence of the changes in the interior of the ocean such as excess CO_2 storage[4], reduction of oxygen content[17,18], and the consequential process of ocean acidification[19,20]. However, there are still limiting factors, including the small number of time series stations, lack of coordination, and infrequent occupations of basin-wide sections to capture variabilities superimposed on secular trends with sufficient temporal resolution. Carbon, biogeochemical, and tracer data have been

d www.ipcc.ch/assessment-report/ar6

e The mention of carbonic acid refers to gaseous CO_2.

f www.goosocean.org/eov

g public.wmo.int/en/programmes/global-climate-observing-system/essential-climate-variables synthesized in a global dataset as part of an ongoing but largely voluntary effort, the Global Ocean Data Analysis Project (GLODAP)[21,22], that has been a boon to studying and modeling basin and global trends in carbon in the ocean.

Measurements of CO_2 in the surface ocean were initiated in the late 1950s and have grown over time through international collaborations and partnerships with shipping companies and research ship operators. The observations from moorings and ships of opportunity have been collated into a comprehensive data holding in the Surface Ocean CO_2 Atlas (SOCAT), with 28 million surface water CO_2 observations spanning 50 years (version 2020, updated from Bakker et al., 2016[23]). These collated data are now the basis for evaluating monthly fields of the air-sea CO_2 flux[24,25,26,27] and for assessing the progress of ocean acidification[28] over the past decades on regional to global scales. However, systematic surface CO_2 measurements have mainly been restricted to the major sea lanes of developed countries, and there remain large data gaps in the vast ocean, particularly for coastal and marginal seas and in the Southern Hemisphere.

Modeling efforts have gone hand-in-hand with observations and surveys. Initial abiotic box models[29,30,31] illustrated how ocean carbon was partitioned between the surface and deep oceans, and the pathways to the deep ocean through high latitude outcrops. These models provided estimates of storage and residence time. Over time, the inorganic carbon cycle was coupled to general ocean circulation models[32], and models of increasing fidelity incorporated representative key biological functional groups of lower trophic levels[33]. Ocean carbonate chemistry is now an integral part of coupled models and Earth System models (ESMs) that are investigated in the Coupled Model Intercomparison Project (CMIP) process[34,35]. These complex models are critical to efforts such as the IPCC and Global Carbon Project (GCP) in estimating the past and projected future levels of carbon in the atmosphere and ocean.

Observations and process level research over the past four decades have provided nuanced insights into the workings of the ocean carbon cycle and its associated parameters. In particular, the connection between the organic and inorganic carbon cycles was explored in endeavors such as the Joint Global Ocean Flux Study (JGOFS) and Land-Ocean Interactions in the Coastal Zone (LOICZ) project, and now the Surface Ocean-Lower Atmosphere Study (SOLAS), the Integrated Marine Biosphere Research (IMBeR) project, and Future Earth Coasts. The concept of carbon pumps, and the interplay between the physical and biological pumps, has been particularly powerful in understanding the changing ocean carbon cycle. Changes in the absolute and relative strength of these pumps could have profound effects on ocean carbon cycling and ecological functioning. Moreover, a holistic understanding of the workings of the organic and inorganic cycles, along with their connectivity to other biogeochemical transformations and cycles such as the oxygen and nutrient cycles, has gained increasing importance in predicting changes in the ocean. Additionally, the importance of micronutrients, such as iron, has been elucidated in models and in field and laboratory studies[36,37,38,39].

Looking forward, the UN Decade of Ocean Science for Sustainable Development (2021-2030) presents a unique opportunity to convene regional and global stakeholders around common scientific priorities that can generate knowledge, applications, services, and tools to strengthen mitigation and adaptation actions related to the changing ocean carbon cycle. The Decade aims to provide an enabling framework for ocean science that is co-designed and co-delivered by a diverse range of actors to result in stronger uptake and use of ocean science for action and innovation.

There is a continued need to quantify carbon uptake by the ocean to constrain the exchanges between the global carbon reservoirs and to predict atmospheric CO_2 levels and pathways to meet the Paris Agreement[40]. More recently, the role of the ocean carbon cycle in ocean health and in negative carbon emissions has gained increasing attention from a socio-economic perspective. To date the ocean health and blue economy aspects have largely evolved around ocean acidification. However, an increasing focus is on additional factors such as the role of organic carbon in eutrophication and deoxygenation processes. To meet atmospheric CO_2 trajectories in accord with the Paris Agreement, negative emissions or increased storage of carbon on land and in the ocean will be necessary. Increased carbon uptake by the ocean through enhancing the biological pump as proposed by John Martin with his iron hypothesis in the early 1990s[41] is being revisited as a means of enhancing carbon sequestration. Other approaches of enhanced CO_2 uptake and biotic or abiotic carbon storage, such as alkalization, to mitigate climate change need further investigation[42]. The enhancement of organic carbon pumps and the optimization of inorganic carbon speciation in the ocean are being investigated as a means to increase the ocean-based economy through sustaining and increasing fish stocks and enhancing coral reef growth or diminishing their decline. It is in this environment that ocean carbon research, and specifically IOC-R, will take center stage.

d. Brief historical overview of ocean biological research (C. Robinson)

Marine life plays a pivotal role in many aspects of the ocean carbon cycle through metabolic processes such as photosynthesis, calcification, and respiration. Ocean biological processes store and transport enough carbon in the ocean's interior to keep pre-industrial atmospheric CO_2 levels at around 220 parts per million (ppm) lower than in an abiotic ocean[43]. Storage is achieved via a series of transport mechanisms, often referred to as pumps, that maintain a surface-to-deep ocean gradient of dissolved inorganic carbon (DIC). The biological pump exports particulate organic and inorganic carbon (POC, PIC) from surface waters to below the wintertime mixed layer through gravitational settling[44]. This biological gravitational pump (BGP) is augmented by ecologically-mediated pumps; for example, the export of carbon from the surface via the production at depth of fecal pellets by diel vertical migrating metazoa[45], the mesopelagic migrant pump (MMP), the seasonal lipid pump (SLP) involving the vertical transport and metabolism of carbon-rich lipids by over-wintering zooplankton at depth[46], and the production of recalcitrant dissolved organic carbon via the microbial carbon pump (MCP)[47,48]. The combination of the BGP, MMP, and SLP annually removes between 5-10 petagrams of carbon (Pg C) in the form of particles from the surface ocean[44].

As observations for the regional scale distribution of plankton biomass, CO_2 concentrations, and carbon export accumulate, understanding increases of the influence of plankton community structure on carbon drawdown and sequestration. Early studies of surface water plankton and carbon chemistry identified correlations between chlorophyll and the partial pressure of CO_2 (pCO_2)[49] and coccolithophore production, alkalinity, DIC, and pCO_2[50], whilst recent global genomic analyses suggest that a significant fraction of the variability in carbon export can be predicted from the relative abundance of a few bacterial and viral genes[51].

It is currently estimated from general ocean circulation models and observations that ~50% of macronutrients supplied to the surface ocean are biologically utilized and transported back into the ocean's interior, along with organic carbon, before being remineralized with the remainder being advected around the ocean without directly contributing fuel for the biological pumps.

It is currently estimated from general ocean circulation models and observations that ~50% of macronutrients supplied to the surface ocean are biologically utilized and transported back into the ocean's interior, along with organic carbon, before being remineralized (i.e., remineralized nutrients), with the remainder being advected around the ocean without directly contributing fuel for the biological pumps (i.e., preformed nutrients[52]). The canonical modeling view is that the influence marine life plays in carbon sequestration can be estimated by the ratio of remineralized versus preformed nutrient inventories in the ocean[53]. A better understanding of what controls the fraction of upwelled nutrients used in biological processes versus that which is subducted unused is key to understanding the integrated impact of the physical, biogeochemical, and biological processes on the ocean and global carbon cycle and possible changes in the future. Influential processes on this remineralized/preformed partitioning include an environmental limitation of nutrient uptake by biota, ocean ventilation rates, and the depth at which sinking organic material is remineralized into inorganic constituents[54].

e. Boundary regions: Land-ocean continuum and air-sea interface (M. Dai)

The land-ocean continuum is typically composed of soils, groundwater, riparian zones, floodplains, rivers, streams, reservoirs, lakes, estuaries, and continental margins before reaching the open ocean interior. Here, we adopt the concept of Liu et al. (2010)[55], which is extended from Wollast (2003)[56], in referring to continental margins or ocean margins as "the region between the land and the open ocean that is dominated by processes resulting from land-ocean boundary interactions." The exact dimensions vary depending on the research issue or chemical element of interest but generally encompass the continental shelf, slope, and adjacent marginal seas. The region is vulnerable to human stressors and contains much of the blue carbon stock.

During lateral transport, carbon is transferred and/or transformed within its pools between dissolved and particulate forms, and exchanged with the atmosphere. On millennium or longer timescales, terrestrially-originated supplies of many elements, including carbon and nutrients, modulated the steady-state chemistry of the ocean and result in a net outgassing of CO_2 from the ocean in pre-industrial times. This region also encompasses the most frequent and intense human socio-economic activities that are vital to societal sustainability.

Two major interfaces in the continuum are the boundaries between inland waters and ocean margins and between ocean margins and the open ocean. The inland water-ocean margin interface has carbon flows across successive filters and/or reactors in which the hydrological, ecological, biological, and biogeochemical processes are strongly coupled. This interface includes estuaries that are generally considered to be net heterotrophic and, therefore, often are sources of atmospheric CO_2[57,58].

The lateral transport of carbon from land to the ocean comprises not only of the natural loop of the global carbon cycle, but also the highly perturbed one by anthropogenic activities[59]. The importance of these human perturbations are substantial, as these interface agitations are of a magnitude sufficient to alter global fluxes. However, the magnitude of impact on the biogeochemistry of marine ecosystems is uncertain[60]. In addition to lateral processes, water-atmosphere exchange during the transport and transformation along the continuum is also an important component of the global carbon cycle[61].

Global lateral fluxes at the land-sea interface are dominated by rivers. Li et al. (2017)[62] recently re-evaluated the spatial patterns of carbon fluxes from global rivers and determined global rivers export ~1 Pg C annually to the oceans, comprised 0.24 Pg C in the form of DOC, 0.24 Pg C as POC, 0.41 Pg C as DIC, and 0.17 Pg C of PIC. Refractory carbon primarily from biomass burning, or black carbon (BC) contributions, is 10-fold lower, with rivers delivering 26.5 Tg (10^{12} g) dissolved BC and 17-37 Tg particulate BC annually to the ocean[63].
Carbon fluxes from several other inputs in the continuum are much less certain. Very limited regional data have shown that DIC and DOC fluxes via submarine groundwater discharge can be comparable in magnitude to the riverine fluxes in estuaries, marshes, and other types of coastal waters[64]. The advective flux of DIC in the intertidal zone is found to be similar to the diffusional flux[65], but ratios are likely very different for different geomorphologies. At the sediment-water interface, bio-irrigation may dominate, while contributions from submarine groundwater discharge and diffusional processes are still being debated.

At the interface of the ocean margin to the open ocean, carbon exchanges are driven by the cross-shelf/slope transport modulated by complex dynamics of flow and topography and by oceanic meso- and submesoscale processes such as eddies, fronts, and jet stream separation[66], along with the baroclinic pressure gradient at depth[67]. Ocean margins not only export but also import material, including carbon and nutrients from the open ocean, for which the stoichiometry between carbon and nutrients can impact the air-sea CO_2 fluxes in ocean-dominated margins[67].

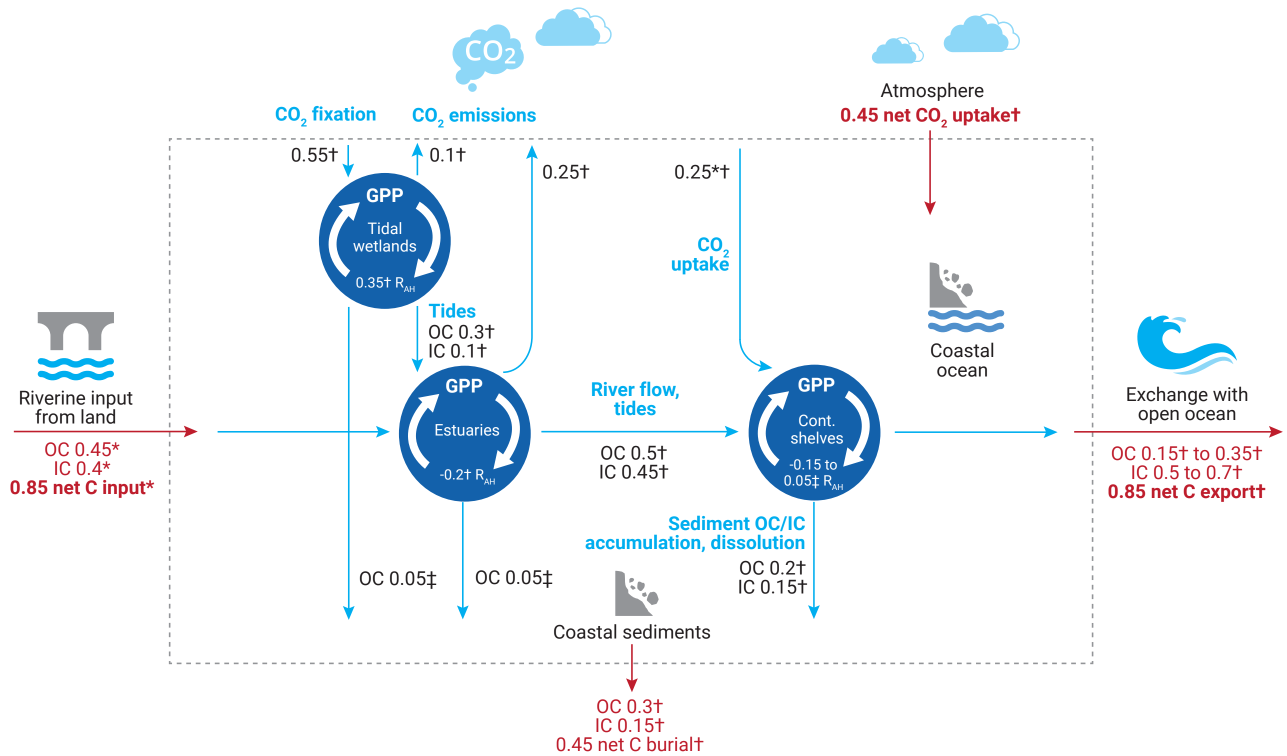

Figure 4. *Major transports and transformations of carbon in the land-ocean continuum in Pg C yr^{-1} rounded to ± 0.05 Pg C yr^{-1}. Values are from Bauer et al. (2013)[58] and differ from other investigations due to large uncertainties from undersampling and extrapolations. Typical uncertainties for carbon fluxes: * 95% certainty that the estimate is within 50% of the reported value; † 95% certainty that the estimate is within 100% of the reported value; ‡ uncertainty greater than 100%. OC is organic carbon, IC is inorganic carbon, GPP is gross primary production (GPP) and R_{AH} is total system respiration (A = autotrophic, H = heterotrophic). Figure adapted by permission from Springer Nature Customer Service Centre GmbH: Springer Nature, Nature, The changing carbon cycle of the coastal ocean, Bauer et al., Copyright © 2013*[58].

Reliable estimates of global carbon exchange fluxes across the ocean margin-open ocean interface are challenging due to the lack of a clearly-defined boundary, sufficient understanding of associated processes, along with the great diversity of ocean margin systems in terms of geomorphology and ecosystems. Globally, canonical estimates of marginal sea transport for organic carbon to the open ocean vary from 2 Pg C yr^{-1} [55] to as great as 29.0 ± 8.0 Pg C yr^{-1} [68]. However, an authoritative review of Bauer et al.[58] (Figure 4) suggests a much smaller export of combined DIC plus DOC flux of 0.85 Pg C yr^{-1} to the open ocean. Synthesis analyses of available data on ocean margins has revealed a sink of atmospheric CO_2 on a global scale, with a flux of 0.19-0.4 Pg C yr^{-1} [67,69,70,71].

Inland waters degas CO_2 at an estimated rate of 2.1 Pg C yr^{-1} into the atmosphere[61]. The air-water CO_2 flux within estuarine systems is subject to strong seasonal and spatial variations, with a range of degassing of 0.1-0.27 Pg C yr^{-1} [70,72].

f. An integrative view of the ocean carbon cycle (G. McKinley)

The ocean has played a critical role in modulating climate warming by absorbing a large fraction of human-emitted fossil carbon and heat. Due to the continual increase of atmospheric CO_2 over the industrial era, the ocean has absorbed an excess amount of carbon equivalent to 41 ± 15%[h] of fossil fuel CO_2 emissions, which is equivalent to 28% of the anthropogenic CO_2 emissions comprised of fossil fuel and land use change. The cumulative global carbon budget up to 2007 illustrates the importance of the ocean in long-term sequestration of carbon (Figure 5). To understand and predict the future carbon sink, improved process understanding and integration of all components of the carbon cycle are essential.

The ocean carbon sink is currently estimated on monthly timescales using three-dimensional ocean models[6,73] and observationally-based products derived from sparse surface ocean pCO_2 data[23,24].

h Observation-based from 1800-2007 (Table 2; Gruber et al., 2019).[4]

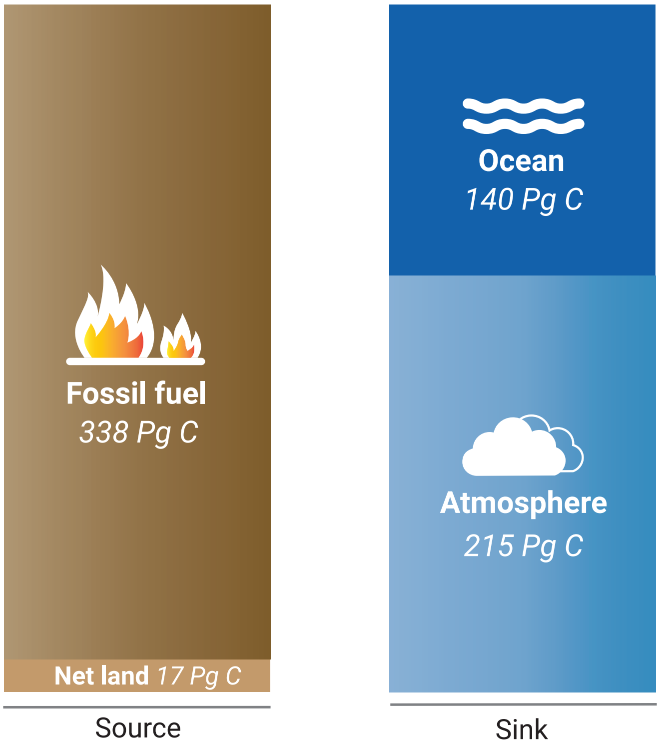

Figure 5. *Cumulative carbon sources and sinks since the start of the Industrial Revolution. Over the entire time period the terrestrial system acted as a net source, while the atmosphere and ocean were the only sinks. Data from Table 2 Gruber et al. (2019)[4]. Note that carbon fluxes from land are often separated into a "natural" land sink and an anthropogenic source attributed to a change in land use. Over the 1765-2007 period, these two components yielded a net source. If land use source is independently estimated as an anthropogenic emission, the remaining terrestrial biosphere has been a net annual sink of comparable magnitude to the ocean in the past 60 years (see Figure 6).*

These estimates are benchmarked by interior observations that allow quantification of the decadal timescale accumulation of C_{anthro} in the ocean[4,5]. Models offer increasingly realistic representations of processes across space and time, and are the basis for future predictions. Data and models used together, along with improvements in data acquisition and handling and model representations of biological processes, performed across time and space scales will improve understanding and quantification of the evolving ocean carbon sink[74] and the fidelity of both observationally-based products and ocean models.

The future response of the ocean to changes in forcing will be strongly dependent on CO_2 emission scenarios. If emissions continue unabated, atmospheric CO_2 will continue to grow through this century. Consequently, the thermodynamic driving force for a portion of that CO_2 to move into the ocean will also continue. In this case, a limitation on the ocean sink will be a reduced buffering capacity and possible changes in the ocean biological pump[75,76,77]. With emission mitigation, the thermodynamic drive for ocean carbon will decrease, but better understanding of the projected change in the ocean sink is needed and may lead to revised estimates of allowable emissions. This will require more model-based studies[78] and a deeper assessment of recent interannual and decadal variability using observations and models[79].

Models, including observing system simulation experiments, are useful tools for assessing where and when additional sampling can most reduce the uncertainty in observationally-based products[80]. The merging of models and data using data assimilation will improve scientific understanding by more fully taking advantage of the information content in observations. Complete uncertainty budgets for observations generated using standardized frameworks are needed so they can be fully utilized in assimilations. For predictive models, where data assimilation cannot be directly applied, studies should consider various future emissions scenarios. The physical, biogeochemical, and biological responses that will occur with the likely asymmetric response of the ocean sink to emissions trajectories need to be carefully assessed.

The recent progress in integrating model and observational studies to understand the abiotic processes of the ocean C_{anthro} sink should be extended to studies of the ocean biological processes that modulate the natural carbon cycle. The degree to which biological feedbacks may begin to alter the natural carbon cycle need to be investigated. To fully understand the socio-economic benefits provided by the ocean (Figures 5 and 6), as well as the potential socio-economic impacts of future feedbacks that should reduce the sink, a holistic and integrated programme of study is required.

III. Fundamental and Emerging Research Questions

a. Will the ocean uptake of anthropogenic CO_2 continue as primarily an abiotic process? (N. Gruber)

The nearly-exponential increase of total anthropogenic CO_2 emissions over the industrial era implies the ocean's abiotic uptake has increased quasi-exponentially, reaching 2.5 ± 0.6 Pg C yr^{-1} for 2009-2018[6,73]. Without the ocean and land sinks, atmospheric CO_2 levels would be close to 600 ppm, compared to the annual average in 2018 of 409 ppm (Figure 6). An atmospheric CO_2 level of 600 ppm is well above the level compatible with a 2°C climate warming target. Thus, the question of whether the ocean will continue to act as a sink for carbon being emitted into the atmosphere as a result of human activities is of fundamental importance for climate science and climate policy.

The abiotic component of uptake will continue as long as atmospheric CO_2 levels increase, but as emission mitigation slows the growth of atmospheric pCO_2, the ocean sink will slow in response[81]. Superimposed on these longer scale trends, observations and models show a substantial amount of variability on seasonal to decadal timescales[25,74,82,83,84]. In particular, the global ocean carbon uptake substantially weakened during the 1990s and then strengthened during the first decade of the 21st century. While evidence of the decrease in ocean carbon uptake is robust, the attribution is less clear[25,85] and requires a robust research effort to disentangle the contributing physical, chemical, and biological processes. Fully resolving these processes will improve our ability to predict the ocean's response to changing atmospheric CO_2 burdens.

Regionally, there have been strong decadal carbon exchange variations in the high latitudes, notably the Southern Ocean[82,84,86], in addition to large multi-annual changes in the equatorial Pacific related to the El-Niño Southern Oscillation (ENSO) phenomena[87]. More recently, globally coherent responses outside of the equatorial Pacific have been observed and modeled. Mechanisms giving rise to these variations require further investigation. Landschützer et al.[25] suggested that temperature variations together with changes in ocean biology play a key role, while DeVries et al. (2017)[85] emphasized the role of the ocean overturning circulation. Other recent work suggests that recent decadal variability of the ocean carbon sink was externally forced by processes such as surface temperature responses to large volcanos[78].

Determining the level of variability in the ocean sink and elucidating the mechanisms and regions that give rise to these variations are absolutely critical for predicting the future ocean carbon sink. Improved representation of these processes in ESMs is needed to gain more robust projections of the ocean carbon sink and carbon-carbon and carbon-climate feedbacks. While the ocean will continue to act as a sink if atmospheric CO_2 levels continue to rise, the increase of inorganic carbon in the ocean will decrease its buffering capacity, as well as its uptake capacity, and increase seasonal amplitudes of surface water pCO_2[88]. The quantification of this is essential, particularly in light of global changes in temperature, wind, and freshwater fluxes[89].

> **The nearly-exponential increase of total anthropogenic CO_2 emissions over the industrial era implies the ocean's abiotic uptake has increased quasi-exponentially, reaching 2.5 ± 0.6 Pg C yr^{-1} for 2009-2018. Without the ocean and land sinks, atmospheric CO_2 levels would be close to 600 ppm [...] well above the level compatible with a 2°C climate warming target.**

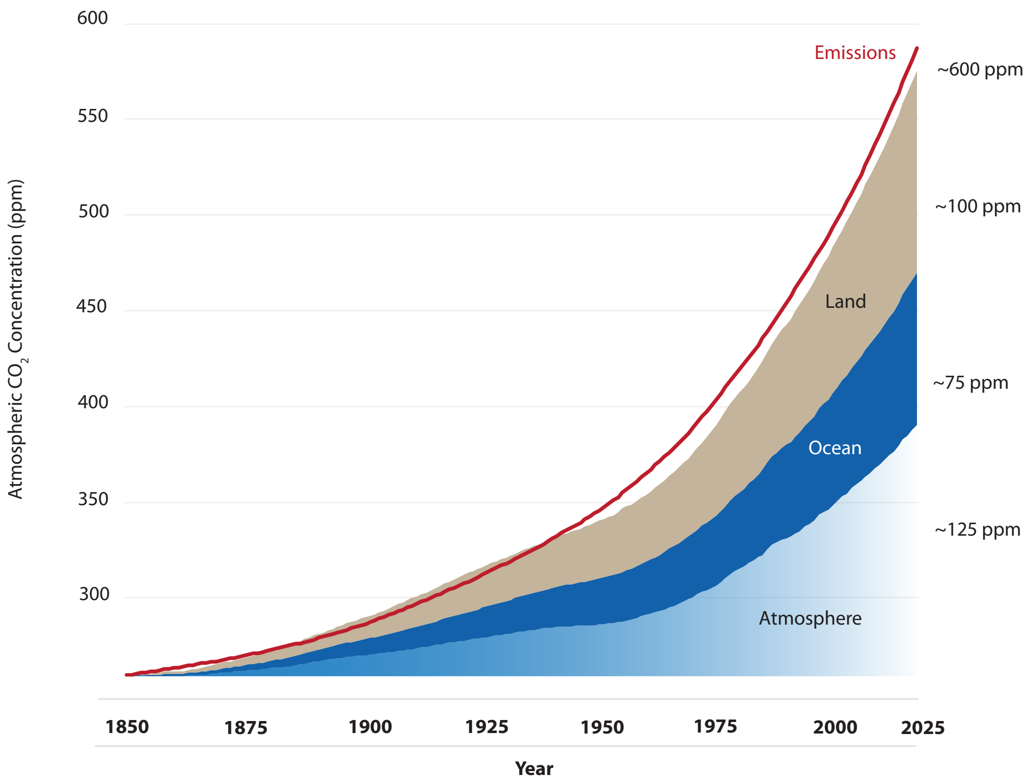

Figure 6. *Evolution of CO_2 emissions from fossil fuels and land-use change, in equivalent atmospheric CO_2 concentrations (top starred line), and their partitioning between the land, ocean, and atmosphere since 1850. Without the ocean and terrestrial sinks, the atmospheric trajectory would be the same as the emission trajectory. Hauck (pers. comm.) based on GCP data[6].*

Aside from forward-looking questions regarding the evolution of the abiotic component of the ocean carbon cycle, there are current discrepancies that must also be resolved to reduce our uncertainty in the role of the ocean in sequestering carbon. The latest estimate of the decadal accumulation of anthropogenic carbon in the ocean interior[4] has a central value that is larger than models, but can be brought into better agreement with the models and estimates from interpolated surface ocean data[74] when taking different definitions of the flux terms into account[6,73]. By capitalizing on the complementary strengths of these different approaches, progress can be achieved in evaluating the true storage rate. The current range of model estimates for carbon uptake in the 1990s spans from 1.6-2.8 Pg C yr^{-1} [6]. The application of more comprehensive data constraints can help decrease this range. This will require improved constraints on air-sea CO_2 fluxes, and a continued improvement in interior ocean observations and synthesis products.

b. What is the role of biology in the ocean carbon cycle and how is it changing? (P. W. Boyd)

In global carbon cycle research, particularly efforts pertaining to long-term carbon uptake by the ocean, biology has been considered in steady state, and sequestration is considered largely abiotic. However, it has long been recognized that seasonal changes in surface water carbon are heavily influenced by biological processes, and more recently, that the decadal modulation of carbon uptake has a biological component[25]. Moreover, in a rapidly changing ocean environment, large changes in the biological pumps are possible that can have large impacts on ocean carbon cycling and ocean ecosystems.

The effect of biology on the ocean carbon cycle in the euphotic layer has been extensively studied[90], and its impact on the global ocean carbon cycle is greatly aided by the ability to remotely sense the sea surface from space[91]. The knowledge gaps are of the impact of changing biological processes on the subsurface ocean, particularly regarding the transport and transformation of living and dead dissolved and particulate matter in the mesopelagic or twilight zone, the stratum between 200 and 1000 m depths (Figure 7).

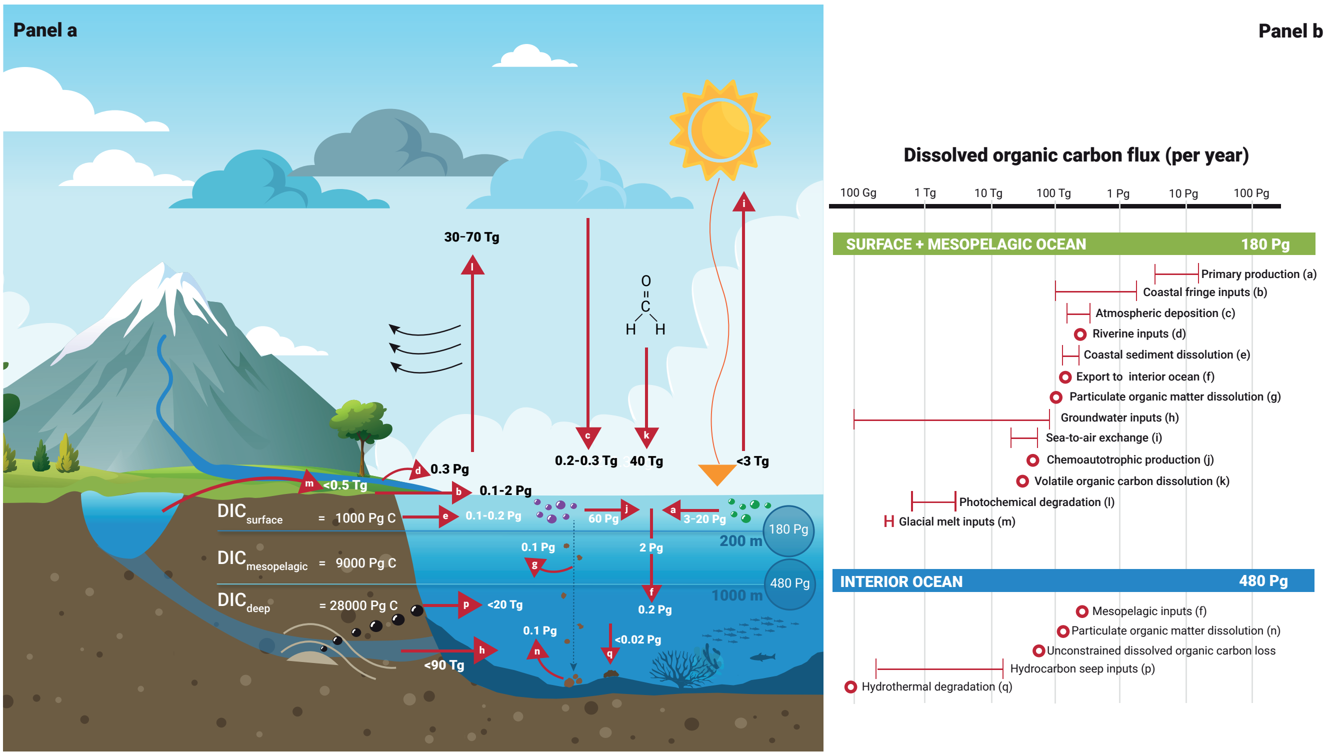

Figure 7. *Panel a depicts organic carbon fluxes and inventories in the ocean. Total dissolved inorganic carbon (DIC) is listed for the different reservoirs, as well as for a comparison of magnitudes. Note that values are provided in both Pg C and Tg C (1 Pg = 1000 Tg). Fluxes are per year. Panel b shows the estimated range of fluxes on a log scale, showing significant uncertainties in the size of organic stocks and fluxes. The organic carbon inventories and fluxes in the ocean are significantly less than the inorganic components, but their importance in the biological carbon cycle and the ocean's health, make these components of the ocean carbon cycle critical for active research (figure redrawn from Wagner et al., 2020[92]).*

There are major uncertainties regarding the magnitude and processes of the biological gravitational pump (BGP), the mesopelagic migrant pump (MMP), and the seasonal lipid pump (SLP) and their interplay within the twilight zone. This has major implications for our ability to detect and determine future changes in the magnitude of these pumps due to climate change. Without knowledge of the baseline and the natural variability around it, changes cannot be detected and attributed in this biologically-mediated component of the ocean carbon cycle. Other unknowns include: spatial patterns of efficiency of the BGP and other pumps; temporal variability; the relative role of particle transformations that set the carbon storage depth; and how these processes will be altered by a changing climate and acidification processes. Changes in the closely interlinked soft tissue pump, consisting of particulate organic material, and hard tissue pump, consisting of particulate inorganic material, and the spatial patterns in the ratio of sinking hard and soft tissue, also require further investigation. These uncertainties will propagate and influence what needs to be included in our conceptual frameworks and models for characterizing future responses to climate change.

Current estimates of the size of the BGP flux are highly variable, in part due to systematic undersampling. For example, measurements of flux attenuation from neutrally buoyant sediment traps are available at less than 10 sites globally[93]. Innovations in profiling floats, free floating sediment traps, gliders, and their coupling to satellite products are likely to substantially narrow the range of estimates regarding BGP strength and change in strength over the next several decades.

Global environmental change is hypothesized to alter the operation of the soft and hard tissue pumps. One key area is how the hard tissue pump will respond to ocean acidification and potentially impact the soft tissue pump[94]. Other factors that can impact the biological carbon cycle and ocean health include mesopelagic fishing[95], seabed mining, the discharge of mine tailings from land to the ocean, deoxygenation, and warming. Temperature can control the turnover of organic matter via respiration, and the resupply of nutrients to the surface ocean via changing stratification[96]. Overfishing is disrupting the mesopelagic food web. Oxygen is changing particle transfer efficiencies[97], while mining can change interior particle fields.

Some international efforts in the twilight zone are being linked under a new umbrella community effort—the Joint Exploration of the Twilight Zone Ocean Network[98]. These initiatives rely on new approaches, and instrumentation will seed other ideas for the coming decade on the impact of the changing processes in the twilight zone. These programmes will yield a better understanding of the time and space dependence of the biologically-mediated flux from the surface to the interior, along with the mechanisms that drive and control this flux.

The links between biogeochemistry and ecology research as they pertain to the ocean carbon cycle need to be enhanced. Higher trophic levels such as zooplankton and midwater fish play a role in both carbon sequestration and food supply. A reorganization of twilight zone food webs driven by fishing needs to be further explored over the next decade[98]. Observations of these changes must be closely coupled to a mechanistic understanding of changes and modeling efforts such that a predictive capacity for changes in the ocean's biological cycles and the ocean carbon cycle can be facilitated.

c. What are the exchanges of carbon between the land-ocean-ice continuum? (M. Dai)

A full integration of the land-ocean continuum and its inclusion in ESMs is essential for understanding the global carbon cycle. This will require breakthroughs in conceptualization and data coverage. Wetland ecosystems possess some of the highest carbon burial fluxes and may hold the potential for new technologies for enhanced carbon sequestration. However, their global carbon storage and efficacy of sequestration are still being debated, and many scientific questions remain to be answered[99,100]. Direct measurements of wetland carbon exchanges with the atmosphere and export to estuaries are important when considering the potential effects of accelerating sea level rise and global warming on the carbon supply of these ecosystems to the coastal ocean[58,70].

Sea ice covers 12% of the world's ocean surface[101] but has not yet been fully included in the global carbon budget. The influence of freezing and melting sea ice on the CO_2 flux has produced conflicting results and needs further investigation[102,103]. There is also uncertainty in how the Arctic Ocean carbon cycle will respond to increasing freshwater input and ocean area due to a reduction in sea ice extent[104].

River/estuarine plumes may extend hundreds of kilometers away from a river mouth and are critical areas of land-ocean interaction, both physically and biogeochemically. There are big gaps in data and understanding regarding plumes in reconciling carbon budgets with potentially high magnitude and the variability of air-sea CO_2 fluxes[105]. The complexity of the interaction between plume dynamics and estuarine/shelf circulation, along with the associated biogeochemical alterations therein, makes it challenging to elucidate and quantify their processes and mechanisms.

The bulk of the global ocean margin represents a carbon sink of ~0.1-0.2 Pg C[69], but a mechanistic-based conceptualization of the coastal carbon cycle remains elusive, hindering its modeling and inclusion in ESMs. The evolution of this sink in light of large changes in the land-ocean continuum is largely unknown. An important step would be an improved categorization of the different ocean margin systems, leading to an improved understanding of the key processes that control carbon cycling in these varied systems[67,106].

d. How are humans altering the ocean carbon cycle and resulting feedbacks? (K. L. Schoo, K. Isensee)

Changes in the ocean carbon cycle due to C_{anthro} uptake and natural changes are altering marine life and ecosystem functioning. As such, the services provided by the open ocean and coastal areas, such as food and livelihood from fisheries, carbon sequestration, tourism, cultural identity, and recreation, among others, may be negatively impacted[107]. Coastal protection provided by coral reefs, in addition to their other key ecosystem functions, has been affected by ocean acidification, weakening them and thereby lessening their protective functions in many coastal regions.

The ongoing expansion of cities and human activities along coastal areas often results in the destruction of coastal ecosystems, such as tidal marshes, mangrove forests, and seagrass meadows. Destroying these habitats reduces the climate change mitigation potential of the ocean. Mangrove forests, in particular, play an important role in the sequestration of carbon, with an annual average sequestration rate of 6-8 Mg CO_2 e/ha (10^6 g of CO_2 equivalent per hectare). Globally, between 30-50% of mangroves have been lost in the last 50 years, and they continue to be lost annually at a rate of 2%[108].

Adaptation, mitigation, and remediation require a knowledge of the past and current state of the affected (coastal) marine environment. Observations are necessary to obtain a baseline against which to measure change. For adaptation and mitigation, multidisciplinary research is needed. Understanding the chemical changes occurring in the ocean and their effect on the biological components of the system, as well as their importance to marine ecosystems as a whole and the services they provide—from economic interests to social impacts—should all be taken into account. Putting a value on these services will be essential in terms of both financial implications and impacts on human and ocean health. This will need to involve stakeholders and scientists across the academic and economic communities. Estimates by the Organization for Economic Cooperation and Development (OECD) valued the ocean economy, including sectors such as shipping, fishing, tourism, transport, and energy, at 2.5% of the global gross domestic product (GDP) or US $1.5 trillion in 2010, and this amount is expected to double by 2030[109]. It is anticipated that ocean renewable energy, and carbon capture and storage will play a more significant role in the future ocean economy[110].

Historically, human perturbations and the valuations described above have not been an integral part of ocean carbon research. However, an incorporation of these aspects is necessary for a more holistic view of the ocean carbon cycle. In particular, the impact of human stressors, over and above C_{anthro} emissions, will involve the incorporation of economic and social sciences and lead to a fundamental shift in approaches.

IV. Approaches to Address Integrated Ocean Carbon Research

a. Strengthen sustained financial support for observing networks (M. Ishii)

In the article entitled *What we have learned from the framework for ocean observing (FOO): Evolution of the global ocean observing system*, Tanhua et al. (2019)[111] succinctly described the needs for sustained observations of the ocean: "Governments and policymakers are facing complex decisions that require information from sustained ocean observations. The observations and integration necessary are lacking to fully meet these needs. In many areas, sustained ocean observations are simply too infrequent, sparse, inadequate, or imprecise. A step-change is required in worldwide investment in order to take advantage of the changes made possible by increasing requirements and the expansion of technological developments and the adoption of open data policies. The improved understanding of the ocean based on decades of scientific effort, in concert with a recognized need for continued coordination of efforts to observe, analyze, understand and predict the ocean will assist in the realization of a return on this important societal investment. The Global Ocean Observing System (GOOS) has had considerable success over the past decade in encouraging voluntary collaborations across the broad community, including increased use of the Framework for Ocean Observations, FOO guidelines and partly effective governance, but much remains to be done."

Observing networks need to be coordinated, co-designed, and operated in cooperative ways by participating organizations and entities, including those of the private sector. They must be sustained over the decades long enough to assess the impact of human activities, as well as the effect of measures to reduce greenhouse gas emissions on the ocean, that occur in addition to natural variability on multiple time and spatial scales. Data synthesis and modeling activities also need to be maintained and developed in sustainable ways for the efficient utilization and application of local-to-global scale analyses and the numerical simulation of ocean carbon across the disciplines of biogeochemistry, physics, and biology.

Observation programmes have shown great value in quantifying and understanding the ocean carbon cycle, and have a level of maturity to offer authoritative synthesis products that contribute to key assessments. However, an operational framework needs to be established to continue these measurements, transition the observing framework and synthesis products to include autonomous observations, and expand systematic observations to include biology.

b. Enhance and coordinate the existing suite of carbon observing and synthesis projects (R. Sanders, S. K. Lauvset, U. Schuster, D. C. E. Bakker)

Two different *in situ* approaches are currently used to quantify surface ocean carbon uptake and interior ocean transport and storage. Surface ocean observations of pCO_2 and associated parameters are combined with remote sensing, reanalysis information, and statistical models (mapping methods) to evaluate the ocean uptake of atmospheric CO_2 across the sea surface at relatively high spatial (100 km) and temporal (monthly) resolution. Surface to bottom vertical profiles of carbon chemistry and associated parameters are used to estimate C_{anthro} concentrations in the interior[4,5]. Because changes in the interior are slower than at the surface, these observations are used to estimate the cumulative uptake over decadal time periods.

Net ocean CO_2 uptake represents the difference between the two much larger natural uptake and release fluxes (Figure 2), which requires large amounts of information to reliably estimate the uptake annually on global and regional scales. Research vessels, ships of opportunity (SOOP), moorings, and autonomous surface vehicles are used to make surface CO_2 measurements continuously and autonomously. The data are then quality controlled, compiled, uniformly formatted, and made publicly available as the Surface Ocean CO_2 ATlas (SOCAT; Bakker et al., 2016[23]).

In some regions consortia of instrumentation operators have formed, mostly informally, to take advantage of synergies and economies of scale such as the global Surface Ocean CO_2 reference NETwork (SOCONET[112]) and the European Research Infrastructure (ICOS[113]). An aligned effort is the Global Ocean Acidification Observing Network (GOA-ON[114]) focused on ocean acidification activities and a broader range of observing capabilities, including data sufficient for local ocean carbon cycle investigations.

Interior ocean observing is based on analyses of discrete water samples throughout the water column. One important application is the quantification of C_{anthro}. C_{anthro} concentrations are 1-3 orders of magnitude lower than the natural background, and measurements need to be highly accurate. Multiple related parameters must be measured contemporaneously to allow corrections for natural changes. Repeat hydrographic sections, under the aegis of GO-SHIP[115], that sample from coast to coast and surface to ocean bottom in all ocean basins are currently the only observational way to obtain global C_{anthro} fields. This effort provides critical data for checking models and contributes to assessments such as the IPCC process.

A recent advancement is the deployment of biogeochemical (BGC) Argo profiling floats. These floats have a particular role to play in increasing sampling density, particularly in areas and in seasons where ships do not routinely go, such as the Southern Ocean. Their first large-scale deployment began in 2015 under the Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) programme and contributed to an improved understanding of the regional carbon fluxes[116]. These floats do not currently carry pCO_2 or DIC sensors and the inorganic carbon system is estimated from measured pH. Calibrating these data to the level required for quantification of the ocean carbon sink requires ship-based measurements.

The interior ocean carbon observing system is focused on quantifying changes in inventory, and separating the processes controlling carbon in biogeochemical ways. Biological processes in the ocean play key roles in transporting carbon into the interior. An important characteristic of many of these processes is that they can move carbon across isopycnal surfaces via the swimming behavior of animals or gravitational settling. The canonical view is that these processes are in steady state, but many are climate change sensitive, and hence, a high priority research activity is to quantify their relative importance on spatial and temporal scales comparable to the scales at which we observe physical uptake. The incorporation of biological measurements from GO-SHIP cruises can take advantage of key technological advances[117]. Ocean biological carbon observing should also capitalize on autonomous platforms.

c. Regional priorities (L. Cotrim da Cunha)

Anthropogenic carbon emissions are causing changes in the physical and biogeochemical properties of the oceans, from coastal to open areas[118]. The extent and impacts of these changes are not homogeneously distributed across the world's oceans and coastal areas and, therefore, need to be addressed regionally. The importance of a regional approach for ocean carbon research is to go beyond the global carbon sinks and sources budgeting efforts, and focus on unique processes for specific regions. Regional carbon dynamics and the related scientific and societal questions are important for understanding the effectiveness of mitigation efforts, controls on ocean-atmosphere CO_2 exchange trends, and interaction with land ecosystems[119]. Specific questions related to regional carbon cycling are provided in Appendix A. Of note is that several regional priorities are in areas with limited research infrastructure and resources that require innovative collaboration and resource allocation for execution.

Regional priorities for ocean carbon research are addressed by considering the geographic uniqueness of regional features such as eastern boundary upwelling systems (EBUS), western boundary current systems, areas under the influence of large rivers, and polar regions. The effects of multiple stressors (e.g., warming, acidification, and deoxygenation) on marine ecosystems need to be addressed and the impact on human communities dependent on these ecosystems. Polar regions, both in the Arctic and Antarctic, are warming faster and losing ice, affecting their roles as carbon sinks. They are also acidifying faster than other regions of the world's oceans, especially in the Arctic[120]. The Arctic Ocean is already undersaturated with respect to aragonite during portions of the year, making it unfavorable for the growth of calcifying organisms[121]. The polar carbon sink is also variable with time with the Southern Ocean showing decadal variability, as indicated by observations and modeling studies[4,82]. Furthermore, both Arctic and Southern Ocean display significant regional and temporal variability in carbon[120] whose change influence the global mean.

d. New process studies and experiments (J. M. Arrieta)

Process studies and focused experimental manipulations make an essential contribution to our understanding of specific processes by providing the mechanistic explanations and parameterizations needed in the development of models and budgets. They can provide high-quality observations needed to calibrate remote sensing and autonomous platforms, as well as assess the performance of the resulting algorithms.

Continued studies on different scales are needed to improve understanding and provide the necessary rate constants that in turn can be used to improve process models. Appreciable advances have been made in process studies with integrated multi-faceted *in situ* studies that have yielded key insights. Efforts such as JGOFS[122] have provided a template for how to study important biomes with large, multidisciplinary expeditions. Notable advances in design have been Lagrangian studies, either using drifters or purposeful tracers to follow a water mass, sometimes including perturbations of the biological cycle such as iron fertilization experiments[38]. Open ocean mesocosm studies, where a water parcel is isolated and manipulated, and the use of autonomous instruments and platforms to increase sampling density have provided key insights. Studies have successfully incorporated remote sensing (e.g., EXport Processes in the Ocean from Remote Sensing, EXPORTS[i]) to increase process level understanding and to create algorithms that can be applied at greater scales. These innovative approaches in the execution of process studies and experiments will be an integral part of ocean carbon research in the next decade, particularly in the nexus of biology and processes controlling organic to inorganic carbon transformations.

Several gaps in our understanding can be addressed through process studies. Important processes like ocean acidification are being studied with great success by means of experimental manipulations at different scales[123,124]. However, recent studies have revealed a number of shortcomings that exist in our understanding of the carbon cycle that have yet to be addressed[125,126]. This includes the largely overlooked exchange of organic compounds between the atmosphere and ocean that regionally can be an important fraction of the total oceanic carbon exchange[127,128,129]. Microbial utilization of these compounds, not included in oceanic carbon budgets, represents a previously unnoticed, but sizeable fraction of microbial metabolism, increasing the flux of organic compounds from the atmosphere into the ocean[127,130,131]. Although not represented in our current models of the oceanic carbon cycle, autotrophic carbon fixation in the dark contributes an additional 1.2-11 Pg C yr^{-1} to oceanic primary production[132]. Despite being a fundamental process in ocean biological cycles, the magnitude of oceanic primary production and respiration is poorly constrained. It is even unknown whether certain ocean regions are net heterotrophic or autotropic[133,134]. Much of the large-scale modeling and interpretation of the ocean carbon cycle relies on assumptions of constant stoichiometry such as fixed ratios of nutrients, carbon, and oxygen (Redfield ratios), and particulate inorganic and organic matter (hard tissue and soft tissue). These ratios are dependent on the environment and ecosystem and will possibly change in a warming and acidifying ocean. Manipulative process studies in the lab and the field are needed to assess these possible changes.

Some envisioned studies cover a much broader interest across several ocean research disciplines but will greatly enhance knowledge of the ocean carbon cycle, as well as improve the physical representation and parameterization of transport and air-sea gas transfer. The study of near surface gradients will also aid in quantifying fluxes. A better understanding and representation of the transfer across the air-

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sea interface will reduce the uncertainty in CO_2 flux estimates[135]. Studies focused on mixing and nutrient supply to the euphotic zone are desired to improve biological productivity estimates.

These are just a few examples of the important knowledge gaps that need to be examined with carefully designed process studies and experimental manipulations that can constrain their importance, evaluate their sensitivity to future climatic scenarios, and incorporate them in our depictions of the carbon cycle.

e. New technologies to enhance autonomous observations and analyses (J. D. Shutler, A. J. Watson)

Implementing the IOC-R research agenda will rely heavily on recent observational and analytical advances. In particular, remote sensing, autonomous platforms and vehicles, and artificial intelligence approaches offer the opportunity to study and solve pressing research questions regarding the workings and perturbations of the ocean carbon cycle.

Satellite remote sensing of the sea surface state, temperature, wind, salinity, ice, rain, and chlorophyll-a plays a critical role in quantifying oceanic carbon. These observations are routinely used for upscaling sparse *in situ* measurements, studying heterogeneous regions, identifying biologically-driven variability within the ocean sink, and providing proxies for gas exchange[91]. Beyond this, remote sensing holds the promise for quantifying spatial and horizontal variability in near-surface concentrations and for observing internal ocean circulation and surface transport[91]. Satellite remote sensing methods for accurately observing multiple inorganic carbon system parameters[136], combined with satellite methods to observe river discharge[137], can aid the quantification of land-to-ocean exchanges of carbon from major rivers. Satellite optical measurements of surface wave and white capping also hold the potential for elucidating atmosphere-ocean exchange processes[138]. Additional optical remote sensing such as active lidars and passive polarimeters can constrain particulate composition (PIC vs POC) and its vertical distribution[139]. Future coincident high-resolution, all-weather observations of sea ice concentrations, water temperature, salinity, and wind speed[140] can elucidate the significance of multiple atmosphere-ocean exchange processes and controls on a global scale, with high frequency sampling making them suitable for studying compound events. The combination of satellite observation-based atmospheric marine boundary layer CO_2[91], carbon monoxide[141], and fluorescence[142,143] holds the potential for quantifying process level fluxes, including the influence of respiration, following similar methods as developed for land fluxes[144].

Machine learning, the autonomous discovery of patterns within data, and artificial intelligence are fast expanding areas of research. These methods are expected to continue to aid climate change research[145]. They are already routinely used to compensate for data sparsity in surface and interior ocean carbon measurements to create observation-based data products of all inorganic carbon system parameters[146], assess current and historic sources and sinks of CO_2[147,148,149], and provide data for model assimilation[150]. Methods for identifying emergent interior ocean dynamics[151] and advances that enable coarse scale ESMs to include mesoscale eddy dynamics[152] can be used to improve model quantification of cross-continental shelf carbon transport[153]. Data driven machine learning techniques such as gradient boosting, deep learning, and ensemble methods have the potential to provide insights into latitudinal variations of carbon quantities and identify when and where different atmosphere-ocean exchange processes dominate. Time series forecasting methods[154,155] are able to follow evolving systems and can enable monthly-to-annual regional forecasts of marine inorganic carbon system parameters and the carbon sink for guiding management and conservation efforts.

Satellite remote sensing of the sea surface state, temperature, wind, salinity, ice, rain, and chlorophyll-a plays a critical role in quantifying oceanic carbon. These observations are routinely used for upscaling sparse *in situ* measurements, studying heterogeneous regions, identifying biologically-driven variability within the ocean sink, and providing proxies for gas exchange.

Autonomous platforms have now come of age with the widespread deployment of sea gliders, profiling smart floats, and unmanned surface vehicles[156]. They offer excellent platforms for rapidly improving chemical and biological sensors. The proposed BGC Argo array will measure key biogeochemical and biological variables such as chlorophyll-a, nitrate, oxygen, pH, suspended particles, and downwelling irradiance[j]. The floats, along with modeling efforts, have already advanced understanding of Southern Ocean atmosphere-ocean CO_2 exchange[116] and identified novel carbon export mechanisms. BGC Argo floats can also be expanded to include particulate organic and inorganic carbon measurements[157]. However, since the current approach only includes a single inorganic carbon parameter, i.e., pH, a carbon observing network based on BGC Argo floats will need additional referencing to provide more chemically comprehensive observations.

Observations from gliders and autonomous surface vehicles have begun to deliver important insights concerning atmosphere-ocean fluxes of CO_2[158]. The buoy-based pCO_2 instruments currently installed on several dozen moorings provide climate quality data in part because of onboard calibration gas. Instrumentation is being developed for other inorganic carbon variables, DIC and total alkalinity (TA), that are critical for constraining the ocean inorganic carbon cycle. Thus, techniques exist for a global marine carbon observing network using satellite observations and autonomous platforms, and referenced to existing ship-based observing efforts, but further development and sustained investment in all, as all components are critical, are needed to fully realize any network.

f. Integrate models and observations (F. Chai)

The carbon cycle and other key biogeochemical processes have been fully incorporated into ocean circulation models and ESMs, along with observations that are capable of determining ocean uptake, transport, and the storage of C_{anthro}[6,159]. On global and decadal scales, these coupled physical-biogeochemical models can be used to estimate the air-sea CO_2 flux and long-term trends of the ocean's uptake of C_{anthro}[160]. Performance varies significantly among different models, especially on regional and interannual scales[159,161]. Such model differences are still large due to inconsistent simulations of the ocean's physical processes and inadequate biogeochemical parameterizations on global and regional scales[159,162,163]. Improving observational coverage and processing multiple datasets with complete and standardized uncertainty assessment are critical steps to guide model development and further their improvement. Therefore, different types of modeling approaches and observations must be integrated to cover the necessary spatial and temporal scales[164].

The range of biogeochemical and ecosystem modeling applications is broad, including re-analyses for the assessment of past and current physical and biogeochemical ocean states, short-term and seasonal forecasts, what-if scenario simulations, and climate change projections. Different models are often used for specific applications. Biogeochemical modeling applications currently lag behind physical ocean modeling and prediction for several reasons:

- ESMs typically have too coarse a resolution to simulate mesoscale dynamics in transporting carbon and other key biogeochemical elements[165,166].
- Global models, even those with a higher spatial resolution configuration, poorly represent the land-ocean carbon continuum because they do not incorporate all pertinent processes in this realm[55,167].
- Biological processes are not configured adequately in current biogeochemical models at the regional scale due to different temporal variabilities and the lack of robust process understanding[44,168].
- Biogeochemical observational datasets are too sparse for the comprehensive evaluation, initialization, and optimization of biogeochemical models[167,169].

The expansion of carbon cycle and biological observing systems will allow for significant advances in improving the performance of biogeochemical models, and for further developing applications and prediction systems with multiple scientific and societal benefits[170]. The direct integration of observational datasets with models on local to global scales, from event scale to long-term trends, will elucidate previously unrecognized shortcomings in biogeochemical models and prompt improvements in model structure, parameterizations, and algorithms for data products. These improved models, along with biogeochemical data assimilation and remote sensing, can offer state estimation for quantifying biogeochemical fluxes that are internally consistent with re-analyses, nowcasts, and forecasts[171]. These can provide spatial and temporal coverage not attainable by direct observation[172,173]. Data assimilation is also a promising technique to optimize key parameters that are less constrained in biogeochemical models[174,175].

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A bottleneck for the development of biogeochemical models is insufficient observations, which induces large uncertainties in model outputs and thus limited forecasting skill. An augmentation of current measurement techniques with autonomous profiling floats that contain BGC sensors will create the needed comprehensive time series of key biogeochemical variables[176,177]. These datasets are expected to be an important resource to increase the capability and credibility of ocean models that can be used to predict the response of ocean carbon sinks and feedbacks to the climate system. The forecasting and prediction capability of these improved models will help mitigate climate and marine ecosystem risks at both global and regional scales[178]. A fully integrated model and data forecasting system will in turn help refine the decision-making process and aid in enacting effective carbon policy.

g. Consider solutions: Mitigation approaches (N. Jiao, H. Thomas)

The negative impacts of increasing atmospheric CO_2 levels are widely recognized, and stabilizing and decreasing the atmospheric CO_2 burden has become a social and economic imperative. There is broad consensus that enhancing carbon sinks need to be explored to attain the scenarios laid out in the Paris Agreement, in addition to an aggressive curtailment of fossil fuel CO_2 emissions. The IPCC special report on *Global Warming of 1.5˚C*[8] points towards the critical role of carbon mitigation strategies. While many possible options rely on increasing land-based sinks or the storage of liquid CO_2 in land or submarine deposits, several ideas have been put forward to increase the ocean carbon sink. Many of the proposed ocean-based options are viewed with concern, and sometimes with staunch opposition from the marine community and society at large, because of unknown and possible deleterious effects to ocean ecosystems. Moreover, the efficacy of these methods over the long-term is doubted. Here, we describe some of these approaches, including a few that are novel. The focus of the IOC-R is to provide the needed research to assess the viability and impacts of current methodologies and new proposals for enhanced ocean carbon sequestration.

Broadly speaking, there are two overlapping ocean mitigation approaches: direct intervention, or ocean geoengineering, and ecosystem-based methods. Here, the approaches that involve the sequestration of carbon will be referred to as ocean or marine carbon dioxide removal (CDR) techniques. Several ocean geoengineering approaches, including CDR, have been summarized in several recent reports[42,179] and highlighted as a topic requiring more research in programmes such as SOLAS. These reports list many possible CDR techniques to sequester and store carbon in the ocean, but large-scale implementation cannot occur until there is clarity on impacts and long-term feedbacks and consequences. Ultimately, decisions on CDR will be based on policy formulation and governance, including a determination on whether some of the approaches would be considered marine pollution and thus be contrary to SDG Target 14.1: "Prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution." The open ocean policy and regulatory aspects of marine geoengineering will be likely entertained through the London Convention/London Protocol (LC-LP). Current available knowledge is insufficient for evidence-based decision-making[42]. These major knowledge gaps also challenge the ability of the scientific community to effectively communicate the many facets of ocean CDR to the general public.

> **SDG Target 14.1: "Prevent and significantly reduce marine pollution of all kinds, in particular from land based activities, including marine debris and nutrient pollution."**

The Group of Experts on the Scientific Aspects of Marine Environmental Protection-Working Group 41 (GESAMP WG-41) report[42] provides eight illustrative marine geoengineering approaches that use the most applicable and pertinent criteria. Several CDR approaches include innovative methods to use the marine biological cycle to enhance sequestration. The performance and impacts of these approaches, as attained by scientific testing, modeling, and experimentation, needs to be assessed, including studies on the enhancement of the biological cycle through fertilization, adding alkalinity to the ocean through different means, and macro algae cultivation (Figure 8). In addition, there are several storage options that are viewed beyond the purview of the IOC-R that involve storing CO_2 in different forms in the ocean or on/under the seafloor.

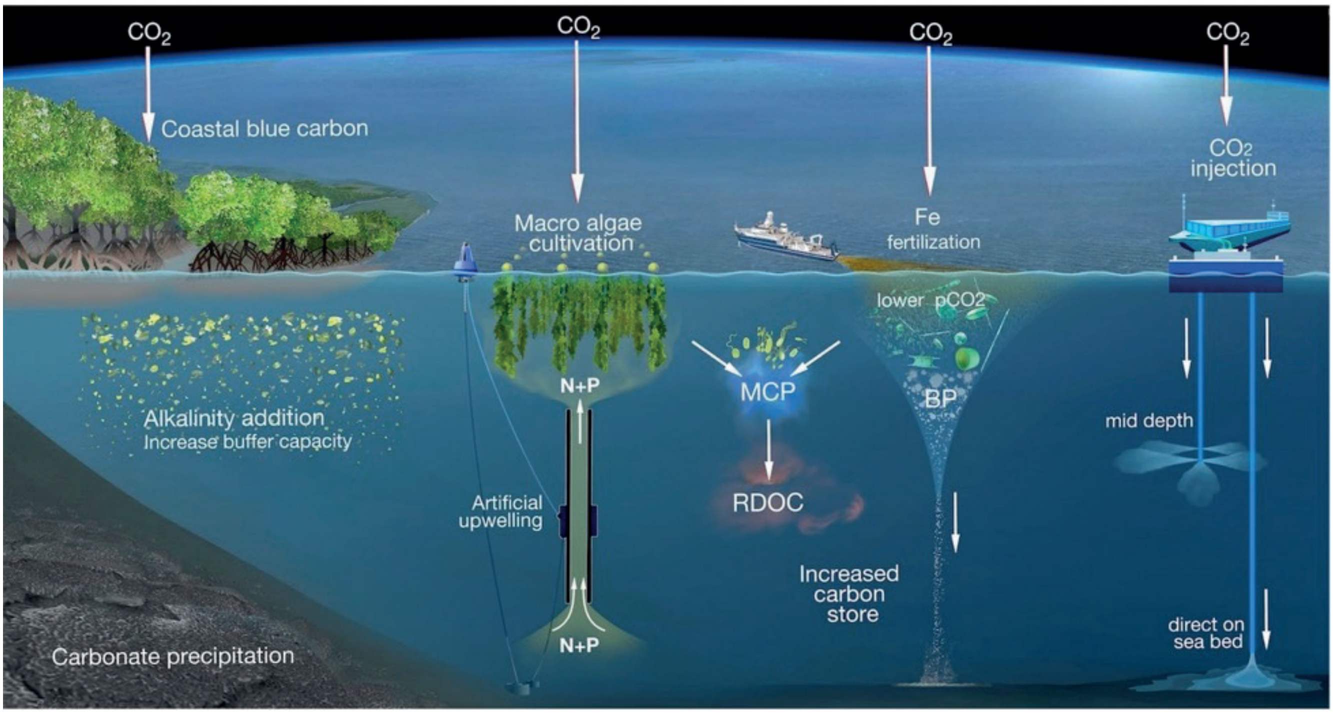

Figure 8. *A sampling of proposed marine ecoengineering and geoengineering approaches with description in the text. Figure is from N. Jiao pers. comm.*

For the IOC-R, the broad issues to be investigated include:

- Efficacy: Do proposed CDR approaches effectively store carbon at large scales?
- Side-effects: Are there deleterious impacts to marine ecosystems?
- Monitoring: Is there an observing scheme to monitor efficacy and impacts?

Proposals such as ocean fertilization for carbon storage and fish stock production, artificial upwelling, direct injection of CO_2 into deep waters, and enhancing ocean alkalinity constitute targets for experimental mesoscale process studies. Combined observational process studies similar to the mesoscale iron fertilization experiments carried out in past decades[38,180] are needed for assessing the safety and efficacy of these proposals before they are attempted for large-scale mitigation. Such studies would produce a wealth of high-quality multivariate data to elucidate the mechanisms underlying the processes involved. This information is also invaluable for improving our understanding of the functioning of the oceanic carbon cycle.

Several novel marine CDR approaches involving internal manipulations of physics, chemistry, and biology focus on carbon pools that have the potential capacity to provide long-term carbon removal from the atmosphere (Figure 8). The sedimentary organic carbon pool can be increased through organic matter burial by coastal "blue carbon" reservoirs (mangroves, salt marches, and seaweeds) or POC export via the biological pump (BP). "Excess" culturing might achieve enhanced sequestration[181]. In particular, a focus on enhancing the growth of biota with high Redfield ratios, such as *Sargassum* sp. with a carbon to nitrogen ratio of ≈50:1 compared to ≈7:1 for most marine biota[182], could contribute to sequestration either by organic detritus accretion or plant material harvest.

Refractory dissolved organic carbon (RDOC) remains in the water column for hundreds to thousands of years[183] and constitutes carbon storage in the ocean of ~700 Pg C[184]. Experimental studies have shown an efficient production of RDOC by the MCP[47], indicating a potential approach for enhancement of this carbon sink in the ocean[185], although the mechanisms creating this refractory carbon need further study. An analysis of the relationship between organic carbon and nutrients in various natural environments and experimental results in estuarine and offshore waters has shown that nutrient-replete conditions are unfavorable for RDOC production and storage[47,186,187,188]. Therefore, reducing the terrestrial input of nutrients could enhance carbon sequestration in coastal waters[47,189] while also addressing coastal eutrophication[190].

Managing the retention of carbon in natural environments is a critical approach for mitigating climate change. One example is the integrated enhancement of carbon sequestration in coastal waters through land-ocean management, possibly implemented in association with reward-based carbon trading. Sewage treatment and land management to reduce soil erosion with the overall aim to reduce carbon transport from land to the ocean and the associated CO_2 outgassing in rivers, estuaries, and the ocean has mutual benefits for carbon sequestration, mitigating the loss of agriculture fertility and coastal ecosystem health[182]. Reversing the decline of highly productive shore-side ecosystems such as salt marshes and mangroves through improved management practices is another means to enhance sequestration.

A synergistic exploitation of approaches shows promise of increasing the yield and efficiency of enhanced CO_2 storage. When considering the possible competition of food production and CO_2 storage (SDGs 2 and 13), a judicious combination of approaches could address several goals. For example, aquaculture sites might be candidates for synergistic approaches[182]. Currently, they often generate anaerobic, eutrophic conditions underneath them because of the respiration of sunken by-products such as DOC, detritus, or fecal pellets. Controlled artificial upwelling and ventilation of these waters could serve as a nutrient and oxygen supply to fuel the growth of biomass.

Mitigation requires several considerations in addition to addressing basic ocean carbon research and modeling described above. It involves purposeful change by humans with significant socio-economic and ethical considerations. Negative or unintended consequences and risks need to be considered. The possible economic incentive of ocean carbon credits will have a large impact on whether to execute ocean CDR activities. IOC-R will focus on the natural science aspects and concepts of geoengineering to improve process level understanding of mechanisms through laboratory studies, modeling, and properly scaled field experiments. Field studies need to be properly scaled to determine efficacy but not cause widespread harm if they go wrong.

h. Governance for the Integrated Carbon Research (IOC-R) programme (S. Aricò)

Developments related to ocean carbon research and to the landscape of ocean carbon research activities in recent years prompted the IOC Secretariat and Member States to strengthen the focus of the IOC's Ocean Science portfolio related to ocean carbon, responding to the scientific community's interest in having a coordinating role. This strengthened focus will also respond to growing demands on behalf of the policy-making constituency, particularly in relation to the UNFCCC and its SBSTA.

Generating new knowledge on the role of ocean carbon in climate regulation and on the effects of climate change on ocean carbon, including biology, will also address the growing need for such knowledge from the IPCC, *inter alia*, through better coordinated ocean carbon cycle simulations in the context of the Sixth Coupled Model Intercomparison Project (CMIP6) and the Global Carbon Project's efforts to establish annual global carbon budgets with reduced uncertainty for each iteration.

In 2018, IOC Member States approved a new IOC focus on ocean carbon research—the Integrated Ocean Carbon Research programme (IOC-R)—to unify the efforts of the global ocean carbon research community in the context of the International Ocean Carbon Coordinating Project (IOCCP), SOLAS, IMBeR, GCP, and CLIVAR, as well as relevant national and multi-national efforts on carbon research that contribute directly to such global efforts on ocean carbon research. The discontinuation in 2017 of the IMBeR and SOLAS carbon working groups that, based on the Joint SOLAS/IMBeR Carbon Implementation Plan, were charged with coordination and synthesis of ocean carbon research related to both the ocean surface and ocean interior, provided an opportunity for a new, expanded initiative on ocean carbon research.

> **The IOC has played a central role in organizing the global ocean carbon research community, notably through the Surface Ocean CO_2 Variability and Vulnerability (SOCOVV) workshop [...]. IOC supported the creation of the IOCCP in the early 2000s, building on joint efforts during the previous two decades with the Scientific Committee on Oceanic Research (SCOR) and the International Council for Science (ICSU), including the CO_2 Advisory Panel of the Committee on Climate Change and the Ocean (CCCO) and the subsequent Joint SCOR-JGOFS-CCCO Advisory Panel on Ocean CO_2.**

The IOC has played a central role in organizing the global ocean carbon research community, notably through the Surface Ocean CO_2 Variability and Vulnerability (SOCOVV) workshop held in April 2007 at IOC headquarters in Paris, France[191] and follow-up meetings[192]. IOC supported the creation of the IOCCP in the early 2000s, building on joint efforts during the previous two decades with the Scientific Committee on Oceanic Research (SCOR) and the International Council for Science (ICSU), including the CO_2 Advisory Panel of the Committee on Climate Change and the Ocean (CCCO) and the subsequent Joint SCOR-JGOFS-CCCO Advisory Panel on Ocean CO_2. IOCCP was hosted at, and its secretariat supported by, IOC until 2012. IOCCP is co-sponsored by IOC and SCOR. While IOCCP focuses on the coordination of ocean carbon observations, assisting in the development of needed new technology and developing relevant capacity, there is a need for an integrative platform on ocean carbon research and a clear role for the IOC therein. The IOC-R programme will act as the main platform for advocating and organizing the implementation of an integrated ocean carbon research agenda, including sustained ocean carbon observations; it will formulate and update key questions and assess the knowledge gathered through relevant expert activities to guide ocean carbon research through the next decade.

The organizational setup of the IOC-R that is envisaged as appropriate will see the Ocean Science Section of IOC operate as the secretariat for the IOC-R programme, in close consultation with IOCCP, SOLAS, IMBeR, GCP, GOA-ON, and CLIVAR. Specifically, the IOC-R programme will report on its progress in relation to advances in the UN Decade of Ocean Science for Sustainable Development, Ocean Decade Challenge 5: "Enhance understanding of the ocean-climate nexus and use this understanding to generate solutions to mitigate, adapt, and build resilience to the effects of climate change, and to improve services including improved predictions and forecasts for weather, climate, and the ocean."

The IOC-R will be part of the reporting obligations of the Ocean Science Section of the IOC vis-à-vis the Member States of the Commission, through the report by the Executive Secretary of IOC on work accomplished; regular reporting on the implementation of the Ocean Science portfolio of programmes and activities of the Commission; and the IOC contribution to the Decade. Through the IOC, IOC-R will also contribute to informing the regular Research Dialogue of the UNFCCC SBSTA, which focuses on the Research and Systematic Observations provisions of the Convention, the UNFCCC Earth Information Day, as well as the newly established Ocean and Climate Change Dialogue under the UNFCCC.

It is through the above-mentioned reporting mechanisms, and subsequent discussions and deliberations by IOC Member States and UNFCCC Parties, that IOC-R will inform relevant decision-making on ocean carbon and climate change mitigation, thus providing the critical contribution of ocean carbon research to the science-policy interface.

Appendix A:
Research questions and recommendations in support of Integrated Ocean Carbon Research (IOC-R)

The vision of IOC-R is built around several levels of research questions that are linked to climate and societal issues as described in the UN Decade of Ocean Science for Sustainable Development, Ocean Decade Challenge 5. Questions are tiered and, while not all are specifically described in the vision document, they contribute directly to the execution of IOC-R. The questions address the IOC-R vision and are categorized by scope and scale. An important point is that IOC-R does not solely focus on global scale issues but recognizes the importance of the regional and local scale, where local, sometimes unique, processes have a disproportionate impact on carbon dynamics and ecological impacts that directly affect local populations. These require a dedicated research effort. The questions and recommendations are categorized, but there is appreciable overlap between categories, as would be expected for an integrated research effort. Moreover, the questions invariably link to the overarching questions that will be addressed by IOC-R:

- Will the ocean uptake of anthropogenic CO_2 continue as primarily an abiotic process?
- What is the (changing) role of biology in the ocean carbon cycle?
- What are the exchanges of carbon between the land-ocean-ice continuum and how are they evolving over time?
- How are humans altering the ocean carbon cycle and resulting feedbacks?

Societal and policy relevant research questions

- Will the oceans continue to act as a sink proportional to the carbon that is being emitted into the atmosphere as a result of human activities?
- What is the vulnerability of the ocean to increasing CO_2 levels and what is our ability and need to mitigate increasing CO_2 levels?
- Can we safely enhance sequestration and storage of carbon by the ocean?

Global research questions

- What are the important natural and human anthropogenic factors that impact the biological carbon cycle and ocean health?
- Are the twilight zone food webs changing, and what effect will this have on the evolution of the ocean carbon cycle?
- Is the changing partitioning between PIC and POC affecting the inorganic carbon cycle, its transport, and fluxes?
- How will global ocean carbon uptake change in the future with decreasing C_{anthro} emissions?
- Is the dissolved organic carbon pool changing, and what are its impacts on climate and environmental change?
- How is carbon burial storage in key reservoirs of the land-ocean continuum changing?
- Will deep water production and the meridional overturning circulation change in an evolving

climate, and what will the consequences be for ocean carbon uptake?
- How can multiple stressors on the ocean carbon system be incorporated in assessing observations and model results?
- What is the impact of deoxygenation on ocean carbon cycling?

Regional research questions

- What is the impact of (changing) sea ice on the ocean carbon cycle?
- What is the historical and future impact of a changing Southern Ocean on the global carbon cycle/budget?
- How can the regional budgeting of carbon sources and sinks be improved over the range of ecosystems?
- What are the trends of ocean acidification within polar regions (Arctic/Antarctic)?
- What are the causes and magnitude of temporal variability of the Southern Ocean carbon sink?
- What is the impact of ocean acidification on high-latitude biota, and how will the impact affect other global biogeochemical cycles and higher trophic levels?
- What is the role of tropical ocean margins in the carbon budget, and is this changing?
- What are the impacts of acidification on marine ecosystem in EBUS?
- What is the role of western boundary systems as poleward conveyors of carbon, including the role of mesoscale variability (eddies)?
- How does effluent, such as sewage and runoff, from large coastal cities influence lateral organic and inorganic carbon input and the resulting coastal sea-air carbon fluxes?
- How will carbon cycling change on the shelves and lateral carbon export to open ocean areas?
- What are the combined socio-economic impacts of changes in ocean carbon chemistry, climate change driven by ocean warming, and sea level rise?
- How should marine carbon management strategies in estuaries and shelf seas be improved to support fisheries, aquaculture, tourism, carbon storage and other maritime activities?

General recommendations advocated by IOC-R

- Maintain and enhance sustained high-quality ocean carbon observations critical for quantifying the strength and variability of the ocean carbon sink.
- Co-design, properly fund, and operate carbon observing systems in cooperative ways through participating organizations and entities, including those of the private sector.
- Further utilize remote sensing for synoptic investigation of the ocean carbon cycle.
- Enhance the development and utilization of new technology with respect to sensors and platforms.
- Support best practices in measurements and data sharing and in quantifying uncertainty budgets.
- Accelerate the use of artificial intelligence in quantifying processes, patterns, and exchanges in the ocean carbon cycle.
- Enhance linkages between biogeochemistry and ecology as they pertain to the ocean carbon cycle.
- Integrate the land-ocean continuum more fully into global carbon cycle assessments and ESMs.
- Close important gaps in our knowledge through laboratory and field-based process studies, including properly scaled geoengineering studies, to elucidate mechanisms and contribute to model parameterization.
- Build reliable and comprehensive ocean carbon and biogeochemistry forecasting systems through enhanced synthesis products, modeling, and model-data fusion activities.
- Advance data assimilation activities in ocean carbon research.

Appendix B: What are the Sustainable Development Goals?

The SDG 14[k] targets and their indicators focus on a range of marine issues, among them SDG 14.1, "Prevent and significantly reduce marine pollution of all kinds, in particular from land-based activities, including marine debris and nutrient pollution"; SDG 14.3, "Minimize and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels"; and SDG 14.a, "Increase scientific knowledge, develop research capacity and transfer marine technology, taking into account the Intergovernmental Oceanographic Commission Criteria and Guidelines on the Transfer of Marine Technology, in order to improve ocean health and to enhance the contribution of marine biodiversity to the development of developing countries, in particular small island developing States and least developed countries". The achievement of these targets depends on national and international actions in the implementation of SDG 14, as well as other related goals and targets in the 2030 Agenda, such as SDG 13 "Take urgent action to combat climate change and its impacts", and SDG 15: "Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification, and halt and reverse land degradation and halt biodiversity loss" as it relates to the land-ocean continuum.

The SDGs 13, 14 and 15 are considered the "environmental basis" for sustainable development, key to the success of the socio-economical and development SDGs. This can only be attained through a concerted effort involving multidisciplinary approaches, deployed on national and transboundary scales, and supported by international efforts and organizations.

k www.un.org/sustainabledevelopment/oceans

The UNFCCC[l] provides the framework to attain the sustainable use of ocean resources in a changing climate. Under Article 4 of the UNFCCC, all Parties are called on to promote sustainable management, conservation, and enhancement of the oceans as sinks and reservoirs of greenhouse gases and to conserve and enhance coastal and marine ecosystems. Building on the Convention, the Paris Agreement[m] requires all Parties to put forward their best efforts through nationally-determined contributions (NDCs) and to strengthen these efforts in the years ahead, including through regular reporting. Of the NDCs submitted in 2015-2016 by Parties to the Paris Agreement, over 70% mention ocean-related issues, highlighting the measure of importance accorded to these ocean matters. The Nairobi Work Programme (NWP)[n] on impacts, vulnerability, and adaptation to climate change, is a workstream and mechanism under the Convention's mitigation topic aiming to facilitate and catalyze the development, dissemination, and use of knowledge that informs and supports adaptation policies and practices, particularly in developing countries, including least developed countries (LDCs) and small island developing States (SIDS). At its 48th session, the UNFCCC/SBSTA concluded that the future NWP should focus on emerging issues in relation to climate change, including oceans, coastal areas, and ecosystems, as well as mega deltas, coral reefs, and mangroves[o]. This decision provides new opportunities to implement actions to help coastal societies impacted by changes in the ocean carbon cycle. Furthermore, under the Cancun Adaptation Framework, Parties can formulate and implement national adaptation plans (NAPs)[p] to identify their adaptation needs and develop/implement strategies and programmes to address those needs, bearing in mind future climate change and variability and including the ocean and resulting vulnerabilities.

l United Nations Framework Convention on Climate Change (UNFCCC): unfccc.int/files/essential_background/background_publications_htmlpdf/application/pdf/conveng.pdf

m Paris Agreement and NDCs: unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement

n Nairobi Work Programme: unfccc.int/topics/adaptation-and-resilience/workstreams/nairobi-work-programme-on-impacts-vulnerability-and-adaptation-to-climate-change#eq-4

o FCCC/SBSTA/2017/7 paragraph 2.

p National Adaptation Plans: www4.unfccc.int/sites/napc/Pages/Home.aspx

Acronyms

BC	Black carbon
BGC	Biogeochemical
BGP	Biological gravitational pump
C_{anthro}	Anthropogenic carbon
CCCO	Committee on Climate Change and the Ocean
CLIVAR	Climate and Ocean – Variability, Predictability and Change project (www.clivar.org)
CMIP6	Sixth Coupled Model Intercomparison Project (www.wcrp-climate.org/wgcm-cmip/wgcm-cmip6)
CO_2	Carbon dioxide
COP	Conference of the Parties
DIC	Total dissolved inorganic carbon
DOC	Dissolved organic carbon
EBUS	Eastern boundary upwelling systems
ECV	Essential Climate Variables (gcos.wmo.int/en/essential-climate-variables)
ENSO	El Niño-Southern Oscillation
EOV	Essential Ocean Variable (www.goosocean.org/eov)
ESMs	Earth System models
EXPORTS	Export Processes in the Ocean from Remote Sensing
FOO	Framework for ocean observations
GCP	Global Carbon Project (www.globalcarbonproject.org)
GDP	Gross domestic product
GEOSECS	Geochemical Ocean Sections Study
GESAMP WG41	Group of Experts on the Scientific Aspects of Marine Environmental Protection Working Group 41
GLODAP	Global Ocean Data Analysis Project (www.glodap.info)
GO-SHIP	Global Ocean Ship-based Hydrographic Investigations Program (www.go-ship.org)
GOA-ON	Global Ocean Acidification Observing Network (www.goa-on.org)
GOOS	Global Ocean Observing System (www.goosocean.org)
GPP	Gross primary production
IC	Inorganic carbon
ICOS	Integrated Carbon Observation System (www.icos-cp.eu)
ICSU	International Council for Science (now ISC)
IMBeR	Integrated Marine Biosphere Research project (www.imber.info)
IOC	Intergovernmental Oceanographic Commission of UNESCO (ioc-unesco.org)
IOC-R	Integrated Ocean Carbon Research programme
IOCCP	International Ocean Carbon Coordinating Project (www.ioccp.org)
IPCC	Intergovernmental Panel on Climate Change (www.ipcc.ch)
ISC	International Science Council (formerly ICSU)
JGOFS	Joint Global Ocean Flux Study
LC-LP	London Convention/London Protocol, Convention on the Prevention of Marine Pollution by Dumping of Wastes and Other Matter 1972 (www.imo.org/en/OurWork/Environment/Pages/London-Convention-Protocol.aspx)
LDC	Least developed countries
LOICZ	Land-Ocean Interactions in the Coastal Zones (futureearth.org/networks/global-research-projects/future-earth-coasts-formerly-loicz)
MCP	Microbial carbon pump
MMP	Mesopelagic migrant pump
MPA	Marine protected area
NAP	National adaptation plan
NDCs	Nationally determined contributions
NGOs	Non-governmental organizations
NWP	Nairobi Work Programme
OC	Organic carbon
OECD	Organization for Economic Cooperation and Development
pCO_2	Partial pressure of CO_2
Pg C	Petagrams of carbon (1 Pg C = 10^{15} g C)
PIC	Particulate inorganic carbon
POC	Particulate organic carbon
ppm	parts per million
R_{AH}	Total system respiration (A = autotrophic, H = heterotrophic)
RDOC	Refractory dissolved organic carbon

SBSTA	UNFCCC Subsidiary Body for Scientific and Technological Advice (unfccc.int/process/bodies/subsidiary-bodies/sbsta)
SCOR	Scientific Committee on Oceanic Research
SDG	Sustainable Development Goal
SIDS	Small island developing States
SLP	Seasonal lipid pump
SOCAT	Surface Ocean CO_2 Atlas (www.socat.info)
SOCCOM	The Southern Ocean Carbon and Climate Observations and Modeling (soccom.princeton.edu)
SOCONET	Surface Ocean CO_2 reference NETwork
SOCOVV	Surface Ocean CO_2 Variability and Vulnerability
SOLAS	Surface Ocean-Lower Atmosphere Study (www.solas-int.org)
SOOP	Ships of Opportunity
SROCC	Special Report on Ocean and the Cryosphere in a Changing Climate
TA	Total alkalinity
UN	United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organization (en.unesco.org)
UNFCCC	United Nations Framework Convention on Climate Change (unfccc.int)
WMO	World Meteorological Organization (public.wmo.int/en)
WOCE/WHP	World Ocean Circulation Experiment/Hydrographic Program (www.nodc.noaa.gov/woce/wdiu/diu_summaries/whp/index.htm)

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The IOC Working Group on Integrated Ocean Carbon Research (IOC-R), established in 2018, aims at filling knowledge gaps in relation to ocean carbon by designing and promoting the implementation of the new generation of integrated ocean carbon research. The Working Group, coordinated by IOC, fosters active collaboration and synergies amongst IOC, the International Ocean Carbon Coordination Project (IOCCP), the Surface-Ocean Lower Atmosphere Study (SOLAS), the Integrated Marine Biosphere Research (IMBeR), the Global Carbon Project (GCP), the core project on Climate and Ocean Variability, Predictability and Change (CLIVAR) of the World Climate Research Programme (WCRP), and relevant national efforts on carbon research. The Initiative is open to any other relevant international efforts on ocean carbon research with a demonstrated scientific record also aims at informing policy-making on ocean and climate and climate change.

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IMBeR Integrated Marine Biosphere Research

surface ocean solas lower atmosphere study

CLIVAR

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