Deliverable D2.2

Report on data delivered to WP7 for DST construction

2025-08-27/version 1.0

UK Research and Innovation

OceanICU was funded by the European Union under grant agreement no. 101083922 and UK Research and Innovation (UKRI) under the UK government's Horizon Europe funding guarantee [grant number 10054454, 1006367, 10064020, 10059241, 10079684, 10059012, 10048179]. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Research Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

About this document

Title	D2.2: Report on data delivered to WP7 for DST construction
Work Package	WP2: State of the Ocean Carbon Cycle
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Due Date	31.08.2025, M34
Submission Date	27.08.2025
Version	**1.0**

Dissemination Level

x	PU: Public – fully open (automatically posted online)
	SEN: Sensitive – limited under the conditions of the Grant Agreement

OceanICU: Improving Carbon Understanding is a Research and Innovation action (RIA) funded by the Horizon Europe Work programme topics addressed: HORIZON-CL6-2022-CLIMATE-01-02. Start date: 01 November 2022. End date: 31 October 2027.

This work was funded by the European Union under grant agreement no. 101083922 (OceanICU) and UK Research and Innovation (UKRI) under the UK government's Horizon Europe funding guarantee [grant number 10054454, 10063673, 10064020, 10059241, 10079684, 10059012, 10048179]. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Research Executive Agency. Neither the European Union nor the granting authority can be held responsible for them.

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Key messages for the Ocean ICU stakeholders

The solubility pump is the dominant pump for anthropogenic carbon uptake. Focusing on the ocean allows us to solve the ocean carbon sink question as it is possible to fully quantify and understand the anthropogenic ocean carbon sink (as opposed to the anthropogenic land sink).

We need to continue and expand the observations, and work to ensure the high quality of observational data. Here, expansion includes both expanding networks and coverage as well as new/additional variables. Related, continuing the synthesis efforts of GLODAP is essential and it is worth noting that there is more than carbon in GLODAP (oxygen, nutrients, salinity, trace gases), and that GLODAP quantify uncertainties. Importantly, archiving data and making them available requires specialized competence and costs money. It is critical that we do not become too reliant on one entity or one country filling this crucial role.

We need to improve the models, including the modelling infrastructure (HPC, storage). Model evaluation and benchmarking is of importance and interest to the Decision Support Tool development.

Abstract

Work Package 2 aims to provide a solid foundation to our current understanding of the ocean carbon cycle, which will serve as a baseline for the other work packages. To achieve this goal, WP2 has 1) collected and distributed new observational data; 2) produced new observation-based estimates of the contemporary changes in the ocean carbon cycle; 3) refined our understanding of the underlying processes; and 4) reviewed the current state of knowledge regarding human pressures (such as mining and fishing) on the ocean carbon cycle. We have published two peer-reviewed papers, and an additional two are currently undergoing peer-review. We have also made available a new data product (currently only for the consortium, but to be

released to the general public after beta testing) and updated an existing data product with new data.

Work carried out and main results

Collection and distribution of new observational data

Collection, evaluation and distribution of observational data is crucial for establishing robust estimations of the state of the carbon cycle and its evolution. In WP2, we have contributed to this effort as detailed hereafter.

At NORCE, work is ongoing to produce the next version of the Global Ocean Data Analysis Project (GLODAPv3). The tasks have been split into “Version Control”; “Secondary Quality-Control” and “Data Product and Paper Generation”. Thus far, we have completed 100% of tasks related to “Version Control” and ~80% of tasks related to “Secondary Quality-Control”. All data holdings to be included in GLODAPv3 have been synchronized, and harmonised. Further, coordinating and contributing to an effort within the reference group, we have collected in-depth metadata for a majority of all currently included cruises, which will increase the usability of the data down the line. In terms of the secondary quality control the crossover analysis has been completed and the results were evaluated by the international GLODAP reference group at an in-person meeting in Brussels in February 2025. A new method to identify adjustments on all cruises in such a way as to minimize the overall differences in the data has been agreed upon, and the quality control method has been further refined by taking into account trends in the data and by identifying cruises where there is a breakpoint in the crossover offsets in space. A beta version of GLODAPv3 is made available to the OceanICU consortium in August 2025.

In parallel, at Heriot-Watt, a global database of coccolithophore calcite production has now been updated with new data, as well as ancillary data on environmental (temperature, nutrients, carbonate chemistry) and biological (chlorophyll, coccolithophore cell densities) parameters. This is in a mature stage of submission to PANGEA, will be accompanied by a publication in Earth System Science Data, and shared with OceanICU modellers (WP6) and DST developers (WP7). In addition, a new database of particulate inorganic carbon measurements is under development. The aim is to highlight the diversity of measurement methods and what is actually being measured (i.e., what proportion of the particulate inorganic pool they include).

New observation-based estimates of changes in the ocean carbon cycle.

Reliable estimates of the past and present changes in the ocean carbon cycle are essential for assessing the impacts of human activities on the ocean carbon cycle. WP2 has contributed to new observation-based estimates of 1) the contemporary atmospheric CO2 uptake by the ocean; 2) the global ocean inventory of dissolved inorganic carbon (DIC); and 3) the size of the carbonate pump. The following paragraphs report on these contributions.

UEXE has generated new estimates of the ocean CO2 uptake since the 1990s using three different methods. 1) New 4D reconstructions of ocean interior dissolved inorganic carbon, nutrients, and oxygen have been generated using machine learning with a “deep” neural net code, applied to GLODAPv2.2023 observations and biogeochemical Argo float data. These are the first full-depth estimates using machine learning. Then, estimates of the air-sea CO2 fluxes have been produced using the Optimal Transformation Method (OTM) and the interior reconstruction as a constraint. The OTM is a novel inverse method that simultaneously satisfies budgets of heat, freshwater and carbon in water mass coordinates while diagnosing the ocean circulation. 2) UEXE led a synthesis of global observations of the atmospheric O_2/N_2 and CO2 concentrations in the marine boundary layer, to provide a new estimate of ocean uptake by the “atmospheric potential oxygen” method. 3) UEXE performed a detailed uncertainty analysis of global ocean-atmosphere CO2 flux by the method of gas transfer applied to ocean surface pCO2 observations, including corrections for near-surface temperature deviations. These three methods provide a mutually consistent description of the evolution of the ocean sink for CO2 over recent decades. We have also begun designing the experiments, and creating the testing framework for evaluating the role and importance of including biology within the surface ocean pCO2 reconstruction method. In addition, CEA/LSCE has contributed observation-based estimates of the ocean carbon sink to the community-wide effort SOCOMv2 (Surface Ocean CO2 Mapping intercomparison initiative: Phase 2). SOCOMv2 aims at understanding the discrepancy in ocean carbon uptake estimates derived from ocean biogeochemistry general circulation models (OBGCM) and ML/statistical methods as highlighted by the Global Carbon Project. SOCOMv2 regroups a series of experiments exploring the sensitivity of surface ocean pCO2 reconstruction to (1) sparse and seasonal biased data coverage; (2) sea-surface temperature gradients; (3) structural uncertainty of predictor fields. The estimates generated cover the period from 1985 onwards and are derived from an ensemble Feed Forward Neural network approach deployed under the Copernicus Marine Services umbrella with monthly updates at low latency.

Beyond improving estimates of the ocean uptake, UiB has been working on quantifying the change in the global ocean inventory of DIC from observations. A fully objective approach is used, avoiding the need for assumptions regarding stoichiometric ratios or steady state. Unlike estimates of anthropogenic carbon change, these new DIC inventory estimates should be consistent with air-sea CO2 flux estimates and will therefore help to understand the discrepancy between model-based and observation-based ocean carbon sink estimates in the Global Carbon Budget. The observation-based estimates of the DIC inventory change is generated over the entire ocean interior from the 1980s onward by performing full depth crossover analyses on the GLODAPv2.2023 data. The statistical method consists of estimating the temporal change in DIC between all cruise pairs that have measurements within 200 km of each other.

Finally, Heriot-Watt has continued the work bringing together estimates of the size of the carbonate pump in terms of upper ocean concentrations of particulate inorganic carbon, production rates, shallow fluxes (<300 m) and deep fluxes (1-2 km). These estimates are split by contributing organisms (coccolithophores, foraminifera, pteropods, fish and others) where information is available. A draft manuscript is in preparation for submission in late 2025, highlighting the comparative roles of different organisms (e.g., pteropods dominate standing stocks while coccolithophores dominate production), and identifying key knowledge gaps (e.g., current estimates of foraminifera export are 10-times higher than estimates of their production).

Constraining process understanding

A robust understanding of the processes driving the carbon cycle is key to assess the response to perturbations. In WP2, we are working towards constraining and refining our current understanding of the processes involved by 1) improving model evaluation; 2) assessing phytoplankton dependence to temperature; 3) running Earth system models with and without ocean biology; and 4) investigating the relationship between ocean circulation and the carbon cycle with a particular focus on the biological carbon pump.

In collaboration with the ORNL, AWI further developed the International Ocean Model Benchmarking (IOMB) system to evaluate the performance of Global Carbon Budget models against state-of-the-art observations. The IOMB is an open-source model benchmarking community platform that can be used to assess the model performance. The evaluation uses statistical metrics and in-situ, remote-sensing, and reanalysis datasets to provide performance scores for the physical and biogeochemical variables of interest: upper ocean temperature, vertical temperature gradient, mixed layer depth, salinity, nutrients, chlorophyll, oxygen, total alkalinity, dissolved inorganic carbon (DIC). However, all the variables in the current version of IOMB evaluate the general performance of the ocean biogeochemistry models, not specifically the ocean uptake of anthropogenic carbon. The new advanced version of IOMB (IOMBv3-GCBv1) includes new targeted metrics such as time series analysis for AMOC, Revelle factor, Southern Ocean Salinity, Stratification Index and CFCs. The new IOMB can provide a benchmark for the current state of global carbon budget models and can highlight the areas for further model development in order to address the uncertainties in anthropogenic carbon uptake by the ocean. The new version is successfully installed at the AWI HPC system.

AWI is working on updating the phytoplankton temperature functions in the AWI's ocean circulation and biogeochemical model, FESOM-REcoM and investigating how different temperature functions affect the predicted phytoplankton community distributions and overall biomass in different future scenarios. The model set-up has been set and 4 different model versions have been run from 1850 to 2015 and continued in the future to 2100 according to two SSP scenarios. The preliminary results point to a limited effect of the change of these functions, especially moving away from the equator, meaning that the projected primary production changes in FESOM-REcoM are robust to changes in these functions. We are currently exploring the possibility of extending the model runs further into the future, to see if these functions will have an impact as temperature continues to rise past 2100.

NORCE and AWI investigated the role of marine biology in the global carbon cycle with various simulations run with emission-driven Earth system models (ESM). NORCE has run an interactive ESM, notably including a coupled land ecosystem component, with and without biology in the ocean. For each case, simulations of the preindustrial, historical and various future climates have been carried out. The analysis of these simulations show that atmospheric CO2 in a new equilibrium state after the marine biology is shut down increases by more than 50%; it is lower than expected as approximately half the carbon lost from the ocean is adsorbed by the land. Besides, this work shows that the abiotic ocean is less capable of taking up anthropogenic carbon because of the warmer climate, the absence of biological surface pCO2 deficit and a higher Revelle factor. AWI has conducted similar simulations that confirm the aforementioned results and demonstrate the long time-scales that a perturbation in the biological carbon pump would have for an impact on atmospheric CO2. Besides, these simulations show that a substantial perturbation of the biological carbon pump (e.g. +/- 25% sinking speed or remineralization rate) over the historical period would lead to a small perturbation of atmospheric CO_2 (+/- 10 ppm) on decadal time-scales.

At NORCE we have performed analyses of future projections of biologically mediated ocean carbon sequestration from CMIP6 models. Biologically mediated ocean carbon - or remineralised DIC - sequestration has been estimated from apparent oxygen utilisation (AOU) that measures the deficit of oxygen compared to saturation. Using a linear regression, we assessed the linear relationship between the spatial fields of trends in age and trends in AOU in four water-masses covering more than 90% the ocean deeper than 1000 metres. The four water-masses are defined using PO-tracer and density thresholds. The slope of the linear regression is the sensitivity of AOU changes to age changes while the intercept and the error of the linear regression gather changes in AOU that are not linearly related to changes in age such as changes in remineralisation rates. The linear relationship is evaluated on the contemporary (1972-2013) and future (2015-2099) periods, using the historical and SSP5-8.5 simulations from 5 ESMs (MPI-ESM1.2-LR, ACCESS-ESM1.5, IPSL-CM6A-LR, MIROC-ES2L and NorESM2-LM) whose required outputs were publicly available. The similar analysis was conducted with the GLODAPv2.2024 data to provide an observation baseline for the contemporary period. The results show that 1) the spatial field of age trends can explain at least 70% of the spatial field of AOU trends in the deep ocean in the contemporary and future period; 2) the observation based estimate of the sensitivity of AOU trends to age trends is consistent with the lower range of the estimates from the ESMs; 3) the linear relationship between present and future sensitivity is promising but not sufficient to constrain deep ocean remineralised DIC increase; and 4) in the ESMs most consistent with observations the age increase contribute between 57% and 81% to increase in remineralised DIC in the deep ocean. This work and the conclusions have been submitted to Biogeosciences in May 2025 and is currently under review.

At NORCE and NOC, work on a manuscript linking AMOC and carbon cycles in the North Atlantic has been completed. This manuscript, currently in revision, considers observations and models over a range of time scales, including paleo timescales, the modern ocean and future projections. In addition, work has continued to investigate the relationship between interannual variability in the AMOC and the regional biological carbon pump and the response of surface air-sea CO_2 fluxes in the subtropical North Atlantic. Analyses have focused on building more robust estimates of both the magnitude and uncertainty of temporal anomalies identified, and their connection to circulation changes over multiple timescales. To enhance reliability, we have extended our approach beyond a single surface CO2 product, instead interrogating a broader ensemble of surface carbon products to better distinguish robust signals while mitigating potential biases and errors inherent in any individual dataset. It has also allowed for a characterization of the potential uncertainty in the estimates. This framework has also been further applied to wind fields and satellite-derived estimates of net primary production, further strengthening confidence in the relationships we are evaluating and links we are making. The manuscript associated with this work is in an advanced stage of preparation.

Impact of human stressors on ocean carbon cycle

For economic reasons companies interested in **deep-sea mining** expect that they need to harvest 2-3 million tons dry weight of polymetallic nodules (PMN) per year and mining operation. In economically interesting areas, such as the Clarion-Clipperton Zone (CCZ) in the NE equatorial Pacific, where the International Seabed Authority (ISA) has issued 18 exploration contracts until today, this equates to an area of about 200 km^2 per year and mining operation. Current technology for mining of PMN will result in the removal of the entire bioturbated layer of the seafloor sediments, including its epi- and endofauna (Boetius and Haeckel, 2018). The main fraction of the removed sediments is suspended into the bottom water at the back of the vehicle and disperses by its own density-driven hydrodynamics and the bottom currents. An additional sediment plume is created in the water column by the discharge of waste material from the surface platform after cleaning of the PMN resource. The largest fraction of the suspended sediments from both these plumes will sink to the seafloor, where it will blanket the fauna, thereby impacting an additional area. First data on the behaviour of the suspended sediment plumes and resulting impacts on the marine environment are available from the MiningImpact project (https://miningimpact.geomar.de), which collected data in connection with the first industrial test of a collector vehicle in the CCZ (Gazis et al., 2025; Vink, 2022). Some additional information was produced in connection with benthic impact experiments conducted more than 25 years ago and that have been revisited during the MiningImpact project (Haffert et al., 2020; Volz et al., 2020; Vonnahme et al., 2020).

The **effect of dredging on sediment carbon burial** has been assessed by NIOZ. The extent of the main bottom trawling activities was reconstructed for more than thirty years from the 1980s (Couce et al. 2020), which enables the quantification of biomass variations before and after trawling disturbance. NSBS data provide individual organism densities at 234 sampling stations. As biomass is crucial for quantifying carbon content, we used median ash free dry mass per species, documented from the literature, and subsequently multiplied those values by individual densities to get biomass densities per square meter. Two biological traits are used to model organism response to trawling gear. Instantaneously, burying depth characterizes an organism's exposition to the gear and consequent mortality rate, while age at maturity is used to approximate the intrinsic rate of natural increase, expressing population recovery rate following disturbance. Out of 552 taxa, 304 were documented for those traits, representing 85 % of total individual density.

The knowledge of the **importance of fish for the injection and sequestration of carbon** in the oceans comes mostly from model simulations (e.g. Saba et al 2021; Pinti et al 2023). While the importance of fish for the carbon flux is relatively modest (about 20% of the total flux) their contribution to the total amount of carbon sequestered is estimated to be more than half of the total sequestration. This is because the main injection of carbon from fish happens at depth, either due to remineralization of fast-sinking fecal pellets, or from deep-living mesopelagic fish. However, the importance of fishing on the flux and the sequestration has not been estimated before

OceanICU. In OceanICU we have made an estimation for cephalopods and model runs in WP5 have assessed the impact of fishing on and off the shelf on the carbon sequestered. The details of these results and the data transferred to WP7 are detailed in D5.2.

Main results summary

- Two published papers: Tjiputra et al (2025) and Ottman et al (2024)
- Several submitted manuscripts currently in review: Couespel et al. and McDonagh et al.
- Four manuscripts in preparation.
- Preliminary version ("beta-version") of GLODAP version 3 made available.
- Updates to a global database of coccolithophore calcite production.
- Observation-based estimates of the ocean carbon sink are made available under the Copernicus Marine Services umbrella with monthly updates at low latency (https://data.marine.copernicus.eu/product/MULTIOBS_GLO_BIO_CARBON_SURFACE_MYNRT_015_008/description)

Contribution to the overall objectives and relevant (KPIs)

The main results are mapped onto their relevant KPIs in Table 1 below.

Table 1: List of KPIs in OceanICU. KPIs relevant to work described in this deliverable are shown in bold.

(1) Full description of the abundance of 10 functional groups and their biogeochemical rates across basin scales or through the mesopelagic
(2) Numerical code describing 10 new processes available for modelling by OceanICU and other CMIP Models
(3) 10 new papers submitted across consortium describing role of different biological processes in carbon uptake and storage Couespel at al. (submitted) Tjiputra et al. (2025) Ottman et al. (2024)
(4) Paper submitted on AMOC C cycle links McDonagh et al. (submitted) examines AMOC variability and its influence on North Atlantic carbon cycling, highlighting trends across paleo, observational, and modeling studies. It identifies key uncertainties in carbon pump responses to AMOC shifts and proposes targeted research strategies to refine future assessments, strengthening our understanding of AMOC-driven carbon dynamics Couespel et al. (submitted) identified linear relationships between AOU trends and age trends in the deep ocean in simulations of the contemporary and future periods from five Earth system models (ESMs). Results indicate that ESMs overestimate the sensitivity of AOU to age changes in the deep ocean, and suggest an overestimation of the BCP strengthening inferred from AOU.
(5) Paper submitted on role of Biology in C_{anth} uptake

Tjiputra et al. (2025) shows that the abiotic ocean is less capable of taking up anthropogenic carbon because of the warmer climate, the absence of biological surface pCO2 deficit and a higher Revelle factor. AWI simulations confirm the Tjiputra et al. results, and in addition demonstrate the long time-scales that a perturbation in the biological carbon pump would have for an impact on atmospheric CO2
(6) Model predictions of C cycle made using 2 OceanICU models containing 5 new parameterizations.
(7) Closure of model/data gap to better than 10%. The figure of 10% is linked to the objectives of the Global Climate Observing System (GCOS). The comparison of three independent observation-based estimates of the global carbon sink reveals a range of ~10% for 7-10 year averages, giving increased confidence in the magnitude of the sink. However, the gap with the models remains, and is estimated at ~30% for the period 2010-2017. Analysis of ocean model benchmarking is ongoing. The physical drivers such as temperature and salinity do not show much differences, except for the mixed layer depth. However, key differences are observed in Revelle factor, AMOC strength, Southern Ocean SPSS biome salinity and Southern Ocean stratification index. Models with the highest ocean sink perform worse in some of the new metrics (e.g., AMOC).
(8) Library of 10 OceanICU parameterizations New data-based and PFT-specific temperature functions in FESOM-REcoM
(9) submission of model runs from OceanICU to CMIP process if running

(10) Inclusion of OceanICU parameterizations in other ESM submissions to CMIP process
(11) 5 key knowledge gaps closed, one per year Estimated the effect of fishing on the carbon sequestration by cephalopods (Ottmann et al 2024). Although cephalopods represent less than 5% of the world's fisheries catch, the total amount of deadfall carbon extirpated by fishing of cephalopods (0.36 MtC yr-1) is about half that of large fish (0.64 MtC year-1).
(12) OceanICU papers cited in IPCC report if in project lifetime
(13) OceanICU PIs involved in IPCC if in project lifetime
(14) OceanICU papers cited in IPBES report
(15) OceanICU PIs involved in IPBES nexus and transformation and WOA III reports
(16) OceanICU papers cited in WOA report (17) OceanICU PIs involved in WOA
(18) Report of Global Ocean Carbon Science Meeting (M40) and associated Special Issue
(19) Presentation of revised Ocean Carbon uptake estimates at COP via GCP/ ICOS

(20) Ocean C in SBSTA process,
(21) Ocean C integrated into the UNFCCC stocktake alongside fossil fuel emissions.
(22) Managers in fishing industry aware of impact on C and integrating this into their planning
(23) Managers in industry aware of impact on C and including this in their forward planning
(24) Blueprint involved in IOCCP report under preparation around pCO2 monitoring
(25) Blueprint reported to 10 plus coastal countries directly
(26) Coastal countries begin to modify their observing system following IOCCP recommendations
(27) Managers in fishing and other industries, & policymakers in coastal states aware of their impact on C and integrating this into their planning
(28) Decision-makers and policy advisors briefed on tensions between long term mitigation/ enhancement options and economic growth

Impact and progress beyond state of the art

The work described in this report around the size of the ocean carbon sink based on data is extremely significant: OceanICU has a considerable effort focused on bringing multiple methods together to address this issue. It is important because it sheds light on the causes of the observed data-model mismatch, and as such it forms one of the key results of OceanICU that has the potential to reshape the way global carbon accounting is done. The work was presented at the annual science meeting in SOPOT in May 2025, and we expect manuscripts to be submitted soon. These will form the basis for an important CDE activity detailed in the CDE plan.

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