PROJECT FINAL REPORT

FULL PROJECT TITLE: Downscaling Climate and Ocean Change to Services: Thresholds and Opportunities
Project acronym: CE2COAST
Starting date: 01.09.2020
End date: 31.05.2024
Date of submission of this report: 31.07.2024
Website address: ce2coast.com

Project coordinator: Richard Bellerby, Professor and Chief Scientist, Norwegian Institute for Water Research, Bergen, Norway

Reporting period: Final report

Tel: +47 90899256

E-mail : richard.bellerby@niva.no

Publishable summary (Max. 2 pages)

Global change from anthropogenic forcing will have significant impacts at regional and coastal scales on marine systems and dependent socioeconomic systems and ecosystem services. A capacity to understand and predict these impacts on regional seas and coasts is essential for developing robust strategies for adaptation and mitigation and therefore for the EUs fulfilment of UN Sustainable Development Goals. Traditionally, projections of climate and ocean change have been delivered at global or basin scales using Earth System Models. However, there is increasing recognition that such models may not be able to provide the necessary resolution to deliver the required accuracy in climate projections. CE2COAST was thus designed to provide improved scientific understanding and more realistic/accurate local projections of ocean service pressures for regional seas and coastal areas on timescales of near-term to end-of-century climate change. Importantly, the project adopts a co-production approach, incorporating stakeholder input and local observations into climate science that can provide improved and better-focused knowledge and management of ocean pressures and services at appropriate scales in European seas, and facilitate scientific dissemination. CE2COAST compiled and analysed marine data to understand changes in ocean climate, biogeochemistry, and ecosystems. This involved creating new datasets and harvesting existing ones, all archived for long-term access. The data provided new knowledge on the state of the ocean and ongoing trends in climate indicators. In the Humboldt region, the study found that surface waters are warming faster than deeper layers, with varying salinity trends at different depths. For the Black Sea, filling gaps in satellite data enabled comparisons with models, highlighting the impact of large-scale climate patterns like the North Atlantic Oscillation. In Irish waters, sea surface temperature changes were linked to the Atlantic Multidecadal Variability index, influenced by both natural factors and human activities. Along the Norwegian coast, research focused on regions with industrial kelp harvesting, examining CO2 and temperature trends crucial for seaweed growth. Icelandic waters showed significant acidification, particularly at the surface, indicating major changes in marine chemistry over time. The North East Atlantic and Mediterranean Sea exhibited clear long-term warming trends in sea surface temperatures, with the Mediterranean warming more consistently. The project faced challenges such as short time series making it hard to identify long-term trends and the COVID-19 pandemic disrupting data collection. However, efforts resumed post-pandemic, contributing valuable insights into regional marine climate variability. The projects findings are essential for predicting future ocean changes and supporting better environmental management and decision-making, ensuring the protection of marine ecosystems. CE2COAST evaluated Earth System Models (ESMs) at regional scales to assess their performance against observations and identify the sources of model biases and uncertainties. This project analysed the physical and biogeochemical dynamics of CE2COAST regions, examining climate and ecological pressures such as temperature, nutrients, and deoxygenation trends. New capabilities for ESM evaluation were introduced through the ESMValTool, facilitating comprehensive assessments of 16 CMIP6 models across various regions. Research findings revealed significant discrepancies in upper ocean deoxygenation and advancements in alkalinity representation moving from CMIP5 to CMIP6 models. Furthermore, studies highlighted the effectiveness of regional simulations in capturing marine heatwaves compared to global models. Investigations into the relationship between ENSO and South Pacific Meridional Mode events emphasized the significance of coastal warming patterns. Statistical downscaling of CMIP6 projections underscored the critical uncertainties affecting model predictions. Emergent constraints based on observational data provided insights into areas requiring improvement in projections of CO2 fluxes, primary production, and deoxygenation. The analysis concluded that although progress had been made, systematic biases remained prevalent in ESMs, necessitating targeted assessments and continued data collection to enhance model fidelity. The project aimed to improve our understanding of coastal climate by refining predictions with Regional and Coastal Ocean Models (RCOMs). By focusing on specific regions, these models provided more detailed insights compared to global models. The Western Norwegian coast model revealed sea surface warming twice as intense as previously projected. The Humboldt region model captured more subtle coastal changes, such as a slower warming trend due to better representation of coastal upwelling. The North Sea model demonstrated faster warming in surface waters and more detailed ecosystem impacts than global projections. In the Northeast Atlantic and Mediterranean, the RCOMs showed stronger warming trends in coastal areas. The Baltic Sea and Gulf of Riga model examined the effects of wave and salinity changes on local algae distribution. The Tagus estuary model assessed impacts from temperature changes, sea level rise, and human activities on the estuary's dynamics. Lastly, the Celtic Sea model forecasted changes with improved resolution,

identifying differences in temperature and pH projections compared to global models. Overall, these RCOMs provided more accurate and localized climate projections, emphasizing the need for better regional models and closer collaboration to refine global climate forecasts. In assessing the impacts of climate change on marine environments, two main approaches were used to determine ecological thresholds and service tolerances. The first method involves evaluating overall ecosystem pressures such as ocean warming, acidification, or deoxygenation over time and across broad regions, which was applied to the North Sea, the Mediterranean Sea, and the North-East Atlantic. This method provides a broad overview of changes and enables comparisons across various environmental pressures. The second method focuses on specific species by comparing model outputs against established scientific thresholds to predict when these thresholds will be breached. This species-focused approach was used in areas like Iceland, the Celtic Sea, and the Tagus estuary, offering a detailed look at how individual species might be impacted within their specific habitats. Thresholds mark critical points where significant changes in species behaviour or ecosystem function occur. Hotspots are regions experiencing multiple growing pressures, while refugia are areas with minimal changes. In the Mediterranean Sea and North-East Atlantic, ecosystem pressures were analysed, revealing that these regions are experiencing increasing warming, acidification, and deoxygenation, with some areas seeing pressures double from near-term to mid-century. The Norwegian fjords showed increased stress on key species like sugar kelp and tangle kelp due to rising temperatures and changing salinity. In Iceland, deep-water coral species are expected to face less suitable conditions due to lower aragonite levels, though shallow waters may become marginally more hospitable. The Humboldt region will undergo significance changes in temperature and oxygen, with consequences for shellfisheries. The Celtic Sea projections indicate declining herring spawning conditions and variable impacts on shellfish and seaweed. The Gulf of Riga faces challenges with rising temperatures and salinity thresholds impacting local fish species. In the North Sea, long-term temperature increases, and deoxygenation issues are notable, while the Tagus estuary may see shifting habitats due to changing salinity levels. Stakeholder consultations highlighted the complexity of implementing legislation related to ocean services and the need for better local engagement to address concerns and improve compliance. The delivery of model outputs varied by stakeholder needs, with some preferring direct data and others seeking trend information. A unified output format remains challenging due to diverse requirements, suggesting that a user-friendly interface like Copernicus could enhance accessibility. Finally, a Continuous Professional Development (CPD) module titled “Our Changing Oceans” was developed to educate ocean managers and stakeholders about ocean modelling. This module aims to enhance understanding of ocean model construction and limitations, tailored to different stakeholder needs and incorporating specific case study data. The CE2COAST project focused on delivering new knowledge to end-users through various dissemination activities and stakeholder engagement. It aimed to facilitate the co-production of targeted science products for scientific, management, regulatory, industrial, and ecosystem service assessments. This involved organizing scientific and training workshops and contributing to reports highlighting gaps and promoting best practices. At the project's outset, diverse stakeholders were identified, and regional meetings were held in the first year. A User Needs workshop was conducted during the first annual meeting. Continuous engagement was maintained throughout the project. The CE2COAST Winter School, "Climate Change in Coastal Waters: From Science to Action," took place in Lisbon, Portugal, in February 2023. It included lectures, practical exercises, and field trips, involving eight early-stage researchers and six expert lecturers. Project communication was managed through a website and a Twitter account. All partners contributed to disseminating findings at various events and conferences, supporting EU Missions on Ocean and Waters restoration and climate change adaptation. CE2COAST produced 40 peer-reviewed papers and several policy reports. CE2COAST contributed to three major reports: The State of the Ocean Report 2024, with insights on ocean prediction and acidification; The Ocean Decade Programme report on Ocean Acidification Research for Sustainability; and The Vision 2030 Outcome document, emphasizing advanced ocean science. CE2COAST organized two capacity development activities instead of a planned international workshop. One focused on downscaling modeling (February 2024) and the other on ocean acidification, targeting young researchers in the Humboldt region. CE2COAST submitted a commitment to the UN Decade Conference and was included in the EU Mission Ocean Catalogue of Solutions: Wavelinks.eu, fostering research and innovation collaborations.

Objective on sustainable development (Max. 0,5 pages)

Through the co-design and co-evaluation to understand coastal and ecosystem service changes in the CE2COAST project, the targeting, delivery and co-evaluation of new understanding of coastal climate change has delivered knowledge addressing a wide range of sustainable development goals. Goal 1 *End poverty on all its forms*

everywhere through increasing collective knowledge of and reducing people´s vulnerability to climate change (T1.5). Goal 2 *End hunger, achieve food security and improve nutrition and promote sustainable agriculture* through sustainable growth and development in the aquaculture industry (T2.4). Goal 4 *Ensure inclusive and equitable quality education and promote lifelong learning opportunities* through training schools and open-access CPD module (T4.7, 4A, 4C). Goal 9 *Build resilient infrastructure, promote inclusive and sustainable industrialisation and foster innovation* through optimising digital and research infrastructure, and securing infrastructure and reducing associated nature loss under climate change (T9.1), and enhance scientific research and inclusive and sustainable industrialisation (T9.5). Goal 11 *Make cities and human settlements inclusive, safe, resilient and sustainable* increasing the number of human settlements intending coastal and climate smart policies and plans towards mitigation to and adaption to climate change (T11B). Goal 12 *Ensure sustainable consumption and production patterns* providing targeted knowledge with industrial partners towards achieving sustainable management of natural resources (T12.2) and promoting sustainable industrial practices (12.6). Goal 13 *Take urgent action to combat climate change and its impacts* guiding local to international strategies towards innovation in marine conservation, management and nature inclusive harvesting, increasing institutional capacity on climate change mitigation and adaptation and impact reduction (T13.1, 13.2, 13.2). Goal 14 *Conserve and sustainably use the oceans, seas and marine resources for sustainable development* increase knowledge of ecosystems and how human activity affects the oceans (T14.2), enhancing knowledge of scales and effects ocean acidification (T14.3), informing on species vulnerability for effective fishery management (T14.4), provide state-of-the-art coastal climate projections for effective conservation of coastal and marine services (T14.5), increase knowledge of, and develop research capacity of, coasts and oceans (T14A). Goal 16 *Promote peaceful and inclusive societies for sustainable development, provide access to justice for all and build effective, accountable and inclusive institutions at all levels* Knowledge provision guiding better legal protection of the sea (T16.3), promoted and informed better decision-making at many levels (T16.7), increased public access and communication of information on ocean state and change (T16.10). Goal 17 *Strengthen the means of implementation and revitalise the global partnership for sustainable development* Proven public, private, cavil society partnerships at international (T17.16), local and regional levels (T17.17)

Scientific report - Work progress and achievements during the period

Work package 1: (Max. 2 pages per work package, please clearly indicate who performed the work)

The main objectives of WP1 were to compile and analyse new targeted, fit-for-purpose (case study driven) marine observations datasets from existing datasets and new project observations of ocean climate, biogeochemistry and relevant ecological indicators. WP1 has determined the mean state, variability on a range of spatial and temporal scales and assessed trends for ocean climate, biogeochemical and ecological indicators (T1.1 to T1.4). Extracted ESM (T2.3) and new regional model simulations (T3.3, T3.5) generated by the project are archived for long-term in national infrastructures for research data (e.g. Zenodo, https://archive.sigma2.no/) assigned unique doi numbers and are publicly accessible and referenced in the DDOMP (T1.1). Using existing and new project observational data, WP1 has evaluated data quality and regional data availability for management purposes in link with WP4. WP1 has fully completed its four deliverables: D1.1 (LEGOS lead), D1.2 (LEGOS lead), D1.3 (LEGOS lead) and D1.4 (NUIG lead).

2. Significant results
We have assessed for each region of interest, mean state, variability and trend when relevant (see section 3 Challenges below):

For the **Humboldt**, we chose to examine the decadal trends from the WOA data over the following 5 depth intervals: 0-200m, 200-800m, 800-1200m, 1200-2000m associated to mean water masses of the region. The whole domain (10N°-50°S, and 110°W-70°W) was split into 6 regions: North: 10ºN-5ºS, 110ºW-70ºW, South: 5ºS-50ºS, 110ºW-70ºW, NW: 10ºN-5ºS, 110ºW-90ºW, NE: 10ºN-5ºS, 90ºW-70ºW, SW: 5ºS-50ºS , 110ºW-90ºW, and SE: 5ºS-50ºS , 90ºW-70ºW. In the latter (South East) subdomain, the trend is positive over the whole period and over the water column from 0.0059 °C/yr in the surface ocean decreasing to 0.0016 °C/yr at 2000m indicating

a faster warming in surface than in the abyss. Salinity trend is positive in the surface layers (0.00598 psu/yr) and between 800 and 1200m (0.00023 psu/yr) whereas it shows a freshening in the other layers (-2.10^{-5} psu/yr in the deep ocean). Both combined trends yield less dense waters in the intermediate and deep waters whereas in the upper ocean they may compensate each other. At Tongo Bay mooring site off Chile, the time series is only 11 years long so too short to illustrate how ENSO events may modulate the oxygen content in the waters of the Southeast Pacific Ocean.

For the **Black Sea**, reconstruction of missing data in the satellite archive records for SST and chlorophyll has been performed using the DINEOF (Data Interpolating Empirical Orthogonal Function) algorithm. Next steps will be the comparison between satellite data and model results from 1997 and 2020 (chlorophyll) and from 1982 and 2019 (SST), the spatial and temporal variability analyzes of the various variables as well as the link with the North Atlantic Oscillation (NAO) and East Atlantic-West Russia (EAWR), as they both appear to play a role, and the analysis of the bloom phenology, the depth and the amplitude of the deep chlorophyll minimum.

For the **Irish EEZ waters,** Malin Head [55.37N, 7.34W] and M3 Data Buoy [51.22N, 10.55W] and the 53°N section time series have been examined. Let's mention that at Malin Head the SST anomaly sign oscillates correspondingly with the annual average Atlantic Multidecadal Variability (AMO) index. AMO was the dominant factor in interannual variability of Irish SST records, including the Malin Head. The interannual variability attributed to the AMO, East Atlantic Pattern (EAP) and North Atlantic Oscillation (NAO) were deemed to exert a warming effect on SST in prior years (2002-2007) approximately equal to the anthropogenically induced warming. The cooling effect from the inevitable negative phase of the AMO, estimated from 2020 onwards, was anticipated to not completely counteract anthropogenic warming, leading to a net residual warming in spite of a negative SST anomaly due to the AMO.

For the **Norwegian Shelf and coastal waters**, the key study area, after discussion with our stakeholders, was the coastal region from outside Sunnhordaland to Rogaland. This region is an area of industrial kelp harvesting for which there are few coastal observations. There are records of surface carbon dioxide and temperature on the SOCAT database where a clear increasing trend is shown in surface CO_2 fugacity at a "station" south of Stavanger, but no clear trend in sea surface temperature. These parameters are key drivers of seaweed growth. To understand state and trends in the northern Kelp region, few data are available from SOCAT so the CMEMS reanalysis has been used which also shows increasing pCO_2 with increased seasonality and periods of lower undersaturation.

For **Icelandic waters**, data used are stored at the Marine and Freshwater Research Institutes database. MFRI serves as a national oceanographic database in Iceland and is also the Icelandic data center for SeaDataNet for CTD data. In the Iceland sea region, in addition to looking at temperature, salinity, nutrients, we used pH, calculated from observations of DIC, pCO_2 and Total Alkalinity from the surface layer in wintertime (J, F, M), as a timeseries presentation of OA parameters. Taking account of the mixed layer thickness in winter, the Iceland Sea data are averaged over 100 m and the Irminger Sea data over 200 m. Changes are observed in the water column, but the highest rate of change is at the surface. In the Irminger Sea in winter time (1984-2020), the rate of acidification is -0,0015 pH units yr^{-1}, estimated by least squares regression of the data (r^2=0.53). In the Iceland Sea in winter time (1985-2020), the rate of acidification is -0.0021 pH units yr^{-1}, estimated by least squares linear regression of the data (r^2=0.80).

For the North East Atlantic ocean and the Mediterranean Sea, the ESAs latest generation of CCI products have been exploited. The datasets of monthly composites were chosen due to their gapless spatial coverage and multidecadal availability Sea Surface Temperature (ESA-CCI-SST v2.2), covering the years 1982-2020 and Ocean Colour (Chlorophyll-a, ESA-CCI-OC v5), covering the years 1998-2020. Over the nearly 40 years of Sea Surface Temperature on record in the ESA-CCI-SST dataset a clear warming trend can be observed in the North East Atlantic annual mean temperature rising from approximately 17.5 °C in the early eighties to more than 18 °C in the first decades of the 21st century. These trends are clearly exceeding the interannual variability over the same period, but are rather non-linear in nature with strong increases over the last decade of the 20st century and comparatively constant conditions over the first period of the 21st century leading to an increase of approximately 0.7°C over the observed period. The Mediterranean Sea exhibits also a clear trend of warming over the almost 30 years of satellite record. Temperatures increase more regularly than over the North-East Atlantic domain and

indicate a warming of about 1° C over the observation period. Similar to the Atlantic domain, the Mediterranean basin does not show a significant trend in basin and annual mean chlorophyll-a concentration over the observation period, but is dominated by a high chlorophyll-a regime during the first decade of the 21st century compared to the periods before and after exhibiting concentrations that are 0.25 mg/m3 higher than during the surrounding period.

Finally regarding data quality and availability for management purpose for our various CE2COAST regions, it was observed that regional and local data are collected by a very wide range of organisations in each country, and stored in a variety of national and international databases, many of which are accessible to the general public online. Both collection and storage of data are supported by a wide variety of funding mechanisms, including national governments and international bodies as well as local government, NGOs, science foundations, universities and research institutes. This multitude of data sources and types, all designed for different purposes and with no online indexing facility to help an end user to search for what they need, needs to be addressed if environmental decision making is to get to the next level.

3. Challenges / difficulties encountered (where applicable)
For certain CE2COAST regions, the length of the time series falls short to be able to truly refer to "trend". We have documented rather variability on interannual time scales on data spanning 20 years and less. For certain sites, data recording can reach 60 years and thus it starts becoming meaningful to refer to trend. The COVID pandemia slowed down new observations acquisition as compared to original plans. After the COVID recovery, oceanographic cruises resumed, and consequently new observations are being acquired and ARGO floats being deployed in our CE2COAST regions.

Work package 2:

WP2 (Earth system models at regional scales) aims to provide robust assessment of ESM performance against observations and advanced understanding of the source of model biases and uncertainties, specifically at regional domains that will be downscaled in the project (WP3). Through this, WP2 elucidates large scale dynamical understanding of physics and biogeochemistry in CE2COAST regions of study, including the delivery of basin scale analysis of climate and ecological pressures of temperature, nutrients, oxygen, pH, CO_2 fluxes, and surface primary production), as well as their time of emergence. Finally, we have applied the concept of emergent constraints to better understand the systematic bias across model ESMs.

ESM evaluation tools (CMCC, NORCE). We have implemented new capabilities to evaluate the performance of CMIP ESMs in the community-based evaluation tool (ESMValTool). This new development, has been made publicly available (https://github.com/ESMValGroup/ESMValTool), allows us to efficiently perform thorough evaluation of the simulated physical and biogeochemical fields at a pre-defined regional scale in a multi-model framework. We applied this tool to produce assessment of 16 CMIP6 models four CE2COAST domains: North Atlantic, Arctic Ocean, Mediterranean Sea, and Southeast Pacific (https://zenodo.org/records/4068027). In addition to spatial climatology bias, the tool also evaluates the spatial variance, correlation, seasonal cycle, and when data is available, historical long-term trends.

Marine deoxygenation trends (NORCE, CMCC). Takano et al. (2023) analyse the upper ocean (0-700m) deoxygenation in recent decades from a suite of the CMIP6 ocean biogeochemical simulations. They examine simulated changes in the O_2 inventory and ocean heat content (OHC) over the past 5 decades across models. The models simulate spatially divergent evolution of O_2 trends over the past 5 decades. The trend in the simulated upper ocean global O_2 inventory is inline with the latest observations based on the World Ocean Database 2018. The multi-model comparison indicates that differences in background mean states due to differences in spin-up duration and equilibrium states result in substantial differences in the climate change response of O_2.

Ocean alkalinity (NORCE, CMCC). Planchat et al. (2023) track the changes from CMIP5 to CMIP6 with respect to the Earth system model (ESM) representation of alkalinity and the carbonate pump which depletes the surface ocean in alkalinity through biological production of calcium carbonate and releases it at depth through export and dissolution. They report an improvement in the representation of alkalinity in CMIP6 ESMs relative to those in CMIP5, with CMIP6 ESMs simulating lower surface alkalinity concentrations, an increased meridional surface gradient and an enhanced global vertical gradient. This improvement can be explained in part by an increase in

calcium carbon- ate ($CaCO_3$) production for some ESMs, which redistributes alkalinity at the surface and strengthens its vertical gradient in the water column. Reviewing the representation of the $CaCO_3$ cycle across CMIP5/6, they find a substantial range of parameterizations. While all biogeochemical models currently represent pelagic calcification, they do so implicitly, and they do not represent benthic calcification. In addition, most models simulate marine calcite but not aragonite. In CMIP6, certain model groups have increased the complexity of simulated $CaCO_3$ production, sinking, dissolution and sedimentation. However, this is insufficient to explain the overall improvement in the alkalinity representation, which is therefore likely a result of marine biogeochemistry model tuning or ad hoc parameterizations.

Marine heatwaves (NORCE). Pontoppidan et al. (2023) present the added value of a regional climate simulation, centered over the Caribbean, when compared to CMIP6-class global models. They show its added value with regards to temporal distribution of marine heatwaves, compared with state-of-the-art CMIP6 models. Here, global models tend to simulate too few heatwaves that last too long compared to the observation. The regional climate model agrees more favourably with the dataset, particularly in winter. While examining potential mechanisms behind the differences they find that the more realistic representation of marine heatwaves in the regional model arises from the sea surface temperatures ability to increase/decrease more quickly in the regional model than in the global model. The reason for this is two fold. Firstly, the regional model has a shallower mixed layer than the global model which results in a lower heat capacity that allows its sea surface temperatures to warm and cool more quickly. The second reason is found during days when marine heatwaves are increasing in intensity. During these days, reduced wind speeds leads to less latent heat release and a faster warming surface, more so in the regional model than in the global models.

Southeast Pacific SST (LEGOS-IRD). Dewitte et al. (2023) investigate the relationship between ENSO and the South Pacific Meridional Mode (SPMM) focusing on strong SPMM events that follows strong El Niño events. This type of events represents more than 60% of such events in the observational record and the historical simulations of the CESM Large ensemble (CESM-LE). Their analyses reveal that strong SPMM events are associated with a coastal warming off northern central Chile peaking in Austral winter resulting from the propagation of waves forced at the equator during the development of El Niño events. The time delay between the ENSO peak (Boreal winter) and this coastal warming (Austral winter) can be understood in terms of the differential contribution of the equatorially-forced propagating baroclinic waves to the warming along the coast. This contributes to the persistence of warm coastal SST anomalies off Central Chile until the Austral summer following the concurrent El Niño event. This coastal warming is favorable to the development of strong SPMM events as the South Pacific Oscillation become active during that season. The analysis of the simulations of the Coupled Intercomparison Project phases 5 and 6 (CMIP5/6) indicates that very few models realistically simulate this ENSO/SPMM relationship and associated oceanic teleconnection.

Statistical downscaling of CMIP6 (NIVA, CMCC). Kristiansen et al. (2024) assessed uncertainties in Earth System Model projections at regional scale for European Seas based on a statistically downscaled ensemble of CMIP6 projections for the main pressures of warming, acidification and deoxygenation. The analysis clearly identified the spatial distribution of relative contributions to total uncertainty from three distinct sources for mid- to long-term changes: internal variability, model uncertainty and scenario uncertainty. The study confirms the outcomes form previous studies that have indicated the increasing importance of scenario uncertainty and decreasing contribution of model uncertainty and internal variability with projection time. In addition, it provides crucial information on the regionally varying contributions of the different studies and thereby suggesting crucial focus areas for model improvements. In addition, the statistical downscaling ensemble constitutes an additional, much more challenging benchmark for dynamic downscaling exercises compared to the raw Earth System Model outputs, as it removes the large-scale biases from and adds high resolution features to the original data.

Emergent constraints of CMIP6 models (NORCE, LEGOS-IRD). We discovered several emergent constraints in CMIP6 ESMs, which then allow us to use observations to constrain the large uncertainties in their projections (air-sea CO_2 fluxes, primary production, and deoxygenation). (i) The bias in CO_2 fluxes in the Southern Ocean can be attributed to bias in the simulated water column stratification, specifically, just north of the circumpolar front. (ii) The large uncertainties in the uptake of anthropogenic CO_2 in the North Atlantic are associated with the ventilation process in ESMs, which govern the efficiency of anthropogenic carbon export from surface to deep ocean. (iii) The CO_2 fluxes in the Equatorial Pacific across ESMs depend on the background mean state of the subsurface alkalinity,

which determines the CO_2 buffering capacity. (iv) In the tropical Atlantic, the projected primary production spread in ESMs can be linked to the temperature sensitivity. (v) The projected deoxygenation in the southeastern Pacific can be constrained by the subsurface oxygen sensitivity to temperature (i.e., ENSO index).

Time of Detection. Tjiputra et al. (2023) analysed the anthropogenically-induced changes in the temperature, salinity, pH, and oxygen in the water column as projected in CMIP6 ESMs. The found that, for most variables, anthropogenic changes emerge earlier in the interior ocean than at the surface, due to the lower background variability at depth. Acidification is detectable earliest, followed by warming and oxygen changes in the subsurface tropical Atlantic. Temperature and salinity changes in the subsurface tropical and subtropical North Atlantic are shown to be early indicators for a slowdown of the Atlantic Meridional Overturning Circulation. Even under mitigated scenarios, inner ocean anthropogenic signals are projected to emerge within the next few decades. This is because they originate from existing surface changes that are now propagating into the interior. In addition to the tropical Atlantic, they call for establishment of long-term interior monitoring systems in the Southern Ocean and North Atlantic in order to elucidate how spatially heterogeneous anthropogenic signals propagate into the interior and impact marine ecosystems and biogeochemistry.

Progress summary and future recommendations. Despite years of developments, biases in ESMs persist. Many of these biases are systematic and explain the model spread in their projections. Prior to any regional downscaling, tailored assessments of ESMs based on the scientific aim of regional models are vital. The emergent constraint demonstrates numerous systematic biases in ESMs, requiring sustained data collections and observation-based process understanding. We discovered previously overlooked parameters, e.g. interior alkalinity and salinity, to be crucial for improving ESM projection fidelity. Regional models are valuable in providing insights and directions for future ESM development, need for continued collaborations.

Work package 3:

WP3. Regional ocean: downscaling past changes and climate projections (ULiege, NIVA). The main objective of WP3 was to develop and evaluate downscaling approaches for hindcasting and projecting coastal physical and biogeochemical fields using Regional and Coastal Ocean Models (RCOMs). This was achieved for a set of Case Study regions, following a coordinated protocol (T3.1) of model input preparation (informed by WP2), RCOM simulation production, and skill assessment and trend analysis using data from WP1 (T3.2-T3.5), leading to refined, validated, and stakeholder-targeted coastal climate projection data for use in WP4.

Case Study 1: West Norwegian coast and fjords, centred on Hardangerfjord region (NIVA). A coupled physical-biogeochemical model was developed for the Rogaland-Hordaland region, using a ROMS model (Shchepetkin and McWilliams, 2005) with 800m horizontal resolution (ROHO800) and a Nordic adaptation of the ERSEM biogeochemical model (Butenschon et al., 2016). Model inputs for atmospheric forcings, oceanic boundary conditions, and river sources, were bias corrected using a novel Quantile Delta Change approach that preserves the full temporal and spatial resolution of the hindcast (renalysis-based) inputs, as well as the long-term trends of the ESM forcing varying over both seasons and quantiles (paper in prep., code developed in collaboration with MI and shared among project partners). This RCOM showed significant skill improvement relative to a reanalysis-forced ocean simulation from the driving CMIP6 ESM (NorESM2), based on a comparison with in situ observational datasets collated and quality-controlled in WP1. RCOM output was further bias-corrected using spline functions of uncorrected values, and mid-century projections under SSP5-8.5 were compared with those of the driving ESM. RCOM-based climatic changes differed significantly, especially for sea surface warming that was roughly twice as strong in the RCOM as in the nearest ESM grid cells. Bias-corrected RCOM output for temperature, salinity, and aragonite saturation state was passed to WP4 for threshold analysis.

Case Study 2: Humboldt region (LEGOS-IRD).
Based on WP2 analyses, one member of the CESM Large ensemble representative of the mean was selected for dynamical downscaling, using the physico-biogeochemical model CROCO-BioEBUS with 1/12° resolution extending from 12°N to 40°S along the coast of Peru and Chile (and in a 1/36° configuration over central Chile). This RCOM was tuned and validated in hindcast mode focusing on oxygen, using observational data from WP1 (Pizarro-Koth et al., 2023; Almendra et al., 2024). To avoid inheriting strong bias in the mean equatorial circulation from the ESM, we applied a delta change approach, adding to boundary conditions of an hindcast run the ESM-derived

changes in a seasonal cycle between the present day (historical) and future (RCP8.5) climates. Projections were produced for the 2050-2100 period (time-slice). The RCOM simulated a warming trend significantly weaker than that of the global model below the mixed layer; this was attributed to its greater skill in simulating the shoreward sloping thermocline (coastal upwelling) along the coast of Peru and Chile.

Case Study 3: North Sea (ULiege). A physico-biogeochemical model of the water column was coupled with a diagenetic model of the sediment bed to simulate dynamics of North Sea ecosystem services until 2100This RCOM used ROMS, the CSTMS sediment model, the Fennel pelagic biogeochemical model, and the OmexDia diagenetic model of the sediment bed, and was coupled with the SWAN wave model and a simple bivalve model for offshore wind farms. Numerical experiments were done on a 5km grid for the hindcast period (1993-2015) and for the SSP3-7.0 future scenario until 2100 with atmospheric forcing from a meteorological model (MAR) forced by MPI-ESM1.2-HR. RCOM output was compared with ESM output for key stakeholder variables. The RCOM demonstrated not only significant improvement in spatial skill (compared with CMIP6 ESMs), but also resolved in more detail the warming in shallow coastal waters and gave significantly different long-term trends to those of the forcing ESM, including ca. 30% faster warming in North Sea surface waters for the next 40 years.

Case Study 4: Northeast Atlantic Ocean and Mediterranean Sea (CMCC). A coupled modelling system was applied to the regional European Seas to simulate physical and biogeochemical dynamics under present and future climate conditions. This RCOM comprised the ocean model NEMO and the biogeochemical model BFM, applied to a numerical domain at ~6km horizontal resolution. Simulations covered the period 1980-2050, using future scenario forcings obtained from the SSP5-8.5 simulation of CMCC-ESM2. Uncorrected RCOM output showed satisfactory skill in reproducing the main observed spatial patterns of physical and biogeochemical metrics (identified by WP2). RCOM outputs supporting the WP4 thresholds assessment (seawater surface temperature, pH, and dissolved oxygen concentration) were further improved through the removal of systematic biases. In comparison with the fields produced by CMCC-ESM2, the high-resolution bias corrected seawater temperature fields showed stronger warming by mid-century in most of the marine coastal areas.

Case Study 5: Baltic Sea and Gulf of Riga (UL). The original climatic calculations have been based on the University of Latvia (UL) set-up of the Hiromb-BOOS model implemented for the operational oceanography in the Baltic Sea and the Gulf of Riga in Latvia. Its parametrization has been empirically adapted for climatic reanalysis in the Gulf of Riga domain. The original output of the model is hourly data series. Reanalysis (1993-2021) and future projection (2015-2100) data was calculated for physical and wave parameters in the area, on a grid with horizontal spacing 0.5 nm and 15 depth layers – 2 m deep surface layer and 4 m step for deeper layers. Wave parameters were included since empirically observed as a limiting factor (in addition to salinity) for the distribution of algal species *Furcellaria lumbricalis* and *Fucus vesiculosus* in the coastal area.

Case Study 6: Tagus estuary (IST). A coupled modeling system simulated the physical and biogeochemical dynamics of the Tagus Estuary under current and future climate conditions. This RCOM used the MOHID model for the Iberian coast, coupled with a coastal model for the estuary at a 400m resolution. Numerical experiments over 50 years assessed various future scenarios, including isolated and combined forcings (worst-case scenario). Factors tested were temperature increase, sea level rise (0.5 m), and human activities like channel dredging. The Tagus River flow variation was analyzed in relation to precipitation and dam discharge, revealing that the flow is mainly controlled, with minimal impact from precipitation. Due to the complexity of predicting flow variations, a reference time series assuming a typical year was used. The RCOM outputs (seawater surface temperature and salinity) enabled WP4 evaluations of the habitat suitability index for Spartina species and the saltwater intrusion in the estuary.

Case Study 7: Celtic Sea (MI). A coupled physical-biogeochemical CROCO-PISCES modelling system of the Celtic Sea was established to forecast the physical and biogeochemical state out to 2075. The “CS1KM” Celtic Sea RCOM is nominally kilometer-scale, with 20 vertical layers sigma layers. A 29-year reference hindcast successfully captured the contemporary ocean climate, using reference boundary forcing data from the CMEMS-IBI Multiyear PHY and BGC models and ECMWF ERA5 atmospheric reanalysis. Oceanic and atmospheric forcing for climate scenarios SSP1-2.6 and SSP5-8.5 were taken from the CMIP6 ESM UKESM1-0-LL. The python script developed to apply NIVA’s Quantile Delta Change method was applied to ensure consistent characteristics between ESM forcing data and contemporary reference quality forcing data from Copernicus CMEMS and ECMWF in the overlapping

period between both sources, while maintaining the long-term trends in the ESM. The primary differences between ocean projections from the RCOM vs. those of the driving ESM were: (1) the orientation of model field gradients (N-S in ESM vs. SW-NE in RCOM); (2) different surface parameter ranges for temperature and pH, amongst others.

Progress summary and future recommendations. Output from our dynamical downscaling coastal ocean models showed significant differences and added value relative to that of CMIP6 ESMs. Not only were spatial features and levels of temporal variability better resolved, yielding better agreement with observations in model hindcasts, but also the projected long term trends departed substantially from those of the driving ESMs. These departures were especially pronounced in coastal regions, suggesting possible need for revision of coastal climate change projections based on ESM output or statistical approaches preserving trends from ESM output. The process of producing dynamical downscaling projections was however labour-intensive (relative to statistical approaches) and involved many subproblems, often regarding the bias-correction of model inputs. Future efforts would likely benefit from a closer collaboration between groups working on regional dynamical modelling, ESM development, and statistical approaches to correct and refine ESM output.

Work package 4: (Max. 2 pages per work package, please clearly indicate who performed the work)

Key Thresholds and Service tolerances

Two different approaches were used by the partners when considering thresholds and service tolerances. The first approach was to consider overall ecosystem pressure, where the downscaled model output is used to show how some generic indicator such as ocean warming, acidification or deoxygenation is changing over time, compared to its natural variability over a reference period. This is applied across large geographical locations and enables comparisons across multiple pressures and was used for the North Sea, the Mediterranean Sea and for the North-East Atlantic. The second approach was to estimate species-specific thresholds derived from the scientific literature and/or expert knowledge and to interrogate output from the downscaled models to establish when a particular threshold for a species of interest will be reached in a particular place. This approach was used for Icelandic waters, the Celtic Sea, the Gulf of Riga, the Norwegian fjords and the Tagus estuary. The combination of these approaches is powerful because it delivers knowledge for a given species in the wider context of the pressures being experienced by the ecosystem on which it depends.

Thresholds, Hotspots and Refugia

Thresholds are a value of a given parameter, e.g. temperature, at which a species or system begins to show significant changes in behaviour or operation. Hotspots can be defined as ocean regions where multiple pressures are increasing, while refugia can be defined as areas where minimal change is occurring over time.

Ecosystem pressures across the Mediterranean Sea and North-East Atlantic were investigated (CMCC) at the ecosystem level rather than focusing on individual species. The pressures evaluated were ocean warming, acidification and deoxygenation, all three of which impact all marine life. Change was defined in this context as the difference between mean states of the indicator for the present-day time slice (2011-2020) and the near-term (2021-2030) and mid-term future (2041-2050). The assumption is made that species are adapted to recent conditions, though in fact some ecosystems are already in an altered state. The most exposed areas to an increase in warming are located in the off-shelf areas of the North-East Atlantic, while in the on-shelf areas temperatures slightly decrease in the near-term. Until the middle of this century warming pressure significantly increases across the entire domain, doubling the exposure in the most affected areas. Exposure to acidification is strongest near the North-West African coast and the West of the Iberian Peninsula where exposure roughly doubles from near to mid-term changes, but pressure is present throughout the domain even in the near term. Deoxygenation roughly reflects the temperature patterns being driven mainly by the gas solubility impact of warming at the surface. Exposure levels are highest in the off-shelf areas of the North-East Atlantic, also in the North-African coast and Aegean Sea local hotspots occur. It clearly emerges that the ecosystem pressure substantially increases in the 20 years from near-term to mid-term with acidification exposure significantly higher than the other two pressures, given its comparatively low natural variability in both the Mediterranean and wider NE Atlantic. At near-term warming and deoxygenation pressures are comparatively small, but increase significantly to more than 50% of the natural variability with the Mediterranean Sea generally showing higher exposures than the North-East Atlantic.

The Norwegian fjord study (NIVA) considered key habitat-forming species sugar kelp (Saccharina latissimi) and Cuvie kelp (Laminaria hyperborea), Green urchins and cold water corals. Results indicate these will experience increased heat, ocean acidification and freshening stress in the near future (2040-2059), particularly within the fjord, with heat stress intensifying mainly in the outer fjord regions. Freshening stress also intensifies, more in the inner fjord areas near to river sources, but the increase is small relative to present day values (<10%). Tangle kelp is the more sensitive of the two species and likely to be more adversely affected.
The Icelandic study (MFRI) considered future habitat suitability for vulnerable marine ecosystem (VME) taxa using indicator species such as seapen (*Kophobelemnon sp*.) and deep-water coral (*Desmophyllum pertussum)*. Results for the 2036-2056 period indicate that habitat suitability will decrease in the deep water regions where *D. pertussum* is currently found, as pH becomes lower, but conditions in shallower waters of the Icelandic shelf will become marginally more suitable than at present.

The Humboldt system contains an extended oxygen minimum zone and a very strong connection with equatorial variability. Loss of aerobic habitat is expected as a result of decreasing oxygen content and increasing temperatures because of increasing mismatches between temperature-driven oxygen supply and demand. The increase in extreme events such as El Niño and multiple La Niña events in the future) have been shown to induce asymmetrical habitat changes that may superimpose to the long-term trend. Eastern Pacific El Niño will produce a strong warming of waters (of stronger magnitude than climate change) that will translate into a sharp increase of metabolic demand. To the contrary, the cooling associated with La Niña supports an increase of shallow aerobic habitat, beneficial for shallow species with high metabolic demand. Deeper in the water column, El Niño will favor a downward expansion of aerobic habitat whereas the weak deoxygenation associated with La Niña weakly impacts aerobic habitat boundaries. These will have important effects on the local shellfish and regional fisheries industries.

In the Celtic Sea (MI, NUIG (now UoG), representative species from 4 taxa were look at – herring, a migratory fish (*C. harengus*), shellfish (oyster, *M. gigas, O. edulis* and blue mussel, *M. edulis*), seaweed (kelp, *L. hyperborea*) and seagrass (*Z. marina*). Projections show a decreasing window each winter where temperatures will be low enough in the current spawning grounds for herring to spawn out to 2045, and no suitable days in winter 2045-2075, under both SSP 2.6 and 8.5. For shellfish, where pH is a liming factor for spat survival and adult growth, western waters of the Celtic Sea appear to remain a suitable habitat while eastern waters show declining pH. By contrast, habitat suitability for seagrass appear to increase around the coast under both future scenarios as waters warm, and CO_2 levels increase, and the same is likely for kelp, though they may be more susceptible to heat stress.

For the Gulf of Riga (LHEI), 3 key habitat forming species were considered – two seaweeds (*Fucus vesiculosus* and *Furcellaria lumbricalis*) and a shellfish (*M. edulis/trossulus*). At some locations, low salinity thresholds are already being reached for *F. lumbricalis and M. edulis,* however small increases in salinity are predicted in future. Conversely, even by 2040, predicted temperature increases at some locations in the Gulf of Riga are expected to breach the thresholds for these species to reproduce successfully, and the frequency and duration of periods with exceptionally high sea surface temperatures (> 23°C) is expected to increase from the 2040s onward.

For the North Sea region (ULiege), both the ecosystem pressure approach and thresholds for key species, sugar kelp (*Saccharina Latissima*) and blue mussel (*Mytilus edulis*), were considered. For most coastal regions the long-term trend in temperature exceeds twice its natural variability. Deoxygenation is not a primary stressor for the North Sea due to its well-mixed water, although for some deep semi-enclosed bays (e.g. Scandinavian coast) it may exceed twice its natural variability. Reduction in available nutrients is more pronounced in the Wadden Sea, where it will twice exceed their natural variability, although its estimates may have a large degree of uncertainty and will largely depend on regional agricultural policies. Based on projected temperature increases in the North Sea, the blue mussel is likely gain an additional month of optimal growth conditions.

For the Tagus estuary (IST), a key consideration was increasing salinity of water used for irrigation, while target species were defined based on their significant roles in the saltmarsh ecosystem and the associated ecosystem services. The species identified were *Spartina maritima*, *Halimione portulacoides*, and *Spartina fruticosa*. These species were selected due to their influence on productivity, biodiversity, structure, and food webs. They also contribute to sediment stability and erosion protection. All tested future scenarios indicate a rise in salinity levels

at the current irrigation water withdrawal site, potentially exceeding the threshold of 1 mg/L required for irrigation. This outcome forces farmers to consider alternative water sources or locations for water extraction, significantly impacting agricultural practices in the region. For the ecological services provided by Spartina species, all future scenarios predict changes in the Habitat Suitability Index (HSI). At the lower estuary the conditions are likely to become less favourable for Spartina species, impacting the associated ecosystem services such as sediment stabilization and erosion protection. However, in the mid estuary the conditions may improve for Spartina, enhancing its role in promoting biodiversity and sediment accretion. Overall, the spatial distribution of suitable habitats is expected to shift. The model simulations suggest that the estuary could gradually evolve into a system resembling a coastal lagoon. This transformation is particularly relevant if the Tagus River discharge decreases over time, either due to climate change impacts or increased water usage and retention upstream. Such a shift would have profound implications for the overall ecological balance and the provision of ecosystem services in the estuary.

Economic instruments and policy options in case study areas

Stakeholders were consulted in four of the case study areas in respect of (a) legislation and (b) policy instruments, that they felt were relevant to the key ocean services of interest to them, and the pressures those services are under. Stakeholders identified a wide range of Global, EU, and National legislation which impacts how they exploit and manage the key ocean services, as well as a range of financial, planning-related and infrastructure-related instruments and policies. While the legislation is complex it is nevertheless well understood by the agencies who have responsibility for it. The issue is most often with implementation. Institutional stakeholders are keen to implement legislation in general, however consultation at local level can result in rejection by the community on a 'good idea but not here' basis. This can then lead to governments emphasising the implementation as a national priority and overriding local objections, which makes the implementation of the next phase of legislation even more difficult. It seems that better consultation processes are needed to inform stakeholders, in particular at local level, about upcoming legislation, and local concerns need to be properly addressed, to reduce the legitimate fears of local stakeholders that legislation will be imposed without consideration for local needs, leading to a backlash.

Delivery of indicator products of system change responding to stakeholder requirements

Each case study had different requirements from its stakeholders in respect of what they felt was relevant information obtainable from the downscaled model output. Stakeholders were asked what they felt was the most accessible way for the data to be presented to them. This varied widely from institutional stakeholders who could handle direct model output in the form of netcdf files, to more hands on stakeholders who preferred data on trends for given parameters of interest, or who had particular requirements for seasonal information. This meant that there is no common output format for indicator products that could be used as the stakeholder requirements were so very different. It was clear however that the consultation process enabled the modellers in the early stages of model development to make changes that would give stakeholders more relevant outputs. However the output from each downscaled model has a very large digital footprint, so is not easily accessible, and this requires a 'middleman' to extract the required information. For future projects with model output, a Copernicus-style interface which stakeholders could interrogate directly would be greatly beneficial in allowing stakeholders to make full use of model outputs.

Continuous professional development (CPD) module

One of the objectives of the project was to leverage the wide knowledge base within the consortium, and the learnings from the project, to create a continuous professional development module that would be of benefit to the wider community of ocean managers and stakeholders. To this end, a CPD module was designed entitled 'Our changing oceans: Understanding and using the outputs from ocean modelling' , intended to provide learners with the knowledge and tools to understand the power and limitations of ocean models by understanding how they are constructed and what they can and cannot tell us about present and future ocean conditions. This module outline is intended to be used by project partners and shared with other institutions as the basis for a CPD module, run by their own institutions, which can be tailored to the needs of different stakeholders and ocean managers as required, using data and model output from their own case study area.

Work package 5: (Max. 2 pages per work package, please clearly indicate who performed the work)

WP5 was tasked with the delivery of key new CE2COAST knowledge to end-users through a range of dissemination activities. It was tasked with the initiation and coordination of stakeholder clusters, participating decision making. The objective was further to facilitate the co-production of relevant and targeted science products tailored for specific scientific, management, regulatory, industrial and ecosystem service applicable assessments. WP5 communicated the scientific results obtained in the other WP through a range of dissemination tools. It supported the organization of a series of scientific and training workshops and a winter school. Finally, WP5 contributed to the production of reports identifying gaps in present approaches and promoting best practices.

Stakeholder engagement and co-production strategies

For each case study regions, stakeholders of a diverse range of sectors (local and regional regulators, NGOS, industry, scientists, among others) were identified at the beginning of the project. Each partner held their regional stakeholder meeting in their respective languages during the 1st year of the project (task 5.1. Stakeholder coordination; milestone M5.1, deliverable D5.2). Toward the end of year 1, all stakeholders were invited to participate in the User Needs workshop held at the 1st project annual meeting (Task 5.2. Co-production strategies; milestone M5.2, deliverable D5.3). Communication and engagement with the different stakeholder groups were pursued throughout the whole duration of the project.

The CE2COAST Winter School "Climate Change in Coastal Waters: From Science to Action" was organised by NIVA with the support of the AIR Centre. It took place in Lisbon, Portugal hosted by Instituto Superior Técnico and AIR Centre from 13-17 February 2023. The Winter School was composed of a mix of lectures by CE2COAST partners, practical exercises, field trip and presentations from students on their case studies. The Winter School brought together eight early-stage researchers from eight different countries across three continents and six lecturers leading in their respective fields of expertise. The field trip included a visit to Núcleo de Interpretação da Duna da Cresmina (Cascais, Portugal), where a guide gave a short presentation on the dune restoration and protection project.

Communication and Dissemination

WP5 co-leads with the support of the coordination team, were responsible for the project communication. A website for the project (www.ce2coast.com) and a Twitter account (https://twitter.com/JPI_CE2COAST; 118 followers) were created at the beginning of the project (Task 5.1 Stakeholder coordination; deliverable D5.2; Task 5.3 Product for dissemination). All partners contributed to the dissemination of the project by attending or participating in events or conferences (see Valorization section). The project was actively disseminating its findings within the framework of the EU Mission: Restore Our Ocean & Waters by 2030, the EU Mission: Adaptation to Climate Change, and the All-Atlantic Ocean Research and Innovation Alliance.

The science produced within CE2COAST generated several scientific papers and contributed to different policy reports. 40 manuscripts have been published in peer-reviewed scientific journals (See Publications section). Multiple technical documents targeting policy and decision makers, as well as the scientific community, produced by the Intergovernmental Oceanographic Commission of UNESCO incorporated and were partly led by CE2COAST scientists and collaborators, benefiting from the latest science produced during the course of the project (deliverable D5.4). These reports are widely distributed at international, intergovernmental, UN events. The Intergovernmental Oceanographic Commission of UNESCO has a mandate in supporting Ocean Science and Observations, as well as its application for sustainable development and the protection of ocean health. IOC also coordinates the UN Decade of Ocean Science for Sustainable Development. Since its launch in 2021, the UN Decade of Ocean Science for Sustainable Development (the Ocean Decade) has evolved into a complex and multi-dimensional ecosystem of national, regional, and international partners and stakeholders who are undertaking Decade Actions, supporting coordination, providing in-kind or financial resources, and engaging in diverse initiatives and activities.

CE2COAST leads and authors contributed to three major reports during the project period: The State of the Ocean Report 2024, relevant topics included the new insights on ocean prediction, ocean deoxygenation and acidification; The Ocean Decade Programme: Ocean Acidification Research for Sustainability publication Ocean

Acidification Research for Sustainability - A Community Vision for the Ocean Decade, particularly the section on ocean projections, which highlights new avenues for ocean acidification projections fit for stakeholder use; and The Vision 2030 Outcome document – stressing the need for new science to advance for ocean solutions, to combat climate and ocean change. A gap analysis delivered advice and input to GOOS and IOCCP and was included in a statement of future work to the WMO.

Capacity Building
Capacity development of and disseminating knowledge about key ecosystems to the next generation of scientists, combined with stakeholder engagement are crucial to co-design science and to ensure the application of research findings. Thus, instead of organising an International workshop to present project findings, recruit partnerships and identify future research priorities (as planned in the proposal) the project organised two international capacity development activities. One with the focus on CE2COAST participating research institutions and topics mainly related to downscaling modeling in February 2024 (CE2COAST Winter School). The second introduced the stressors of ocean acidification and deoxygenation to an international community of young researchers with a regional focus on the Humboldt, one of the CE2COAST focus areas (Task 5.5 International workshops; milestone M5.4 and deliverable D5.6).

CE2COAST submitted a voluntary commitment to the UN Decade Conference (see here) (milestone M5.3), the project was inserted into the EU Mission Ocean Catalogue of Solutions: Wavelinks.eu. WaveLinks is an application that maps the research and innovation landscape of the Mission Ocean, fosters collaborations between projects and reinforces links between academia, industry and society.

Deliverables and Milestones

Deliverables (where applicable)

Deliverable Nr.	Deliverable Title	due	Actual planning	Deliverable achieved	Comments on deviation
D1.1	Data and Digital Outputs Management Plan	June 2024		June 2024	
D1.2	Data submission to international data bases	June 2024		June 2024	
D1.3	Estimates on mean state, variability and trends in CE2COAST regions established	June 2024		June 2024	
D1.4	Estimates of data quality and availability for management purposes for CE2COAST regions	June 2024		May 2024	
D2.1	Validation toolkit for the evaluation of ESM performance at regional scale	M8 (April 2021)		M8	On time.
D2.2	Report on ESMs performance and ranking at regions of interest (September 2021).	M12 (August 2021)		M13	Delayed due to scheduled maintenance of the Norwegian storage infrastructure.
D2.3	Report on relevant emergent constraints and mechanisms of propagation	M24 (August 2022)		M44 (April 2024)	Delayed due to project extension.

	across the regional systems and systematic biases				
D3.1	Set of priority CMIP6 scenarios for downscaling within the project (M5)	M5		M6	No significant delay.
D3.2	Review of current downscaling methods for RCOMs and recommendations for future protocols (e.g. for CMIP7)	M36		Cancelled.	Recent review Drenkard et al. (2021) would make this mostly redundant.
D3.3	Biascorrected inputs for RCOM hindcasts (M12) and projections (M15).	M12, M15		M16, M19	3-month delay due to unforeseen complications re: boundary conditions and atmospheric forcing.
D3.4	Assessment of bias in RCOM hindcasts (M18)	M18		M21	Delayed due to delay in inputs (D3.3).
D3.5	Bias-corrected RCOM hindcasts (M20) and projections (M24)	M20, M24		M26, M30	Delayed due to delay in inputs (D3.3) plus further discussions needed about bias correction methodology.
D3.6	Uncorrected RCOM hindcasts (M16) and projections (M22).	M16, M22		M19, M25	Delayed due to delay in inputs (D3.3).
D3.7	Skill assessment of RCOM hindcasts (M20)	M20		M23	Delayed due to delay in inputs (D3.3).
D3.8	Comparison of RCOM vs. ESM/global model hindcast skill (M26)	M26		M29	Delayed due to delay in inputs (D3.3).
D3.9	Analysis of RCOM vs. Global model trends for hindcasts (M24) and projections (M30)	M24, M30		M30, M36	Delayed due to delay in inputs (D3.3) plus further discussions needed about bias correction methodology.
D3.10	Bias-corrected, averaged/interpolated RCOM output for WP4 (hindcasts M21, projections M25).	M21, M25		M27, M31	Delayed due to delay in inputs (D3.3) plus further discussions needed about bias correction methodology.
D4.1	Maps and tables of stakeholders in each case study area and key services identified	M9 (May 2021)		M12 (Aug 2021)	Some revisions were made to case study areas as model domains mutated, plus all stakeholder meetings were not completed by M9.
D4.2	(a) Key ocean services tolerance boundaries established and assessed against past and contemporary climate drivers and assessed against climate change prognoses for near-term (e.g. 2030) and mid-term (e.g. 2050)	M27 (Nov 2022)		M34 (June 2023)	Delays in model output from WP3 (6 months) plus extra time needed for discussions on tolerance boundaries (1 month).

D4.3	Maps indicating 'hotspots' and 'refugia' for single and multiple pressures	M30 (Feb 2023)		M40 Sept 2023)	Delays in model output from WP3 and consequent delays in D4.2 (7 months) plus further discussions on map production (3 months).
D4.4	Assessment of currently available instruments and policy options in case study areas in addressing changing pressures and tolerances identified in T3.5 and T4.2	M34 (June 2023)		M41 (Jan 2024)	Variable availability of stakeholders and delays in model output from WP3 and consequent delays in D4.2.
D4.5	Indicator evaluation pressures of case study services	M34 (June 2023)		M41 (Jan 2024)	Delayed due to delays in model output from WP3 and consequent delays in D4.2 & D4.3.
D4.6	Open access 5 ECTS blended learning CPD module	M36 (Aug 2023)		M45 (May 2024)	Partly based on other project outputs so due end of project
D5.1	Inventory of participating stakeholders	M6		M10	Inventory was prepared after all stakeholder meetings were held.
D5.2	Communication strategy	M6		M15	Delayed due to slow feedback from stakeholders
D5.3	User needs catalogue	M13		M47	Deliverable on stand by due to project member leaving for maternity leave
D5.4	IOC Technical Series Publication	M36		M47	This deliverable is a listing of all the publications in which CE2COAST have contributed.
D5.5	Visualization products	M15, M34		M47	The deliverable is a listing of all the presentations in different meetings were project findings were presented.
D5.6	Workshop report in EoS	M36		M47	Instead of organising a workshop in the project organised two international capacity development activities.
D5.7	Gap Analysis Report	M36		M47	The deliverable lists documents that reports gaps identified in CE2COAST.

Milestones (where applicable)

Milestone Nr.	Milestone Title	due	actual planning	Milestone achieved	Comments on deviation
M2.1	Benchmark ESM data and related observational data for regional systems in project database	M12 (August 2021)		M12 (August 2021)	

M3.1	Workshop on downscaling protocols for RCOMs (joint with WP2)	M3		M3	On time.
M3.2	Workshop on suitable skill assessment metrics (joint with WP2)	M12		M13	1 month delay due to scheduling difficulties during/after summer holidays.
M4.1	Workshop with stakeholders establishing case study areas and key services	M3 (Nov 2021)		M12 (Aug 2021)	Variable stakeholder availability
M4.2	Workshop on key ocean service tolerance boundaries in case study areas	M12 (Aug 2021)		M13 (Sept 2021) and M25 (Sept 2022)	Considerable discussion with experts re thresholds and tolerance boundaries meant 2nd workshop needed.
M4.4	Workshop with stakeholders in case study areas to establish the range of current instruments and policy options and to explore new ones relevant to a changing climate	M3, M24		M3, M16, M24	Variable availability of stakeholders meant workshops were spread out.
M5.1	Stakeholder meeting to initiate stakeholder group	M3		M7	Instead of one meeting, each region held its own meeting. Delays due to schedule constraints.
M5.2	User needs workshop at first annual	M12		M13	Moved to annual meeting on M13
M5.3	Voluntary commitment to the UN Oceans Conference 2020 Meeting completed and reported	M35		M22	Made a commitment to UN Conference and became an approved project
M5.4	International workshop held	M34		M30, M39	Instead of organising a workshop, the project organised two international capacity development activities.

Financial Status

Name of partner	Grant budgets spent (in EUR and %)	Comments (if necessary) planning
NIVA	406645 (100)	
NORCE	272000 (100)	
IST	71957 (91)	
LHEI	97751.66 (97.8)	
UL	197633.67 (98.8)	
MI	176,316.54 (88.16)	Underspend on T&S due to COVID (~10k), and subcontracts & external services (14k) due to underspend on

		HPC as CS1KM model was cheap to run.
LEGOS IRD	162 948,95 (96.55%)	
CMCC	149.800 (100%)	

Dissemination activities in the period in question

Type (Peer-reviewed journals, Books or chapters in books)	Partners involved	Title and authors	doi (if available) or link
Peer-reviewed journals	NORCE	Bourgeois, T., N. Goris, J. Schwinger, and J. Tjiputra (2022), Stratification constrains future heat and carbon uptake in the Southern Ocean between 30°S and 55°S, *Nature Communications*, 13, 1-8.	doi:10.1038/s41467-022-27979-5
Peer-reviewed journals	NORCE, MFRI	Fransner F., F. Fröb, J. Tjiputra, N. Goris, S. K. Lauvset, I. Skjelvan, E. Jeansson, A. Omar, M. Chierici, E. Jones, A. Fransson, S. R. Ólafsdóttir, T. Johannessen, and A. Olsen (2022), Acidification of the Nordic Seas, Biogeosciences, 19, 979–1012.	doi:10.5194/bg-19-979-2022
Peer-reviewed journals	NORCE	Bertini, L. and J. Tjiputra (2022), Biogeochemical timescales of climate change onset and recovery in the North Atlantic interior under rapid atmospheric CO_2 forcing, J. Geophys. Res. Oceans, 127, 4, e2021JC017929.	doi:10.1029/2021JC017929
Peer-reviewed journals	NORCE	Vaittinada Ayar, P., L. Bopp, J. R. Christian, T. Ilyina, J. P. Krasting, R. Séférian, H. Tsujino, M. Watanabe, A. Yool, and J. Tjiputra (2022), Contrasting projections of the ENSO-driven CO_2 flux variability in the equatorial Pacific under high-warming scenario, Earth Syst. Dynam., 13, 1097–1118.	doi:10.5194/esd-13-1097-2022
Peer-reviewed journals	NORCE	Tjiputra, J. F., J. Negrel, and A. Olsen (2023), Early detection of anthropogenic climate change signals in the ocean interior, *Sci Rep* 13, 3006.	doi:10.1038/s41598-023-30159-0
Peer-reviewed journals	NORCE	Pontoppidan, M., C. De Falco, P. A. Mooney, P.A., A. Nummelin, and J. Tjiputra (2023), Added value of a regional coupled model: the case study for marine heatwaves in the Caribbean. *Clim Dyn*.	doi:10.1007/s00382-023-06758-y
Peer-reviewed journals	NORCE, CMCC	Planchat, A., L. Kwiatkowski, L. Bopp, O. Torres, J. R. Christian, M. Butenschön, T. Lovato, R. Séférian, M. A. Chamberlain, O. Aumont, M. Watanabe, A. Yamamoto, A. Yool, T. Ilyina, H. Tsujino, K. M. Krumhardt, J. Schwinger, J. Tjiputra, J. P. Dunne, and C. Stock (2023), The representation of alkalinity and the carbonate pump from CMIP5 to CMIP6 Earth system models and implications for the carbon cycle, Biogeosciences, 20, 1195–1257.	doi:10.5194/bg-20-1195-2023
Peer-reviewed journals	NORCE	Goris, N., K. Johannsen, and J. Tjiputra (2023), The emergence of the Gulf Stream and interior western boundary as key regions to constrain the future North Atlantic carbon uptake, Geosci. Model Dev., 16, 2095–2117.	doi:10.5194/gmd-16-2095-2023

Peer-reviewed journals	NORCE	Vaittinada Ayar, P., D. S. Battisti, C. Li, M. King, M. Vrac, and J. Tjiputra (2023), A regime view of ENSO flavors through clustering in CMIP6 models, Earth's Future, 11(11).	doi:10.1029/2022EF003460
Peer-reviewed journals	NORCE, CMCC	Takano, Y., T. Ilyina, J. Tjiputra, Y. A. Eddebbar, S. Berthet, L. Bopp, E. Buitenhuis, M. Butenschon, J. R. Christian, J. P. Dunne, M. Groger, H. Hayashida, J. Hieronymus, T. Koenigk, J. P. Krasting, M. C. Long, T. Lovato, H. Nakano, J. Palmieri, J. Schwinger, R. Seferian, P. Suntharalingam, H. Tatebe, H. Tsujino, S. Urakawa, M. Watanabe, and A. Yool (2023), Simulations of ocean deoxygenation in the historical era: insights from forced and coupled models, Frontiers Marine Science, 10:1139917.	doi:10.3389/fmars.2023.1139917
Peer-reviewed journals	NORCE	Couespel, D. and J. Tjiputra (2024), What goes in must come out: the oceanic outgassing of anthropogenic carbon, Environ. Res. Lett., 19.	doi:10.1088/1748-9326/ad16e0
Peer-reviewed journals	NORCE	Couespel, D., J. Tjiputra, K. Johannsen, P. Vaittinada Ayar, and B. Jensen (2024), Machine learning reveals regime shifts in future ocean carbon dioxide fluxes inter-annual variability, Communications Earth & Environment.	doi:10.1038/s43247-024-01257-2
Peer-reviewed journals	LEGOS-IRD	Dewitte, B., E. Concha, D. Saavedra, O. Pizarro, C. Martinez-Villalobos, D. Gushchina, M. Ramos, and A. Montecinos (2023), The ENSO-induced South Pacific Meridional Mode, Front. Ma. Sci., 4.	doi:10.3389/fclim.2022.1080978
Peer-reviewed journals	LEGOS-IRD	Parouffe, A., V. Garcon, B. Dewitte, A. Paulmier, I. Montes, C. Parada, A. Mecho, and D. Veliz (2023), Evaluating future climate change exposure of marine habitat in the SE Pacific based on metabolic constraints, Front. Mar. Sci., 9.	doi:10.3389/fmars.2022.1055875.
Peer-reviewed journals	LEGOS-IRD	Almendra, I., B. Dewitte, V. Garcon, P. Munoz, C. Parada, I. Montes, O. Duteil, A. Paulmier, O. Pizarro, M. Ramos, W. Koeve, and A. Oschlies (2024), Emergent constraint on oxygenation of upper SE Pacific oxygen minimum zone in the 21st century, Comm. Earth and Env.	https://doi.org/10.1038/s43247-024-01427-2
Peer-reviewed journals	NIVA, CMCC	Kristiansen, T., M. Butenschön, and M. A. Peck (2024), Statistically downscaled CMIP6 ocean variables for European waters, Sci. Rep., 14, 1209.	doi:10.1038/s41598-024-51160-1
Peer-reviewed journals	NIVA	Zhou, X., J. Ge, P. Wallhead, and S. Shi (2023), Changes in nutrient concentration resulting from floods and their impact on the estuary–sea continuum, J. Geophys. Res. Oceans, 128, e2022JC019327.	doi:10.1029/2022JC019327
Peer-reviewed journals	NIVA	Møller, E. F., A. Christensen, J. Larsen, K. D. Mankoff, M. H. Ribergaard, M. Sejr, P. Wallhead, and M. Maar, (2023), The sensitivity of primary productivity in Disko Bay, a coastal Arctic ecosystem, to changes in freshwater discharge and sea ice cover, Ocean Sci., 19, 403–420,	doi:10.5194/os-19-403-2023
Peer-reviewed journals	LHEI, UL	Aigars, J., Suhareva, N., Cepite-Frisfelde, D., Kokorite, I., Iital, A., Skudra, M., Viska, M. 2024. From green to brown: two decades of darkening coastal water in the Gulf of Riga, the Baltic Sea. Frontiers in Marine Science	https://doi.org/10.3389/fmars.2024.1369537
Peer-reviewed journals	ULiege	Evgeny Ivanov, Arthur Capet, Emil De Borger, Steven Degraer, Eric J. M. Delhez, Karline Soetaert, Jan Vanaverbeke and Marilaure Grégoire, 2021 Offshore Wind Farm Footprint	https://doi.org/10.3389/fmars.2021.631799

		on Organic and Mineral Particle Flux to the Bottom.. Frontiers in Marine Science.	
Peer-reviewed journals	CMCC	Elizabeth J Drenkard, Charles Stock, Andrew C Ross, Keith W Dixon, Alistair Adcroft, Michael Alexander, Venkatramani Balaji, Steven J Bograd, Momme Butenschön, Wei Cheng, Enrique Curchitser, Emanuele Di Lorenzo, Raphael Dussin, Alan C Haynie, Matthew Harrison, Albert Hermann, Anne Hollowed, Kirstin Holsman, Jason Holt, Michael G Jacox, Chan Joo Jang, Kelly A Kearney, Barbara A Muhling, Mercedes Pozo Buil, Vincent Saba, Anne Britt Sandø, Désirée Tommasi, Muyin Wang, 2021. Next-generation regional ocean projections for living marine resource management in a changing climate. ICES Journal of Marine Science	https://doi.org/10.1093/icesjms/fsab100
Peer-reviewed journals	NIVA, SKLEC	Yang A., Bellerby R.G.J., Wang Y. and Li X., 2021. Growth and Nutrient Uptake Characteristics of Heterosigma akashiwo (Raphidophyceae) under Nitrogen and Phosphorus Concentrations in the East China Sea. Water	https://doi.org/10.3390/w13223166
Peer-reviewed journals	ULiege, LEGOS-IRD, IOC	Marilaure Grégoire, Véronique Garçon, Hernan Garcia, Denise Breitburg, Kirsten Isensee, Andreas Oschlies, Maciej Telszewski, Alexander Barth, Henry C. Bittig, Jacob Carstensen, Thierry Carval, Fei Chai, Francisco Chavez, Daniel Conley, Laurent Coppola, Sean Crowe, Kim Currie, Minhan Dai, Bruno Deflandre, Boris Dewitte, Robert Diaz, Emilio Garcia-Robledo, Denis Gilbert, Alessandra Giorgetti, Ronnie Glud, Dimitri Gutierrez, Shigeki Hosoda, Masao Ishii, Gil Jacinto, Chris Langdon, Siv K. Lauvset, Lisa A. Levin, Karin E. Limburg, Hela Mehrtens, Ivonne Montes, Wajih Naqvi, Aurélien Paulmier, Benjamin Pfeil, Grant Pitcher, Sylvie Pouliquen, Nancy Rabalais, Christophe Rabouille, Virginie Recape, Michaël Roman, Kenneth Rose, Daniel Rudnick, Jodie Rummer, Catherine Schmechtig, Sunke Schmidtko, Brad Seibel, Caroline Slomp, U. Rashid Sumalia, Toste Tanhua, Virginie Thierry, Hiroshi Uchida, Rik Wanninkhof and Moriaki Yasuhara	https://doi.org/10.3389/fmars.2021.724913
Peer-reviewed journals	NIVA, SKLEC	Jing Liu, Richard G. J. Bellerby, Xiaoshuang Li and Anqiang Yang, 2022. Seasonal Variability of the Carbonate System and Air–Sea CO2 Flux in the Outer Changjiang Estuary, East China Sea. Frontiers in Marine Science	https://doi.org/10.3389/fmars.2021.765564
Peer-reviewed journals	NIVA, SKLEC	Jing Liu, Richard G. J. Bellerby, Qing Zhu, Jianzhong Ge, 2022. Estimation of sea surface pCO2 in the East China Sea using in-situ and satellite data. Estimation of sea surface pCO2 in the East China Sea using in-situ and satellite data. Estimation of sea surface pCO2 in the East China Sea using in-situ and satellite data	https://doi.org/10.1016/j.csr.2022.104879
Peer-reviewed journals	LEGOS-IRD	Alexandra Parouffe, Veronique C. Garçon, Boris Dewitte, Aurélien Paulmier, Ivonne Montes, Carolina Parada, Ariadna Mecho and David Veliz, 2023. Evaluating future climate change exposure of marine habitat in the South East Pacific based on metabolic constraints. Frontiers in Marine Science	https://doi.org/10.3389/fmars.2022.1055875

Peer-reviewed journals	NORCE	Shuang Gao, Jörg Schwinger, Jerry Tjiputra, Ingo Bethke, Jens Hartmann, Emilio Mayorga, and Christoph Heinze, 2023. Riverine impact on future projections of marine primary production and carbon uptake. Biogeosciences	https://doi.org/10.5194/bg-20-93-2023
Peer-reviewed journals	NORCE	Nadine Goris, Klaus Johannsen, & Jerry Tjiputra, 2023. The emergence of the Gulf Stream and interior western boundary as key regions to constrain the future North Atlantic carbon uptake. Geoscientific Model Development.	https://doi.org/10.5194/gmd-16-2095-2023
Peer-reviewed journals	NORCE	Filippa Fransner, Are Olsen, Marius Årthun, Francois Counillon, Jerry Tjiputra, Annette Samuelsen, & Noel Keenlyside. 2023. Phytoplankton abundance in the Barents Sea is predictable up to five years in advance. Communication earth & environment	https://doi.org/10.1038/s43247-023-00791-9
Peer-reviewed journals	LEGOS-IRD	Matias Pizarro Koch, Oscar Pizarro, Boris Dewitte, Ivonne Montes, Aurélien Paulmier, Veronique Camille Garcon,Hector Hito Sepulveda, Andrea Corredor Acosta, Catalina Aguirre, 2023. On the interpretation of changes in the subtropical Oxygen Minimum Zone volume off Chile during two La Niña events (2001 and 2007). Frontiers in Marine Science	https://DOI: 10.3389/fmars.2023.1155932
Peer-reviewed journals	NORCE	Alban Planchat, Lester Kwiatkowski, Laurent Bopp, Olivier Torres, James R. Christian,Momme Butenschön, Tomas Lovato, Roland Séférian, Matthew A. Chamberlain, Olivier Aumont, Michio Watanabe, Akitomo Yamamoto, Andrew Yool, Tatiana Ilyina, Hiroyuki Tsujino, Kristen M. Krumhardt, Jörg Schwinger,Jerry Tjiputra, John P. Dunne, and Charles Stock. 2023. The representation of alkalinity and the carbonate pump from CMIP5 to CMIP6 Earth system models and implications for the carbon cycle. Biogeosciences	https://doi.org/10.5194/bg-20-1195-2023, 2023
Peer-reviewed policy report	LEGOS-IRD, IOC	Véronique Garçon, Martin Hernandez Ayon, Sam Dupont , Kirsten Isensee , Kim Currie, Stephen Widdicombe , Maciej Telszewski, Jan Newton, Alexis Valauri-Orton,Richard Feely, Benjamin Pfeil , Jessie Turner, Sophie Seeyave, Libby Jewett, Andrew Dickson, Mark Venus, Burke Hales, 2024. OUTCOME #3 Co-design and implement observation strategies, Ocean Acidification Research for Sustainability (OARS). Ocean Acidification Research for Sustainability – A Community Vision for the Ocean Decade. IOC-UNESCO. (IOC Technical Series, 185.) Paris, UNESCO. (pp 27-37).	https://doi.org/10.25607/YPE3-0H04
Peer-reviewed journals	LEGOS-IRD	Zouhair Lachkar, M. Cornejo ;Ottone, A. Singh, J. Arístegui, B. Dewitte, S. Fawcett, V. Garcon, E. Lovecchio, V. Molina, and P. Vinayachandran. 2024. Biogeochemistry of greenhouse gases in boundary upwelling systems: processes and sensitivity to global change. Elementa: Science of the Anthropocene	https://doi.org/10.1525/elementa.2023.00088
Peer-reviewed journals	ULiege	Grégoire, M., Alvera-Azcaráte, A., Buga, L., Capet, A., Constantin, S., D'ortenzio, F., Doxaran, D., Faugeras, Y., Garcia-Espriu, A., Golumbeanu, M. and González-Haro, C. 2023. Monitoring Black Sea environmental changes from space: New products for altimetry, ocean colour and salinity.	https://doi.org/10.3389/fmars.2022.998970

		Potentialities and requirements for a dedicated *in-situ* observing system. Frontiers in Marine Science	
Peer-reviewed journals	NORCE	Pradeebane Vaittinada Ayar, David S. Battisti, Camille Li, Martin King, Mathieu Vrac, Jerry Tjiputra. 2023. A Regime View of ENSO Flavors Through Clustering in CMIP6 Models. Earth's Future	https://doi.org/10.1029/2022EF003460
Peer-reviewed journals	NIVA, SKLEC	Zhou, Jie; Zheng, Yanling; Hou, Lijun; An, Zhirui; Chen, Feiyang; Liu, Bolin; Wu, Li; Qi, Lin; Dong, Hongpo; Han, Ping; Yin, Guoyu; Liang, Xia; Yang, Yi; Li, Xiaofei; Gao, Dengzhou; Li, Ye; Liu, Zhanfei; Bellerby, Richard; Liu, Min. 2023. Effects of acidification on nitrification and associated nitrous oxide emission in estuarine and coastal waters. Nature Communications	https://doi.org/10.1038/s41467-023-37104-9
Peer-reviewed journals	NIVA, SKLEC	Song, Shuzhen; Bellerby, Richard; Wang, Zhaohui Aleck; Wurgaft, Eyal; Li, Daoji, 2023. Organic Alkalinity as an Important Constituent of Total Alkalinity and the Buffering System in River-To-Coast Transition Zones. Journal of Geophysical Research (JGR): Oceans	https://doi.org/10.1029/2022JC019270
Peer-reviewed journals	NIVA, SKLEC	Song, Shuzhen; Bellerby, Richard; Liu, Jing; Guo, Wenyun; Yu, PeiSong; Ge, Jianzhong; Li, Daoji. 2023. Impacts of an extreme Changjiang flood on variations in carbon cycle components in the Changjiang Estuary and adjacent East China sea. Continental Shelf Research	https://doi.org/10.1016/j.csr.2023.105137
Peer-reviewed journals	NIVA, SKLEC	Liu, Jing; Bellerby, Richard; Zhu, Qing; Ge, Jianzhong. 2023. Estimating Sea Surface Salinity in the East China Sea Using Satellite Remote Sensing and Machine Learning. Earth and Space Science	https://doi.org/10.1029/2023EA003230
Peer-reviewed journals	NIVA, SKLEC	Fu, Yutao; Bellerby, Richard; Ji, Hongyu; Chen, Shenliang; Fan, Yaoshen; Li, Peng. 2023. Impacts of Riverine Floods on Morphodynamics in the Yellow River Delta. Water	https://doi.org/10.3390/w15081568

Valorization:

Conferences:

CE2COAST gave 49 international presentations at conferences including COP26, Artic Council, Ocean acidification week, EGU, ICES, Ocean Sciences, ECCWO5, Baltic Earth Day, Particles Day, Environ 2023, ICED 23, EuroGOOS, Unihak cross border, APEC Sustainable Cities symposium, Monaco Ocean Week, UN decade conference, ASLO, ECSA53, Ocean in a high Co2 World, Norkyst working group, Blue Carbon International Science working group, UN Decade megadelta, UN Ditto summit, 8th WMO Impact workshop, Ocean Acidification for sustainability, AMOC, BOOS, Climate Change in coastal waters, Ocean Predict24, World ocean deoxygenation day, EU Mission days

Social media:

- Twitter: @JPI_CE2COAST
- Website: https://www.ce2coast.com/

Online events:

- TEDx Event was organized in Toulouse, France, by the Toulouse Business School and partner LEGOS-IRD (V. Garçon, WP1 co-leader) gave a presentation on: "Let's the ocean breathe again", https://www.youtube.com/watch?v=8A4LVIxu374
- Presentation of Ce2Coast hindcast and climatic projection for Gulf of Riga at Latvian Forum for Marine Bioeconomics, 15-Jun-2021, online event
- The online workshop "Desenvolve 21 - International Workshop for the Integrated Development of Sustainable Technologies in Energy, Oceans and Health" held 28-30 June 2021 through AIR Centre

mentioned CE2COAST within the presentation "Sustainable Aquaculture for Food Security and Ocean Conservation"

- CE2COAST included during the WCRP Climate Research Forum for South America 8-9 September 2021 by key collaborator of the project CEAZA
- Presentation of Ce2Coast hindcast for Gulf of Riga at International Scientific Conference of the University of Latvia, 28-01-2022, online event, DOI: 10.22364/luszk.80.mmre.ab
- Networking Friday with CE2COAST webinar and YouTube live stream hosted by AIR Centre 18 February 2022:
    - An introduction to coastal climate change, Richard Bellerby, NIVA, Norway
    - Sensitivity of South Eastern Pacific Oxygen Minimum Zone to climate change constrained by ENSO-induced oxycline variability, Véronique Garçon, LEGOS, France
    - Building capacity for modelling the marine environment in European Seas under climate change, Momme Butenschön, CMCC, Italy
    - Scientists v. Stakeholders: the co-production conundrum, Kirsten Isensee, IOC-UNESCO and Rachel Cave, NUI Galway, Ireland

Impact (Max. 2 pages)

Contributions to regulations, policies and management practices

CE2COAST contributed to three major reports informing science policy The State of the Ocean Report 2024, relevant topics included the new insights on ocean prediction, ocean deoxygenation and acidification; The Ocean Decade Programme: Ocean Acidification Research for Sustainability publication Ocean Acidification Research for Sustainability - A Community Vision for the Ocean Decade, particularly the section on ocean projections, which highlights new avenues for ocean acidification projections fit for stakeholder use; and The Vision 2030 Outcome document – stressing the need for new science to advance for ocean solutions, to combat climate and ocean change. A gap analysis delivered advice and input to GOOS and IOCCP and was included in a statement of future work to the WMO. With representation at local and national levels by government and environmental agencies at case study stakeholder meetings, CE2COAST approach and scientific advances in coastal climate change is now being discussed to be implemented into observation, conservation and management policies Europe-wide. With tight collaboration with EU Mission projects and presentations at several Mission meetings, conferences, investment and stakeholder and actor meetings, CE2COAST science has positioned our outcomes into future policy development and research funding directions.

Research assistants connected to the project:

- Aedin McAleer, NUI Galway (NUIG), Ireland – Funded full time during the month of October 2021, then 50% since 01 November 2021

Scientific data programmers connected to the project:

- Jean Negrel, NORCE, Norway/Global, Caribbean, Equatorial Pacific, Nordic Seas – Direct funding

PhD students connected to the project:

- Julia Ruiz-Girona, LEGOS-IRD, France/Humboldt region – Funded full time by CE2COAST
- Jing Liu. East China Normal University, China – Externally funded collaborative partner
- Jie Liu, University of Bergen – Externally funded collaborative partner

Postdocs connected to the project:

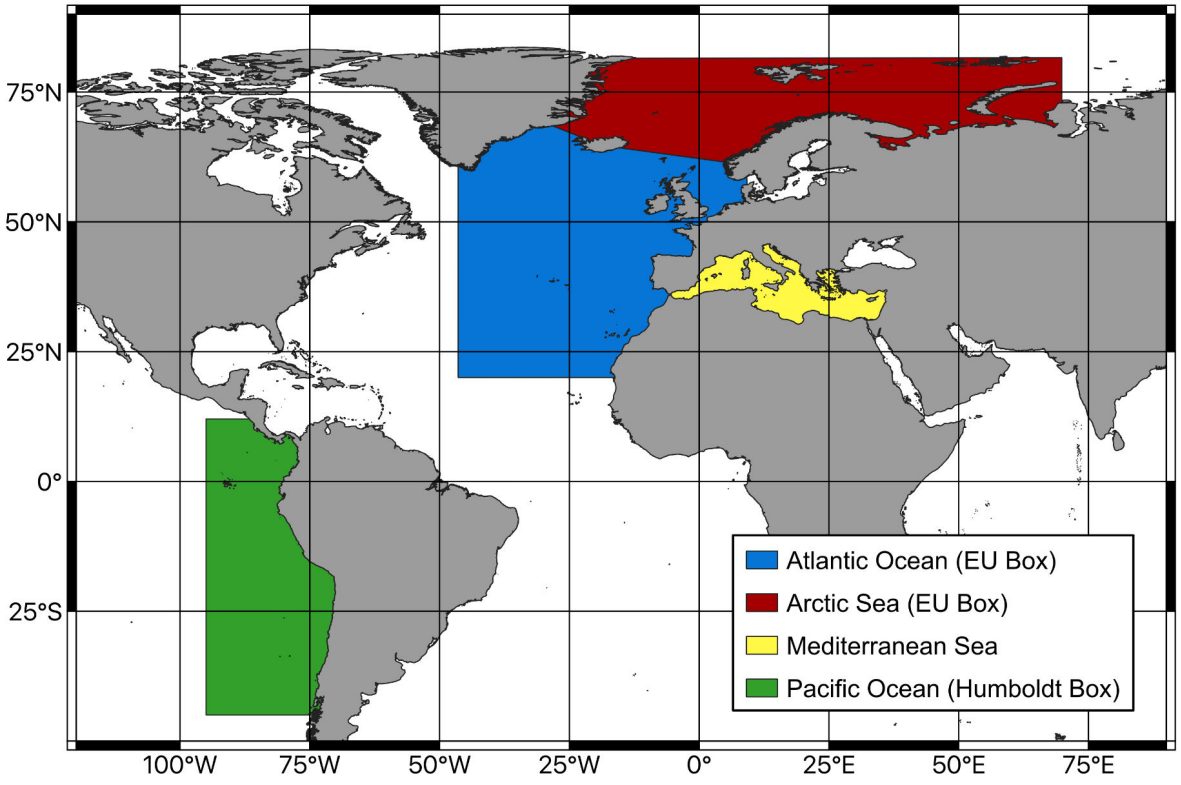
- Pradeebane Vaittinada Ayar, NORCE, Norway/Global, Caribbean, Equatorial Pacific, Nordic Seas – Direct funding
- Damien Couespel, NORCE, Norway/Global, Caribbean, Equatorial Pacific, Nordic Seas – Direct funding
- Marie Pontoppidan, NORCE, Norway/Global, Caribbean, Equatorial Pacific, Nordic Seas – No direct funding
- Chiara DeFalco, NORCE, Norway/Global, Caribbean, Equatorial Pacific, Nordic Seas – No direct funding
- Janina Buescher, NUI Galway (NUIG), Ireland – Funded full time by CE2COAST since 01 October 2021
- Shuzhen Song, NIVA/East China Normal University, China – Externally funded collaborative partner

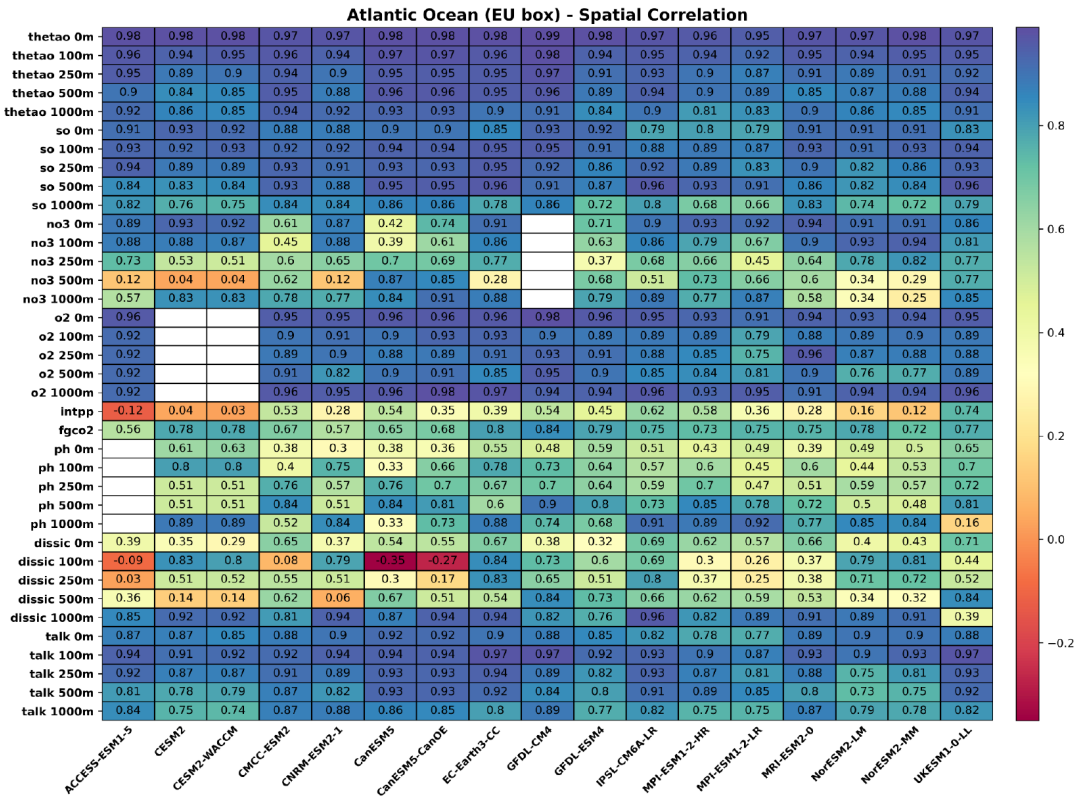
Interlinkages with other JPI Oceans and/or JPI Climate projects:
Other JPI projects attended the 1st annual meeting and presented overviews of their projects. Synergies and expressions of collaboration were agreed. Joint presentations and discussions were held in Brussels in 2024 at JPI Offices.

Results

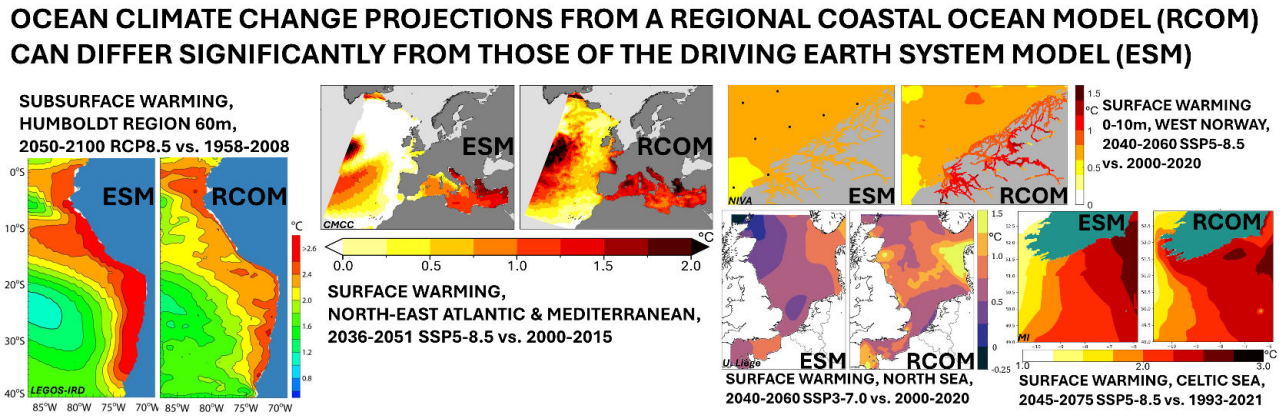
Valorisation results 1. An evaluation of Earth System Model skill in representing regional and depth-dependant ocean and coastal state

An evaluation of CMIP6 ESMs was performed over four large marine regions (Atlantic Ocean, Arctic Ocean, Mediterranean and the Humboldt Box of the Pacific ocean) and which allows to include all the key areas of CE2COAST regional downscaling applications and to ensure an adequate data coverage using coarse global scale data. ESMs data were systematically evaluated against observational datasets using the ESMValTool community diagnostic framework, developed by the CE2COAST project. Each marine region is addressed by considering the comparison of the available ESMs historical data with gridded observational datasets for the set of physical and biogeochemical variables. In the example, for the Atlantic Ocean, most ESMs are able to capture the spatial variability of temperature and salinity quite well. The correlation is generally high at the surface and noticeably low at 1000m depth. The study illustrated that the ESMs' had weaknesses in simulating the high productive coastal regions, while in the open ocean, the observed high productivity regions are well reproduced, and thus strongly supported the CE2COAST objectives of downscaling to regional and local levels.



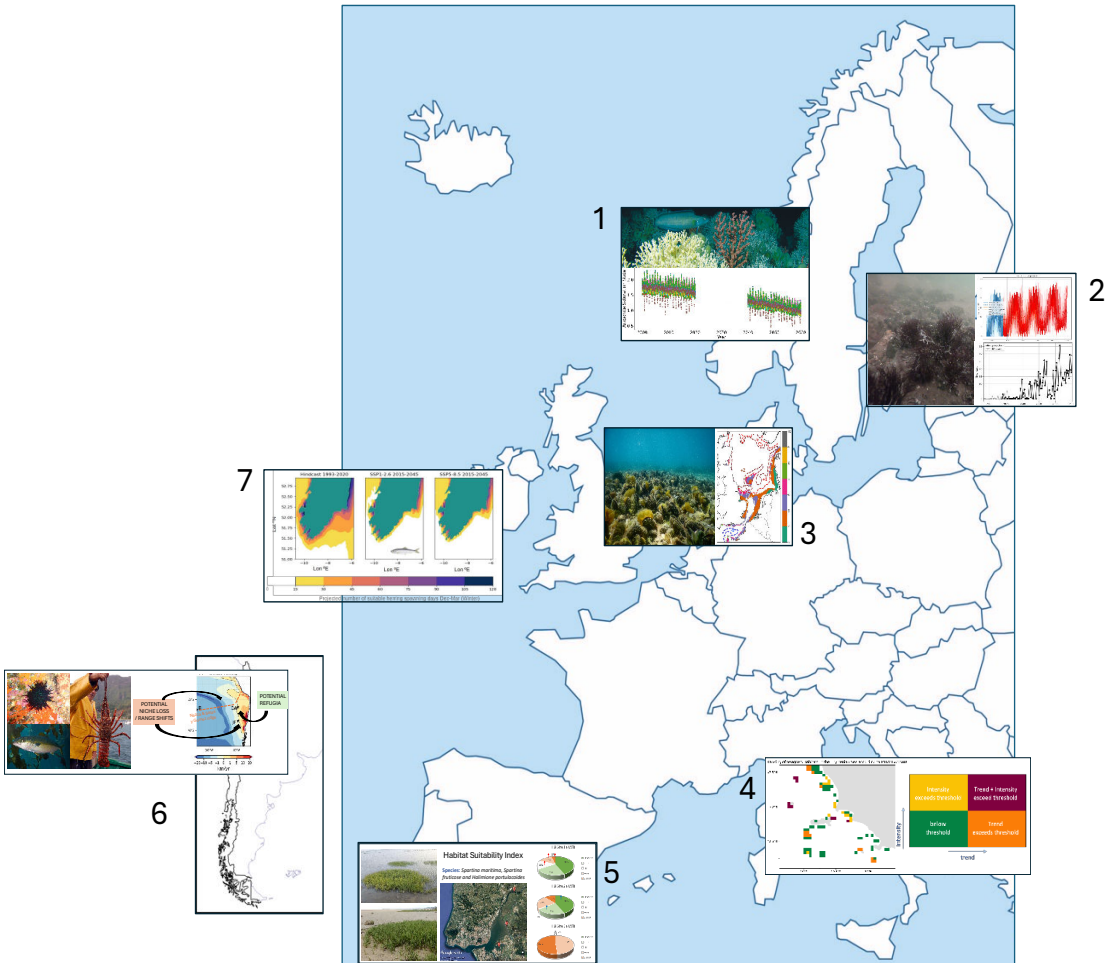

Atlantic Ocean (EU box) - Spatial Correlation
thetao 0m 0.98 0.98 0.98 0.97 0.97 0.98 0.98 0.98 0.99 0.98 0.97 0.96 0.95 0.97 0.97 0.98 0.97
thetao 100m 0.96 0.94 0.95 0.96 0.94 0.97 0.97 0.96 0.98 0.94 0.95 0.94 0.92 0.95 0.94 0.95 0.95
thetao 250m 0.95 0.89 0.9 0.94 0.9 0.95 0.95 0.95 0.97 0.91 0.93 0.9 0.87 0.91 0.89 0.91 0.92
thetao 500m 0.9 0.84 0.85 0.95 0.88 0.96 0.96 0.95 0.96 0.89 0.94 0.9 0.89 0.85 0.87 0.88 0.94
thetao 1000m 0.92 0.86 0.85 0.94 0.92 0.93 0.93 0.9 0.91 0.84 0.9 0.81 0.83 0.9 0.86 0.85 0.91
so 0m 0.91 0.93 0.92 0.88 0.88 0.9 0.9 0.85 0.93 0.92 0.79 0.8 0.79 0.91 0.91 0.91 0.83
so 100m 0.93 0.92 0.93 0.92 0.92 0.94 0.94 0.95 0.95 0.91 0.88 0.89 0.87 0.93 0.91 0.93 0.94
so 250m 0.94 0.89 0.89 0.93 0.91 0.93 0.93 0.95 0.92 0.86 0.92 0.89 0.83 0.9 0.82 0.86 0.93
so 500m 0.84 0.83 0.84 0.93 0.88 0.95 0.95 0.96 0.91 0.87 0.96 0.93 0.91 0.86 0.82 0.84 0.96
so 1000m 0.82 0.76 0.75 0.84 0.84 0.86 0.86 0.78 0.86 0.72 0.8 0.68 0.66 0.83 0.74 0.72 0.79
no3 0m 0.89 0.93 0.92 0.61 0.87 0.42 0.74 0.91 0.71 0.9 0.93 0.92 0.94 0.91 0.91 0.86
no3 100m 0.88 0.88 0.87 0.45 0.88 0.39 0.61 0.86 0.63 0.86 0.79 0.67 0.9 0.93 0.94 0.81
no3 250m 0.73 0.53 0.51 0.6 0.65 0.7 0.69 0.77 0.37 0.68 0.66 0.45 0.64 0.78 0.82 0.77
no3 500m 0.12 0.04 0.04 0.62 0.12 0.87 0.85 0.28 0.68 0.51 0.73 0.66 0.6 0.34 0.29 0.77
no3 1000m 0.57 0.83 0.83 0.78 0.77 0.84 0.91 0.88 0.79 0.89 0.77 0.87 0.58 0.34 0.25 0.85
o2 0m 0.96 0.95 0.95 0.96 0.96 0.96 0.98 0.96 0.95 0.93 0.91 0.94 0.93 0.94 0.95
o2 100m 0.92 0.9 0.91 0.9 0.93 0.93 0.9 0.89 0.89 0.89 0.79 0.88 0.89 0.9 0.89
o2 250m 0.92 0.89 0.9 0.88 0.89 0.91 0.93 0.91 0.88 0.85 0.75 0.96 0.87 0.88 0.88
o2 500m 0.92 0.91 0.82 0.9 0.91 0.85 0.95 0.9 0.85 0.84 0.81 0.9 0.76 0.77 0.89
o2 1000m 0.92 0.96 0.95 0.96 0.98 0.97 0.94 0.94 0.96 0.93 0.95 0.91 0.94 0.94 0.96
intpp -0.12 0.04 0.03 0.53 0.28 0.54 0.35 0.39 0.54 0.45 0.62 0.58 0.36 0.28 0.16 0.12 0.74
fgco2 0.56 0.78 0.78 0.67 0.57 0.65 0.68 0.8 0.84 0.79 0.75 0.73 0.75 0.75 0.78 0.72 0.77
ph 0m 0.61 0.63 0.38 0.3 0.38 0.36 0.55 0.48 0.59 0.51 0.43 0.49 0.39 0.49 0.5 0.65
ph 100m 0.8 0.8 0.4 0.75 0.33 0.66 0.78 0.73 0.64 0.57 0.6 0.45 0.6 0.44 0.53 0.7
ph 250m 0.51 0.51 0.76 0.57 0.76 0.7 0.67 0.7 0.64 0.59 0.7 0.47 0.51 0.59 0.57 0.72
ph 500m 0.51 0.51 0.84 0.51 0.84 0.81 0.6 0.9 0.8 0.73 0.85 0.78 0.72 0.5 0.48 0.81
ph 1000m 0.89 0.89 0.52 0.84 0.33 0.73 0.88 0.74 0.68 0.91 0.89 0.92 0.77 0.85 0.84 0.16
dissic 0m 0.39 0.35 0.29 0.65 0.37 0.54 0.55 0.67 0.38 0.32 0.69 0.62 0.57 0.66 0.4 0.43 0.71
dissic 100m -0.09 0.83 0.8 0.08 0.79 -0.35 -0.27 0.84 0.73 0.6 0.69 0.3 0.26 0.37 0.79 0.81 0.44
dissic 250m 0.03 0.51 0.52 0.55 0.51 0.3 0.17 0.83 0.65 0.51 0.8 0.37 0.25 0.38 0.71 0.72 0.52
dissic 500m 0.36 0.14 0.14 0.62 0.06 0.67 0.51 0.54 0.84 0.73 0.66 0.62 0.59 0.53 0.34 0.32 0.84
dissic 1000m 0.85 0.92 0.92 0.81 0.94 0.87 0.94 0.94 0.82 0.76 0.96 0.82 0.89 0.91 0.89 0.91 0.39
talk 0m 0.87 0.87 0.85 0.88 0.9 0.92 0.92 0.9 0.88 0.85 0.82 0.78 0.77 0.89 0.9 0.9 0.88
talk 100m 0.94 0.91 0.92 0.92 0.94 0.94 0.94 0.97 0.97 0.92 0.93 0.9 0.87 0.93 0.9 0.93 0.97
talk 250m 0.92 0.87 0.87 0.91 0.89 0.93 0.93 0.94 0.89 0.82 0.93 0.87 0.81 0.88 0.75 0.81 0.93
talk 500m 0.81 0.78 0.79 0.87 0.82 0.93 0.93 0.92 0.84 0.8 0.91 0.89 0.85 0.8 0.73 0.75 0.92
talk 1000m 0.84 0.75 0.74 0.87 0.88 0.86 0.85 0.8 0.89 0.77 0.82 0.75 0.75 0.87 0.79 0.78 0.82
ACCESS-ESM1-5
CESM2
CESM2-WACCM
CMCC-ESM2
CNRM-ESM2-1
CanESM5
CanESM5-CanOE
EC-Earth3-CC
GFDL-CM4
GFDL-ESM4
IPSL-CM6A-LR
MPI-ESM1-2-HR
MPI-ESM1-2-LR
MRI-ESM2-0
NorESM2-LM
NorESM2-MM
UKESM1-0-LL
0.8
0.6
0.4
0.2
0.0
−0.2

Valorisation results 2



Comparison of mid-century ocean warming projections from dynamical downscaling Regional Coastal Ocean Models (RCOMs) vs. those of the Earth System Models (ESMs) used to drive the RCOM projections. Leftmost subfigure shows subsurface warming at 60 m in the Humboldt region between 1958-2008 and 2050-2100 under scenario RCP8.5, from CESM1 (ESM, left) and from CROCO-BioEBUS 1/12° (RCOM, right). Second from left subfigure shows sea surface warming in the Mediterranean and North-East Atlantic regions between 2000-2015 and 2036-2051 under scenario SSP5-8.5, from the CMCC-ESM2 (ESM, left) and from NEMO-BFM 6km (RCOM, right). Top right subfigure shows sea surface warming (0-10 m average) in the western Norwegian coast and fjords, considering annual maximum monthly averages between 2000-2020 and 2040-2060 under scenario SSP5-8.5, from NorESM2 (ESM, left) and from ROMS-ERSEM 800m (RCOM, right). Bottom second from right subfigure shows surface warming in the North Sea between 2000-2020 and 2040-2050 under scenario SSP3-7.0, from MPI-ESM1.2-HR (ESM, left) and from ROMS-Fennel 5km (RCOM, left). Bottom right subfigure shows surface warming in the Celtic Sea between 1993-2021 and 2045-2075 under scenario SSP5-8.5, from UKESM1-0-LL (ESM, left) and from CROCO-PISCES 1km (RCOM, right). In all subfigures, ESM output has been interpolated onto the higher-resolution RCOM grid, and in some areas extrapolated conservatively towards coastlines using nearest neighbour ESM grid cells (e.g. see black dots marking ESM grid cell centres in top right ESM subfigure). Contributing institutions are shown in bottom left corners of ESM subfigures, and include: Laboratoire d'Etudes en Géophysique et Océanographie Spatiales (LEGOS), Centro Euro-Mediterraneo sui Cambiamenti Climatici (CMCC), Norwegian Institute for Water Research (NIVA), University of Liège (U. Liège), Marine Institute (MI).

Valorisation results 3. Habitat suitability modification under climate change for selected species across the CE2COAST regions



1. The Hardangerfjord region of Western, known for its diverse marine habitats such as kelp forests and cold-water coral reefs, is particularly vulnerable to warming, freshening and acidification under climate change. At the locations where the cold-water coral reefs were found, their aragonite saturation levels, crucial for maintaining coral habitats, are expected to drop below critical thresholds by 2040-2060 compared to the relatively stable levels observed from 2000-2020. This decline is due to ocean acidification, which threatens the habitat for key marine species in the fjord. Understanding these changes is vital for informing conservation and management strategies aimed at protecting the ecological integrity and ecosystem services of the Hardangerfjord region.
2. *Furcellaria lumbricalis* host and support fish populations in coastal waters of the Gulf of Riga, particularly Baltic sea herring (*Clupea harengus*), spawning and nursery grounds. The *F. lumbricalis*. population depth distribution are being affected by changes in light climate caused by eutrophication, alterations in land use and sub-optimal water salinity levels. Further alterations in species spatial distribution can be expected by 2040 when increases in water temperature reach species tolerance levels especially in light of prognosed increase of heatwave frequency as well as duration.
3. Depicts the annual number of optimal months for the blue mussels in the current climate (colored) and its change in the future change (dashed lines) (SSP370) defined as the number of months during which the average temperature varies between 8 – 15 °C (optimum for the blue mussels). Blue mussels are important filter feeders, naturally inhabiting the sea bottom in the shallow waters. However, with the rise of artificial structures in the North sea (such as offshore wind farms), the blue mussels extended their habitats onto the upper part of the submerged monopiles, consuming phytoplankton and excreting rapidly sinking carbon-saturated pellets, contributing therefore to the local carbon sequestration. While

optimal temperature conditions for the blue mussels will increase in area, the extent of offshore artificial structures demands an assessment of the blue mussels contribution into carbon sequestration on the regional (North Sea) scale.

4. Shows a classification of Thyrrenian Sea habitats to Marine Heatwaves in terms of mean severity per year (the integral of heatwaves days over category of the heatwave) and increasing trend over the past three decades. Purple areas are the most exposed areas being in the upper quartile in terms of both mean heatwave severity and increase of heatwave severity exposure. Yellow areas are in the upper quartile of mean severity only. Orange areas are in the upper quartile of increased trend in severity exposure. Green areas are in the lower three quartiles for both mean exposure and increased trend.
5. The Tagus estuary, Portugal's largest, spans 320 km² at high tide and supports 2.8 million people, offering crucial ecosystem services like seafood provision, agriculture support, carbon sequestration, and biodiversity maintenance. However, it faces significant challenges from human activities, including hydropower dams affecting river flow and sediment transport, urban and industrial pollution, and habitat degradation. Emerging issues like sea level rise, temperature increases, and channel dredging further threaten the estuarine ecosystem. Stakeholders identified critical concerns such as freshwater availability for irrigation and biodiversity protection. Model simulations predict increased salinity and habitat shifts, impacting agricultural practices and key species like Spartina. Habitat Suitability Index for future scenarios reveal that Spartina species will be impacted, mostly in the lower estuarine areas. Addressing these changes is essential to safeguard the estuary's ecological integrity and its capacity to provide vital ecosystem services.
6. The Humboldt system hosts the most productive system in the world and several chains of seamounts with thriving biodiversity sustaining many coastal communities. It is under pressure of ocean warming and deoxygenation which will likely accelerate in the future. Warming and deoxygenation are deleterious when tolerance thresholds are exceeded. The impacts go form the individual to the ecosystem level and consequences such as biodiversity and biomass loss are to be expected. Mobile species would likely respond by migrating whereas benthic species would simply lose their habitat.
7. Projections based on temperature threshold for spawning of Atlantic herring (*Clupea harengus* Linnaeus 1758). The Celtic Sea stock now spawns only during the Winter period (December to March) due to rising bottom water temperatures in their traditional spawning grounds in coastal waters around the south of Ireland.

Annex I: Identification of project participants/beneficiaries

(1) Richard Bellerby, Norwegian Institute for Water Research (NIVA), Norway/Arctic and North Atlantic
Philip Wallhead, Norwegian Institute for Water Research (NIVA), Norway/Arctic and North Atlantic
Trond Kristiansen, Norwegian Institute for Water Research (NIVA), Norway/Arctic and North Atlantic
Gabrielle Hairabedian, Norwegian Institute for Water Research (NIVA), Norway/Arctic and North Atlantic
Jie Liu, Norwegian Institute for Water Research (NIVA), Norway/Arctic and North Atlantic
Pipatthra Saesin, Norwegian Institute for Water Research (NIVA), Norway/Arctic and North Atlantic

(2) José Moutinho, Atlantic International Research Centre (AIR Centre), Iberian Peninsula, Portugal and Spain
Tânia Li Chen, Atlantic International Research Centre (AIR Centre), Iberian Peninsula, Portugal and Spain

(3) Momme Butenschön, CMCC, European Atlantic and Mediterranean
Tomas Lovato, CMCC, European Atlantic and Mediterranean

(4) Kirsten Isensee, IOC-UNESCO, Europe

(5) Marcos Mateus, Instituto Superior Técnico (IST), Iberian Peninsula, Portugal and Spain
Lígia Pinto, Instituto Superior Técnico (IST), Iberian Peninsula, Portugal and Spain
Ramiro Neves, Instituto Superior Técnico (IST), Iberian Peninsula, Portugal and Spain

(6) Boris Dewitte, LEGOS-IRD, France/Humboldt region

Véronique Garçon, LEGOS-IRD, France/Humboldt region
Patrick Marchesiello, LEGOS-IRD, France/Humboldt region
Julia Ruiz-Girona, LEGOS-IRD, France/Humboldt region

(7) Juris Aigars, Latvian Institute of Aquatic Ecology (LHEI), Latvia and Baltic Sea
Māris Skudra, Latvian Institute of Aquatic Ecology (LHEI), Latvia and Baltic Sea

(8) Sólveig Rósa Ólafsdóttir, Marine & Freshwater Research Institute (MFRI), Iceland
Hrönn Egilsdóttir, Marine & Freshwater Research Institute (MFRI), Iceland
Julian Burgos, Marine & Freshwater Research Institute (MFRI), Iceland
Alice Benoit-Cattin, Marine & Freshwater Research Institute (MFRI), Iceland

(9) Tomasz Dabrowski, Marine Institute (MI), Ireland
Joseph McGovern, Marine Institute (MI), Ireland

(10) Jerry Tjiputra, NORCE, Norway/Global, Caribbean, Equatorial Pacific, Nordic Seas
Jean Negrel, NORCE, Norway/Global, Caribbean, Equatorial Pacific, Nordic Seas
Pradeebane Vaittinada Ayar, NORCE, Norway/Global, Caribbean, Equatorial Pacific, Nordic Seas
Damien Couespel, NORCE, Norway/Global, Caribbean, Equatorial Pacific, Nordic Seas
Marie Pontoppidan, NORCE, Norway/Global, Caribbean, Equatorial Pacific, Nordic Seas
Chiara DeFalco, NORCE, Norway/Global, Caribbean, Equatorial Pacific, Nordic Seas

(11) Rachel Cave, NUI Galway (NUIG), Ireland
Janina Buescher, NUI Galway (NUIG), Ireland
Aedin McAleer, NUI Galway (NUIG), Ireland

(12) Uldis Bethers, University of Latvia, Latvia and Baltic Sea
Daiga Cepīte-Frišfelde, University of Latvia, Latvia and Baltic Sea
Inese Suija, University of Latvia, Latvia and Baltic Sea
Andrejs Timuhins, University of Latvia, Latvia and Baltic Sea

(13) Marilaure Gregoire, University of Liège (ULiège), Black Sea and North Sea
Evgeny Ivanov, University of Liège (ULiège), Black Sea and North Sea
Arthur Capet, University of Liège (ULiège), Black Sea and North Sea
Catherine Meulders, University of Liège (ULiège), Black Sea and North Sea
Luc Vandenbulcke, University of Liège (ULiège), Black Sea and North Sea