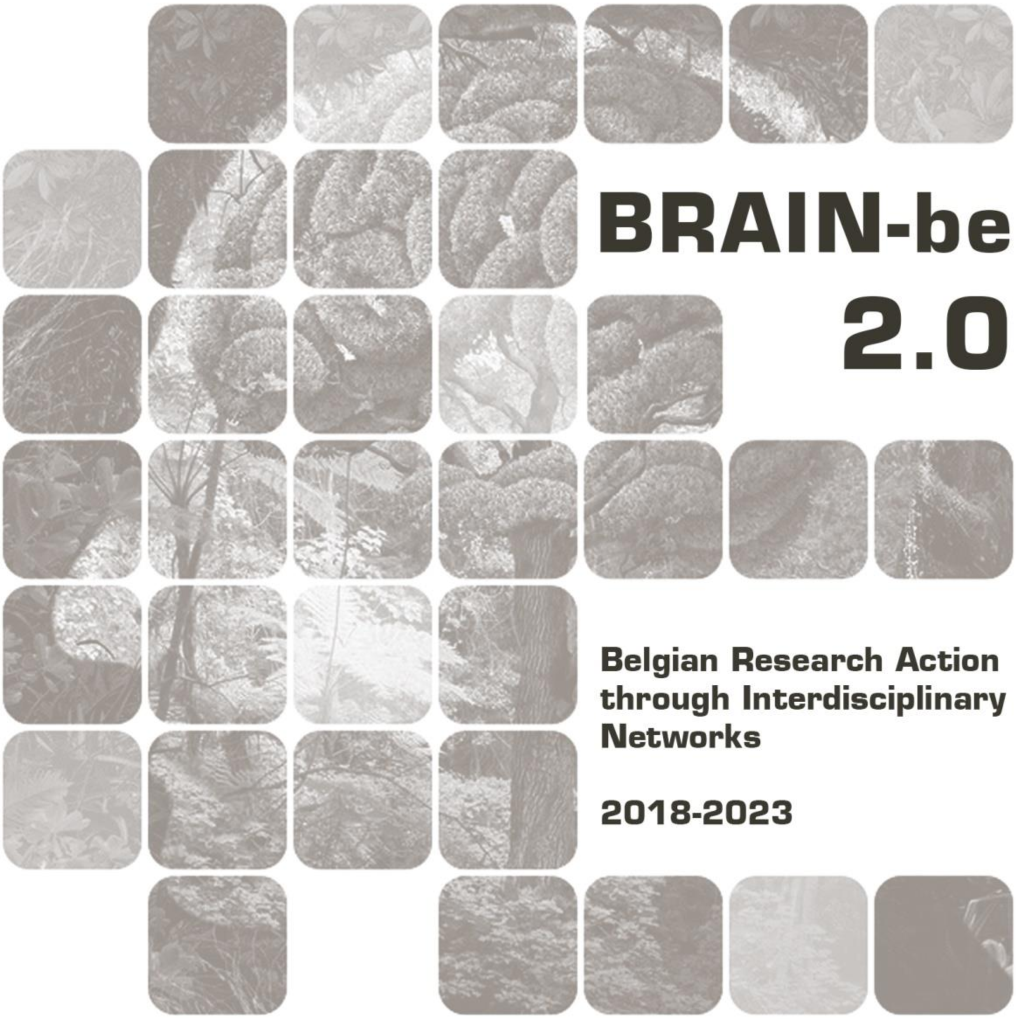

CE2COAST

Evgeny Ivanov, Marilaure Grégoire (University of Liège)

NETWORK PROJECT

CE2COAST

Downscaling Climate and Ocean Change to Services: Thresholds and Opportunities

Contract - B2/20E/P1

FINAL REPORT

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Project B2/20E/P1/CE2COAST, JPI project.

Published in 2024 by the Belgian Science Policy Office
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Final Report. Brussels: Belgian Science Policy Office 2024 – 19 p. (BRAIN-be 2.0 - (Belgian Research Action through Interdisciplinary Networks))

TABLE OF CONTENTS

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ABSTRACT

Context

The Earth's climate is rapidly changing, and nowhere in the ocean is this change as pronounced as in its coastal regions. Understanding these changes and the driving mechanisms behind them allows us to choose a long-term strategy for sustainable development and opens paths to mitigating negative consequences. Robust Earth System Models (ESMs) have traditionally been used to predict the future state of the Earth; however, their accuracy in coastal oceans is not sufficient for regional policymaking. The assessment of trends in marine pressures and services can be accomplished using downscaling models.

Objectives

The aim of the international CE2COAST project has been to downscale the results of ESMs to European coastal seas using high-resolution regional models (RCOMs) to assess the impact of various pressures imposed by the changing climate on coastal oceans and the services they provide. The role of the University of Liège in the project has been the assessment of regional pressures on the North Sea, such as warming and eutrophication, as well as the ecological services it provides, such as primary production and carbon sequestration, with a special focus on offshore wind farms. The assessment has been conducted through a long-term model run covering the recent past (1993–2023) and a future projection (2023–2100) under the "regional rivalry" IPCC scenario, using a coupled benthic-pelagic model calibrated for the region. The RCOM results and the results from the ESM used for the projection have been compared to demonstrate the benefits of using high-resolution downscaled models.

Conclusions

The downscaled model is able to capture more temporal and spatial variability of North Sea surface temperature than the ESMs. The rise in water temperature in the North Sea by about 1.5°C will negatively impact its ability to sequester carbon (-8%) but will expand the distribution of certain species tolerant to warmer waters and open new opportunities in marine aquaculture. The variety of project objectives has contributed to knowledge addressing the Sustainable Development Goals.

Keywords

Downscaling, ocean modelling, climate projection, North Sea, carbon sequestration, heat waves, offshore wind farms, blue mussels, macroalgae.

1. INTRODUCTION

Global climate change affects all parts of the world's oceans, but in coastal regions, the trends are more pronounced, making their ecosystems more vulnerable to various pressures driven by anthropogenic forcing. Understanding and assessing these pressures on marine ecosystems not only allows for the analysis of the capacity of services that ecosystems can provide, but also provides insights into potential regulation and mitigation of the negative effects of climate change.

Climate projections are traditionally delivered using ESMs, which include coupled ocean, land, and atmosphere models. ESMs have limited resolution due to high computational costs, and their predictions for coastal seas do not necessarily capture enough temporal or spatial variability to inform policymaking. To produce a usable prediction, a dynamical downscaling approach can be employed, where a high-resolution regional model is forced by the results from the ESM. This regional model can include and simulate more biogeochemical processes than an ESM, depending on its configuration and complexity, allowing for deeper insights into processes and trends particularly relevant to stakeholders.

The CE2COAST project aims to improve understanding of trends in various pressures on the North Sea, such as warming, changes in circulation, alterations in nutrient supply from rivers, and deoxygenation, as well as in services like carbon sequestration and primary production. The project also studies marine services of anthropogenic origin, such as offshore wind farms and macroalgae farms, and their contributions to carbon sequestration.

2. STATE OF THE ART AND OBJECTIVES

The North Sea is a shallow sea characterized by strong tidal circulation and intense mixing, resulting in a particularly sharp trend in water temperature increase in recent decades (0.3°C per decade compared to 0.2°C for the global ocean) (NOAA, 2023). In addition, the North Sea is one of the most altered coastal seas, being enclosed by developed countries, which enrich the sea with nutrient discharge from their rivers. It has also become a site for large-scale offshore wind farm construction. The foundations of these farms are colonized by bivalves, which play a significant role in carbon sequestration by excreting organic matter as pellets that rapidly sink to the bottom (Ivanov, 2021). However, the primary role in carbon sequestration in the region belongs to phytoplankton, which has a permanent presence in shallow coastal waters and expands rapidly during the spring plankton bloom. Recently, a North Sea Farm project has been proposed to install a floating macroalgae farm between the offshore wind farms to sequester carbon by consuming nutrients left after the local phytoplankton population is diminished due to predation by offshore wind farm bivalves. All these services align with sustainable development goals, and therefore require an assessment of their long-term trends.

3. METHODOLOGY

The model domain has been designed to cover the North Sea and the English Channel (Figure 1), with the SBNS located roughly in the center. The vertical resolution is set to 30 sigma layers to ensure good connectivity between the surface and the bottom. The number of rivers in the domain is set to 50, including 17 principal rivers (with discharges greater than approximately 30 m^3/s) and the remainder consisting of smaller rivers to ensure nutrient enrichment of the coastal waters.

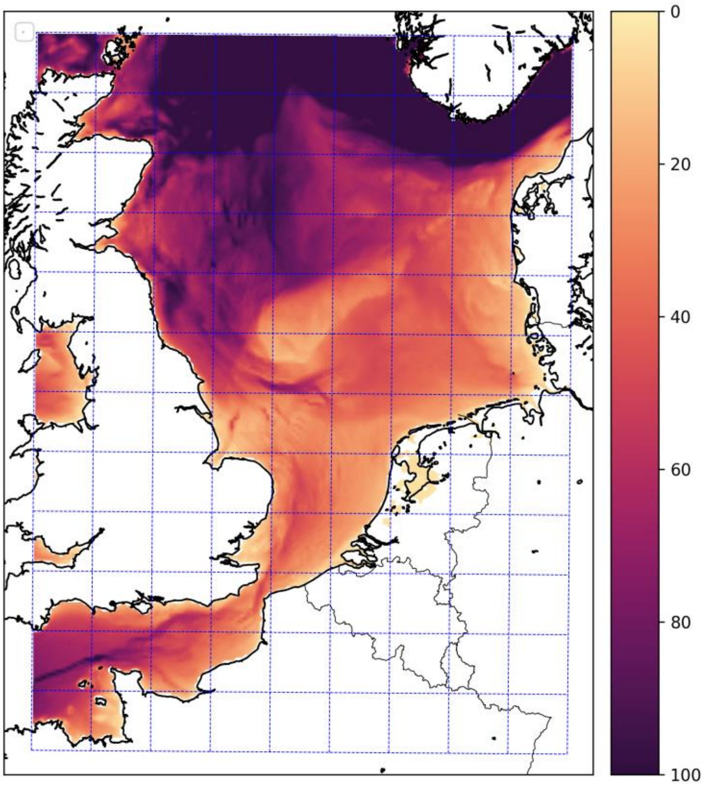

Figure 1: Model domain (each blue cell represents a 5x5 grid), with colors indicating bathymetry.

The RCOM used in this study is COAWST (Coupled Ocean-Atmosphere-Wave-Sediment Transport model), which consists of a hydrodynamic model (ROMS), a sediment model (CSTMS) (Warner et al., 2010), and a wave model (SWAN) (Booij et al., 1996), utilized in several experiments. The RCOM has also been coupled with a biogeochemical model of the water column (Fennel et al., 2006) and a diagenetic model (OmexDia) (Soetaert et al., 1996), ensuring a connection between the pelagic and benthic realms for biogeochemistry. This connection links dead organic matter and solutes in the water column with their counterparts in the sediment through settling, resuspension, advection, and diffusion. Additionally, simple models of bivalves (Ivanov et al., 2021) and macroalgae (Becquet, 2023) have been integrated into the system for the experiments.

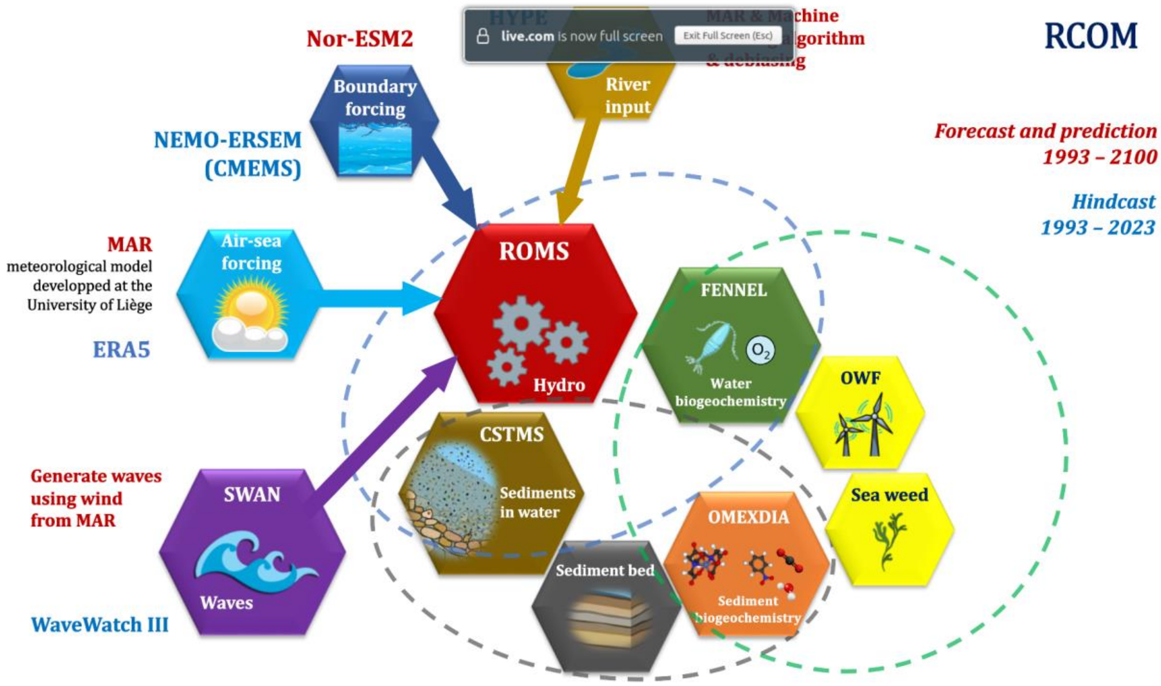

Figure 2: Sketch of the coupled model.

Figure 2 shows a sketch of the RCOM used in the simulations, including coupling of individual models and the data used for forcing. For the model hindcast, the setup was primarily forced with high-resolution CMEMS ocean and ERA5 atmospheric model data for better calibration. For the long-term run, which includes the hindcast and predictions until 2100, Nor-ESM2 results were used at the open boundaries, while results from a meteorological model MAR (Fettweis, 2006) were used to force the RCOM at the air-sea boundary.

The model has been validated for various physical and biogeochemical variables against satellite data (SST, SPM, surface chlorophyll), in-situ stationary and field campaign data (temperature, salinity, tides, oxygen, nutrients, bottom biogeochemistry), other models (tides, mixed layer depth, waves), and general knowledge from the literature (residual currents, tides).

4. SCIENTIFIC RESULTS AND RECOMMENDATIONS

To demonstrate the added value of downscaling, prediction results from the ESM (MPI-ESM2-1-HR), which was also used to force the MAR meteorological model to produce air-sea boundary forcing for the RCOM, have been compared with the RCOM results. The difference in SST between the mid-century climate (2040–2060) and the present-day climate (2000–2020) has been calculated and compared side by side (Figure 3). The RCOM shows a slightly hotter overall trend; however, the most significant difference is seen in the spatial analysis, where the RCOM exhibits a more complex texture. The strongest warming (1–1.5°C) occurs near the Danish coast, Dogger Bank, and the northwestern UK coast, while the ESM shows a much lower trend (<0.5°C). This difference is likely related to the more refined bathymetry resulting from the higher resolution of the RCOM, as well as a higher resolution of the atmospheric forcing from MAR.

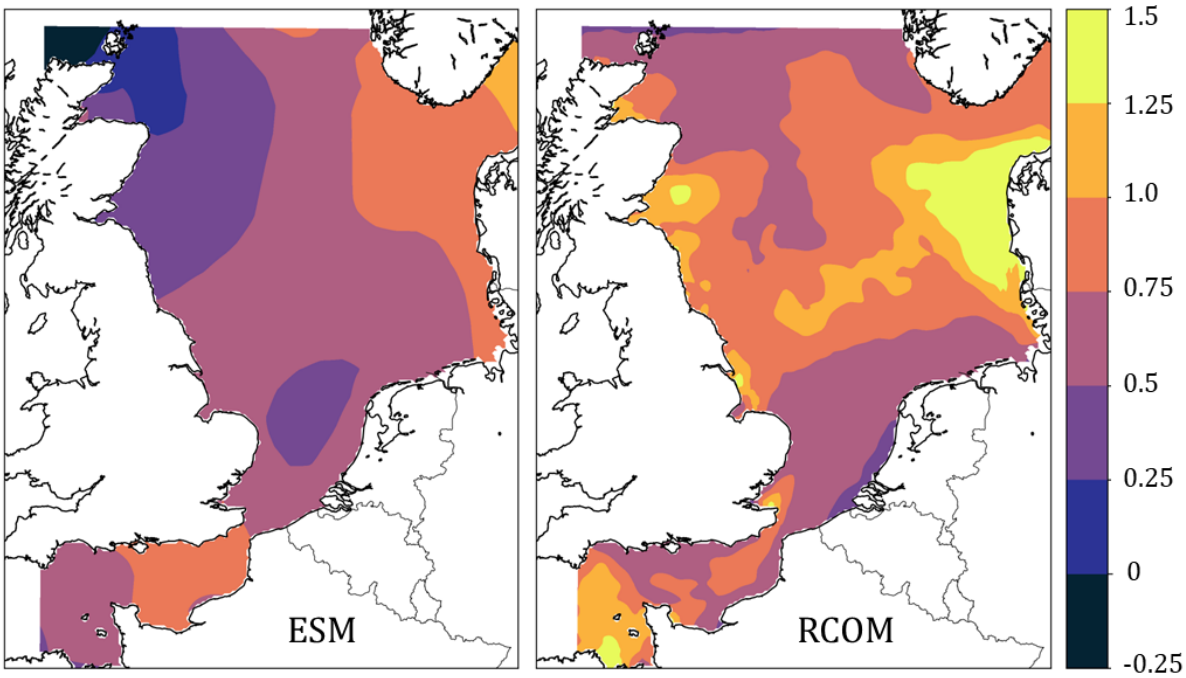

Figure 3: Comparison of mid-century SST increase relative to the modern climate by the MPI-ESM2-1-HR (left) and by the RCOM (right). Color scale in °C.

The ongoing warming of the North Sea will lead to more frequent heat waves (Figure 4, left). The most affected seasons are expected to be winter and autumn, while summer is projected to be the least affected, likely due to heat being stored in the deeper parts of the water column. The increase in water temperature is not expected to result in significant changes in primary production as simulated by the model (Figure 4, right). However, carbon sequestration will be impacted by rising temperatures, resulting in higher remineralization rates in both the water column and the sediment. The released nutrients may help offset the long-term decrease in nutrient runoff from rivers and the open ocean.

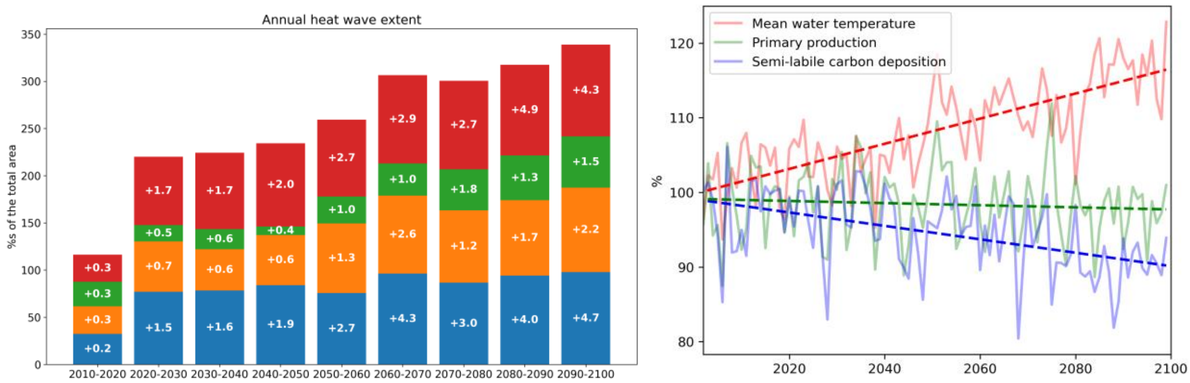

Figure 4: Left: Dynamics of months with heat waves by decade. A "heat month" is defined as a month where the average sea surface temperature exceeds the 90th percentile for that month, calculated based on 1993–2023 climate data. Color denotes seasons: blue for winter, orange for spring, green for summer, and red for autumn. The height of each bar corresponds to the percentage of the domain where monthly SST exceeds the 90th percentile (100% if the whole domain exceeds the threshold, allowing a maximum of 400% for four seasons stacked together). The values indicated on each bar reflect the temperature excess compared to the 90th percentile. **Right:** Evolution (in %) of domain-averaged vertically averaged water temperature, vertically-integrated primary production, and semi-labile carbon deposition relative to the year 2000.

Rising temperatures are not the only factor affecting marine organisms. Figure 5 illustrates “climate velocities” for different North Sea regions in relation to the natural distribution of macroalgae in shallow waters. The climate velocity diagram shows how much the long-term trend of a stressor (warming, deoxygenation, and available nutrients) will exceed its current natural variability (the innermost circle, 90th percentile). Zones 1, 2, 3, and 4 indicate an excess of trend over current variability by 1, 2, 4, and 8 times, respectively. The rise in water temperature is expected to be the principal stressor—particularly in coastal regions, where it will exceed twice its natural variability. Nutrient reduction is also anticipated to become a stressor in the Wadden Sea.

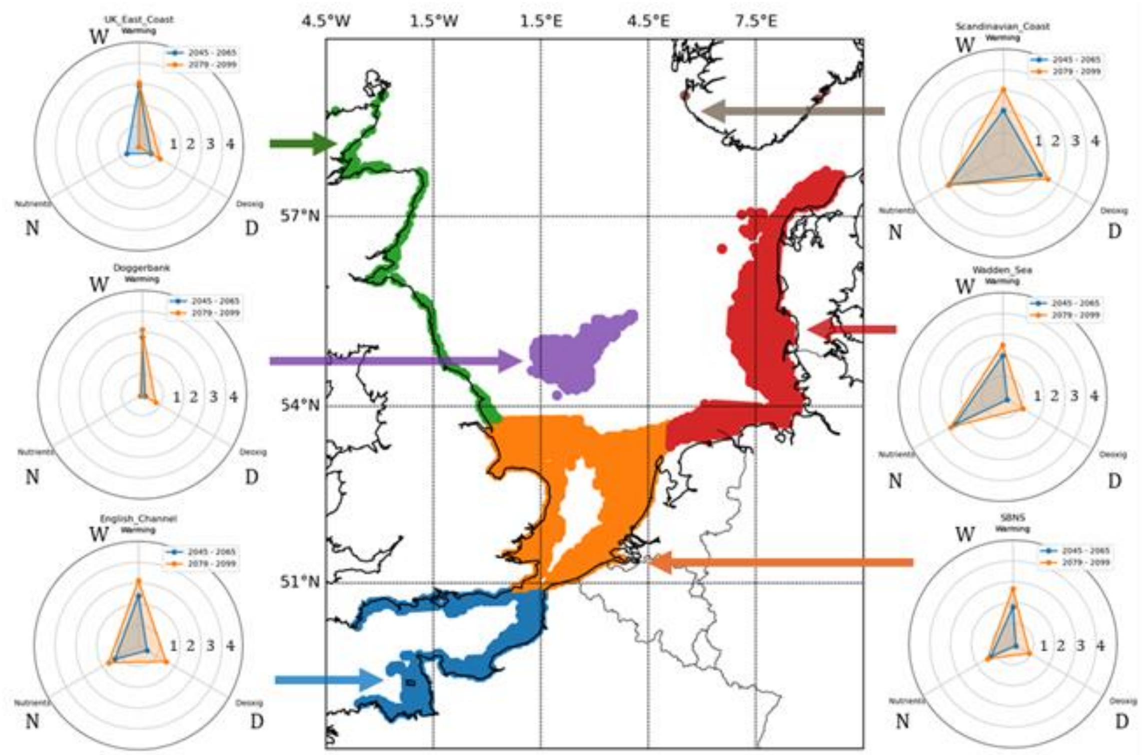

Figure 5: Compound diagram illustrating "climate velocities" (explained in detail in the CMCC contribution) with stressors (warming – W, change in available nutrients – N, and deoxygenation – D) affecting macroalgae in various regions of the domain suitable for their growth (depths shallower than 30 m).

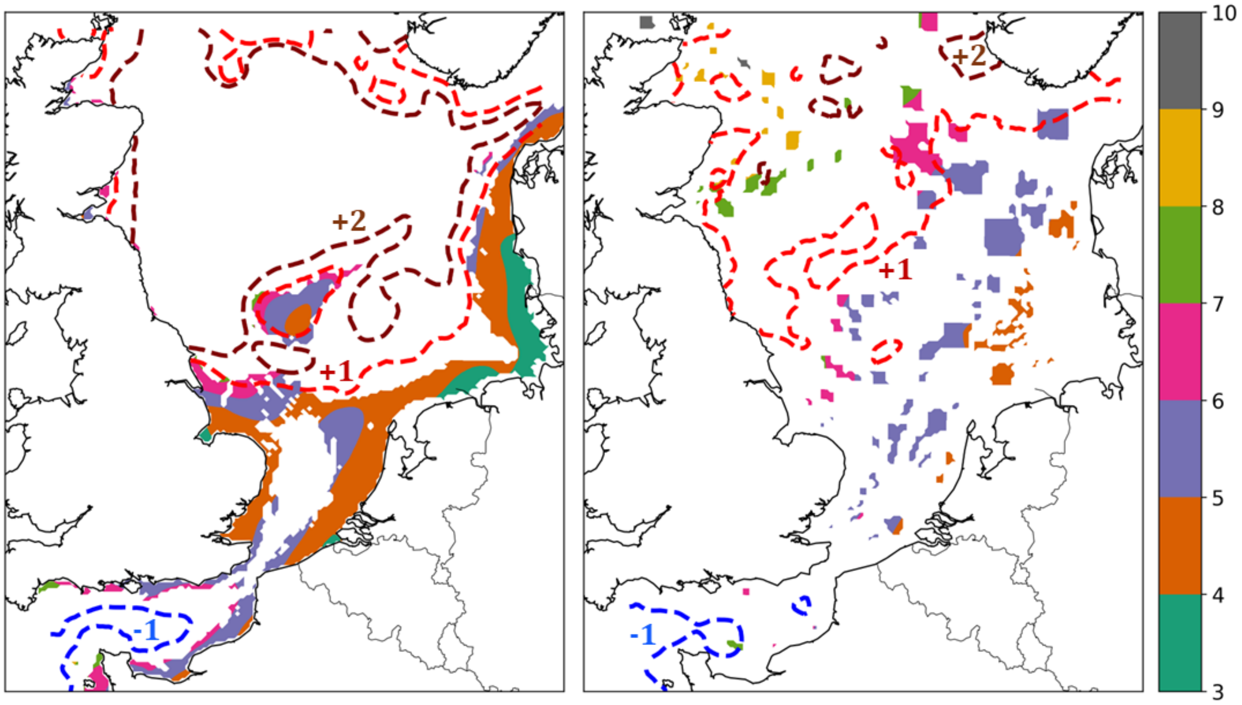

Figure 6: Blue mussel suitability map in their natural habitats at the sea bottom (**left**) and at offshore wind farms (OWFs) (**right**) for the current climate (1993–2023). Colored areas denote the number of months with optimal average bottom temperatures (8–15 °C) at shallow depths (<30 m, left) and optimal SST for mussels at the OWFs (right). Isolines indicate changes in the number of optimal months by the end of the 21st century (2069–2099).

Figure 6 (left) shows how blue mussels may expand their habitats by the end of the 21st century, gaining an additional month of optimal growth conditions due to increasing bottom water temperatures. Blue mussels fouling offshore installations (Figure 6, right) will also benefit from one more month of optimal conditions in the Central North Sea due to rising surface water temperatures. This is likely to lead to an expansion of their habitat offshore and toward the north. However, waters of the English Channel are expected to experience heat waves that will decrease the number of optimal growth months.

Figure 7 illustrates how blue mussels will likely change organic carbon deposition over the North Sea. Organic carbon deposition is expected to increase significantly (by 30%) at offshore wind farms and their immediate surroundings, while deposition in the spaces between these farms is likely to decrease. The assessment of the benefits of the wind farms for carbon sequestration will be presented in the forthcoming published paper (see section 6).

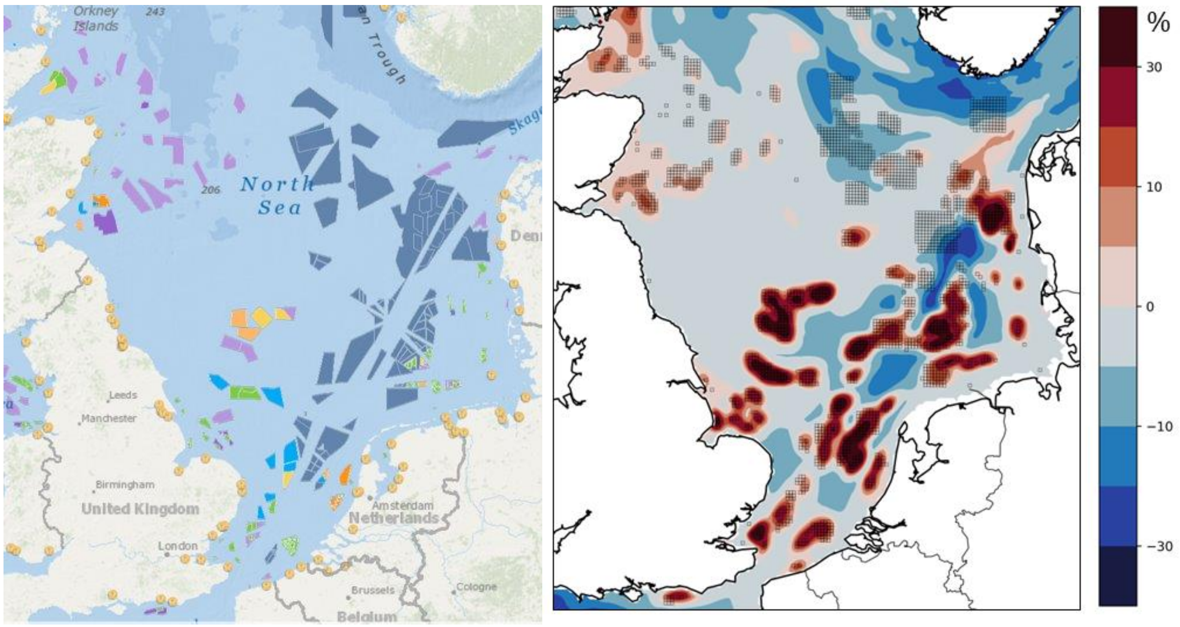

Figure 7: Percentage change in carbon deposition on the sediment bed between an OWF model run and a run without OWFs (2035–2036). The small grids indicate the locations of the planned OWFs for 2035.

5. DISSEMINATION AND VALORISATION

Recent examples:

- Marine Data and SGD’s (workshop on marine science data in Brussels). 06/04/2024. Marine research at the Liège University.

https://www.kaowarsom.be/fr/node/8331;

- Particle Day 2024 in Ostende (scientific conference), 06/05/2024. SPM representation in coupled hydro-bio-sediment models: case of the North Sea study on offshore wind farms.

https://x.com/VLIZnews/status/1787406913010843820;

- International Ocean Liège colloquium (16/05/2024 – 20/05/2024). Conference on deoxygenation.

https://www.ocean-colloquium.uliege.be/cms/c_16806724/en/oceancolloquium-overview;

- World ocean deoxygenation day (conference in Liège) for public. Title: Le role de l'océan dans l'oxygène que nous respirons.

https://www.rejouisciences.uliege.be/cms/c_19679973/fr/ocean-a-bout-de-souffle;

- Ocean Predict 2024 (symposium in Paris on operational oceanography for society), 18/10/2024 – 22/10/2024. Title: Using a coupled model to downscale the effects of climate change and human offshore installations until the year 2100 on the North Sea ocean services

https://www.oceanpredict24.org/.

REMARK: Note that this report synthesizes the contribution of ULiège to the Case study on the Southern Bight of the North Sea. An extended description of this case study and of the other case studies investigated during the project is available at: Final report.

6. PUBLICATIONS

The following publications are in preparation and are planned to be submitted during this academic year.

- Evolution of the North Sea under changing pressures of the XXI century: a downscaling approach.

- Carbon sequestration by blue mussels at offshore wind farms at the 2035 Horizon.

- Benefits of macroalgae aquaculture at offshore wind farms.

7. ACKNOWLEDGEMENTS

The authors thank the Belgian Federal Science Policy Office (BELSPO) for financing the current research in the frames of the BRAIN CE2COAST project (contract B2/20E/P1/CE2COAST). This work has been supported by the JPI Ocean and Climate CE2COAST project coordinated by the Norwegian Institute for Water Research (NIVA). The authors thank the University of Liège for providing the needed infrastructure. Computational resources have been provided by the Consortium des Équipements de Calcul Intensif (CÉCI), funded by the Fonds de la Recherche Scientifique de Belgique (F.R.S.-FNRS) under Grant No. 2.5020.11 and by the Walloon Region. This study has been conducted using E.U. Copernicus Marine Service Information. This work was also supported by data and infrastructure provided by the European Centre for Medium-Range Weather Forecasting (ECMWF). We acknowledge the CMIP community for providing the climate model data, retained and globally distributed in the framework of the ESGF. The CMIP data of this study were replicated and made available for this study by the DKRZ.

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ANNEXES

An extended description of this case study and of the other case studies investigated during the project is available at: Final report.