JERICO-S3 DELIVERABLE

Joint European Research Infrastructure for Coastal Observatories

Science, Services, Sustainability

DELIVERABLE #, WP# and full title	JERICO-S3 D2.3 - WP2 - "Regional connectivity and multi-scale processes"
5 Key words	Coastal-estuarial continuum, fit-for-purpose information, offshore wind industry, gap analysis, integrated monitoring-modelling
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Final version date/ Submission date (dd.mm.yyyy)	31.10.2023

Nature: **R**

(R = Report, P = Prototype, D = Demonstrator, O = Other)

Dissemination level : **PU**

PU = Public, PP = Restricted to other programme participants (including the Commission Services), RE = Restricted to a group specified by the consortium (including the Commission Services), CO = Confidential, only for members of the consortium (including the Commission Services)

GRANT N°: 871153
PROJECT ACRONYME : JERICO-S3
PROJECT NAME : Joint European Research Infrastructure for Coastal Observatories - Science, services, sustainability
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DOCUMENT TECHNICAL DESCRIPTION

Document ID	JERICO-S3-WP2-D2.3-31.10.2023-V1.0

REVISION HISTORY

Revision	Date	Modification	Author
V1.0	31/10/2023	Initial delivery	Jun She, Johannes Schulz-Stellenfleth

APPROVALS

	Name	Organisation	Date	Visa
Coordinator	Delauney Laurent	Ifremer	31.10.2023	X
WP Leaders	Holger Brix	HZG	31.10.2023	X

Diffusion list

Consortium beneficiaries	Third parties	Associated Partners	other
x	x		

This work can be cited as: Jun She, Johannes Schulz-Stellenfleth, Anouk Blauw, Lauri Laakso, Baptiste Mourre, Henning Wehde (2023). Regional connectivity and multi-scale processes. JERICO-S3 Deliverable D2.3.

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Executive summary

Coastal regions are dynamic, complex systems where multiple physical, biological, and chemical processes interact across various spatial and temporal scales. The areas are also characterized with high connectivity. Effective monitoring of these systems requires a holistic and integrated approach that combines advanced environmental modeling with monitoring techniques to provide a comprehensive understanding of estuarial-coastal ecosystems. This study aims to assess if existing estuarial-coastal observing system fit for the purpose of resolving high connectivity and multi-scale processes, identify gaps and make recommendations.

This work consists of three studies: the first one is to assess current estuarial-coastal observation and modelling capability in the EU member states, and identify gaps and make recommendations; the second one is to further review current monitoring and modelling capability in resolving Baltic-North Sea connectivity in the transition waters, with focus on carbon observations; the third study focuses on fit-for-purpose information for offshore wind energy, its user needs and potential solutions, current monitoring and modelling capacity, gaps and recommendations.

National observation and modelling capability in estuarial-coastal continuum – assessment and gap analysis:
This study identifies gaps in monitoring systems run by six European countries. The monitoring capacity in this study represents an integrated capacity by combining in-situ, remote sensing and modelling. The gaps in the monitoring capacity were identified to fit for the purposes in key service sectors, i.e., ocean health, climate change, operational forecast and blue economy. Naturally, the focus of the observing systems not only differs between different countries, but also depends on the institutions running the monitoring systems. The project partners responsible for this document represent a mix of operational centers and research institutions and thus provide a quite wide range of different perspectives.

DMI investigated Danish marine monitoring capacities in national waters, including i) observing capacities, both in-situ and remote sensing, in operational agencies, coastal authority, environment agency and part of observing capacities from Fishery monitoring, research community and commercial companies, ii) modeling capacity, consisting of models for operational forecasting, coastal erosion, climate change adaptation, biogeochemical and lower trophic level models, high trophic level models and models for commercial applications, as well as data assimilation capacities wherever relevant. The existing monitoring capacity is reviewed and gaps are identified to fit for the purposes of information services for operational activities, climate change adaptation and ocean health.

FMI analyzed information on Finnish marine observing platforms, modelling and remote sensing. The focus is on operative observations and modelling, and the research activities listed here are carried out mainly by the Finnish Meteorological Institute (FMI) and Finnish Environmental Institute (SYKE).

HEREON reviewed existing in-situ and remote sensing and modelling (including data assimilation) capacity in Germany, and identified correspondent gaps on the particular case of offshore windfarming, which is very illustrative and currently of extremely high relevance in Germany. This application is useful as a demonstrator because it demands information on a wide range of spatial and temporal scales as well as across various disciplines (physics, chemistry, biology).

Deltares focuses on monitoring for eutrophication assessments in the context of OSPAR and MSFD. In 2020 and 2021 the methodology for eutrophication assessments has been revised, using:

- New assessment areas
- New threshold levels and
- Addition of satellite data to complement in-situ observation data for chlorophyll-a.

In the process of revising the methodology for eutrophication assessments, several limitations in the currently available observation data have been encountered.

IMR study covers the Norwegian marine monitoring activities within the territorial waters. The monitoring gaps are identified to serve the purpose of holistic national management plans for their regions in Norway since the beginning of the 2000s.

SOCIB investigated data needs and gaps in the northwestern Mediterranean Jerico-S3 Pilot Super Site where the Italian, French and Spanish monitoring systems are used to reconstruct the 3D dynamics and describe the regional and coastal circulation in the region. In this area, the Northern Current flowing along the slope from Italian to French and Spanish waters is an essential driver of the regional connectivity. Its path, extent and strength have a significant impact on the transport of materials, contaminants, plastics or fish larvae within the region. The WMOP hydrodynamic modelling system developed at SOCIB is used to integrate the maximum number of transnational observations together with modelling tools through data assimilation. A preliminary gap analysis of the regional monitoring and modelling systems is presented.

Although there are differences in the gaps identified in different cases, come common gaps can be identified:

- Need more frequent T/S and BGC profile observations
- Need better BGC data coverage in space
- to integrate observations between operational and non-operational observing sectors
- to improve NRT in-situ data delivery in non-operational observing sectors
- to increase use of coastal observations in modelling via model-observation integration, including assimilation, tuning model parameters, model calibration and validation, hybrid modelling using AI/ML with model data and observations
- to increase use of integrated monitoring and forecast products in non-operational services

Observations for resolving Baltic-North Sea connectivity:
In this study, connectivity of water, nutrients, carbon and pollutants are qualitatively analyzed, observing strategy in the Baltic-North Sea transition waters to improve the understanding and prediction of the connectivity is recommended. A more detailed observation gaps analysis on carbon connectivity is also given.

Gaps in monitoring capacity for Baltic-North Sea connectivity are identified in following areas:

- Lack of in-situ pCO2, DOC/POC profiles and microplastic measurements in Kattegat
- Lack of high frequency profile observations for currents (hourly) and T/S (synoptic scale) for calibration and validation (cal/val), and biogeochemical variables (synoptic scale) for both cal/val and assimilation in Kattegat
- Integration of existing monitoring capacities, both in national and regional level, are essential. Such integration includes, but is not limited to,
    - to share observations between operational and non-operational observing sectors
    - to improve NRT in-situ data delivery in non-operational observing sectors
    - to increase use of coastal observations in modelling via model-observation integration, including assimilation, tuning model parameters, model calibration and validation, hybrid modelling using AI/ML with model data and observations
    - to increase use of integrated monitoring and forecast products in non-operational services
    - Robotics are prospective instruments in the Baltic-North Sea transition waters: AUV for both shallow (<30 m deep) and deep waters (>30 m deep), sail drones for surface and gliders for the deep waters.

Fit-for-purpose information for offshore wind energy:
The rapid expansion of offshore wind farms (OWFs) in European seas is accompanied by many challenges, including efficient and safe operation and maintenance, environmental protection, and biodiversity conservation. Effective decision-making for industry and environmental agencies relies on timely, multi-disciplinary marine data to assess the current state and predict the future state of the marine system. Due to high connectivity in space (land–estuarial–coastal sea), socioeconomic (multi-sectoral and cross-board), and environmental and ecological processes in sea areas containing OWFs, marine observations should be fit for purpose in relation to multiple OWF

applications. This study represents an effort to map the major observation requirements (Part-I), identify observation gaps, and recommend solutions to fill those gaps (Part-II) in order to address multi-dimension challenges for the OWF industry.

In Part-I, six targeted areas are selected, including OWF operation and maintenance, protection of submarine cables, wake and lee effects, transport and security, contamination, and ecological impact assessments. For each application area, key information products are identified, and integrated modeling–monitoring solutions for generating the information products are proposed based on current state-of-the-art methods. The observation requirements for these solutions, in terms of variables and spatial and temporal sampling needs, are therefore identified. These application areas show many examples of spatial and interdisciplinary connectivity between different types of observation data required for different applications.

A fit-for-purpose observation requirement assessment approach is used first to identify user needs on key information products, then to suggest an integrated modeling–monitoring solution for deriving the information products, and finally, to identify observation demands with regard to the use of observations in implementing the solutions. The results should show that demands from governmental stakeholders, OWF operators, and the research community can only be fulfilled by multi-scale and multi-disciplinary observations and dedicated monitoring–modeling integration.

In addition, several important issues such as multi-use of OWF platforms, Model-Observation Integration in Areas with High Connectivity and Multiple Scales, Coordinated Data Management for OWF Applications, and Data Transmission, Interoperability, and Accessibility are also discussed.

In Part-II, A gap analysis was presented for observation systems and respective integrations with numerical models in the context of fit-for-purpose information products required in the offshore wind energy sector. The study is the second part of two papers, with the first one concentrating on the identification of requirements for six use cases. It was explained that gap analysis is a powerful tool to optimize decision processes by enforcing the development of clear ideas about target scenarios and the transparent assessment of the initial situation. The study also discussed the challenges of applying this tool in the context of offshore wind energy. One key challenge is the balancing of economic and environmental target definitions because this includes discussions about values and ethical aspects that require a broader discussion in society, i.e., this is not a purely scientific issue.

The study provided an overview of the monitoring and modeling solutions that are presently used to provide information products for the offshore wind community. It became quite clear that the observation and model systems used today have evolved due to requirements associated with a number of standard applications, e.g., storm surge forecasts or wave predictions for shipping. It also appeared that the monitoring of ecosystem parameters is less mature than respective systems for the measurement of physical quantities.

By comparing the present situation with the requirements identified in [8], gaps were identified, which were structured along different categories, e.g., spatial and temporal sampling or data availability and accessibility. Many of the identified gaps have to do with the fact that the existing monitoring systems are not adequate to capture characteristic length scales of today's offshore wind farms, e.g., related to the spacing of turbines. This means that different types of wake effects and turbine impacts on the environment cannot be assessed appropriately with the available observations. In addition, OWFs create new types of physical, chemical, and biological processes, which are not captured by the present monitoring systems at all, e.g., the generation of turbulence by turbine structures in the water and the atmosphere. Furthermore, it was discussed that most of the fit-for-purpose information products for the offshore energy sector have to include various types of connectivity aspects, e.g., the continuum of land, wind farm, and open ocean spatial scales. Likewise, the treatment of most optimization problems occurring in offshore wind farming requires detailed knowledge about interaction processes between different earth system compartments, e.g., the atmosphere, the ocean, the sea floor, and the ecosystem. There is still a lack of suitable measurements for this purpose, although information about these coupling mechanisms is also highly relevant in other contexts, e.g., climate change. There are also still observations missing to identify, understand, and predict two-way interactions between the technology and the environment. This has become increasingly challenging because of the rapid development of OWF installations in terms of turbine size and OWF coverage. It was also found that with regard to temporal sampling, a measurement strategy is missing to assess the environmental conditions before and after windfarms were installed. The issue is of growing urgency since locations not impacted by OWFs are increasingly hard to find.

A number of recommendations to fill the gaps were formulated. These include different technological aspects, e.g., autonomous systems like drones, but also suggestions concerning data policies and cooperation between science and industry. Due to the large-scale interactions of OWFs with the environment and also among each other, the development of measurement strategies across country borders was identified as an essential step forward. It is foreseeable that this step will also be of vital importance for a further synchronization and optimization of the energy system on a larger scale, e.g., across Europe. Another important recommendation concerns the exploitation of synergies by identifying common interests and requirements in different communities and sectors, e.g., the OWF community and operational forecast centers.

Finally, it is important to emphasize that this study is meant as a contribution to a discussion, which needs to be continued and extended. The task at hand is challenging not only because of the complexity and the rapid evolution of technology but also because of the diversity of the different communities that have to be brought together to find suitable solutions for the future. The experience in the past has shown that the respective communication and synchronization processes take time and that makes a structured and transparent approach even more important.

1. Objectives

The aim of JERICO-S3 WP2.4 is to explore potential enhancements of monitoring capacities on the national and regional level through an integrated modelling-monitoring approach. The scope of the study is limited to monitor regional connectivity in Baltic-North Sea (Kattegat and Skagerrak, WP2.4.1) and estuarial-coastal continuum in national waters in 6 partner countries (WP2.4.2), i.e., Denmark (DMI), Finland (FMI), Germany (HEREON), Norway (IMR) and Spain (SOCIB), Netherlands (Deltares). In the first phase, the existing monitoring capacity in resolving Baltic-North Sea connectivity and multiscale processes in coastal-estuarial continuum have been assessed, gaps identified and recommendations for how to filling the gaps were given. In the second phase, we performed a detailed fit-for-purpose information assessment, including user needs, potential monitoring and modelling, solutions, current capacity and gaps, for offshore wind farm sector.

This report is organized as follows: section 2 is about gap analysis on national monitoring and modelling capacity in estuarial-coastal continuum, sections 3 is about the regional connectivity: an analysis on carbon monitoring in Baltic-North Sea transition waters, section 4 is on fit-for-purpose information for offshore wind farms: requirements and solutions, sections 5 is on fit-for-purpose information for offshore wind farms: gaps and recommendations. The section 4 and section 5 have been published as peer reviewed papers (She et al., 2023; Schulz-Stellenfleth et al., 2023)

2. National monitoring and modelling capacity in estuarial-coastal continuum

2.1 Methodology

In this study, the monitoring capacity is defined as an integrated capacity to monitor the marine environment and ecosystems. This capacity is realized by combining observations, modelling and model-data integration techniques (e.g., data assimilation). The purpose of the marine monitoring is to support marine-related operations, planning and decision making for public safety, sustainable blue economy, climate change adaptation and ocean health preservation. Each partner will choose one or more national monitoring cases to perform the monitoring capacity gap analysis. For each partner country, one or more national cases will be selected for the monitoring capacity gap analysis. The existing monitoring capacities in the national EEZ waters, including observations (both in-situ and remote sensing), modelling and model-observation integration, will be reviewed. Then we investigate if the current national monitoring capacity is fit for the purposes in marine information service areas, i.e., operational forecasting, marine climate, ocean health and blue economy. For the fit-for-purpose gap analysis, a list of the service elements in the above service areas have been identified:

Operational forecasting service (OS)

OS1. Storm surge & coastal flooding
OS2. Port management
OS3. Coastal erosion
OS4. Ocean-wave-ice forecast
OS5. Estuary-coastal interaction (PHY)
OS6. Estuary-coastal interaction (BGC)
OS7. Algae bloom
OS8. Hypoxia
OS9. Suspended particulate matter (SPM)

Climate service (CS)

CS1. Seasonal-to-decadal scale climate service

    - a. Seasonal forecast
    - b. Rapid environment assessment (interim reanalysis)
    - c. Interannual-to-decadal forecast
- CS2. Coastal climate change adaptation service
    - a. Storm surge & coastal flooding
    - b. Port management
    - c. Coastal erosion
    - d. Habitat: Estuary & Coastal nursery for fish
    - e. Habitat: Nature-based solution
    - f. Extremes: marine heatwaves, river flooding
- CS3. Climate change adaptation: marine carbon
    - a. Sea-air carbon exchange
    - b. Blue carbon
    - c. Estuary-coastal Carbon cycle

Ocean health service (OHS)

- OHS1. Ecosystem service
    - a. Eutrophication assessment
    - b. Fishery management
    - c. Biodiversity
- OHS2. Zero pollution
    - a. Marine plastics
    - b. Underwater noise
    - c. Heavy metals
    - d. radioactive tracers
    - e. Oil spill

Blue economy service (BES)

- BES1. Aquaculture
    - a. Flexibility and optimal siting
    - b. Maintenance & operation service (breeding, monitoring)
    - c. Disease prevention and healthy growing
    - d. Impact assessment
- BES2. Offshore wind farms
    - a. Flexibility and optimal siting
    - b. Maintenance service
    - c. Operational service
    - d. Impact assessment
- BES3. Shipping
    - a. Ship performance service (route optimization)
    - b. Navigation impact assessment
- BES4. Tourism
    - a. Coastal & offshore tourism

It is noted that the four service areas are partly overlapping, e.g., operational forecasting on algae bloom also serves the ocean health area, port forecast also serves the port management and shipping sector in the blue economy. State-of-the-art monitoring capacity of a given country is based on the integration of modelling, in-situ and remote sensing observations. Therefore, the gaps of the monitoring capacity are identified not only on in-situ observations, but also on modelling-observation integration and data management.

It should be noted that i) the focus of this study is on the regular monitoring activities; ii) fit-for-purpose assessment is mainly based on expert knowledge from the partners; and iii) gap analysis is performed only for selected service areas.

2.2 Denmark

This study covers Danish marine monitoring capacities in national waters, including i) observing capacities, both in-situ and remote sensing, in operational agencies Danish Meteorological Institute (DMI), Joint GEOMETOC Support Center (GEOMETOC), coastal authority KDI, Environment Protection Agency EPA and part of observing capacities from Fishery monitoring, research community and commercial companies, ii) modeling capacity, consisting of models for operational forecasting, coastal erosion, climate change adaptation, biogeochemical and lower trophic level models, high trophic level models and models for commercial applications, as well as data assimilation capacities wherever relevant. The existing monitoring capacity is reviewed and gaps are identified to fit for the purposes of information services for operational activities, climate change adaptation and ocean health.

2.2.1 Review on existing monitoring capacities

Marine observing

- **In-situ:** the marine observing capacity consists of operational observing on coastal sea level, SST and SSS, currents and waves from DMI, KDI and GEOMETOC; national environmental monitoring program NOVANA, including environmental observations on hydrochemistry, habitat, biota, river runoff, underwater noise and marine litter, and hydrochemistry monitoring from fishery monitoring program, research projects and commercial monitoring for which part of data can be retrieved from ICES and EMODnet. Coastal erosion (variability of beach and seabed profiles) is monitored by KDI and sediment and substrate by GEUS and KDI.
- **Remote sensing:** in Denmark, marine remote sensing monitoring capacity are developed at DMI Remote Sensing Division (SST, sea ice and sea surface height and marine meteorology), DTU Space (sea ice, sea surface height, hydrology etc.), including DTU Space DroneCenter dealing with unmanned monitoring in the air and waters, and DHI GRAS (hydrology, water quality and environmental assessment). Although there are operational, research and commercial remote sensing data products for Danish waters, open access to the remote sensing products mainly comes from CEMES (SST, sea ice, sea surface height, winds, waves, chl-a, SPM and optical parameters etc.).

Modelling capacity

This includes operational forecasting models at DMI for ocean-ice-wave-biogeochemistry-oil sleek drift, and FCOO for ocean-wave-oil sleek drift, research model of climate-ocean-ice-wave-BGC-SPM-low trophic-high trophic layer models are developed in a MEMC (Marine Ecological Modelling Centre) common modelling framework which is a modelling collaboration between DMI, Aarhus University and DTU-Aqua. A commercial modelling tool for coastal ocean-wave-ice-BGC-SPM-pollutants-ecosystem simulations has been developed by DHI Group. Coastal flooding forecast is currently handled via coupling DMI storm surge model with a simple inundation model, operated by a SME Scalgo. A full version of flood forecasting model will be developed by DMI in the coming years. Coastal erosion (variability of beach and seabed profiles) is monitored by KDI and modelled by a beach nourishment model XBEACH.

Model-data integration and hybrid modelling

Observations are mainly used to assess the environment and ecosystem status, calibrate and validate the models. Data assimilation techniques are only developed at DMI on SST, sea level, T/S and sea ice for ocean forecast and reanalysis. Similar assimilation techniques are also developed by DHI Group for their coastal models. In addition, assimilation has been applied in the spectral wave model MIKE21 SW to improve the skill of numerical sediment models during dredging activities, and also chlorophyll and nutrients assimilation in DHI ecological model ECOLab. Model-data fusion has been applied to improve sea level forecast (Multi-model ensemble) and quality of reanalysis products at DMI. Machine Learning has been applied in sea level and sea ice data quality control (DMI, DTU) and other service areas in recent years.

2.2.2 *Major gaps identified*

1. In-situ monitoring:
    a. Hydrochemistry: current hydrochemistry observations are observed 4-24 times a year (in NOVANA), does not meet requirements for synoptic forecast, higher frequency data are required.
    b. Waves: little wave data are available in inner Danish waters
    c. Sediment concentration and sedimentation rate: little data are available
    d. Carbon: little data are available for DOC and POC; pCO2 in Kattegat are rare.
    e. Pollutants: plastic concentration both micro and macro, are not available in Danish rivers, and in water column.
2. Remote sensing:
    a. Specific high resolution water quality products are not operationally available.
    b. High resolution sea surface winds, height and wave products in Danish waters are needed.
    c. Observing with unmanned instruments should be enhanced for river-estuary-coastal continuum, to improve forecast service on flooding and inundation, coastal erosion and terrestrial impacts on the estuarial-coastal environment and ecosystems.
3. Data management
    a. A major gap is that observations from different agencies are not coordinated and harmonized. Operational data from DMI, KDI and GEOMETOC are shared in a certain level but there are still many observations are not shared. NOVANA observations are now managed by MSP and can be retrieved from their data portal but right for data distribution is still limited. Access to fishery, research and commercial observations are mainly on-request. It is suggested that a common marine data portal should be presented for Danish marine data dissemination.
    b. Operational near real time (NRT) delivery of non-operational data: currently the non-operational data, e.g. from NOVANA and ICES, are delivered in a delayed mode, thus only used for long-term reanalysis. Operational forecast needs to access data no more than 3days old and reanalysis in interim scale no more than one month old. It is therefore a urgent need to improve delivery of non-operational data in interim and NRT scales.
4. Model-data integration:
    a. More operational modelling capacity should be developed, e.g., for SPM transport, coastal erosion, rapid environment assessment, plastics, water quality
    b. Model-data fusion and hybrid modelling (including ML and AI) should be developed for improve product quality on algae bloom, oxygen depletion and eutrophication assessment.
    c. By filling gaps in data management, more data should be available and used for developing new operational modelling capacities and model-data integration including data assimilation.

2.2.3 *Plans to address the identified gaps*

Within JERICO activities, there are no activities to address the identified gaps in coastal observations and models in Denmark.

2.3 *Finland*

This section contains information on Finnish marine observing platforms, modelling and remote sensing. The focus is on operative observations and modelling, and the research activities listed here are carried out mainly by the Finnish Meteorological Institute (FMI) and Finnish Environmental Institute (SYKE).

In general, responsibilities for marine monitoring and modelling in Finland are distributed: Finnish Meteorological Institute is responsible for meteorological and physical oceanographic observations and modelling; SYKE is responsible for marine BGC, biodiversity, noise etc., Natural Resources Institute Finland (LUKE) for aquaculture and fisheries, regional and local authorities (centres for Economic Development, Transport and the Environment "ELY"; local minicipalities) for local observations. Companies (e.g. fish farming, wind and nuclear energy production, shipping companies) participate in monitoring related to their on needs and required impact assessments. The responsibilities are described by the government (Ministry for Environment, 2021). The full list of requirements observations for the period 2020-26 is given by Attila et al, 2020.

Figure 2.1 shows the joint open sea monitoring network of SYKE and FMI.

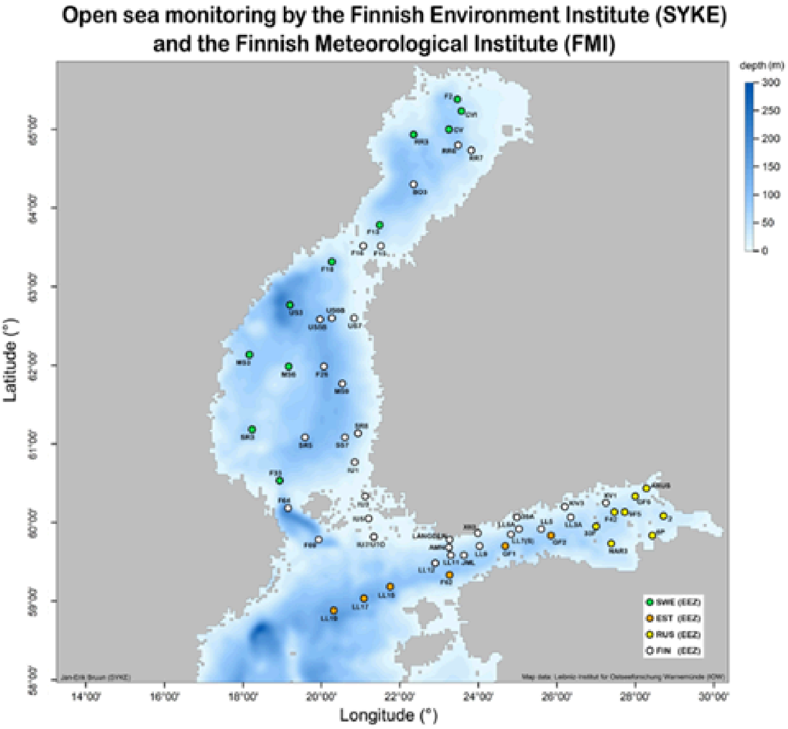


Figure 2.1 Open Sea monitoring by SYKE and FMI

2.3.1 *Review on existing monitoring capacities*

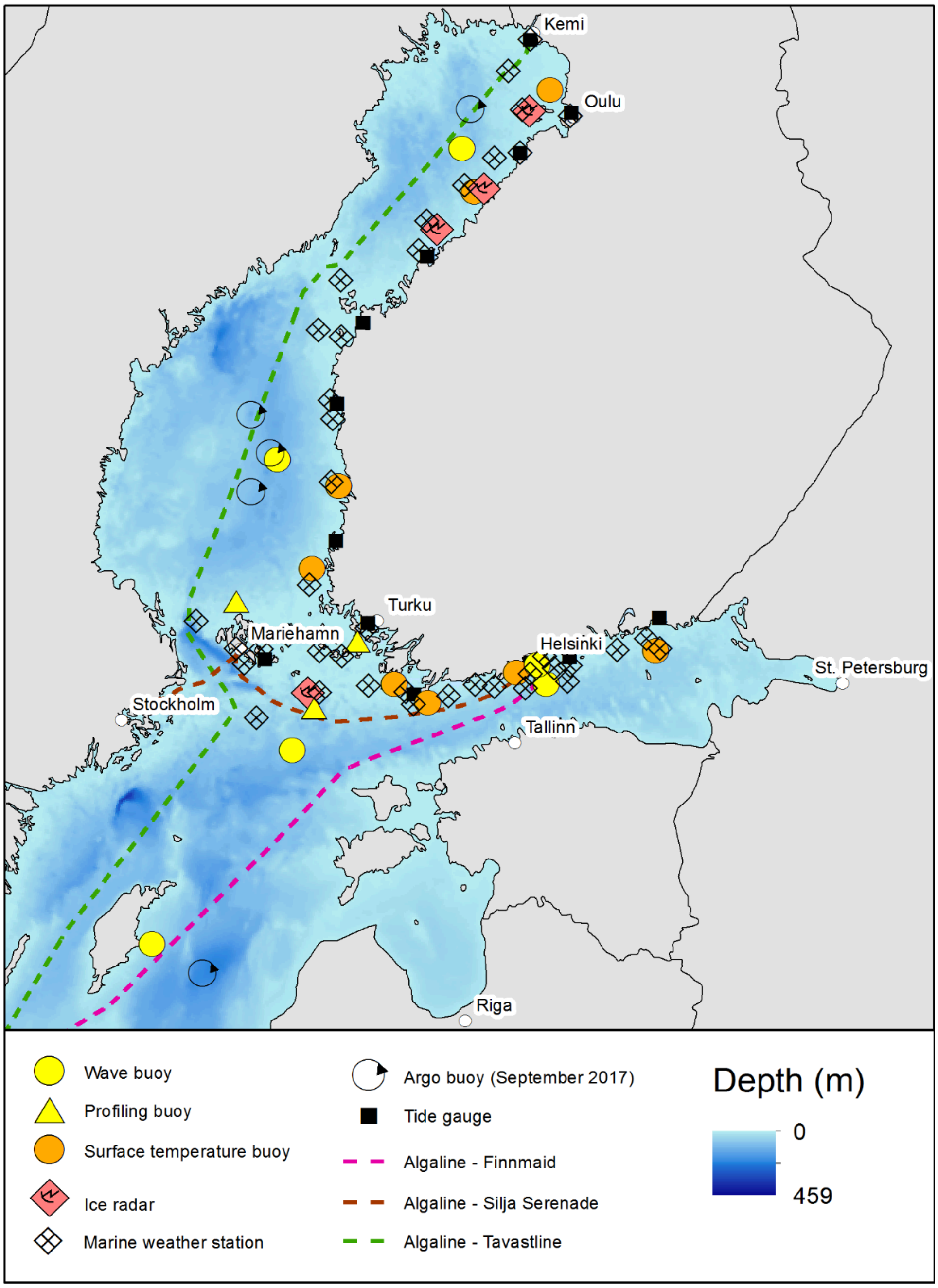


***Figure 2.2** Finnish operative marine observing network (for physical parameters like temperature, salinity, waves, sea level, sea ice) operated by FMI*

Marine observations

Marine research observations in Finland are coordinated by the Finnish Marine Research Infrastructure (FINMARI). FINMARI (https://www.finmari-infrastructure.fi/) represent all research institutes and universities doing marine research in Finland and it is on the national research infrastructure roadmap. The FINMARI partners include Finnish Meteorological Institute (FMI), Finnish Environment Institute (SYKE), Geological Survey of Finland (GTK) and Natural Resources Institute Finland (LUKE), University of Helsinki (UHEL), University of Turku (UTU), and Åbo Akademi (ÅAU)

- **In-situ:** the operative marine observations related to physical processes of the sea and operated by the Finnish Meteorological Institute (FMI) are shown in Figure 2.2. They include sea level, temperature, salinity, currents, waves, sea ice observations and marine meteorology. The biological observations including e.g. algae are SYKE. Example of cyanobacterial observations in 2021 is shown in Figure 2.3. Other observations by SYKE include hydrochemistry, habitat, biota, river runoff, underwater noise and marine litter. Observations relevant for the fisheries are carried out by LUKE. All observations related to marine geology, e.g. sediments are carried out by GTK. In addition to operative data collected by the state research institutes (FMI, SYKE, LUKE, GTK), universities (UHEL, UTU, ÅAU) are collecting long-term data related especially to the barine biology and ecosystem functioning

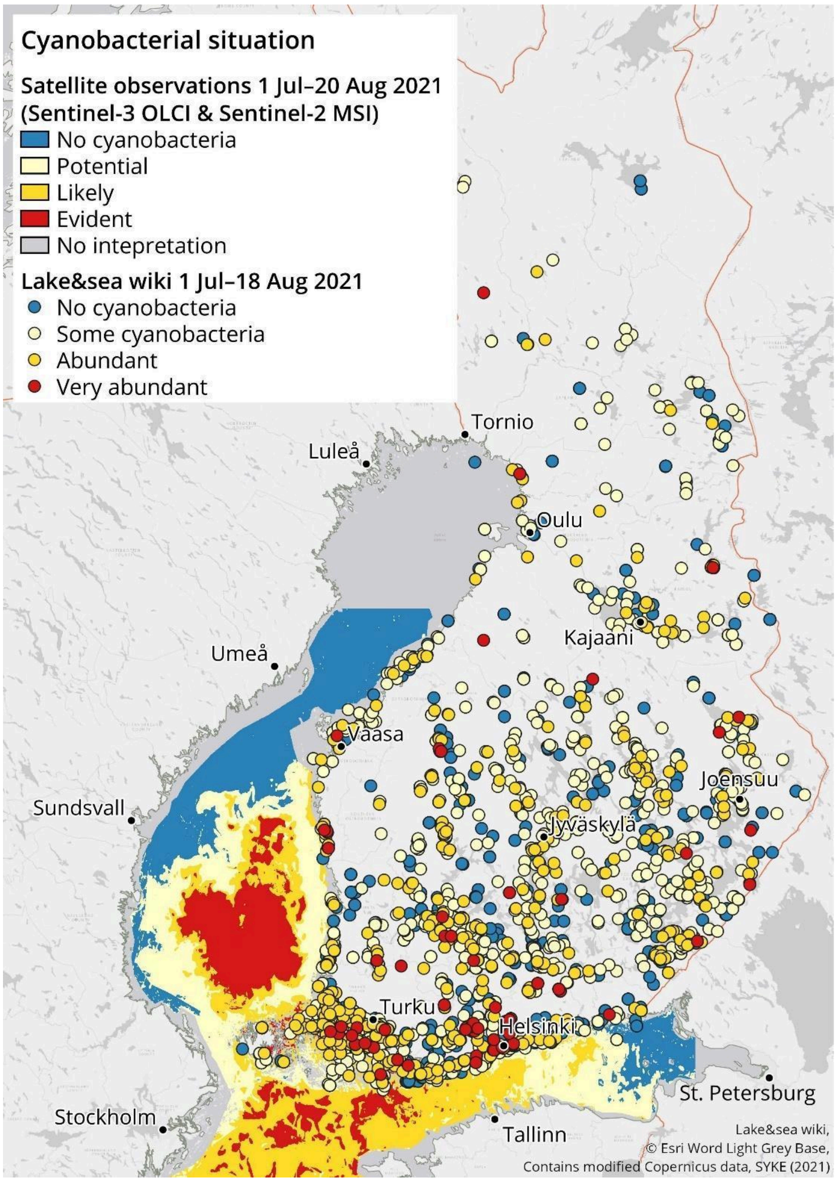


Figure 2.3: *Cyanobacteria observations based on remote sensing and in-situ observations during the summer 2021.*

- **Remote sensing:** in Finland, FMI operates a satellite receiving station in Sodankylä, with access to major polar orbiting satellites. The remote sensing products are used by several institutes for a variety of purposes. The Ocean color observations are utilized by SYKE, while FMI focus especially on SST and sea ice products.

Modelling capacity:

Currently, FMI is using the following operative models:

- 3D hydrodynamic model (HBM, NEMO): temperature, salinity, currents, sea level variation
- 2D hydrodynamic models (OAAS, Wetehinen): sea level variation
- Wave model (WAM): significant wave height, wave direction, wave period
- Ice model (HELMI): ice concentration, ice thickness, different ice categories, ice compression
- Drift model (SeaTrackWeb): drift of substances

2.3.2 Major gaps identified

1. In-situ monitoring:
    a. limited observations on marine biogeochemistry
    b. limited number of physical, biological, and chemical observations from the Bothnian Sea and Gulf of Bothnia
    c. Limited number of observations inside the archipelago areas.
2. Modelling
    a. 3D- biogeochemical model not currently in use in Finland
3. Remote sensing:
    a. Limited human resources for remote sensing data utilization.
4. Data management
    a. Finland currently lacks a National Oceanographic Data Center.
    b. A major gap is that observations from different agencies are not coordinated and harmonized.
    c. Operational near real time (NRT) delivery of non-operational data:
5. Model-data integration:
    a. More operational modelling capacity should be developed

2.3.3 Plans to address the identified gaps

The plans to address the identified gaps listed below are funded mainly by other sources than JERICO-S3, but they support the development of JERICO research infrastructure and are thus described here.

1. In-situ monitoring

   New platforms are currently developed for marine observations especially on land-sea continuum and archipelago areas. These include merging of Gulf of Finland observations carried out by Finland, Estonia and Germany in the framework of JERICO GoF PSS, providing seamless data flows and harmonized data. In the Archipelago Sea, a local ferry operating on regular route will be equipped with a mobile marine weather station including SST observations. On Bothnian Sea, there are on-going negotiations to equip a regular ship operating between Finland (Vaasa) and Sweden (Umeå) with suitable instrument for e.g. sea ice and SST observations, and potentially with a flow-through system.
2. Modelling

   FMI and SYKE are currently investigating the possibilities to start to use NEMO-ERGOM-LIM3-model for the northern Baltic Sea.
3. Remote sensing

   Currently, no major needs for changes
4. Data management

   FINMARI has started a data management group coordinating and planning the marine data issues. In this planning, the focus is on European data bases and existing services. In addition, FMI and SYKE are discussing about the possibility to create a National Oceanographic Data Center node for Finland as a part of national Decade of Oceans- activities.
5. Model-data integration

Data-assimilation combining ARGO-floats and NEMO model are developed. If the use of NEMO-ERGOM-LIM3 model start, it will be utilized together with all suitable physical and biogeochemical observations

2.4 Germany

Germany has two coastlines along the North Sea and the Baltic with very different characteristics. The German Bight is dominated by tides and very shallow with maximum water depths of about 50 m. Large Wadden Sea areas are falling dry during low tide and represent a unique and fragile habitat for a large number of specialized species.

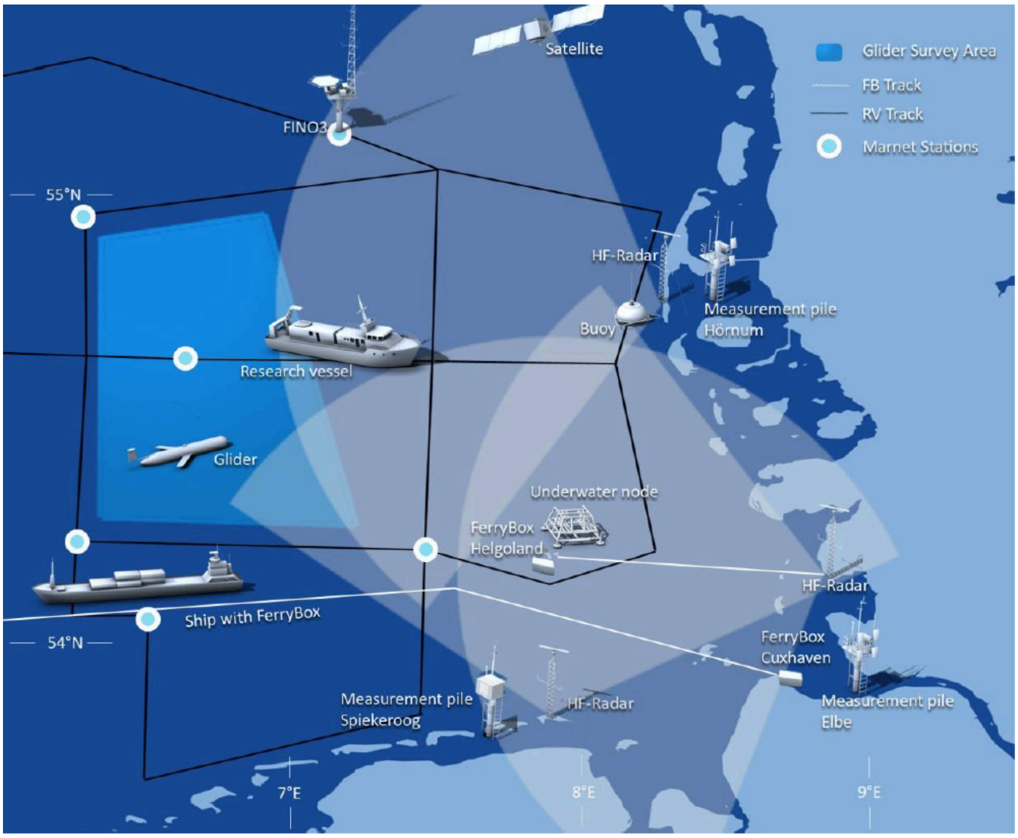
The salinity is dominated by water from the Atlantic and complicated secondary circulation processes take place in the river estuaries of the Elbe, Weser and Ems with consequences for biology and sediment transport processes. At the same time, the German Bight is an extremely busy area with ship traffic to the harbor of Hamburg and extensive and strongly growing activities concerning offshore wind energy.

The following assessment of the status of observations along the German coast puts a little bit more weight on aspects related to offshore wind farming , because this topic is of acute relevance for Germany and it illustrates gaps concerning the monitoring of physical, chemical and biological parameters on different spatial and temporal scales very well. It is also important to emphasize that Hereon is a research institution and not an operational center, i.e. the assessment in this document may be slightly biased towards research aspects and incomplete concerning the operational framework. This issue will be worked on and addressed in more detail in the report to be provided as deliverable D2.3. The close cooperation between Hereon and the Federal Maritime and hydrographic Agency (BSH) and the extensive use of operational observations (e.g. MARNET) by Hereon will help in this work.

2.4.1 Review on existing monitoring capacities

Marine observing:

- **In-situ:** The core element of the in-situ observation system along the German coast is the network of tide gauges with about 19 stations in the German Bight and 32 stations in the Baltic. A significant number of additional tide gauges can be found upstream the rivers (e.g. Elbe, Weser, Ems). Nine stations of the MARNET network (Maritimes Umweltmessnetzwerk) operated by the Federal Maritime and Hydrographic Agency of Germany (BSH) measure salinity, temperature and surface currents (see Figure 2.4 (bottom)) . Furthermore, about 9 wave buoys provide sea state information. Within the pre-operational Coastal Observing System for Northern and Arctic Seas (COSYNA) a number of stationary and mobile platforms measure physical, geochemical, biological and key sediment variables (see Figure 2.4 (top)). HEREON operates three HF radar stations at Wangerooge, Sylt and in Büsum to measure surface currents in the German Bight. HEREON has also operated gliders in the German Bight for certain periods and continues to operate FerryBox systems both on ships and as stationary systems. Regular measurement campaigns are performed with ships (e.g. Ludwig Prandtl), e.g. including scanfish measurements



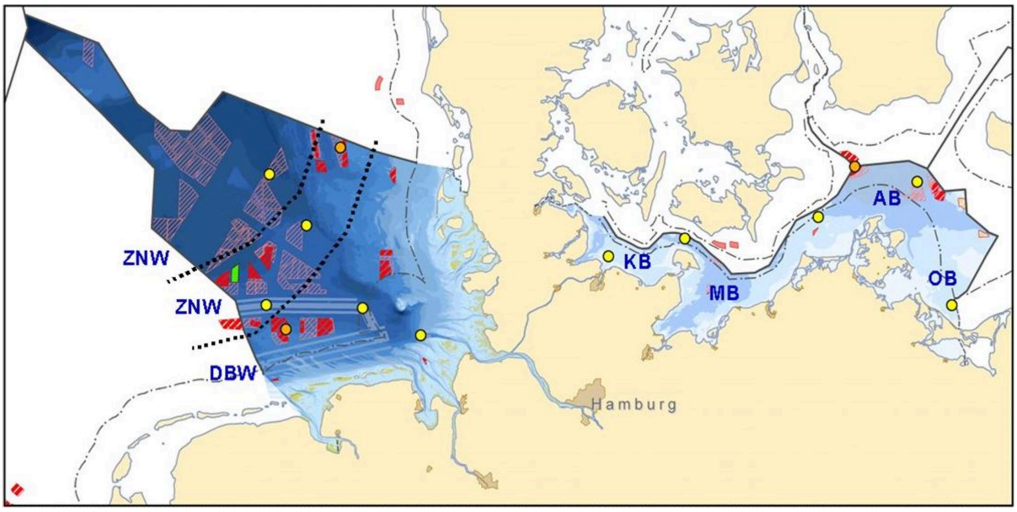


Figure 2.4: (top) Map showing components of the COSYNA observation system. (bottom): Positions of MARNET observation stations operated by BSH.

- **Remote sensing:** In Germany the operational use of remote sensing data in coastal areas is still quite rare. Most of the use is in the context of scientific studies or in test setups at operational centers. HEREON has used satellite SST and altimeter data for validation and assimilation of circulation and ocean wave models along the German coast. This also included studies using recent high resolution CFOSAT data. Optical satellite data were used to study sediment transport processes and for data assimilation. HEREON is also using satellite radar data for the study of high resolution wind fields around offshore wind parks in the German Bight, e.g., wake effects. BSH is using satellite data (e.g. SST) in pre-operational setups for data assimilation. Most of the satellite data is accessed via CMEMS, but in some cases (e.g. TerraSAR-X or CFOSAT) other channels have to be used as well.

Modelling capacity: The operational model forecast for German coasts are performed by BSH. The core element of the BSH model system is the 1 km BSHcmod 3D circulation model for the German coastal water, which is two-way nested into a coarser North Sea/Baltic Sea model. HEREON is using various model setups for the coastal German waters with a strong emphasize on research aspects related to the coupling between atmosphere, wave and ocean circulation. The standard models used in this context are NEMO, WAM and the unstructured grid model SCHISM, which is suitable to analyse small scale processes in the estuaries and rivers or around offshore wind farms. This model has also been used to analyse exchange processes between North Sea and Baltic. On top of these physical models, simulations of sediment transport, biological and chemical processes are performed at HERON with a variety of research objectives. For example, SCHISM-ECOSMO is used for eutrophication and carbon cycle assessments. SCHISM-SED3D is used for simulations of sediment transport processes. SCHISM-ECOSMO-E2E includes additional simulation capabilities for benthos and fish dynamics. SCHISM-Ptrack3 is used for oil spill and marine plastics simulations. A strong cooperation exists between HEREON, the university of Hamburg and the Max-Planck-Institute for meteorology (MPI) in the context of multiscale ocean modelling, e.g. combining the MPIOM and ICOM models with SCHISM.

Model-data integration and hybrid modelling: The core application of observations is still the validation of models used in the operational or research context as well as continuous environmental monitoring. BSH is taking steps towards assimilation of satellite data, but this is not fully integrated into the operational system yet. HEREON has done various studies using observations for the assimilation into models. Recently a study together with the BSH was performed to assimilate a combination of HF radar surface currents, ADPC currents profiles and tide gauge data into a 3D circulation model, which mimics the BSHcmod setup using a 4DVAR approach. HEREON is also working on integration of model and observation information using machine learning approaches, e.g. in the context of short term wave forecasts. A further study was about the use of satellite SST data for data assimilation with a focus on the analysis of the model response to the injection of observation data.

2.4.2 Major gaps identified

Here, we will concentrate on the particular case of offshore windfarming, which is very illustrative and currently of extremely high relevance in Germany. This application is useful as a demonstrator because it demands information on a wide range of spatial and temporal scales as well as across various disciplines (physics, chemistry, biology).

1. In-situ monitoring:
    a. There is information about the lower atmospheric boundary layer missing (e.g. stability) to better understand/predict atmosphere ocean exchange processes (in particular momentum and heat)
    b. There should be more efforts to develop long term measurement strategies to monitor the massive growth of offshore wind farms. This is strongly linked to the error analysis for models available today, because observations are not needed where models are known to perform well.
    c. Insitu measurements used for operational applications are increasingly affected by offshore wind parks. The large scale effects of wind farms in the North Sea are illustrated in Akhtar et al. [2021].
    d. There should be dedicated observation campaigns to analyse conditions before and after wind farm installations
    e. There are too few measurements of the 3D structure of ocean circulation in coastal areas. This is necessary to better monitor possible impacts of offshore wind farm installation with secondary effects on biological processes. The coastal circulation is two-way coupled to the regional dynamics and therefore a variety of spatial scales have to covered by monitoring systems as well (see e.g. Ricker et al. [2020]).
    f. There is a need for more observations of primary production, zooplankton and fish abundance. This will be of increasing importance with the expansion of wind farms.
    g. More precise information on river runoffs are desirable

   h. More frequent updates of the bathymetry, in particular in the tidal dominated German Bight, are desirable. This is of interest in the context of offshore wind farms but is also relevant concerning dredging activities in the Elbe river. Furthermore, a realistic bathymetry of the Danish Straits is critical to capture the connectivity between the North Sea and Baltic Sea with sufficient accuracy (Haid et al. [2020]). The small scale structure of the tidal currents in the German Bight are illustrated with both model and HF radar data in Schulz-Stellenfleth et al. [2021].

2. Remote sensing:
   a. The interpretation of satellite radar data for high resolution wind speed measurements requires additional information about boundary layer stability
   b. Many satellite data are still optimized for open ocean conditions (e.g. altimeter, scatterometer) and more efforts should be invested to optimize them for coastal usage.
   c. Satellite data should be better integrated with existing insitu measurements (e.g. super-observations) in order to get a more consistent picture. This is of particular importance for the extrapolation of surface measurements into the water column, e.g. to extend the memory in an assimilation system.
   d. There should be more and easier to use information about remote sensing observation errors
3. Data management
   a. There should be more efforts to develop long term measurement strategies to monitor the massive growth of offshore wind farms. This is also of relevance in the climate change context.
   b. Ocean observations should be better integrated with atmospheric measurements.
   c. There should be dedicated observation campaigns to analyse conditions before and after wind farm installations, e.g. to validate models needed for scenario simulations.
4. Model-data integration:
   a. More work is needed towards two-way coupled high resolution atmosphere/ocean modelling systems (including waves and wind turbine effects)
   b. More information on model prediction uncertainty is required by end-users. This probably requires model ensembles in combination with suitable observations
   c. Offshore wind farms have to be integrated into operational models, because the assimilated observations are increasingly affected by these installations
   d. Two-way coupled high resolution atmosphere/ocean modelling systems (including waves and wind turbine effects) are required. The SST impacts on atmospheric boundary layer has to be considered in more detail (e.g. coastal gradients related to water depth variations)
   e. More work need to make optimal use of heterogeneous observations (e.g. satellite data affected by cloud coverage)
   f. There is still more work needed with regard to the simulation of higher trophical levels
   g. There is still work to do in order to define best practices for model validation with different types of data (different spatial and temporal correlation properties)

2.4.3 Plans to address the identified gaps

Hereon is involved in a number of projects, in which observations are taken by research institutions over a limited time for specific applications, like offshore wind farming. These data can be very helpful for the improvement of process understanding or the reduction of systematic errors in numerical models. However, long term activities like offshore wind farming require a continuous monitoring of physical and biological parameters to optimise planning, building and operations of the installations. The COSYNA system will be further developed and will play an important role in an application oriented and multidisciplinary monitoring of the German coast. More information about these aspects will be provided as part of milestone MS11 and deliverable D2.3.

2.5 Netherlands – North Sea and Channel Super Site

This chapter focuses on monitoring for eutrophication assessments in the context of OSPAR and MSFD. In 2020 and 2021 the methodology for eutrophication assessments has been revised, using:

- New assessment areas
- New threshold levels and
- Addition of satellite data to complement in-situ observation data for chlorophyll-a.

The methodology has been developed in the JMP-EUNOSAT project (Enserink et al, 2019; Blauw et al., 2019; van der Zande et al., 2019) and has been refined by member states collaborating the OSPAR working groups on eutrophication assessments (ICG-EUT) and ecological modelling (ICG-EMO). The Netherlands took part in these developments. In the process of revising the methodology for eutrophication assessments, several limitations in the currently available observation data have been encountered.

Monitoring data are used in the new methodology in two ways:

- To validate the models that are used to derive threshold values for the indicators winter mean DIN, winter mean DIP and growing season mean chlorophyll-a, as part of the definition and acceptance of new threshold values,
- To compare the current status of these indicators to the thresholds as part of the eutrophication assessment.

2.5.1 Review on existing monitoring capacities

OSPAR eutrophication assessments are based on a dataset that is compiled by ICES, based on data that OSPAR member states provide. For each assessment period ICES creates a separate database that is archived for future reference. ICES also performs part of the eutrophication assessment, with the COMPEAT tool, by comparing the observations in the database to the threshold values per assessment area. To this end the COMPEAT tool calculates the season mean values of indicators per assessment area.

Figure 2.5 shows the number of observations available for the period 2009 – 2014 for the 3 indicators (winter mean DIN, winter mean DIP and growing season mean chlorophyll-a). The figure shows that different countries use different monitoring strategies: some regularly visit fixed locations to create time series with an approximately monthly resolution. The locations are visibly as green to orange circles. They are mostly located close to shore. Other monitoring programmes choose to have cruises crossing different areas and different time periods resulting in every location being visited only once or a few times. These locations are visible as dark purple circles on the map and they generally have a larger spatial coverage, including offshore waters, then the time series locations.

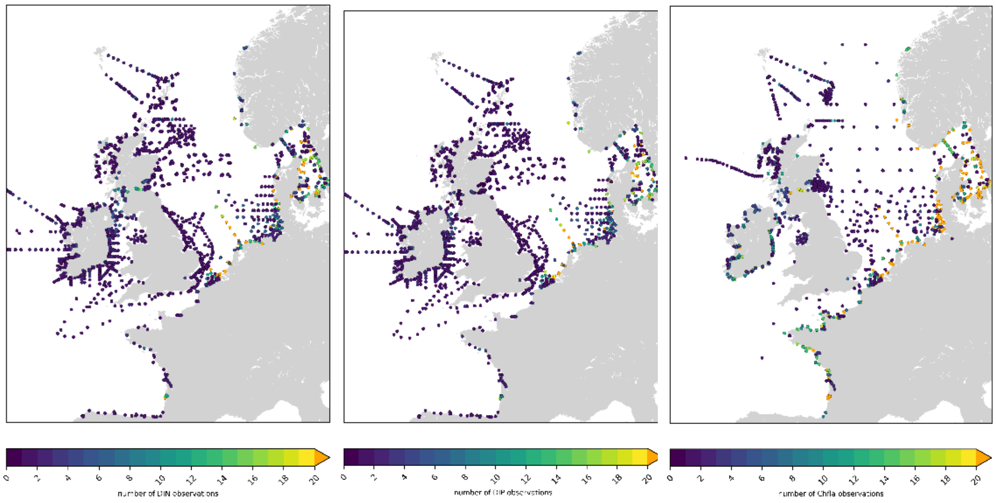


Figure 2.5: Number of observations for eutrophication indicators available in the ICES database, during the years 2009 – 2014 and during the months used in the indicator definition: winter is December – February, growing season is March – September.

2.5.2 Major gaps identified

Since the thresholds for eutrophication indicators are defined as season means, the models have primarily also been validated with season mean values from the observations. For the locations with time series data the observation data were representative of temporal variability within the season. For the locations that were only sampled once or a limited number of times the season mean values were biased by the time of year that the sampling took place. Nutrient concentrations tend to increase from December to February, due to mineralization of organic matter in the water, so observations done in December would lead to a lower season mean estimate than observations made in February. For chlorophyll-a, temporal variability during the growing season is even stronger, so the uncertainty in season mean estimates is relatively large. This is a problem both for the assessment and the model validation. To overcome this problem 3 solutions have been applied. For the model validation, also monthly mean data were used, to limit the bias due to sampling date. Also, additional monitoring locations have been added to the database for model validation, that had not been included in the ICES database before. For chlorophyll-a, satellite data have been included, both in the model validation and in the assessment procedure. These data were particularly useful in offshore waters, where relatively limited observations were available and where satellite data are relatively reliable. In offshore waters, concentrations of colored substances in the water, other than phytoplankton, are relatively low. Hence the algorithms estimating chlorophyll-a from water color are more accurate.

For the assessment procedure, observation data are needed for each assessment area, shown in Figure 2.6 However, for many assessment areas, particularly offshore, limited or no observation data are available during the assessment period.

In summary, for OSPAR assessments a wider spatial and temporal coverage is needed for monitoring data of the main eutrophication indicators: dissolved inorganic nitrogen, dissolved inorganic phosphorus and chlorophyll-a. Additionally, observations of oxygen concentrations in deeper water layers and of primary production would be required to enable the use of these as additional eutrophication indicators.

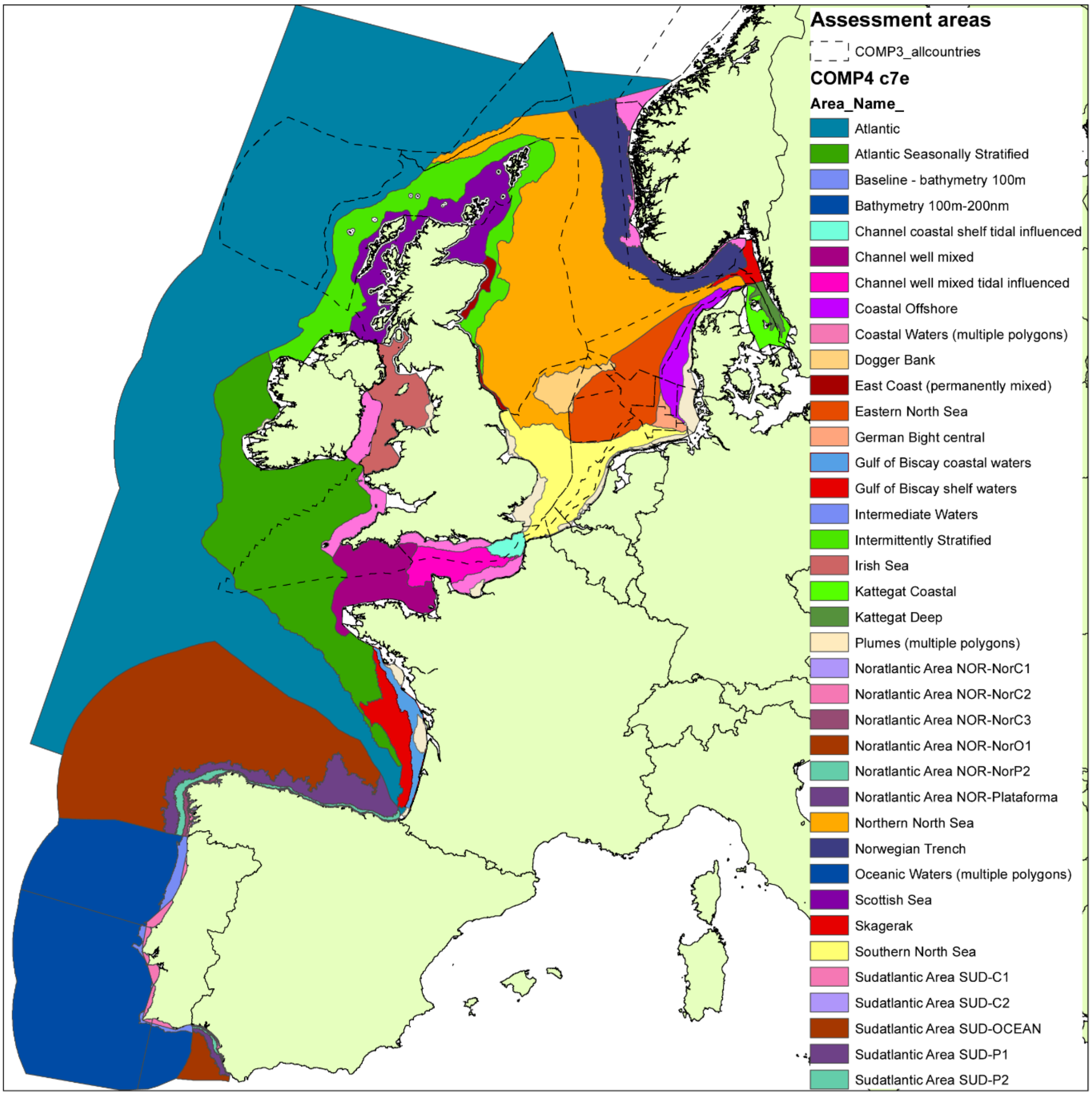


Figure 2.6: Assessment areas to be used in the upcoming eutrophication assessments for OSPAR and MSFD.

2.5.3 Plans to address the identified gaps

OSPAR member states are aware of the current gaps in monitoring programmes but have not yet identified solutions. In the pilot super site research as part of the North Sea and Channel PSS in Jerico-S3 WP4, we are including additional monitoring data sources, such as Ferrybox data to a database to have a more complete coverage of available monitoring data and better insight in remaining gaps. Also, approaches are tested to make sensor data more easy to include in assessments. In the Netherlands we are developing a new Ferrybox trajectory in collaboration with NIVA in Norway, including an auto-sampler to enable a better spatial and temporal coverage of monitoring data.

2.6 Norway

This study covers the Norwegian marine monitoring activities within the territorial waters. Norway has neither signed nor is bound to the regulations of the Marine Strategy Framework Directive (MSFD) but has developed holistic management plans for their regions since the beginning of the 2000s.

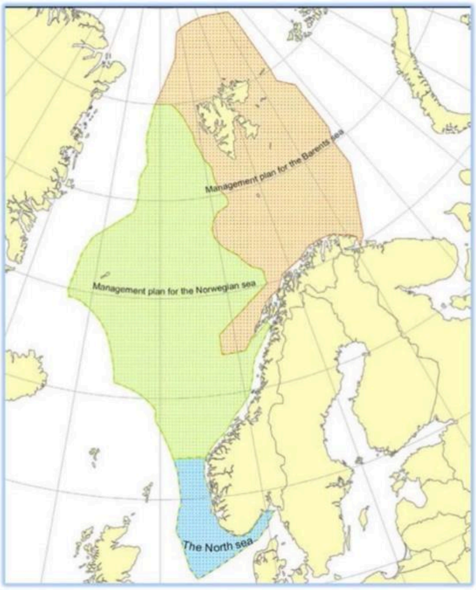


Figure 2.7: Area for the holistic Norwegian Management plans to be monitored for assessments.

Within those management areas monitoring is conducted for assessing the environmental status of the marine area. Within Norway the Institute of Marine Research (IMR) is the main institute conducting the InSitu monitoring activities based on support from the Ministry of Trade, Industry and Fisheries and complemented by the support of the Ministry of Climate and Environment and further institutes.
This InSitu monitoring is complemented by the use of remote sensing techniques as well as modelling.

2.6.1 Review on existing monitoring capacities

InSitu: The core element of the marine monitoring is the research vessel based cruise activity. IMR hosts the Norwegian Research vessel fleet consisting of 6 oceangoing research vessels conducting altogether around 2500 shipdays a year. In addition, those observations are complemented by chartered vessels with around 2000 days a year providing additional information. Furthermore, autonomous vehicles, fixed stations Ferryboxes, SOOPs and further methodologies complementing the monitoring systems. For obtaining the temporal development of the physical/biological and chemical state of the ocean the IMR is conducting observations on frequently repeated transects and station (Figure 2.8, initialized in the 1930s) and in Figure 2.9 an example for the spatial coverage of InSitu observations is given displaying the sites the sites of trawl stations conducted in 2018.

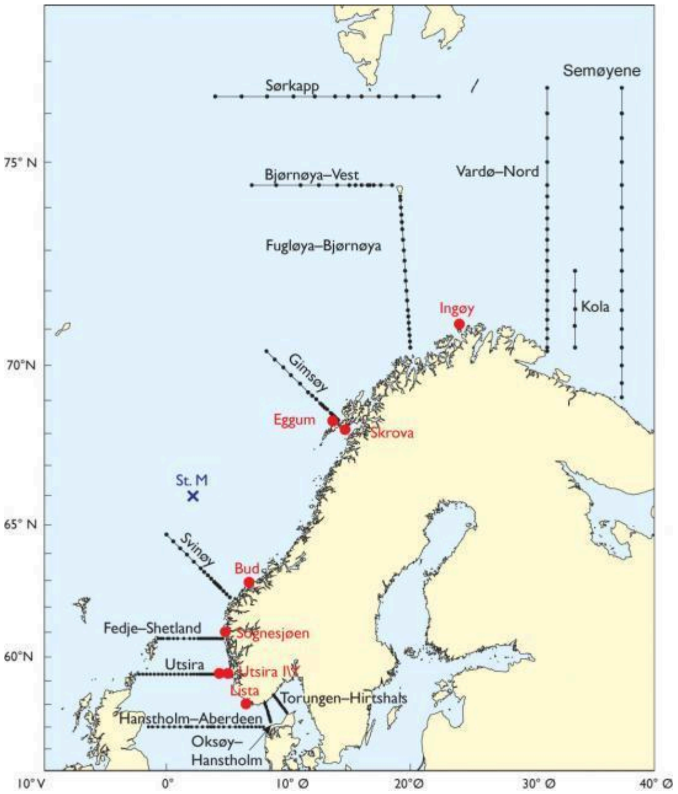


Figure 2.8: Map displaying the position of frequently repeated observation on transects and fixed stations which are conducted for following the variability of the ocean state.

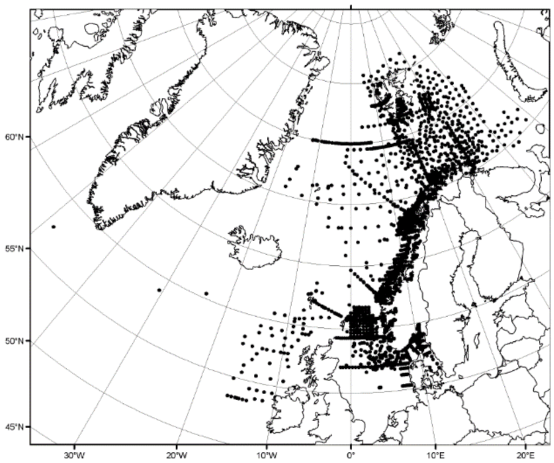


Figure 2.9: Conducted trawl stations for the year 2018 by IMR.

Remote sensing: The analysis of the information of Remotely sensed observation is distributed to several institutes in Norway. Those institutes (such as MetNorway, NERSC, NIVA, NTNU etc) are providing dedicated operational user products to extend information provided via the Copernicus Marine Service production line for the parameters SST, sea ice, sea surface height, winds, waves, chl-a, SPM and optical parameters etc.

Modelling capacity

While the Meteorological Institute in collaboration is mainly aiming on the operational forecasting capacity for the open Ocean, IMR is also in collaboration aiming for the improvement of forecasting the regional near coastal circulation as well as individual based modelling in order to obtain knowledge of disease spreading as well as fish stock behavior. This includes BGC coupled models as well as ocean wave modeling

Model-data integration and hybrid modelling

Hereby, the InSitu and remotely sensed observations are subject to be assimilated or serve as validation data. The main development of assimilation techniques is placed at NESRC. A focal point of development is laid on the use of artificial Intelligence in order to optimize the use of observed capacity

2.6.2 Major gaps identified

Since the coast of Norway is extremely long with a severe number of fjords and rivers, it is impossible to cover the whole coast with InSitu monitoring activities. The Norwegian approach is therefor to identify pilote areas which are aimed to be intensively observed and which can serve as example areas for other regions.
Due to the strong aquacultural activity near shore and the oil and gas exploration activity offshore with their related monitoring programs is the Norwegian area within the focal areas named above relatively good covered by the monitoring. Due to the fact that not all areas can be included in that monitoring (see above) a mapping activity is necessary in order to prove the validity to use the pilote observational approach which is than used for the whole coast.

In addition to that there is a lack of current measurements. To intensify the activity in that direction would lead to a better knowledge of the uncertainties within the model simulations.
Due to the long coastline there are many actors involved in the observational activities. The coordination between the different actors could be subject of improvement

2.6.3 Plans to address the identified gaps

The further integration of the different actors within InSitu monitoring, Remote Sensing as well as numerical modeling under the so called Coastwatch approach which forms the Norwegian contribution on the JERICO Research infrastructure is crucial for addressing the fragmentation of the observational efforts.

2.7 Spain - Northwestern Mediterranean Pilot Super Site

The Italian, French and Spanish monitoring systems are used to reconstruct the 3D dynamics and describe the regional and coastal circulation within the northwestern Mediterranean Jerico-S3 Pilot Super Site. In this area, the Northern Current flowing along the slope from Italian to French and Spanish waters is an essential driver of the regional connectivity. Its path, extent and strength have a significant impact on the transport of materials, contaminants, plastics or fish larvae within the region. Moreover, the instabilities associated with this current generate eddies and potential retention areas which also significantly influence the connectivity patterns and their variability.

The WMOP hydrodynamic modelling system developed at SOCIB is used to integrate the maximum number of transnational observations together with modelling tools through data assimilation. WMOP, together with Copernicus Marine Service models, CNRS-Sirocco-Symphonie and Ifremer-MENOR modelling systems, will be used to describe the dispersal of materials from the Var and Roya river mouths within the PSS region after a major storm event in October 2020. We present here a preliminary gap analysis of the regional monitoring and modelling systems that will be used for this specific connectivity study.

2.7.1 Review on existing monitoring capacities

Marine observing

The map in Figure 2.10 shows all sustained observations from fixed stations, HF radars and gliders routinely collected in the NWMed PSS.

- **In-situ:** the routine observing system is based on a network of moorings, tide gauges and glider endurance lines, completed by regular ship surveys. This network was implemented and is maintained by several institutions in Italy, France and Spain, including CNR, the ILICO consortium, Puertos del Estado, SOCIB, Universitat Politècnica de Catalunya and IEO. It provides observations of T, S, sea level, waves, O2, fluorescence, turbidity, nutrients, carbonate, zooplankton, phytoplankton, genomics, pH. Surface drifters and Argo floats are also regularly deployed in the area.
- **Land-based remote sensing:** the surface currents are monitored by High-Frequency radar systems in four coastal areas, namely the Ibiza Channel, the Ebro Delta region, the French coast between Toulon and Nice and the Ligurian coast.
- **Satellite remote sensing:** satellite provide very valuable complementary measurements of sea surface temperature, sea level, ocean color, surface roughness and surface winds.

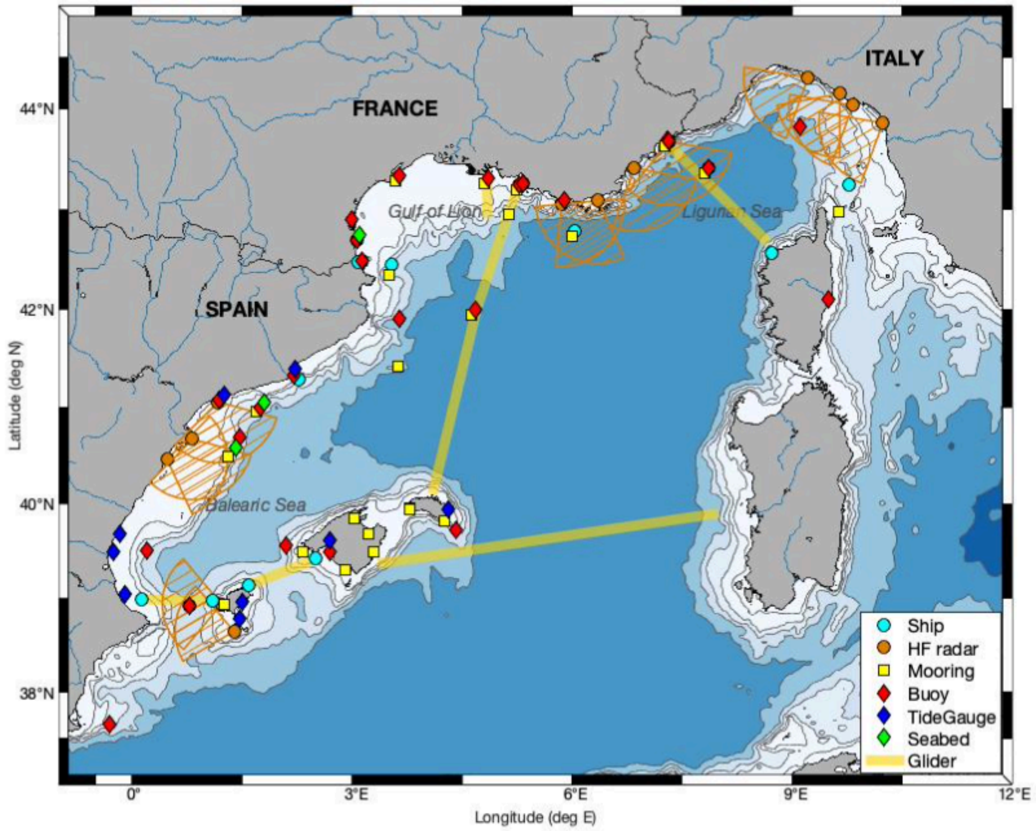


Figure 2.10: Observations from fixed stations, HF radars and gliders routinely collected in the NWMed PSS

Modelling

Several high-resolution models reaching coastal scales are available and will be used to study the connectivity in the NWMed PSS. These models are 1) the Copernicus Marine Service IBI and MED models, 2) the SOCIB data-assimilative WMOP model (SOCIB), 3) the Ifremer MENOR pre-operational model, and 4) the CNRS SYMPHONIE/SIROCCO model. The availability of these different models will allow the intercomparison of simulations, providing insights into the impact of the modelling setups and assimilated data on the representation of the regional connectivity.

Model-data integration

The WMOP model is used to integrate multiplatform coastal observations from HF radar, gliders and moorings along the whole path of the Northern Current. Figure 2.11 shows the position of the observations which are presently assimilated in the WMOP system.

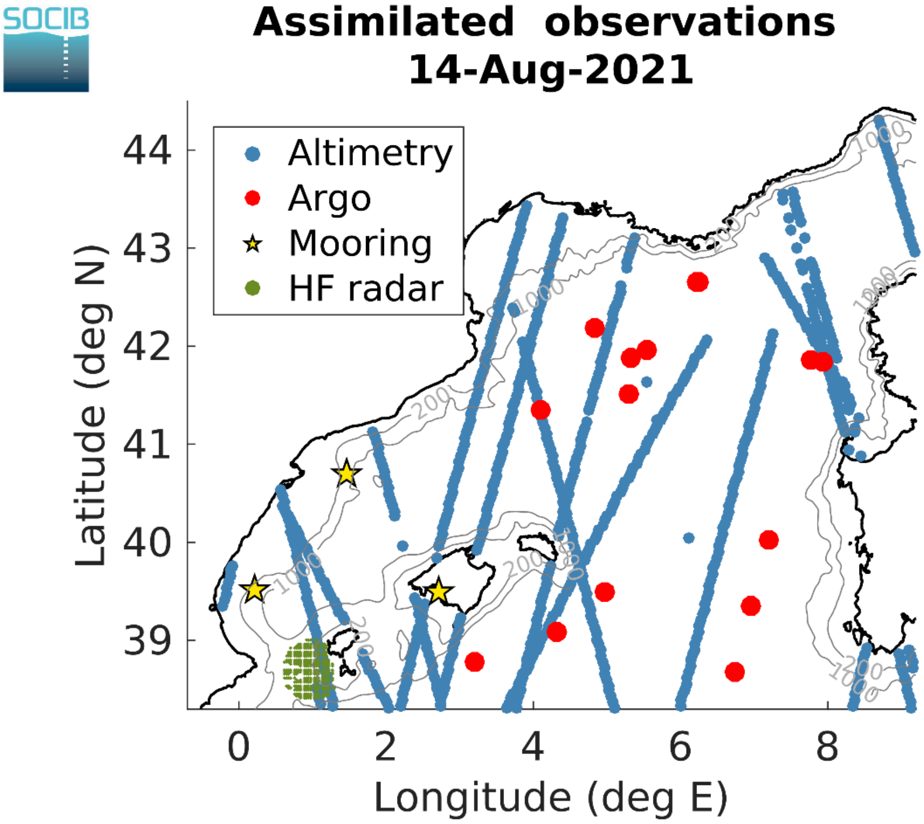


Figure 2.11: Position of the observations which are presently assimilated in the WMOP system

2.7.2 Major gaps identified

Marine observing:

- The whole path of the Northern Current is monitored by altimetry but only at scales larger than O(100)km.
- The details of the circulation are captured by HF radars in specific areas, but most of the NWMed PSS coast is still not covered by the present HF radar systems.
- The Var river discharge measuring system was not working during the October 2020 extreme event.

Data management:

- Access to the data is not fully centralized yet, platforms are being incorporated into the international databases (Copernicus Marine Service, EmodNet) but some data are still missing there.

Model-data integration:

- French moorings, glider observations and Toulon and Ebro Delta HF radar measurements are not presently assimilated into the system.

2.7.3 Plans to address the identified gaps

- Data from the French moorings will be soon incorporated into the assimilation system.

- Research will be performed to assimilate the operational glider data in the simulations. Data access and quality control are two main aspects that will need to be carefully considered.
- The impact of the assimilation of Ebro Delta and Toulon HF radar data will be evaluated before a possible implementation in the operational system.

2.8 Summary on estuarial-coastal continuum monitoring and modeling capacities

This document describes an important milestone in the identification of gaps in monitoring systems run by six European countries. The monitoring capacity in this study represents an integrated capacity by combining in-situ, remote sensing and modelling. The gaps in the monitoring capacity were identified to fit for the purposes in key service sectors, i.e., ocean health, climate change, operational forecast and blue economy. Naturally, the focus of the observing systems not only differs between different countries, but also depends on the institutions running the monitoring systems. The project partners responsible for this document represent a mix of operational centers and research institutions and thus provide a quite wide range of different perspectives.

DMI investigated Danish marine monitoring capacities in national waters, including i) observing capacities, both in-situ and remote sensing, in operational agencies, coastal authority, environment agency and part of observing capacities from Fishery monitoring, research community and commercial companies, ii) modeling capacity, consisting of models for operational forecasting, coastal erosion, climate change adaptation, biogeochemical and lower trophic level models, high trophic level models and models for commercial applications, as well as data assimilation capacities wherever relevant. The existing monitoring capacity is reviewed and gaps are identified to fit for the purposes of information services for operational activities, climate change adaptation and ocean health.

FMI analyzed information on Finnish marine observing platforms, modelling and remote sensing. The focus is on operative observations and modelling, and the research activities listed here are carried out mainly by the Finnish Meteorological Institute (FMI) and Finnish Environmental Institute (SYKE).

HEREON reviewed existing in-situ and remote sensing and modelling (including data assimilation) capacity in Germany, and identified correspondent gaps on the particular case of offshore wind farming, which is very illustrative and currently of extremely high relevance in Germany. This application is useful as a demonstrator because it demands information on a wide range of spatial and temporal scales as well as across various disciplines (physics, chemistry, biology).

Deltares focuses on monitoring for eutrophication assessments in the context of OSPAR and MSFD. In 2020 and 2021 the methodology for eutrophication assessments has been revised, using:

- New assessment areas
- New threshold levels and
- Addition of satellite data to complement in-situ observation data for chlorophyll-a.

In the process of revising the methodology for eutrophication assessments, several limitations in the currently available observation data have been encountered.

IMR study covers the Norwegian marine monitoring activities within the territorial waters. The monitoring gaps are identified to serve the purpose of holistic national management plans for their regions in Norway since the beginning of the 2000s.

SOCIB investigated data needs and gaps in the northwestern Mediterranean Jerico-S3 Pilot Super Site where the Italian, French and Spanish monitoring systems are used to reconstruct the 3D dynamics and describe the regional and coastal circulation in the region. In this area, the Northern Current flowing along the slope from Italian to French and Spanish waters is an essential driver of the regional connectivity. Its path, extent and strength have a significant impact on the transport of materials, contaminants, plastics or fish larvae within the region. The WMOP hydrodynamic modelling system developed at SOCIB is used to integrate the maximum number of transnational observations together with modelling tools through data assimilation. A preliminary gap analysis of the regional monitoring and modelling systems is presented.

Gaps in monitoring capcity for estuarial-coastal connectivity in national level
Although there are differences in the gaps identified in different cases, come common gaps can be identified:

- Need more frequent T/S and BGC profile observations
- Need better BGC data coverage in space
- to integrate observations between operational and non-operational observing sectors
- to improve NRT in-situ data delivery in non-operational observing sectors
- to increase use of coastal observations in modelling via model-observation integration, including assimilation, tuning model parameters, model calibration and validation, hybrid modelling using AI/ML with model data and observations
- to increase use of integrated monitoring and forecast products in non-operational services

3. Marine observing in Baltic-North Sea connectivity

In this study, connectivity of water, nutrients, carbon and pollutants are qualitatively analyzed, observing strategy in the Baltic-North Sea transition waters to improve the understanding and prediction of the connectivity is recommended. A more detailed observation gaps analysis on carbon connectivity is also given.

3.1 Connectivity and monitoring in Baltic-North Sea transition waters

Connectivity, including both exchange and transformation of waters, nutrients, pollutants and biomass between Baltic and North Sea is impotant for blue economy, sustainable marine ecosystems and climate change adaptation. Understanding and prediction of this connectivity is largely dependent on the integrated monitoring capacities both in the Baltic-North Sea scale and in the Kattegat-Skagerrak (KATSKA).

Connectivity of water - the sea water exchange between Baltic and North Sea is dominated by the large-scale transport: the fresh Baltic outflow in the upper layer and dense North Sea inflow in the lower layer, governed by large scale wind forcing as well as density structure of the Baltic and North Sea. For the North Sea inflow, there are 3 sources: water from English Channel, joined with Netherlands and German coastal waters; water from west and central North Sea entering upper layer in Skagerrak and water from North Atlantic entering the deep layer of Skagerrak. According to a recent research (Lin et al., 2022), the waters entering the Baltic Sea from the North Sea are mainly the first two categories. For applications where transport estimates are critical (e.g. pollution, carbon, major inflow events into Baltic) information about bathymetry with higher accuracy and better continuity is required. This is in particular true for narrow straits (e.g. Danish straits) and for areas with strong morphodynamics, e.g. German Bight. This problem is of growing importance with the increasing spatial resolution of numerical models (e.g. unstructured grid models). Assuming that a Baltic-North Sea model can well resolve the Danish straits and correctly simulating Baltic-North Sea open water density structure, if with right meteo- and river forcing and initial T/S field, exchange of water between Baltic and North Sea can be well predicted. Observations (T/S, currents) in KATSKA will mainly be used for calibration and validation purposes instead of assimilation. Such a model capacity is already available, e.g., from HBM and NEMO-Nordic forecasting system operated at DMI and SMHI.

Connectivity of nutrient and carbon - for nutrient exchange, nutrients from UK, Belgium, Netherlands and Germany, after going through local nutrient cycles, will join together with Danish, Norwegian and Swedish nutrient loads as part of the sources entering the Baltic Sea via western Kattegat, the Great Belt and then lower layer saline inflow in the western Baltic Sea. The Baltic nutrient outflow, originated from the Baltic river loads and atmospheric deposition, will dominate the upper layer nutrient transport in the Eastern Kattegat and the Sound. The gross transports are large at the Skagerrak border. Here an inflow of deep water rich in inorganic nutrients enters the Kattegat bottom water, and eventually is mixed to the surface water and re-exported to the Skagerrak, either in inorganic or organic form, dependent on the season. The Baltic Sea outflow to the Danish straits is low in bio-available nitrogen. On the other hand, the North Sea inflow to the Baltic Sea has high bio-available nitrogen due to relatively shorter residence time. Nutrient loads from surrounding lands are important sources of bio-available nutrients comparing to the contribution from the advection. Furthermore, local transformation of nutrients in the transition waters will decide how much the riverine nutrients loads will end in the open waters, thus are also important for Baltic-North Sea nutrient exchange. Riverine loads are well observed in all countries. However nutrient in national EEZ waters are measured with low frequency, thus can be under-sampled in order to reconstruct the 3D structure of nutrient concentrations. The nutrient measurements with higher frequency are needs fo data assimilation.

For carbon connectivity, a review on existing carbon observations and data gaps is made in Annex 1. The results show that 80% of the horizontal carbon fluxes is from advection. Local riverine loads only have a small contribution. This leads to a similar observing strategy with T/S profiles that carbon observations in the transition waters will mainly be used for model calibration, validation and process study, instead of data assimilation. The modelling capacity is essential in reconstructing and predicting the Baltic-North Sea exchange of carbon. Currently observation gaps are identified for lack of pCO2 data in Kattegat, especially high resolution ones, lack of DOC/POC profile data in entire waters.

Connectivity of pollutant - with regard to pollutants both local and non-local measurements are important, which is similar to nutrients. Taking microplastics as an examples, due to relatively long residence time in the Baltic Sea, the biofouling and sedimentation processes, most of the microplastic litter has been deposited in the Baltic Sea before they are transported to the Danish straits. Hence the local riverine inputs of microplastics in the transition waters is an important contribution, comparing with the advection. Local transformation in the estuarial-coastal continuum plays a key role to determine the fate of the microplastics in the sea. There is a lack of observations suitable to follow contaminants from the river scale to the regional scale including observations of the 3D dynamics. For the tracing of pollutants with complicated and variable buoyancy properties (e.g. microplastics) more 3D information on the density structure (salinity and temperatures) of the coastal ocean is required with higher spatial and temporal resolution. The details depend on the specific oceanographic situation (e.g. shallow tidal dominated or stronger control by eddies) and on the status of the existing modelling systems. It is of high importance to distinguish between systematic and stochastic errors in models. For the treatment of systematic errors limited measurement campaigns may be sufficient. For stochastics errors a continuous stream of observation may be required to correct model errors in an operational data assimilation system. It appears that there is still work to do to better understand the model error sources and characteristics in order to better identify the observation requirements for model optimisation and data assimilation for the different regions. For biological parameters, e.g. related to eutrophication, there is additional need for continuous measurements to follow the seasonal cycle.

3.2 A review on carbon observations in Skagerrak–Kattegat for Baltic-North Sea carbon connectivity

3.2.1 Background

The Kattegat-Skagerrak is a key region in the Baltic-North Sea carbon cycle (Fig. 3.1). It receives waters from the Baltic, which drains the rapidly changing FennoScandian Peatland Complex and thus has some of the highest terrestrial dissolved organic carbon concentrations found anywhere in the world, and transfers water to the North Sea where it is ultimately lost to the North Atlantic via the Norwegian trench. The Kattegat/ Skagerrak receives carbon and nutrients from multiple-sources: rivers, subsurface North Sea inflow (Jutland coastal current), upper layer Baltic outflow and deeper North Atlantic waters. The major part of the carbon flux is a net Baltic contribution to the North Sea estimated as 7.7 Tg C /y^{-1} among which 22% are Dissolved Organic Carbon (DOC). The net air-sea flux in Skagerrak is 0.45 Tg C /y^{-1}. The river discharge of carbon in the region is about 0.22 Tg C /y^{-1} with an increasing trend of Total Organic Nitrogen (TON) and Total Organic Carbon (TOC) in the last two decades. Carbon from different sources are transported and transformed between reservoirs (atmosphere, land, ocean and sediments) and between forms (inorganic vs organic, particulate vs dissolved) with multi-scale physical-biogeochemical-biological processes. It is therefore highly relevant to quantify marine carbon cycling in these waters so that the fluxes are resolved, can be compared to those resulting from anthropogenic activities on land, and that society is aware of how our use of the marine waters can influence their role as a carbon source, transformer or sink. The central questions to be addressed are:

- What is the role of (shelf) marine waters in the regional carbon cycle?
- How do anthropogenic activities influence this role at local and regional levels?
- What are the dominant elements or processes determining the role of the region as a carbon sink or source?

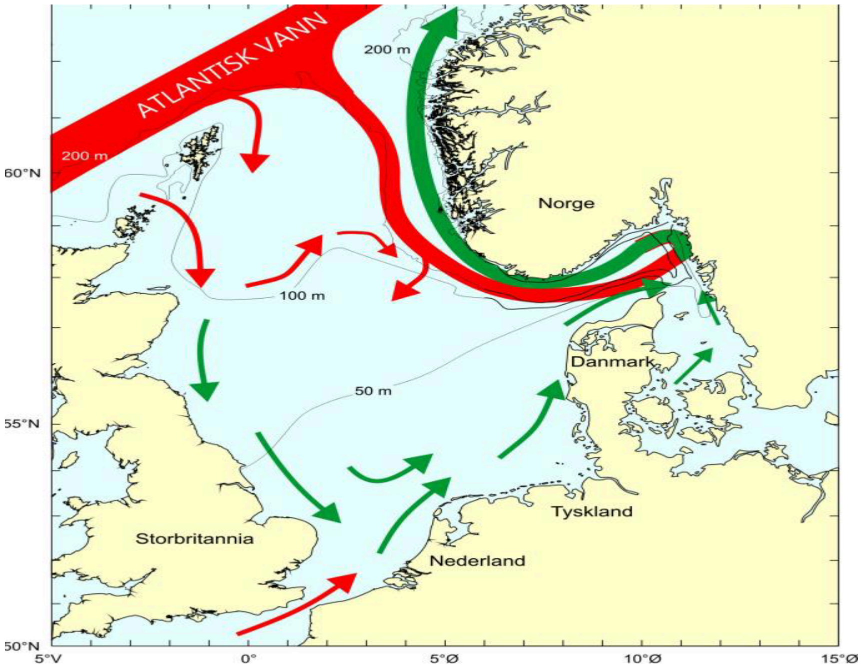


Figure 3.1 Map showing the general surface currents in the study area (Source: IMR)

The carbon observations in Skagerrak-Kattegat region provide essential information for the stakeholders, such as

- **To assess and managing national CO2 budget calculation** to reduce uncertainties due to lack of marine pCO2 information:
  - High resolution pCO2 data from national EEZ waters is needed. Diurnal and short-term variability pCO2 in the coastal waters can be quite high, thus affecting the air-sea CO2 flux calculation.
  - Establish a database on terrestrial DIC/TOC inputs to the coastal waters from rivers
  - The carbon/CO2 budget in the region is largely dominated by Baltic-North Sea water exchange (up to 80%). Non-local factors (e.g. advection) largely steer the air-sea CO2 flux in the region thus the national CO2 budget. Quantitative assessment of the non-local factors is still not available yet.
  - Assessment of the blue carbon system in national EEZ waters
- **To preserve and restore blue carbon system**
  - In the past 140 years, eelgrass coverage in Kattegat has largely reduced. It is estimated that eelgrass in Denmark today constitutes 10%–20% of its historic distribution and that the depth distribution has become more shallow by approximately 50%, resulting in a loss of most offshore populations. Along the Swedish Skagerrak coast, over 60% of meadows have been lost since the 1980s, largely attributed to coastal eutrophication and overfishing of large predatory fish, causing a trophic cascade and an increase in ephemeral macroalgae that smother *Z. marina*.
- **To understand better carbon's role in ecosystem functions** related to primary production, eutrophication and deoxygenation. Traditional assumption is that N/P availability governs the CO2 fixation and carbon export. However recent studies indicate that the assumed C-N/P link is highly variable in the coastal waters. The amount of carbon incorporated into biomass is still not clear.
- **To manage uutrient load** in a changing climate: although DIN has been reduced in past decades, TOC-TON may have largely increased. This will affect the water quality, eutrophication and deoxygenation. The impact of nutrient load is also linked with climate change, with wetter winter and warming water.

3.2.2 Carbon observing: a review on existing capacity

pH and Alkalinity

pH and alkalinity are measured by National Monitoring Program in DK, NR, SE and DE. - New or improved monitoring methodology for pH have been developed by SMHI and BSH. Each year there are $10^{1\text{-}2}$ observation stations in this region. Danish national monitoring program NOVANA has collected 38000 pH observations in DK waters. The Norwegian monitoring program has annual water column observations from the Torungen-Hirtshals section and monthly data from the coastal station Arendal since 2011 (Arendal 2015). Data are stored in Norwegian Marine Data and in Vannmiljø. Regional data are collected in ICES database, as shown in Fig. 3.2 and Fig. 3.3.

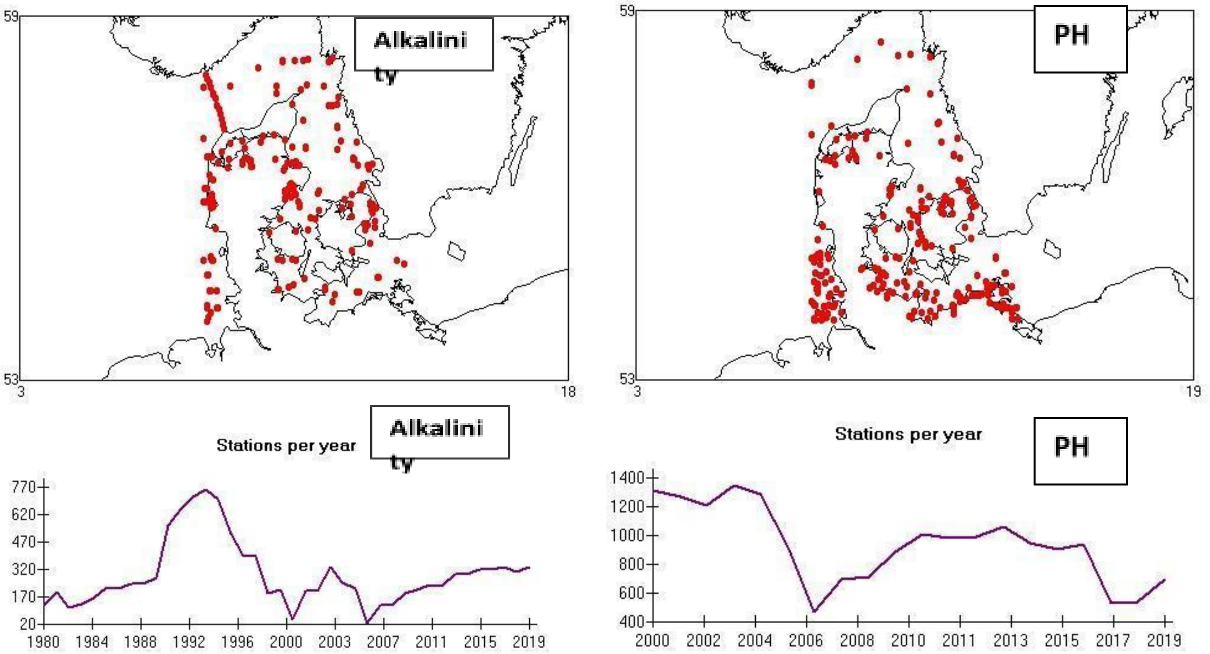


Figure 3.2 Alkalinity and pH data during 1980-2019 (ICES).

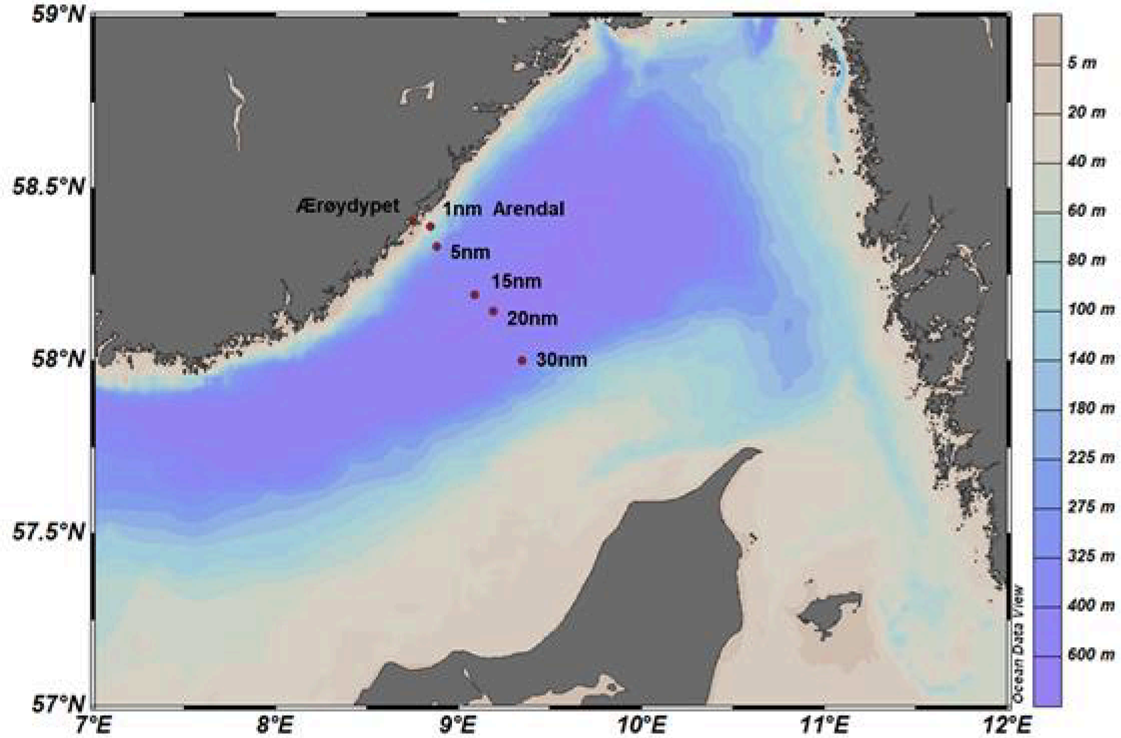


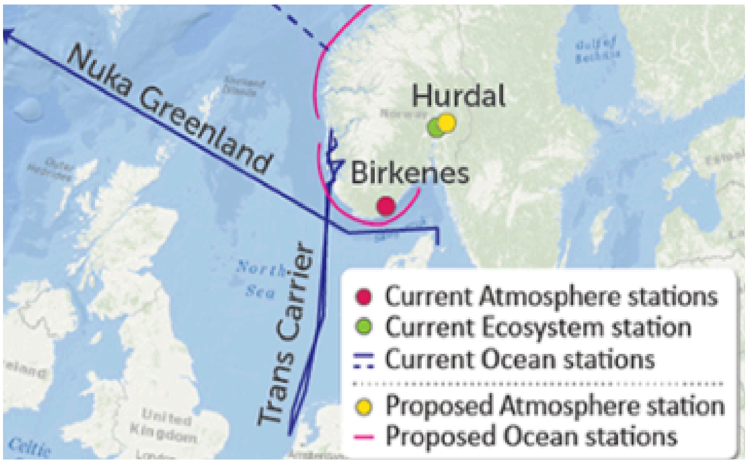
Figure 3.3 Sampling locations from the IMR Torungen-Hirtshals section including the coastal station Arendal where IMR (NO) perform measurements on annual (T-H) and monthly basis (Arendal) since 2011.

pCO2/fCO2

SOOP technology for measuring fCO2/pCO2 has been developed, applied and improved in the past decade, esp. by ICOS community- pCO2 can also be calculated from either of DIC, pH and Alkalinity, e.g. using the program CO2sys: http://cdiac.ornl.gov/oceans/co2rprt.html. The CO2calc software can be found in http://pubs.usgs.gov/of/2010/1280/ or http://cdiac.ornl.gov/ftp/oceans/Handbook_2007/Guide_all_in_one.pdf

Several monitoring and data integration activities have been taken in the region:

- ICOS SOOP cruises contribute to direct fCO2 measurements in Skagerrak. (Fig. 3.4)
- Landschützer (2017) aggregated historical data of pCO2 to produce a 1deg x 1deg, monthly dataset.
- SOCAT fCO2 0.125*0.125deg (Becker et al., 2020)
- EuroGOOS FB Task Team pCO2 data (Macovei et al., 2021, Fig. 3.5)



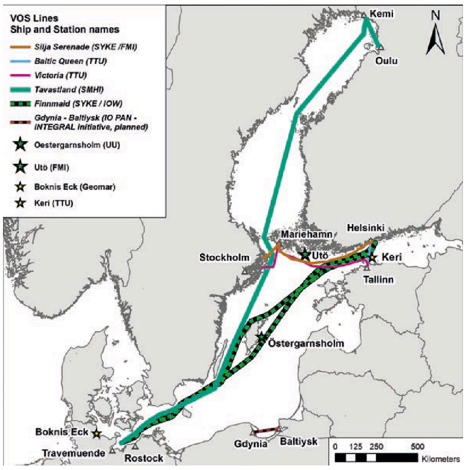


Figure 3.4: ICOS SOOP lines in Baltic and North Sea (Source: ICOS)

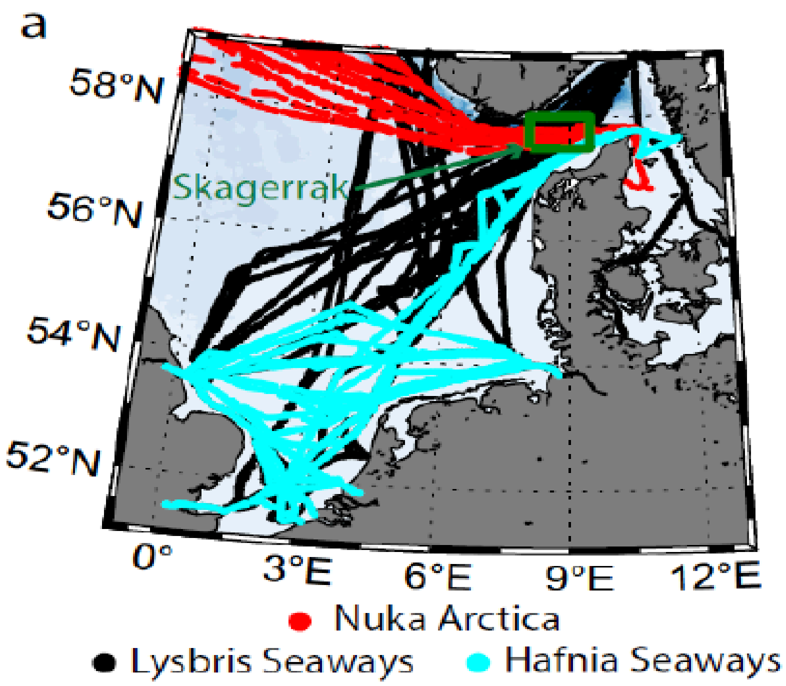


Figure 3.5: EuroGOOS Ferrybox lines with pCO2 measurements (source: Macovei et al., 2021)

DIC/POC/DOC measurements

In addition to pCO2/fCO2, pH and alkalinity, observations are made for DIC, DOC and POC, e.g. cruises data of DIC were collected at 6-10 stations in Skagerrak (2005-2015, Clargo et al., 2015; Omar et al., 2019); national monitoring cruise also provide some DIC, DOC and POC data. However, since carbon is not part of the HELCOM eutrophication indicator, DIC/DOC/POC observing are much less than pH and alkalinity measurements. IMR (Norway) has DIC observations at same sites as pH and total alkalinity in Torungen-Hirtshals as well as at Arendal coastal station. This includes also data on DOC,POC, PON.

Blue carbon measurements

The blue carbon in general includes mangroves, salt marshes and seagrass. In Skagerrak and Kattegat region, the blue carbon is mainly represented by eelgrass. A historical, multi-decadal database is available for the Kattegat (Boström et al., **2014**).

River data

A darkening of coastal waters has been observed in the North Sea and Skagerrak over the past decades. It is hypothesized that this phenomenon might be related to the increased riverine discharge of freshwater (i.e. reduced salinity), as well as the increased discharge of terrestrial organic matter into coastal zones. Deininger et al. (2020) found that, in 5 major NOR rivers to the Skagerrak, although DIN has been decreased but TOC and TON loads steadily increasing especially since 2005.

In 20 years, the Norwegian river monitoring programme surveys several rivers in Norway every year and investigates river water quality with respect to a number of chemical variables (organic and inorganic carbon and nitrogen, acidification, minerals, humic substances and more):

http://ww.vann-nett.no
https://niva.brage.unit.no/niva-xmlui/bitstream/handle/11250/215635/6235-2011_72dpi.pdf?sequence=1&isAllowed=y

Baltic rivers in the region are mainly from Sweden. Table A.1 below shows the TIC and TOC loads. The largest river is Gota. The local Baltic river flux contributes 0.22 Tg C/yr in the region.

Table A.1 TIC and TOC loads in Swedish rivers in the Skagerrak-Kattegat region

River	Country	Latitude	Longitude	Waterflow	TIC	TOC
				km^3/y	Gg/y	Gg/y
Gota	Sweden	57_410	11_540	18.1	63.8	80.5
Lagan	Sweden	56_320	12_560	2.8	4.8	37.9
Nissan	Sweden	56_390	12_510	1.6	3.0	24.5
Ronnean	Sweden	56_160	12_500	0.4	5.4	4.1

3.2.3 Spatial features

The net air-sea flux in Skagerrak is 0.45 Tg C/y, TON and TOC has an increasing trend in Norwegian rivers to the Skagerrak in the last two decades. In the Kattegat, the air-sea flux is negative. The river discharge of carbon in the region is about 0.22 Tg C/y. Major part of the carbon flux is Baltic-North Sea carbon exchange, which is estimated as 7.7 Tg C/y, much larger than the sum of river discharge and air-sea flux. Therefore the carbon condition in the region is dominated by Baltic-North Sea water exchange.

Existing studies found that Carbon exchange between the Baltic Sea and the North Sea is highly hydrology-dependent. Among the effect of salinity, biological processes and air–sea CO_2 exchange on the monthly DIC change in Skagerrak, salinity was one of the major drivers for the DIC change. This simply means that local DIC change is mainly caused by advection (Baltic outflow).

It was also found that DOC plays an important role in Baltic-North Sea carbon exchange.

Air-Sea CO2 flux

It is quite certain that Skagerrak is a net CO2 sink area (0.45 Tg C year^{-1} was estimated, Becker et al., 2020). However, it is not so certain if Kattegat is a CO2 Source or sink area. Becker et al., 2020 showed that it may be a CO2 source area while Lansø et al., 2014 showed that Kattegat is a sink of atmospheric CO2. The estimated air-sea CO2 flux is controlled by several parameters in the applied model setup: choice of transfer velocity parameterisation, wind speed, temperature, salinity, atmospheric CO2 concentration and marine CO2 surface values. Each of these is connected with some uncertainty and errors. The uncertainty in the Kattegat sub-domain is estimated to be up to 50 - 100% because of the relatively small seasonal amplitude, twice as much as in the open Baltic Sea.

Short term variability was detected in the pCO2 of surface water (Dai et al., 2009; Leinweber et al., 2009; Rutgersson et al., 2008; Wesslander et al., 2011). Lack of water pCO2 observations and lack of resolving high frequency variability of water pCO2 can be a major uncertainty in estimating air-sea co2 flux.

Air-sea CO2 flux has a strong seasonal signal: summer season (April-Sep) the water serves as a CO2 sink in all regions while in winter time, pCO2 in the water increased so that some areas can become a source to atmospheric CO2. Studies also found that in some years 1998-20, 2015-16, the marine CO2 uptake can increase quickly, see Fig. 3.6

It should be noted that DIC in the Skagerrak and Kattegat region is mainly controlled by Baltic-North Sea water exchange. The DIC change due to river load and biological processes are much less than Baltic outflow. Thus air-sea CO2 flux in the region is largely decided by the Baltic Sea-North Sea water exchange.

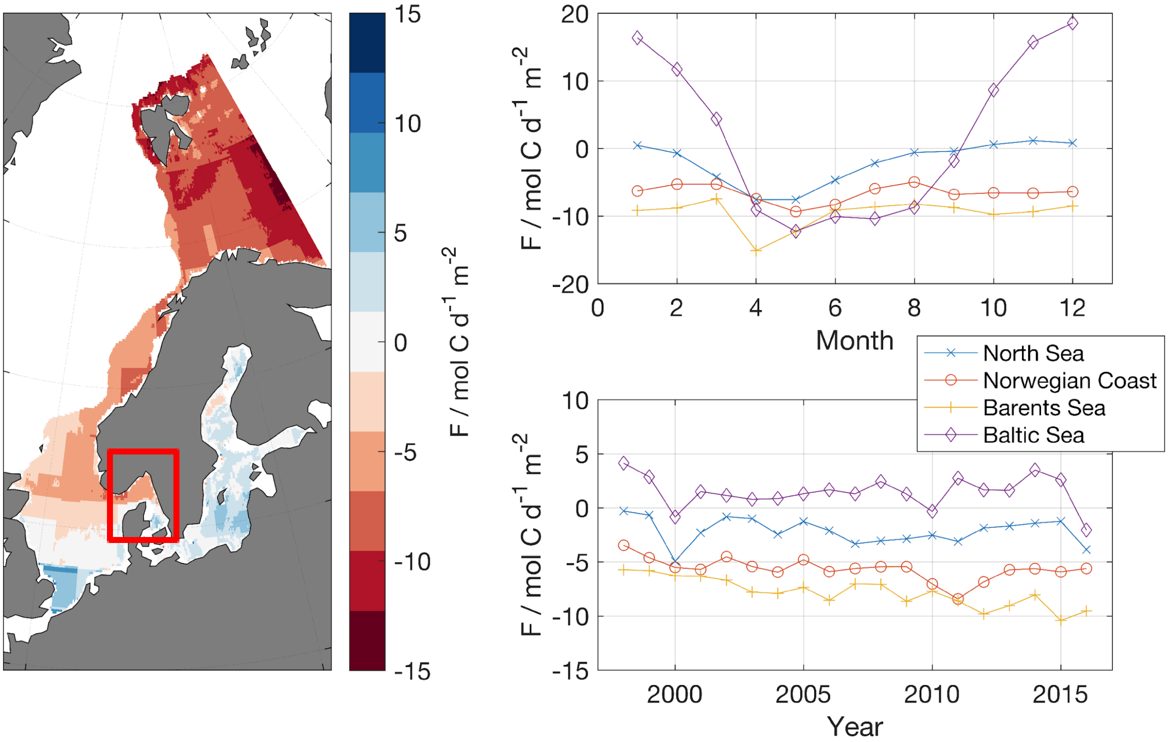


Figure 3.6 The average air-sea CO2 flux over the period 1998-2016 (left hand panel, red colors indicate sink regions, while blue colors indicate source regions, source: Becker et al., 2020).

Analysis of long-term (winter) data revealed statistically insignificant trends in pCO2 and pH in the Skagerrak contrary to the Northern North Sea where stronger and significant trends were observed. Trends in alkalinity and/or biological activity are thought to contribute to the absence of significant trends in the Skagerrak (Omar et al 2019)

Baltic-North Sea carbon exchange

Based on measured DIC and DOC data and DMI ocean model (Hjalmarsson et al., 2010; Kullinski et al., 2011), it was estimated that the export of TIC from Baltic to the North Sea, is 5.5 Tg/y, total carbon is 7.7 Tg/y carbon, among which 22% was from DOC. It was concluded that Baltic Sea is a net source of carbon to the North Sea, carbon exchange between the Baltic Sea and the North Sea is highly hydrology-dependent, and among the effect of salinity, biological processes and air–sea CO_2 exchange on the monthly DIC change in Skagerrak, salinity was one of the major drivers for the DIC change.

Eelgrass in Skagerrak–Kattegat

- Biological pump in the region is not so clear, which should be monitored and simulated
- **Blue carbon - eelgrass *Z. marina*:** in the Skagerrak–Kattegat region has experienced drastic decline over the past 140 years.
- It is estimated that eelgrass in Denmark today constitutes 10%–20% of its historic distribution and that the depth distribution has become more shallow by approximately 50%, resulting in a loss of most offshore populations.
- Along the Swedish Skagerrak coast, over 60% of meadows have been lost since the 1980s, largely attributed to coastal eutrophication and overfishing of large predatory fish, causing a trophic cascade and an increase in ephemeral macroalgae that smother *Z. marina*.

These losses have largely been attributed to coastal eutrophication and overfishing of large predatory fish, causing a trophic cascade and an increase in ephemeral macroalgae that smother *Z. marina* (Baden et al., 2012). Population genetics have also been used to understand how dispersal and gene flow affect temporal–spatial population structure of seagrasses (Hernawan et al., 2016), which in *Z. marina* is driven by dispersal via pollen or negatively buoyant seeds in the range of metres (McMahon et al., 2014), and long-distance dispersal over 10s – 100s km via surface-floating flowering shoots (McMahon et al., 2014) or via grazing waterfowl and fish (Sumoski & Orth, 2012)

3.2.4 Use modelling for ocean carbon cycle research

Carbon cycle in Skagerrak-Kattegat region involved physical-biogeochemical-biological processes in terristial-estuary-coastal-Baltic-North Sea scales. This complicated issue can only be resolved by using an integrated monitoring-modelling approach.

Why modelling is important?

Modelling, as part of the marine monitoring, has been widely used in providing national and European marine services. The marine modelling plays an essential role in understanding the data, filling data gaps, filling the knowledge gaps and optimizing observational networks by

- Integrating different physical, biogeochemical and biological processes into a mathematic framework
- Resolving different scales estuary-coastal-sills-open sea
- Integrating data into models
- Assessing and optimizing impact of the observations
- Predicting high impact ecological events, e.g., impact from flooding, marine heatwaves, algae bloom etc.

Since Skagerrak-Kattegat is the transition area between the Baltic and North Sea, Baltic-North Sea carbon exchange is the largest carbon flux in this region, therefore modelling carbon cycle in this region will need to resolve both Baltic and North Sea, including narrow Danish Straits. Hence a high resolution Baltic-North Sea model is needed. In addition, in order to resolve terrestrial carbon inputs to the sea, an estuary-resolving capacity is also required in the model system.

Current carbon cycle modelling capacities

Ocean-biogeochemical-biological models have been used to investigate carbon cycle in the Skagerrak-Kattegat region, especially on Baltic-North Sea Carbon (DIC/DOC) exchange (Hjalmarsson et al., 2010; Kullinski et al., 2011) and to understand to understand how dispersal and gene flow affect temporal–spatial population structure of seagrasses (Jahnke et al., 2018).
Carbon cycles are now implemented in biogeochemical models without two-way coupling with atmospheric chemistry models. Kuznetsov and Neumann (2013) presented "simulation of carbon dynamics in the Baltic Sea" with a 3D BGC model ERGOM. At present, ERGOM carbon subsystem has been further improved, which can simulate the carbon-related processes in the water and sediment using non-stoichiometry redfield coefficient which largely improve the air-sea co2 exchange simulation. The simulated variables include, pH, alkalinity, DIC, DOC and POC.

DMI currently runs two sets of coupled hydrodynamic-biogeochemical models, both covering the Baltic-North Sea, well suited for detailed processes in the Skagerrak –Kattegat region. One system is HBM-ERGOM, which has a two-way nesting facility which can resolve coastal-estuary continuum in high resolution (eg 100m) and used for process studies; another system is NEMO-ERGOM, which has a single resolution of 1km. This system is now used producing multi-decadal physical-biogeochemical reanalysis in Baltic-North Sea, with data assimilation.

The partners working with DMI on the two modelling systems include Arhus University and BSH (on BGC modelling, assimilation) and SMHI (on NEMO modelling and ocean data assimilation). In addition, Arhus Univ. developed a FLEXsem BGC model for coastal-estuary area with finite element grid and additional eelgrass model.

3.2.5 Sampling strategy assessment and optimal design

Data gaps to fit for the purposes

Air-sea CO2 flux (national co2 budget assessment): Existing ICOS and EuroGOOS FB has a good coverage on pCO2 in Skagerrak and northern Kattegat. In the southern Kattegat, water pCO2 can be estimated from DIC, pH and alkalinity. For pCO2 observations, more observations are needed for Kattegat; high frequency measurements are needed to reduce the uncertainty of the air-sea co2 flux estimation.

Ecosystem management: Significant gaps are identified in the profile observations of DIC, DOC and POC, which was also suggested by BONUS INTEGRAL project. Gaps also exist on our knowledge on the role of carbon in eutrophication, hypoxia and acidification. Without such knowledge, the targeted ecosystem processes for the carbon observing system cannot be well defined.

Climate change mitigation (blue carbon): impacts of light conditions, eutrophication and climate change on the eelgrass are among the most important factors. For restoring eelgrass in the region, the eelgrass seeds can be broadcasted to the favorable nearshore water environment. The process can be monitored. Model can be used to design the experiment and assess its impact.

Existing methodology

Quantitative methods for assessing and optimizing observing networks have been developed in EU projects Optimal Design of Observational Networks (ODON), ECOOP, Operational Ecology (OPEC), JERICO and EMODnet Baltic CheckPoint. DMI is the leading partner of the relevant studies. One method is to use model-simulated physical-biogeochemical ocean as a proxy of real ones and then to sample the proxy with different sampling schemes. The efficiency of the sampling schemes thus can be assessed and optimized in terms of sampling error (e.g., She et al., 1996), effective coverage (e.g., She et al., 2007) and reconstruction or forecast error (She et al., 2018). As an example, the effective coverage of HELCOM-BOOS chl-a observational network is shown in Fig. 3.7.

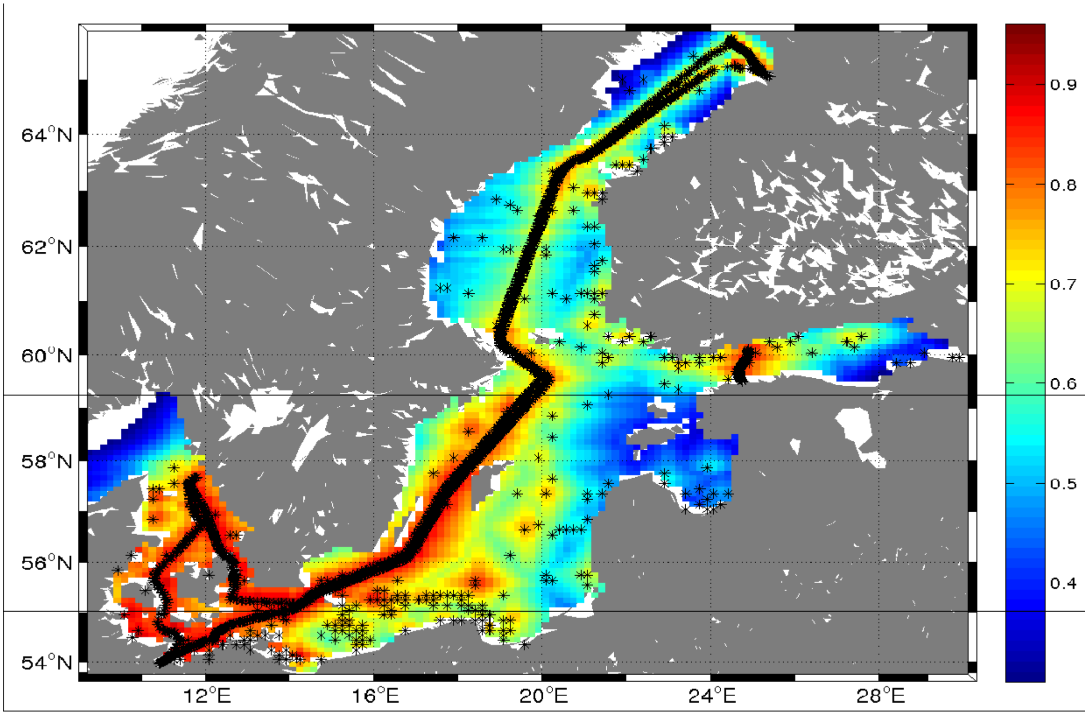


Figure 3.7 Effective coverage of HELCOM-BOOS chl-a observational network.

Optimization of observing networks (recommendations)

The implementation of a carbon (incl. blue carbon) observing system in the S-K region should aim to reduce the uncertainty in national CO2 budget estimation, improving understanding the role of carbon cycle in the coastal-open sea marine ecosystems, the connectivity between Baltic-North Sea nutrient cycle and ecosystem-based management measures on eutrophication and acidification, as well as preserving and restoring the blue carbon system.

Missing knowledge gaps should be addressed by using an integrated monitoring-modelling approach, so that the key carbon-involved processes can be well targeted in the design of the carbon observing system to fit for the purposes. Physical-biogeochemical-biological models should be used as a proxy to assess and optimize the sampling design strategies.

Strategically, homogenization and joined planning of technologies and data between the countries need to be continued.

3.3 Summary on observations for Baltic-North Sea connectivity

Gaps in monitoring capacity for Baltic-North Sea connectivity are identified in following areas:

- Lack of in-situ pCO2, DOC/POC profiles and microplastic measurements in Kattegat
- Lack of high frequency profile observations for currents (hourly) and T/S (synoptic scale) for calibration and validation (cal/val), and biogeochemical variables (synoptic scale) for both cal/val and assimilation in Kattegat
- Integration of existing monitoring capacities, both in national and regional level, are essential. Such integration includes, but is not limited to,
    - to share observations between operational and non-operational observing sectors
    - to improve NRT in-situ data delivery in non-operational observing sectors
    - to increase use of coastal observations in modelling via model-observation integration, including assimilation, tuning model parameters, model calibration and validation, hybrid modelling using AI/ML with model data and observations
    - to increase use of integrated monitoring and forecast products in non-operational services
    - Robotics are prospective instruments in the Baltic-North Sea transition waters: AUV for both shallow (<30 m deep) and deep waters (>30 m deep), sail drones for surface and gliders for the deep waters.

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4. Fit-for-purpose information for offshore wind farms – Part I: requirements and solutions

Abstract

The rapid expansion of offshore wind farms (OWFs) in European seas is accompanied by many challenges, including efficient and safe operation and maintenance, environmental protection, and biodiversity conservation. Effective decision-making for industry and environmental agencies relies on timely, multi-disciplinary marine data to assess the current state and predict the future state of the marine system. Due to high connectivity in space (land–estuarial–coastal sea), socioeconomic (multi-sectoral and cross-board), and environmental and ecological processes in sea areas containing OWFs, marine observations should be fit for purpose in relation to multiple OWF applications. This study represents an effort to map the major observation requirements (Part-I), identify observation gaps, and recommend solutions to fill those gaps (Part-II) in order to address multi-dimension challenges for the OWF industry. In Part-I, six targeted areas are selected, including OWF operation and maintenance, protection of submarine cables, wake and lee effects, transport and security, contamination, and ecological impact assessments. For each application area, key information products are identified, and integrated modeling–monitoring solutions for generating the information products are proposed based on current state-of-the-art methods. The observation requirements for these solutions, in terms of variables and spatial and temporal sampling needs, are therefore identified.

Keywords: spatial connectivity; observation requirements for ocean renewable energy; monitoring in land–sea continuum; integrated monitoring-modeling; multi-scale processes

1. Introduction

1.1. Offshore Wind Farm and Connectivity: Significance and Complexity

In Europe, as is the case globally, there is a need to reduce the use of fossil fuels and replace them with climate-neutral alternatives. In coastal areas, the most rapidly increasing form of new energy is offshore wind energy.

The large spectrum of industrial and research activities concerning OWF is driven by ambitious goals towards climate neutrality, as defined by the European Green Deal. The pressure to rapidly advance OWF technology is further amplified by the recent energy crisis. Wind Europe envisions 450 GW of offshore wind energy generation by 2050 [1]. Although major OWF operations have taken place in the northern European seas (up to 380 GW), there are also planned OWFs in the Mediterranean and Black Seas (Figure 1). More than 26 GW of this energy production is envisioned to take place in northern Baltic Sea areas with annual wintertime sea ice cover. Planning an OWF in cold areas differs from ice-free regions in many respects, and this requires specific observations, including the properties and dynamics of sea ice and icing of structures [2]. The icing of structures also causes significant risks for maintenance personnel during the winter period and directly impacts production due to the icing of blades.

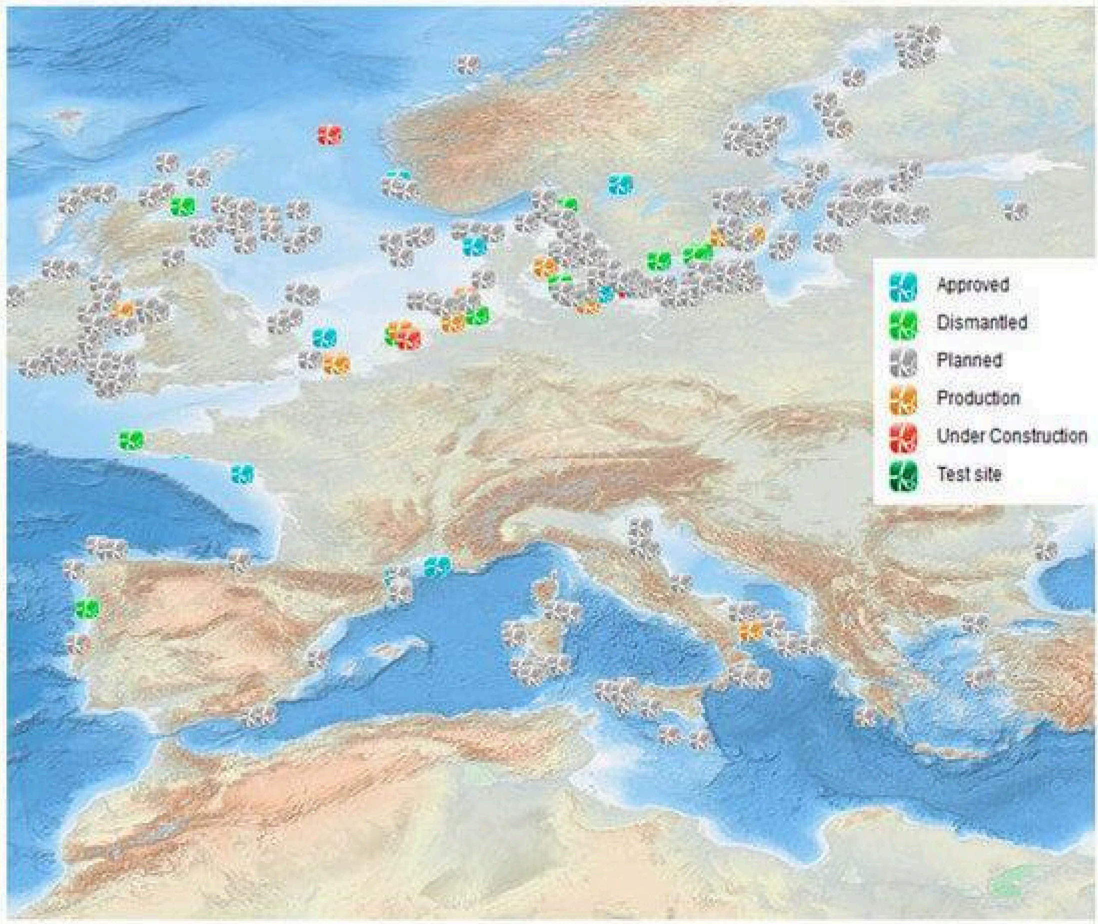

Figure 1. Map of existing and planned OWFs in European coastal seas (source: EMODnet.eu, accessed on 8 June 2023).

The OWF industry involves several different sectors, and the value chain of the OWF industry can be divided into four phases: the development phase (4–6 years), the construction phase (2–4 years), the operation phase (up to 20 years), and the deconstruction phase. During the development phase, the site must be optimally designed so that the farm will demonstrate both high power productivity and safety at a relatively low cost and that it will meet environmental protection requirements. During the following phases, marine forecasts are required for the construction, operation, and maintenance of OWFs. Observations on-site and nearby will be needed concerning air, seawater, seabed, and biota to support both short-term operations and long-term planning and impact assessment.

OWF applications both affect and are affected by several natural and socioeconomic players, between which there is high connectivity. There are two major connectivity aspects to be considered: in space, the OWFs are located in shallow water areas with high land–coast–offshore connectivity (Figure 2); in processes, OWF applications are featured with physical–biogeochemical–ecological–socioeconomic connectivity (Figure 3) [3,4,5]. Spatial connectivity is of high relevance to OWF for several reasons (Figure 2):

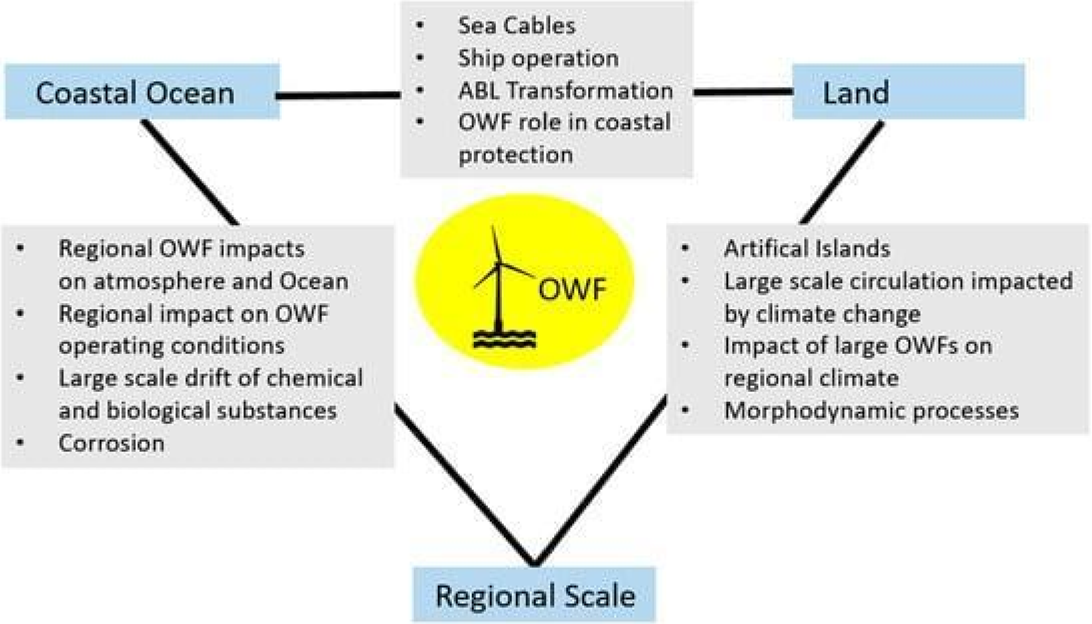

Figure 2. Spatial connectivity relations in offshore wind farm sector.

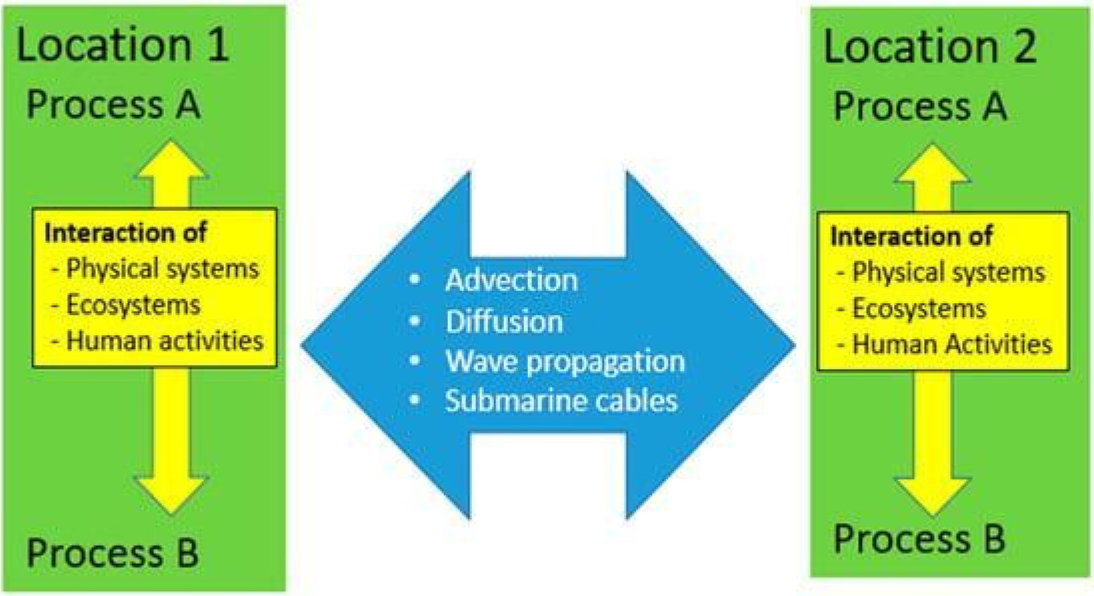

Figure 3. Connectivity represented by interactive processes in the physical–ecological–social systems and their non-local impacts.

- Most OWFs are located in the transition zone between the oceanic and land atmospheric boundary layer [6], where a complex transformation process (including the formation of an intermediate boundary layer (IBL)) takes place, which is conditioned by different ocean processes, e.g., ocean waves and water temperatures.
- OWFs are known to potentially add to the connectivity between different ecological habitats by serving as a habitat themselves. The fact that OWF areas are declared as no-fishing zones plays an important role in this context as well.
- With the growing number and size of OWF installations, the respective impacts on the environment will take place on larger scales and thus contribute to regional connectivity. This concerns the release and drift of substances as much as the impacts on momentum and heat fluxes between the ocean and the atmosphere.
- Sea cables are required to connect OWFs to land, and this comes with several challenges, e.g., related to morphodynamic processes or heating of the sea floor.

- Artificial islands are a recent development leading to new requirements concerning observations and modeling.

The impacts of OWFs on the environment cover a large spectrum of physical, chemical, and ecological system components. With the ongoing growth of installations, short-term operational aspects (e.g., shadowing of one wind farm by another wind farm) must be considered, as well as long-term impacts on ecological systems. The OWF topic is particularly challenging with respect to the information required concerning the multi-scale processes in the ocean/atmosphere boundary layer and marine ecosystems, as shown in **Figure 3**.

1.2. Observation Requirements and Gap Analysis for OWF

To improve the safety and efficiency of the OWF business, a data-driven approach has been adopted by the OWF industry. The digital information for supporting OWF business is generated by monitoring and modeling technologies. A set of monitoring platforms has been applied [7], e.g., grab and sampling, epi-benthic beam trawling, and drop down video (DDV) for benthic surveys; beam trawls, otter trawls, lobster pots, gill nets, plankton nets, or local fishing vessels for fishery and shell fish surveys; boat-based and digital aerial surveys, GPS tracking, and radar and coastal vantage point (VP) surveys for ornithological environmental surveys; visual surveys, static and towed acoustic monitoring, tagging of individuals with satellite transmitters, and remotely controlled video monitoring for marine mammal environmental surveys; met mast, wave buoys, current meters, (floating) lidar for resource assessment, and metocean monitoring; seismic methods, echo sounding, magnetometry, and acoustic seismic profiling for geophysical surveys; vibrocores, boreholes with soil/rock sampling, and cone penetration testing (CPT) for geotechnical surveys; supervisory control and data acquisition (SCADA), remotely-operated vehicles (ROVs), autonomous underwater vehicles (AUVs), and unmanned aerial vehicles (UAVs, mostly multi-rotor copter drones equipped with a digital, thermographic camera) for operation and maintenance (inspection, repair) monitoring. Emerging cost-effective technologies such as ferrybox, HF radar [8], and LoRa (long range)-based wireless sensor networks for monitoring the quality of water in coastal areas [9,10] can also be deployed in coastal areas to provide a significant amount of high-resolution observations for OWF applications. The latter provides a basis for using the Internet of Things (IoT) in marine monitoring for OWF applications.

In addition to the integrated use of monitoring platforms, monitoring strategies, including observation requirements, data adequacy, and sampling strategies for the entire OWF value chain, have also become an important issue as they may significantly reduce the cost and risks of the implementation and operation of OWFs. A summary of observation requirements was provided in an OWF guide report by The Crown Estate and the Offshore Renewable Energy Catapult in 2019 [7]. A summary is provided in **Tables S1–S3**, including surveys on geophysics, geotechnology, hydrography, benthic, fish and shellfish, habitat, birds, marine mammals, and human impacts; monitoring for resource and metocean assessment, data requirements for weather forecasting, metocean conditions, data for corrosion protection, scour protection, offshore cable installation and protection, operation, maintenance and condition monitoring, and decommissioning. However, the description in the guide is very brief. In terms of in situ monitoring activities, only the functions, methodologies, and some measuring variables are mentioned; detailed requirements for spatiotemporal dimensions and sampling strategies are still missing. In recent years, some studies have investigated more detailed observation requirements in a specific application area. Monitoring requirements and strategy for OWF structure health were investigated by Martinez-Luengo et al. in 2016 [11]. In Europe, DG-MARE contracted several so-called "Sea basin check point" projects to assess if European marine data are adequate for offshore wind siting in European regional seas [12]. A fit-for-purpose observation requirement and gap assessment for OWF siting in the Baltic Sea was provided by She and Murawski in 2019 [13]. This study first identified user requirements, targeted information products, and observation and model requirements, then generated the information products based on an integrated modeling–monitoring approach. In this process, the availability of existing observations was mapped, the adequacy of observations was evaluated, and gaps were identified for use in the information product generation. OWF impacts on biodiversity and fisheries are a major focus of many studies. A review of the monitoring requirements and strategy for biodiversity in the Baltic–North Sea was provided by [14]. The NRDC (Natural Resources Defence Council) in the USA also initiated a monitoring guide for marine life during offshore wind energy development in 2023 [15].

There are still a few gaps in the knowledge base regarding the observation requirements and data adequacy assessment for the OWF industry. First, there is a lack of fit-for-purpose analysis for multi-application areas. The current analysis mainly focuses on one application. In addition, a fit-for-purpose assessment regarding targeted information products is often missing [13]. Second, recent research reveals several emerging application areas related to OWF which need extensive monitoring, e.g., multi-use of OWF platforms [16], wake and lee effects of OWFs on atmosphere and ocean environment [17,18,19,20], monitoring for sea bed cable protection [21,22], contamination caused by OWF [23,24], and OWF-related security issues [25,26,27,28]. Observation requirements and adequacy analysis are rarely performed in these emerging application areas. Third, models play an important role in providing the required information in different OWF applications. The capacity of modeling and integration of modeling and monitoring for specific applications is therefore essential for identifying observation requirements and gaps. In addition, remote sensing is also a significant source of surface observations. By integrating in situ remote sensing and models, the fit-for-purpose observation assessment and gap analysis for multi-applications produce more robust results. However, modeling–monitoring integration and the use of multi-source datasets have not been sufficiently addressed in the previous data gap analysis. Fourth, the OWF is a sector with high connectivity in space and human–nature systems. Such connectivity represents links between subsystems with multiple scales and multiple purposes. Depending on OWF applications, information may be required for different scales. For the spatial scale, observations are required to resolve the wind turbine-to-farm scale, inter-farm scale, farm-to-coast scale, and cross-border/regional scale; for the temporal scale, this can be an operational (synoptic) scale or long-term (OWF life span) scale. Existing observation requirements and gap analysis for the OWF sector have not focused on resolving connectivity with multiple spatiotemporal scales.

The purpose of this study is to fill the above research gaps: (i) the observation and gap analysis is based on an integrated monitoring–modeling approach, and satellite and in situ observations, models, and data assimilation are considered for the analysis; (ii) the analysis is performed for six OWF application areas, including four emerging areas for which a fit-for-purpose observation requirement and gap assessment has not been addressed, i.e., optimized monitoring for the protection of sea bed cables; wake and lee effects on atmosphere, sea, and shoreline change; OWF-related contamination; OWF impacts on transport and security. Two other application areas, operation and maintenance (O&M) and ecological impact, as basic OWF applications, have always been affected by the rapid expansion of OWFs and thus pose new challenges; (iii) a fit-for-purpose observation requirement and gap assessment method will be developed, with defined targeted information products in different applications; (iv) the observation requirements and gaps are analyzed for resolving multi-scale processes wherever relevant, e.g., wind-turbine-to-farm scale, inter-farm scale, farm-to-coast scale, and cross-border/regional scale in space, and synoptic and/or long-term (OWF life span) scales in time.

The above research is implemented using a six-step approach: first, the application areas are introduced, and key information products required for each application are identified; second, we propose integrated monitoring–modeling solutions based on state-of-the-art methods to generate the necessary information products; third, required marine observations and modeling capacities for implementing the solutions are identified; fourth, the availability of current monitoring (both in situ and satellite) and modeling capacities are mapped; fifth, based on the work in the third and fourth steps, the adequacy of current capacity can be evaluated, and related gaps can be identified; finally, we provide recommendations to fill these gaps. Due to the large number of application areas and the complexity of the assessment analysis, the publication of the results is divided into two parts: results in steps 1–3 are presented in Part I, and steps 4–6 in Part II.

Part I is organized as follows: Section 2 describes the method and materials; Section 3 introduces application areas and defines key information products; Section 4 identifies the existing and/or potential solutions for generating the products, as well as the associated marine data requirements; the discussion is presented in Section 5, and the conclusion is provided in Section 6.

2. Methodology

The fit-for-purpose analysis method on marine observation requirement and adequacy assessment is adopted from [13], developed and applied in EMODnet Sea Basin Checkpoint projects [12]. Part I implements research steps 1–3. This study is based on the authors' knowledge and research experiences in the related application areas and literature review to identify existing knowledge gaps, user requirements on key information products, potential solutions, and observation requirements. The authors are involved in a variety of research projects, e.g., JERICO—Joint European Research Infrastructure for Coastal Observation, EMODnet Sea Basin Checkpoint projects, OLAMUR—Offshore Low-Trophic Aquaculture in Multi-use Scenario Realisation in North and Baltic Seas, and national information service projects for offshore wind farms, operational oceanography, and environment assessment in Denmark, Finland, Germany, The Netherlands, Norway, and Spain. These projects cover research (observation, modeling, and model–observation integration) and information services on all focused application areas. The individual knowledge and experiences also cover state-of-the-art methods at the institutional and national levels.

2.1. Step 1: User Requirements for Key Information Products

The user requirements for key information products are considered from three categories of users: governmental agencies, OWF operators, and the research community. Requirements from governmental agencies mainly concern the OWF's impacts on the marine environment and ecosystems and confliction with other sea-going activities, which is reflected in the application areas of ecological impact, contamination, and transport and security. Requirements from OWF operators are to reach low cost, low risk, and high efficiency, which is the case in the application areas of O&M and optimized monitoring for sea bed cable protection. Requirements from the research communities include understanding OWF impact mechanisms, filling knowledge gaps, improving the quality of information products, and resolving OWF impacts in the forecast models. This is the case in all six application areas, particularly in wake and lee effects, O&M, and ecological impact applications. These requirements are defined based on the most recent publications, research, and service projects.

2.2. Step 2: Identifying Potential Solutions Based on Integrated Monitoring–Modeling Approach

In this part of the research, solutions for generating the key information products will be recommended based on the best practices currently available. If not available, state-of-the-art monitoring and modeling capacities will be combined to form a potential solution to generate the key information products. In this study, best practices in different application areas tend to be linked with specific national and institutional research and information service practices for OWFs. One may find that O&M-related analysis is mainly based on German practices, sea bed cable-related analysis is mainly based on Danish practices, wake and lee effects are mainly based on Danish and German practices, transport and security are mainly based on Finnish practices, thus focusing on icing waters, and ecological impact related analysis is mainly based on Norwegian and Dutch practices.

2.3. Step 3: Identifying Requirements for Using Observations and Improving Models

Addressing the challenges related to the growing number of OWF installations in diverse environments will require a significant effort both in improving numerical modeling and in the integrated use of modeling and observations, including both satellite and in situ data. On the one hand, there are still many uncertainties about suitable parameterization to include OWFs in models and forecasting sediment transport in the seabed. Optimization and validation of such new model components require dedicated observations of various parameters on a wide range of spatial and temporal scales. On the other hand, OWF installations add complexity to the environment with new challenges regarding forecasts, e.g., OWF will have an increasing impact on the routine observations, which are currently used in data assimilations systems at operational forecast centers. In the six application areas, a large set of models will be used. The requirements for using observations to improve modeling are evaluated with a similar method in **Section 2.2**.

3. Application Areas, Challenges, and Required Information Products

In this section, the six application areas of the OWF sector with high connectivity will be introduced, and challenges and required information products in the six application areas will be identified.

3.1. OWF Operation and Maintenance

Operation and maintenance (O&M) can contribute approximately 30% to the total lifetime costs of an offshore wind farm. Therefore, the optimization of the respective activities is a major factor in the economic success of this technology. In general, O&M costs contain a large variety of components, e.g., spare parts, regular maintenance, insurance, administration, and repair, and each of these items has individual requirements with respect to observation-based information products, as shown in **Tables S2 and S3**. In the following, we will concentrate on two activities that lead to information demand specifically for the ocean:

- Ship operations for OWF maintenance.
- OWF fatigue assessments are needed for lifetime extensions.

According to industry standards, O&M operations are split into two main categories [29]. The first type of operation is "weather-restricted" activities, where the operation is relatively short (typically 72 h or less), and metocean forecasts can be used to obtain information concerning the conditions to be expected. If the operation is longer than that, the activity is classified as "weather-unrestricted", and many more conservative assumptions about the conditions based on long-term extreme statistics must be used to make decisions about the mission.

Usually, strict limits exist for sea state parameters to allow maintenance ships to anchor at offshore wind turbines and to transfer personnel. Typically, insurance companies define significant wave heights of approximately 1.5 m, below which maintenance operations can be conducted [30]. The exact limit depends on the ship size and type. As the costs for the operation of maintenance ships are a major factor, optimized planning of these operations is crucial. Decisions about whether to leave the harbor and go out to an OWF are made based on sea state forecasts, which are, of course, affected by errors.

A strategy for an optimal decision regarding an O&M operation can be designed if two additional pieces of information are available, i.e., the accuracy of the wave forecast provided by a probability density function and the costs associated with the decisions on different operation scenarios.

In this case, the expected costs for a decision to go out or stay in the harbor can be estimated as

$$\text{cost(“stay in harbour”)} = \text{cost(“B”)} \times \text{Prob}(Hs > \text{limit}) + \text{cost(“D”)} \times \text{Prob}(Hs < \text{limit})$$

$$\text{cost(“go out”)} = \text{cost(“A”)} \times \text{Prob}(Hs < \text{limit}) + \text{cost(“C”)} \times \text{Prob}(Hs > \text{limit}),$$

and the scenario with the lowest expected costs can be chosen.

To make this optimal decision, a wave forecast product, together with its uncertainty estimation, is required. The product should cover the area of OWFs and surrounding coastal waters. We will explain in **Section 4** that such a product contains several important connectivity aspects.

The second application in the context of O&M is related to OWF lifetime extensions. Typical lifetimes of OWFs are 25–30 years, and any potential extension of that lifetime has beneficial consequences for the overall costs of the OWF life cycle. One important factor for a decision concerning a lifetime extension is the fatigue and extreme loads experienced by the OWF throughout its lifetime. As before, ocean wave conditions, particularly extreme sea states (and in the northern sea areas, sea ice), play an important role in this context. Similar to the case of the wave forecast, such a product contains several connectivity aspects; however, the details are a little bit different and will be explained further in the next section.

3.2. Protection of Submarine Cables

There are several challenges related to sea bed geological properties in the installation and protection of submarine cables. These include bedrock and hard sediments, boulder fields, sea bed gradients, mobile sediments, acoustic blanking, gas/fluid seepage features, sediment instability, and man-made activities and features such as fishing and debris. Among them, the responses to the mobile sediment and sediment instability are extremely challenging as the situations are highly dynamic and variable. A comprehensive geological survey is required to assess all these factors before installing the cable (Table S2). Near and offshore sea beds can be highly variable in space with sand dunes, channels, bunkers, and depressions, as shown by existing surveys [31]. Most often, these features are related to sediment transport, entrainment, and erosion. Since these processes are highly dynamic, geological properties in the areas with mobile sediments will also be dynamic. The moving sediments may bury or expose the cable, which should be avoided since excess burial depth may result in overheating, and exposure will leave cables vulnerable to damage.

Several solutions have been applied for protecting cables in mobile sediment areas, e.g., pre-dredging or pre-sweeping the cable route prior to laying and trenching, using rock placement on top of the laid cable. However, due to the dynamic sediment environment, ongoing maintenance is required. Frequent burial depth measurements and burial remediation, for example, on a yearly basis in critical areas, are often used as an economically viable mitigation method. For the industry, it is essential to know where the critical areas are and how fast the burial depth changes in the critical areas. In addition, the impact of sea ice on cable protection needs to be taken into account in the northern Baltic Sea since packed sea ice can reach depths of tens of meters [32]. Hence, the required information product is the changing rate of the sea bed sediment layer and the packed sea ice information. The product should cover areas around the cable arrays.

For this analysis, we use cable protection in Danish waters as an example (Figure 4). Danish cables are placed not only in Danish waters but also connect to Norway, Sweden, Germany, the UK, and other countries. In Denmark, submarine cable protection is managed at company and community levels, promoted and coordinated by the Danish Cable Protection Committee (DKCPC), an association of gas, telecommunication, and electricity companies owning submarine cables and pipelines in Danish maritime territory.

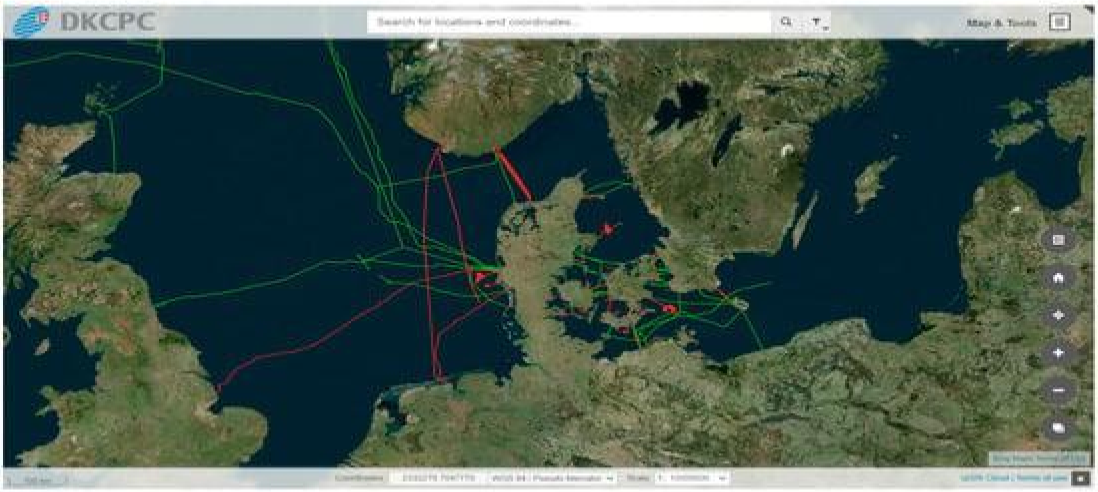

Figure 4. Submarine cable lines connected in and to Denmark, as of 3 December 2022, including power cables (red) and telecommunication cables (green) (source: The Danish Cable Protection Committee (DKCPC)).

3.3. Wake and Lee Effects

Recent research found that OWFs have significant wake effects, which have been captured by both in situ [17] and satellite observations, as shown in Figure 5. OWFs can cause a 2–20% reduction in mean downstream wind speed at 10 m above mean sea level, with some wakes extending over 100 km. The average wind wakes are 20–40 km in size, suggesting that future offshore wind farms should be built at least that distance from the nearest neighboring wind farm site [18]. The OWF wake effect also changes air–sea boundary layers such as air and sea temperature, visibility, and icing, as well as changes the local waves, currents, water mixing, suspended particulate matter (SPM) transport [33], and sea ice formation. The wake effect is largely determined by OWFs' output power capacity, the farm layout, and air–sea temperature differences [34]. The change in the winds may significantly affect wind power prediction, and changes in water mixing and SPM may degrade water quality and further affect marine ecosystems. Hence, wake effects should be included in weather, ocean, and ecological models to provide better predictions.

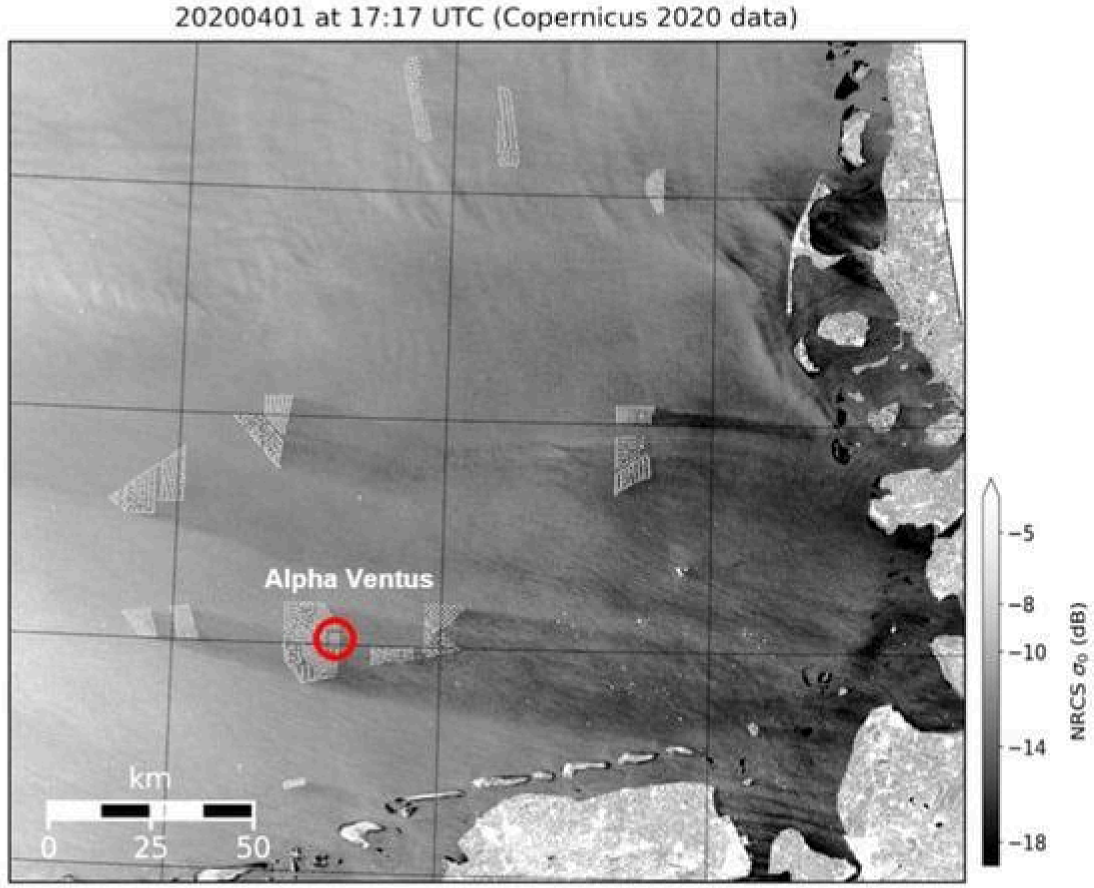

Figure 5. SENTINEL-1A satellite radar image acquired on 1 April 2020, showing atmospheric wakes downstream of offshore wind parks in the German Bight (Copernicus 2020 data). The grey values correspond to the small-scale sea surface roughness, strongly correlated with near-surface wind speeds. The red circle indicates the location of the first German offshore windpark, "Alpha Ventus", commissioned in 2010, with the measurement platform FINO-1 on the left side.

The hydrodynamic impacts are transferred to the ocean via two routes: (1) modification of the wind field affecting the wave and current fields, and (2) wind turbine foundations' direct effects on ocean waves and currents and consequently on turbulence, mixing, and vertical stratification [35]. Existing studies [19,20,36,37] found that wind turbine foundations could extract energy from the background currents, enhancing turbulence mixing in the wakes.

A modeling experiment showed that the wave height could easily be reduced in the order of 4–5% 2 km down-wind of the OWF and up to 2% 10 km down-wind. The direction of the incoming waves is also modified [38]. The lee effects of the OWF result in sediment accumulations similar to what can be seen behind shore parallel offshore breakwaters. The sediment is accumulated as a salient, for which the sand can be taken from neighboring beaches, thus leading to shoreline erosion. The change in shoreline is on a scale of a few meters every ten years, depending on the location and layout of the OWF and the natural conditions (nearshore currents, waves, and beach types), etc.

In this application, OWF users will require improved weather–ocean–ice–wave and sediment–biogeochemistry predictions by resolving the wake effects and assessing their long-term impacts. The information products required in this application comprise the change in weather and ocean conditions (e.g., winds, waves, currents, SPM, turbidity, and sea bed sediments) and long-term shoreline change rate per coastal stretch due to OWFs.

For the research community, parameterizations of OWF impacts in weather–ocean–wave–SPM models are still underdeveloped; thus, observation products on wind profiles, waves, currents, T/S, and SPM in the wake area are required to calibrate and optimize model parameterizations.

3.4. Impacts of OWF on Transport, Maritime Safety, and Weather Forecasting

OWFs also impact the human use of marine areas. There are two specific aspects relevant to Northeast Europe. Firstly, the Northern Baltic Sea is covered with seasonal ice, typically between November and May [39]. In addition to the direct mechanical impacts on windmills, large OWFs impact the normal movement of sea ice by creating artificial areas where sea ice fields freeze more easily, and fast ice may form instead of moving ice fields. Thus, the locations of OWFs have an impact both on local ecosystems and shipping traffic requiring ice-breaking activities. The changes in sea ice may also impact the icing of windmill blades and thus reduce/increase the expected annual energy production depending on the direction of changes [40]. The sea ice also impacts the OWF inspection and maintenance (Section 3.1 and Section 4.1), such as the sea state.

Secondly, large wind farms have an impact on marine vessel radars [25], HF radars [26], marine surveillance radar networks [27], and weather radars [28]. The continuous movement of blades creates disturbances on the backscatter of the radar signals, and as the wind direction and speed continuously changes, forecasting the signal disturbances is challenging and, in some cases, not possible, even with state-of-the-art radar technology. The military aspects of this second challenge have led to a situation where large sea areas in the eastern Gulf of Finland, the Baltic Sea, are currently excluded from wind energy production. These military aspects are also connected to the protection of submarine cables; with an increasing share of energy produced with OWFs, submarine cables are part of critical infrastructure, and surveillance radars are thus an essential part of cable protection.

From a forecasting and research perspective, OWFs may influence observations of surface currents and waves from HF radars, sea ice movements from coastal radars [41,42], and meteorological observations over the sea from weather radars (providing, e.g., wind field observations used as inputs for wave forecasting models), and thus the existing and planned locations of OWF must be taken into account while designing the observing networks and methods to fill the meteorological observing gaps within and behind the OWF.

Due to security issues, a significant part of radar-related research is not public, and to support open discussion and fact-based decision-making, more open and independent academic research is necessary in this field of research [43].

In these applications, the national weather surveys and maritime authorities require methods and measurements to fill the radar observation gaps related to wind and precipitation observations and marine surveillance in the areas shadowed by the OWFs. Additionally, in situ observations are required to address the changes in ice field motion and sea ice processes.

3.5. Contamination Assessment and Response

OWFs can also be at the origin of a release of contaminants in the ocean. Protection systems used to ensure the durability of offshore infrastructures in the highly corrosive marine environment are based on either cathodic systems, increased steel thickness, or chemical coatings. These protection systems emit metals such as Aluminium, Zinc, Cadmium, and Indium (metal emissions) or organic compounds (chemical emissions) such as Bisphenol A [23,24]. These emissions can be as large as 45 tons of Aluminium and 2 tons of Zinc per year for a wind farm with 80 turbines [23]. Moreover, the transportation, construction, and maintenance of OWFs also imply an increase in ship traffic and the probability of marine pollution accidents.

The above emissions mostly occur in the OWF site, steadily for the OWF lifespan, and may also affect surrounding areas due to the transport of the contaminants emitted by the OWF. In such a case, the three-dimensional distribution of the pollutant concentration in the seawater, sediment, and biota, both in the OWF site and surrounding waters, is a key information product for impact assessment and response. Knowledge of the regional oceanographic connectivity and observations is necessary to characterize ocean transports from the OWF sites toward the rest of the ocean basins.

3.6. Ecological Impacts of OWFs

The construction and operation of OWFs can have significant impacts on marine ecosystems and the habitats of marine organisms through different pathways. Ecological impacts are mainly caused by changes in (1) noise, (2) habitat, (3) electromagnetic fields, and (4) water quality. Moreover, the rotator blades of the OWF can pose a collision risk to birds and bats. An overview of potential effects on the marine ecosystem is provided in [24,44] for floating OWFs by summarizing the existing literature.

Underwater noise: during the construction and operation of offshore wind farms, underwater noise is generated, which may affect marine life. The assessment should evaluate the sound propagation, intensity, and frequency to understand the potential impacts on fishes, mammals, and sea birds, particularly those that rely on acoustic communication.

Noise mainly acts as a disturbance that many swimming marine organisms would try to avoid. Fish, mammals, and many invertebrates can perceive vibrations associated with low-frequency sound and react via changes in behavior, physics, or physiology [45,46,47]. Most of the focus on invertebrates in the literature concerns the harmful effects of impulsive noise and vibrations [48,49], but continuous noise can also lead to behavioral changes [50]. Therefore, it is possible that increased noise levels are one of the reasons why the facilities are quickly colonized by bottom-dwelling invertebrates [51,52]. A three-dimensional noise distribution map in the OWF and surrounding waters, together with biodiversity data before and after the OWF installation, is required to conclude whether noise from wind turbines will have mostly positive or negative effects on invertebrates.

Habitat alteration: during the operation phase, both the benthic and pelagic habitats are changed by the presence of underwater structures, such as support foundations and cable protection systems, which can create artificial reefs. Studies from some European countries show that the turbine foundations have a clear positive effect on the occurrence of algae and benthic animals through fouling. This means that many species of fish are attracted to the facilities. It is uncertain whether the increase in the area around the wind power plants is only the movement of local fish or a real increase in the population [53]. Furthermore, the benthic habitat can be indirectly affected by enhanced turbulence in the wake and by reducing the impacts of bottom-trawling fisheries. Lastly, the pelagic habitat is affected through a chain of cascading effects through the ecosystem, starting from the direct impacts described above, with culminating effects throughout the food web within the OWF and stretching far beyond the OWF due to wake and lee effects. Due to the changes in benthic habitats, more opportunities for invasive species may be created. Understanding the nature and magnitude of these ecological impacts is crucial for the sustainable development of OWFs and minimizing their impacts on marine biodiversity. The information products needed for this application are habitat change and its potential impact on organisms and their associated ecosystems.

Electromagnetic fields (EMFs): submarine cables and electrical infrastructure associated with OWFs emit electromagnetic fields and potentially impact marine creatures [54]. Different fish species have shown different sensitivity to changes in EMF by either showing changes in behavior [55] or no reaction [56]. The information products required in this application are EMF levels and their potential effects on migratory patterns, behavior, and sensory systems of marine species.

Collision risk: offshore wind turbines can pose collision risks for birds and bats, especially during migration or feeding activities. Impact assessments analyze the species composition, flight patterns, and population densities to estimate the potential risks and inform mitigation measures. Observation of this direct impact on bird populations is complicated because birds that are hit cannot be collected below the wind turbines as is performed for wind turbines on land [57]. In the absence of observation data, models are commonly used to calculate collision risks, e.g., in [58].

Indirect effects: the ecological impact assessment should also consider the indirect effects of OWFs, such as changes in water quality, sedimentation, and the food chain. These factors can affect the availability of prey species for fishes, mammals, and sea birds. Modeling studies and satellite data show wake effects on vertical mixing, enhanced suspended sediment concentrations [59], the break-up of stratification, and big changes in primary production. This, in turn, is also likely to affect the carrying capacity for higher trophic levels.

Displacement and barrier effects: OWFs can cause temporary or permanent displacement of fishes, mammals, and sea birds from their natural habitats. Assessments examine potential changes in migration routes, foraging grounds, and breeding areas, as well as the overall impact on population dynamics.

Therefore, key information products required for the ecological impact assessment should be short- and long-term changes of ecosystem indicators, including (i) pressure indicators, e.g., underwater noise level, electromagnetic field level, physical and chemical environment, water quality (including contaminants directly released from the turbines), and habitat, and (ii) biota indicators, such as biomass for both low and high trophic levels, biodiversity, or taxa of conservation concern.

4. Solutions and Required Data and Modeling Technologies

With regard to the key information products identified in **Section 3**, effective solutions are required to generate the products. Such solutions are often based on integrating models (dynamic, statistical, and ML/AI algorithms) and in situ and remote sensing observations. In this section, we describe solutions for each product defined in **Section 3** and identify the observation data and models required for the solutions.

It should be noted that, due to the fast-growing number of OWFs and spatial connection of atmosphere, coast, offshore, and marine ecosystems, most of the information products for OWFs, either local forecasts or assessment of the impacts, will need to consider impacts of all OWFs in the regional sea scale. Thus, the solutions here represent a regional-scale solution that fits the purposes of individual OWFs, the research community, and national and regional stakeholders.

4.1. OWF Operation and Maintenance

As mentioned in **Section 3**, to make the optimal decision for short-term OWF O&M, a wave forecast product, together with an uncertainty estimate, is required. This includes both the wind sea part generated by the local wind field and a swell component, which is generated by some distant high wind speed event earlier on. The swell can significantly impact ship operations, particularly if the swell periods match the eigenmodes of the ship. In practice, such a forecast is routinely generated by global–regional–local wave forecasting systems.

Global–regional wave monitoring and forecasting systems have been constantly improved in recent decades. For example, recent changes in the ocean wave model used in ECMWF's Integrated Forecasting System (IFS) and Meteo France WAM model include new parametrizations for wind input and deep-water dissipation of waves, which improve forecasts of some of the most common ocean wave variables, including significant wave height [60]. The new formulation reduces the overprediction of long-period swell energy and small wave height underestimation in storm tracks. Wave forecasts on global and regional scales are regarded as sufficiently good for users. The focus of the O&M forecasting service is on the local forecast in the farm and areas between and farm and the coast. Due to the presence of OWFs and complex coastal topography, there are a few challenges in the local wave forecast:

- The impact of OWFs on winds and waves is currently not resolved by weather and wave forecasts.
- Wave propagation and dissipation terms in shallow waters and areas with land–sea blended grids require specific treatment [61]. Complex coastlines, including islands, will change wave propagation, but the model resolution is insufficient.
- Interaction between waves and currents must be resolvedas the sea level becomes significant in coastal waters.

These issues will lead to forecast errors in current coastal wave models. The proposed solutions are: (i) to use shallow water wave models with improved shallow water wave source terms; (ii) to assimilate wave, currents, and sea level observations in a coupled wave–ocean forecasting system; (iii) to parameterize impacts of OWFs in weather, ocean, and wave models (more details will be provided in **Section 4.3**); (iv) to develop an individualized optimal local forecast by aggregating different forecasts and observations. When developing the above solutions, local wind, wave, and sea level observations in the OWF and nearby areas are essential for quantifying forecast uncertainties and optimizing the forecast [62]. Current data, e.g., measured by HF radar, are also useful for improving wave–current interactions in the wave forecast model. In icing seas, forecasts of sea ice conditions are essential for operating maintenance vessels. Sea ice forecasts and services are provided in Nordic countries using sea ice models. Observations on the type, concentration, and thickness of the sea ice are required to improve the model forecast and quantify the uncertainties. Currently, monitoring and forecasts of sea ice thickness and fast ice still pose major challenges. Wave forecasts in the ice-marginal zone (with an ice concentration of less than 85%) due to less resolved wave–ice interaction in the model still have large uncertainties. Observations in the ice-marginal zone are required to calibrate and validate the models.

The forecast of structural icing on wind turbines is another important factor, as it limits local maintenance operations. This relies on better parameterizing the OWFs' impacts in the atmospheric boundary layer, which has not been sufficiently resolved in present-day numerical weather-prediction models. In such a case, local observations on the atmospheric boundary layer will be important for reducing the forecast uncertainties.

Another application area is OWF lifetime extensions. In this application, wave and sea ice time series data are required to estimate fatigue and extreme loads. In practice, this means that the temporal sampling of the time series must be sufficiently high to capture extreme conditions.

4.2. Protection of Submarine Cables

In order to provide the required information products for the cable protection problem caused by the mobile sediments, i.e., changes in cable burial depth, two solutions can be applied: a survey-based solution and a survey-modeling integrated solution.

Survey-based solution: first, multiple surveys with a certain elapsed time, e.g., one year, need to be conducted; then, based on the result, the speed and volume of sediment transport can be calculated. In this way, areas with high sediment mobility can be identified. It is often necessary to perform this as a pre-lay practice since post-lay activities can be very expensive and are not always effective. This also means years will pass before the cable installation if a survey-based solution is adopted.

Survey-modeling integrated solution: in this solution, in situ and satellite observations and models capable of simulating the sea sediment variability are integrated to produce the required information products. The survey-modeling integrated solution has several advantages. It can be performed in a large area, save both expenses and time (in the order of years) for cable installation and protection, and predict future changes in burial depth.

The model for this purpose consists of sediment transport and morphology modules, which support both bedload and suspended load transport of non-cohesive sediments and suspended load of cohesive sediments due to waves and currents. In the model, the sediment is categorized as "mud" (cohesive suspended load transport), "sand" (non-cohesive bedload and suspended load transport), and "bedload" (non-cohesive bedload only or total load transport) fractions. The simulation may include as many an arbitrary number of these fractions as computer memory and simulation time allow. The hydrodynamic and wave energy equations are solved to determine the suspended transport due to currents and waves for "sand" and "mud" fractions. The sea bed composition can be modeled either as a single well-mixed layer or as a multi-layer bed to keep track of the development of different layers of sediment over time. A comprehensive sediment and morphology transport model has been developed by industrial software developers such as Deltares (D-Morphology, https://oss.deltares.nl/web/delft3d/manuals, accessed on 8 June 2023).

Numerical models must be calibrated using historical survey data, including bathymetry, currents, substrate types and grain sizes, and the changing rate of burial depth. If the model is proven to be sufficiently good, it can be used to identify critical areas and predict the future evolution of the burial depth. In practice, the model development can be divided into two stages: the first stage is to develop large-scale drift models of suspended load and bedload, while the second stage is to develop downscaled fine-scale models which can be applied to a given case of cable protection. To develop and implement this integrated solution, waves, currents, fine-resolution bathymetry, and substrate types are required to configure the sediment transport models. Observations of ocean currents, grain size and related sedimentation rate, and sea bed sediment layer depth are necessary to calibrate and validate the model.

In ice-covered sea areas, submarine cables close to the sea surface may be impacted by moving sea ice. To avoid these adverse impacts, information on the maximum depths sea ice can reach is required. This can be achieved with a combination of sea ice models and in situ observations providing statistics of sea ice properties in a specific area.

4.3. Wake and Lee Effects

Since there are significant knowledge gaps on the wake and lee effects of OWFs, a process-oriented in situ monitoring and modeling approach is required both to improve the OWF parameterizations in the models and assess the differences in atmosphere, ocean, sediment, and coast morphology before and after the OWFs are deployed. For the selected OWF sites, relevant marine environment parameters should be monitored before and after OWF deployment so that the impacts of OWFs can be quantitatively assessed. However, due to natural variability, the OWF impact cannot be accurately assessed only using observations. It is necessary to use well-calibrated OWF-resolving atmospheric–hydrodynamic–wave–sea–ice models to simulate impacts. However, due to the resolution limits (currently a kilometer grid for weather and 10 s of meters grid for hydrodynamics) in these models, individual turbines will not be explicitly resolved; instead, their effects will be parameterized according to the model grid size. The data and knowledge obtained in the individual OWF impact study can be used to derive parameterizations of the wake and lee effects of OWFs. Such parameterizations can then be applied in coarser resolution, large-scale weather, ocean, and wave forecast models so that the OWF impacts can be simulated. Downstream impacts on sediment transport and coastal erosion can also be modeled, with forcing from the impact-resolving weather–ocean–wave–sea–ice models.

Key variables are required to calibrate and validate model forecasts and assessments, including winds, waves, currents, temperature/salinity profiles, turbidity, sea ice, substrate, SPM, and shoreline positions. Other data, such as OWF geographic and power configurations, are required for model parameterization. The area of interest is mainly in OWF and surrounding areas up to the coast, especially the wake area. For wake effect forecast application, hourly data for a short period, e.g., a few months to a year, will be required. For long-term impacts on the coastal morphology, multi-year or decadal observations will be required for the assessment, while the sampling frequency can be a few times a year or adaptive sampling focusing on severe erosion events.

4.4. Specific Impacts of OWF on Sea Ice and Safety

There are two important areas of particular interest, especially in the northern and eastern Baltic Sea, the impact of large OWFs on sea ice and the impact on radar observing networks.

In the northern seas, estimating and analyzing the impacts of OWF on marine transport and local ecosystems requires an understanding of the interactions between the OWF and sea ice, representing a knowledge gap. Typically, the resolution in existing sea ice models is not high enough to include processes in the scales of OWF. Thus, models with flexible grids are required. The development and validation of these models require detailed observations of sea ice properties, local meteorology, mechanical forcing, and wind tower design.

Addressing the second challenge created by the increasing number of OWFs on radars requires developments both on the observing and modeling sides. Part of the solution is to use additional weather and surveillance radars and marine weather stations to cover shadowed areas. In particular, additional observations of vertical wind profiles and precipitation are essential to maintain the accuracy of marine forecasts (relying on weather radars) at the current level. However, due to the seasonal ice cover, solutions based on measurement buoys are impossible, making the challenges sometimes difficult to solve. Additionally, further basic research is required to develop methods to estimate the impacts of OWFs on, for example, (radar) electromagnetic signal propagation in the marine boundary layers as the OWFs also have indirect impacts on radars due to boundary layer processes such as changes in the sea surface evaporation layer.

4.5. Contamination Assessment and Response

In order to derive the distribution of the major contaminants emitted from the offshore wind turbines in seawater and sediment and their impacts on biota, an integrated monitoring–modeling laboratory experiment is required. The laboratory experiment, together with field monitoring, will determine the emission rates of major metals and chemicals; numerical models are required to simulate the transport pathways of the chemicals, both in seawater and sediment. These models should include modules of hydrodynamics, waves, and particle sedimentation and resuspension. Field monitoring should be carried out to obtain contaminant concentrations and hydrodynamic and wave conditions, which can be used for calibrating and validating the models. The contaminant concentration in species such as seagrass, benthic, and fish can be obtained from monitoring data in biota, while the impacts of the contaminants must be assessed via toxicity experiments. The observation requirements for this application are summarized in **Table A1**. An accurate representation of ocean currents and their variability is required to track the path of contaminants released at sea. Operational ocean circulation models provide very valuable tools in this respect. These models are ideally coupled with wave models to account for the effect of wave-driven currents on surface drift. Wake and lee effects of OWFs on winds, waves, and currents should be resolved. A high resolution (i.e., a few hundred meters in terms of the grid size) is generally required to resolve the impact of OWFs. Satellite altimetry sea level observations can now cover coastal waters with a 1 km resolution [63]. Data-assimilative models which integrate this information and combine it with other multiplatform in situ measurements provide adequate tools to represent these observed fields as well as the smaller-scale variability associated with it. These models, by representing the full 4D variability of multivariate ocean fields, are able to describe the spatiotemporal ocean connectivity associated with ocean currents, which is especially useful for the identification of remote areas likely to be affected by the contamination possibly generated at OWF sites.

4.6. Ecological Impacts

As analyzed in **Section 3.6**, the key information products for assessing the ecosystem impacts of OWFs include short- and long-term changes in both pressure and biota indicators. To derive these indicators, information is required from all variables in the effect chain, starting from changes in vertical mixing around the wind turbines, resulting in changes in stratification, turbidity, light climate, primary production, and phytoplankton in the OWF and its wake. Furthermore, information is required on noise levels, changes in benthic substrate and benthic communities in the OWF, and changes in the abundance of zooplankton, fish, and marine mammals within the OWF and its wake. Since the identification of changes is the key objective of required information products, consistent observations over a sustained period are required, starting before the construction of the OWF. Ecological impacts are likely to reach far beyond the areas of individual OWFs. Particularly, if the number of OWFs increases as is presently foreseen, the wake effects of different OWFs are likely to interfere and lead to larger cumulative impacts than impacts from individual OWFs. Fish, marine mammals, and birds migrate over large areas, so changes in their abundance will not only be affected by the local effects of OWFs. Rather, they respond to ecosystem change over larger areas, across national borders, with a particular sensitivity to changes in their spawning and nursing grounds. Thus, understanding of ecological impacts of OWFs would require the sharing and integration of data between countries in combined information products.

It should be noted that in situ observations can have large gaps in space, while for most of the pressure indicators (e.g., noise, EMF) and some biota indicators (e.g., plankton), we require a continuous 3D distribution. An ideal solution is to use calibrated numerical models, including marine biogeochemical and ecosystem models, noise propagation models, and pollutant and sediment transport models. In addition, the models can also be used to estimate variables that are hard to observe (such as bird collisions), test different hypotheses on causal relations between different observed variables, and extrapolate to future scenarios.

Ecological impact assessments are conducted both before the construction of offshore wind farms and during the operation phase. Assessments before construction are used to apply for construction permits and optimize the location and design to minimize potential ecological risks. In this stage, potential impacts are mainly estimated from observations of the current situation and model simulations of future scenarios. During the operation phase, monitoring the change in noise level, water quality and habitat, and ecological impacts is required to assess the level of environmental change and check whether the ecosystem is unacceptably affected. To this end, long-term observation data are required for trend detection. Additionally, interpretation of any trends is required to detect the causes of the trends, and selecting adaptive management approaches is essential to ensure that any unforeseen impacts are identified and addressed promptly, helping to minimize adverse effects on marine species and their habitats.

Impact assessments often include recommendations for monitoring programs to track the long-term effects of offshore wind farms on marine life. They also propose mitigation measures, such as adjusting turbine design, optimizing cable routes, or implementing seasonal restrictions to minimize potential impacts on fish, mammals, and sea birds.

5. Discussion

Since this study mainly focuses on the monitoring requirements, several other important issues related to OWF observations, such as demands on coordinated data management between different sectors, data transmission, interoperability, and accessibility, have not been addressed. There are also emerging areas missing, such as the multi-use of OWF platforms, in this study. Furthermore, further research should be carried out to synthesize observation requirements resolving multi-scale processes and multi-application objectives. These are discussed below.

5.1. Multi-Use of OWF Platforms

The selection of applications is not exclusive in this study; other applications, such as optimal OWF siting and multi-use of offshore platforms, are also important when designing integrated monitoring for OWFs. Observation requirements and gap analysis of OWF siting have been investigated in previous studies [13]. The multi-use of OWF has been an intensive research area in the EU research framework FP7, Horizon 2020, and Horizon Europe [16]. The observation requirements for multi-use are related not only to OWF applications but also to specific co-utilization, e.g., aquaculture farms and tourism. Since the focus of this study is mainly on OWF-only applications, the topic of multi-use offshore platforms is not covered by this paper. A separate study on observation requirements and adequacy analysis for the multi-use of OWFs can be conducted in the future.

5.2. Model-Observation Integration in Areas with High Connectivity and Multiple Scales

Due to the high spatial connectivity of the applications in the land–coastal–open sea continuum, the observation requirements are considered in a multi-application, multi-scale, and multi-process framework with integrated monitoring–modeling solutions. The information products are required at four scales: local scale, i.e., within the farm and cable line area; inter-farm scale; coastal scale, i.e., between the farms and coasts; the cross-border or regional scale, which is between nations. In order to derive these multi-scale information products, both marine monitoring and modeling will be used. The monitoring will obtain real physical, chemical, and biological states of the ocean, but with spatial and temporal gaps. Models, with seamless and on-demand modeling capacity, will be able to resolve the multiple scales of spatial connectivity, coupled physical–chemical–biological marine system, as well as multiple time scales from days to decades, and finally produce four-dimensional gap-free data of the marine system state. However, model data may be far away from reality. Observations, both in situ and remote sensing, are required to calibrate the models and reduce the model error or initial field error via data assimilation. For each application area, an integrated monitoring–modeling approach has been recommended as a solution for generating the key information products. Additionally, addressing and understanding some of the impacts of OWFs require further basic research on the process level.

5.3. Coordinated Data Management for OWF Applications

The application areas in this paper showed many overlaps and linkages between variables for which information is required. This provides opportunities for synergies if the information is obtained with an integrated approach for multiple application areas. In this way, the observations and modeling approaches can serve multiple purposes, including providing realistic statuses of the air, sea, biota, and sea bed; model calibration and validation; improving forecasts using model–data integration. Winds, currents, waves, and ice (if relevant) are basic variables required for high-frequency (hourly or daily) long-term monitoring. Water temperature, salinity, and biogeochemical parameters can be sampled 4–24 times a year, while sediment, contaminants, habitat, and biodiversity only need to be surveyed 1–4 times a year. The monitoring should be carried out on-site and between OWF and coasts years before the OWF construction so that the impact of the OWF can be assessed.

There is also a demand for an efficient channel or framework for collaboration between governmental agencies, OWF companies, the research community, and aggregated data centers. The OWF sector, together with governmental agencies, will need to establish a framework for declassification of the environmental monitoring data created by the OWFs, similar to that practiced in The BVG Associates Limited in the UK. Community data centers, such as EMODnet in Europe, should also enhance dialogue and set up an agreement with the OWF sector so that the part of the open environment observations from the OWF can be smoothly transferred to the community database.

5.4. Data Transmission, Interoperability, and Accessibility

Data transmission: with the rapid expansion of OWFs and increasing environmental monitoring needs, efficient, low-cost, and near-real-time data transmission is becoming increasingly important. This includes the collection of turbine data using the SCADA system and environmental observations from multi-sensors and then transferring the data to land. Satellite-based data transfer has been used in this procedure, which is efficient but expensive. LoRaWAN (Long Range Wireless Area Network) is a low-power mode with long range (with gateways transmitting and receiving signals over a distance of over 10 km in open space), which has been tested for coastal water quality, aquaculture, and turbine monitoring communication, together with IoT technology. Combined with robotic monitoring platforms, such as drones, UAVs, and ROVs, it is expected that future collection and transmission of environmental data in OWF application areas can be significantly improved.

Data interoperability: in situ observations in OWFs and their wake areas are mainly determined by industrial companies (OWF operators and monitoring service providers) and research projects. Currently, there is a lack of common data standards between commercial monitoring (OWF industrial data), research monitoring, and environmental and operational monitoring. An industrial data standard that is interoperable with environmental and operational data standards will largely facilitate the use of multi-source observations.

Data accessibility: currently, most of the commercial monitoring data are confidential. This has hampered research and assessment activities for OWFs. A subset of commercial monitoring data, especially data for ecological impact assessment, should be made freely available. This has also been suggested by the Natural Resources Defence Council, a group of more than 20 environmental organizations, in a concise guide to the science-based principles and priorities for environmental monitoring that are crucial to advance responsible offshore wind development in the United States [15].

6. Conclusions

In this study, key information products, solutions for production, and observations required for the six OWF application areas with high connectivity have been identified to plan, operate, and assess the impacts of OWFs on the environment and marine ecosystems. The application areas cover information services for OWF operation and maintenance, optimizing monitoring for the protection of submarine cables, prediction of atmospheric and marine wake and lee effects, impacts on maritime transport and security, contamination monitoring and assessment, and ecological impact assessment. These application areas show many examples of spatial and interdisciplinary connectivity between different types of observation data required for different applications.

A fit-for-purpose observation requirement assessment approach is used first to identify user needs on key information products, then to suggest an integrated modeling–monitoring solution for deriving the information products, and finally, to identify observation demands with regard to the use of observations in implementing the solutions. The results should show that demands from governmental stakeholders, OWF operators, and the research community can only be fulfilled by multi-scale and multi-disciplinary observations and dedicated monitoring–modeling integration.

The identified observation requirements for the six OWF application areas are summarized in Table A1. Based on the outcomes of this paper, the availability and gaps of the observations will be analyzed, and the results will be reported as Part II of this study [64].

Supplementary Materials

The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/jmse11081630/s1. Table S1. An overview of required environmental monitoring activities. Table S2. An overview of required metocean monitoring activities and geological and hydrographical surveys. Table S3. An overview of other required monitoring activities.

Author Contributions

Conceptualization: J.S. and J.S.-S.; methodology: J.S.; analysis: J.S.-S. is responsible for operation and maintenance related continents, J.S. is responsible for submarine cable protection and wake and lee effects, L.L. for maritime safety in icing waters and radar aspects, B.M. for contamination, A.B. and H.W. for OWF impacts on habitat, NIS, fish, sea bird, and marine mammals; writing—original draft preparation, all; writing—review and editing, all. All authors have read and agreed to the published version of the manuscript.

Appendix A. Required Observations for OWF Applications with High Connectivity

Table A1. Observation requirements for OWF applications with high spatial connectivity.

Application area & information product	Purpose of using observations	Variables	Spatial needs	Temporal needs
O&M: Forecast and related uncertainties of waves, sea ice, sea level, currents and icing	Model parameterization, cal/val, model-data integration for optimal forecast	Waves Surface winds Surface currents Sea ice properties Icing, humidity, etc.	A few sites per OWF and connectivity area	Hourly daily, real-time
O&M: Long-term and extreme load	fatigue/extreme load estimation	Waves	A few sites per OWF	Hourly, lifetime
		Sea ice	OWF area	Daily, lifetime
Sea bed cable protection: Shear stress, sediment layer thickness above cable for cable protection	Inputs to model	Bathymetry	Model area	Static
		Sea bed substrate	Model area	Static
		Riverine SPM discharge	Model area	Daily or hourly
	Model cal/val, parameterization, process study	Waves	Cable area	Hourly
		SPM concentration	Model area	hourly or daily
		Sedimentation rate	Model area	Static
		Sea bed sediment (size, layer thickness)	Cable area	Monthly or quarterly
Wake/lee effects: Weather–ocean–wave–ic	Calibrating and validating models;	Wind/current profiles, surface wave spectra	One site per OWF	Hourly for two periods before/after OWF

e–SPM forecast with impacts of OWFs	optimal forecast by integrating local observations and model forecast	ABL variables, waves, T, S	A few sites per OWF	deployment; or for a dedicated campaign period.
		Surface currents	A few sites per farm, 2D distribution	
		Shoreline positions	Coastal stretch, OWF downstream	
		Sea ice	A few sites per OWF and model area	Hourly daily
Security and marine forecasting: Impacts of OWF on radar signal propagation	Fill the spatial data gaps due to shadowing effects	Precipitation, winds, radar targets	3-dimensional	Hourly
Contamination: 3D distribution of metal and chemical contaminant concentrations	Calibrate models, data assimilation, impact assessment	Concentration of Al, Zn, Cd, In, BBA, etc.; surface currents	Seawater, sediment, biota, both on-site and in surrounding areas	Long-term, seasonal or annual sampling
Ecological impacts: Changes in abiotic conditions, leading to changes in biota	Trend detection, analysis of cause–effect relations, model validation	Noise, bed topography and composition, vertical profiles of T, S, turbidity, light, population densities of biota: phytoplankton, zooplankton, benthos, fish, marine mammals, birds	In OWFs and their lee area, vertical profiles of pelagic variables	Long-term consistent for trend detection, high temporal resolution for representativeness and detecting interactions between variables

Supplementary materials: An overview on the required monitoring for offshore wind energy based on the "Guide to an offshore wind farm" by BVG Associates Limited (2019).

The Crown Estate and the Offshore Renewable Energy Catapult produced a report "Guide to an offshore wind farm" in 2019 for BVG Associates Limited [7]. In the report, monitoring requirements for entire OWF value chain, from siting to decommissioning, are covered. Although the information is still lack of details, it provides a good overview on the state-of-the-art on the monitoring requirement for OWF sectors. The Tables S1-S3 are produced based on the information collected from this report.

Table S1. An overview on required environmental monitoring activities

Monitoring activity	Purposes	Sampling method	Sampling locations	What to measure
Benthic environmental surveys	To categorise areas of similar environmental conditions to inform habitat and species impact studies.	Grab & sampling, epi-benthic beam trawling and drop down video (DDV).	Be able to produce the most effective broad-scale categorisation	Species living on the sea bed and in sediment
Fish and shellfish surveys	To identify species presenting in the farm site and surrounding areas, to inform impact analysis and reporting.	Beam trawls, otter trawls , lobster pots, gill nets, plankton nets or local fishing vessels	The farm site and surrounding areas	Species in the area, spawning
Ornithological environmental surveys	To establish the presence and behaviour of birds within the farm and surrounding areas for assessing risks to birds (collision with turbines, disturbance and displacement, and habitat loss)	Boat-based/digital aerial surveys, GPS tracking, radar and coastal vantage point (VP) surveys, min. two years	Farm and surrounding area	Annual cycle of bird abundance & distribution behaviour (e.g. flight height)
Marine mammal environmental surveys	To establish seasonal and inter-annual changes of marine mammals and assess OWF impacts on the mammals (incl. potential disturbance/ displacement, physical and auditory injury during pile driving, and habitat loss	Visual surveys, static and towed acoustic monitoring, tagging of individuals with satellite transmitters and remotely controlled video monitoring, monthly sampling, min. 2yr.	Within the wind farm boundary and surrounding areas.	mammals the diversity, abundance, distribution and behaviour of cetaceans (including porpoises, dolphins and whales) and seals
Human impact studies	To assess OWF impact on the community	Visual assessments, socio-economic study	Coastal area near the wind farm.	Photomontages, noise level, fisheries and archaeology, changes in employment, transportation, recreation etc.

Table S2. An overview on required metocean monitoring activities, geological and hydrographical surveys

Monitoring activity	Sampling locations	Purpose	Sampling method	What to measure

Resource and metocean assessment	The proposed wind farm	To provide metocean data for estimating future energy production, and to fully describe the likely operating conditions, incl. extreme wind and wave climate.	Met-mast, metocean buoys, (floating) lidar, weather models to inform turbulence and horizontal wind gradients in the site	Wind profile, surface meteo-variables, waves and tides for long-term (> 15 years).
Geophysical surveys	Along transects across zones within the proposed wind farm site and cable routes.	To establish sea floor bathymetry, features, water depth and soil stratigraphy, hazardous and risky areas on the seafloor; to aid the design and implementation of the benthic/geotechnical surveys, site layout design.	Seismic methods, echo sounding and magnetometry; acoustic seismic profiling methods and high resolution digital surveys.	bathymetry, soil stratigraphy, hazardous and risky areas on the seafloor
Geotechnical surveys	Within the proposed wind farm site and along cable routes.	To identify soil/rock strata boundaries & engineering properties or specific sea floor features; to monitor the soil behaviour under the constant dynamic loading on the foundation by the wind, waves and current, and to improve the geological model prior to the design and installation of foundations.	Boreholes with soil/rock sampling, and cone penetration testing (CPT).	Sea bed soil stratigraphy in upper 5m for cables, and 50-70m on physical characteristics.
Hydrographic surveys	Along transects across zones within the proposed wind farm site and cable routes.	To examine the OWF impact on local sedimentation and coastal processes such as erosion.	Post-construction monitoring	Sedimentation environment related to scour characteristics of the site
Weather forecasting and metocean data	Within OWFs and between OWF and coast	Forecasts to support short-term planning of offshore activities; Observations to support offshore activity, to verify forecast tools and to resolve disputes regarding weather downtime	Weather models, lidar, wave buoys, current meter etc.	Forecasts: wind profiles, waves and visibility, lightning risk, fog, etc. Observations: winds, waves, currents

Table S3. An overview on other required monitoring activities

Monitoring activity	Sampling locations	Purpose	Sampling method	What to measure
Data for corrosion protection	Within OWFs	To assess corrosion rate and potential risks	Metocean sensors, modelling	Humidity, icing, salinity, waves etc.
Data for scour protection	Turbine foundations	To estimate scour rate of the sea bed caused by the speed-up of water moving around the foundation	Not specified	Sediment particle size distribution and the strength, waves, currents, scour depths, depth of non-cohesive sediments.

Data for offshore cable installation and protection	Along cable lines	To support subsea cable protection and installation by defining an optimal route, assessing sediment layer thickness above the cable, and identifying vulnerable locations.	Models; vibrocores and CPTs up to 5m under sea bed; sediment samples; magnetometry; ROVs.	A survey to define the route and identify any UXO, followed by a pre-lay grapnel run (or alternative method) to clear debris from the cable route.
Operation and condition monitoring	With OWF	To support OWF operation and real-time health check and repair	SCADA, ROVs, Service Operation Vessel (SOV)	Windmill operational status variable, winds
Environmental monitoring in operational period	Within the farm	To understand the effect of the wind farm on the local environment and wildlife	Not specified	Not specified
Monitoring for turbine inspection	Within OWF	To inspect turbine's health condition	Unmanned aerial vehicles (UAVs, mostly multi-rotor copter drones equipped with a digital, thermographic camera)	Visual images of tower, nacelle, rotor blades and bolt jointing; Thermographic image on blade
Environmental surveys for decommissioning	Within OWF	To support post-decommissioning management of the site in line with the Energy Act 2004	Before and after decommissioning. No details specified on the method	Not specified

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5.Fit-for-purpose information for offshore wind farms – Part II: gaps and recommendations

Abstract

Offshore wind energy installations in coastal areas have grown massively over the last decade. This development comes with a large number of technological, environmental, economic, and scientific challenges, which need to be addressed to make the use of offshore wind energy sustainable. One important component in these optimization activities is suitable information from observations and numerical models. The purpose of this study is to analyze the gaps that exist in the present monitoring systems and their respective integration with models. This paper is the second part of two manuscripts and uses results from the first part about the requirements for different application fields. The present solutions to provide measurements for the required information products are described for several European countries with growing offshore wind operations. The gaps are then identified and discussed in different contexts, like technology evolution, trans-European monitoring and modeling initiatives, legal aspects, and cooperation between industry and science. The monitoring gaps are further quantified in terms of missing observed quantities, spatial coverage, accuracy, and continuity. Strategies to fill the gaps are discussed, and respective recommendations are provided. The study shows that there are significant information deficiencies that need to be addressed to ensure the economical and environmentally friendly growth of the offshore wind farm sector. It was also found that many of these gaps are related to insufficient information about connectivities, e.g., concerning the interactions of wind farms from different countries or the coupling between physical and biological processes.

Keywords:
offshore renewable energies; fit-for-purpose information products; monitoring systems; data assimilation; observation system optimization

1. Introduction

The offshore wind energy sector has grown massively worldwide since the first wind park at sea was commissioned in Denmark in 1991. The building of offshore wind parks has accelerated over the last decade, and this development will likely continue at least until the middle of this century [1]. According to the European Union (EU) Strategy on Offshore Renewable Energy [2], the installed offshore wind capacity in Europe will grow by a factor of five, from 12 GW today to 60 GW by 2030. The Global Wind Energy Council (GWEC) Market Intelligence forecasts that by 2030, more than 205 GW of new offshore wind capacity will be added globally, including at least 6.2 GW of floating offshore wind power [3]. This development is driven by very ambitious and concrete goals defined by politics, e.g., to achieve climate neutrality by 2050 in Europe. In Germany, a target of 30 GW installed offshore wind power by 2030 is written in law, which means an almost quadrupling of the capacity that existed in 2022. In the wider European context, the development of new offshore wind farm (OWF) activities also takes place in new areas with currently little or no existing OWFs. These areas include the Northern Baltic Sea and Mediterranean Sea, with challenges specific to these regions. As the development of new OWFs is expected to be fast and local legislation may be behind, best practices from other, previously developed regions should be utilized, and approaches and impacts potentially harmful to the society and environment should be avoided.

The growth of the OWF sector comes with a large number of scientific and technological challenges [4,5], e.g., in the fields of:

- OWF design and planning;
- Installation of OWFs;
- Operation and maintenance (O&M) of OWFs;
- Environmental impact assessments;
- Dismantling, repowering, or recycling of OWFs.

The sustainable evolution of offshore wind energy technology in terms of cost efficiency and environmental impacts requires detailed information about the two-way interaction between the OWFs and their environment [6]. A key component to meeting this demand is dedicated monitoring systems that are integrated with up-to-date numerical models for the environment and the technology. The combination of simulation tools and observations for specific-use cases has gained new attention in the context of digital twins [7], which are seen as an efficient tool for decision making. In [8], an overview of the requirements for integrated information was provided from observations and modeling. In the current study, we perform a gap analysis to evaluate to what extent the current observation and modeling capabilities are sufficient for providing the required information during different lifetime phases of OWFs. We identify what capabilities are still missing and how these can potentially be developed.

Gap analysis is applied in different fields, e.g., in the private sector, and is seen as a powerful tool to develop and grow business [9]. More specifically, it helps to:

- Define priorities;
- Identify areas for improvement;
- Allocate resources in a strategic way;
- Measure progress in an objective way;
- Achieve goals within a given time frame.

A variety of observation gap analysis methods have been investigated in the field of operational oceanography, which can be divided into two categories: one is to assess data adequacy for reconstructing a four-dimensional, continuous ocean state [10,11]; the other is to assess data adequacy to fit for certain given purposes, e.g., operational forecast, environmental assessment or offshore wind farm siting [12]. The first type of method quantitatively evaluates a data impact index, e.g., "effective coverage", "sampling error", or "initial uncertainty", for a given sampling scheme. Observing system simulation experiments (OSSEs) fall into this category as well. Here, the quality of observations is assessed in terms of the ability to improve model forecasts in a data assimilation scheme using general statistical parameters like RMSE or using a more basic approach based on assumptions about the correlation structure of the model errors [11]. The fit-for-purpose gap analysis, on the other hand, consists of three stages. The first stage is to define an application area, e.g., offshore wind farm siting and tailored products needed for this service; then, all the available observations and modeling approaches will be used to generate the tailored products; finally, adequacy of the observations is assessed according to experiences in generating the products. This method can be either qualitative or quantitative. A fit-for-purpose data adequacy assessment was performed for OWF siting in the Baltic Sea [13]. In EMODnet (European Marine Observation and Data Network) CheckPoint projects, data adequacy in multiple application areas, such as OWF siting, oil slick forecasting, river discharge, climate change, and fishery management, was assessed for European regional seas [12]. However, these applications were analyzed separately.

In this study, we apply a fit-for-purpose gap analysis with reference to requirements for the OWF sector identified in [8]. In that study demands concerning observations were identified and discussed for the six application fields, which differ in characteristic temporal and spatial time scales. The focus of the study was on aspects with high connectivity either across spatial scales, system compartments (e.g., atmosphere/ocean), or ecosystems.

(1) Operation and maintenance (O&M);
(2) Submarine cables;
(3) Wake and lee effects;
(4) Transport and security;
(5) Contamination;
(6) Ecological impacts.

Gap analyses have been performed in the context of offshore wind energy in a number of studies. For example, [14] performed a study about monitoring gaps in the ecosystem in the Dogger Bank region. Data gaps with regard to offshore wind resource assessments and optimal designs were discussed in [15,16]. A gap analysis concerning rules, regulations, and standards is provided by [17,18]. Missing knowledge about the impacts of sea power cables on the environment is discussed in [19]. An early report about guidelines for data acquisition to support marine environmental assessments for offshore renewable energy projects was given by [20]. The general importance of the topic was discussed in various documents, e.g., a recent report by the European Marine Board [21] stated that the "lack of sustained funding for Ocean observations and marine monitoring has created the lack of baseline knowledge across European seas needed to develop the ORE (Offshore Renewable Energies) required by European ambitions."

The present study extends and complements the existing investigations in different ways, e.g.,
(1) Oceanic and air/sea interaction aspects are put into the focus;
(2) The discussion is centered around fit-for-purpose information products for different use cases;
(3) Particular focus is put on high connectivity aspects, which are of high importance for decisions about trans-European monitoring strategies;
(4) The discussion includes physical, chemical, and ecosystem aspects.

The manuscript is structured as follows: In Section 2, a short description is provided of the methodology applied for the gap analysis. In Section 3, a very brief introduction is presented of the six use cases and the existing modeling and monitoring capacities are summarized. Different European countries are used as examples to explain the present situation. In Section 4, gaps in the existing monitoring systems and model integrations are summarized. In Section 5, these gaps are discussed in a larger context and recommendations are formulated. Finally, Section 6 provides a summary and conclusions.

2. Methodology for Gap Analysis and Input Data

In this section, a brief introduction is given to the general concept of a gap analysis. This includes the objectives, as well as characteristic properties of the method as an optimization tool. In addition, several aspects are discussed, which have to be considered when using this approach in the context of observation systems in the offshore wind energy sector.

The gap analysis conducted in this study follows general principles used in different contexts and in particular in the business sector [22]. Four basic steps need to be considered in the analysis (see Figure 1):

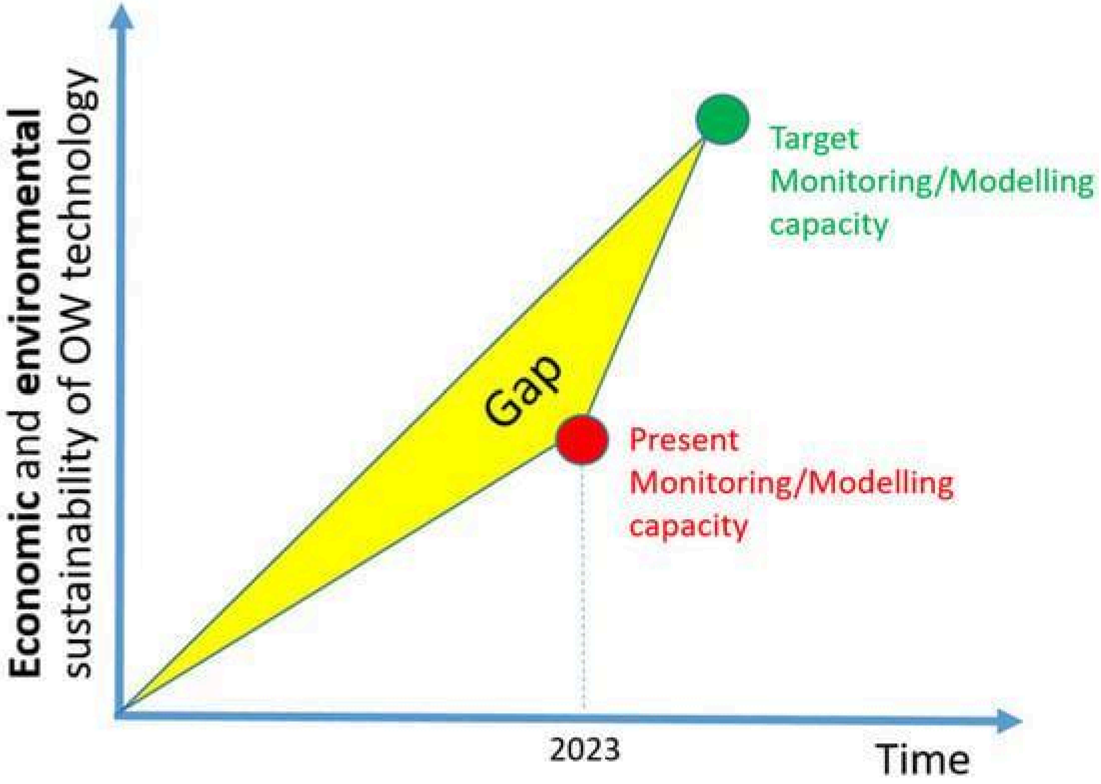

Figure 1. Diagram illustrating the major components of the gap analysis.

1. A desirable target scenario has to be defined;
2. The current situation has to be assessed;
3. Gaps have to be identified;
4. Strategies to fill the gaps have to be developed.

The target scenario should comply with the SMART principle, i.e., it should be specific, measurable, achievable, relevant, and time-bound. The target scenarios for offshore wind energy are very specific for Europe, including definitions of very ambitious timelines. The growth of OWF installations can be measured in terms of installed power, but it is clear that this metric is not sufficient for a holistic assessment of the technology. Apart from the energy costs for the final consumer, the safety of the energy supply and potential societal and environmental impacts have to be considered as well. The definition of respective metrics to measure the fitness of the associated monitoring systems and progress in the implementations is even more challenging. The final goal should be to answer the following question:

- How well do the observations fit for the purposes of applications in terms of cost efficiency and environmental friendliness in technology and operations, and where are the gaps?

The most underdeveloped part of such assessments is the quantification and evaluation of environmental damages in relation to economic benefits. This is related to the definition of concepts like "green economy", which still requires further sharpening [23]. In this study, we will not enter into the broader political and ethical dimension of this debate but rather concentrate on the more technical aspects. We will, however, include discussions on data policies as well as the communication between different actors in the offshore wind sector because they are of direct relevance to the efficient use and evolution of monitoring systems.

The gap analysis presented here is based on the identification of requirements given in [8] and covers a variety of aspects:

- Availability and suitability of sensors;
- Observation coverage in time and space;
- Observation accuracies;
- Observation consistency (metadata, validation procedures, etc.);
- Use of observations in combination with models for model optimization, assimilation, and validation.

Information about the present status of available measurements was gathered from the existing literature as well as freely accessible information. Metadata of satellite observations in European seas are obtained from the Copernicus Marine Environment Monitoring Service (CMEMS). For in situ observations, metadata are obtained from both EMODnet and national databases, which consist of in situ observations from operational agencies, environmental monitoring, geological survey, and fishery monitoring from Denmark, Finland, Germany, Netherland, Norway, and Spain. In addition, data from research infrastructures such as Danubius, ICOS-OTC, EURO-ARGO, and the suite of JERICO (Joint European Research Infrastructure of Coastal Observatories) projects are used, highlighting the essential importance of the ESFRI (European Strategy Forum on Research Infrastructures) activities for sustainable development of OWFs and use of ocean energies. For some application areas, research and commercial observations are also used. Information about OWF installation plans was gathered from different sources, e.g., OSPAR (Oslo and Paris Conventions) and documents issued by national agencies, e.g., the Federal Maritime and Hydrographic Agency in Germany (BSH) [24]. The authors are taking part in the JERICO-S3 (Joint European Research Infrastructure of Coastal Observatories: Science, Service, Sustainability) project and are familiar with the latest developments in the ocean monitoring sector both on the European level and on the national level.

The focus of the analysis is on gaps concerning information products, that require knowledge about processes with high connectivity. We are using the term connectivity in a wider sense, such that it includes both connectivity in the spatial dimension and connectivity across different processes including human activities.

3. Existing Monitoring and Modeling Capacity

In this section, a very short introduction is given to the different use cases, and the main overall information requirements identified in [8] are summarized. The main technological and environmental components, as well as a number of key parameters addressed in this study, are visualized in **Figure 2**. Subsequently, present solutions to provide the required observations in combination with model simulations are presented. The solutions are discussed using the situation in a number of European countries as an example. Experiences from existing solutions are analyzed, and recommendations for the further development of OWF in other regions are provided. The evolution of OWF is diverse in European seas, and the discussion uses a limited number of regions with interesting developments as examples, namely the southern North and Baltic Seas, the northern North/Norwegian and Baltic Sea, and the Mediterranean Sea.

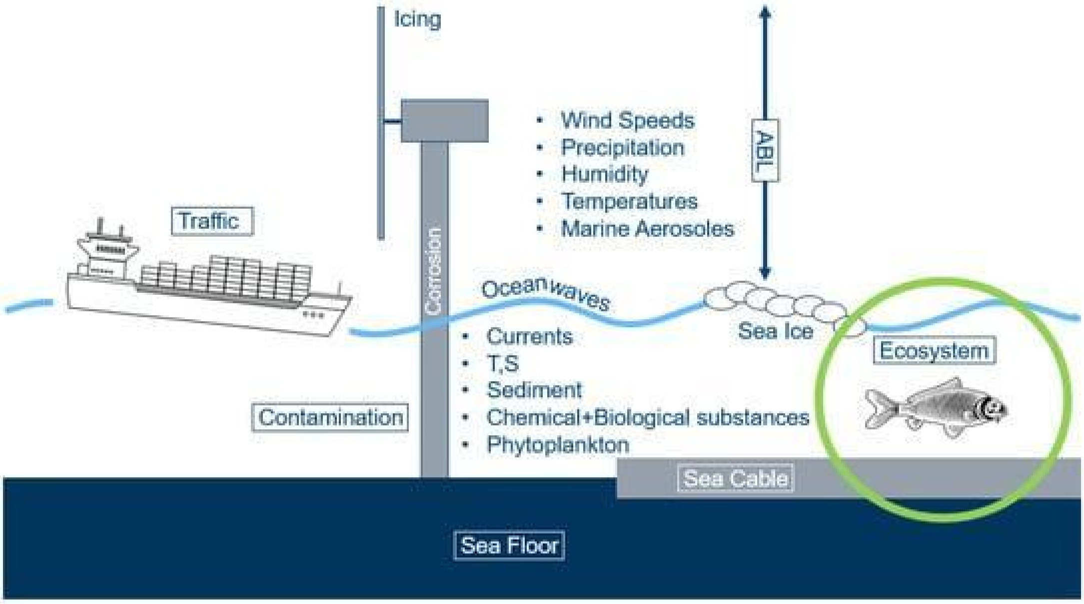

Figure 2. Main components of the technology and the environment considered in the gap analysis for the offshore wind sector.

3.1. OWF Inspection and Maintenance

Operation and maintenance (O&M) costs constitute a substantial part of the total financial investment required for OWF project lifecycles [25]. With about 14–30% of the total expenditure spent on O&M [26], the optimization of the respective procedures and technologies is of vital importance to make offshore wind profitable and economically sustainable. Ship operations are a particularly relevant component in this context since the costs for vessels sum up to about 50% of the total O&M costs, with typically about six visits required per year for mostly minor O&M activities at each turbine [27,28]. For the optimized use of ship time, reliable information about environmental conditions is crucial [29]. For example, depending on the ship type, limits exist for the significant wave height H_s, at which crew transfer vessels (CTVs) are allowed to transfer personnel to the turbines (e.g., 1 m for Monohull or 1.2 m for Catamaran). Environmental information is furthermore required in the context of predictive maintenance, which is of relevance in the context of corrosion [30] or structural health [31]. For the monitoring of the aging process, dedicated measurements of the structure response to wind, waves, or currents are of interest, e.g., obtained from strain sensors or accelerometers [32]. In particular, with regard to corrosion protection, possible environmental impacts are of concern as well. The general topic of pollution will be discussed in more detail in **Section 3.5**.

3.1.1. Existing Monitoring Solutions for O&M

The most important variables for O&M are waves and currents. In the European seas, CMEMS provides 30-year altimetry data (significant wave height, wind speed, and sea level anomaly). Regular along-track products have a resolution of about 7 km, while 5 Hz products provide 1.2 km resolution data, which greatly increases the availability of coastal, especially nearshore, observations. EMODnet has data from 219 wave buoys in the Baltic–North Sea. For currents, the Baltic–North Sea is well covered by 116 mooring stations. In addition, there are

11 HF radars in the North Sea [33]. This provides a base for solid model validation in the Baltic–North Sea scale. A more detailed overview of the observations in German waters is provided below.

In situ: The core element of the in situ observation system along the German coast is the network of tide gauges with about 19 stations in the German Bight and 32 stations in the Baltic. A significant number of additional tide gauges can be found upstream the rivers (e.g., Elbe, Weser, Ems). Nine stations of the MARNET network (MARitimes UmweltmessNETzwerk) operated by BSH measure salinity, temperature, and surface currents. Furthermore, about nine wave buoys provide sea state information [34]. Within the pre-operational Coastal Observing System for Northern and Arctic Seas (COSYNA), a number of stationary and mobile platforms measure physical, geochemical, biological, and key sediment variables [35]. The research center Hereon operates three HF radar stations to measure surface currents in the German Bight [36], and it has operated gliders for certain periods as well as FerryBox systems both on ships and as stationary systems. Regular measurement campaigns are performed with ships (e.g., Ludwig Prandtl), e.g., including scanfish measurements. Dedicated airborne campaigns to analyze the OWF impacts on sea state were conducted by the University of Braunschweig [37,38].

Very few open-access operational measurements are taken dedicated to the offshore windfarm topic. One exception is the FINO-1 platform located next to the first German offshore wind park Alpha Ventus. Because of the rapid growth of installations in the vicinity, this platform is not suitable any more to measure free stream conditions.

Remote sensing: In general, the operational use for OWF applications in coastal areas is still quite rare. For Germany most of the use is in the context of scientific studies or in test setups at operational centers. Hereon has used satellite SST and altimeter data for validation and assimilation of circulation and ocean wave models along the German coast. Optical satellite data were used to study sediment transport processes and for data assimilation. Furthermore, satellite radar data were used to study high-resolution wind fields around OWFs, e.g., wake effects. BSH is using satellite data (e.g., SST) in pre-operational setups for data assimilation. Most of the satellite data are accessed via CMEMS (Copernicus Marine Environment Monitoring Service), but in some cases (e.g., TerraSAR-X or CFOSAT), other channels have to be used as well.

3.1.2. Existing Modeling Solutions for O&M

The operational model forecast for German coasts is performed by BSH for the circulation part. Operational ocean wave forecasts with 3 days lead time are provided by the German Weather Service (DWD). The core element of the BSH model system is the 1 km BSHcmod 3D circulation model for the German coastal water, which is two-way nested into a coarser North Sea/Baltic Sea model. DWD uses the WAM model in combination with the atmospheric ICON model. Six-day wave forecasts with about 1.5 km resolution are available for the North West Shelf area from the European Copernicus system [39]. Hereon is using various model setups for the coastal German waters with a strong emphasis on research aspects related to the coupling between atmosphere, wave, and ocean circulation. The standard models used in this context are NEMO, WAM, and the unstructured grid model SCHISM, which is suitable for analyzing small-scale processes in estuaries and rivers or around offshore wind farms [40]. Strong cooperation exists between Hereon, the University of Hamburg, and the Max-Planck Institute for Meteorology (MPI) in the context of multiscale ocean modeling, e.g., combining the MPI-OM and ICON models with SCHISM. Offshore wind farms were included in parameterized form in the atmospheric COSMO model as well as in the ocean circulation model SCHISM, which are both part of the Hereon GCOAST system [41]. OWFs are, however, not yet included in operational models.

3.2. Protection of Submarine Cables

For protection of submarine cables, the key information product is sediment layer thickness above the cable. In Part I [8], a cost-effective solution for generating this product was proposed, i.e., through integrated use of survey observations and coupled ocean–wave–sediment modeling tools. Below, we analyze the availability and assess the adequacy of community observations and modeling capacity for performing the survey-modeling integrated approach for predicting areas with high mobile sediments and burial depth changing rate. Here, the "community observation" means data measured by public agencies, or private or citizen data openly available.

In this application, Danish and adjacent waters are used as an example in the analysis. Danish EEZ is located in both Baltic and North Seas, and is part of Baltic–North Sea transition waters. In order to simulate sediment transport in the Danish EEZ, both the Baltic–North Sea area and Danish EEZ waters should be resolved, especially high resolution with 1 km or smaller grid is needed. Input data for a sediment model, including both bedload and suspended sediment, consist of bathymetry, currents near seabed, waves, sediment discharges from land, median grain size, bed slope, sediment density, salinity, and temperature. Among these variables, the most important information is waves, currents, sediment density and grain size, and bed slope. Sediment layer thickness itself is one of the model outputs, and observations are needed to validate the model.

3.2.1. Existing Monitoring for Submarine Cable Protection

For all applications, as long as an integrated monitoring-modeling approach is used, bathymetry and river discharges are the two basic input datasets.

Bathymetry: in European seas, EMODnet Bathymetry provides gridded bathymetry data with about 115 m resolution. In shallow water, more recent bathymetry was mapped using data from satellites, e.g., Sentinel 2. DHI-Group offers such data at DHI bathymetry portal as commercial products with spatial resolution of 10 m and 2 m, as well as an uncertainty measure that indicates accuracy for each data point. This method can produce bathymetry in different times using frequently revisited Sentinel 2 (since early 2016). For Danish waters, data with 50 m resolution or higher in 50 m can be obtained from Danish Geodata Styrelsen. In addition, bathymetry can be measured using acoustic devices operated from ships [42].

Lateral sediment flux to the sea: this includes sediments from the rivers and coastal erosion. The data are needed as lateral forcing in the sediment models, including both suspended and bedload components. In [43], 79 major rivers were used for the Baltic–North Sea region. For the area of the North Sea, the main source of information were the Delft Hydraulics study Contaminant retention in North Sea estuaries [44] and the OSPAR (Oslo and Paris Conventions) report on Riverine Inputs and Direct Discharges (RID) [45]. This report is regularly updated. The most recent one is published in 2021 [46]. The RID database, which is maintained in the Norwegian Institute for Bioeconomy Research (NIBIO), can be accessed online. The riverine SPM inputs in Sweden were obtained from [47]. SPM inputs in major rivers from other Baltic Sea countries can be obtained from Global River Water Quality Archive (GRQA) [48].

Coastal erosion is another source of sediment entering the sea, for example, the English cliffs of Suffolk, Norfolk, and Holderness. The west coast of Denmark has soft cliffs consisting of very fine particles such as clays and fine sands. The shoreline in this region has been retreating at a speed of 0.5–4 m per year due to coastal erosion during the past 40 years [49]. Severe fine sand transport occurs mainly during storms. The sea level rise and increasing extreme events, e.g., flooding and storm surge, can increase risks of the nearshore section of the submarine cables and the cable stations [50].

Seabed substrate: in the Baltic–North Sea, EMODnet Geology provides a seabed substrate map in a scale of 1:100,000 with an EUNIS category. In Danish waters, GEUS provides a seabed substrate map in a scale of 1:250,000, with seven substrate categories. The sediment classification expresses the sediment type of the upper 0.50 m of the seabed. Each sediment class is defined based on the specific grain size distribution. In addition, information about sediment distributions can be obtained using acoustic instruments mounted on ships [51,52]

SPM concentration in the sea: hourly SPM concentration has been measured intensively using, among others, the SmartBuoy, FerryBox, and glider methodologies in the European seas since 2000 [53]. Turbidity data from many mooring buoys can also be transformed into SPM concentration. Some of those data are available, for example, in the REPHY database [54] for the North Atlantic Shelf Seas. In the Baltic Sea, there are several research datasets, containing a few hundred samples that cover the western, eastern, and northern Baltic Sea. In inner Danish waters, SPM concentration has been measured in three transections. These in situ observations are available from EMODnet Geology and can be used to validate the satellite and model products. For surface SPM concentration, CMEMS provides comprehensive satellite products in the Baltic–North Sea, including an open sea product in 4 km resolution, an offshore product of 300 m resolution (up to 200 km from the coast) and a nearshore product of 100 m resolution. However, the SPM products were only validated using in situ measurements from the REPHY (Observation and Monitoring Network for Phytoplankton and Hydrology in coastal waters) database.

Sedimentation rate, sediment layer thickness, critical shear stress: observations on seabed net sedimentation rate and/or sediment layer thickness are required for model calibration and validation. EMODnet Geology has collected such data, which well cover the Baltic Sea, the Skagerrak, and the Norwegian Trench. However, there are little data existing in the Danish EEZ (Exclusive Economic Zone) and the open North Sea. In addition, information on the critical shear stress for moving gravel sediments are rarely available. These data or information are only available from geological surveys for the industrial sector or individual research such as in [55].

Waves and currents: In general, current and wave measurements are rarely existing for European waters, although currents profiles near seabed are especially valuable for validating sediment transport models. However, such observations are mainly made by the oil and gas exploration industrial sector.

3.2.2. Existing Modeling Capacities for Submarine Cables

The models required for submarine cable protection are coupled ocean–wave–sediment transport models. Such models are already available, e.g., Coupled Ocean–Atmosphere–Wave–Sediment Transport Modeling System (COWAST) [56], developed by USGS (United States Geological Survey). The sediment transport model includes both cohesive and non-cohesive sediment dynamics [57]. Another model is a finite element coastal ocean–wave model SCHISM (Semi-implicit Cross-scale Hydroscience Integrated System Model)—WWM (Zhang et al., 2016a,b [58,59]). A sediment transport module is also included. The model system has been applied in the North Sea and the Baltic Sea [58,60]. However, these models have not been applied and validated for submarine cable protection.

In addition, knowledge of critical shear stress and settling velocity of sediments with different grain sizes are still of high uncertainty in the sediment transport module [61]. Observations are needed to improve the parameterizations.

3.3. Wake and Lee Effects

For applications related to the wake and lee effects of OWFs, the key information product is the impact of OWFs on winds, ocean conditions, waves, and sediment transport. In Part I [8], an integrated monitoring-modeling approach was proposed. The models required include weather, ocean, wave, and sediment transport models, which can resolve multiple scales ranging from individual OWF scale to coastal connectivity scale and multi-farm and cross-border scale. These models will not resolve individual turbines. Instead, the effects of individual turbines are parameterized according to the models' grid sizes. Such parameterizations can be developed using observations or combined with turbine-resolving very high-resolution computational fluid dynamics (CFD) simulations such as large eddy simulations (LES). Observations in the farm site and surrounding waters are required to derive the turbine-effect parameterizations and to calibrate and validate the CFD and ocean–wave–sediment transport models.

3.3.1. Existing Monitoring Solutions for Wake and Lee Effects

Observations to study and assess wake and lee effects are gathered by OWF operators, research programs, operational monitoring agencies, environmental monitoring, and coastal agencies. Sea state, sea level, currents, and winds within OWFs are often monitored exclusively by OWF operators. These data are confidential and can be used for research after a non-disclosure agreement (NDA) is signed. Nacelle wind speed and operational variables are measured by SCADA (Supervisory Control And Data Acquisition) systems from all turbines, together with wave data from buoys and winds from ground-based LIDAR data. Research projects may also obtain permission to carry out multi-disciplinary monitoring activities, including physical, wave, sediment, biogeochemical, and biological monitoring. For EC-funded projects, research data should be released as soon as possible, following the FAIR (find, access, interoperate, and reuse) principles. In particular, multi-disciplinary datasets obtained from research projects dedicated to studying the wake and lee effects will be very useful for deriving and validating parameterizations of turbine and OWF impacts. One example is the three FINO research platforms, which provide hourly meteorological and oceanographic observations in German EEZ waters, including wind profile data from a mast of 103 m high. Operational and coastal agencies are responsible for carrying out operational monitoring on, e.g., sea level, waves currents, and winds in the coastal waters, using fixed platforms of tide gauge stations, moorings and coastal morphological stations, and FerryBox. Sometimes, these stations are in the outskirts of OWFs, e.g., MARNET buoys operated by BSH, tide gauge, FerryBox, and HF radar networks in European coastal seas, so the observations can be used to quantify the wake and lee effects and validate the OWF impact-resolving models. Environmental monitoring is regular low-frequency (4–24 times a year) sampling in air, seawater, biota, and seabed. These data can be used for model validation. In Europe, operational and environmental monitoring observations and part of the research observations have been collected and centrally disseminated by EMODnet. Furthermore, OWF lee effects were analyzed in the framework of dedicated airborne campaigns [62,63]. Airborne data were used as well to evaluate OWF parameterizations in atmospheric models [64].

Regular observations of atmospheric wakes are provided by satellite synthetic aperture radar (SAR) data as flown on the European Sentinel-1/2 platforms. Analysis of these data and derivation of empirical parameters to describe the spatial structure of wakes have been presented in a number of studies (e.g., [65,66]). The measurements have big potential because of the high spatial resolution (<100 m) and the large coverage (>100 km). The observations are however limited by relatively poor temporal sampling caused by the dusk/dawn acquisition cycle with overflights every couple of days. We are not aware of the use of these data on a routine basis for wake monitoring.

Another standard measurement technique to study wakes in the atmosphere [67] is based on long-range Doppler light detection and ranging (lidar). These ground-based measurements have a smaller spatial but higher temporal resolution than satellite SAR systems.

3.3.2. Existing Modeling Solutions for Wake and Lee Effects

The models for assessing the wake and lee effects can be divided into two categories according to their grid resolution: OWF-resolving models with a grid size larger than the turbine foundation but smaller than the OWF coverage and turbine-resolving model with a grid size smaller than the radius of a turbine foundation. The atmospheric wake effects have been parameterized (e.g., [64,66,68,69]), and implemented in mesoscale numerical weather prediction (NWP) models. To our knowledge, these parameterizations are not yet included in operational models for forecast production. Sensitivity experiments of the OWF-resolving HARMONIE in the Baltic–North Sea region can reproduce the wake effects in the atmosphere [70]. A study concerning atmospheric OWF wakes for the North Seas using the COSMO model in combination with the Fitch parameterization was presented in [71]. Engineering models with simpler parameterizations and less computational costs are used in industry (e.g., [72]).

The impacts of atmospheric wakes on hydrodynamics and waves have been recently studied by [73,74] using an unstructured grid model SCHISM and by [75] using COWAST coupled atmosphere–ocean–wave models. However, these models do not include turbine parameterization in hydrodynamic and wave models. An early analysis of the impacts of OWFs on sea state was provided in [76]. The study concluded that the strongest effects are associated with the reduced wind forcing. Additional impacts are related to reflection and diffraction of waves at the foundation structure as well as wave dissipation caused by friction at the piles. For the effects on hydrodynamics, a parameterization of the additional mixing and friction due to a turbine structure is developed as an extension of the k—ε two-equation turbulence closure model [77]. A high-resolution Reynolds-averaged Navier–Stokes (RANS) model of the local scale is used to calibrate this parameterization. Unstructured grid ocean models have also been used in turbine-resolving impact modeling studies [78]. For OWF impacts on waves, the turbine can be treated as unresolved obstacles (UOST), and parameterization on UOST has already been included in popular wave models such as WAM, WWIII, and WWM [79].

3.4. Transport and Security

OWFs have impacts on observations and logistics on the sea. There are different types of impacts, which require more research and further observations. Here, we focus on two of them influencing the transport and safety sector in the Baltic Sea. First, while the research focus has mainly been on the impacts of sea ice on mechanical construction of OWFs (e.g., [80]), the large offshore installations influence the environment by changing the natural motion of ice fields. This has an impact on wintertime marine transport, as especially in the Northern Baltic Sea, conditions for winter maritime transport change. The changes in ice fields also influence marine ecosystem due to the impacts on mixing, sea–air exchange, and underwater light conditions. Secondly, marine surveillance is based on a coastal radar network, which is strongly impacted by the large OWFs, as the OWFs create reflections and shadowing of objects [81]. This limits the construction of OWF, especially in the Gulf of Finland, but also in areas in the vicinity of Kaliningrad. The OWFs also influence the functioning of the weather radars and limit both wind and precipitation observations over the sea areas. The decreased accuracy of observations needed for weather forecasting increases the potential security risks related to lack of accurate environmental information. A comprehensive analysis of the situation in the Finnish territorial waters has been published (in Finnish, with abstract in English) by [82].

In accordance with the oil and gas industry, ship traffic inside the OWF is regulated and activities such as fishery is very limited. There are several research projects ongoing aiming to optimize the multiuse of marine space. The recent evolvement of the political situation in Europe makes it also necessary to take terroristic activity and the impact of militaristic actions into account including ship traffic inside OWFs (e.g., fishery, terrorism, military).

In the following, we concentrate on the Northern Baltic Sea, with a rapidly increasing number of OWFs in the near future and seasonal ice conditions, which causes additional challenges for the OWF sector.

3.4.1. Existing Monitoring Solutions for Transport and Security

Currently, there are practically no OWFs in the Northern Baltic Sea [8]. However, the number of planned OWFs is very large and the situation will change rapidly in only a few year time scale. The existing observing network is an optimized balance between the current needs and available financial resources. The current observing network consists of a limited number of marine weather stations, mainly manual ice observations, wave and temperature buoys, few FerryBox lines, and Argo (Array for Real-Time Geostrophic Oceanography) floats. These are supported by remote sensing methods utilizing X-band coastal radars, AIS (automatic identification system) network for ship tracking, weather radars, satellite remote sensing products, and irregular monitoring cruises. Some additional data are obtained through other observations, like maritime cameras and hydrophones, but it is typically not available for public research or forecasting purposes. Additionally, the current political situation impacts the reliability of AIS data as there are cases both with falsified AIS signals and dark vessels (i.e., AIS transponders turned off). All these security aspects combined also influence the protection of seabed cables (**Section 3.2**), whether damaged accidentally (environmental conditions) or intentionally (hostile human activities). Thus, several overlapping and independent methods are needed [83].

3.4.2. Existing Modeling Solutions for Transport and Security

The ocean models used in the Northern Baltic Sea are developed for a range of societal needs on transport, security, and environments. These models include an operative hydrodynamic model with sea ice forecasting capabilities (NEMO-LIM3) and wave models (WAM, SWAN). The atmospheric modeling, including wind fields, is carried out with the Harmonie–Arome NWP model. These models produce sea state and weather fields necessary for environmental analysis and transport sector forecasts. They are also used as modeling input values for assessing the impacts of OWFs on (radar) electromagnetic signal propagation over the sea.

Sea ice forecast is an important product for transport and security related to the OWF industry. In the Baltic Sea, several sea ice models such as LIM, CICE, HELMI, and HBM-ICE have been developed and coupled with hydrodynamic models to provide an operational forecast of the sea ice. Assimilation of sea ice concentration observations is now available in the CMEMS BAL MFC forecasting system [84]. In Finland and Sweden, the model forecast and sea ice charting are combined for providing the ice service for operations in the sea.

In case of collisions of ships or damage of submarine cables, there might be severe leaks of oil, gas, or chemicals from the vessels. Three-dimensional drift modeling of pollutants will be needed. The on-demand oil drift models have been operational in most of the Baltic Sea countries [85]. The similar drift models have also been used for search and rescue. Oil drift model in pack sea ice has been developed by [86], which is very useful for the Northern Baltic Sea.

3.5. Contamination

There are two main aspects to be considered to evaluate the impact of contaminants associated with OWF installations. On the one hand, metal and chemical concentrations need to be monitored and modeled in the vicinity of the emitting sources. On the other hand, ocean currents need to be observed and/or simulated to assess the regional dispersion of these contaminants toward the rest of the oceanic basin.

Corrosion protection systems used for OWF turbines might be responsible for the release of aluminum, cadmium, zinc, and indium into the ocean) [87,88,89,90,91], with potential toxic effects on marine life. Aluminum, cadmium, and indium are non-essential metals for marine organisms. When introduced artificially in an environment with a relatively high concentration, aluminum can negatively affect important regulation and respiratory functions of adult fishes [92]. Cadmium is recognized as an environmentally highly toxic metal that can accumulate in marine flora and fauna, be transmitted through the food web and eventually affect human bodies [93,94]. While zinc is a necessary element for the functioning of marine organisms, it also represents a risk of toxicity with increased concentration [95]. Once in the ocean, these metals were found to be able to latch onto floating plastics, favoring ingestion by marine organisms and insertion into the food web, thus representing a threat to ecosystems at large [96,97]. Organic compounds with high toxicity, including biosphenol A [98], are also part of the substances associated with corrosion protection measures that may end up in the ocean due to material damage or weathering processes [91]. While the effect of these emissions from corrosion protection systems is probably relatively low compared to other sources such as rivers, atmospheric depositions, or fossil fuel industries [88], the potential toxic risk for marine organisms makes it necessary to monitor the presence of these different components in the vicinity of the wind farms.

Ocean currents then have the capacity to transport these contaminants over large distances. While they may have a dispersive effect that progressively reduces their concentrations as long as they are transported over the basin, currents may also accumulate them in specific locations due to oceanographic or topographic singularities. Knowing the possible trajectories of these contaminants once released at the OWF sites is crucial to characterizing the oceanic connectivity, evaluating the impact of these installations over entire ocean basins, and understanding the path of these substances across administrative boundaries.

3.5.1. Existing Monitoring Solutions for Contamination

Monitoring the concentration of metals and other contaminants typically requires taking samples of either water, bottom sediments, or tissues of marine organisms. The concentration of metals dissolved in seawater can be measured by collecting water samples and analyzing them after filtering in the laboratory. Since the toxicity may also depend on water hardness, pH, dissolved organic carbon, and temperature conditions, these complementary chemical parameters should also be monitored. The analysis of samples of sediments and tissues can provide additional information on the presence of metals on the ocean floor, and the potential impact of bioaccumulation processes in marine organisms. While sample analysis techniques are available, they remain quite costly and, to the best of our knowledge, they have not been implemented for operational automated measurements.

Concerning ocean currents, a routine monitoring of large-scale features is performed by satellite altimeters through the measurement of sea surface height anomalies and subsequent determination of associated geostrophic currents. However, these observations suffer from limitations in the coastal zone and only represent spatial scales larger than a few tens of kilometers. In coastal areas, high-frequency radars (HFRs), installed on the shore, have the capacity to measure the surface flows with a kilometer-scale resolution and a spatial coverage of a few tens of kilometers from the coast [99,100]. When covering wind farms areas, HFR measurements represent an ideal solution to monitor ocean currents and water pathways in the vicinity of the OWF. Surface drifters may also be deployed in the area of interest to infer drifting trajectories from the OWF infrastructure, but they might not necessarily provide robust information since their trajectory strongly depends on the ocean conditions at the time of the deployment given the high spatio-temporal variability of ocean currents in the coastal zones.

3.5.2. Existing Modeling Solutions for Contamination

Hydrodynamic modeling provides a tool to represent the evolution of ocean currents over wide areas and characterize the ocean connectivity at the regional scale. Nowadays, simulations and predictions of ocean currents are generated operationally with a spatial resolution close to 1 km in some regions of the world (e.g., **https://marine.copernicus.eu/**, accessed on 1 June 2023) [101,102,103,104]. The incorporation in the models of the information provided by routine and multi-platform observations (from satellite, profiling floats, underwater gliders, HFR) through data assimilation provides a way to constrain the simulations to be as close as possible to the observed conditions. Hydrodynamic-wave coupling can also be implemented to enlarge the range of resolved processes and in particular represent the wave-induced drift at the ocean surface. Telescopic model nesting then also allows for refining the spatial resolution in limited areas of specific interest. Sediment transport modules are also useful to model the sedimentation and resuspension of particles. On top of this, Lagrangian modeling [105] can be applied to calculate trajectories from simulated currents and explore the spatio-temporal ocean connectivity at the regional scale.

3.6. Ecological Impacts of OWFs

The development of OWFs has impacts on the marine ecological environment [89,106]. There are aspects that, in general, can be associated with positive impacts, such as that renewable energy helps reduce greenhouse gas emissions and mitigate the climate change effect. In addition, OWF development can contribute to the development of artificial reefs that provide opportunities for benthic organisms to develop a higher diversity than in unchanged environments. Those areas are also potentially attracting several fish species, leading to new environments for development and increased biodiversity (i.e., [107]). Those positive effects are potentially in exchange with the negative effects caused by the development of OWFs, where noise and vibration under construction and in the drift phase can potentially impact marine species such as fish, mammals, and invertebrates [108,109]. In addition, OWFs can pose a collision risk for birds and bats, especially during migration or when placed in important feeding or breeding areas (i.e., [110]). Furthermore, the installation of wind turbines and the associated infrastructure (e.g., cables and substations) can cause physical habitat alteration and loss. For example, the installation of OWF can disrupt the seabed and benthic ecosystems and have an impact on the behavior of the marine species via the change in the electromagnetic fields, which is caused by undersea cables transmitting electricity from OWFs [111,112]. Furthermore, the currents around monopiles in OWFs increase turbulent mixing, potentially leading to the break-up of stratification [113,114], increased turbidity [115], and changes in primary production [6,116,117].

3.6.1. Existing Monitoring Solutions for Ecological Impacts

Monitoring the ecological impacts of offshore wind farms is crucial to assessing and mitigating potential effects on marine ecosystems and for model validation. Underwater acoustic monitoring systems are used to assess the impact of noise generated during OWF construction and drift on marine organisms following procedures developed and implemented (i.e., [118]). These systems can track and analyze sound levels, underwater noise propagation, and the behavior of marine species in response to noise. Visual and radar systems are employed to monitor bird and bat activity around wind farms. These systems can detect and track the flight paths of birds and bats to assess collision risks. Additionally, bird and bat observers may be stationed on vessels or offshore platforms to conduct real-time monitoring. Video monitoring using underwater cameras and remotely operated vehicles (ROVs) allows for direct observation of the marine environment around OWF. These surveys can assess the presence, behavior, and interactions of marine species, including fish, marine mammals, and benthic organisms. Satellite imagery and remote sensing techniques can provide valuable information on changes in sea surface temperature, total suspended matter and phytoplankton biomass, and the distribution of marine species at the water surface over larger spatial scales. Observations of vertical profiles of physical and water quality variables require profiling buoys or profiles observed from ships. Benthic surveys are conducted to sample and monitor the seabed and associated organisms in the vicinity of OWF (for example, [51]). The conduction of eDNA analysis involves collecting and analyzing water samples to detect and identify genetic material shed by organisms in the environment. It can provide information on the presence, abundance, and diversity of species and potentially provide information on changes in behavior.

3.6.2. Existing Modeling Solutions for Ecological Impacts

The construction and operation of OWFs can have significant impacts on marine ecosystems and the habitats of marine organisms. Those impacts are mainly caused by changes in (1) noise, (2) habitat, (3) electromagnetic fields, and (4) water quality. Spatially explicit frameworks to analyze the integrated effects of wind farms on the marine environment aiming to evaluate how wind farms can contribute to the protection of the marine environment through strategic and economically viable location choices are developed and applied for quite a long time (i.e., [119]). Systematic methods for mapping how increased pressures from human activities may cause cumulative ecological effects on marine ecosystems are developed [120]. Those frameworks aim to provide answers regarding the integrated effect. A couple of such frameworks are established for specific regions. In the Netherlands, the Deltares model D-FLOW-FM-DCSM is used to evaluate the potential effects of future OWFs on currents, vertical mixing, suspended sediment concentrations, phytoplankton dynamics, and benthic filter-feeders [121]. For validation of this model, vertical profiles of temperature, salinity, suspended matter, and phytoplankton are the main gaps in required observations for model validation. In the area of water quality modeling, there is a long tradition of developing models for the human impact on the marine ecosystem (i.e., [116,122]).

Those integrated frameworks depend crucially on the realistic modeling of the specific impact factors on the ecosystem. In order to be able to calculate the sound level at a given distance from the source, it is important to have sufficient knowledge of the parameters that must be included in such a model [123], such as sound source, water depth, bottom topography, properties of the bottom and water column (density, sound speed, and attenuation). Parameters that are often not sufficiently known. For habitat changes, there exists a variety of model approaches for the specific components of the ecosystem (i.e., fishes: [124]). The modeling of the electromagnetic field and changes via the implementation of OWFs is in a premature state, and many approaches are taken from terrestrial applications. However, [125] have conducted modeling evaluations investigating EMF (electromagnetic fields) by subsea power cables. For all types of ecological models, system understanding of the long-term impacts of OWFs is the main gap for further model development and testing. We are only starting to observe and understand these impacts as the implementation of OWFs is under development.

4. Gap Analysis

In the following, gaps are identified for all six use cases. The analysis is structured along different gap categories, e.g., gaps in accessibility and availability of observed variables, as well as deficiencies in spatial and temporal sampling or in model-observation integration. It is obvious that this analysis can never be totally objective. It is, however, a view that is shared among the authors, who come from six European countries and who were involved in various projects with industry and agency involvement. We are also aware that the assessment of gaps will change over time because of the extremely dynamic situation in terms of technology developments and the largely unpredictable political boundary conditions. As the authors are not representing the entire offshore wind sector, we are not trying to make strong statements regarding priorities, but we rather see this analysis as a contribution to a broader discussion among industry, agencies, politics, and research that is necessary on a European level and beyond.

A condensed overview of gaps regarding monitoring and modeling is provided in Table 1 and Table 2, respectively. We will discuss these deficiencies in more detail in the following.

Table 1. Monitoring gaps in the OWF sector for different use cases.

Variable	Use Case	Gaps
Bathymetry	O&M	More regular surveys desirable to optimize wave forecasts
	Protection of sea cables	Detailed bathymetry near cables (for accurate bed slope calculation) not accessible
	Wake and lee effects	Detailed OWF bathymetry is still challenging to obtain, but this is not the main source of modeling errors
	Transport and security	n.a.
	Contamination	n.a.
	Ecological impacts	Limited data availability on stability of sediments as habitat for benthic organisms
Shoreline	O&M	No major gaps

Variable	Use Case	Gaps
	Protection of sea cables	No major gaps
	Wake and lee effects	Regularly updated shorelines; more observations desirable in Wadden Sea areas because of impacts on ABL
	Transport and security	n.a.
	Contamination	n.a.
	Ecological impacts	n.a.
Wave height	O&M	More consistent wave observations on coastal and regional scale desirable, including accuracy information
	Protection of sea cables	Dedicated wave observations near cables are needed
	Wake and lee effects	Dedicated wave observations in the wakes
	Transport and security	Availability will improve radar performance estimates and sea state forecasting close to OWFs
	Contamination	n.a.
	Ecological impacts	No major gaps
2D wave spectra	O&M	Homogeneous spatial distribution of 2D observations, including OWF sites desirable
	Protection of sea cables	Dedicated wave observations near cables are needed
	Wake and lee effects	Dedicated wave observations in the wakes
	Transport and security	Availability will improve radar performance estimates and sea state forecasting close to OWFs
	Contamination	n.a.
	Ecological impacts	n.a.
Surface winds	O&M	To improve coupled wave and atmosphere models, more wind profile observations are required inside and outside OWFs
	Protection of sea cables	No major gaps
	Wake and lee effects	Observations in the wakes
	Transport and security	OWFs weather radar shadowing effects need to be compensated with additional observations
	Contamination	n.a.
	Ecological impacts	n.a.

Variable	Use Case	Gaps
Wind profiles	O&M	To improve coupled wave and atmosphere models, more wind profile observations are required inside and outside OWFs
	Protection of sea cables	No major gaps
	Wake and lee effects	Observations inside OWFs and in surrounding areas
	Transport and security	Changes in vertical wind profiles and turbulence may influence radar signal propagation close to the sea surface OWFs weather radar shadowing effects need to be compensated with additional observations
	Contamination	n.a.
	Ecological impacts	n.a.
Atmospheric boundary layer parameters (including icing and humidity)	O&M	More vertical profiles of temperature and humidity are needed to improve ABL stability and icing conditions in forecast models, as well as corrosion prediction
	Protection of sea cables	No major gaps
	Wake and lee effects	Observations inside OWFs
	Transport and security	Vertical temperature and humidity profile observations necessary for modeling electromagnetic signal propagation
	Contamination	n.a.
	Ecological impacts	n.a.
Precipitation	O&M	Standardized measurements suitable for training of ML models insufficient
	Protection of sea cables	n.a.
	Wake and lee effects	n.a.
	Transport and security	OWFs weather radar shadowing effects need to be compensated with additional observations
	Contamination	n.a.
	Ecological impacts	n.a.
Surface current	O&M	More observation required in particular in the vicinity of OWFs
	Protection of sea cables	Nearshore currents in brackish waters
	Wake and lee effects	Incomplete coverage of nearshore currents (esp. in brackish waters)
	Transport and security	Additional observations in and around OWF

Variable	Use Case	Gaps
	Contamination	Incomplete coverage of coastal areas by HF radars
	Ecological impacts	n.a.
Current profiles	O&M	It is debatable whether more profile information is needed to better capture abrasion processes
	Protection of sea cables	Currents near seabed in cable areas
	Wake and lee effects	Currents and turbulence measurements in the wakes and nearby OWFs
	Transport and security	n.a.
	Contamination	n.a.
	Ecological impacts	Limited data availability for both inside and outside of OWF for comparison
T&S	O&M	More observations required, in particular, near OWFs for corrosion prediction
	Protection of sea cables	No major gaps
	Wake and lee effects	Inside and nearby OWFs, especially in wakes
	Transport and security	Inside and nearby OWFs
	Contamination	Local observations required to (1) constrain simulations of hydrodynamics, and (2) evaluate toxicity of contaminants
	Ecological impacts	Limited data availability of vertical profile data and long time series for trend detection
Underwater sound/noise	O&M	n.a.
	Protection of sea cables	n.a.
	Wake and lee effects	n.a.
	Transport and security	Additional underwater noise observations may be needed
	Contamination	n.a.
	Ecological impacts	Limited data availabillity
Land-based sediment discharge	O&M	n.a.
	Protection of sea cables	Lack of daily or monthly data
	Wake and lee effects	Lack of daily observations
	Transport and security	n.a.

Variable	Use Case	Gaps
	Contamination	n.a.
	Ecological impacts	n.a.
SPM concentrations and composition, settling velocity	O&M	n.a.
	Protection of sea cables	No major gaps
	Wake and lee effects	Need dedicated in situ data in wakes and lee area
	Transport and security	Changes in underwater visibility may impact the use of optical underwater methods
	Contamination	n.a.
	Ecological impacts	Limited data availability of vertical profile data and long time series
Seabed sediment properties (type, sedimentation, and erosion rate)	O&M	n.a.
	Protection of sea cables	Lack of regularly updated basin-scale dataset, esp. in cable areas
	Wake and lee effects	Need regularly updated data in OWFs and wake/lee impact areas
	Transport and security	Changes in seabed may need additional surveys
	Contamination	n.a.
	Ecological impacts	Limited availability of long time series to detect changes
Sea ice	O&M	More reliable observations needed in vicinity of OWFs
	Protection of sea cables	Lack of in situ ice thickness and fast ice data
	Wake and lee effects	Lack of in situ ice thickness and fast ice data
	Transport and security	More reliable observations needed in vicinity of OWFs
	Contamination	n.a.
	Ecological impacts	Limited data available for ice conditions impacting ecosystem
Concentration of Al, Zn, Cd, In, BBA, etc.	O&M	n.a.
	Protection of sea cables	n.a.
	Wake and lee effects	n.a.
	Transport and security	n.a.
	Contamination	Lack of regular measurements in the vicinity of OWF sites

Variable	Use Case	Gaps
	Ecological impacts	Lack of regular measurements in the vicinity of OWF sites
Concentrations of dissolved oxygen, pH, pCO2, alkalinity	O&M	More observations required for corrosion prediction
	Protection of sea cables	n.a.
	Wake and lee effects	n.a.
	Transport and security	n.a.
	Contamination	Lack of regular measurements in the vicinity of OWF sites
	Ecological impacts	Lack of long consistent time series for trend detection and interpretation
Plankton	O&M	n.a.
	Protection of sea cables	n.a.
	Wake and lee effects	n.a.
	Transport and security	n.a.
	Contamination	n.a.
	Ecological impacts	Limited availability of long consistent time series of primary production and species composition for trend detection and interpretation
Fish, marine mammals, birds	O&M	n.a.
	Protection of sea cables	n.a.
	Wake and lee effects	n.a.
	Transport and security	n.a.
	Contamination	n.a.
	Ecological impacts	Limited availability of long-term time series to assess changes in distribution around OWFs

Table 2. Modeling gaps in the OWF sector for different use cases.

Model	Use Case	Gaps
Hydrodynamic model	O&M	Atmospheric wakes not included in meteo forcing of operational ocean models
	Protection of sea cables	On-demand (re-locatable) modeling capacity is needed
	Wake and lee effects	Wake effects not included in operational weather and ocean models

Model	Use Case	Gaps
	Transport and security	Accurate, combined hydrodynamic models needed for estimating impact of sea surface properties on radar signal propagation
	Contamination	High-resolution (<1 km) regional models constrained by observations
	Ecological impacts	Smooth coupling between high-resolution models in OWFs with larger-scale models
Wave model	O&M	Two-way coupled wave/atmosphere models with wake parameterization still not consolidated. Atmospheric wakes not included in operational forecast models
	Protection of sea cables	Wave-induced vertical momentum flux needs to be validated
	Wake and lee effects	Two-way coupled wave–atmosphere models with wake parameterization still not consolidated. Atmospheric wakes not included in operational forecast models
	Transport and security	Accurate information on wave properties inside OWF's needed for estimating sea clutter
	Contamination	High-resolution (<1 km) regional models in areas where they are not yet available
	Ecological impacts	No major gaps
Weather model	O&M	Effects of OWFs on observations used in operational data assimilation schemes not considered so far
	Protection of sea cables	No major gaps
	Wake and lee effects	Wake effect-resolving operational forecast model is needed
	Transport and security	Accurate NWP modeling inside and in vicinity of OWFs needed for radar performance modeling
	Contamination	Wake effect-resolving operational forecast models would bring added value
	Ecological impacts	No major gaps
Metal pollutant modeling	O&M	Contamination models related to corrosion protection not mature (see also contamination use case)
	Protection of sea cables	n.a.
	Wake and lee effects	n.a.
	Transport and security	On-demand modeling capabilities in case of accidents not mature
	Contamination	Metal emission models from OWF infrastructures
	Ecological impacts	Metal emission models from OWF infrastructures
Suspend particulate matter model	O&M	n.a.

Model	Use Case	Gaps
	Protection of sea cables	Need more validation and calibration for storm cases in shallow waters
	Wake and lee effects	Need more validation and calibration for storm cases in shallow waters
	Transport and security	n.a.
	Contamination	n.a.
	Ecological impacts	Validation of OWF impact on vertical profiles of SPM needed
Chemical pollutant modeling	O&M	Contamination models related to corrosion protection not mature (See also contamination use case)
	Protection of sea cables	n.a.
	Wake and lee effects	n.a.
	Transport and security	On-demand modeling capabilities in case of accidents not mature
	Contamination	Chemical emission models from WOF infrastructures
	Ecological impacts	Validation is needed
Seabed sediment model	O&M	n.a.
	Protection of sea cables	Estimate of critical shear stress needs further improvements
	Wake and lee effects	More validation and calibration needed in nearshore waters and storm cases
	Transport and security	n.a.
	Contamination	n.a.
	Ecological impacts	Interaction between biota and physical processes needs to be better understood
BGC low trophic model	O&M	n.a.
	Protection of sea cables	n.a.
	Wake and lee effects	n.a.
	Transport and security	n.a.
	Contamination	n.a.
	Ecological impacts	Further validation is needed and coupling between OWF scale and ecosystem scale
Habitat model	O&M	n.a.

Model	Use Case	Gaps
	Protection of sea cables	n.a.
	Wake and lee effects	n.a.
	Transport and security	See ecosystem use case
	Contamination	n.a.
	Ecological impacts	Further development and validation needed
High trophic food web model	O&M	n.a.
	Protection of sea cables	n.a.
	Wake and lee effects	n.a.
	Transport and security	See ecosystem use case
	Contamination	n.a.
	Ecological impacts	Processes yet insufficiently understood to be realistically modeled

4.1. Gaps in the Accessibility of Observed Variables

In this section, two types of gaps are addressed. Firstly, gaps in data availability are discussed, which refer to relevant variables that are currently not observed at all. Secondly, the problem of data accessibility is analyzed, which refers to the obstacles encountered when trying to access existing datasets.

The effects of OWFs on the atmosphere and the ocean are strongly conditioned by processes in the atmospheric boundary layer (ABL). For example, the ABL stability has a big impact on the length of atmospheric wakes [65]. Currently there are very few measurements suitable to assess the state of the atmosphere (e.g., profiles of temperature, wind, and humidity). Furthermore, many of the available measurements, e.g., from FINO-1 are affected by the surrounding wind parks, i.e., they do not provide information on free stream conditions. For a better understanding and model representation of OWF interaction with the ocean it is paramount to have more information about fluxes of momentum and heat in the vicinity of the wind farms.

For the O&M use case, measurements of momentum and heat fluxes near the sea surface would contribute to optimizations of coupled atmosphere/wave/circulation models, which are required to provide reliable short-term forecasts of the conditions during maintenance operations. Furthermore, there is a lack of reliable measurements needed for predictive maintenance related to corrosion, in particular dissolved oxygen, sulfate, and pH. Dissolved oxygen and pH are provided by the CMEMS modeling system, but sulfate is not. Of particular concern with respect to corrosion are the pile segments, which are periodically wetting and drying due to wave impacts, as well as the structure above, which is affected by marine aerosols. For both processes, more detailed information on wave breaking and respective statistics in the vicinity of the wind parks is required.

For contamination assessment, concentrations of most of the contaminations (e.g., Al, Zn, BBA) in the OWF and surrounding areas have not been monitored. The data are needed in water samples and in benthic and pelagic bio-samples.

Accessibility to existing data related to offshore wind farm applications can be quite different according to which type of observations are concerned: operational, environmental, commercial, or research data. For operational data access, CMEMS, INS, TAC, and EMODnet have collected most of the in situ observations in Europe and made them freely available to the public. For observations from environmental monitoring, the data are also freely available via EMODnet, ICES (for the Baltic–North Sea), SeaDataNet, and national ocean data centers. However, these data are mainly sampled by research vessels and distributed in a delayed mode. The locations are not chosen to detect changes in environmental conditions due to OWFs. Some countries, e.g., Norway, Sweden, and Estonia, have initiated near real-time ship data, especially CTD (conductivity, temperature, and depth) data delivery. Other countries, such as Germany, Denmark, and Finland, have their CTD data available in a few weeks, while data from EMODnet chemistry, ICES, and SeaDataNet can only be available months to a couple of years after the monitoring. For OWF operational applications, e.g., O&M, near real-time access to the data is required, but this is mainly for metocean variables with high-frequency observations.

Commercial and research monitoring provides more data on a local scale compared to operational and environmental monitoring, i.e., within OWFs and surrounding areas. However, these data are more limited for public access. The data usages are often subjected to signing NDAs (non-disclosure agreements). In recent years, there have been some efforts for collecting and disseminating commercial and research observations related to OWFs. 4C Offshore (https://www.4coffshore.com/, accessed on 1 June 2023) provides worldwide offshore wind farm information with a membership fee. The Crown Estate Marine Data Exchange (MDE, https://www.marinedataexchange.co.uk/, accessed on 1 June 2023) holds data from a variety of industries, including marine aggregates, subsea cables, tidal and wave energy, offshore wind, and also data from research and evidence projects, which have grown to almost 300 TB of survey data from over 50 offshore projects across the U.K.; over 2600 survey campaigns covering over 15 survey themes, from geophysical data to marine mammal surveys.

According to the Crown Estate Data policy, regarding environmental data, despite the contractual position with regard to confidentiality, in general the Crown Estate will not release data relating to a particular project, until consent is awarded and the period for judicial review has passed. Once a firm consent decision has been determined, the data are effectively in the public domain, so generally will be released thereafter.

For physical survey data including geophysical and geotechnical data, the Crown Estate will hold survey data relating to geophysical, geotechnical, metocean, and meteorological data, confidentially until a Financial Investment Decision (FID), subject to a biannual review from the date of consent, where the time period between consent and FID is extended.

However, not all countries have an organized data collection and release system for OWF survey data as the Crown Estate in the U.K. Considering that the OWF applications need survey data and environmental data in OWFs, such data collection and dissemination mechanism is crucial. OWFs also measure metocean data, e.g., winds and waves in the farm in near real time. These data are usually held by the OWFs. They may be used for research purposes if an NDA is signed. For research at the ecosystem scale, observations from different countries need to be combined. A centralized EC focal point for OWFs to upload their publishable data or metadata should be available to facilitate OWF data sharing and exchange.

Offshore meteo-masts have been built up and operated to measure meteorological and oceanographic observations in the past decade for research purposes. These data have been well managed at the national level and made available for research. In Germany, three masts (FINO 1, 2, and 3) have been maintained since 2007, and data access can be made at https://login.bsh.de/fachverfahren/, accessed on 1 June 2023 after registration. In the Netherlands, wind@sea (https://www.windopzee.net/en/wind-op-zee/, accessed on 1 June 2023) collects, processes, and makes data available at eight offshore wind farm sites. In Denmark, DTU has maintained a website http://www.winddata.com for collecting and disseminating wind data, including 75 datasets at present, mostly from Danish waters. However, there is no centralized focal point from EC to collect and disseminate research data in OWFs, especially from EU FP7, Horizon 2020 (H2020), and Horizon Europe (HEU) projects. For H2020 and HEU programs, projects are mandatory to deliver a Data Management Plan (DMP), which, in principle, ensures that a project-oriented data policy based on FAIR principles is in place. Efforts are needed for centralized data delivery and publication of these projects.

4.2. Gaps in Spatial Data Sampling

For the six applications analyzed in this study, observations are required at four different spatial scales: (S1) within OWFs, (S2) between OWFs and the coast, (S3) cross-OWFs, and (S4) across national borders.

The atmosphere and ocean dynamics around OWFs is characterized by a strong coupling of these different spatial scales. For example, the presence of the adjacent land has an impact on the land/sea wind speed gradients [126,127]. The length of atmospheric wakes can extend up to 100 km downstream and the impacts on waves can reach even farther. The inhomogeneous sampling of atmospheric and oceanic parameters existing at the moment is not able to provide a complete picture of the 3D dynamics around OWF.

With regard to the O&M use case, the very heterogeneous sampling of wave and atmospheric boundary layer information is not optimal. As pointed out before, ocean wave dynamics encompasses a large spectrum of spatial scales with high connectivity, and in order to optimize wave forecasts, e.g., using data assimilation, a more regular sampling would be highly beneficial. This situation will get even more challenging with growing OWF installations, which can potentially impact waves on all scales (S1–S4).

For seabed cable protection, data are mainly needed in S2–S4 scales, with a focus on sections along seabed cables. Observations are mainly managed by energy agencies. All sediment conditions along the cable lines are monitored regularly. However, this monitoring can be optimized. With validated models, one can predict the sediment layer thickness above the cable, identify the areas with high risk, and optimize the sampling strategy. This may reduce the cost of monitoring largely. For validating models, a suitable research database on bathymetry, currents, waves, sediment types and concentrations, sedimentation, and erosion rates in the cable area is needed. In the sediment survey along the cable lines, if possible, the integrated measurements for these variables should also be made.

For assessing and predicting wake and lee effects, observations of wind, currents, turbulence in the sea, and ABL, waves, and sediment concentration are needed in all four scales, especially in the wakes. At the current stage, the main priority is to fill the knowledge gaps on the impacts and develop high-quality weather–ocean–wave–sediment models, which can predict the wake and lee effects. Currently, there is a lack of dedicated observations in the S1 scale in wake areas. Existing data have a limited number of stations in a farm and often close to the turbine. This is not suitable for wake study. There is also a lack of profiles of water temperature, salinity, and currents in the wakes. Danish and German waters can be a suitable testbed for the wake and lee effect study, as there is an operational monitoring network combined with HF radar, ADCP (Acoustic Doppler Profiler), moorings, tide gauge stations, and FerryBox, which can complement the commercial and research datasets.

For transport and security applications in icing waters, operational observations, especially waves and sea ice (concentration, edge, type, drift, and thickness) data, are needed. It is still not clear how the turbines may affect ice formation and drifting, considering enhanced turbulence in the wakes. The interaction between ice and waves is also an important process for correctly predicting the sea ice and waves. To fill the knowledge gaps, dedicated in situ measurements of sea ice and waves in offshore wind farms are required for model calibration and definition. The in situ sea ice thickness is also important to quantify and reduce the uncertainties of the satellite observations. Currently, in situ sea ice and wave measurements in icing waters in the Northern Baltic Sea are quite sparse.

For the assessment of ecological impacts, the main gaps in spatial data availability are observations of vertical profiles of physical and biochemical variables and consistent data over the whole gradient where ecological impacts can occur. This covers at least the wind farm itself, including the monopiles and the area in between (S1), as well as the wake, which often exceeds national borders (S2–S4).

For most of the considered use cases, there is a lack of simultaneous observations inside (S1) and outside (S2–S4) of offshore wind parks, e.g.:

- To assess and forecast the conditions for O&M-based observations in free stream conditions outside the areas influenced by wind farms;
- To assess sea surface properties (waves, SST, ice) marine boundary layer parameters, which are relevant for radar signal propagation in the transport and security context;
- Sea ice observations required for model validation and data assimilation are missing;
- Some observations, e.g., from weather and military radars, are compromised by offshore wind farms, and this needs to be compensated by other observations;
- To assess the ecological impacts of no-fishing zones in the wind farm areas;
- To assess local and regional environmental impacts of anti-corrosion measures, e.g., sacrificial anodes [91];
- To assess wake effects inside of OWFs as well as larger-scale effects associated with neighboring OWFs, including those in neighboring countries (S4).

For some of the application areas, there is also a deficit concerning the simultaneous observation of coastal gradients and observations inside of the wind farms, e.g.,:

- To relate potential chemical contamination by anti-corrosion measures to contamination by rivers;
- To improve the understanding of the interaction between coastal wind speed gradients and atmospheric wakes.

For larger-scale effects, e.g., long atmospheric wakes, transports of contaminants, or the connectivity of habitats, harmonized datasets across European countries (S4) are still lacking. As discussed in the previous section, this is related to ongoing challenges concerning regulations and interactions between industry, agencies, and research.

4.3. Gaps in Temporal Availability

There are three major time scales of relevance for the discussed use case: T1 (operational time scale of a few days), T2 (installation lifetimes of about 25 years), and T3 (climate change time scales of 30 years and beyond).

Ideally, OWF impact studies should make use of observations taken before the installations were built, in the operation phase, as well as after decommissioning or repowering (T2–T3). The reality is that for most OWF sites, consistent observations of this kind do not exist. It is recommended to start observations three years prior to the start of the OWF installation. What is urgently needed is to define respective monitoring strategies for the OWF installations, which are planned for the future. In addition, there is no consistent strategy for long-term monitoring, e.g., to track the ecological impacts and impacts of climate change on offshore wind energy (T3).

In O&M application, we focus on two activities: platform dismantling assessment and operational maintenance. The former needs mainly long-term (T3), high-frequency wave data in S1, while the latter needs near real-time (T1) metocean data, especially winds and waves, mainly in S1 but also S2–S4 areas. Currently, most of the European OWFs have their own wind and wave conditions monitored operationally with an update frequency of 10 min or 1 h in the S1 scale. For areas of S2–S4, since no maintenance operations will be carried out, a combination of operational monitoring (in situ and satellite) and model prediction can meet most of the requirements. Furthermore, for the O&M use case the availability of near real-time data with short latency is critical for the optimization of short-term forecasts. Such access does, in fact, exist for many observations, e.g., from the MARNET stations operated by BSH. The lack of consistent information about observation accuracy is still an ongoing issue, however.

For ecological impact assessment applications, long-term biogeochemical, habitat, and biodiversity data are required (T2–T3). The sampling needs to be made before and after the installation of the OWFs. The focus should be first put on the OWF and surrounding area in order to enable OWF siting in an area causing minimal impact, then in the area of S2–S4. Existing observations for this purpose are made during surveys for impact assessment of OWFs and research projects. Long-term, sustainable observations for ecological impact assessment are still lacking.

In general, one can say that a strategy is missing to develop a balance between long-term, consistent measurements and more flexible monitoring activities, which can become necessary to look at unexpected environmental impacts, improve process understanding, or validate on-demand modeling systems.

Another challenge that still exists is a mismatch between spatial and temporal sampling. An extreme example is satellite radar measurements, which provide very high spatial resolution and coverage, but the temporal sampling is not sufficient to capture the dynamics of the observed processes. On the other hand, observations from fixed platforms provide sufficient temporal sampling, but the coverage is often so poor that processes like advection related to spatial gradients are not resolved at all.

4.4. Gaps in Observation/Model Integration

When an integrated modeling-monitoring approach is applied for information provision, the basic idea is that the monitoring should provide quality-assured observations to fit for the purpose of improving model quality while models, on the other hand, can be used to optimize the sampling strategy and improve the cost efficiency of the monitoring activities. The applications in this study can be divided into four categories: (i) operational service (O&M, transport and security), (ii) regular or long-term assessment (cable protection, contaminants, ecological impacts), (iii) applications with significant knowledge gaps (e.g., cable protection, wake and lee effects), and (iv) on-demand and what-if service (e.g., O&M, cable protection, transport and security, contamination). The requirements and gaps can be quite different among the four categories. For the operational services, a major concern is the timeliness and quality of the forecasts for, e.g., winds, waves, and currents. Major gaps for this category of applications are:

1. Observations used for data assimilation in operational forecast systems start to get affected by OWFs, and this is not yet taken into account in the modeling systems;
2. There is a lack of strategy about the use of observations taken by the wind farm operators, e.g., in data assimilation schemes;
3. There is a lack of suitable observations for model validation and parameter tuning;
4. Machine learning (ML) and artificial intelligence (AI) tools should be developed to improve the local forecast by integrating local OWF observations and forecasts; long-term local observations are therefore valuable for training and optimizing the algorithms.

For long-term assessments, regular and long-term information products are needed; thus, model-observation integration should serve this purpose. Major gaps in this area are:

1. There is a lack of strategy concerning long- and short-term measurements, e.g., required for improved process understanding and respective model representation, model parameter optimization, or operational data assimilation;
2. There is a lack of information about realistic pan-European future OWF installation scenarios that can be used for optimization of monitoring systems using OSSE approaches, as well as model scenario calculations.

For applications with knowledge gaps, the model-observation integration should serve the purpose of adding new knowledge, including calibrating and optimizing relevant model parameterizations. Major gaps in this area are:

1. There is a lack of observations in the targeted areas, such as along cable lines or in wake and lee areas, which are needed for optimizing OWF parameterizations in the models;
2. To understand processes such as sediment erosion in the seabed and wake and lee effects, integrated observations are needed. Targeted sampling strategies should be designed to fill the knowledge gaps and improve model parameterizations.

For the applications that need on-demand and/or what-if scenario service, e.g., in case of collision, search and rescue, and pollution, on-demand modeling tools and observations are required. Major gaps in this area are:

1. Existing on-demand modeling systems, e.g., oil spill, search and rescue systems, should be dedicated to the OWF industry and, therefore, be able to integrate local observations;

2. The integrated model-observation system should be developed to supply extra information based on simulations of what-if scenarios when a critical environmental condition is likely to be reached and a decision on the operations has to be made.

In addition, it is essential to have information on observation accuracies, which is particularly critical for applications in the O&M context, where decisions with large financial implications have to be taken based on monitoring and modeling information. In the wake and lee effect studies, since the mean impacts of OWFs on the winds and waves are just a few percent, accurate data on winds and waves are thus very important to calibrate and validate the models. For wind power forecasts, the required accuracy for wind speed information is 3% due to the cubic dependence of wind power on wind speed [128]). Currently, there is a significant gap both in the availability as well as the standardization of such information. Activities to improve this situation do exist (e.g., [34]) and should be extended significantly.

Concerning the O&M use case, the integration of observations and numerical models is still not well developed. One of the challenges is the very short time scale of wave dynamics and the domination of sea state errors by inaccuracies in the driving wind fields. This means that the observed errors have to be traced back in order to realize efficient data assimilation schemes. Furthermore, some of the errors are caused by the forcing of the model at the open boundaries, and respective corrections are not trivial. Observations near these boundaries would add much value to the data assimilation schemes. It appears that the combination of classical data assimilation schemes and machine learning (ML) approaches or pure ML techniques [129] has the potential to address these problems, and more research is required in this field. For the training of ML methods, quality control and consistency of large observation datasets become even more important.

5. Discussion and Recommendations

In the previous section, gaps were identified in observation systems as well as in the integration of measurements with numerical models. The analysis was structured along different OWF use cases and along different observation characteristics, e.g., spatial sampling.

It seems obvious that the evolution of the existing monitoring systems was driven by a number of use cases, which had high priority in the past. For example, tide gauges were necessary for the development of storm surge forecast systems. Likewise, wave buoys have been important components in coastal management system, e.g., in the context of coastal erosion, for a long time. More sophisticated measurements, e.g., acquired by ADCPs, have become necessary to validate 3D circulation models, which are key elements in drift forecasts.

There is a general trend in the modeling community toward stronger coupling of different physical, biological, and chemical model compartments, which is necessary to capture interaction processes of practical importance, e.g., the Stokes contribution of waves to the currents. As explained before, coupled models are an absolute necessity to capture processes in the vicinity of offshore wind farms and to provide respective information products. These coupled modeling systems have increased complexity in terms of dynamics and numerical implementation, i.e., model validation has become an even more challenging task, with broader requirements concerning observation systems. In particular, the validation of fluxes (e.g., energy, momentum, substances) between different model compartments is of growing importance for the new generation of coupled modeling systems. Many of the observation gaps identified in the previous section are related to missing information about the connectivity of different processes in the ocean and the atmosphere. This is a major bottleneck for the further optimizations of modeling systems and fit-for-purpose information products.

Due to the increased computational capacity available today, there is also a trend to finer spatial model resolutions. Unstructured grid models, which allow grid cells of only a few meters in size near the coast, have almost become a standard. As the typical spacing between offshore wind turbines is about 1km or below, it is obvious that model simulations for the offshore wind sector require fine spatial grids to resolve interactions between offshore wind farms and the environment. The validation of high-resolution models leads to new challenges for observation systems as well. Either one has to make sure that the sensor matches the resolution of the model, or one has to apply appropriate statistical methods for the validation. A careful characterization of the measurement process, e.g., spatial and temporal integration windows, is of increasing importance to make models and observations comparable. Likewise, reliable information about systematic and stochastic observation errors is essential for the assessment and optimization of models.

The formulation of recommendations for the evolution of monitoring systems in the context of offshore wind farming is complicated by the fact that various actors in this sector have to be considered. In addition, there is a larger spectrum of instruments that are on the table to drive certain developments. In the following, we will focus on the following pathways:

- Optimization of regulations and policies concerning data acquisitions and sharing, obligatory data sharing;
- Incentives for monitoring technology developments;
- Identification of synergies with other user groups of observation data;
- Additional observations and modeling to fill the observing gaps due to OWF radar shadowing effects and changes in sea surface properties;
- Implementation of a dynamic trans-European platform for information exchange and identification of changing requirements;
- Platform for communication between industry, agencies, and researchers;
- Complementary research, in particular concerning model/observation integration toward the development of a digital twin for the two-way coupled system of technology and environment.

With regard to data sharing, regulations should be put in place that make sure that offshore wind farm operators do not have a competitive disadvantage by opening access to their observations. We think that a combination of three strategies should be applied:

- Regulations should be implemented to make sure that standard observations are made public by all wind farm operators. Starting with the opening of the historical datasets would already be a step in the right direction. The approach used in the U.K. can be used as a first guideline;
- It should be more transparent how the different actors in the offshore wind sector can benefit from data sharing. In this context, research should better quantify the potential improvements in forecasts on different spatial and temporal scales;
- Regulations should be adjusted to allow cross-border measurement campaigns, e.g., with aircraft, ocean gliders, AUV, or drones. These systems can often operate autonomously, which leads to additional regulation requirements.

It is important to note that some OWF operators have already started to publish their observations for non-commercial use, e.g., Ørsted, and this development should be further encouraged.

With regard to incentives for technological developments, we see a number of areas with much potential:

- Drone technologies, whether in the air (AAV), at the sea surface (ASV), or underwater (AUV), are seen as very flexible tools both in the technological (e.g., blade inspections) and also in the earth system context (e.g., measurements in the atmospheric boundary layer/sea surface/underwater). In particular, developments toward a full automatization of this technology could lead to a step change with regard to monitoring in the offshore wind sector. Apart from the technological challenges, this will also require adjustments on the regulative side and in legislation;

- There are many promising applications of machine learning techniques in the offshore wind sector, e.g., in the context of corrosion modeling. These approaches rely on big, consistent, and quality-controlled observation datasets. There should be more joint efforts of industry and research to produce such datasets with open access.

Concerning synergies with other user communities, we see much added value in the following strategies:

- The offshore wind community should team up with the operational weather and forecast community. Operational observations are already affected by OWFs, and these have to be included in parameterized form in operational models. This, in particular, requires information about the operational status of OWFs;
- It becomes increasingly important to assess cumulative environmental impacts originating from different technologies. We, therefore, see many benefits in the design of combined monitoring strategies, including sectors like shipping, fishing, oil and gas, and industry discharging into rivers. There are also obvious synergies with military monitoring programs that could be exploited more;
- Offshore wind farm sites are areas with a relatively high density of observations and are therefore interesting candidates as test and validation sites for satellite systems. This would also provide the opportunity to optimize satellite observing systems for offshore wind applications.

For the security and transport use case, the following issues should be addressed:

- The potential need for additional weather radars to compensate for shadowing effects, joint planning with neighboring countries;
- Additional surveillance radars in OWFs shadow-specific areas;
- Additional sea ice observations (thickness, forces) are needed, especially in the beginning, to study the impacts of OWFs on sea ice;
- Additional vertical wind measurements; precipitation on marine weather stations; new marine weather stations;
- Wind turbines act as wind sensors: the data can be used to fill the measurement gaps due to the shadowing effects;
- Implementation of OWF-module to HARMONIE METCOOP NWP [69,130] and other regional high-resolution NWP models;
- Small-scale ice model development;
- Improved OWF parameterizations for radar signal propagation models.

With regard to a trans-European information platform, it is recommended that:

- The platform should contain consistent and updated information about the status and concrete future plans concerning OWF installations in Europe. This information should be sufficient to allow the integration of these installations into operational models and model scenario calculations;
- The platform should contain information in the form of datasets or interactive information systems, which allow wind farm operators and agencies to learn from the experiences, e.g., concerning environmental impacts in other regions;
- The platform should contain observation datasets, which are suitable for studying environmental conditions before and after offshore wind parks were built;
- The platform should define and contain observation datasets, which are suitable for long-term analysis of climate change impacts on the offshore wind sector;
- The platform should provide information about best practices for quality control of observation data and the definition as well as estimation of observation accuracies;

- The platform should provide best practice information on optimized OWF siting (i.e., siting with a minimal environmental impact and best coexistence with other industries).

With regard to a platform for communication between industry, agencies, and researchers, we see much potential in the following strategies:

- There should be a platform with continuity for the communication between industry, agencies, and researchers, which goes beyond the typical three-year cycle of national and European research projects. We think that this will help to build trust between these groups, and it will contribute to longer-term strategic planning, e.g., of scientific measurement activities;
- There has to be a continuous update and exchange of information about industry requirements, legislative frameworks, and new research developments.

With regard to complementary research and modeling activities, we have the following recommendations:

- The approach of on-demand modeling is seen as a very efficient tool to react quickly and in a flexible way to emerging new challenges, e.g., unexpected environmental impacts. This requires a respective modeling infrastructure and model interface harmonization;
- More dedicated observations should be gathered to optimize and validate coupled modeling systems, which are essential to capture the two-way interaction between the installations and the environment. Particular deficits exist in the atmospheric boundary layer and for ecosystems;
- OWFs have to be included in operational weather and ocean forecast models. Neglecting these installations will not only disregard the environmental effects of the OWFs, but also compromise the use of operational observations, which are impacted by the turbines. Data from OWFs would also help in filling the observing gaps due to radar shadowing effects;
- Integration of cross-border modeling and observation systems should be implemented to study and assess the impacts of OWFs on neighboring countries. This is also important to develop respective legislative frameworks related to, e.g., environmental impacts and ecosystems;
- The development of OWFs is currently going much faster than the development of observations, modeling, and understanding of their ecological impacts. This bears the risk that we only understand their ecological impacts after it is too late to reduce the number of OWFs in our coastal waters. By sharing data and experiences from existing OWFs, we can speed up the development of understanding, which would allow some time for adaptive management.

As a final comment one should say that the "static" view of a classical gap analysis as depicted in **Figure 1** is to some extent oversimplifying the situation in the offshore wind energy sector. This is because of (1) the lack of process understanding, (2) fast technological developments, and (3) unpredictable dynamics in economic market developments and politics. This means that the design of monitoring systems for this sector should have considerable flexibility to allow for later adjustments concerning commercial focus areas and research priorities.

6. Summary and Conclusions

A gap analysis was presented for observation systems and respective integrations with numerical models in the context of fit-for-purpose information products required in the offshore wind energy sector. The study is the second part of two papers, with the first one concentrating on the identification of requirements for six use cases. It was explained that gap analysis is a powerful tool to optimize decision processes by enforcing the development of clear ideas about target scenarios and the transparent assessment of the initial situation. The study also discussed the challenges of applying this tool in the context of offshore wind energy. One key challenge is the balancing of economic and environmental target definitions because this includes discussions about values and ethical aspects that require a broader discussion in society, i.e., this is not a purely scientific issue.

The study provided an overview of the monitoring and modeling solutions that are presently used to provide information products for the offshore wind community. It became quite clear that the observation and model systems used today have evolved due to requirements associated with a number of standard applications, e.g., storm surge forecasts or wave predictions for shipping. It also appeared that the monitoring of ecosystem parameters is less mature than respective systems for the measurement of physical quantities.

By comparing the present situation with the requirements identified in [8], gaps were identified, which were structured along different categories, e.g., spatial and temporal sampling or data availability and accessibility. Many of the identified gaps have to do with the fact that the existing monitoring systems are not adequate to capture characteristic length scales of today's offshore wind farms, e.g., related to the spacing of turbines. This means that different types of wake effects and turbine impacts on the environment cannot be assessed appropriately with the available observations. In addition, OWFs create new types of physical, chemical, and biological processes, which are not captured by the present monitoring systems at all, e.g., the generation of turbulence by turbine structures in the water and the atmosphere. Furthermore, it was discussed that most of the fit-for-purpose information products for the offshore energy sector have to include various types of connectivity aspects, e.g., the continuum of land, wind farm, and open ocean spatial scales. Likewise, the treatment of most optimization problems occurring in offshore wind farming requires detailed knowledge about interaction processes between different earth system compartments, e.g., the atmosphere, the ocean, the sea floor, and the ecosystem. There is still a lack of suitable measurements for this purpose, although information about these coupling mechanisms is also highly relevant in other contexts, e.g., climate change. There are also still observations missing to identify, understand, and predict two-way interactions between the technology and the environment. This has become increasingly challenging because of the rapid development of OWF installations in terms of turbine size and OWF coverage. It was also found that with regard to temporal sampling, a measurement strategy is missing to assess the environmental conditions before and after windfarms were installed. The issue is of growing urgency since locations not impacted by OWFs are increasingly hard to find.

A number of recommendations to fill the gaps were formulated. These include different technological aspects, e.g., autonomous systems like drones, but also suggestions concerning data policies and cooperation between science and industry. Due to the large-scale interactions of OWFs with the environment and also among each other, the development of measurement strategies across country borders was identified as an essential step forward. It is foreseeable that this step will also be of vital importance for a further synchronization and optimization of the energy system on a larger scale, e.g., across Europe. Another important recommendation concerns the exploitation of synergies by identifying common interests and requirements in different communities and sectors, e.g., the OWF community and operational forecast centers.

Finally, it is important to emphasize that this study is meant as a contribution to a discussion, which needs to be continued and extended. The task at hand is challenging not only because of the complexity and the rapid evolution of technology but also because of the diversity of the different communities that have to be brought together to find suitable solutions for the future. The experience in the past has shown that the respective communication and synchronization processes take time and that makes a structured and transparent approach even more important.

Author Contributions

Conceptualization: J.S.-S. and J.S.; methodology: J.S. and J.S.-S.; analysis: J.S.-S. was responsible for operation and maintenance related continents, J.S. was responsible for submarine cable protection and wake and lee effects, L.L. was responsible for maritime safety in icing waters and radar aspects, B.M. was responsible for contamination, A.B. and H.W. were responsible for OWF impacts on habitat, NIS, fish, sea birds, and marine mammals; writing—original draft preparation, all; writing—review and editing, all. All authors have read and agreed to the published version of the manuscript.

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