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

Joint European Research Infrastructure network for Coastal Observatory
Science, Services, Sustainability

MS#, WP# and full title	MS10 – WP2 - "Identify gaps in resolving regional connectivity and multiscale processes in observations and modelling systems"
5 Key words	Regional connectivity, coastal-estuarial continuum, fit-for-purpose monitoring capacity, gap identification, integrated monitoring-modelling
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Submission date	31 Jan. 2022

→ Please specify the type of milestone:

- ❏ Report after a workshop or a meeting (TEMPLATE A)
- ■ Report after a specific action (TEMPLATE B) (test, diagnostic, implementation,…)
- ❏ Document (TEMPLATE B) (guidelines,...)
- ❏ Other (TEMPLATE B) (to specify) …………………….

Diffusion list			
Consortium beneficiaries	Third parties	Associated Partners	Other

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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 Milestone 10, the gaps of monitoring capacity in resolving Baltic-North Sea connectivity and multiscale processes in coastal-estuarial continuum should be identified and a respective list is to be provided in month 24 of the project.

2. Implementation process

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.

3. Main report

3.1 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.

3.1.1 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.

3.1.2 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.

3.1.3 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.

3.2 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, Appendix 1

Figure 3.2.1 shows the joint open sea monitoring network of SYKE and FMI.

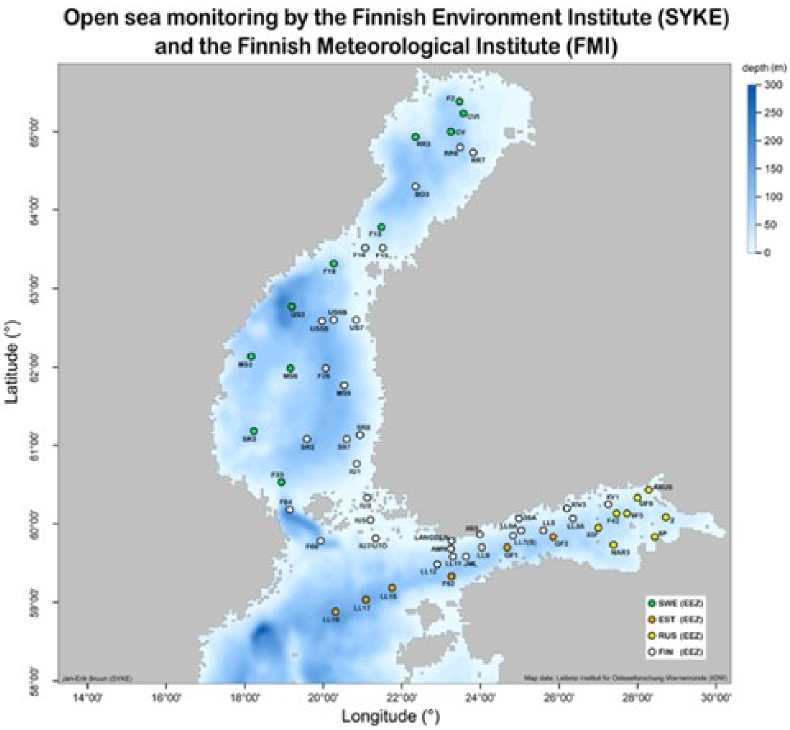


Figure 3.2.1 Open Sea monitoring by SYKE and FMI

3.2.1 Review on existing monitoring capacities

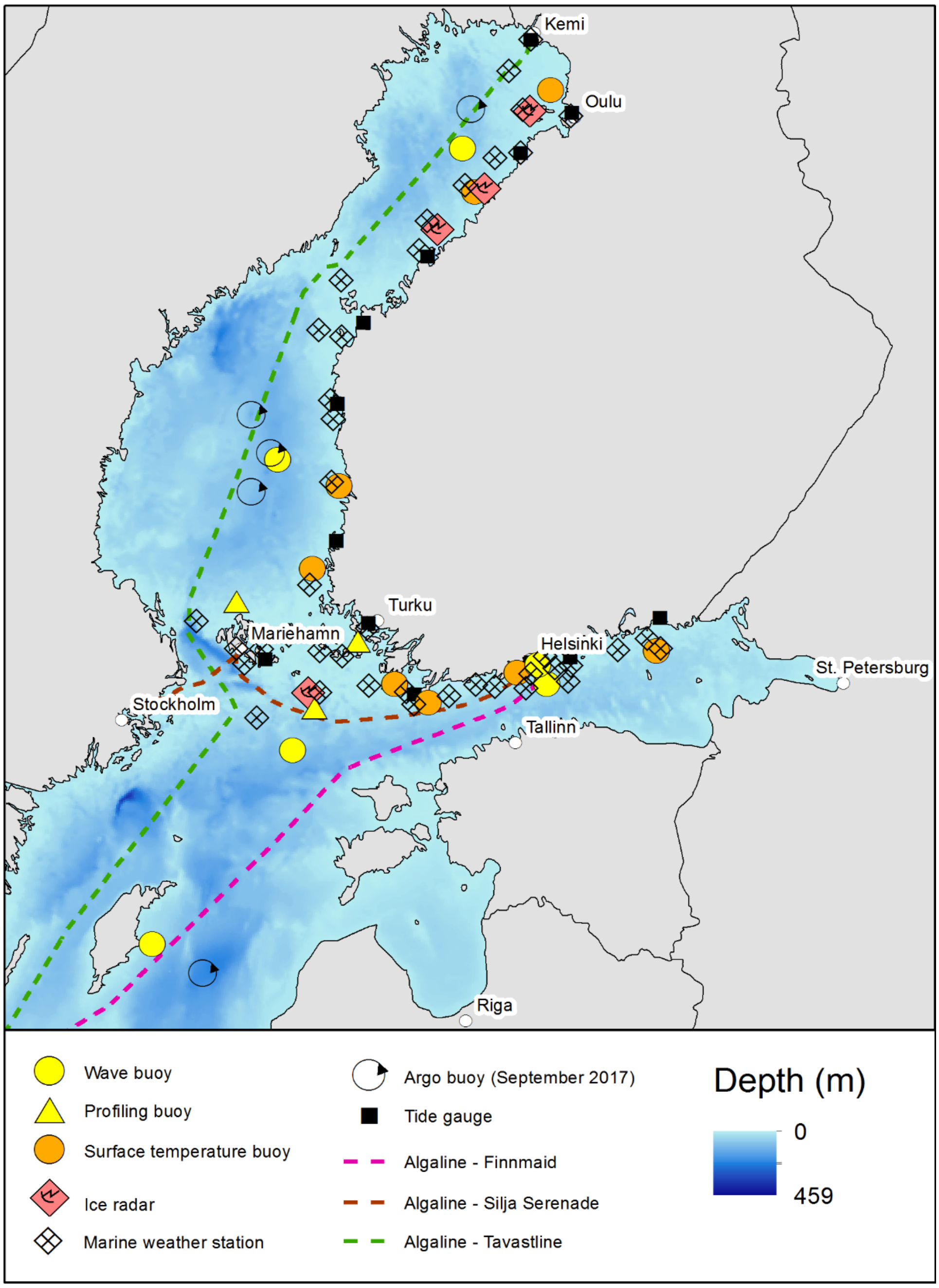


Figure 3.2.2 *Finnish operative marine observing network (for physical parameters like temperature, salinity, waves, sea level, sea ice) operated by FMI*

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 3.2.2. 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 3.2.3. 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

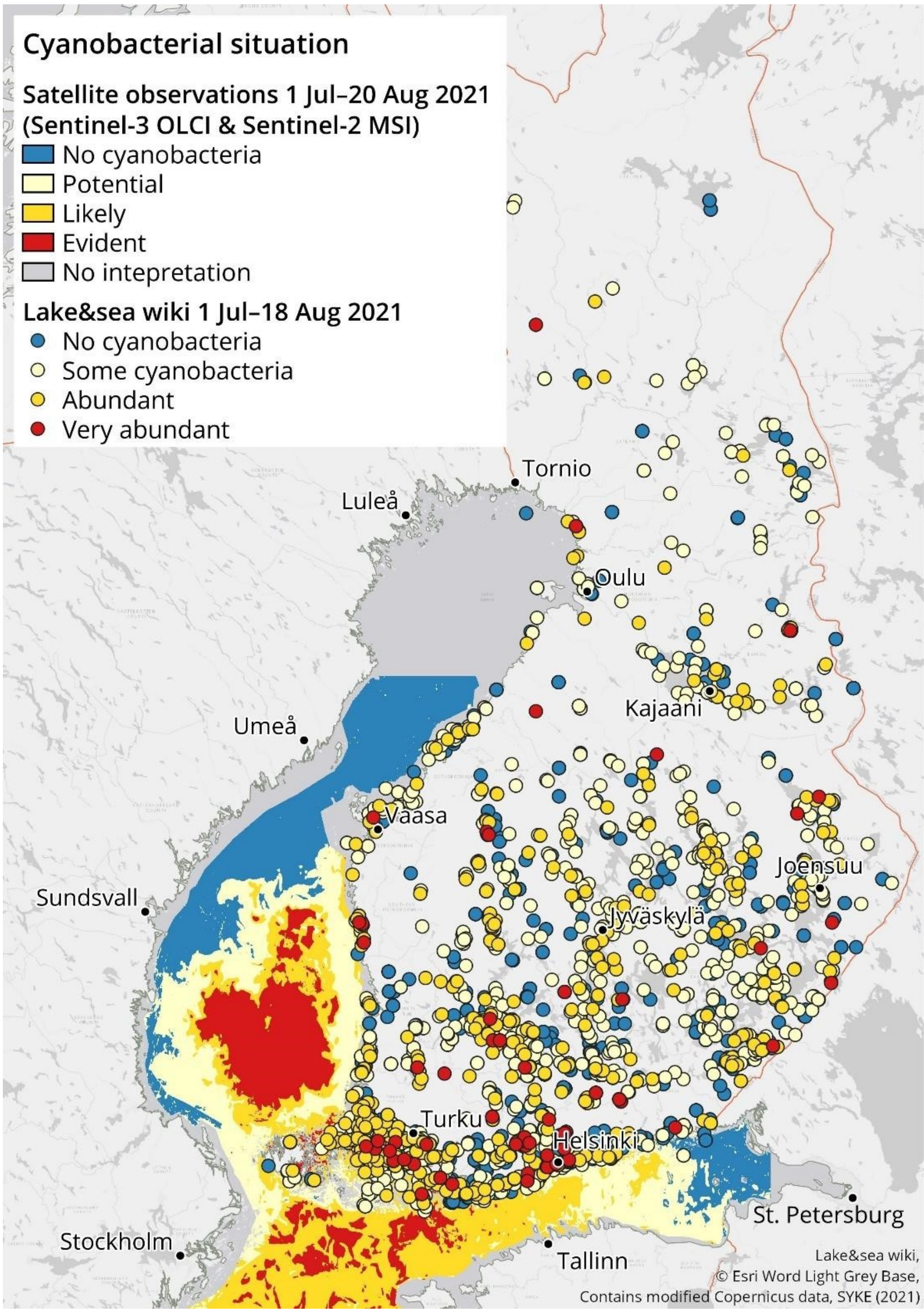


Figure 3.2.3: *Cyanobacteria observations based on remote sensing and in-situ observations during the summer 2021.*

- **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

3.2.2 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

3.2.3 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

3.3 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.

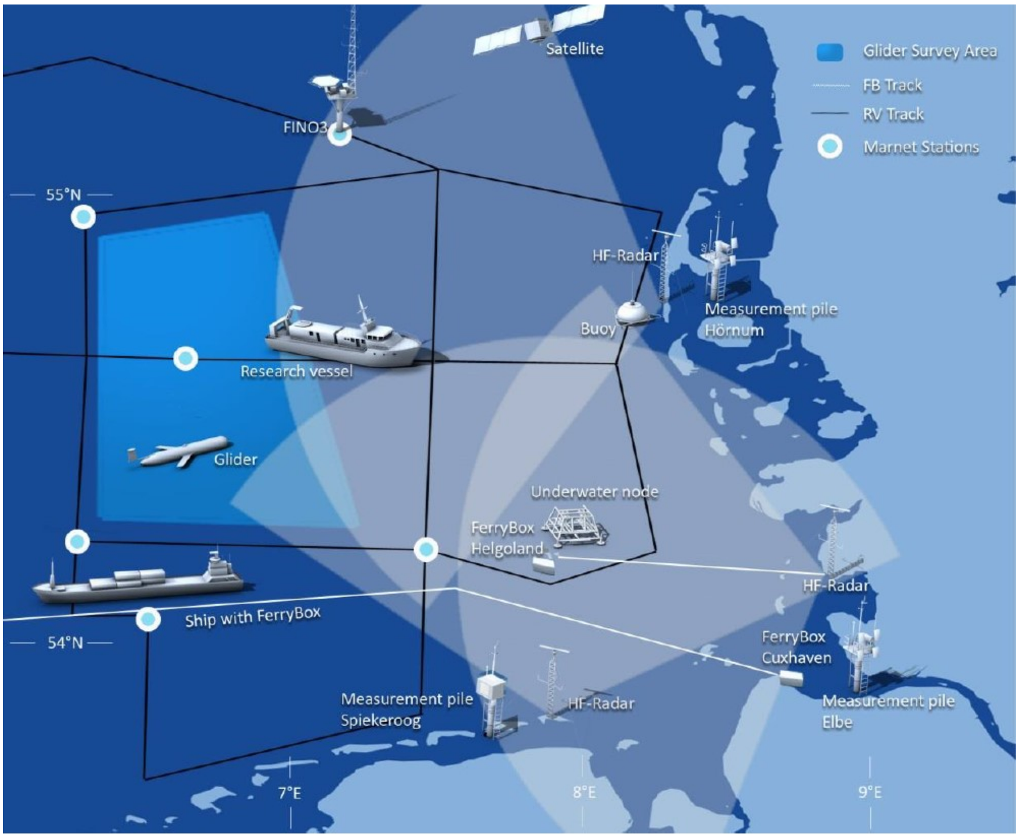
The salinity is dominated by water from the Atlantic and complicated secondary circulation processes take place in the river estuaries of the Elbe, Weser and Ems with consequences for biology and sediment transport processes. At the same time, the German Bight is an extremely busy area with ship traffic 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.

3.3.1 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 3.3.1 (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 3.3.1 (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



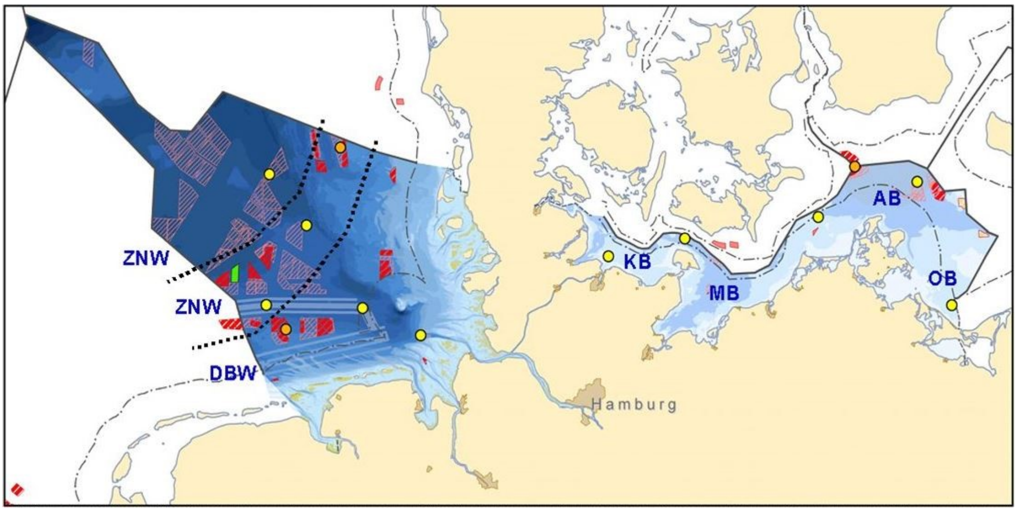


Figure 3.3.1: (top) Map showing components of the COSYNA observation system. (bottom): Positions of MARNET observation stations operated by BSH.

- **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.

3.3.2 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)

3.3.3 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.

3.4 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.

3.4.1 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 3.4.1 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.

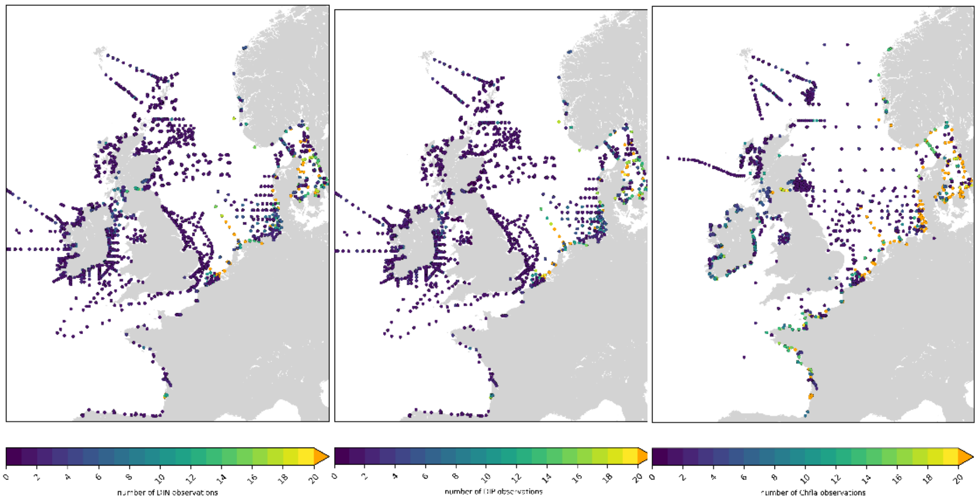


Figure 3.4.1: Number of observations for eutrophication indicators available in the ICES database, during the years 2009 – 2014 and during the months used in the indicator definition: winter is December – February, growing season is March – September.

3.4.2 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 3.4.2 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.

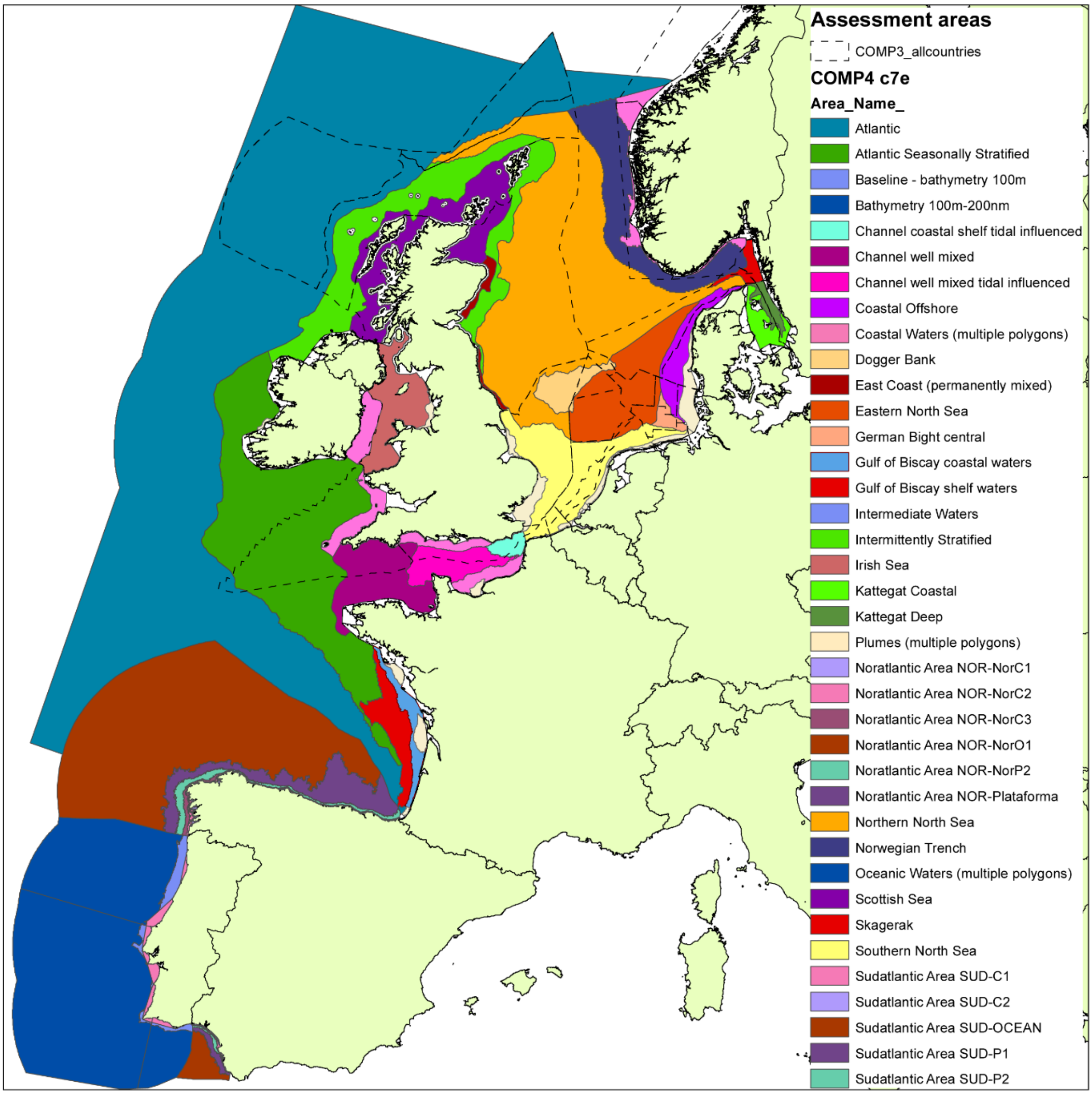


Figure 3.4.2: Assessment areas to be used in the upcoming eutrophication assessments for OSPAR and MSFD.

3.4.3 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.

3.5 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.

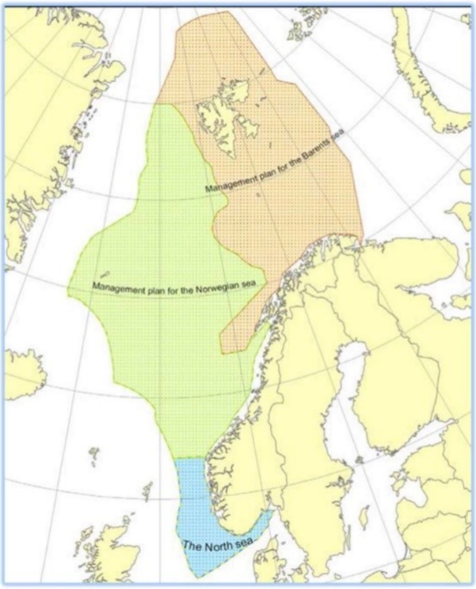


Figure 3.5.1: Area for the holistic Norwegian Management plans to be monitored for assessments.

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.

3.5.1 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 3.5.2, initialized in the 1930s) and in Figure 3.5.3 an example for the spatial coverage of InSitu observations is given displaying the sites the sites of trawl stations conducted in 2018.

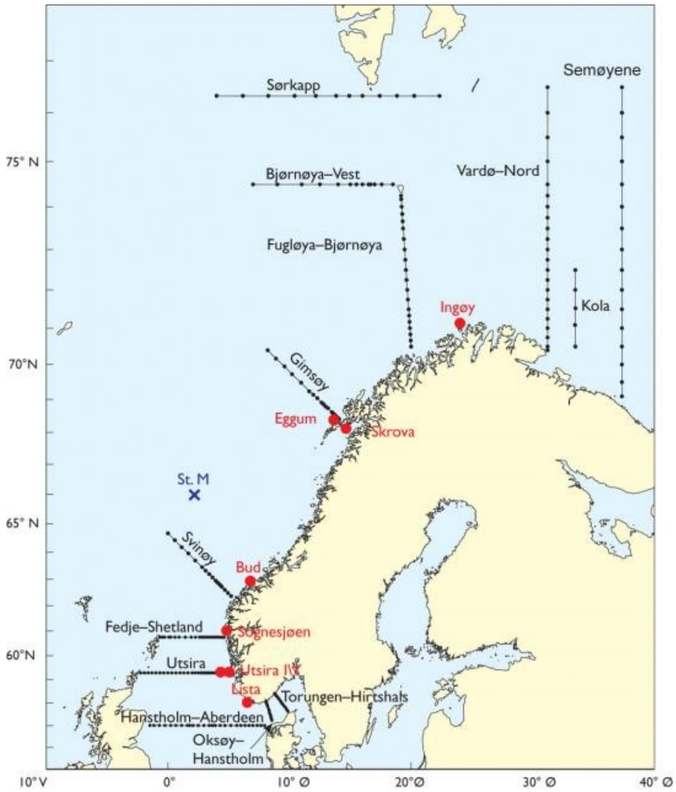


Figure 3.5.2: Map displaying the position of frequently repeated observation on transects and fixed stations which are conducted for following the variability of the ocean state.

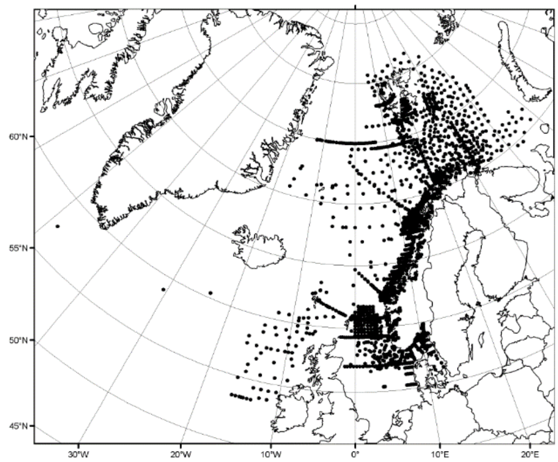


Figure 3.5.3: Conducted trawl stations for the year 2018 by IMR.

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

3.5.2 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

3.5.3 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.

3.6 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.

3.6.1 Review on existing monitoring capacities

Marine observing

The map in Figure 3.6.1 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.

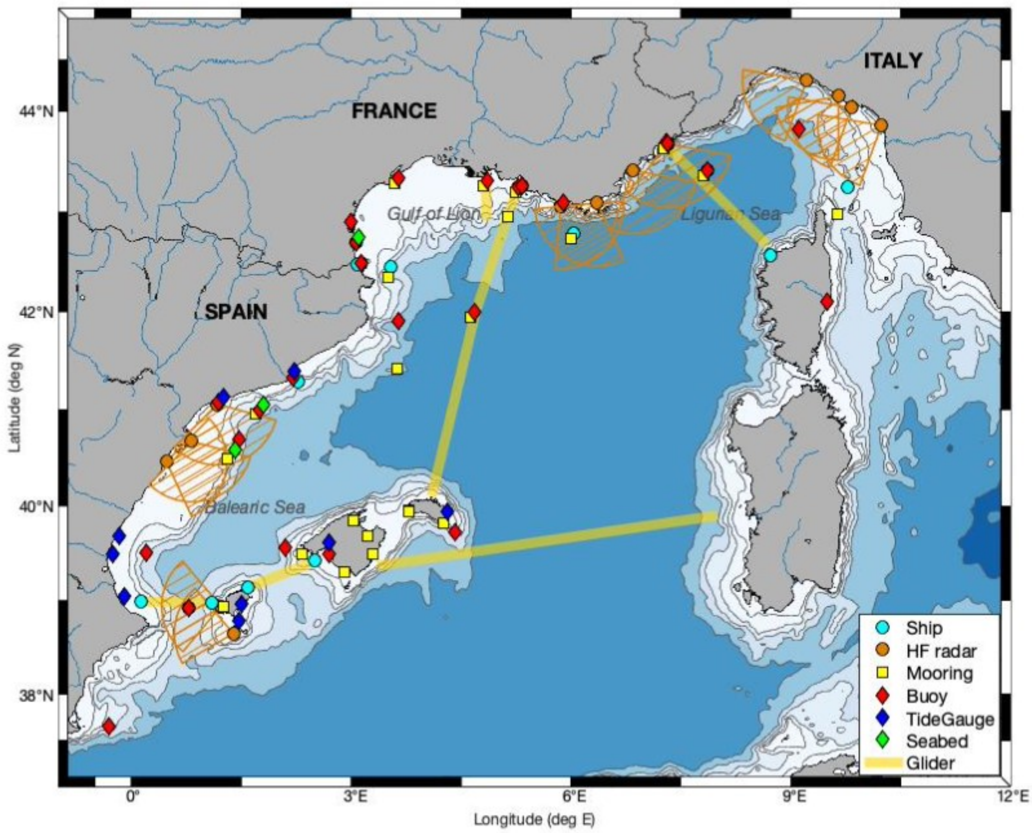


Figure 3.6.1: Observations from fixed stations, HF radars and gliders routinely collected in the NWMed PSS

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 3.6.2 shows the position of the observations which are presently assimilated in the WMOP system.

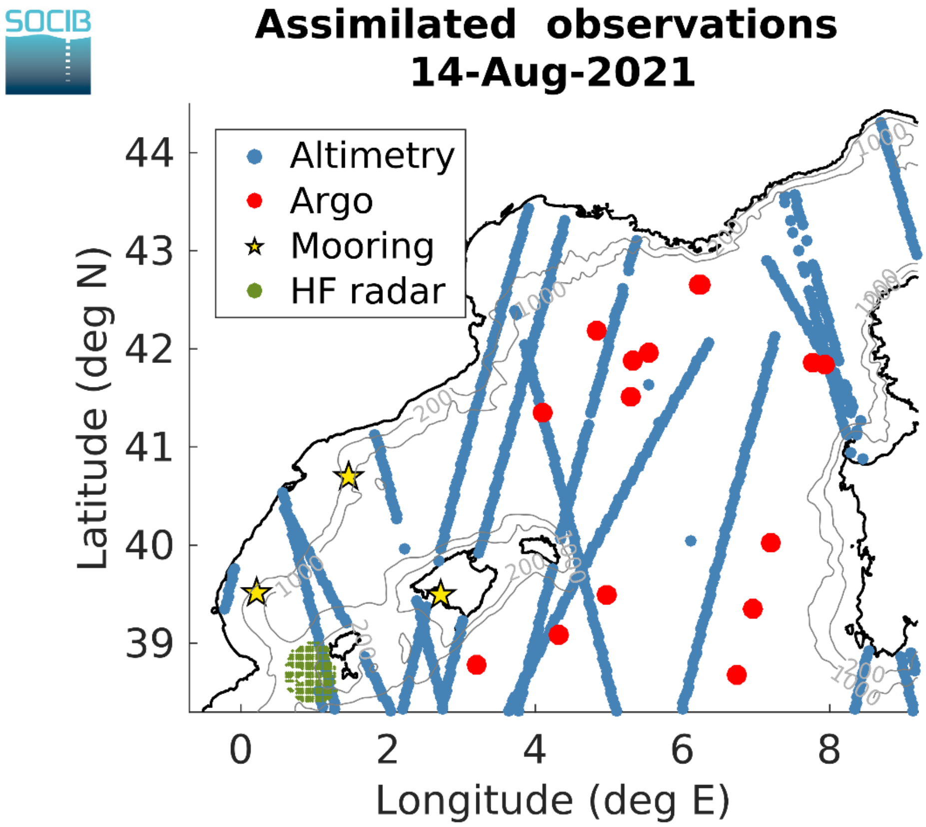


Figure 3.6.2: Position of the observations which are presently assimilated in the WMOP system

3.6.2 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.

3.6.3 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.

3.7 Monitoring capacity for Baltic-North Sea connectivity

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.

4. Conclusion

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. For task 2.4.1, 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 given in Annex 1. For task 2.4.2, gaps were identified for understanding and predicting esturial-coastal connectivity in national scale for six European countries, i.e. Denmark, Finland, Germany, Netherland, Norway and Spain. 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.

4.1. Synthesis of main conclusion

Gaps in monitoring capacity for Baltic-North Sea connectivity

- 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.

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

4.2.Next steps (work plan)

Current efforts in WP3.4 is a very first step towards a more complete overview of gaps in the existing observation systems. There is more work to do in particular with regard to a suitable structuring of requirements along different application fields, user groups and regions with certain dynamical characteristics. This document is a very valuable component in the ongoing work within WP2.4 and will be used to further optimize the analysis and discussion of monitoring systems. A further development step of the analysis will be presented in the next milestone for WP2.4, which is

- MS11: "Recommendations for treatment of regional connectivity and multi-scale processes in future integrated observing-modelling systems"

to be achieved in month 36 of the project, i.e., one year after the milestone described in this document. This will be a list of recommendations to fill gaps in existing monitoring systems.

A more detailed report about final conclusions concerning the identification of gaps and recommendations for future evolution of monitoring systems for different applications will be provided as deliverable D2.3

- D2.3: Report on regional connectivity & multi-scale processes in land-coast-open sea continuum

in month 42 close to the end of the project.

4.3.Annexes and references

Annex 1: A review on carbon observations in Skagerrak–Kattegat for Baltic-North Sea carbon connectivity

A.1. Background

The Kattegat-Skagerrak is a key region in the Baltic-North Sea carbon cycle (Fig. A.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?

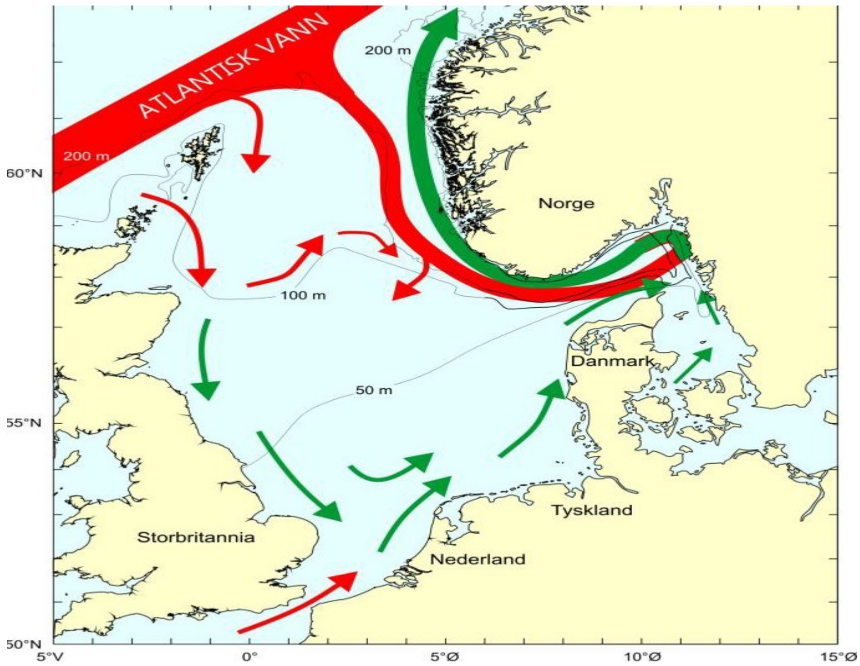


Figure A.1 Map showing the general surface currents in the study area (Source: IMR)

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.

A.2. Carbon observing: a review on existing capacity

2.1 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^{1-2} 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. A.2 and Fig. A.3.

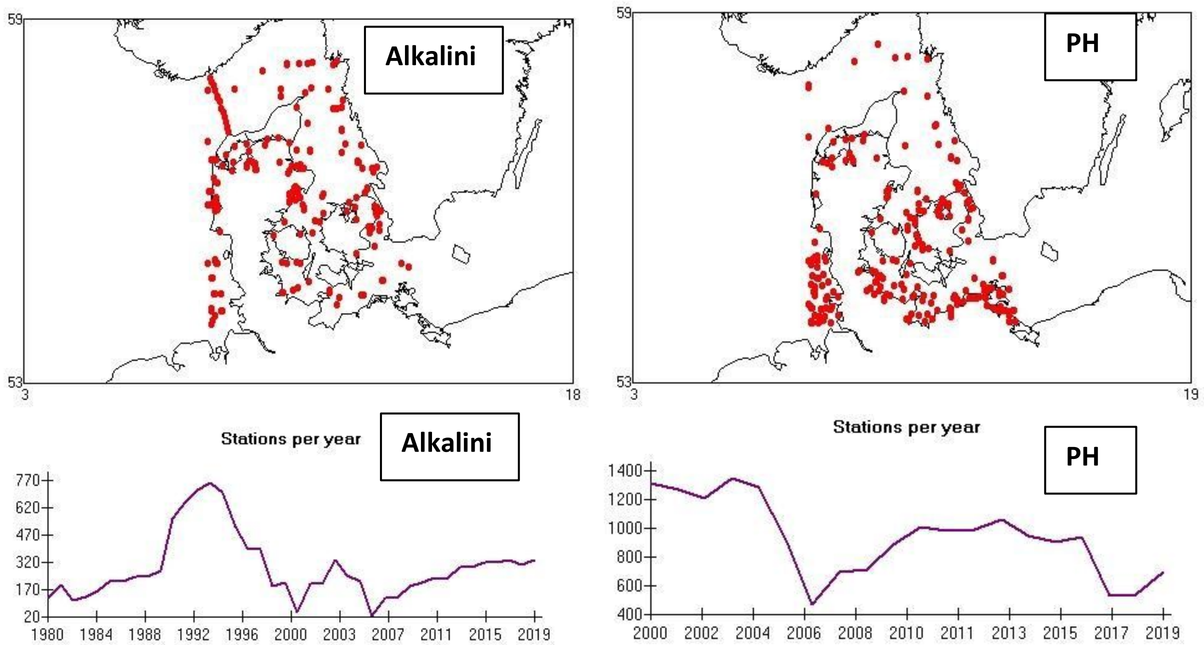


Figure A.2 Alkalinity and pH data during 1980-2019 (ICES).

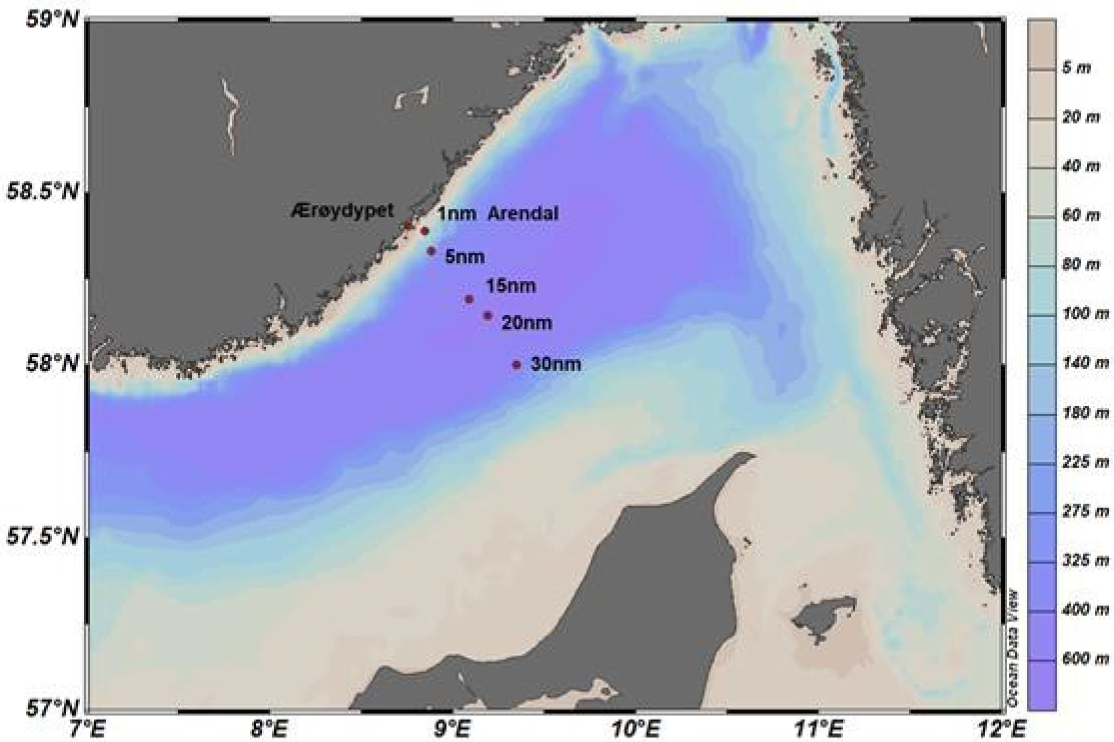


Figure A.3 Sampling locations from the IMR Torungen-Hirtshals section including the coastal station Arendal where IMR (NO) perform measurements on annual (T-H) and monthly basis (Arendal) since 2011.

2.2 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. A.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. A.5)

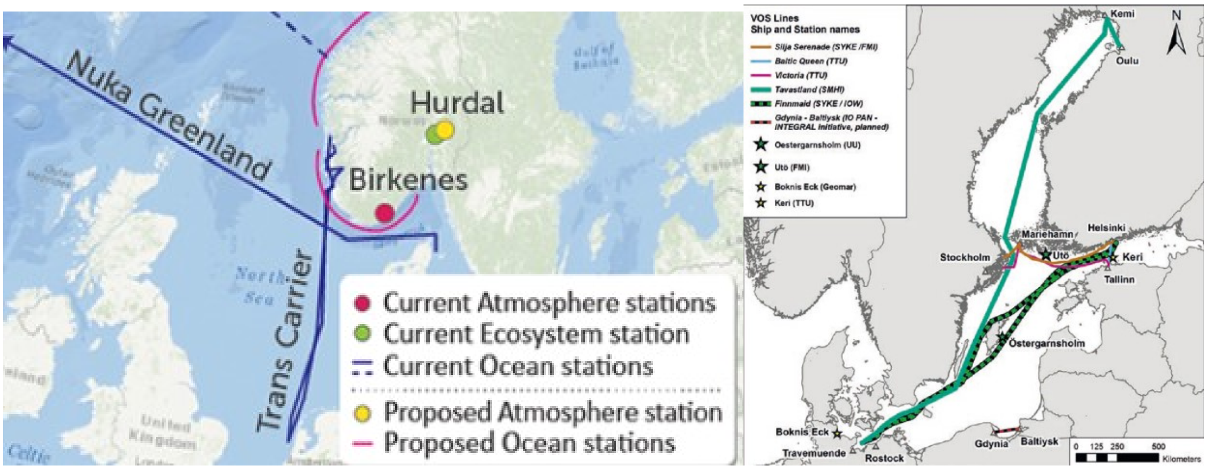


Figure A.4: ICOS SOOP lines in Baltic and North Sea (Source: ICOS)

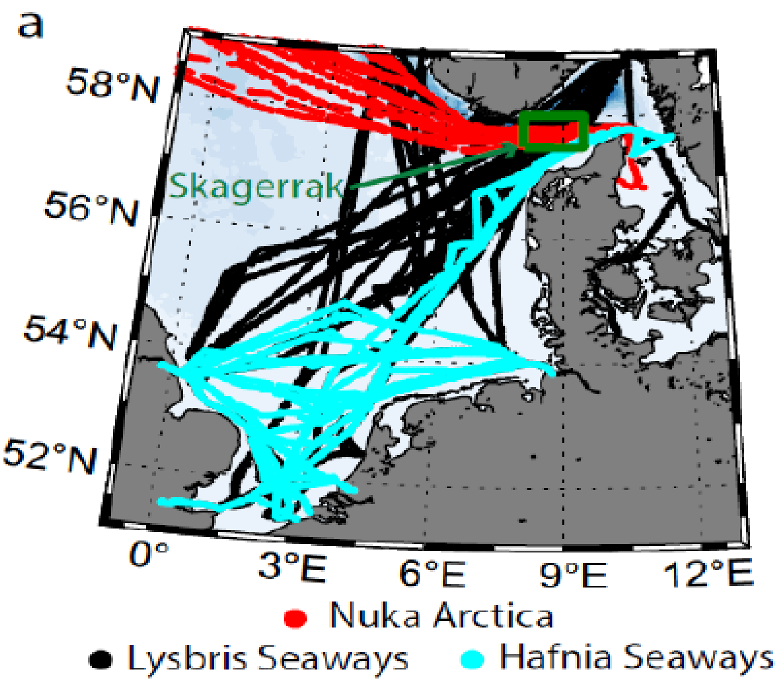


Figure A.5: EuroGOOS Ferrybox lines with pCO2 measurements (source: Macovei et al., 2021)

2.3 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.

2.4 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**).

2.5 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

A.3. Spatiotemporal 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.

3.1 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. A.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.

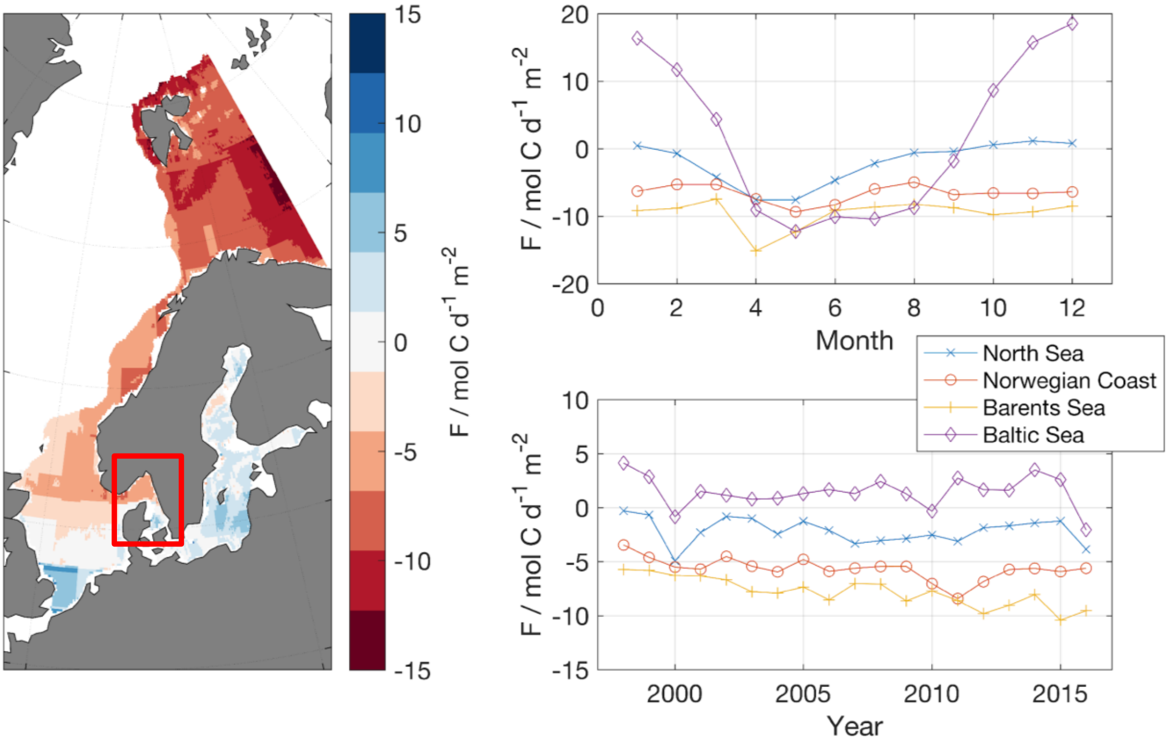


Figure A.6 The average air-sea CO2 flux over the period 1998-2016 (left hand panel, red colors indicate sink regions, while blue colors indicate source regions, source: Becker et al., 2020).

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)

3.2 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.

3.3 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)

A.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.

4.1 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.

4.2 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.

A.5. Sampling strategy assessment and optimal design

5.1 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.

5.2 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. A.7.

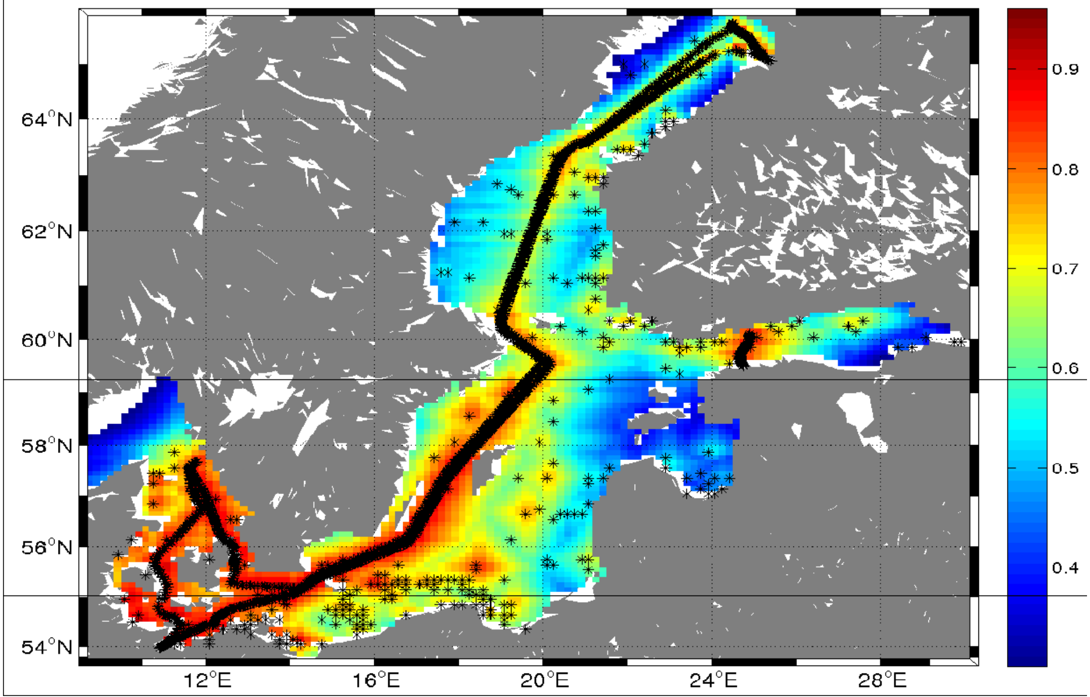


Figure A.7 Effective coverage of HELCOM-BOOS chl-a observational network.

5.3 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.

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