The Coastal Observing System for Northern and Arctic Seas (COSYNA)

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Abstract

The Coastal Observing System for Northern and Arctic Seas (COSYNA) was established in order to better understand the complex interdisciplinary processes of northern seas and the arctic coasts in a changing environment. Particular focus is given to the German Bight in the

North Sea as a prime example for a heavily used coastal area, and Svalbard as an example of an arctic coast that is under strong pressure due to global change.

The automated observing and modelling system COSYNA is designed to monitor real time conditions, provide short-term forecasts, data and data products to help assess the impact of anthropogenically induced change. Observations are carried out combining satellite and radar remote sensing with various *in situ* platforms. Novel sensors, instruments, and algorithms are developed to further improve the understanding of the interdisciplinary interactions between physics, biogeochemistry, and the ecology of coastal seas. New modelling and data assimilation techniques are used to integrate observations and models in a quasi-operational system providing descriptions and forecasts of key hydrographic variables. Data and data products are publicly available free of charge and in real time. They are used by multiple interest groups in science, agencies, politics, industry, and the public.

1 Introduction

A large part of humanity lives near the coasts and depends on the coastal oceans. At the same time, global problems such as climate change, sea level rise, or ocean acidification influence the ecosystems and communities along the coasts in particular. Shelf seas host unique ecosystems and provide essential sources for life in the ocean and the bordering land while regions like the North Sea are heavily used for a multitude of human activities, from tourism and ship traffic to the exploitation and exploration of food resources, energy and raw materials. Shelf seas are also heavily influenced by terrestrial processes due to continuous influx of natural and anthropogenic material from river systems and the atmosphere. They therefore act as important interfaces for global material cycles, for example through the uptake, emission, and transport of carbon compounds.

Understanding coastal systems is therefore of a high value, not only from a scientific point of view, but also due to its societal value. Coastal research has, however, long been hampered by the effort involved in investigating the highly complex coastal systems, the diversity of disciplines and institutions involved, and the difficulties in obtaining long-term and high-resolution, consistent measurements.

Current observations in the North Sea reveal substantial changes in biogeochemistry and food webs accompanied by the occurrence of new and the disappearance of established species (Gollasch et al., 2009; Buschbaum et al., 2012). The causes for these shifts are only partially known. Changes in physical quantities (e.g. temperature, wind) as well as anthropogenic influences (e.g., pollution, over-fishing, invasive species) most probably act as major drivers (Emeis et al., 2015). In the Arctic, the thawing of permafrost has started to cause coastal erosion and an increase of greenhouse gas emissions (IPCC, 2014). These examples highlight the sensitivity and dynamic behavior of such complex systems that are still barely understood and insufficiently documented and monitored.

Recent advances in technology enable the use of remotely controlled automated measurements and to develop 'intelligent' integrated systems that combine measurements and numerical modeling to create a synoptic view of coastal systems. The Coastal Observing System for Northern and Arctic Seas (COSYNA) has been established to demonstrate the feasibility of this idea for shallow, coastal areas. COSYNA focuses on the complex interdisciplinary processes of German Bight in the North Sea and the Arctic coast near Svalbard, to assess the impact of anthropogenic changes, and to provide a scientific infrastructure. The focus regions have been chosen because they are ideal test beds in terms of natural variability and processes, human use and change, as well as accessibility.

The principal objective of observations, instrument development, and modeling is to improve our understanding of the interdisciplinary interactions between physical, biogeochemical, and ecological processes in coastal seas, to investigate how they can be best described at present, and how they will evolve in the future. To this end, COSYNA combines its measurement capabilities in the German Bight in a network that is designed to expand beyond individual platforms, areas, campaigns, and quantities to generate a holistic view of the entire coastal system by analyzing the multitude of measurements taking into consideration the combination of different data sources as well as integrating them into model analyses.

In COSYNA, data and knowledge tools are developed and provided to be of use for multiple interest groups in industry, agencies, politics, environmental protection, or the public. These data and products are publicly available free of charge and can be used to support national monitoring authorities to comply, for example, with the requirements of the European Water Framework Directive and the Marine Strategy Framework Directive. The coastal observatory involves national and international contributions to international programs, such as the coastal module of the global ocean observing system (coastal GOOS), the European Ocean Observing system (EOOS as supported by EuroGOOS), the Global Earth Observations

System of Systems (GEOSS), Marine Geological and Biological Habitat Mapping (GEOHAB), and COPERNICUS Marine Environment Monitoring Service (CMEMS).

COSYNA is coordinated by the Helmholtz-Zentrum Geesthacht (HZG), Germany, and has been jointly developed, implemented, and operated with ten other German partner institutions (s. Table 1).

The present Ocean Science and Biogeochemistry inter-journal special issue “COSYNA: integrating observations and modeling to understand coastal systems“ collects contributions highlighting various aspects of the complex observing system. This article provides an overview of COSYNA, its observational and modelling approach as well as the diverse associated scientific studies and activities. It aims at connecting the articles in the special issue to previously published results from COSYNA. To this end, we will first describe the focus regions (Section 2), objectives (Section 3), and the international context of COSYNA (Section 4), before giving an overview of the observations (Section 5), sensor and instrument development (Section 6), as well as modeling and data assimilation activities (Section 7). Data, data products, and outreach activities are then described (Sections 8, 9) before a brief outlook over future activities is given (Section 10).

2 Coastal focus regions

The focus regions of COSYNA, the German Bight of the North Sea and the Arctic coast at Svalbard, are representative for two extremes in the broad spectrum of Northern and Arctic coasts. The German Bight is one of the most intensely used coastal seas worldwide with often opposing interests of economy, nature conservation, and recreation. Arctic seas and coasts are among the areas mostly affected by and vulnerable to global warming. For a recent assessment of impacts of climate change on the North Sea Region see NOSCCA (2016).

2.1 The German Bight

The German Bight (Fig. 1) is located at the south-eastern corner of the North Sea, a temperate, semi-enclosed shelf sea. Sündermann et al. (1999) define its seaward boundaries at 6°30’E and 55°00’N. The German Bight is relatively shallow with water depths of generally less than 40 m. The main topographical features are the glacially formed Elbe River valley that spreads out to the northwest and a chain of barrier islands along the Dutch, German, and

Danish North Sea coast. The islands protect the major part of the Wadden Sea, the largest unbroken system of intertidal sand and mud flats in the world.

The North Sea is characterized by the transition from oceanic to brackish water with variable fresh water input at the coasts. Physical drivers such as wind, sea surface temperature (SST), or tides control the natural variability in circulation and exchange processes with the open sea and the coastal fringe boundaries over a broad range of temporal and spatial scales (Schulz et al., 1999; Sündermann et al., 1999; Emeis et al., 2015; NOSCCA, 2016).

Strong tidal currents and intermittent strong wind events form a regime of high kinetic and turbulent energy with significant bed-water column exchange in the North Sea. Westerly winds typically prevail in the North Sea, but variations exist and southerlies and easterlies may produce secondary circulation patterns (Otto et al., 1990). The currents are dominated by the M2 lunar tidal component that is entering the North Sea from the north and is moving as Kelvin wave cyclonically through the North Sea (Otto et al., 1990; Howarth, 2001). Strong tidal currents in the channels connecting the Wadden Sea with the German Bight drive an intense exchange and a net import of suspended particulate matter and nutrients into the Wadden Sea (Burchard et al., 2008; Staneva et al., 2009; van Beusekom et al., 2012) and sustain its muddy component and the high productivity of the intertidal mud flats (Postma, 1984; van Beusekom et al., 1999; van Beusekom and de Jonge, 2002; Colijn and de Jonge, 1984). The tides thus cause a complex pattern of mixing conditions just off the barrier islands and the mouths of the estuaries of the rivers Elbe, Weser, and Ems.

Global and local anthropogenic impacts overlay and interfere with these natural forcings. The global increase of CO_2-concentrations led to a long-term increase of SST that accelerated to 0.08°C y^{-1} in the last decade (Loewe, 2009), while the average annual sea level rise reached 1.6 mm y^{-1} for the last 110 years (Wahl et al., 2013), and the average pH decreased from 8.08 to 8.01 in the years 1970 to 2006 (Lorkowski et al., 2012).

The North Sea is surrounded by densely populated, highly-industrialized countries and is directly affected by multiple, often conflicting uses. One of the densest ship traffic lines worldwide crosses the German Bight and demands regular dredging of shipping channels and harbour basins. The Wadden Sea region, a UNESCO World Natural Heritage Site since 2009, is exposed to an import of pollutants and nutrients from land. The high biomass production caused by the latter resulted in the identification of the entire German Bight as a problem area by the OSPAR commission (OSPAR, 2008). Overfishing with bottom trawls impacts benthic invertebrate communities and leads to a decrease of biomass and species richness of fish communities (Emeis et al., 2015). As the latest development, the massive construction of offshore wind farms – under way or planned – is likely to have a significant impact on marine mammals (Koschinky et al., 2003), seabirds (Garthe and Hüppop, 2004; Busch et al., 2013), but possibly also mixing (Lass et al., 2008; Ludewig, 2015; Carpenter et al., 2016) and nutrient transport.

2.2 The Arctic Coast

While Spitsbergen (79°N) is geographically classified as fully arctic, it is significantly influenced by Arctic and Atlantic water masses from the Fram Strait (Fig. 2; Hop et al., 2002). Due to an increased advection rate of warmer Atlantic water masses in the fjord systems over the last decade, first signs of an overall warming in the fjords have been observed with a decrease in seasonal ice coverage (Stroeve et al., 2007) and significant changes throughout the food web (Hegseth et al., 2013; Van de Poll et al., 2016; Willis et al., 2006, Brand and Fischer, 2016).

The 20 km long Kongsfjord is located at the west coast of Svalbard and opens to a shelf system in westerly direction. It has no sill and shares the outlet to the Atlantic with the more northern Krossfjord (Cottier et al., 2005). From this outlet, an underwater canyon runs through the shelf to the continental edge, establishing a connection to the deeper waters masses of the West Spitsbergen Current off the shelf. Complex mixing processes between the arctic shelf water masses, the Atlantic deep water masses, and the highly seasonal fresh water runoff from the inner part of the fjord result in strong environmental gradients from the inner parts of the fjords to its mouth (Svendsen et al., 2002). These gradients and their short- and long-term variability directly influence the pelagic and benthic realms of the fjord and the local food web (Stempniewicz et al., 2007). Due to the condensed temporal and spatial patterns of Atlantic and polar realms in a single fjord system, as well as the observed increase in mean water temperatures, the retreat of glaciers, and decrease in sea ice coverage over the last decades, the Kongsfjord ecosystem (Fig. 2) became an international focal point of climate change research.

The first research station addressing the Kongsfjord ecosystems was built by the Norsk Polar Institute in NyÅlesund (Fig. 3) at 78°55’N, 11°56’E in 1970. Since then, more than 15 nations operate their own research stations in this northernmost year-round inhabited research-village of the world including the German-French research station AWIPEV (www.awipev.eu).

Even in Kongsfjord with its ideal and year-round available research infrastructure, most field research has been done in summer (Fischer et al., 2016) and only very little is known about the several month long polar winter with its prevailing darkness. The winter months are, however, essential for life cycles, the reproduction of many species (Fischer et al., 2016), and hence for the entire ecosystem (Hop et al., 2012). It is COSYNA's aim to help close this observational gap providing year-round observations in this polar fjord system.

COSYNA activities also comprise remote sensing techniques, that have been proved and tested in the North Sea, to coastal waters in the Lena Delta, Siberia for the quantification of suspended matter and chlorophyll as well as *in situ* measurements of inherent optical properties (Örek et al., 2013). The Lena Delta covers 32.000 km^2 and discharges freshwater from a catchment area of 2.400.000 km^2 into the Arctic Ocean.

3 Objectives and Benefits

Complex, highly interdisciplinary natural processes characterize the North Sea across several time and length scales. It is COSYNA's goal to help disentangle natural processes and anthropogenic impact in this region by combining consistent long-term time series at representative locations with process-oriented high-resolution observations. Numerical models of various resolutions are used to provide context for observations ranging from the turbulent to basin wide spatial scales. Observations are integrated into models using data assimilation techniques for resolutions, time-scales, and quantities where such integration is possible and useful. It has therefore been COSYNA's approach to build an integrated observing system that is geared towards high flexibility and can be used on a variety of scales and problems that are of scientific or societal interest.

Routine observations of key variables and data assimilation techniques are employed to improve model performance for hindcasts, nowcasts, and short-term forecasts. The implementation of such a system achieves several objectives: it bridges spatial and temporal scales, while it establishes a backdrop against which key processes, such as exchange processes between North Sea and Wadden Sea, the impact of extreme events, biological productivity variations, and the influences of e.g. offshore wind farm construction can be investigated. The extensive development of offshore wind farms, for instance, requires sound environmental statistics and improved forecasts for planning and operation, while their influence on hydrodynamics, let alone biogeochemistry or biology, of the North Sea is still poorly understood.

The benefits of the COSYNA system are expected to be manifold. It contributes to technology development of key sensors and infrastructure, data interpretation algorithms such as for satellites and HF radar, as well as to modelling and data assimilation techniques suitable for operational use and monitoring. These developments and the creation of products of interest for various user groups contribute to the sciences while also benefitting society, e.g. through supplying coastal and sea floor observations of the North Sea in support of the European framework strategies and directives towards the goal of achieving a "good environmental status" of the marine environment.

As for the dissemination of data and products, COSYNA's objective is to make them available free of charge to the broadest possible audience in near-real-time, while ensuring high quality standards and rigorous monitoring of data quality. Additional quality controls taking long-term perspectives into account are to be performed on an on-going basis ultimately resulting in data publications.

4 International Context

With the initiation of the permanent Global Ocean Observing System GOOS (Intergovernmental Oceanographic Commission, 1993) and stepwise implementation of its many separate observing systems, new concepts regarding the world-wide systematic and sustained observation of the oceans have been put in place. Considering the role of coastal areas for ecological communities and their exposure to massive human utilization, a GOOS coastal module was proposed to provide a basis for extended predictability of the coastal environment in both model and observations (Intergovernmental Oceanographic Commission, 1997). Awareness of the multitude of societal benefits (ABARE, 2006; https://ioos.noaa.gov/about/societal-benefits/) stimulated considerable investment into the worldwide implementation of integrated coastal ocean observatories (ICOOS).

In Europe, EuroGOOS (http://eurogoos.eu) is the pan-European GRA that co-ordinates six regional operational systems (ROOSes), such as the North West Shelf Operational Oceanographic System (NOOS, http://eurogoos.eu/roos/north-west-european-shelf-operational-oceanographic-system-noos). In addition to providing operational oceanographic services and carry out marine research, EuroGOOS puts considerable effort into unlocking fragmented and hidden marine data and making them openly available. Its data plays a key role in the development of the European Marine Observation and Data Network (EMODnet) data portals (http://www.emodnet.eu). EMODnet is designed to cover all European coastal waters. The European ROOSes feed data into EMODnet either directly or through SeaDataNet (Schaap and Lowry, 2010; http://www.seadatanet.org/) and the Copernicus Marine Environment Monitoring Service (CMEMS, http://marine.copernicus.eu).

COSYNA contributes through the Helmholtz-Zentrum Geesthacht (HZG), as EuroGOOS member, to the definition and implementation of operational services for near coast, shallow ocean waters. Based on the FerryBox project funded by the EU in 2002-2005, HZG is co-chairing the FerryBox EuroGOOS Task Team (http://www.ferrybox.org). Via NOOS, the FerryBox data are fed into the EMODnet portals, while COSYNA's High-Frequency radar data are delivered directly to the EMODnet Physics data portal and the glider data to the CMEMS data server.

5 Observations

The COSYNA observation network was designed to cover spatial scales ranging from a tidal catchment area in the Wadden Sea to the southern North Sea (Fig. 1). An additional observing station was installed at the west coast of Svalbard. Nearly all platforms deliver a set of COSYNA standard observables comprising key meteorological, oceanographic, and biogeochemical bulk parameters (Table 2). Tables 3 and 4 provide a comprehensive overview of the COSYNA platforms.

Four stationary systems were installed on poles placed in three tidal basins of the East Frisian and one in the North Frisian Wadden Sea. They provide highly resolved COSYNA standard parameters (s. Table 2) and allow the integration of energy and matter budgets over the sampled catchment areas. An additional pole and a stationary FerryBox monitor the exchange between the German Bight and the Elbe river as its main tributary.

To estimate transports across the northern cross-section of the German Bight, a FerryBox was installed on the wind-turbine research platform FINO3 (Forschungsplattformen in Nord- und Ostsee). Upstream of it, along the mean transport pathway in the German Bight, the FINO1 platform is located at the site of a station belonging to the Marine Environmental Monitoring Network in the North Sea and Baltic Sea (MARNET) operated by the German Federal

Maritime and Hydrographic Agency (BSH). In general, MARNET complements the fixed COSYNA platforms (Table 3) towards the offshore regions of the German exclusive economic zone (EEZ). FerryBox systems operated on several ships of opportunity extend the COSYNA Network to the North Sea-scale, with several regular routes (Fig. 9).

To provide a good spatial coverage, remote sensing with high frequency (HF) radar and satellites is used. Two HF radar arrays are installed at the North Frisian and one at the East Frisian coast with nearly rectangular viewing angle to the other two systems. This configuration allows the determination of horizontal surface current vectors over most of the German Bight. The surface concentrations of total suspended matter, chlorophyll-a, and yellow substances "Gelbstoff" were obtained from 2003 to 2012 with MERIS (Medium Resolution Imaging Spectrometer) onboard ENVISAT, followed by MODIS (Moderate Resolution Imaging Spectroradiometer).

To go beyond the limitations in power and data transmission rates that most COSYNA platforms face, two COSYNA Underwater-Node Systems were developed and installed. They are pilots towards long-term observations of parameters beyond the COSYNA standard observables, such as optical systems for non-invasive determination of plankton or fish populations and their behavior. The underwater node off the island of Helgoland is the first installation in a shallow water environment worldwide subject to strong wave forces. At Svalbard, the underwater node allows year-round observations under the sea ice in harsh environmental conditions. To explore physical and biogeochemical processes at the sediment-water interface over longer periods of time in high detail, three lander systems were developed, that can be connected to the Underwater-Node Systems for longer operations.

Observations of the vertical distribution of variables over most of the water column were achieved with two alternating gliders operating for several weeks north-west off the island of Helgoland. Ship cruises with an undulating towed fish were carried out two to four times per year along a repeated grid covering the German Bight with the MARNET stations at its crossing points. For details on the moving platforms used in COSYNA see Table 1.

All data are transferred in near-real time to the COSYNA data server and are publicly available in the COSYNA data portal (http://codm.hzg.de/codm/). Quality control processes are applied and data are flagged accordingly following SeaDataNet definitions[1].

[1] http://seadatanet.maris2.nl/v_bodc_vocab/browse.asp?order=entrykey&l=L201

5.1 Stationary Measurements

Six fixed stations are the central element of COSYNA and serve as platforms to record point-like time series of meteorological and marine parameters. They provide high frequency observations to resolve variability well below tidal periods in order to estimate statistically significant tidal fluxes as well as long-term records or trends over several years at the same location. Measuring poles were implemented at three tidal inlets, the inner Hörnum Basin, the Jade Bay, and the Otzumer Balje close to the island of Spiekeroog, to capture the hydrodynamics and suspended particulate matter concentrations (SPMC) typical of the East Frisian and North Frisian Wadden Sea. An additional pole was placed in the outer Elbe estuary (Fig. 1).

While the inner Hörnum Basin represents the zero usage zone of the National Park of the North Frisian Wadden Sea, the Jade Bay is exposed to intense activity of building a new deep water port. The Otzumer Balje discharges a catchment area that is typical for the East Frisian Wadden Sea and was intensely investigated during the ecosystem research project ELAWAT (Dittmann, 1999). The Elbe pole was operated to contribute to the sediment management plan of the Elbe Estuary and to complement the data of the stationary Cuxhaven Ferry-Box on the southern side of the Elbe mouth. The FerryBox on FINO3 captures offshore conditions in the German Bight. All these stations are described in the following in more detail (Table 3).

5.1.1 Poles Hörnum Basin, Jade Bay, and Elbe Estuary

The poles at the inner Hörnum Basin, the Jade Bay, and in the Elbe Estuary were mounted from March to November to prevent ice damage in the winter months. They consisted of a 15 m long steel tube, 5 m of which were jetted into the sea bed. A platform accessible via a ladder was mounted on top of the 40 cm-diameter tube, resulting in an overall length of 18 m (Fig. 4). The platform carried meteorological sensors and radiometer, solar panels for energy supply, an automated yet remotely controllable water sampler, and logger boxes for temporary data storage and wireless communication. A manual winch was used to retrieve the underwater instrument unit for maintenance. This unit was mounted with its lower end 1 m above the sea floor. It was equipped with sensors for all COSYNA standard observables of physical oceanography and biogeochemistry (Onken et al., 2007; Table 2).

In order to reduce sensor fouling, the underwater unit was cleaned at least twice a month. Possible sensor drift and cleansing effects were monitored by direct comparison with a wellcalibrated reference system before, during, and after maintenance. Water samples were taken during maintenance to relate optical signals to SPMC.

To observe heat fluxes between the tidal flats and the water body, a vertical temperature sediment profiler was developed and deployed in the intertidal sediments close to the pole (Onken et al., 2010). It was operated for more than a year. At a distance of 5 nautical miles, an additional mooring with an upward looking ADCP (Acoustic Doppler Current Profiler) and a Datawell wave rider buoy was deployed.

In order to compute along-channel fluxes in the Hörnum Basin, occasional ship surveys were carried out over full tidal cycles relating across- and along-channel transects to the pole data. They were complemented by water samples and turbidity measurements. As an example, measurements over three weeks are shown (Fig. 5) comprising a significant wind event with peak velocities up to 20 ms^{-1} resulting in a sea level rise of more than 1.5 m and significant wave heights up to 1.7 m. Water temperature and salinity after the storm exhibit the characteristic tidal (mainly M2) variability. Current velocities are predominantly at frequency M4, with a clear ebb-flood asymmetry. SPMC shows a complex variability reflecting the M4 tidal current dependencies as well as horizontal along-channel gradients. Interestingly, the onset of the rise in SPMC and its peak value lag behind the significant wave height by nearly one tidal period indicating that the source of the additionally suspended material is located remote from the pole.

The observations at the pole also indicate that the steady import of particulate matter is closely connected to the specific thermodynamic processes of the amphibic Wadden Sea area (Burchard et al., 2008; Onken et al., 2007; Onken and Riethmüller, 2010; Flöser et al., 2011).

5.1.2 Pole Spiekeroog

Time series of oceanographic, meteorological, and biogeochemical data are continuously recorded since 2002 at a measuring pole of the Institute for Chemistry and Biology of the Marine Environment in the tidal channel of the Otzumer Balje close to the island of Spiekeroog (Fig. 1, Fig. 4; Reuter, 2009; Badewien et al., 2009). The time-series station Spiekeroog (position 53°45'0.10''N, 007°40'16.3''E, mean sea level 13 m) consists of a 35.5 m long pole, with a diameter of 1.6 m that is driven 10 m into the sediment. The temperature, conductivity and pressure sensors are deployed within five horizontal tubes (1.5 m, 3.5 m, 5.5 m, 7.5 m, 9 m above the seafloor) that are aligned in the main current direction. A platform is mounted on top of the pole, about 7 m above sea level. It consists of two laboratory containers hosting a second platform at 12 m above sea level that is equipped with solar panels, a wind turbine and meteorological sensor systems. Oceanographic sensors are installed in special tubes within the pole that are oriented in the main direction of the tidal flow. An Acoustic Doppler Current Profiler is mounted 1 m above the sea floor on a horizontal arm of 12 m length. The time-series station Spiekeroog is capable of withstanding storm events and ice conditions. It is part of COSYNA since 2012.

The acquired data sets are fundamental for the improvement and validation of model results (Burchard and Badewien, 2015; Grashorn et al. 2015; Lettman et al., 2009; Staneva et al., 2009; Burchard et al., 2008) as well as to answer various research questions (Rullkötter, 2009; Badewien et al., 2009; Hodapp et al., 2015; Meier et al., 2015; Holinde et al., 2015) such as concerning the impact of storm surges, algal blooms on sediment dynamics and exchange processes. The data sets are also valuable for assessing the long-term variability of oceanographic and biological parameters and determining anthropogenic impacts. The experience gained at the pole also helped to improve fouling-prone sensing methods and quality assurance (Garaba et al., 2014; Schulz et al., 2015; Oehmcke et al., 2015).

5.1.3 Stationary FerryBoxes

As part of the COSYNA network, a stationary FerryBox was installed inside the pole of research platform FINO3. Water is pumped from approx. 5 m and 16 m below mean sea level height for the continuous analysis near-surface and sea floor waters. The FerryBox is equipped with sensors for standard oceanographic parameters (Table 2). Temporarily, nutrient analysers and a pCO_2 sensor were added.

Despite harsh operating conditions, the FerryBox is operational since July 2011, with short interruptions during storm periods that were caused by sea spray and condensation that occurred notwithstanding the use of a heated steel cabinet for the protection of its electronics. Due to its remote position in the North Sea, personnel and spare parts had to be transported by helicopter to the platform for maintenance. Weather conditions therefore constrained the accessibility of the platform and sensors requiring regular maintenance could only be used temporarily. The software was operated remotely.

Since August 2010, a stationary FerryBox is also installed in a container directly at the waterfront of Cuxhaven Harbour. It samples the tidally influenced, highly turbid lower Elbe river, the main freshwater discharge into the COSYNA observation area. The FerryBox was complemented by the Elbe estuary measurement pole located 18 km upstream on the northern side of the river (Section 5.1.1) to contribute to a better understanding of the SPM dynamics and transport through the Elbe estuarine turbidity zone into the German Bight.

The water intake is located at a mean depth of 4 m. The oceanographic sensors are described in Section 5.4. The FerryBox is also equipped with a nitrate, phosphate, and silicate analyser as well as a fluorescence-based instrument for phytoplankton group determination. A meteorological station mounted on the top of the container provides wind speed and global radiation values.

Due to its easy and constant accessibility, the FerryBox Cuxhaven is an ideal platform for the testing of the long-term performance of new sensors under environmental conditions.

As example, a time-series of several parameters is shown for 2012 and 2013 (Fig. 6). A strong discharge period in summer of 2013 led to a substantial decrease of salinity with nearly fresh water conditions at low water for a two week period (Voynova et al., this issue).

5.2 Ocean Gliders

Ocean gliders are autonomous underwater vehicles, propelled by a buoyancy engine. In the last decade they have become an established oceanographic platform in the open ocean autonomously collecting data with a high temporal resolution along (re)programmable transects. Due to their operational flexibility and a long endurance on the order of months, gliders sample the oceans at low cost in a way no other platforms currently do (Testor et al., 2010).

The use of ocean gliders in shallow coastal waters is, however, challenging. COSYNA and a few other observatories have pioneered this particular use. Due to bathymetric constraints, currents can reach magnitudes in excess of the nominal glider speed, making it difficult to follow a prescribed transect. Intense commercial and recreational shipping traffic significantly increases the likelihood of a glider-ship collision (Merckelbach, 2013). This will almost certainly result in the loss of the glider and possibly in a hull rupture, if a fast light-weight craft is involved (Drücker et al., 2015). Therefore, COSYNA collaborates closely with the authority responsible for safety regulations in the German sector of the North Sea (Wasser- und Schifffahrtsamt) to develop prediction methodologies to mitigate the risk at sea involving gliders (Merckelbach, this issue).

COSYNA maintains three Slocum Littoral Electric gliders (Jones et al., 2005). These gliders have been used in the German sector of the North Sea in different operational modes. Gliders are particularly well suited for surveying repeated transects over long periods of time (months). Their long endurance makes it viable to run two gliders in an alternating service. While one glider is operational, the second one is refurbished. The gliders have also been deployed for shorter, targeted experiments. The use of multiple gliders provides additional spatial information. In order to fly gliders in formation, operational techniques have been developed so that they act as a single entity facilitating the interpretation of the spatial variability. The measurements taken with COSYNA gliders are available on CODM. With the help of a Java applet, glider data can be visualized in 3 dimensions (Breitbach et al., 2016).

The evolution of stratification during 2012 and part of 2014 is shown in Fig. 7 to illustrate glider measurements. The data were collected by two gliders in alternating service in 2012, and within a single experiment in 2014. From May to August, the potential energy and stratification of the water column increases due to solar heat flux. During that time, the water column is partially mixed by wind and waves at several instances. After September, mixing dominates and the heat fluxes are too low to create a stable stratification. Data from 2014 shows interannual variability with a strong stratification in August and a subsequent complete mixing of the water column caused by a storm. After this event, the stratification was not restored.

5.3 High-Frequency Radar System

In order to detect surface currents, a High Frequency (HF) radar network was established in the German Bight of the North Sea. It consists of three “Wellen Radar” (WERA) systems (Gurgel et al., 1999) located on the isles of Sylt and Wangerooge and in Büsum (Fig. 8).

The radar signal propagates along the ocean surface beyond the horizon and is backscattered by surface waves with wave lengths between 5 and 50 m (half the electromagnetic wave length of the radar). The WERA systems typically cover a range distance of 100 km with a resolution of 1.5 km. All systems transmit via a rectangular array of four antennas with a total power of 32 W. The systems on Sylt and in Büsum operate at 10.8 MHz with a linear receiver array consisting of 12 antennas, while the radar on Wangerooge operates at 12.1 MHz with a 16-antenna array.

The acquired data are subject to quality control and are publicly available within 30 min of acquisition. In an additional processing step, the radial components of each radar site are assimilated into a numerical simulation model (Stanev et al., 2014) that is also used for short-term forecasts.

Since 2013, the HF radar network is also used for ship detection, tracking, and fusing information of the radars with other sources of ship information such as from the Automated Identification System. Although the HF radar network was setup for the retrieval of oceanographic parameters, leading to a limited resolution and detection performance, ship detection can be performed at each HF radar station every 33 s (Dzvonkovskaya et al., 2008). Tracking and fusion is performed as a post processing task utilizing state-of-the-art algorithms (Bruno et al., 2013; Maresca et al., 2014; Vivone et al., 2015).

5.4 FerryBox

In order to obtain oceanographic near-surface variables in a cost-effective way on a routinely basis, FerryBox-systems have been developed within COSYNA and were installed on several ships-of-opportunity such as ferries or cargo ships, research vessels, or as stationary units (Fig. 9). They deliver key physical state variables of the North Sea and the Arctic coast off Svalbard and fill gaps concerning robust biogeochemical observations of the oceans. In particular, observations of the coastal carbon cycle with high temporal and spatial resolution along the ship tracks help to understand impacts of climate change or eutrophication on productivity, as well as the influence of single events such as storms or floods on the system. The recorded variables include temperature, conductivity, salinity (derived from temperature and conductivity), chlorophyll-a fluorescence, turbidity, dissolved oxygen (DO), the partial pressure of CO_2 (pCO_2), pH, alkalinity, nutrients, and algal groups (derived from patterns of algal fluorescence by excitation at different wavelengths). The data are used for model validation (Petersen et al., 2011; Haller et al., 2015) and assimilation studies (Stanev et al., 2011; Grayek et al., 2011; Fig. 7).

The FerryBox is a modular system that can be easily extended with additional sensors. Compared to other platforms, such as buoys, the FerryBox-systems have fewer limitations due to space, power consumption, or harsh environmental conditions allowing the operation of experimental and less robust sensors (Petersen, 2014). Due to a self-cleaning mechanism, the system maintenance intervals can be extended up to several months. All data are stored in the FerryBox-system and are transferred to the COSYNA server when the vessel has a stable internet connection.

5.5 Underwater-Node System

While cabled underwater observatory technology has been developed for deep sea research applications over the last decades, cabled underwater observatories for shallow water were only recently initiated due to the predicted dramatic effects of climate change especially in the world's coastal regions. They are needed as core research infrastructures when either a continuous high-frequency or real-time monitoring of hydrographical or biological data is required or when scientific instrumentation requires more power than batteries can provide. Cabled underwater observatories enable new research approaches in marine science by providing long-term time series. Similar to atmospheric or terrestrial research, they are suitable to form the backbone of international coastal and climate change research.

The harsh environments of shallow waters with extreme wave impact, storms, sea ice, strong currents, as well as biofouling and the direct impact of fishing vessels require the development of very robust cabled systems. COSYNA has started with this development in 2010, with the goal to observe multidisciplinary processes in the harsh environmental conditions in the North Sea and in the arctic areas – in particular during storms and in winter when access with vessels is difficult or impossible.

The COSYNA Underwater-Node System is designed for water depth between 10 m (in high-energy environments like the North Sea) to a maximum of 300 m. It comprises a land based power unit and server providing 1000 VDC, a GBit-network connection, and virtual computer technology for up to 20 different users. This land-based control system is connected to the underwater node unit via a fibre-optic and power hybrid cable that can be up to 10 km long (Fig. 8).

The underwater unit is built as basic lander system. Up to 10 underwater plugs provide power and network connection. The underwater unit can be outfitted with an uninterrupted low-power battery supply for 6-8 hours operating time to enable temporary disconnection from the high voltage electricity. From this central underwater node unit (Fig. 81-3), sensors or sensor units with a power consumption of up to 200 W (Fig. 81-4) can be connected via an up to 70 m long cable. Communication and data transfer with the attached sensors or sensor units are realized via TCP/IP. Completely separated ports allow scientists to directly communicate with the instruments independent of other users. From the primary node system, an uplink power and network connection allows the serial connection of a secondary and tertiary underwater node unit (Fig. 81-5) to reach a maximal range of 30 km from the land based support unit.

Since 2012, COSYNA operates two Underwater-Node Systems. One node system with 10 separated ports is located off the island of Helgoland at 59° 11'N / 8° 52,79E in 10 m water depth close to the long-term time series station “Helgoland Roads” and the AWI underwater experimental area MarGate (Wehkamp and Fischer, 2012; 2013a; 2013b). It is operated as permanent monitoring facility for the main hydrographical parameters in the southern North Sea (temperature, conductivity, O_2, pH, turbidity, currents), as docking and support system for complex sensor systems with high power and data transfer demands, such as stereo-optical cameras (Wehkamp and Fischer, 2014), and as test facility for the development and operation of the Underwater-Node Systems in the shallow environment of the North Sea. Since 2012, the Helgoland node system endured two severe storms with wind speeds of up to 12 Bft. (190 km h^{-1}) providing evidence that the operation of cabled observatories is possible under extreme conditions.

The southern North Sea is well known as a high-energy environment with wind speeds above 10m/s (> 6 Bft) during considerable phases of the year. Research cruises with intense sampling programs are therefore often problematic and cabled observatories provide an invaluable extension for continuous and long-term monitoring programs. They may therefore help fill a significant gap in our understanding of ecosystem behaviour in coastal environments beyond 6-8 Bft.

The second continuously operated COSYNA underwater observatory is deployed since 2012 off Svalbard at 78° 92'N, 11° 9'E. It is located at the west coast of Spitsbergen close to the international research village of NyÅlesund. It comprises a FerryBox system and a COSYNA Underwater Node System at the “Old Pier” (Fig. 3) close to the research village of NyÅlesund. It provides a continuous year-round monitoring system as well as an access point for international project partners. Since 2015, the COSYNA underwater observatory is part of the EU project Jerico-Next, the long-term research strategy of the NyÅlesund research council, and the Kongsfjord Flagship Program.

Also the Svalbard observatory is operated as permanent monitoring facility for the main hydrographical parameters in the fjord system (temperature, conductivity, O_2, pH, turbidity, currents) and as docking and support system for complex sensor systems. It is fully remotely controlled and all sensors and sensor units can be accessed via the internet from Germany. The Svalbard observatory is equipped with 4 access points and is specifically designed for national and international cooperation in the Kongsfjorden ecosystem. A main feature of the Svalbard observatory is a vertical profiling sensor unit, which allows to remotely position attached sensors at a specific depth on a daily or even hourly basis. Thus, the entire water column can be sampled year-round, even under sea ice.

With the remotely controlled sensor setup of the COSYNA Underwater-Node System, it was for the first time possible to gain data with a temporal resolution of up to 1 Hz with both CTD and ADCP sensors, and with highly complex sensors like a stereo-optical camera system that is able to measure abundance, species composition and length frequency distributions of macroscopic organisms (Wehkamp and Fischer, 2014). No data set of this kind has previously been available from any Arctic ecosystem worldwide, thus providing unique insights into the dynamics of a polar ecosystem with very high temporal and spatial resolution (Fig. 92).

5.6 Landers

Under the COSYNA framework, different autonomous sea floor observatories (landers) have been developed and are applied in various past and ongoing research programmes. These landers bridge the observational gap between long term monitoring stations, remote sensing applications, and ship-based field campaigns. They are mobile, and can be used to spatially interpolate between monitoring stations and provide data with very high temporal resolution (Kwoll et al., 2013; Kwoll et al., 2014; Oehler et al., 2015; Ahmerkap et al., subm.). Lander operations aim at measuring various processes close to the sea floor or in the sediment and are designed to have minimal impact on the environment and quantities that are measured. The landers can be either operated autonomously for days or weeks at a time, or may be connected to the COSYNA Underwater-Node System that is providing power and data connection for the landers.

The landers developed and used in COSYNA are i) the lander SedObs (Sediment Dynamics Observatory) measuring seafloor dynamics, ii) the lander NuSObs (Nutrient and Suspension Observatory), and iii) the Lander FLUXSO (Fluxes on Sand Observatory).

5.6.1 Lander SedObs

The lander Sediment Dynamics Observatory (SedObs) is used to investigate seafloor dynamics and to improve the fundamental knowledge of multi-phase flows and the interaction of physical and biological processes. The sea floor and lower water column are characterized by morphodynamic processes acting on a large range of spatial and temporal scales. Observations with SedObs focus on short-term dynamics from turbulence to tides or storm events. Particular focus is given to the interaction of water motion by currents and waves as well as the transport of sediments and other substances with the sea bed evolution under the influence of (micro-)biological stabilizing and destabilizing organisms (Ahmerkamp et al., 2015).

SedObs consists of a 2×2 m steel frame with a platform providing space for battery power supply and the installation of sensors (Fig. 103). The platform rests on four adjustable and inclined legs. Foot plates provide stable stand, prohibit subsidence, and reduce scouring around the legs. Sensors can be attached to the legs for measurements close to the sea bed. The lander is deployed with a launching frame from a research vessel orienting it in the direction of main currents. After release of the lander, the frame is recovered in order to minimize flow disturbances. For recovery, a floating buoy with recovery line is released acoustically. Typical deployment times exceed 25 h to account for the diurnal inequality in tidal variations. Deployments can be extended to longer periods of several weeks depending on measuring frequency, battery and storage limitations, and the increasing risk of damage by trawlers.

Flow velocities and turbulence above and below the lander are measured with two Acoustic Doppler Current Profilers. The upward-looking ADCP also captures the directional surface wave spectrum. Two Acoustic Doppler Velocimeters record velocity at two levels with high frequency. Turbulence characteristics are computed from high frequent velocity fluctuations (Amirshahi et al., 2016).

The small-scale bathymetry below the lander is measured with a 3D-Acoustic Ripple Profiler (Bell and Thorne, 1997). The sensor is installed about 1.8 m above the seafloor covering a circular area of 6.2 m diameter. Sediment transport characteristics are measured with Sequoia Lisst 100X instruments providing *in situ* particle size distributions of suspended sediments. Characteristics of suspended matter concentration are provided by optical backscatter sensors and the backscattered signal strengths of the hydroacoustic instruments. Additional parameters comprise the COSYNA standard observables. Observations are complemented by investigations of benthic species as well as sedimentological and granulometric analysis (Laser diffraction) of the sediments sampled with grab samplers, box corers, and multi-corer equipment.

SedObs supports several applied and fundamental research projects, such as KÜNO NOAH (North Sea Observation and Assessment of Habitats). Until 2015, eleven ship surveys were carried out, field data were collected, and analysed at different reference sites in the German Bight with sedimentological and morphological characteristics that are representative for large areas of the German EEZ in the North Sea. A combination with other COSYNA sea floor observatories has produced consistent and extensive data sets on various physical and (micro-)biological properties of the domains (Krämer and Winter, this issue). Data are published at http://www.noah-project.de.

During some parts of the tidal cycle a periodic stratification of the water column has been observed in shallow areas of the German Bight forming distinct layers that move independently with a decoupled tidal ellipticity (Krämer and Winter, this volume; Kwoll et al., 2013; Kwoll et al., 2014; Ahmerkap et al., submitted). The difference in sea bed dynamics between fair weather conditions and storms is also investigated in the research area “Seafloor Dynamics“ of the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) Research Center / Cluster of Excellence „The Ocean in the Earth System“.

5.6.2 Lander NuSObs

The benthic lander system NuSObs (Nutrient and Suspension Observatory) was designed to quantify the exchange of nutrients and oxygen across the sediment-water-interface and to sample surface sediments *in situ* (Oehler et al, 2015a; Oehler at al., 2015b). The aim was to study the remineralization of organic matter, the reflux of nutrients into the bottom water, the dissolution of biogenic silica (e.g. Diatoms) and transport processes across the sediment-water transition zone, such as biologically mediated transport (e.g. bioirrigation) or wave induced pore water advection. Target area was the North Sea. Three time series sites were selected and revisited three to four times a year in order to identify seasonal variations.

NuSObs (Fig. 103) was equipped with two “Mississippi” type chambers (Witte and Pfannkuche, 2000). After the deployment of the lander, both chambers were moved slowly into the sediment by a motor each enclosing a sediment area of 400 cm^2 for typically 12–24 h.

Each chamber was equipped with a syringe sampler (seven 50 ml glass syringes) to obtain water samples from the incubation chamber for subsequent chemical analysis. In addition, an oxygen Optode and pH sensor were mounted in each chamber. The syringe sampler was pre-programmed to obtain water samples from the chamber every 2–3 h yielding time series data of oxygen, nitrate, or silicic acid concentrations within the chambers.

5.6.3 Lander FLUXSO

The benthic lander system FLUXSO (Fluxes on Sands Observatory) was recently developed for studying *in situ* solute fluxes of nutrients, DIC, and oxygen in permeable consolidated sediments. The goal is to assess the importance of the seafloor as sink or source of nutrients and benthic-pelagic coupling and to study advection-related processes in permeable shelf sediments. The lander was successfully applied on sandy sediments of the North Sea (Figure 16; Friedrich et al., 2016; Neumann et al., 2016; Ahmerkamp under review).

The lander consists of a tripod base frame that is recovered from the seafloor using two pop-up buoys (Fig. 114). Power supply is provided by a deep-sea battery. The lander contains two wiggling chambers that are both equipped with oxygen and CO_2 optodes, a pH sensor, and a conductivity sensor. A stirrer disk with variable speed and direction allows the simulation of advective or diffusive flow regimes in each chamber by creating rotationally symmetric pressure gradients between the center and the circumference of the enclosed sediment surface. The shape and magnitude of the pressure gradients closely resemble natural conditions. Two syringe samplers are used for tracer injection and sampling from the chambers. Outside water parameters are measured with a CTD with fluorescence and turbidity sensors, a PAR sensor, an oxygen optode and pH sensor, as well as a Doppler current sensor.

The FLUXSO lander can be deployed at the seafloor, where it autonomously measures solute fluxes between sediment and sea water using isolated sampling chambers. An innovative wiggling mechanism is used, permitting gentle and deep penetration of the chambers into consolidated sediments with minimum disturbance (Janssen et al., 2005).

5.7 Satellite Oceanography

Satellite remote sensing is unique in providing a synoptic view over larger areas of the sea surface (Robinson, 2004). Standard algorithms are used widely to determine the optically dominant water constituents and the chlorophyll-a concentration in clear oceanic waters

(Carder et al., 1991; Lee et al., 1998; Gohin et al., 2002). These simple band-ratio algorithms, however, often fail in optically complex coastal waters. To gain concentrations of one coastal water constituent, other optically active substance categories have to be considered in the development of algorithms for the inversion of satellite spectral data. The correction of the atmospheric influence is more sensitive and complex as it accounts for 90% to 98% of the radiance seen at the satellite. The algorithms for coastal waters developed by HZG and used in COSYNA are included in the ESA (European Space Agency) operational processing scheme for the sensors MERIS (MEdium Resolution Imaging Spectrometer) on ENVISAT (Doerffer and Schiller, 2007) and OLCI (Ocean and Land Colour Instrument) on Sentinel-3 providing chlorophyll-*a* and total suspended matter (TSM) concentrations and the absorption by chromophoric dissolved organic matter (CDOM, “Gelbstoff").

MERIS provided COSYNA data (Fig. 12) for the North Sea until 2012 when ENVISAT failed. With the adaptation of the coastal algorithm to MODIS (on AQUA) and OLCI (Ocean and Land Colour Instrument) on Sentinel-3 providing chlorophyll-*a* and total suspended matter (TSM) concentrations and the absorption of “yellow substances” (Gelbstoff) whose main part is chromophoric dissolved organic matter (CDOM).

5.8 Seabird Tracking

Seabirds are top predators depending on marine resources. Their foraging behavior may therefore indicate changes in their food resources which are often associated with variability in the marine environment (Furness and Camphuysen, 1997). In COSYNA, the Northern Gannet (*Morus bassanus*) has been selected as the target seabird species due to their size and large foraging range (Fig. 136; Garthe et al., this issue). Northern Gannets are widely distributed in the North Atlantic and breed in large colonies. Individual Northern Gannets were equipped with modern, lightweight GPS data loggers to track their flight patterns and foraging behavior. In particular, information is collected on position, flight speed, altitude, and partly also on dive depth and water temperature. A strong feature of most modern data loggers is that they are powered by solar cells thus enabling long-term tracking for several weeks, months, or even years. Furthermore, an increasing number of devices provide data transfer via UHF, satellite, and mobile phone networks (Wilson and Vandenabeele, 2012; Kays et al., 2015). A combination of the data collected by seabirds with environmental parameters from other COSYNA observations, such as salinity, sea surface temperature, or chlorophyll facilitates the understanding of the seabirds’ foraging behavior, their likely food intake and habitat choice (Fig. 147). On the other hand, the recorded spatial and temporal flight patterns and environmental parameters can help to characterize the environmental status of the North Sea.

5.9 *In situ* mapping of the COSYNA observation area

The regular operational observations in COSYNA primarily detect variables at the sea surface (currents observed with HF radar; chlorophyll-a concentration, TSM, and SPMC observed with satellite remote sensing), at constant depths at fixed high-resolution time-series stations (Poles, FINO3 platform, MARNET stations), or at constant depth along regular ship routes (FerryBox transects). In order to observe the vertical distribution of key variables and their temporal development, these observations were complemented by extended *in situ* mapping of the North Sea during several research cruises and glider surveys. *In situ* observations taken with Wadden Sea poles, FINO3 platform, MARNET stations and FerryBox are also used in modelling (Stanev et al., 2016).

In particular, the surveys aimed at investigating the representativeness of single-point time-series observations, delivering larger-scale validation data for the COSYNA remote sensing systems and numerical models, testing the functioning of new sensors for permanent missions under North Sea conditions, and relating concentrations and characteristics of living and non-living water constituents to optical surrogate variables.

The regular COSYNA mapping grid covers estuarine, Wadden Sea, and open shelf sea water (Fig. 1). It consists of four East-West and four South-North cross-shore transects and touches the fixed COSYNA and MARNET stations covering the whole German Exclusive Economic Zone (EEZ). The land side is limited by a water depth of 10 m and its most seaward reach by the borders of the German EEZ.

From 2009 to 2013, up to four cruises per year were carried out with RV Heincke. The cruises took place between March and October to take seasonal variations into consideration. At a ship's speed of 6 to 8 knots, the grid was completed in less than a week. During this time, the water masses did not move substantially as confirmed by model studies using Lagrangian tracers. The observations thus provide a good approximation of the spatial distribution of the observed variables.

Along the grid lines, an undulating towed Scanfish Mark II ™ by EIVA was operated yielding vertical profiles of oceanographic and bulk biogeochemical parameters at a vertical resolution of several centimeters and a horizontal resolution of 150 m at mid water depth. A FerryBox system was used to analyze water continuously taken at a depth of 4 m with respect to the standard oceanographic parameters temperature, salinity, pH, chlorophyll-fluorescence, turbidity, CDOM, nutrients, dissolved oxygen, and pCO_2. During the cruises, the FerryBox also served as platform for testing newly developed sensors. This includes a flow-through PSICAM (Point-Source Integrating Cavity Absorption Meter) for high frequency hyperspectral absorption coefficient measurements (Wollschläger et al. 2013; 2014), a sequential injection analysis (SIA) approach for phosphate measurement (Frank and Schroeder, 2007), as well as high precision spectrophotometric methods for the determination of pH and total alkalinity (Aßmann et al. 2011; Aßmann, 2012). Vertical current profiles were recorded with an ADCP. During two cruises, gliders were operated in parallel enhancing the spatial observation density. At the cruise track crossing points, additional vertical profiles were taken and complemented with Secchi depth determination, light transmission, and scattering spectra taken from water samples.

As an example, the spatial distribution of σ_T (potential density – 1000 kg m^{-3}) and chlorophyll-*a* fluorescence are shown for the cruise at the end of July, 2010 (Fig. 18). Vertical density gradients at the 5 m thick pycnocline of up to 0.3 kg m^{-4} indicate a strong stratification typical for the summer months. In the outer reaches of the observation area, two pycnoclines can be discerned. In the presence of stratification, chlorophyll-*a* shows a typical deep water maximum at the upper pycnocline. The sudden increase of oxygen saturation directly above this maximum can be attributed to photosynthesizing phytoplankton. By coupling the observed vertical distribution of potential density and SPMC with a modeled turbulence parameter field, the spatial distribution of settling velocities in the COSYNA observation area was derived (März et al., 2016). Characteristic scales for the coupling of physical submesoscale and mesoscale processes and the distribution of chlorophyll-a were identified by North et al. (2016) by applying wavelet analyses to Scanfish data.

6 Sensor and Instrument Development

In COSYNA, well-proven commercially available sensors and sensor systems are used. However, to automatically measure the main parameters that control and influence the North Sea and arctic ecosystem, several novel, automated, and reliable sensors had to be developed and tested by the COSYNA partners. These are, in particular, sensors and samplers for biogeochemical and optical parameters as well as micropollutants. An overview is given in the following. For most of these sensors, the FerryBox was used as a test platform because it is protected from the environment, it provides a continuous sea water supply, and offers high-frequency data acquisition and real-time data transmission.

6.1 pH Sensor

pH can be used to estimate a system's state in terms of phytoplankton and primary production in regions of high biological activity, one of four parameters characterizing the oceanic inorganic carbon system, and an indicator for the increasing acidification of sea water. In order to quantify the components of the carbon cycle in the context of climate change, a precise characterisation of the carbonate system is required.

In COSYNA, commercially available pH glass electrodes are routinely used. They are very sensitive to bio-fouling as bacterial biofilms on the electrodes changes the pH thus requiring cleaning and re-calibrating intervals of 7-10 d in summer. Although an accuracy of ±0.05-0.1 pH units can be achieved in FerryBox systems for several weeks due to their regular automatic cleaning procedures, a higher precision of < 0.01 pH units is necessary to detect the acidification process in coastal waters with a pH decrease of about 0.0019 pH units per year (Dore et al., 2009; Feely et al., 2009).

In COSYNA, a more precise sensor based on a spectrometric approach was developed (Aßmann, 2012) that detects the colour of a suitable indicator dye in a miniaturised flow-through system. A precision of ±0.0007 pH units with an offset of +0.0081 pH units to a certified standard buffer was achieved for several weeks. It is, however, not yet suitable for low-energy applications.

6.2 Alkalinity Sensor

CO_2 flux estimates for the coastal ocean are subject to large uncertainties (Borges, 2005; Chen and Borges, 2009) due to strong seasonal variability. For a description of the carbonate system at least two of the following parameters have to be measured: pH, partial pressure of CO_2 (pCO_2), total alkalinity (AT), and total dissolved inorganic carbon (CT). Because a combination of pH and pCO_2 only yields a precision of about 1%, a sensor for the additional measurement of alkalinity was developed that will allow to document the fast changing carbonate chemistry in the North Sea (Aßmann, 2012).

The approach for the photometric pH determination (Section 6.1) was modified for alkalinity, with the advantage that the same equipment can be used for both parameters. The chemical titration can either be accomplished by using an “open-cell technique” applying a simple sea water model as calculation tool. The titration occurs at pH <4.5 leading to a removal of all carbonate species by outgassing of CO_2. The precision is ±1.1 mol kg^{-1} with an accuracy of ±8 mol kg^{-1}. In a more complex “closed-cell technique” a broader pH range is used and no CO_2 escapes yielding an accuracy of ±0.8 mol kg^{-1} with a precision of ±4.4 mol kg^{-1}.

6.3 Nutrient Sensor

COSYNA uses commercially available nutrients analysers on FerryBoxes for long term investigations of the nutrients ammonia, nitrite, nitrate, phosphate, and silicate which are important parameters regarding eutrophication. However, as small-scale processes often require faster sensor response times, a flow-through system was developed for the fast determination of ammonia and phosphate based on sequential injection analysis (SIA) causing a chemical reaction of both species with a reagent that can be detected by fluorescence (Frank et al., 2006). The detection limits are 0.3 µmol L^{-1} for phosphate and 1 µmol L^{-1} for ammonia. 180 samples can be processed per hour and analyzed.

This reliable analyser is especially useful for high-resolution surface mapping of ammonia and phosphate in coastal areas and for long-term monitoring due to the low amount of reagents used in this system (Frank and Schroeder, 2007). Nitrite and nitrate underway measurements were performed using ultraviolet absorption techniques with parallel temperature and salinity corrections, thus enabling application of this approach in coastal and estuarine waters (Zielinski et al., 2011; Frank et al., 2014).

6.4 Flow-through Spectral Light Absorption Measurements

One of the most important biogeochemical parameters for the assessment of the environmental status of the North Sea is the phytoplankton concentration. The standard method that is routinely used in COSYNA is the continuous *in situ* measurement of chlorophyll-*a* fluorescence as a proxy for biomass estimation. Since fluorescence depends on factors, such as plankton species, plankton physiology, or light climate, frequent sampling with subsequent lab analysis is necessary to reduce the large errors of up to one order of magnitude (UNESCO, 1980; SCOR Working Group, 1988).

Better suited to determine estimates of phytoplankton concentrations is the spectral absorption coefficient. To overcome the disturbing effects of the light scattering of inorganic and organic suspended matter, a flow-through Point-Source Integrating Cavity Absorption Meter (ft-PSICAM) was developed in COSYNA yielding continuous measurement of spectral absorption coefficients in the range of 400–710 nm with high temporal and spatial resolution. Additional useful information on CDOM/gelbstoff, algal pigments, and suspended matter can be obtained as well.

By using an integrating sphere, photons cannot get lost and the optical path length is increased allowing the measurement of very clear waters. This PSICAM principle (Kirk, 1997; Lerebourg et al., 2002; Röttgers et al., 2005) was modified into a flow-through unit that can be used unattended on FerryBoxes or other platforms (Wollschläger et al., 2013; Wollschläger et al., 2014). To reduce the contamination of the integrating sphere, it has to be cleaned automatically. The ft-PSICAM delivers data with high temporal and spatial resolution.

6.5 Molecular Observatory

Information on marine photosynthetic biomass distribution and biogeography with adequate temporal and spatial resolution is needed to better understand consequences of environmental change in marine ecosystems. Since COSYNA methods can only automatically measure proxy parameters for biomass, such as chlorophyll-*a*, a method for the automatic determination of phytoplankton taxonomic composition is required. Molecular analyses, e.g. next generation sequencing (NGS) or molecular sensors are very well suited to provide comprehensive information on marine microbial or protist composition.

In COSYNA, the remotely controlled Automated Filtration System (AUTOFIM) for automated collection of samples for molecular analyses was developed. Resulting samples can either be preserved for later laboratory analyses, or directly subjected to molecular surveillance of key species aboard the ship or at a monitoring side via quantitative polymerase chain reaction or an automated biosensor system (Metfies et al., this issue). The latter is based on an automated pre-treatment of the samples with an ultrasound sample preparation unit that was developed in COSYNA alongside with AUTOFIM. The sampling system can either be deployed on a fixed monitoring platform or aboard a ship for near-real time information on abundance and distribution of phytoplankton key species. Currently, two AUTOFIM-systems are operating on Helgoland and aboard RV Polarstern in order to collect samples for molecular analyses.

6.6 Zooplankton Sampling

In addition to phytoplankton distributions, the heterogeneities of the spatio-temporal zooplankton community assemblage are a key environmental parameter. Based on the established Lightframe On-sight Keyspecies Investigation technique (LOKI; Schulz et al., 2010), an imaging head for autonomous, moored operations was developed and attached to the COSYNA Underwater-Node System. A 360°-open flow chamber ensures optimal flow. The data are transferred to shore in near-real time.

LOKI combines several features bringing it close to the feasible borders set by the laws of optics (Schulz, 2013). These are an integrated flash unit providing sufficient light for short shutter times of < 30 µs to avoid motion blurring, very high resolution of <15 µm $pixel^{-1}$ to resolve fine taxonomical characteristics, and a depth of field of several millimetres. This was achieved by using two optical cones (Fig. 19e). The first one is attached to the camera housing and allows adjustment of the focal plane at a certain distance from the camera, while the tapering enhances water exchange in the flow chamber. The opposite cone houses a high-power LED flash unit. The LEDs are arranged circular and off-axis to provide indirect and homogenous illumination resulting in high-resolution images of minute specimens and a large depth of field. The operation time is, however, limited by bio-fouling (Fig. 19).

6.7 Active- and Passive Sampling Tools

To determine the potential effects of micropollutants on the marine environment and biota, a set of integrative active and passive samplers has been developed. Suitable instruments for unattended use under the harsh conditions do not exist and pure concentration data of micropollutants are often not very meaningful.

For passive sampling, a Chemcatcher Metal (Petersen et al., 2015b) as well as DGTs have been used, while blue mussels (*mytilus edulis sp*.) have been applied as active sampling devices. After a deployment period of several weeks, the samples are analysed with conventional analytical laboratory methods. In contrast to spot sampling, passive samplers allow to measure the more representative time weighted average water concentrations (TWA). Passive sampling data also provide information about the biologically available trace element fraction of the analysed water body (Booij et al., 2016). Besides the measurement of contaminant body burdens, the application of mussels as active sampling devices allows also the analysis of potential biological effects induced by the contaminants present in the surrounding water. This is done with an analysis of the up and down regulation of specific proteins, whose expressions are related with certain detoxification mechanisms.

In COSYNA, two systems (Helmholz et al., 2016) have been developed featuring a modular design for the installation on different instrumental platforms, such as different passive sampling devices, SPM traps, and cages for biota deployment. An elevator enables the manual deployment and recovery of the experimental device at a fixed position approximately 3 m above the sea floor. The use of titanium reduces corrosion. The systems are deployed next to the FerryBox Station in Cuxhaven at the mouth of the river Elbe and at the MARGate underwater testing site near Helgoland at a water depth of approximately 10 m.

A continuous flow box has been developed to overcome bio-fouling problems as well as to minimize effects of changing currents on the sampling rate, as it allows the integration into FerryBox systems (Petersen et al., 2015b) for passive sampling e.g. during ship cruises to obtain TWA contaminant data. Normaly, the pumped water intake systems is installed at the bow of the ship hull several meters below the sea level thus ensuring that the sampled water body is continuously exchanged due to the movement of the ship and the water is not contaminated by the metal construction of the ship. Alternatively, a metal free pump system can be deployed on a crane several meters away from the ship hull.

For the calculation of uptake rates, a calibration was carried out for Ni, Cu, Zn, Cd, Pb, Sc, Ti, Mn, Co, Ga, Sr, Y, Ba, U and rare earth elements under different environmental conditions (Petersen et al., 2015a). Up to now, these calibrations were not available for most elements of environmental concern besides Cu, Cd, Pb, Ni, and Zn. With these developments, a real multi-element analysis using passive sampling was possible for the first time.

6.8 Radiometric Ocean Colour Measurements

The colour of the ocean is related to its optically active constituents and can be assessed with radiometric measurements within the water column and from above the water surface (Moore et al., 2009; Garaba and Zielinski, 2013a). The latter includes satellite and airborne platforms as well as measurement poles or vessels (Zielinski et al., 2009).

As part of COSYNA, the applicability of different low altitude hyperspectral radiometer installations was investigated. Measurement poles at Spiekeroog (Fig. 150) and in the Alfacs Bay (Ebro Delta, Mediterranean) were outfitted with TriOS RAMSES hyperspectral radiometers. Underway observations were performed from research vessels Otzum and

Heincke, the latter with a permanent installation of a twin remote sensing reflectance setup to account for different sun angles along the track.

One of the major challenges is the corruption of data from sun glint and white caps. It is therefore key for any operational observing system that robust automated quality assurance methods are applied, which is achieved by parallel image acquisition and analyses (Garaba et al, 2012) or from spectral feature utilization (Busch et al, 2013; Garaba and Zielinski, 2013b). An ensemble of sun glint detection methods improves the flagging performance of the data quality algorithm (Garaba et al., 2015a). The remote sensing spectra of good quality are used to derive in water constituents like chlorophyll, coloured dissolved organic matter, and suspended particulate matter along cruise tracks in the North West European Shelf Sea (Garaba et al., 2014b) and Arctic (Garaba et al., 2013a), and at a time series station in the Wadden Sea (Garaba et al., 2014a). A very recent application is the calculation of the Forel-Ule-Colour-Index from reflectance spectra, which opens the possibility to link modern observations to long term records and to involve citizens with smartphones in ocean colour measurements (Busch et al., 2016; Garaba et al., 2015b; http://www.eyeonwater.org).

6.9 Temperature Sensor for Sediments

To measure the exchange of heat and particulate matter between the German Bight and the Wadden Sea, the heat fluxes between the tidal flats and the water body have to be determined (Onken et al., 2007). As the stratification in the sediment is directly related to the heat content, the latter can easily be calculated and the heat flux between seabed and atmosphere or overlying water derived.

For these investigations, a vertical temperature sediment profiler was developed. The self-contained probe measures the temperature of intertidal sediments at depths of 0.02 m, 0.1 m, 0.2 m, 0.3 m, and 0. 4 m. Two electrodes located about 2 cm above the sediment indicate whether the tidal flats are wet or dry. The probe was deployed close to the Hörnum measurement pole (Section 5.1.1) where sea water temperatures were measured (Onken et al., 2010).

7 Modelling and Data Assimilation

Observations – and even automated observation networks – are limited by the fact that we cannot measure everywhere and at all times, which is in particular a challenge given the coastal ocean's strong variability. One of the distinguishing features of COSYNA lies therefore in the integration of observational data into models in order to close the spatial and temporal gaps of the observations and to calculate energy or matter fluxes (Stanev at al., 2016). Model studies are also essential for identifying regions with high sensitivity or variability in certain quantities that warrant the deployment of measurement devices. On the other hand, state-of-the-art numerical models of coastal dynamics require monitoring data to reasonably manage large model uncertainties. The observations are used to bring models closer to the "real" state of the ocean, either by verifying model output or by assimilating them into models. These data sets should be representative and coherent. In order to continuously provide accurate pre-operational coastal ocean state estimates and forecasts, COSYNA integrates near-real time measurements in numerical models in a pre-operational way that is meant to improve both historical model runs and forecasts.

In this context, COSYNA has explored different techniques to assimilate data into models. Satisfactory assimilation results were achieved when 2D-data fields were available, such as derived from HF radar or satellite observations (Stanev et al., 2015) providing a 12 h-forecast. The assimilation of data from single locations or sections usually only influences the immediate vicinity of the locations where the observations were made and has limited value for greater spatial extensions (Grayek et al., 2011; Stanev et al., 2011). Data assimilation based on physical values is generally more easily achieved than with biogeochemical quantities. The successful assimilation products of COSYNA encompass surface currents, significant wave height, period and wave direction, as well as temperature.

For the assimilation of current observations, a nested 3D-hydrodynamic model is used. *In situ* current time series are measured with stationary ADCPs at the FINO-1 and FINO-3 research platforms. Remote sensing of surface currents is carried out with three HF radar systems installed in the German Bight (Section 5.3). For technical details of data processing and accuracy see Stanev et al. (2015). The flow of observational data including observing nodes, data management system, and data assimilation capabilities is streamlined toward meeting the needs for high-quality operational data products in the German Bight (Fig. 161).

Although there are hundreds of HF radar systems installed worldwide, their operational use in numerical models, in particular at sub-tidal periods, is not well established. The assimilation of HF radar data is a challenge due to irregular data gaps in time and space, inhomogeneous observational errors, as well as inconsistencies between boundary forcing and observations.

Furthermore, due to the high sampling frequency of typically several times per hour, it is difficult for the model to reach equilibrium between two time steps. Therefore, the Spatio-Temporal Optimal Interpolation (STOI) filter has been developed by Stanev et al. (2015). It enables a blending of model simulations from a free run and radar observations by extending the classical Kalman analysis method to time periods of at least one tidal cycle by using the Kalman analysis equation.

The modelling suite is based on the 3D-primitive equation General Estuarine Transport Model (GETM; Burchard and Bolding, 2002). It is used in two configurations: a North Sea–Baltic Sea model of 5.6 km resolution and a one-way nested German Bight model with a horizontal resolution of about 1 km (Stanev et al., 2011). Both models use terrain-following equidistant vertical coordinates (s-coordinates) with 21 non-intersecting layers.

The validation of the model and the physical interpretation of the results showed the good skills of STOI not only in the area covered by HF radar observations but also outside it, revealing its upscaling capabilities (Stanev et al., 2015). By using HF radar data in the STOI system, homogeneous and continuous 2D-current fields were thus generated over the entire model area. The quality is superior to a free model run, demonstrating that data assimilation can enhance coastal ocean prediction capabilities by making use of observations and modeling, which is an essential aspect of an operational system. The combination of HF radar data and numerical model results can therefore also provide a deeper insight into the German Bight dynamics and provide useful indications where further model developments (improvements) are needed.

COSYNA also provides a pre-operational wave-forecast based on the WAM Cycle 4 wave model (release WAM 4.5.3; Komen et al., 1994; Guenther et al., 1992). The computational system consists of a regional WAM for the North Sea with a spatial resolution of ~5 km and a nested-grid with a spatial resolution of 900 m for the German Bight. Wind fields and boundary information are provided by the German Weather Service (DWD) derived from their regional wave model EWAM. A number of wave parameters such as significant wave height, period, and total wave direction are calculated (Staneva et al., 2015). It is continuously providing hindcasts and forecasts since December 2009. Daily at 0:00 UTC and 12:00 UTC, a 24 h regional forecast is issued for the North Sea and a local one for the German Bight. As an example, a typical wave height distribution with low values close to the coasts and higher values off shore is shown for the German Bight for 1 November 2006 (Fig. 172).

A combination of biogeochemical observational data and numerical models in COSYNA has been instrumental for a better understanding of material dynamics including steep cross-shore gradients ranging from shallow near-shore waters to the continental shelf, strong lateral gradients and mesoscale patchiness, as well as singular events, such as storms or ice winters. These processes are intimately linked to the functioning of coastal ecosystems but also affect efforts to maintain shipping pathways and coastal defense, as well as water quality.

A model- and data-based analysis (März et al., 2016) highlights a remarkable cross-shore separation of the coastal ocean with a maximum settling velocity of suspended material in the transition zone between the shallow Wadden Sea and the continental shelf, which modifies the traditional concept of continuous gradients. This acceleration of vertical deposition fluxes is likely due to enhanced particle aggregation induced by organic substances, which in turn are released by planktonic microorganisms (Su et al., 2015; Hofmeister et al., subm.). Enhanced deposition in the coastal transition zone is accounting for an effective trapping of lithogenic material within near-shore waters, while it may act as a barrier for offshore organic particles. Even higher variability at scales below the cross-shore gradients is evident in COSYNA lander observations (Section 5.6) of total benthic oxygen consumption.

Using an ecosystem model that includes turbidity fields, estimated from Scanfish observations (Section 5.9), and accounts for the acclimation capacity of phytoplankton, spatial variability in chlorophyll-*a* can be reproduced to a high degree (Fig. 183; Wirtz and Kerimoglu, submitted). Previous modeling attempts such as of van Leeuwen et al (2013) or Schrum et al (2006) do not capture the extreme vertical squeezing of chlorophyll-*a* within thin layers, which may affect model derived estimates of total primary production. Our new model results also reveal how reconstructed pelagic patterns decouple from benthic respiration patterns. Vertical deposition of freshly produced material greatly varies within the coastal ocean. In a few, mostly deeper regions, deposition prevails over resuspension, leading to depositional hotspots (Wirtz et al, in prep).

Vertical structures in nutrient concentration are key to understand whether, when, and where phytoplankton blooms form after storm events (Su et al., 2015). Vertical structures in chlorophyll-*a* below the meter scale (thin layers) as recently observed by gliders and Scanfish (Sections 5.2, 5.9) as a persistent feature indicate that a considerable amount of primary production takes place unnoticed from satellite observations. To include these vertical patterns into modeling studies requires sophisticated formulations like those by Riegman and

Colijn, (1991), Behrenfeld and Falkowski (1997), and Behrenfeld et al. (2005). For the German Bight model validations using COSYNA data can help to significantly improve estimates of total primary production.

8 Data Management and Data Products

8.1 Data Management

The COSYNA data management system (CODM) was established to make observational and model data publicly available in near-real time (Breitbach et al., 2016). The time between observations and the availability of data on CODM is ranging from a few minutes for stationary measurements to about 24 h for data obtained from ships of opportunity and satellites.

Due to the various observational platforms and model output, it is a significant challenge to provide a comprehensive overview of the observations with their diverse data formats in terms of parameters, dimensionality, and observational methods. It is achieved by describing the data using metadata and by making all data available for different analyses and visualisations in a combined way independent of data dimensionality. This concerns in particular the presentation of different data types together in one plot, such as the mapping of the same variable derived from satellite imagery and *in situ* observations. Key for this is the harmonisation of parameter names. The various internally used parameter names for the same observed property are mapped to the corresponding Climate and Forecast (CF) standard name (Eaton et al., 2010).

Another important aspect of CODM is the use of standardised metadata that are adapted for the use in direct web service requests (Fig. 194). Two types of metadata are used in CODM: For observations, the first type describes an observational platform, its sensors, and observed properties, the second type describes the observed data.

The metadata are created automatically, if the data sets have a distinct beginning and ending. Examples are ship or glider transects, or single satellite scenes. For stationary platforms, only one metadata record is created for the entire time-series. For models, the first type of metadata describes the model itself, while the second type is describing the model run. Data-metadata are ISO19115 and INSPIRE compliant (EC Directive, 2007) and contain all necessary information to access the data as download, plot, or map. The metadata itself are also mapped to a Web Feature Service (Fig. 5).

The observational data have to pass a number of automated and supervised tests, before they become publicly accessible in the data portal. Depending on the test results for range, stuck values, spikes, and – for some parameters – gradients quality flags are assigned to the data. The procedures and quality flags are in line with international guidelines (Breitbach et al., 2016; SeaDataNet, 2010).

CODM is a publicly available Open Data portal. There are no restrictions or fees for downloading and using the data, but CODM requires a basic user registration. Users are asked to provide country of origin, a user category, and the city. No other personal information is mandatory. Users are also asked to acknowledge COSYNA as data source in their publications. The majority of users are in the science sector followed by administration (Fig. 20).

8.2 Data Products

COSYNA is monitoring the current state of the coastal system in the North Sea and is generating modelled pre-operational state reconstructions and forecasts. These routinely provided data can be grouped into four "product" categories:

a) High-resolution time series at fixed positions: Meteorological, oceanographic, water quality, and biological parameters are continuously observed at the measuring poles (Section 5.1) Spiekeroog, Hörnum Deep, and Elbe, the research platform FINO3 (Section 5.1.2), and at the stationary FerryBox systems in Cuxhaven and Helgoland (Section 5.4).

b) Repeated transects: Oceanographic and biogeochemical parameters are measured during regular ship and glider surveys (Sections 5.2, 5.9) and with automated FerryBox systems on ships of opportunity (Section 5.4).

c) Remote sensing information: Regular maps of currents, chlorophyll distribution and optical sea water properties are obtained with remote sensing by HF radar (Section 5.3) and satellites (Section 5.7). The data cover large areas of the German Bight and are integrated with observational *in situ* data.

d) Integrated COSYNA products: The automatically produced data fields of the German Bight are continuous in space and time and provide hindcast, nowcast, and short-term forecasts. The latter two are improved with data assimilation procedures (Section 7).

The COSYNA product "Surface Current Fields" provides data fields and maps of tidal hindcasts and forecasts of sea surface currents in the German Bight. The fields are updated every 30 min. They are created by assimilating regular HF radar measurements into a 3D circulation model (Stanev et al., 2011; 2015; Section 7).

The pre-operational COSYNA wave forecast model system runs twice a day and provides a 72 h forecast on the regional scale for the North Sea and on the local scale for the German Bight. Significant wave height, period, and total wave direction are calculated (Staneva et al., 2014).

In order to provide the spatial distribution of sea surface temperature and salinity in the North Sea, FerryBox observations taken along ship tracks are extrapolated to larger areas combining them with information from numerical models. Data from the route Cuxhaven-Immingham are assimilated into a three-dimensional circulation model every 24 h (Grayek et al., 2011).

9 Outreach and Stakeholder Interaction

COSYNA aims to make scientific data, results, and data products publicly available by reaching out to different target groups and users, such as the scientific community, potential users in business enterprises and authorities, and to the general public. To serve this purpose, COSYNA publishes several print products in German and English that are publicly available for download at the COSYNA website, or can be ordered. Flyers and more comprehensive brochures provide an overview of the goals, approaches, activities, and results of COSYNA. The annual progress reports are intended for COSYNA partners and users and describe selected results and activities of the various working groups and subprojects within COSYNA. Newsletter and product fact sheets provide COSYNA partners and users as well as interest groups or the general public with information on activities, events, or data products.

COSYNA maintains the website http://www.cosyna.de that informs about motivation, approach, observations, modelling, products, and outreach activities. The COSYNA data portal is linked to that web site and provides access to data download and visualisation. On average, the COSYNA website has been visited by more than 500 different external visitors per month.

Furthermore, COSYNA has developed an interactive app with versions for iPad and other tablet PCs as well as Android and iOS based smartphones. The app provides explanatory texts and pictures describing the observing systems, instruments, models and products, as well as the COSYNA partners. Near real-time data for several platforms are available. COSYNA is also presenting the app in permanent exhibits in museums, or temporarily at public events or trade shows.

It is one of the main goals of COSYNA to bridge the gap between operational oceanography and the users of marine data in local authorities, non-governmental organizations, science and industry. In order to ensure that products are applicable, COSYNA has been initiating a dialogue with stakeholders allowing for direct feedback and input to COSYNA. In the initial phase of COSYNA, a national and an international survey showed that the COSYNA data products are useful to a great number of users from different sectors and fit into the international context. Follow-up workshops and an external evaluation of the integrated COSYNA product "Surface Current Fields" have clearly improved COSYNA products and their usability. To explore the streamlining of COSYNA products for the offshore wind energy industry, several workshops were held to pave the way for future co-operation with offshore wind energy companies (Eschenbach, this issue).

10 Conclusions and Outlook

COSYNA was established with its sight on understanding the state and variability of complex interdisciplinary processes in the North Sea and the Arctic. During its first years, work concentrated on establishing the observational network, developing sensors and numerical models, testing and applying data assimilation techniques, building a data management system and testing outreach strategies. Now, that the core of what had been envisioned in the original concepts is operational and functioning, COSYNA will expand into new areas, spatially as well as scientifically.

Currently, COSYNA is being extended to the western part of the Baltic Sea (in cooperation with a new partner, GEOMAR, Helmholtz Centre for Ocean Research) by installing an Underwater-Node System in spring 2016 in the Eckernförde Bight near the location of GEOMAR's long established Boknis Eck time-series station (Lennartz et al., 2014). COSYNA already contributes to observations of other coastal areas in the world, such as the Lena delta, the Bohai Sea in China, or with instruments on research vessels and cruise ships operating in various parts of the world ocean. In the long run, COSYNA will be part of HZG's Global Coast project that aims at identifying representative coastal regions worldwide that will help evaluate the role of coastal areas for global processes, while using a global context for understanding regional and coastal processes.

To this end and for use in large national and international research projects, COSYNA plans to develop mobile observing systems with high resolution capabilities in space and time, that have very short deployment times in order to be able to react to extreme events such as storms and floods. As the focus of research projects will be shifting more and more to an integrated understanding of complex systems, this approach will require cooperation with partners in the atmospheric and terrestrial research communities. In the future, COSYNA will be closely interlinked with the Elbe River Supersite of DANUBIUS, the most recent European ESFRI Roadmap project studying river-delta-sea systems, and will be part of the Helmholtz Association's MOSES (Modular Observing System for the Earth System) research infrastructure.

Intensified modeling efforts, especially regarding biogeochemical models and data assimilation are needed to put the COSYNA observations in a broad context and help understand coastal systems. This will also yield future data products including wind fields, ship detection, and biogeochemical parameters. Chlorophyll maps and maps of suspended particulate matter will be obtained from satellites on a regular basis. The assimilation of other quantities is work in progress and will be published, when they become available.

The successful technology development of underwater nodes will continue. Currently, experiments with smaller, more flexible units are underway. Alternative forms of power supplies, such as fuel cells, are being tested and may allow for a flexible network of nodes.

New partners are joining COSYNA: GEOMAR in Kiel and the Franzius-Institute for Hydraulic, Estuarine, and Coastal Engineering at the University of Hannover have recently agreed to become COSYNA partners. For the future, discussions with international partners will be sought and international cooperation will be intensified – in particular with the countries bordering the North Sea.

While COSYNA has evolved into a well-established integrated pre-operational observing system, research will become more central to defining COSYNA's endeavors. Utilizing the combined expertise of its various partner institutions, COSYNA's science foci will include biogeochemical cycles from rivers to the North Sea and the Northern Atlantic, the role of wind farms for physical, biogeochemical, and biological processes in the coastal ocean as well as associated engineering questions, Land – Wadden Sea – North Sea exchange processes with an extensive experiment spanning from the Netherlands, along the German coast to Denmark involving physics and biogeochemistry, and exploration of the possibilities and challenges associated with citizen science.

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References

ABARE: Economics of Australia's sustained ocean observing system, benefits and rationale for public funding, The Australian Bureau of Agricultural and Resource Economics and Economic Consulting Services, Report 44, 2006.

Ahmerkamp, S., Winter, C., Janssen, F., Kuypers, M. M. M., and Holtappels, M.: The impact of bedform migration on benthic oxygen fluxes, J. Geophys. Res. Biogeosci., 120, doi:10.1002/2015JG003106, 2015.

Ahmerkamp, S., Winter, C., Krämer, K., de Beer, D., Janssen, F., Kuypers, M. M. M., and Holtappels, M.: Bedform control of benthic oxygen dynamics in a shallow shelf sea. Under review.

Aßmann, S.: Entwicklung und Qualifizierung autonomer Messsysteme für den pH-Wert und die Gesamtalkalinität von Meerwasser, PhD-Thesis, Christian-Albrechts-University, Kiel, 2012.

Aßmann, S., Frank, C., and Körtzinger, A.: Spectrophotometric high-precision seawater pH determination for use in underway measuring systems, Ocean Sci., 7, 597–607, http://www.ocean-sci.net/7/597/2011, doi:10.5194/os-7-597-2011, 2011.

Badewien, T. H., Zimmer, E., Bartholoma, A., and Reuter, R.: Towards continuous long-term measurements of suspended particulate matter (SPM) in turbid coastal waters, Ocean Dyn. 59:227-238, doi:10.1007/S10236-009-0183-8, 2009.

Behrenfeld, M. J., Boss, E. and Siegel, D.A., and Shea, D.M.: Carbon-based ocean productivity and phytoplankton physiology from space, Global Biogeochemical Cycles, 19 (1), GB1006, doi:10.1029/2004GB002299, 2005.

Behrenfeld, M.J. and Falkowski, P. G., Photosynthetic Rates Derived from Satellite-Based Chlorophyll Concentration, Limnology and Oceanography, 42 (1), 1-20, 1997.

Bell, P. S., and Thorne, P. D.: Application of a high resolution acoustic scanning system for imaging sea bed microtopography, Seventh International Conference on Electronic Engineering in Oceanography, Tech. Trans. Res. Ind., 128–133, doi:10.1049/cp:19970673, 1997.

Booij, K., Robinson, C.D., Burgess, R. M., Mayer, P., Roberts, C. A., Ahrens, L., Allan, I. J., Brant, J., Jones, L., Kraus, U. R., Larsen, M. M., Lepom, P., Petersen, J., Pröfrock, D., Roose, P., Schäfer, S., Smedesp, F., Tixier, C., Vorkamp, K., and Whitehouse, P.: Passive Sampling in Regulatory Chemical Monitoring of Nonpolar Organic Compounds in the Aquatic Environment, Environ. Sci. Tech, 50, 3-17, doi:10.1021/acs.est.5b04050, 2016.

Borges, A. V.: Do we have enough pieces of the jigsaw to integrate CO2 fluxes in the coastal ocean?, Estuaries, 28, 1, 3–27, doi: 10.1007/BF02732750, 2005.

Brand, M., and Fischer, P.: Species composition and abundance of the shallow water fish community of Kongsfjorden, Svalbard, Polar Biol, 1–13, doi:10.1007/s00300-016-2022-y, 2016.

Breitbach, G., Krasemann, H., Behr, D., Beringer, S., Lange, U., Vo, N., and Schroeder, F.: Accessing Diverse Data Comprehensively - CODM the COSYNA Data Portal, Ocean Sci. Discuss., doi:10.5194/os-2016-6, 2016.

Bruno, L., Braca, P., Horstmann, J., and Vespe, M.: Experimental Evaluation of the Range-Doppler Coupling on HF Surface Wave Radar, IEEE Geosci. Remote Sens. Lett., 10, 4, 850–854, doi:10.1109/LGRS.2012.2226203, 2013.

Busch, J.A., Hedley, J.D., and Zielinski, O.: Correction of hyperspectral reflectance measurements for surface objects and direct sun reflection on surface waters, International J. Rem. Sens., 34.2013, 19, 6651-6667, doi:10.1080/01431161.2013.804226, 2013.

Busch, J., Price, I., Jeauson, E., Zielinski, O., and v.d. Woerd, H.J.: Citizens and satellites: Assessment of phytoplankton dynamics in a NW Mediterranean aquaculture zone, Intl. J. Applied Earth Obs. Geoinf., 47, 40-49, doi:10.1016/j.jag.2015.11.017, 2016.

Burchard, H., Flöser, G., Staneva, J.V., Badewien, T.H., and Riethmüller, R.: Impact of Densitiy Gradients on Net Sediment Transport into the Wadden Sea, J. Phys. Oceanogr., 38, 566–587, doi:10.1175/2007JPO3796.1, 2008.

Burchard, H., and Bolding, K.: GETM: A general estuarine transport model. European Commission Joint Research Centre Tech. Rep. EUR 20253 EN, 157, 2002.

Burchard, H., and Badewien, T.H.: Thermohaline circulation of the Wadden Sea, Ocean Dynam 65,1717-1730, doi:10.1007/s10236-015-0895-x, 2015.

Busch, M., Kannen, A., Garthe, S., and Jessopp, M.: Consequences of a cumulative perspective on marine environmental impacts: offshore wind farming and seabirds at North Sea scale in context of the EU Marine Strategy Framework Directive, Ocean Coastal Manag., 71, 213-224, doi:10.1016/j.ocecoaman.2012.10.016, 2013.

Buschbaum, C., Lackschewitz, D., and Reise, K.: Nonnative macrobenthos in the Wadden Sea ecosystem, Ocean Coastal Manag., 68, 89-101, doi:10.1016/j.ocecoaman.2011.12.011, 2012.

Brand, M., and Fischer, P.: Species composition and abundances of the shallow-water fish community of Kongsfjorden, Svalbard, Polar Biology, in press.

Carder, K. L., Hawes, D. K., Baker, K. A., Smith, R. C., Steward, R. G., and Mitchell, B. G.: Reflectance model for quantifying chlorophyll a in the presence of productivity degradation products, J. Geophys. Res., 96, 20599–20611, doi: 10.1029/91JC02117, 1991.

Carpenter J.R., Merckelbach L., Callies U., Clark S., Gaslikova L., and Baschek B. (2016) Potential Impacts of Offshore Wind Farms on North Sea Stratification. PLoS ONE 11(8): e0160830. doi:10.1371/journal.pone.0160830.

Chen, C. T. A., and Borges, A. V.: Reconciling opposing views on carbon cycling in the coastal ocean: continental shelves as sinks and near-shore ecosystems as sources of atmospheric CO_2, Deep Sea Res. II, 56, 8–10, 578–590, doi:10.1016/j.dsr2.2009.01.001, 2009.

Colijn, F. and de Jonge, V.N.: Primary production of microphytobenthos in the Ems_Dollard estuary. Mar. Ecol. Progr. ser. 14: 185-196, 1984.

Cottier, F., Tverberg, V., Inall M., Svendsen, H, Nilsen, F., and Griffiths, C.: Water mass modification in an Arctic fjord through cross-shelf exchange: The seasonal hydrography of Kongsfjorden, Svalbard, J Geophys Res., 110, C12005, doi:10.1029/2004JC002757, 2005.

Dittmann, S. (ed.): The Wadden Sea Ecosystem: stability properties and mechanism, Springer Berlin Heidelberg, ISBN: 978-3-642-64256-2, doi:10.1007/978-3-642-60097-5, 1999.

Doerffer, R., and Schiller, H.: The MERIS Case 2 water algorithm, Intl. J. Rem. Sens., 28, 3-4, 517-535, doi: 10.1080/01431160600821127, 2007.

Dore, J. E., Lukas, R., Sadler, D.W., Church, M. J., and Karl, D. M.: Physical and biogeochemical modulation of ocean acidification in the central North Pacific, Proc. Natl. Acad. Sci. USA, 106, 12235–12240, doi:10.1073/pnas.0906044106, 2009.

Drücker, S., Steglich, D., Merckelbach, L., Werner, A., and Bargmann, S.: Finite element damage analysis of an underwater glider–ship collision, J. Mar. Sci. Tech., 1–10, doi:10.1007/s00773-015-0349-7, 2015.

Dzvonkovskaya, A., Gurgel, K.-W., Rohling, H., and Schlick, T.: Low power high frequency surface wave radar application for ship detection and tracking, Proc. Int. Conf. Radar, Adelaide, SA, 627–632, doi:10.1109/RADAR.2008.4653998, 2008.

Eaton, G., Drach, T., and Hankin: netCDF Climate and Forecast (CF) Metadata Conventions, Version 1.5, http://cf-pcmdi.llnl.gov/documents/cf-conventions/cf-conventions-version-1.5/cf-conventions.pdf, 2010.

EC Directive: Directive 2007/2/EC of the European Parliament and of the Council of 14 March 2007 establishing an Infrastructure for Spatial Information in the European Community,http://eurlex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2007:108:0001:0014:EN:PDF.

Emeis, K.-C., van Beusekom, J., Callies, U., Ebinghaus, R., Kannen, A., Kraus, G., Kröncke, I., Lenhart, H., Lorkowski, I., Matthias, V., Möllmann, C., Pätsch, J., Scharfe, M., Thomas, H., Weisse, R., and Zorita, E.: The North Sea - A shelf sea in the Anthropocene, J. Mar. Syst., 141, 18–33, http://dx.doi.org/10.1016/j.jmarsys.2014.03.012, 2015.

Eschenbach, C.: Bridging the Gap between Observational Oceanography and Users, Ocean Science, submitted, 2016.

Feely, R. A., Doney, S. C., and Cooley, S. R.: Ocean acidification: Present conditions and future changes in a high-CO2 world, Oceanogr., 22, 36–47, doi:10.5670/oceanog.2009.95, 2009.

Fischer, P., Schwanitz, M., Loth, R., Posner, U., Brand, M. and Schröder, F.: First year of the new Arctic AWIPEV-COSYNA cabled Underwater Observatory in Kongsfjorden, Spitsbergen, Ocean Science Discussions, 2016, 1–34, doi:10.5194/os-2016-52, 2016.

Flöser, G., Burchard, H., and Riethmüller, R.: Observational evidence for estuarine circulation in the German Wadden Sea, Cont. Shelf Res., 31, 1633-1639, doi:10.1016/j.csr.2011.03.014, 2011.

Frank, C., Meier, D., Voss, D., and Zielinski, O.: Computation of nitrate concentrations in coastal waters using an *in situ* ultraviolet spectrophotometer: Behavior of different computation methods in a case study a steep salinity gradient in the southern North Sea. Meth. Oceanogr., 9, 34-43, doi: 10.1016/j.mio.2014.09.002, 2014.

Frank, C., Schroeder, F., Ebinghaus, R., and Ruck, W.: A Fast Sequential Injection Analysis System for the Simultaneous Determination of Ammonia and Phosphate, Microchim. Acta 154, 31–38, doi:10.1007/s00604-006-0496-y, 2006.

Frank, C., and Schroeder, F.: Using Sequential Injection Analysis to Improve System and Data Reliability of Online Methods: Determination of Ammonium and Phosphate in Coastal Waters, J. Autom. Method. Manag., 49535, doi:10.1155/2007/49535, 2007.

Friedrich, J., van Beusekom, J.E.E. , Neumann, A., Naderipour, C., Janssen, F. Ahmerkamp, S., Holtappels, M., Krämer, K.: Long-term impact of bottom trawling on pelagic-benthic coupling inthe southern North Sea (German Bight)?. EGU2016-15791, 2016.

Neumann, A., Friedrich, J., van Beusekom, J.E.E., Naderipour, C.: Spatial and temporal patterns in oxygen and nutrient fluxes in sediment of German Bight (North Sea). EGU 2016-14238, 2016.

Furness, R. W., and Camphuysen, C. J.: Seabirds as monitors of the marine environment, ICES J. Mar. Sci., 54, 726-737, doi:10.1006/jmsc.1997.0243, 1997.

Garaba, S.P., Schulz, J., Wernand, M.R., and Zielinski, O.: Sunglint detection for unmanned and automated platforms, Sensors 12, 9, 12545-12561, doi: 10.3390/s120912545, 2012.

Garaba, S.P., and Zielinski, O.: Comparison of remote sensing reflectance from above-water and in-water measurements west of Greenland, Labrador Sea, Denmark Strait, and west of Iceland, Opt. Expr., 21, 13, 15938-15950, doi:10.1364/OE.21.015938, 2013a.

Garaba, S.P., and Zielinski, O.: Methods in reducing surface reflected glint for shipborne above-water remote sensing, JEOS:RP, doi:10.2971/jeos.2013.13058, 2013b.

Garaba, S.P., Badewien, T.H., Braun, A., Schulz, A.-C., and Zielinski, O.: Using ocean colour remote sensing products to estimate turbidity at the Wadden Sea time series station Spiekeroog, JEOS:RP, doi:10.2971/jeos.2014.14020, 2014a.

Garaba, S.P., Voß, D., and Zielinski, O.: Physical, bio-optical state and correlations in North–Western European Shelf Seas, Rem. Sens., 6, 6, 5042-5066, doi:10.3390/rs6065042, 2014b.

Garaba, S.P., Friedrichs, A., Voss,D., and Zielinski, O.: Classifying natural waters with Forel-Ule Colour Index System: Results, Applications, Correlations and Crowdsourcing, Intl. J. Environ. Res. Publ. Health, 12, 16096-16109, doi:10.3390/ijerph121215044, 2015a.

Garaba, S.P., Voß, D., Wollschläger, J., and Zielinski, O.: Modern approaches to shipborne ocean colour remote sensing, Appl. Optics, 54, 12, 3602-3612, doi:10.1364/AO.54.003602, 2015b.

Garthe, S., and Hüppop, O.: Scaling possible adverse effects of marine wind farms on seabirds: developing and applying a vulnerability index, J. Appl. Ecol., 41, 724–734, doi:10.1111/j.0021-8901.2004.00918.x, 2004.

Garthe, S., Peschko, V., Kubetzki, U., and Corman, A.-M.: Seabirds as samplers of the marine environment – a case study in Northern Gannets. Submitted to this issue.

Gohin, F, Druon, J.N., and Lampert, L.: A five channel chlorophyll concentration algorithm applied to SeaWiFS data processed by SeaDAS in coastal waters, Int. J. Rem. Sens., 23, 8, 1639–1661, doi:10.1080/01431160110071879, 2002.

Gollasch, S., Haydar, D., Minchin, D., Wolff, W.J., and Reise, K.: Introduced aquatic species of the North Sea coasts and adjacent brackish waters, In: Rilov, G. and Crooks, J.A. (Eds.): Biological Invasions in Marine Ecosystems, Ecological Studies, 204, 507-528, doi:10.1007/978-3-540-79236-9_29, 2009.

Grashorn, S., Lettmann, K.A., Wolff, J.-O., Badewien, T.H., and Stanev, E.V.: East Frisian Wadden Sea hydrodynamics and wave effects in an unstructured-grid model, Ocean Dyn., 65, 419-434, doi:10.1007/s10236-014-0807-5, 2015.

Grayek, S., Staneva, J., Schulz-Stellenfleth, J., Petersen, W., and Stanev, E.V.: Use of FerryBox surface temperature and salinity measurements to improve model based state estimates for the German Bight, J. Mar. Syst., 88, 45–59, doi:10.1016/j.jmarsys.2011.02.020, 2011.

Gurgel, K.-W., Antonischki, G., Essen, H.-H., and Schlick, T.: Wellen Radar (WERA): A new ground-wave based HF radar for ocean remote sensing, Coastal Eng., 37, 3, 219–234, 1999.

Haller, M., Janssen, F., Siddorn, J., Petersen, W. and Dick, S.: Evaluation of numerical models by FerryBox and fixed platform *in situ* data in the southern North Sea, Ocean Sci., 11, 879-896, www.ocean-sci.net/11/879/2015/, 2015.

Helmholz, H., Lassen, S., Ruhnau, C., Pröfrock, D., Erbslöh, H.-B., and Prange, A.: Investigation on the proteome response of transplanted Blue mussel (*Mytilus sp.*) during a long term exposure experiment at differently impacted field stations in the German Bight (North Sea), Mar. Environ. Res. 110, 69-80, 2015.

Hegseth, E. N. and Tverberg, V.: Effect of Atlantic water inflow on timing of the phytoplankton spring bloom in a high Arctic fjord (Kongsfjorden, Svalbard), J. Mar. Syst., 113–114, 94–105, doi:10.1016/j.jmarsys.2013.01.003, 2013.

Booij, H.-B. K., Robinson, C. D., Burgess, R. M., Mayer, P., Roberts, C. A., Ahrens, A., Allan, I. J., Brant, J., Jones, L., Kraus U. R., Larsen, M. M., Lepom, P., Petersen, J., Pröfrock, D., Roose, P., Schäfer, S., Smedes, F., Tixier, C., Vorkamp, K., and Whitehouse, P.: Passive Sampling in Regulatory Chemical Monitoring of Nonpolar Organic Compounds in the Aquatic Environment, Environ. Sci. Technol., 50, 3−17, doi:10.1021/acs.est.5b04050, 2016

Hodapp, D., Meier, S., Muijsers, F., Badewien, T. H., and Hillebrand, H.: Structural equation modeling approach to the diversity-productivity relationship of Wadden Sea phytoplankton, Mar. Ecol. Progr. Series, 523, 31-40, doi:10.3354/meps11153, 2015.

Holinde, L., Badewien, T. H., Freund, J.A., Stanev, E. V. and Zielinski, O.: Processing of water level derived from water pressure data at the Time Series Station Spiekeroog, Earth Syst. Sci. Data, 7, 289-297, doi: 10.5194/essd-7-289-2015, 2015.

Hofmeister, R., Flöser, G., and Schartau, M.: Estuarine circulation sustains horizontal nutrient gradients in freshwater-influenced coastal systems. Submitted to Geo-Marine Letters, under revision.

Hop, H., Pearson, T., Hegseth, E. N., Kovacs, K. M., Wiencke, C., Kwasniewski, S., Eiane, K., Mehlum, F., Gulliksen, B., Wlodarska-Kowalczuk, M., Lydersen, C., Weslawski, J. M., and Cochrane, S.: The marine ecosystem of Kongsfjorden, Svalbard, Polar Res 21,167–208, doi:10.1111/j.1751-8369.2002.tb00073.x, 2002.

Hop, H., Wiencke, C., Vögele, B., Kovaltchouk, N. A.: Species composition, zonation, and biomass of marine benthic macroalgae in Kongsfjorden, Svalbard, Bot. Mar., 55, 399–414, doi: 10.1515/bot-2012-0097, 2012.

Howarth, M. J.: North Sea circulation, Encyclopedia of Ocean Sciences, 1, 1912–1921, 2001.

Intergovernmental Oceanographic Commission (of UNESCO): The Case for GOOS. Report of the IOC Blue Ribbon Panel for a Global Ocean Observing System (GOOS). IOC/INF-915, Paris, 62, 27 January 1993.

Intergovernmental Oceanographic Commission: GOOS Coastal Module Planning Workshop Report. Scientific Committee on Oceanic Research of ICSU for J-GOOS. Workshop Report No. 131. GOOS No. 35. Miami, 57, 24-28 February 1997.

IPCC: Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, Core Writing Team, R. K. Pachauri and L. A. Meyer (eds.), IPCC, Geneva, Switzerland, 151 pp, 2014.

Janssen, F., Färber, P., Huettel, M., Meyer, V. and Witte, U.: Pore-water advection and solute fluxes in permeable marine sediments (I): Calibration and performance of the novel benthic chamber system Sandy, Limn. and Oceanogr., 50, 768-778, 2005.

Jones, C., Creed, E., Glenn, S., Kerfoot, J., Kohut, J., Mudgal, C., and Schofield, O.: Slocum gliders - a component of operational oceanography, Proc. UUST, Autonomous Undersea Systems Institute, 2005.

Kays, R., Crofoot, M. C., Jetz, W., and Wikelski, M.: Terrestrial animal tracking as an eye on life and planet, Science, 348, aaa2478, doi:10.1126/science.aaa2478, 2015.

Kirk, J. T. O.: Point-source integrating-cavity absorption meter: theoretical principles and numerical modeling, Appl. Optics, 36, 24, 6123–6128, doi: ttp://dx.doi.org/10.1364/AO.36.006123, 1997.

Komen, G. J., Cavaleri, L., Donelan, M., Hasselmann, K., Hasselmann, S. and Janssen, P.: Dynamics and Modelling of Ocean Waves, Cambridge University Press, Cambridge, UK, 560, 1994.

Koschinsky, S., Culik, B., Henriksen, O. D., Tregenza, N., Ellis, G., Jansen, C., and Kathe, G.: Behavioral reactions of free-ranging porpoises and seals to the noise of a simulated 2 MW windpower generator, Mar. Ecol. Progr. Series, 265, 263–273, doi:10.3354/meps265263, 2003.

Kwoll, E., Winter, C., and Becker, M.: Intermittent suspension and transport of fine sediment over natural tidal bedforms, In: Venditti, J. G., Best, J., Church, M. and R. J. Hardy (eds.): Coherent Structures in Flows at the Earth's Surface, Wiley-Blackwell, London, doi:10.1002/9781118527221.ch15, 2013.

Kwoll, E., Becker, M., and Winter, C.: With or against the tide: the influence of bedform asymmetry on the formation of macroturbulence and suspended sediment patterns, Water Resources Res., 50, 1-16, doi:10.1002/2013WR014292, 2014.

Krämer K, Winter C (2016) Predicted ripple dimensions in relation to the precision of in situ measurements in the southern North Sea. Ocean Sci 12:1221–1235. doi: 10.5194/os-12-1221-2016

Lass, H. U., Mohrholz, V., Knoll, M., and Prandke, H.: Enhanced Mixing Downstream of a Pile in an Estuarine Flow, J. Mar. Syst., 74, 505–527, ttp://dx.doi.org/10.1016/j.jmarsys.2008.04.003, 2008.

Lee, Z. P., Carder, K. L., Steward, R. G., Peacock, T.G., Davis, C. O., and Patch, J. S.: An Empirical Algorithm for Light Absorption by Ocean Water Based on Colour, J. Geophys. Res. – Oceans, 103, C12, 27967–27978, doi:10.1029/98JC01946, 1998.

Lennartz, S.T., Lehmann, A., Herrford, J., Malien, F., Hansen, H.-P., Bister, H., Bange, H. W.: Long-term trends at the Boknis Eck Time Series Station (Baltic Sea), 1957–2013: does climate change counteract the decline in eutrophication? Biogeosci., 11, 6323-6339, doi:10.5194/bg-11-6323-2014, 2014.

Lerebourg, C.J.Y., Pilgrim, D.A., Ludbrook, G.D. and Neal, R.: Development of a point source integrating cavity absorption meter, J. Opt. A Pure Appl. Opt. 4, 4, S56–S65, http://stacks.iop.org/JOptA/4/S56, 2002.

Lettmann, K. A., Wolff, J. O. and Badewien T. H.: Modeling the impact of wind and waves on suspended particulate matter fluxes in the East Frisian Wadden Sea (southern North Sea), Ocean Dyn., 59, 239-262, doi:10.1007/S10236-009-0194-5, 2009.

Loewe, P. (Ed.): System Nordsee — Zustand 2005 im Kontext langzeitlicher Entwicklungen, Berichte des BSH, 44, Bundesamt für Seeschifffahrt und Hydrographie, Hamburg und Rostock, 270, 2009.

Lorkowski, I., Paetsch, J., Moll A., and Kuehn, W.: Interannual variability of carbon fluxes in the North Sea from 1970 to 2006 — competing effects of abiotic and biotic drivers on the gas exchange of CO_2, Estuarine, Coastal and Shelf Science 100, 38–57, http://dx.doi.org/10.1016/j.ecss.2011.11.037, 2012.

Ludewig, E.: On the Effect of Offshore Wind Farms on the Atmosphere and Ocean Dynamics, Hamburg Studies on Maritime Affairs 31, Springer International Publishing Switzerland, doi:10.1007/978-3-319-08641-5_1, 2015 ISBN: 978-3-319-08640-8 (Print) 978-3-319-08641-5, 2015.

März, J., Hofmeister, R., van der Lee, E.M., Gräwe, U., Riethmüller, R. and Wirtz, K. W.: Evidence for a maximum of sinking velocities of suspended particulate matter in a coastal transition zone, Biogeosciences Discuss., doi:10.5194/bg-2015-667, in review, 2016.

Maresca, S., Braca, P., Horstmann, J. and Grasso, R.: Maritime surveillance using multiple high-frequency surface-wave radars, IEEE Trans. Geosci. Remote Sens., 52, 8, 5056–5071, 2014.

Meier, S., Muijsers, F., Beck, M., Badewien, T. H., and Hillebrand H.: Dominance of the non-indigenous diatom Mediopyxis helysia in Wadden Sea phytoplankton can be linked to broad tolerance to different Si and N supplies, J. Sea. Res., 95, 36-44, doi: 10.1016/J.Seares.2014.10.001, 2015.

Merckelbach, L.: On the probability of underwater glider loss due to collision with a ship, J Mar Sci Techonol, 18, 75–86, doi:10.1007/s00773-012-0189-7, 2013.

Merckelbach, L.: Depth-averaged instantaneous currents in a tidally dominated shelf sea from glider observations. Submitted to this issue.

Metfies, K., Schroeder, F., Hessel, J., Wollschläger, J., Micheller, S., Wolf, C., Kilias, E., Sprong, P., Neuhaus, S. and Petersen, W.: High resolution monitoring of marine protists based on an observation strategy integrating automated on board ship filtration and molecular analyses. Submitted to this issue.

Moltmann, T., Lara-Lopez, A., Donoghue, S., and Hill, K.: IMOS Integrated Marine Observing System, National Science and Implementation Plan 2015-2015, Univ. Tasmania, Report 206, 2010.

Moore, C., Barnand, A., Fietzek, P., Lewis, M., Sosik, H., White, S., and Zielinski, O.: Optical tools for ocean monitoring and research, Ocean Science, 5, 661-684, doi:10.5194/os-5-661-2009, 2009.

North, R.P., Riethmüller, R., and Baschek, B.: Detecting small–scale horizontal gradients in the upper ocean using wavelet analysis. Submitted to Estuarine, Coastal and Shelf Science, in review.

NOSCCA, 2016. North Sea Climate Change Assessment, eds. Quante, M. and Colijn, F., Springer, 528 pp, 10.1007/978-3-319-39745-0.

Oehmcke, S., Zielinski, O., and Kramer, O.: Event detection in marine time series data. Proceedings of KI 2015: Advances in Artifical Intelligence, Lecture Notes Comp. Sci., 9324, 279-286. doi: 10.1007/978-3-319-24489-1_24, 2015.

Onken, R., Callies, U., Vaessen, B., and Riethmüller, R.: Indirect determination of the heat budget of tidal flats, Continental Shelf Research 27, 1656-1676, doi:10.1016/j.csr.2007.01.029, 2007.

Onken, R., and Riethmüller, R.: Determination of the freshwater budget of tidal flats from measurements near a tidal inlet, Cont. Shelf Res., 30, 924-933, doi:10.1016/j.csr.2010.02.004, 2010.

Onken, R., Garbe, H., Schröder, S., and Janik, M.: A new instrument for sediment temperature measurements, J. Mar. Sci. Technol. 15, 427-433, doi: 10.1007/s00773-010-0096-8, 2010.

Oehler, T., Martinez, R., Schückel, U., Winter, C., Kröncke, I., and Schlüter, M.: Seasonal and spatial variations of benthic oxygen and nitrogen fluxes in the Helgoland Mud Area (southern North Sea), Cont. Shelf Res., 106, 118-129, doi:10.1016/j.csr.2015.06.009, 2015.

Oehler, T., Schlüter, M., and Schückel, U.: Seasonal dynamics of the biogenic silica cycle in surface sediments of the Helgoland Mud Area (southern North Sea), Continental Shelf Research, 107, 103–114. doi:10.1016/j.csr.2015.07.016, 2015.

Örek, H., Doerffer, R. Röttgers, R., Boersma, M., and Wiltshire, K. H.: Contribution to a bio-optical model for remote sensing of Lena River water, Biogeosci., 10, 7081–7094, doi:10.5194/bg-10-7081-2013, 2013.

OSPAR: Second OSPAR Integrated Report on the Eutrophication Status of the OSPAR Maritime Area, OSPAR Commission, 2008.

Otto, L., Zimmerman, J. T. F., Furnes, G. K., Mork, M., Saetre, R., and Becker, G.: Review of the physical oceanography of the North Sea, Netherlands J. Sea Res., 26, 161–238, http://www.sciencedirect.com/science/article/pii/007775799090091T, 1990.

Petersen, J., Pröfrock, D., Paschke, A., Broekaert, J. A. C., and Prange, A.: Laboratory calibration and field testing of the Chemcatcher Metal for trace levels of rare earth elements in estuarine waters, Environ. Sci.: Water Res. Technol., 22, 20, 16051-16059, doi:10.1007/s11356-015-4823-x, 2015a.

Petersen, J., Pröfrock, D., Paschke, A., Langhans, V., Broekaert, J. A. C., and Prange, A.: Development and field test of a mobile continuous flow system utilizing Chemcatcher for monitoring of rare earth elements in marine environments, Environ. Sci.: Water Res. Technol. (2015), doi:10.1039/c5ew00126a, 2015b.

Petersen, W., Schroeder, F., and Bockelmann, F.-D.: FerryBox - Application of continuous water quality observations along transects in the North Sea, Ocean Dyn., 61,1541–1554, doi:10.1007/s10236-011-0445-0, 2011.

Petersen, W.: FerryBox Systems: State-of-the-Art in Europe and Future Development, J. Mar. Syst., 140A, 4-12, doi:10.1016/j.jmarsys.2014.07.003, 2014.

Postma, H.: Introduction to the symposium on organic matter in the Wadden Sea, Neth. Inst. Sea Res. Publ. Ser., 10, 15-22, 1984.

Reuter, R., Badewien, T.H., Bartholoma, A., Braun, A., Lubben, A. and Rullkötter, J.: A hydrographic time series station in the Wadden Sea (southern North Sea), Ocean Dyn., 59, 195-211, doi:10.1007/S10236-009-0196-3, 2009.

Riegman, R. and Colijn, F.: Evaluation of measurements and calculation of primary production in the Doggerbank area (North Sea) in summer 1988. Mar. Ecol. Progr. Ser., 69, 125-132, 1991.

Robinson, I.S.: Measuring the oceans from space: the principles and methods of satellite oceanography, Berlin, Germany, Springer/Praxis Publishing, 669, 2004.

Röttgers, R., Schönfeld, W., Kipp, P.R., and Doerffer, R.: Practical test of a point-source integrating cavity absorption meter: the performance of different collector assemblies, Appl. Opt., 44, 26, 5549–5560, doi: http://dx.doi.org/10.1364/AO.44.005549, 2005.

Rullkötter, J.: The back-barrier tidal flats in the southern North Sea – a multidisciplinary approach to reveal the main driving forces shaping the system. Ocean Dyn., 59, 157–165, 2009.

Schaap, D., and Lowry, R. K.: SeaDataNet—Pan-European Infrastructure for Marine and Ocean Data Management: Unified Access to Distributed Data Sets, International Journal of Digital Earth, 3, S1, 50-69, http://dx.doi.org/10.1080/17538941003660974, 2010.

Schulz, M., von Beusekom, J., Bigalke, K., Brockmann, U. H., Dannecker, W., Gerwig, H. , Grassl, H., Lenz, C.-J., Michaelsen, K., Niemeier, U., Nitz, T., Plate, E., Pohlmann, T., Raabe, T., Rebers, A., Reinhardt, V., Schatzmann, M., Schlünzen, K.H., Schmidt-Nia, R., Stahlschmidt, T., Steinhoff, G., and von Salzen, K.: The atmospheric impact on fluxes of nitrogen, POPs and energy in the German Bight, German J. Hydrogr., 51, 2/3, 133-154, doi: 10.1007/BF02764172, 1999.

Schulz, A. C., Badewien, T. H., and Zielinski, O.: Impact of currents and turbulence on turbidity dynamics at the time series station Spiekeroog (Wadden Sea, Southern North Sea). Current, waves and turbulence measurement (CWTM), 11th IEEE/OES, 2015, ISBN: 978-1-4799-8418-3; DOI 10.1109/CWTM.2015.7098095, 2015.

Schulz, J.: The geometric optics of subsea imaging. Invited chapter for the book 'Subsea optics and imaging', Woodhead Publishing, Editors: Watson and Zielinski. ISBN: 9780857093417; Kapitelreferenz: doi://10.1533/9780857093523.3.243, 2013.

Schulz, J., Barz, K., Ayon, P., Lüdtke, A., Zielinski, O., Mengedoht, D., and Hirche, H.-J.: Imaging of plankton specimens with the Lightframe On-sight Keyspecies Investigation (LOKI) system. Journal of the European Optical Society – Rapid publications 10017s. doi://10.2971/jeos.2010.10017s. 2010.

Schrum, C., Alekseeva, I., and St. John, M.: Development of a coupled physical–biological ecosystem model ECOSMO: part I: model description and validation for the North Sea. Journal of Marine Systems, 61.1, 79-99, 2006.

SCOR Working Group 75: Methodology for oceanic CO2 measurements, UNESCO technical papers in marine science, 65, 44, 1988.

SeaDataNet: Standards for Data Quality Control, http://www.seadatanet.org/standards_software/data_quality_control, 2010.

Stanev, E.V., Schulz-Stellenfleth, J., Staneva, J., Grayek, S., Seemann, J. and Petersen, W.: Coastal observing and forecasting system for the German Bight – estimates of hydrophysical states, Ocean Sci., 7, 569-583, doi:10.5194/os-7-569-2011, 2011.

Stanev, E.V., Ziemer, F., Schulz-Stellenfleth, J., Seemann, J., Staneva, J., and Gurgel, K. W.: Blending Surface Currents from HF Radar Observations and Numerical Modelling: Tidal Hindcasts and Forecasts, J. Atmos. Ocean Techn., 32, 256-281, doi:10.1175/JTECH-D-13-00164.1, 2015.

Stanev, E. V., Schulz-Stellenfleth, J., Staneva, J., Grayek, S., Grashorn, S., Behrens, A., Koch, W., and Pein, J.: Ocean forecasting for the German Bight: from regional to coastal scales, Ocean Sci., 12, 1105-1136, doi:10.5194/os-12-1105-2016, 2016.

Staneva, J., Stanev, E.V., Wolff, J. O., Badewien, T. H., Reuter, R., Flemming, B., Bartholoma, A., and Bolding, K.: Hydroynamics and sediment dynamics in the German Bight. A focus on observations and numerical modelling in the East Frisian Wadden Sea, Cont. Shelf Res., 29, 302-319, doi:10.1016/J.Csr.2008.01.006, 2009.

Stempniewicz, L., Błachowiak-Samołyk, K., and Węsławski, J.M.: Impact of climate change on zooplankton communities, seabird populations and arctic terrestrial ecosystem—A scenario, Deep-Sea Res. II 54,2934–2945, doi:10.1016/j.dsr2.2007.08.012, 2007.

Stroeve, J., Holland, M. M., Meier, W., Scambos, T., and Serreze, M.: Arctic sea ice decline: Faster than forecast, Geophys. Res. Lett., 34, L09501, doi:10.1029/2007GL029703, 2007.

Su, J., Tian, T., Krasemann, H., Schartau, M. and Wirtz, K.: Response patterns of phytoplankton growth to variations in resuspension in the German Bight revealed by daily MERIS data in 2003 and 2004, Oceanologia, 57, 4, 2015, 328-341, ISSN 0078-3234, doi:10.1016/j.oceano.2015.06.001, 2015.

Sündermann, J., Hesse, K.-J., and Beddig, S.: Coastal mass end energy fluxes in the southeastern North Sea, German J. Hydrogr., 51, 2/3, 113-132, doi: 10.1007/BF02764171, 1999.

Svendsen, H., Beszczynska-Møller, A., Hagen, J.O., Lefauconnier, B., Tverberg, V., Gerland, S., Ørbæk, J. B., Bischof, K., Papucci, C., Zajaczkowski, M., Azzolini, R., Bruland, O., and Wiencke, C.: The physical environment of Kongsfjorden/Krossfjorden, an Arctic fjord system in Svalbard, Polar Res., 21,133–166, doi: 10.1111/j.1751-8369.2002.tb00072.x, 2002.

Testor, P., Meyers, G., Pattiaratchi, C., Bachmayer, R., Hayes, D., Pouliquen, S., de la Villeon, L. P., Carval, T., Ganachaud, A., Gourdeau, L., Mortier, L., Claustre, H., Taillandier, V., Lherminier, P., Terre, T., Visbeck, M., Krahman, G., Karstensen, J., Alvarez, A., Rixen, M., Poulain, P., Osterhus, S., Tintore, J., Ruiz, S., Garau, B., Smeed, D., Griffiths, G., Merckelbach, L., Sherwin, T., Schmid, C., Barth, J., Schofield, O., Glenn, S., Kohut, J., Perry, M., Eriksen, C., Send, U., Davis, R., Rudnick, D., Sherman, J., Jones, C., Webb, D., Lee, C., Owens, B., and Fratantoni, D.: Gliders as a component of future observing systems, OceanObs'09: Sustained Ocean Observations and Information for Society, edited by Hall, J., Harrison, D. and Stammer, D., vol. 2 of OceansObs'09, Venice, Italy, eSA Publication WPP-306, doi: 10.5270/OceanObs09.cwp.89, 2010.

UNESCO (1980): Determination of chlorophyll in seawater: Report of intercalibration tests. UNESCO technical papers in marine science 35, 21, 1980.

U.S. IOOS Office: U.S. Integrated Ocean Observing System: A Blueprint for Full Capability. V. 1.0., 254, November 2010.

van Beusekom, J. E. E., Brockmann, U. H., Hesse, K.-J., Nickel, W., Pormeba, K., and Tillmann, U.: The importance of sediments in the transformation and turnover of nutrients and organic matter in the Wadden Sea and German Bight, German J. Hydrogr., 51, 2/3, 245-266, doi: 10.1007/BF02764176, 1999.

van Beusekom, J. E. E., and de Jonge, V. N.: Long-term changes in Wadden Sea nutrient cycles: importance of organic matter import from the North Sea, Hydrobiol., 475/476, 185-194, doi:10.1023/A:1020361124656, 2002.

van Beusekom, J. E. E., Buschbaum, C., and Reise, K.: Wadden Sea tidal basins and the mediating role of the North Sea in ecological processes: scaling up of management?, Ocean Coastal Manag., 68, 69–78, doi:10.1016/j.ocecoaman.2012.05.002, 2012.

van De Poll, W. H., Maat, D. S., Fischer, P., Rozema, P. D., Daly, O. B., Koppelle, S., Visser, R. J. W. and Buma, A. G. J.: Atlantic Advection Driven Changes in Glacial Meltwater: Effects on Phytoplankton Chlorophyll-a and Taxonomic Composition in Kongsfjorden, Spitsbergen, Frontiers in Marine Science, 3, 60, doi:10.3389/fmars.2016.00200, 2016.

van Leeuwen, S. M., van der Molen, J., Ruardij, P., Fernand, L., and Jickells, T.: Modelling the contribution of deep chlorophyll maxima to annual primary production in the North Sea. Biogeochemistry, 113, 1-3, 137-152, 2013.

Vivone, G., Braca, P., and Horstmann, J.: Knowledge-Based Multi-Target Ship Tracking for HF Surface Wave Radar Systems, IEEE Trans. Geosci. Remote Sensing, 53, 7, 3931-3949, doi: 10.1109/TGRS.2014.2388355, 2015.

Voynova, Y. G., Petersen, W., and Brix, H.: Coastal and estuarine vulnerability to extreme floods: how did the June, 2013 Elbe flood affect the German Bight?, Biogeosci, submitted to this issue.

Wahl, T., Haigh, I. D., Woodworth, P. L., Albrecht, F., Dillingh, D., Jensen, J., Nicholls, R. J., Weisse, R., and Wöppelmann, G.: Observed mean sea level changes around the North Sea coastline from 1800 to present, Earth-Sci. Rev., 124, 51–67, doi:10.1016/j.earscirev.2013.05.003, 2013.

Wehkamp, S., and Fischer, P.: Impact of hard-bottom substrata on the small-scale distribution of fish and decapods in shallow subtidal temperate waters, Helgoland Mar. Res., doi:10.1007/s10152-012-0304-5, hdl:10013/epic.39252, 2012.

Wehkamp, S., and Fischer, P.: The impact of coastal defence structures (tetrapods) on decapod crustaceans in the southern North Sea, Mar. Environ. Res., 92, 52-60, doi:10.1016/j.marenvres.2013.08.011, hdl:10013/epic.47436, 2013a.

Wehkamp, S,. and Fischer, P.: Impact of coastal defence structures (tetrapods) on a demersal hard-bottom fish community in the southern North Sea, Mar. Environ. Res., doi:10.1016/j.marenvres.2012.10.013, hdl:10013/epic.40445, 2013b.

Wehkamp, S., and Fischer, P.: A practical guide to the use of consumer-level digital still cameras for precise stereogrammetric *in situ* assessments in aquatic environments, Underw. Tech., 32, 2, 111-128, doi:10.3723/ut.32.111, hdl:10013/epic.43817, 2014.

Willis, K., Cottier, F., Kwasniewski, S., Wold, A., and Falk-Petersen, S.: The influence of advection on zooplankton community composition in an Arctic fjord (Kongsfjorden, Svalbard), J. Marine Syst., 61, 39–54, doi:10.1016/j.jmarsys.2005.11.013, 2006.

Wilson, R. P., and Vandenabeele, S. P.: Technological innovation in archival tags used in seabird research, Mar. Ecol. Prog. Ser., 451, 245–262, doi:10.3354/meps09608, 2012.

Witte, U., and Pfannkuche, O.: High rates of benthic carbon remineralization in the abyssal Arabian Sea, Deep Sea Res. II: Top.Stud.Oceanogr, 47, 2785–2804, doi:10.1016/S0967-0645(00)00049-7, 2000.

Wirtz, K., and Kerimoglu, O.: Optimality and variable co-limitation controls autotrophic stoichiometry, Front. Mar. Sci., submitted.

Wollschläger, J., Grunwald, M., Röttgers, R., and Petersen, W.: Flow-through PSICAM: a new approach for determining water constituents absorption continuously, Ocean Dyn., 63, 7, 761-775, doi: 10.1007/s10236-013-0629-x, 2013.

Wollschläger, J., Röttgers, R., Petersen, W., and Wiltshire, K. H.: Performance of absorption coefficient measurements for the *in situ* determination of chlorophyll-a and total suspended matter, J. Exp. Mar. Biol. Ecol., 453, 0, 138-147, doi:10.1016/j.jembe.2014.01.011, 2014.

Zielinski, O., Busch, J. A., Cembella, A. D., Daly, K. L., Engelbrektsson, J., Hannides, A. K., and Schmidt, H.: Detecting marine hazardous substances and organisms: sensors for pollutants, toxins, and pathogens, Ocean Sci., 5, 329–349, doi:10.5194/os-5-329-2009, 2009.

Zielinski, O., Voss, D., Saworski, B., Fiedler, B., and Koertzinger, A.: Computation of nitrate concentrations in turbid coastal waters using an *in situ* ultraviolet spectrophotometer. J. Sea Res., 65, 456-460, 2011.

Table 1. COSYNA Partner

Helmholtz-Zentrum Geesthacht (Co-ordination)	HZG
Alfred Wegener Institute, Helmholtz Centre for Polar and Marine Research	AWI
Center for Marine Environmental Sciences at Bremen University	MARUM
Institute for Chemistry and Biology of the Marine Environment at the University of Oldenburg	ICBM
Research and Technology Centre at the University of Kiel	FTZ
German Federal Maritime and Hydrographic Agency	BSH
Center for Earth System Research and Sustainability	CEN
Hamburg Port Authority	HPA
Lower Saxony State Department for Waterway, Coastal and Nature Conservation	NLWKN
Schleswig-Holstein's Agency for Coastal Defence, National Parks, and Marine Conservation	LKN
German Federal Waterways Engineering and Research Institute	BAW

Table 2. Standard COSYNA observables.

Platform	Parameter
Meteorology	pressure, temperature, global radiation, wind vector
Physical oceanography	pressure, temperature, salinity, current, wave height, and direction
Biogeochemistry	optical turbidity, total suspended matter concentration, chlorophyll-a concentration, dissolved oxygen

Table 3. Fixed platforms used in COSYNA. Abbreviations: M: meteorology, P: physical oceanography, B: biogeochemistry. For abbreviations of the partner institutions see Table 1.

Platform	Years	Position	Mean tidal range [m]	Parameters	Partners

Pole Hörnum Basin	2002-2013 (Mar-Nov)	54°47.6'N 008°27.1'E	2.3	M, P, B	HZG
Pole Elbe Estuary	2012-2013 (Mar-Nov)	53°51.5'N 008°56.6'E	2.8	M, P, B	HPA, HZG
Pole Spiekeroog	2002-now (year round)	53°45.0'N 007° 40.3'E	2.8	M, P, B	ICBM
FerryBox FINO-3	2011-2016 (year round)	55°11,7'N 007° 9,5'E	0.9	P, B	HZG
FerryBox Cuxhaven	2010-now (year round)	53°52,6'N 008° 42,3'E	2.9	P, B	HZG
Lander		n.a.	n.a.	P, B	MARUM, AWI, HZG
Underwater Node Helgoland	2012 – now (year-round)	59° 11'N 008°52,8'E		P, B	AWI, HZG
Underwater Node Spitsbergen	2012 – now (year-round)	78° 92'N, 011° 9'E		P, B	AWI, HZG
Marine Radar Fino	2011-now (year-round)	55°11,7'N 007° 9,5'E		M, P	HZG
Marine-Radar Sylt	2012-now (year-round)	54 ° 49,2' N 8 ° 16,8' E		M,P	HZG
HF-Radar Sylt	2009-now (year-round)	54 ° 49,2' N 8 ° 16,8' E		P	HZG
HF-Radar Büsum	2009-now (year-round)	54 ° 7,2' N 8 ° 51,6' E		P	HZG
HF-Radar Wangerooge	2009-now (year-round)	53 ° 47.4' N 7 55,2' E		P	HZG

Table 4. Moving Platforms used in COSYNA. Time resolution is given between repeated measurements at the same location. Abbreviations: M: meteorology, P: physical oceanography, B: biogeochemistry; S: water surface, U: upper water column, FC: Full water column. The abbreviations of the partner institutions are explained in Table 1.

Platform	Vertical range	Time resolution	Parameters	Partner
FerryBox	U	½ day to a week	P, B	HZG
Glider	FC	days to months	P, B	HZG
Seabird	U	-	P	FTZ
Satellites	S	2 times in 3 days	B	HZG
Ship surveys	FC	months	M, P, B	HZG

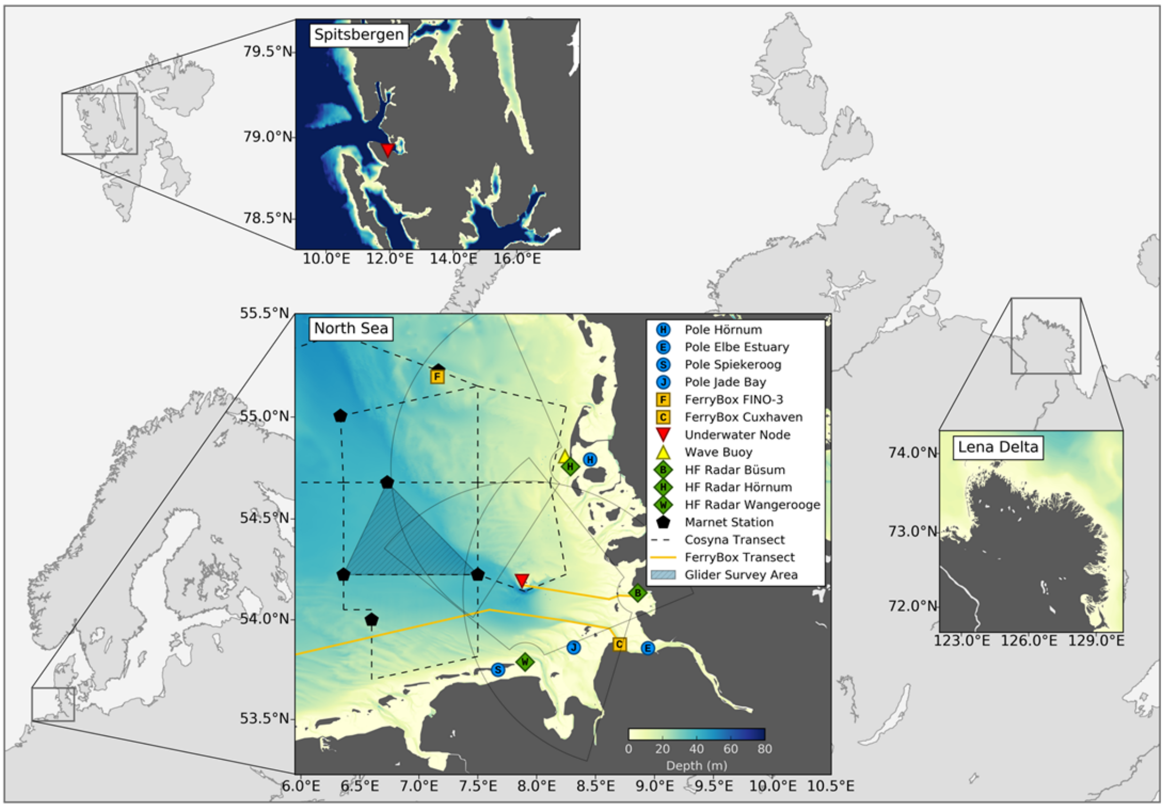

Fig. 1. Map showing the pre-operational components of the coastal observing system COSYNA.

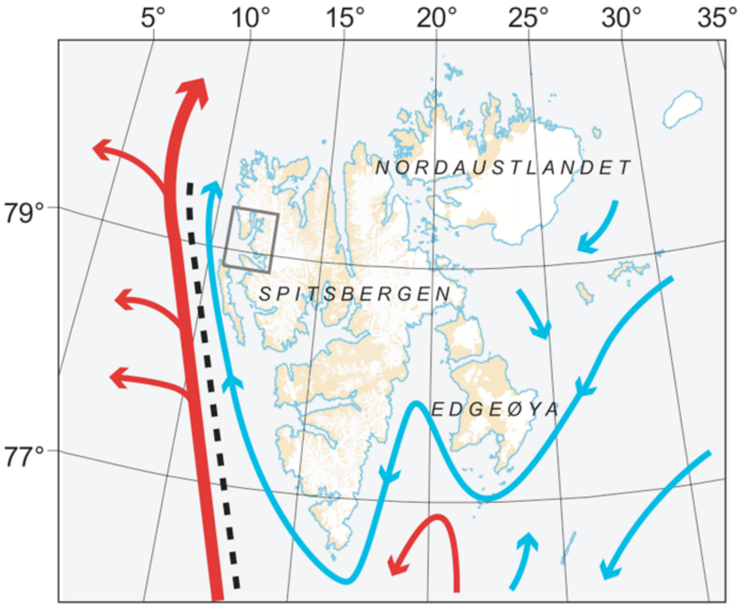

Fig. 2. Spitsbergen with Kongsfjord (small rectangle) at the west coast of Svalbard. Arrows indicate the warmer Atlantic water masses (red) from the West Spitsbergen current and by colder less saline Arctic water (blue) from the East Spitsbergen (Cottier et al., 2005).

Fig. 3. Research village NyÅlesund. The Spitsbergen Underwater-Node is located about 30 m in front of the "Old Pier" (A). The control station is located at the base of the old pier on land (B).

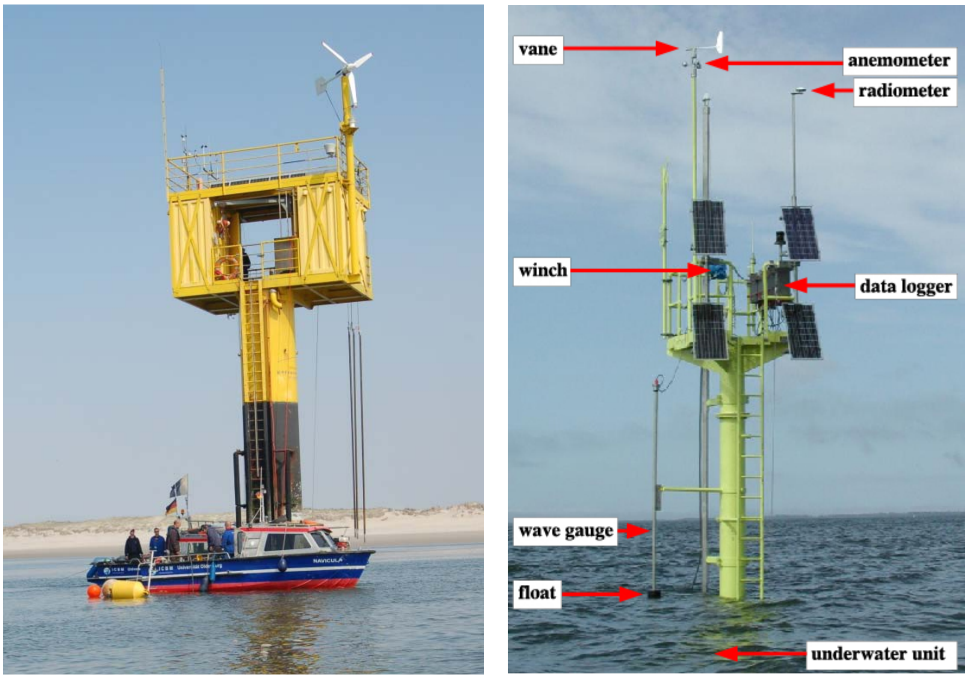

Fig. 4. The measuring poles at Spiekeroog (left) and in the inner Hörnum tidal basin (right). For details see Section 5.1.

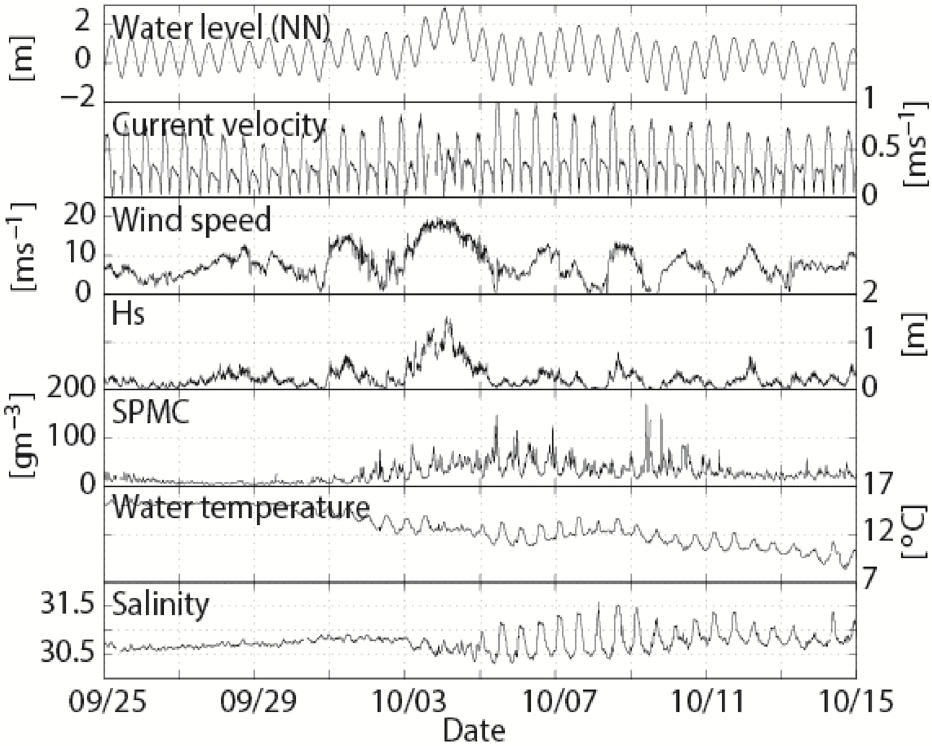

Fig. 5. Time-series of the measuring pole in the Hörnum Basin showing three weeks of data with a sampling frequency of 10 min.

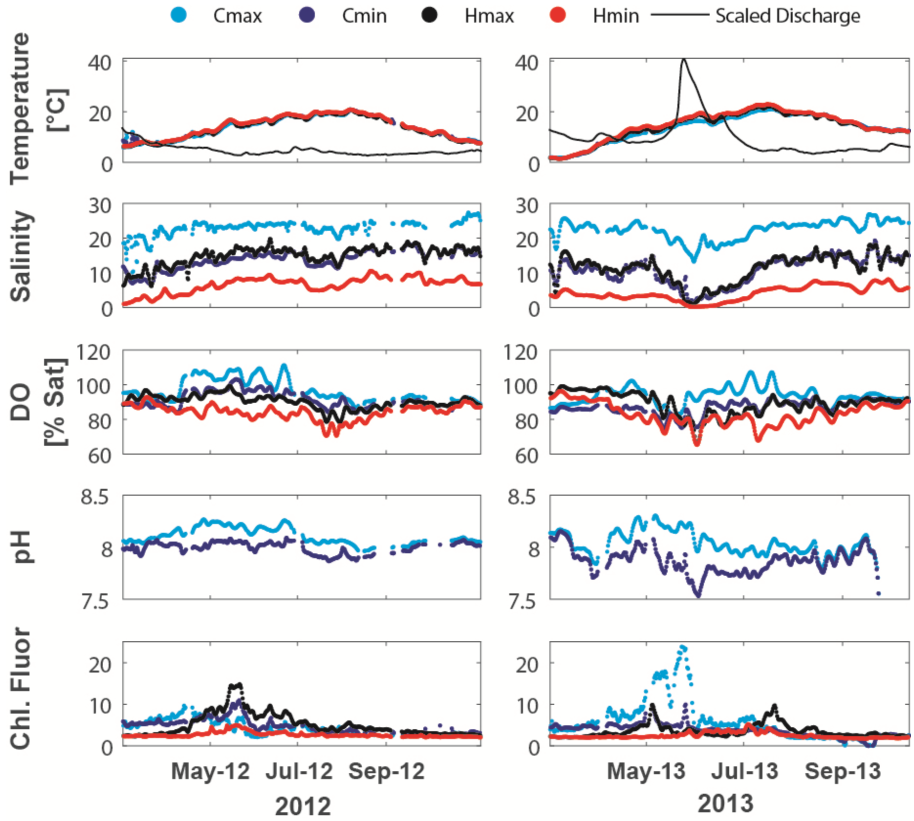

Fig. 6. Time series of the stationary FerryBox located at Cuxhaven at the Elbe river mouth for 2012 (left panels) and 2013 (right panels). Top to bottom: water temperature and Elbe river discharge (m^3 s^{-1}) at Neu Darchau station scaled by dividing it by 100 (thin black line), salinity, dissolved oxygen saturation (DO), pH, chlorophyll-a fluorescence. Shown are the Cuxhaven values at low tide (brown, Cmin), high tide (blue, Cmax) and from the Elbe estuary measurement pole at low tide (red, Hmin) and high tide (black, Hmax).

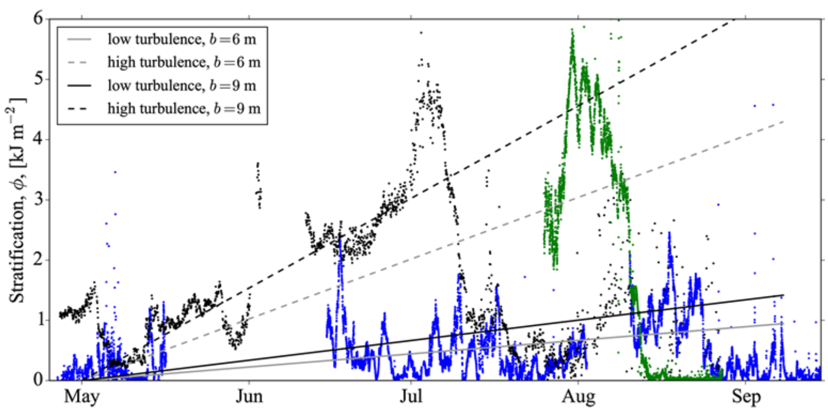

Fig. 7. Measurements showing the observed build up of stratification ϕ over the summer months unaffected by offshore construction (dots; Carpenter et al., 2016) and the estimated rate of stratification removal by the turbine foundation structures in offshore wind farms

(straight lines). The stratification is computed as $\phi(t) = \int_0^H [\rho_{mix} - \rho(z,t)] gzdz$, with water depth H, density ρ, gravitational acceleration g, and vertical coordinate z and time t. Measurements are from a thermistor mooring at Marnet Station NSB3 in 2009 (black dots), glider data collected in the vicinity (54˚40.8'N; 6˚43.9' E) in 2014 (green dots), and from larger scale transects passing through NSB3 in 2012 (blue points). The rate of stratification removal for thermocline thicknesses b = 6, 9 m is based on a simple one-dimensional analytical model (Carpenter et al., 2016).

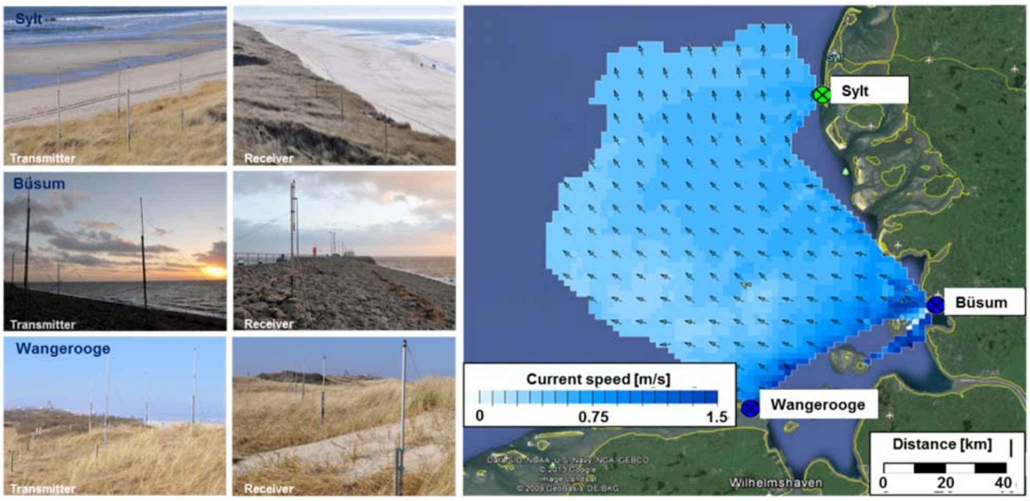

Fig. 8. HF radar system in the German Bight with its three stations in Büsum and on the isles of Sylt and Wangerooge. The right panel shows an example of the 2D-current field derived from overlapping radar signals.

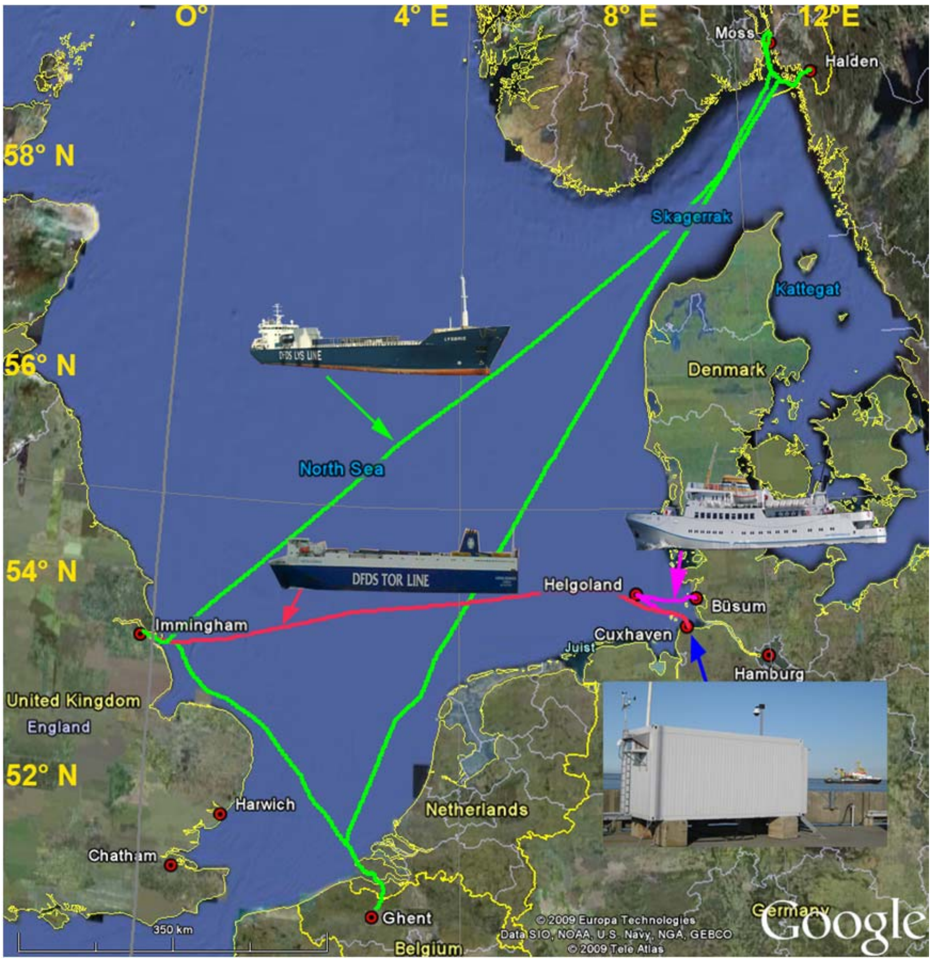

Fig. 9. Map of FerryBox routes and stationary platforms equipped with FerryBoxes.

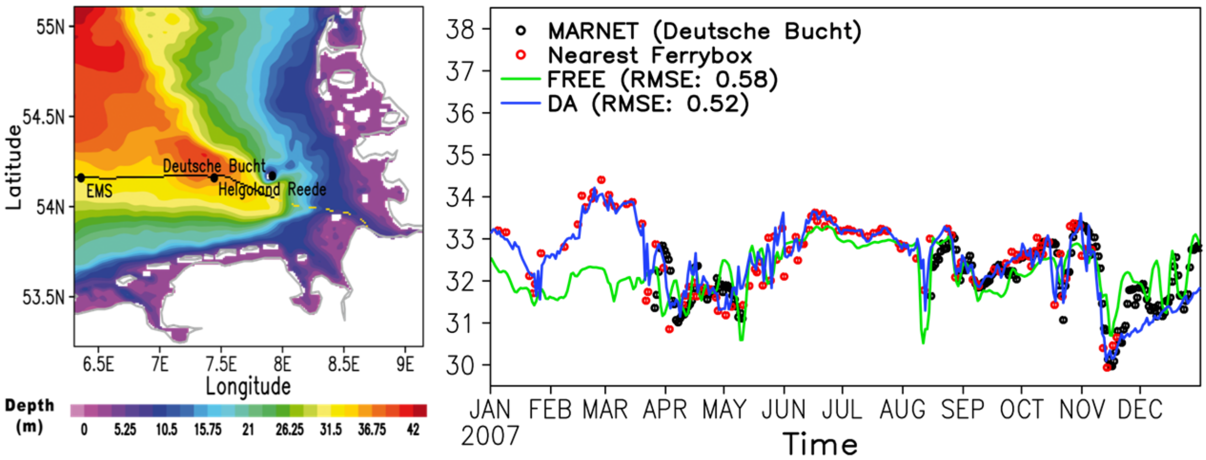

Fig. 70. Left panel: Topography of German Bight and FerryBox track. Right panel: Comparison of simulated sea surface temperature from a free model run and a run with data assimilation (DA) against MARNET and nearest FerryBox observations (Grayek et al., 2011).

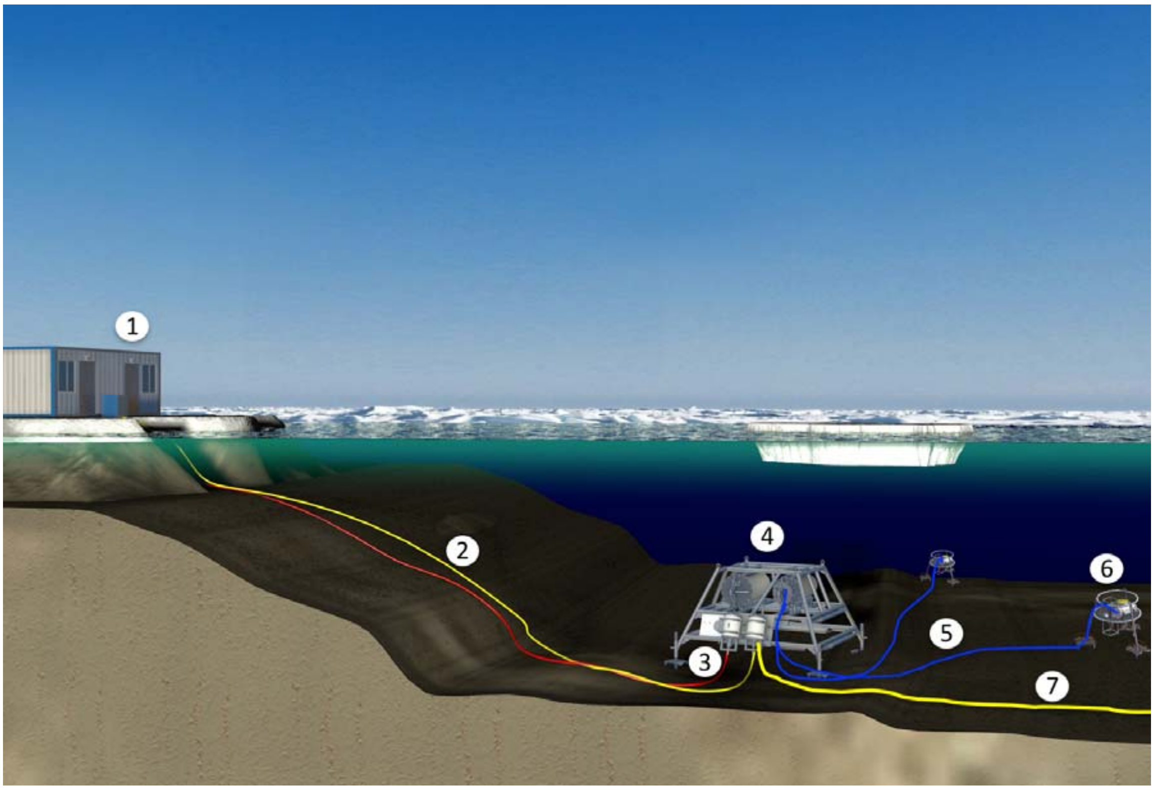

Fig. 81. Setup of the COSYNA Underwater-Node System with (1) land-based server and power supply, (2) cable connection (max. 10 km) to the first primary underwater node, (3) Breakout Box to connect the primary node to the underwater cable, (4) primary node system, (6) cable connection (max. 70 m) to sensor units, and (7) cable connection to a second node. A third node can be connected to the second node.

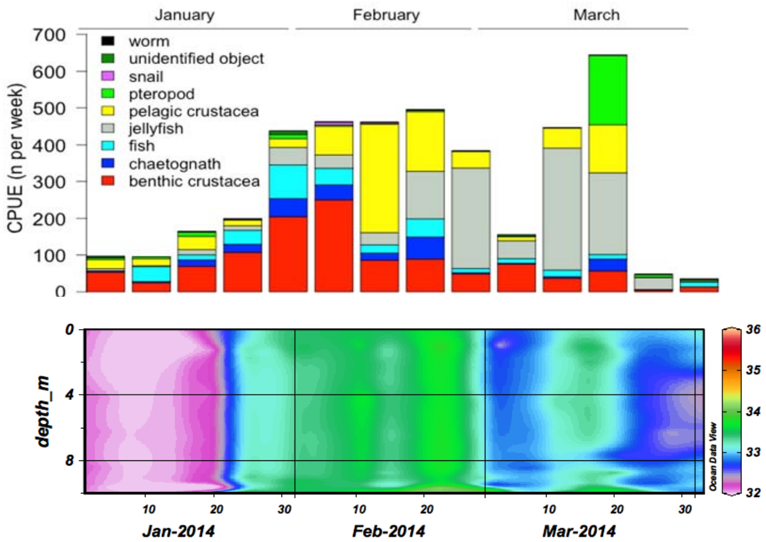

Fig. 92. Upper panel: The temporal abundances of the main biota groups assessed with a stereo-optic sensor attached to the Underwater-Node System in Spitsbergen from January 2014 to March 2014. CPUE (catch per unit effort) refer to total number of organisms per group counted per week. Lower panel: The temporal and spatial pattern of salinity in the

depth range between 0 to 10 m assessed with one remote controlled vertical CTD profile per day during the same time period when the biota measurements (upper panel) were done.

Fig. 103. Deployment of landers SedObs (left) NuSObs (right).

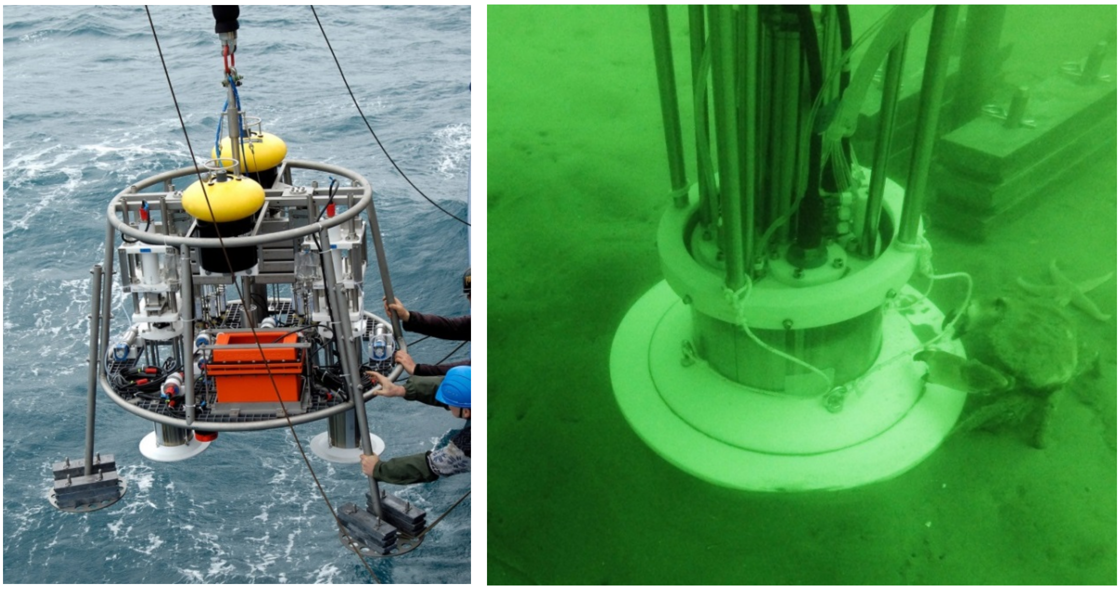

Fig. 114. Left panel: lander FLUXSO deployed for autonomous sampling in June 2015; right panel: sampling chambers in mobile fine sand at 25 m depth.

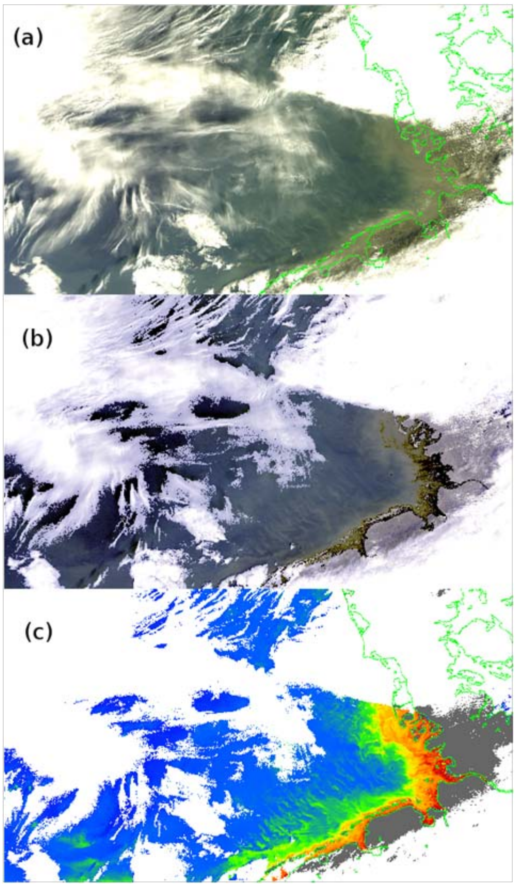

Fig. 125. Satellite scene of the German Bight taken on 2012-03-10 by MERIS. a) Radiance in atmosphere; b) reflectance at the bottom of the atmosphere (after atmospheric correction); c) chlorophyll-a concentration showing filaments of *phaeocystis* blooms along the west- and east-Frisian coast.

Fig. 136. Solar-powered GPS data logger attached to a tail of a Northern Gannet (Photo: J. Dierschke).

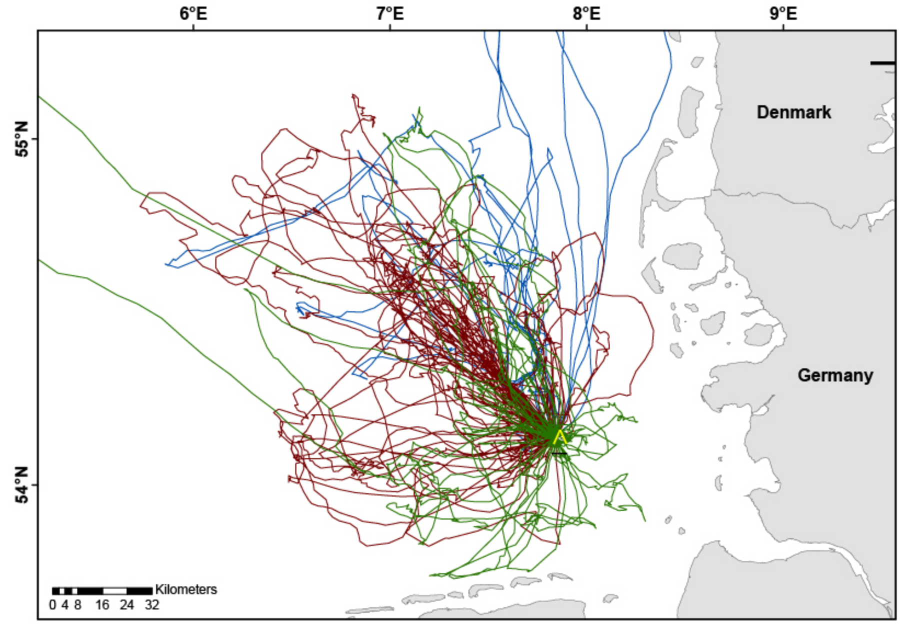

Fig. 147. Foraging flights of three Northern Gannets (*Morus bassanus*) in 2015 starting from Helgoland.

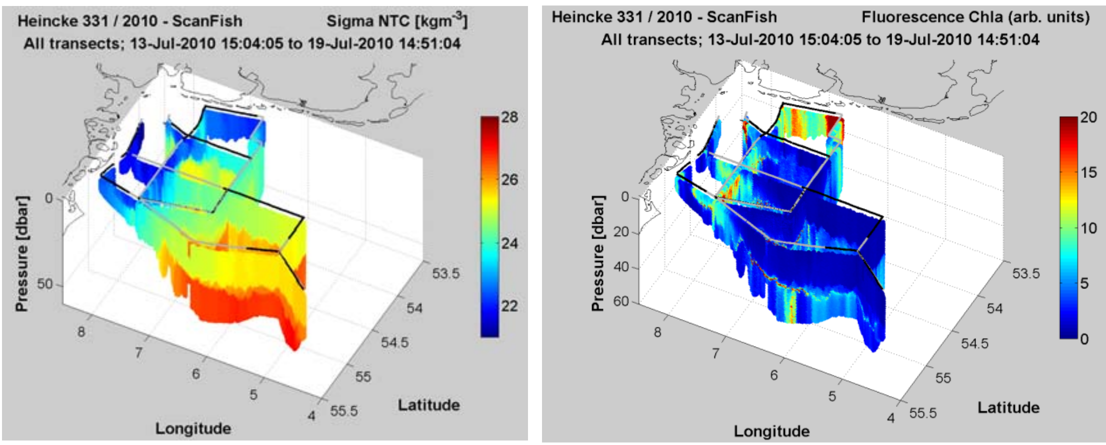

Fig. 18. Spatial distribution of σ_T and chlorphyll-*a* observed during RV Heincke Cruise HE331 in July 2010.

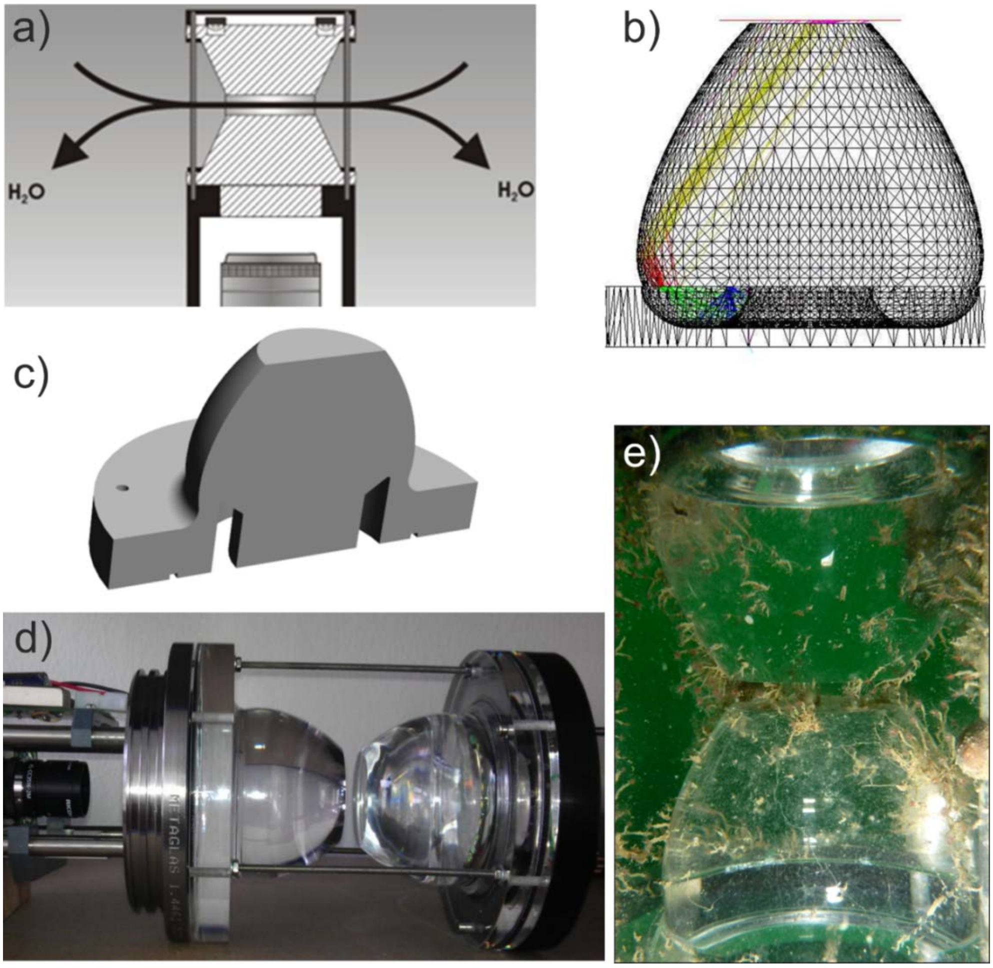

Fig. 19. Design of the LOKI imaging head for moored operation. a) Schematic overview. b) Ray-tracing design-model to investigate the best shape to increase efficiency. c) Cross-section of a 3D-model. The LEDs of the flash unit are positioned in the notch. d) Imaging head with two optical cones: the right cone carries the circular flash unit, the left one the visual path of the camera's field of view. The camera is mounted on the left. e) The system requires periodical cleaning in the field. The image shows bio-fouling after 5 weeks of operation in the North Sea.

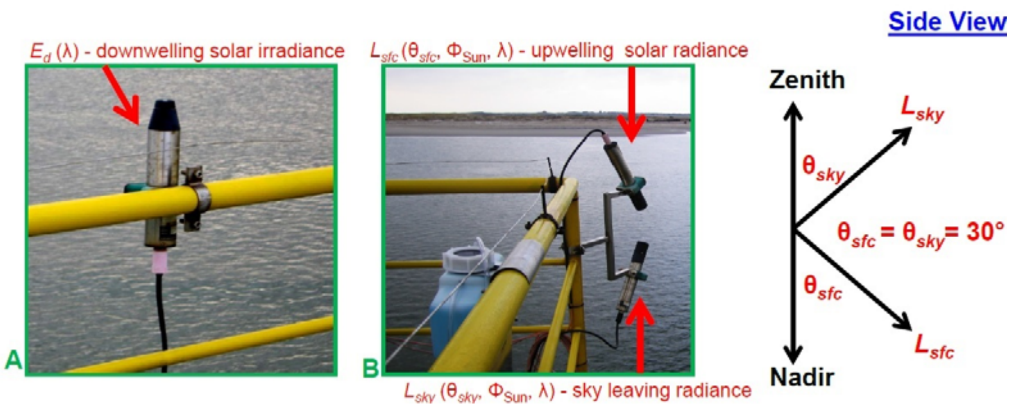

Fig. 150. Setup of RAMSES radiometers at the Wadden Sea measurement pole Spiekeroog.

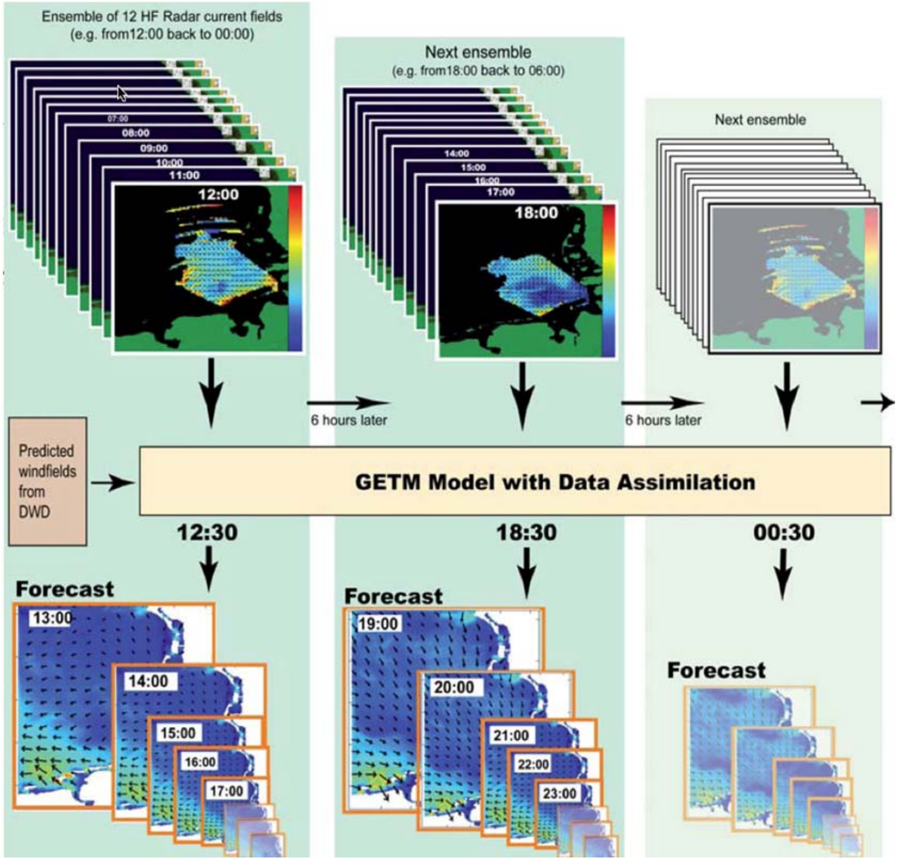

Fig. 161. The functioning of data assimilation and forecasting in the pre-operational COSYNA system. HF radar system covering the German Bight. Radial current components are sent to the HZG data server, where current vectors are calculated and presented on the COSYNA data portal (Stanev et al., 2015).

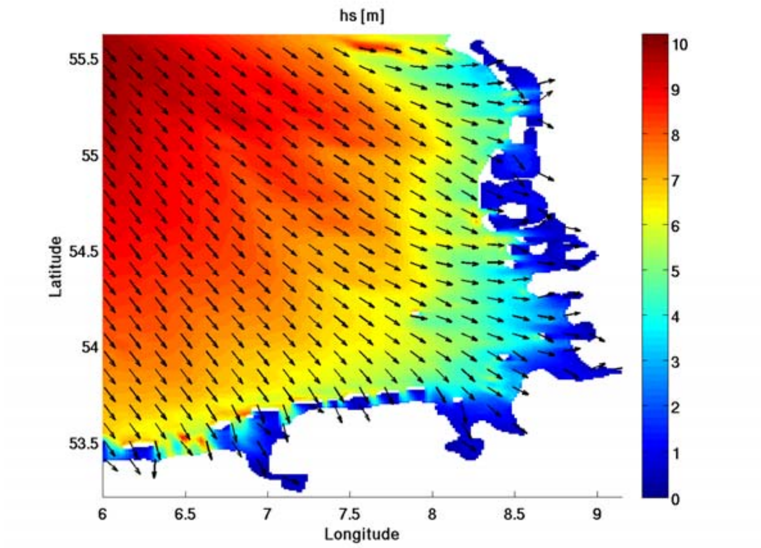

Fig. 172. Significant wave height calculated for the German Bay on 1 November 2006 with the WAM wave model used in COSYNA.

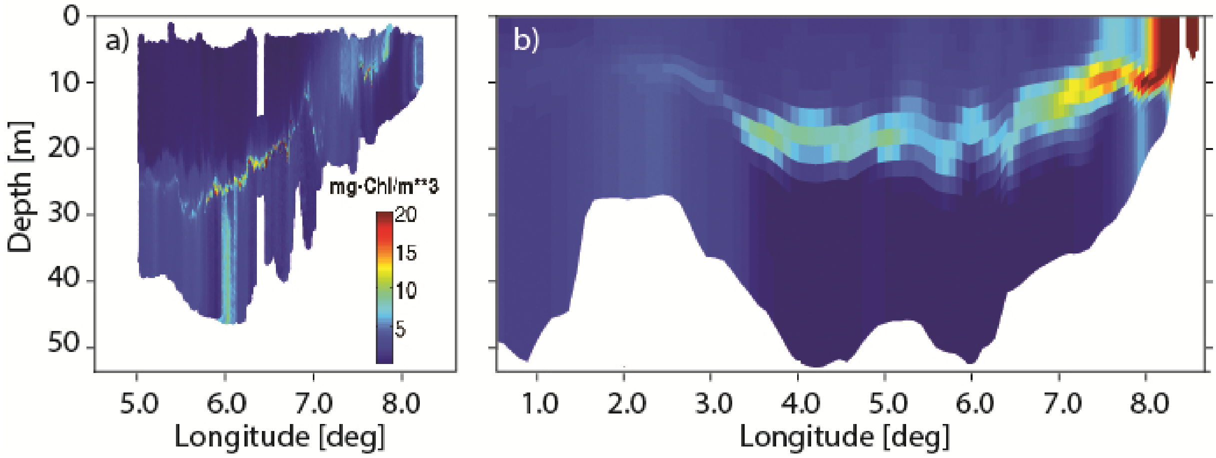

Fig. 183. Chlorophyll transects around 55°15' latitude in the German Bight a) observed with a Scanfish in July 2010 (Section 5.9) and b) as result of a coupled GETM and an adaptive ecosystem model showing a 1-week mean (Wirtz and Kerimoglu, submitted).

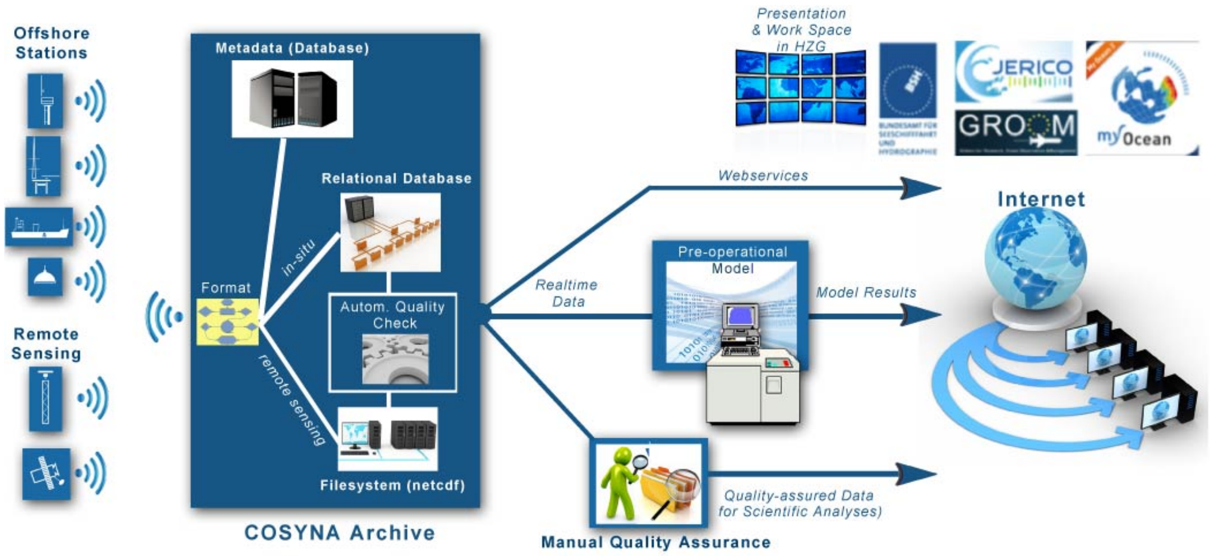

Fig. 194: Data Flow in COSYNA.

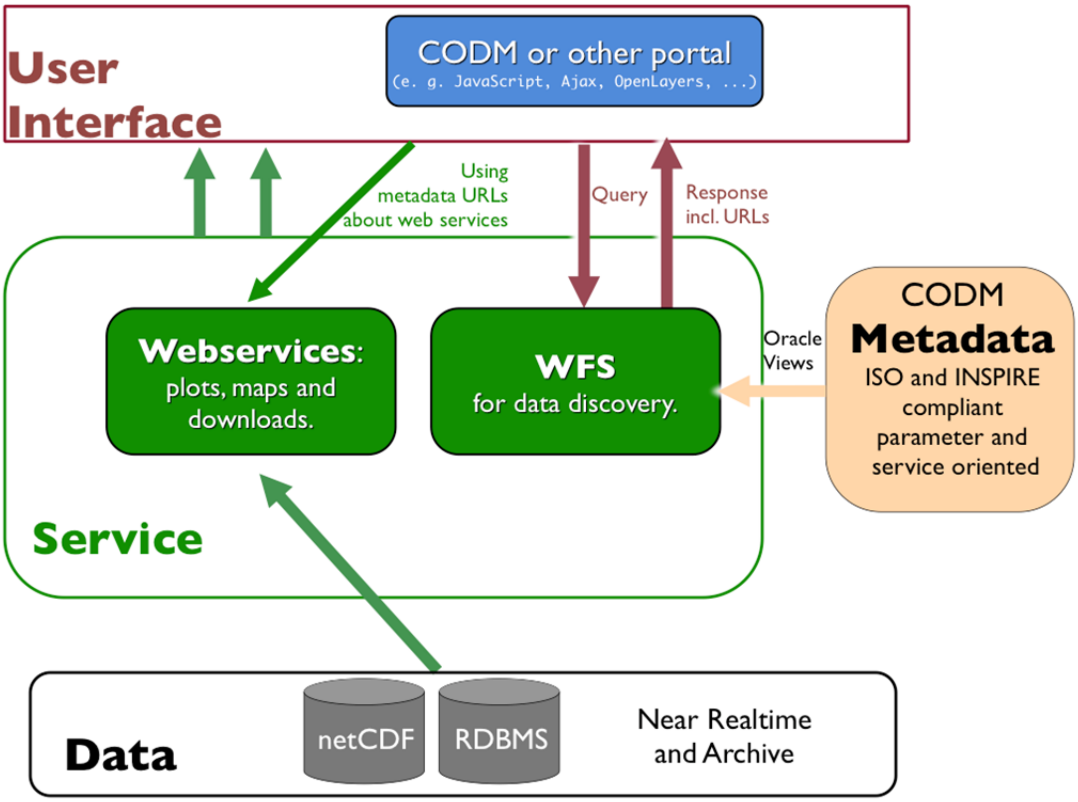

Fig. 25. Data Management architecture: The connection between user interface on one side and data or metadata on the other side is handled solely by web services like Web Feature Services (WFS) or Web Map Services (WMS).

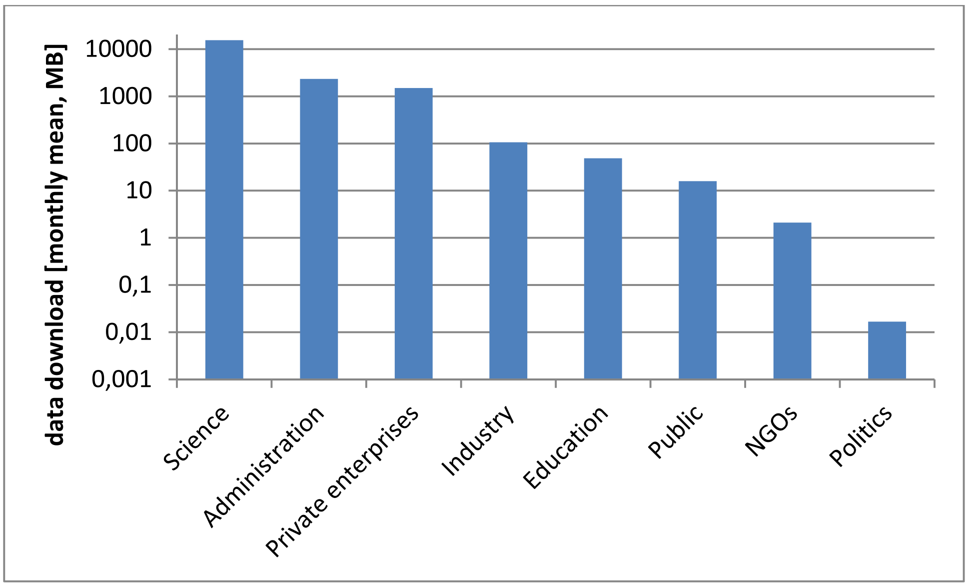

Fig. 206. Mean monthly data use for different categories of users. Data are shown for the time period between November 2014, when the user registration started, and January 2016.