FerryBox - Application of continuous water quality observations along transects in the North Sea

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Abstract In 2002, the Helmholtz-Zentrum Geesthacht, Germany, started to use FerryBox-automated monitoring systems on Ships of Opportunity to continuously record standard oceanographic, biological and chemical in situ data in the North Sea. The present study summarises the operational experience gathered since the beginning of this deployment and reflects on the potential and limits of FerryBox systems as a monitoring tool. One part relates to the instrumental performance, constancy of shipping services, and the availability and quality of the recorded in situ data. The other considers integration of the FerryBox observations in scientific applications and routine monitoring campaigns. Examples are presented that highlight the added value of the recorded data for the study of both long- and short-term variability in water mass stability, plankton communities and surface water productivity in the North Sea. Through the assessment of technical and scientific performance, it is evident that FerryBoxes have become a valuable tool in marine research that helps to fill gaps in coastal and open ocean operational observation networks.

Keywords FerryBox · In situ data · Water quality ·
Automated monitoring · Ships of Opportunity · North Sea ·
Hydrodynamic model

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1 Introduction

Traditional monitoring of marine environments using survey vessels is costly and often lacks the spatial coverage and temporal resolution that is required to study variability in physical, chemical and biological conditions on seasonal or interannual time scales. Yet, these gaps in the data are a serious problem for accurate assessments of climate- and human-induced changes in marine environments. Marine biogeochemical cycles, for instance, are currently undergoing fundamental changes due to the increase in water temperature and rising carbon dioxide levels in the atmosphere and oceans (IPCC 2007). In Europe, the lack of monitoring systems that enable continuous observation of coastal seas is a major hindrance when it comes to understand the implications for ecosystem dynamics and functioning (Hydes et al. 2010). To deal with these issues, the use of "Ships of Opportunity" (SoO) in marine observation networks has been promoted by Euro Global Ocean Observing System (GOOS; Flemming et al. 2002).

Unattended autonomous observing systems aboard SoO are cost-effective and reliable alternatives to obtain continuous observations on near-surface parameters with high spatial coverage and temporal resolution. Such underway platforms can be ferries or other commercial ships on regular routes

The first use of commercial ships for continuous monitoring of marine biological data started in 1931 when the Continuous Plankton Recorder (CPR) came to operate (cp. Reid et al. 1998). The CPR survey's methods of sampling and plankton analysis have remained unchanged since 1948, delivering over 60 years of records of marine plankton dynamics. Today, SoO are also extensively used to observe marine meteorology (Kent et al. 2010), surface ocean (and atmospheric) pCO2 (Schuster et al. 2009) and

support a worldwide programme that collects upper ocean termal profiles with eXpendable BathyThermographs (Goni et al. 2010).

Within the GOOS and EuroGOOS framework, the concept is being extended to develop automatic measuring systems for biological oceanographic parameters and to test them under operational conditions. Different autonomous water quality monitoring systems (called "FerryBox") on SoO have been developed and the concept was tested in the EU FP5 project "FerryBox" (2002–2005). In this project, at least four "core" sensors for temperature, salinity, chlorophyll fluorescence and turbidity were operated by all the partners (Petersen et al. 2007). The experiences within the EU project have proven that such systems are cost-effective in delivering reliable high-frequency data and improve, supplement and optimise conventional monitoring strategies by reducing maintenance efforts and running costs. Most of the activities of the partners are continued on a voluntary basis and have even been extended to more shipping lines (www.ferrybox.org).

Applying FerryBox systems has several advantages because (1) the measuring device is protected from damage caused by waves and currents, (2) biofouling can be more easily prevented by using inboard sensors, (3) energy supply is not limited as in the case of buoys, (4) maintenance during frequent and regular port calls is easy and cost-effective, (5) the costs of ship operation are omitted, (6) the measurements are continuous and yield spatial information along a transect. One obvious limitation of FerryBox systems is that they provide only data on surface water properties and, if necessary, have to be complemented with depth profiles obtained by conductivity, temperature and depth (CTD) measurements from research vessels or buoys. A disadvantage is also that the ship cannot stop during its cruise in order to perform more detailed onsite investigations and the dependency on the availability of voluntary ships in the area of interest.

In recent years, various studies on the analysis and use of FerryBox data have been published. Kelly-Gerreyn et al. (2004), for example, traced a body of low-saline water (<35 psu) in FerryBox data from the route Portsmouth to Bilbao. They showed that upon its arrival in the western English Channel a monospecific bloom (~100 mg chlorophyll-a/m^3) of the dinoflagellate *Karenia mikimotoi* has occurred within 2 days and thus, were able to explain short-term variability in the plankton community. In a later study, Petersen et al. (2008) combined regular FerryBox measurements with satellite data (Medium Resolution Imaging Spectrometer (MERIS) on Environmental Satellite (ENVISAT)). They demonstrated that information gained from in situ FerryBox data could be used to complement and ground truth satellite data. In their study, it was the combination of two independent methods that gave insights

into the dynamic of an algal bloom. Further examples include (1) the combination of a FerryBox system with an Acoustic Doppler Current Profiler (ADCP) that is mounted under the hull of a ferry to calculate the exchange of water masses in a semi-enclosed area between the North Sea and the Marsdiep inlet in the Wadden Sea (Buijsman and Ridderinkhof 2007), (2) the classification of water bodies in the Oslo Fjord based on FerryBox measurements of salinity, chlorophyll-a and nitrate by the Norsk institutt for vannforskning (Petersen et al. 2007), (3) the estimation of seasonal productivity and nitrogen fixation in different regions of the Baltic Sea based on FerryBox measurements of chlorophyll-a, sea water pCO2 and alkalinity (Schneider et al. 2006), and (4) the estimation of carbon fixation based on FerryBox measurements of dissolved oxygen, water temperature and wind data obtained on the route Portsmouth to Bilbao (Bargeron et al. 2006). The latter study suggests that the estimation of new production from oxygen sea–air fluxes can be an alternative to the use of nitrate assimilation in areas of the shelve seas where nitrate is added to the system through advection or entrainment. In addition to the studies mentioned above, the most recent application by Grayek et al. (2011) suggests that assimilation of FerryBox data can also improve the prognostic capabilities of circulation models, especially in areas with a complex hydrography, such as the German Bight. However, their analyses also showed that, in contrast to sea surface temperature (SST), the natural variability of sea surface salinity (SSS) along the FerryBox track was small compared to the measurement errors. They hence concluded that the improvement in SSS state estimates by assimilation of FerryBox data is more demanding as compared to SST data.

There is also much benefit from installing a FerryBox flow unit in a container onshore due to the stable long-term operation and its easy maintenance. Schroeder and Knauth (personal communication) applied such a stationary FerryBox unit for high-frequency water quality monitoring of the Brantas River, East Java, Indonesia, which is in operation since 2001. They showed that by using high-frequent measurements of the main water quality parameters, it is possible to gain better insight into the important processes such as primary production and oxygen consumption. Together with a very simple process model, recommendations for water quality improvements could be given. A similar investigation was carried out in the Bay of Paranaguá, Southern Brazil, where a stationary FerryBox was installed in 2007 close to an outlet of the Bay (Mizerkowski et al. 2008). It could be demonstrated that the regular self-cleaning procedure of the installed systems was an important feature to get reliable data in such subtropical regions with strong biofouling problems.

The present paper summarises our experience gained from 8 years of FerryBox deployments on SoO in the North Sea.

Different aspects of the operational capability and quality of the data are discussed. Examples of scientific applications of FerryBox data are given to point out the added value of FerryBox systems for the assessment of water quality issues as well as limitations of their applicability.

2 Material and methods

2.1 FerryBox system

The FerryBox continuously measures oceanographic parameters in a flow-through system (Fig. 1). Depending on the draught of the ship, the water intake is fixed at a depth between 2 and 7 m. A debubbling unit removes air bubbles, which may enter the system during heavy sea. Coupled to the debubbler is an internal water loop in which the water passes different sensors as it circulates. The basic sensors used measure temperature and salinity, turbidity and chlorophyll-a fluorescence. In addition, an oxygen sensor (Clark electrode or oxygen optode), a pH sensor and a coloured dissolved organic matter probe (CDOM; not used in all systems) were installed. This basic setup was extended to include an optical nitrate sensor, an algal group detector and chemical analyzers

for nutrients (ammonia, nitrite, nitrate, o-phosphate, silicate) measurements (after filtration by a hollow-fibre cross-flow filter). The technical specifications of the sensors are given in Table 1. An automated refrigerated water sampler was used to collect seawater at predefined positions and/or in an event controlled mode for subsequent laboratory analysis and quality assurance. Housekeeping parameters such as flow rates and pressures inside the water loops were measured to supervise the system which was developed in collaboration with an industrial partner and is commercially available (4H-Jena engineering GmbH, Germany).

The main features of the FerryBox system are its modular concept which allows easy extension of other sensors, the debubbling device for removal of air bubbles and its self-cleaning mechanism. The latter ensures the long-term stability and accuracy of the system by preventing biofouling. The whole system is controlled by GPS positioning. A typical measuring cycle starts when the ship leaves the harbour and ends automatically just before it reached the port of destination. This setting avoids contamination by harbour water. Upon arrival, all data are automatically transferred to the shore station where they are stored in an Oracle database with web access (http://ferrydata.hzg.de).
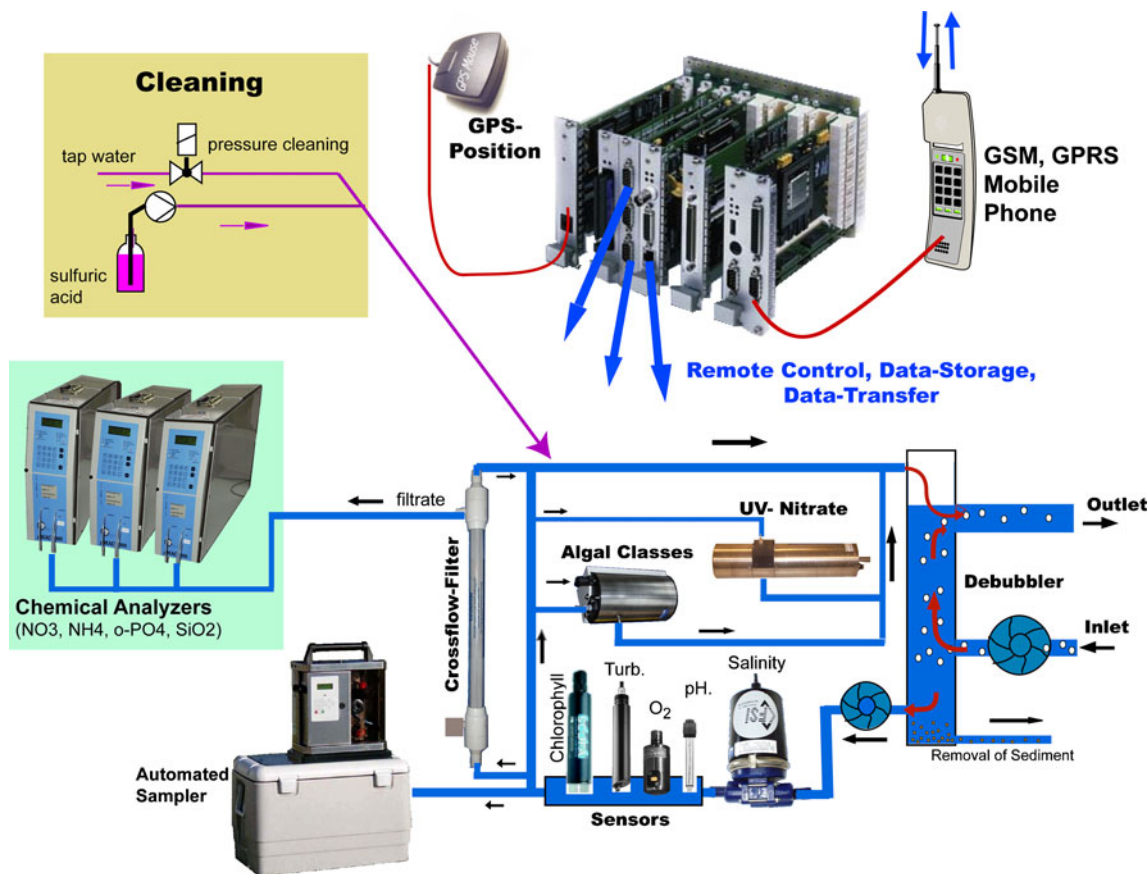

Fig. 1 Schematic representation of the configuration of the FerryBox flow-through system

Table 1 Specifications of sensors in the FerryBox system as reported by the manufacturer

Parameter	Range	Unit	Accuracy	Resolution	Uncertainties or bias	Instrument, Manufacturer
Water temperature	−10 to 50	°C	0.1	0.01	Due to heating up in the tubes (max. 0.5°C)	Excell, Falmouth Scientific Inc., USA
Salinity	0 to 50		0.02	0.001		
Turbidity–E&H	0 to 9,999	FNU	10%	0.01	Due to very small bubbles	TurbiMax W CUS 41, Endress&Hauser, Germany
Dissolved oxygen	0 to 500	μmol/l	8 or 5%	1		Optode 3830, Aanderra, Norway
pH	0 to 15		0.05	0.01		CPS 11, Endress&Hauser, Germany
Chlorophyll-a fluorescence	0 to 200	μg/l	10%	0.5	Due changing fluorescence yield	SCUFA-II, Turner Design, USA
Turbidity–Turner	0 to 50	NTU		0.05	Offset due to very small bubbles	
Ammonia	0.1 to 30	μmol/l	~15%	0.001		Micromac 1000, Systea, Italy
Nitrate	0.5 to 500	μmol/l	~15%	0.01		
o-Phosphate	0.2 to 50	μmol/l	~15%	0.05		
Silicate	0.1 to 100	μmol/l	~15%	0.01		
Algal groups	0 to 200.	μg/l		0.5	Accuracy depending on calibration and algal group	AOA, bbe Moldaenke, Germany
Nitrate (UV detection)	2 to 100	μmol/l	0.1	0.05		ProPS, TRIOS, Germany
CDOM	0.2 to 1,000	ppb quinine sulphate				Cyclops-7, Turner Design, USA

CDOM coloured dissolved organic matter

Before starting a new measurement cycle, the flow-through system is flushed with acidified freshwater that contains sulfuric acid (pH ~2) and oxalic acid (the latter was used to remove iron coatings) in order to clean the tubes and sensors. This regular cleaning procedure prevents biofouling of the sensors. The oxalic acid removes effectively ship-related rust-coloured deposits that were sometimes found on the surface particularly affecting the performance of optical-based measurements. At the end of the cleaning cycle, the FerryBox remains in a standby mode filled with freshwater until the next trip starts. In addition to this cleaning procedure, the FerryBox system is equipped with a back-flushing mode to rinse the inlet tube with freshwater each time decreasing flow rates pointed to a blockage of the loops.

In order to check the calibration of the system, bottle samples (stored at 7°C in the water sampler) were taken from time-to-time along the route for salinity, dissolved nutrients (nitrate, nitrite, phosphate, silicate and ammonia) and chlorophyll-a. For nutrient analysis and chlorophyll-a, the water samples were filtered with a glass microfiber filter (Whatman, 0.7 μm pore size) immediately after the ship was docked. Both the filtrate (50 ml) and the filter were maintained at −18°C. For salinity, the bottle samples were measured using a salinometer (Portasal, Guildline, Canada) located in an air-conditioned laboratory. Nutrients were analysed in the lab according to Grasshoff et al. (1999) with an autoanalyzer (AutoAnalyzer II, Bran+Luebbe GmbH, Germany). For chlorophyll-a filtering, handling of the filters and high-performance liquid chromatography (HPLC) analysis were done according to the procedure described by Wiltshire et al. (1998).

2.2 Calculation of oxygen fluxes

For the calculation of carbon fluxes, FerryBox data of salinity, dissolved oxygen and water temperature were averaged to 0.1° longitude and weekly time intervals. Hourly wind fields were taken from re-analysed data produced with a regional model (Feser et al. 2001; www.coastdat.de).

From the oxygen anomaly $\Delta[O_2]$ calculated as difference of observed oxygen concentration ($[O_2]_{obs}$) and oxygen saturation concentration ($[O_2]_{sat}$)

$$\Delta[O_2] = [O_2]_{obs} - [O_2]_{sat} \tag{1}$$

the oxygen flux at the sea–air water interface can be calculated:

$$O_{2flux} = k(\Delta[O_2]), \tag{2}$$

where, k is the mass transfer coefficient calculated from wind speed and water surface temperature (Wanninkhof 1992). The flux is composed of a biological and thermal component. The carbon fluxes were calculated assuming a Redfield molar ratio of 0.77 (C106:O138).

2.3 FerryBox transects

The first FerryBox system was installed on a ferry between Harwich (GB) and Cuxhaven (DE), initially aboard the "Admiral of Scandinvia". Later, the equipment had to be moved to the vessel "Duchess of Scandinavia". These two ferries crossed the English Channel and travelled along the Dutch and German coast from 2002 to 2005 with one interruption due to the change of vessels in winter 2002/2003. After the operation of this ferry line was terminated in September 2006 the equipment was reinstalled on a Ro/Ro vessel ("TorDania") that travels between Cuxhaven (DE) and Immingham (GB; Fig. 2).

In 2007, a second system was installed on a cargo ship ("LysBris") travelling between Germany, England and Norway and later on to Spain as well. In 2008, a third FerryBox was installed on a passenger ferry that runs between the island of Helgoland and Büsum (summer time) and Cuxhaven (winter time). All ferry transects are depicted in Fig. 2. In this article, data are shown from the routes Harwich (UK) to Cuxhaven (DE) and Immingham (UK) to Cuxhaven (DE). Both routes cover sea areas of the southern North Sea. Most parts of these transects are shallow (10–20 m) and well mixed. Summer stratifications occurs only in the English Channel region (2–4.2°E) on the Harwich–Cuxhaven transect and in the open North Sea westwards of the island of Helgoland on the Immingham–Cuxhaven transect, where water depth is up to 50 m.

2.4 Particle drift simulations

The Lagrangian transport module PELETS-2D (http://www.coastdat.eu/tools/trajectories/pelets/index.html.en) was used to compare FerryBox data that were recorded in 2008 on the Immingham–Cuxhaven transect with results from particle drift simulations. The aim of this exercise was to identify a possible relationship between short-term salinity changes that were observed in May 2008 and changing marine flow conditions. The ensemble simulations involved the integration of 500 particle trajectories, initialized on the 4th of May (12 pm), 16th of May (11 am) and 28th of May (10 am) within a circle of 1 km diameter positioned at 54.04°N, 5.2°E in the centre of the observed salinity anomaly. Hourly particle trajectories were calculated backward in time to obtain a vector of percentages of particles that have ever visited predefined regions during a 12-day period prior to release. This integration time was chosen to avoid overlapping of the

conditions that drive particle movements. The resulting so called Cumulative Travel History (CTH) aggregated the entire history of particle movements in each period and should not be confused with a final particle distribution. The network of regions in which the CTH patterns were defined was organised in a cobweb structure around the source region consisting of 24 sectors and circles, with their width increasing from 1 to 24 km. All particle drift simulations were conducted on pre-calculated current fields stored in the database coastDat (www.coastdat.de). The hourly data were produced with the baroclinic, hydrostatic 3-D finite difference hydrodynamic model BSHcmod (Dick et al. 2001), Version 4, which is operational at the Federal Maritime and Hydrographic Agency (BSH). The model is, among other, forced by daily freshwater fluxes (real-time or modelled) and run in a nested mode with a resolution of 11 km in the area of interest. For the particle transport simulations, vertically averaged flow fields were used. The effect of particle spread trough random motion was accounted for by allowing for horizontal diffusivity of 1.0 m^2/s.

3 Results and discussion

The FerryBox system as a tool has been developed to fill existing gaps in operational observation networks and has already contributed to a better data coverage and hence understanding of marine environments worldwide (e.g. Kelly-Gerreyn et al. 2006; Schneider et al. 2006; Mizerkowski et al. 2008; Hydes et al. 2009). In the following section, we first outline our experience from 8 years of continuous FerryBox research in the North Sea and then allude to some of the possible applications. The latter includes the analysis of seasonality and long-term trends in biological productivity, in particular with respect to changes in the timing and community structure of phytoplankton blooms. For this task, FerryBox systems on SoO are ideal as they survey a determined path and thus eliminate randomness and stationarity which is otherwise inherent to infrequent field trips of research vessels and buoys, respectively. We also demonstrate that continuous FerryBox observations over a large area increase the chance of recording unpredictable short-term events such as the occurrence of nutrient-rich fresh water intrusions which are meaningful with respect to the assessment of water quality and eutrophication. It is shown that this information can be used in combination with circulation models to estimate the spatial distribution of an observed water body or trace its transport over time. Furthermore, we show that the suite of sensors that are at disposal for the FerryBox systems and continuous time series along the track enables the quantification of important processes. This is exemplified by means of the estimation of biological productivity from measurements of oxygen, temperature and wind speed. Finally, we come to discuss the
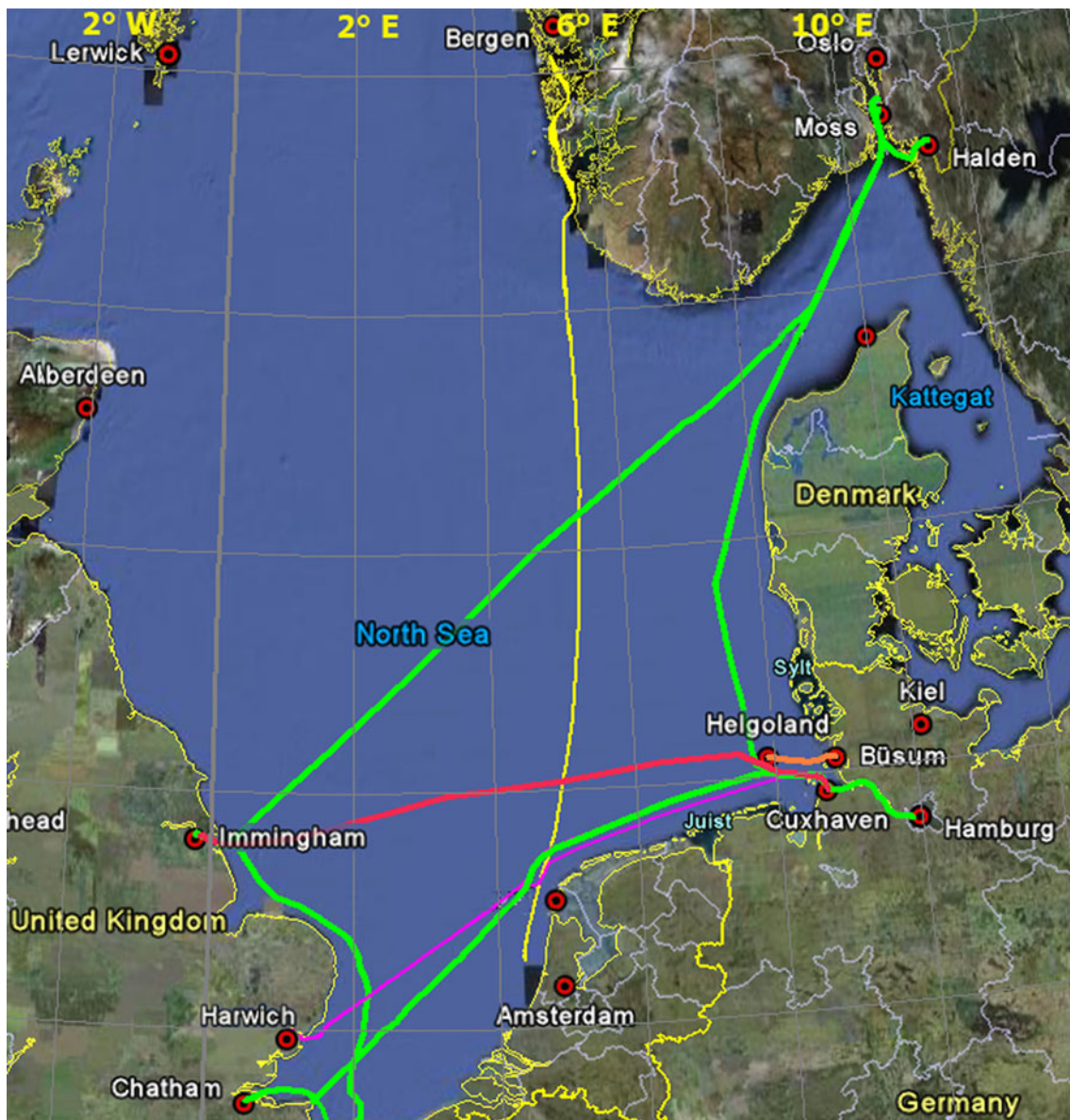
Fig. 2 FerryBox lines operated in the Southern North Sea in 2009

advantage of using FerryBoxes aboard research vessels to quasi synoptically monitor-sensitive regions in a large area such as the North Sea by surveying suitable transects within short time periods.

3.1 Eight years of FerryBox operation

3.1.1 Data availability

The FerryBox system described in this paper has been operated continuously in the southern North Sea on different ships for a time span of 8 years between 2002 and 2010. Missing data during this time period were caused mainly by two factors, the interruption of ship operation

due to ship maintenance, stoppage of the service due to rerouting of the ship, and the failure of the FerryBox system or its sensors. Figure 3 gives an overview of the availability of quality checked standard data (e.g. salinity) as well as the time periods of missing data for all years. For some years, interruption of ship operation plays an important role, especially in the years 2003 when one of the FerryBox system had to change ship, 2006 due to the termination Cuxhaven–Harwich ferry service (change to cargo ship route Cuxhaven–Immingham), and 2009 when some services were temporarily closed due to the economic crisis. In total, 30% of the failure times were caused by interruption of ship operation. However, 47% of the time the standard parameters could be measured.
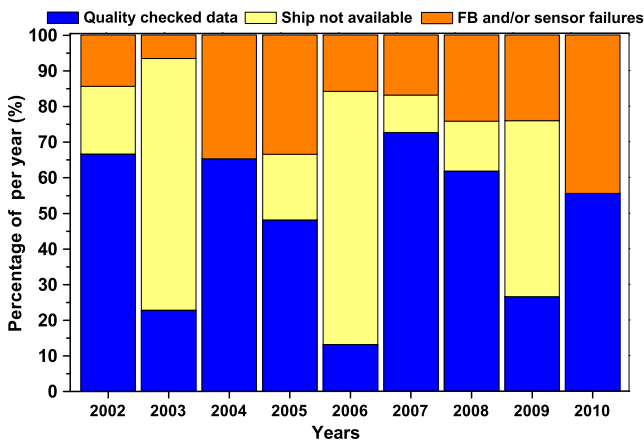
Fig. 3 Failure statistics of the FerryBox system for the years 2002–2010 showing the percentage of time for which the quality of standard data (e.g. salinity and temperature) was high (*blue*), the ship was not available (*yellow*) and failure of the FerryBox system occurred (*orange*)

3.1.2 Data reliability

The sensors were routinely calibrated in the lab prior to field work. The (re-) calibration intervals of the Ferry-Boxes were relatively long due to the automated cleaning and anti-fouling procedures. Maintenance-free intervals of 2–4 months were possible for salinity, temperature, dissolved oxygen, optical sensors (turbidity and chlorophyll-a), while nutrient analysers and pH sensors (accuracy <0.1 ph units) had to be re-calibrated every 2 weeks. For quality assurance, the calibrated sensors were also frequently checked against bottle samples collected during the trips by an automated water sampler. In Fig. 4a, a comparison is made between turbidity measured by a FerryBox sensor and data from bottle samples obtained in the lab by a turbidimeter (Hach model 2100vis, ISO method 7027). It is evident that the correlation is highly significant ($R=0.994$, $p\ll0.001$). Note that the scaling in NTU does not take into account seasonal and spatial variations (expressed in milligramme per litre) caused by changes in the composition of suspended matter. This influence, however, is clearly observed by comparing FerryBox data on chlorophyll-a fluorescence for April and May 2008 with HPLC lab measurements (Fig. 4b). The corresponding correlations between the two measuring systems are significant for both periods (April, $R=0.659$, $p<0.1$; $N=12$; May, $R=0.937$, $p<0.1$, $N=11$) but the relations clearly differ probably due to different species compositions. A comparison of salinity data for the period 2007–2010 is presented in Fig. 4c. A nearly perfect fit ($R=0.9999$, $p<0.001$, $N=203$) with a regression coefficient of almost 1 reassures the high accuracy and long-term stability in FerryBox salinity measurements.
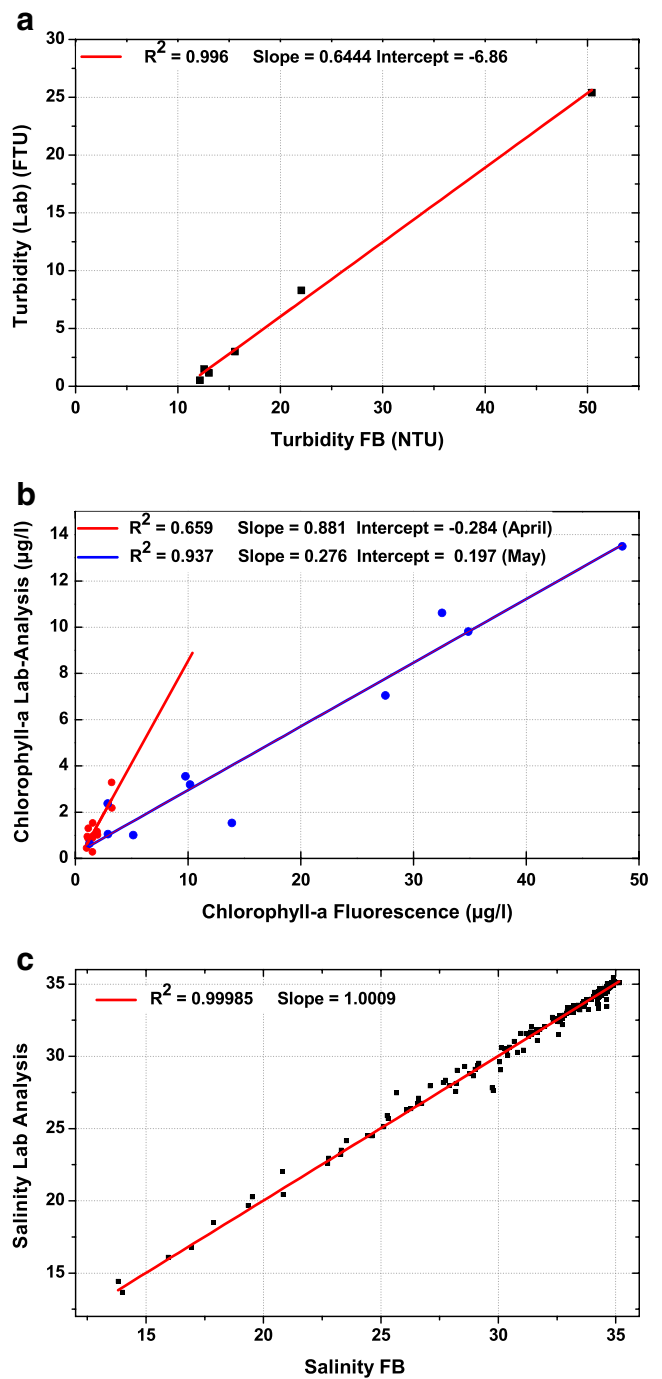

Fig. 4 Comparison of FerryBox data with bottle samples analysed in the lab; **a** turbidity data from one cruise in 2008, **b** chlorophyll-a fluorescence against HPLC measurements from April (*red*) and May (*blue*) in 2005; **c** pooled salinity data from 2007 to 2010

3.1.3 General implications

After 8 years of FerryBox operation, considerable experience has been gained. It becomes clear, that data access and usability are strongly dependent on the type of ship that is used. While ferries usually run regular schedules on short-

distance routes, cargo ships mostly operate on longer routes. This inevitably requires a trade-off between spatial coverage and temporal resolution, and hence limits the type of scientific questions that can be dealt with.

In essence, we see the main benefits of FerryBox systems in the controlled flow rates and operationally friendly conditions on SoO. This enables the application of new, highly sophisticated sensors/analyzers for measuring biochemical parameters such as equilibrium sensors for measuring pCO2 and genetic sensors for the detection of algal species (Diercks et al. 2010). Contrary to the operation of buoys and poles, the operation of FerryBox systems also allows easy maintenance of sensors. Together with the possibilities of effective antifouling measures (no power restrictions, availability of fresh water), this ensures a constant long-term data quality. However, a regular (every few days) check of the received data is important to secure long-term data quality and availability. The operation of complex chemical analyzers in a FerryBox, such as nutrient analyzers requires technicians with a background in chemistry. Furthermore, for nutrients, there is still a need for development of more mature analytical instruments which are able to operate unattended over a longer time period.

Operation and maintenance of a FerryBox is more difficult when installing it on a cargo ship, as compared to ferries. On one hand, this is due to less frequent and shorter port calls, and, in the worst case, can cause substantial data loss if spare parts are unavailable or the system fails shortly after the cargo ship left the harbour. On the other hand, it is caused by more irregular schedule of cargo ships which makes servicing logistically difficult. In contrast to ferries, cargo ships usually also do not have stabiliser systems to reduce rolling. FerryBox systems on cargo ships therefore run the risk of being "contaminated" with air bubbles in choppy seas which can lead to erroneous measurements of turbidity (most sensitive to air bubbles) and chlorophyll-a fluorescence.

3.2 Seasonal observations from FerryBox measurements

Many SoO service the same transect over many years. If such transects are located in regions that are critical for the water quality of a larger area, important information can be gained from long-term measurements. Such observations have been carried out over several years on the ferry route from Harwich to Cuxhaven (see Fig. 2). Figure 5 depicts the time series of salinity, chlorophyll, oxygen and pH for the year 2005. Single transects were pooled in a scatter plot to provide an overview of the temporal and spatial variability in each parameter. The seasonal behaviour is more or less characteristic for many years and is outlined below separately for four of the measured parameters.

Water temperature Temperature shows a typical seasonal signal with lowest values in January and February. In spring (April), temperatures increase rapidly with higher values close to the shore and lower values in the region influenced by the English Channel (2–4°E). Mid of September the temperature decreases slowly with a stronger decrease in the shallow regions.

Salinity High salinities prevail year-round in waters that originate from the English Channel. Near the River Elbe estuary, low salinity values point to several freshwater intrusions into the German Bight. These are possibly the effect of rainwater and/or result of River Elbe runoff. For 2005, no salinity data are available between early March and the beginning of April due to malfunction of the salinity sensor.
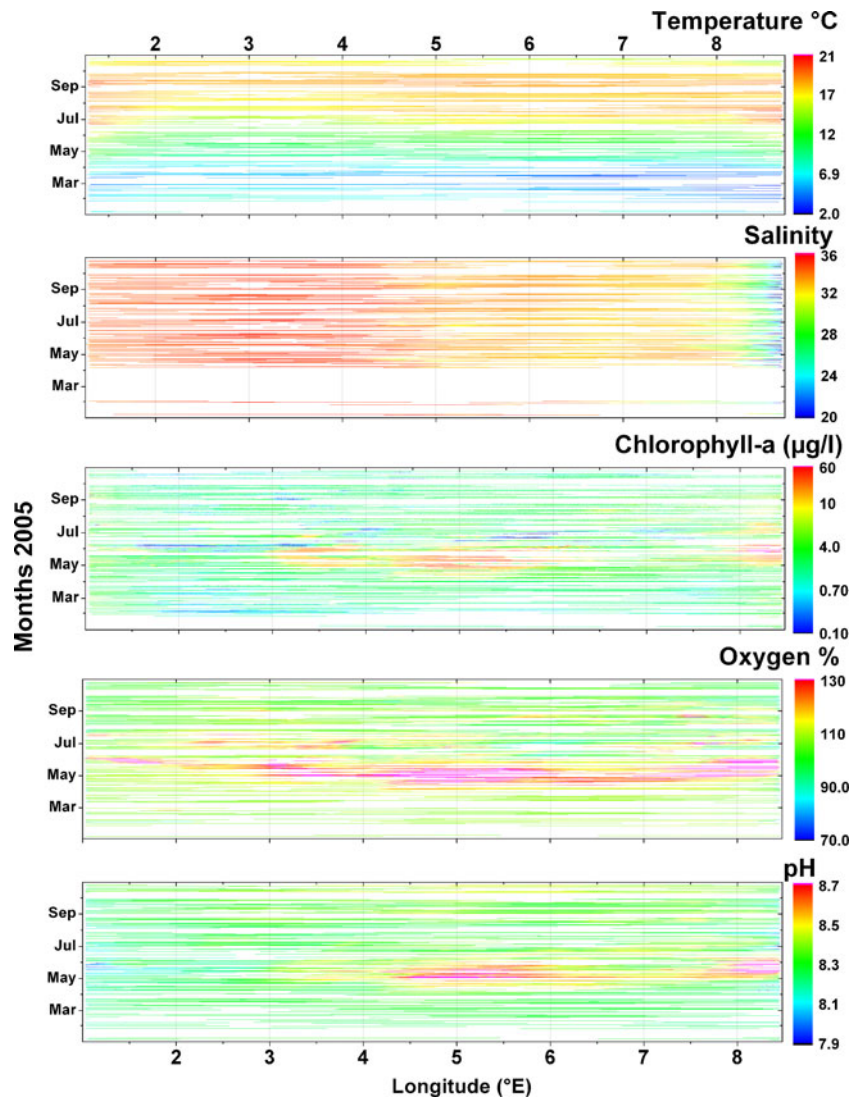
Chlorophyll-a fluorescence A typical feature observed in the chlorophyll-a fluorescence data of all surveyed years is the phytoplankton spring bloom off the Dutch coast (4.5–6.5° E) that starts between April and May when light intensity increases. At that time, nutrients that have accumulated during winter provide ample resources while rising water temperature and low wind stress increase stratification and allow rapid phytoplankton growth. Shortly after its development, the spring bloom spreads eastwards along the Dutch–German coast. By July, when most of the nutrients have been consumed and concentrations are too low to sustain copious production, only a small chlorophyll-a signal remains. A different situation can be observed in front of the Elbe estuary (7.5–8.7° E) where algae blooms also occur in early summer. This most likely result from the high nitrate input of the River Elbe and the release of ammonia and phosphate from Wadden Sea sediments.

Oxygen saturation Oxygen saturation over 100% generally mimics the chlorophyll-a pattern due to primary production while oxygen under-saturation occurs in areas where bacterial consumption is associated with decaying algal blooms. However, in the second half of May, oxygen oversaturation is evident in regions that are influenced by the English Channel (1–2 and 3–4°E) although chlorophyll-a fluorescence is still low. This observation suggests that the chlorophyll-a maximum was below the water inlet of the vessel at that time, probably due to a deepening of the thermocline after stratification, while oxygen diffused upward.

3.3 Detection and analysis of short term events

Figure 6 depicts the pooled salinity data measured along the transect between Immingham and Cuxhaven in 2008. A

Fig. 5 Pooled data of water temperature, salinity, chlorophyll-a fluorescence, oxygen saturation along the transect from Harwich (UK) to Cuxhaven (DE) from January to November 2005. Missing data points are due to sensor failure or malfunction of the FerryBox and docking times of the ferry

Fig. 6 Pooled salinity data along the Immingham to Cuxhaven transect in 2008. The *grey circle* indicates the time period in detail

freshwater signal indicated by a distinct decrease in salinity is evident between 4°E and 6°E. The concurrent increase in nitrate concentrations suggests a fluvial origin of these water masses (Fig. 7). The occurrence of this low-saline water mass could be verified independently by measurements of a second FerryBox that operates between Amsterdam and Bergen (maintained by The Netherlands Waterdienst of Rijkswaterstaat). Comparison of the two transects revealed that the low-saline water body extended southward of the crossing point (54.04°N, 5.0°E; Fig. 8), corroborating the idea that River Rhine runoff was the most likely source. The good agreement of the two independently recorded time series for the whole year 2008 also confirms the high quality of the FerryBox data in the long term (Fig. 9). Both datasets correspond in the depletion of salinity at the beginning of May 2008, and show that this coincides with marked increase in water temperature of about 2°C.
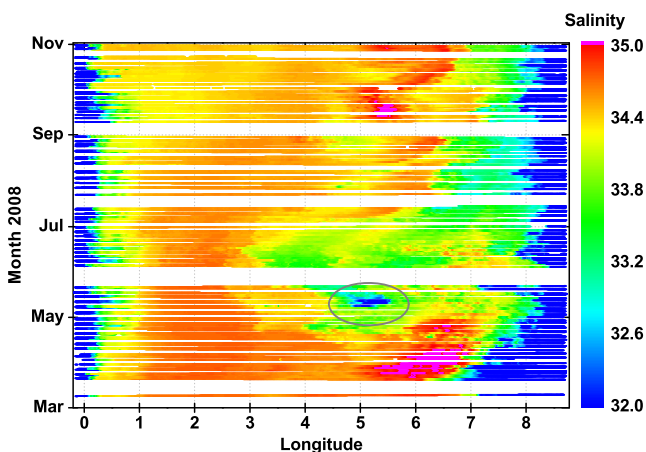
The anomalous high nutrient concentrations observed on the Immingham–Cuxhaven transect could only be observed during a specific time period. This indicates the transient occurrence of a riverine influenced water body that
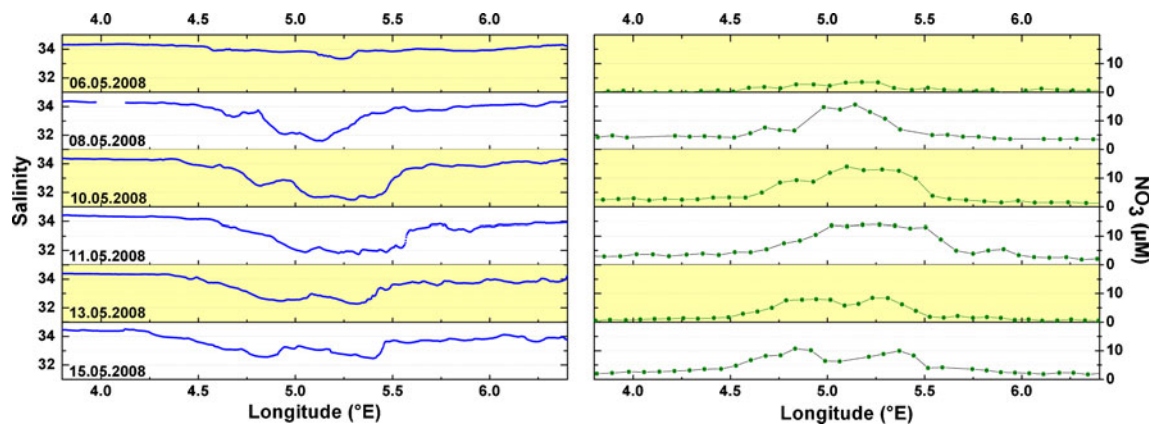
Fig. 7 Salinity and nitrate concentrations measured on the transect from Immingham to Cuxhaven in May 2008

probably conveyed from the south (see above). To prove this hypothesis, the transport history of this water body was estimated by running a series of hydrodynamic drift simulations using the Lagrangian transport module PELETS-2D. Results of three such simulations initialized shortly before, at the end and well after the observed salinity anomaly are shown in Fig. 10. From the first CTH pattern, which results from particle initialization on the 4th of May (Fig. 10a), it is apparent that advection from southwesterly direction dominated during the 12 preceding days. In contrast, the second initialization on the 16th of May (Fig. 10b) yields a CTH pattern that shows that particles have not drifted much during the previous 12 days and distribute evenly around the source region. The third CTH pattern, due to particle release on the 28th of May (Fig. 10c) indicates that surface water transport during the previous 12 days has taken place mainly from East to West. The distinction of this three clearly different CTH patterns lends credit to the following scenario. The salinity decrease that started on 6th May was most likely caused by the arrival of a low saline water mass from the southwest. The persistence of this water body at that location was then brought about by a decrease in surface water advection that

was followed by almost stagnant flow conditions for a period of about 10 days (cf. Fig 7). Finally, in the event of a following westward drift the salinity anomaly was transported westward (cf. Fig. 6) and eventually got intermixed with surrounding sea water. We assume that the observed salinity anomaly was detached from the northeastward flowing coastal current as an eddy-like structure which carried freshwater from River Rhine runoff. Drift simulations with an integration time of 60 days back in time (started on the 6th of May) support this hypothesis by showing more clearly that during this period particles indeed distributed in southwesterly direction, eventually reaching the River Rhine estuary (results not shown). At that time, freshwater discharge of the River Rhine was probably at a maximum as is indicated by surface water flow rates that average 3,200 m^3/s in March to April (annual mean ~2,100 m^3/s) at measuring station Lobith, Rhine km 863 (data available at http://live.waterbase.nl/waterbase_wns.cfm?taal=en). Putting together the evidence from data on nutrient concentrations, river discharge rates and drift simulations makes a plausible case that the observed low-salinity patch was the result of high freshwater input by the River Rhine.

Fig. 8 Transects of the Ferry-Box line Amsterdam–Bergen (north–south) and Immingham–Cuxhaven (east–west) showing their crossing point in the North Sea. Routes are depicted as salinity data for the 10th of June 2008
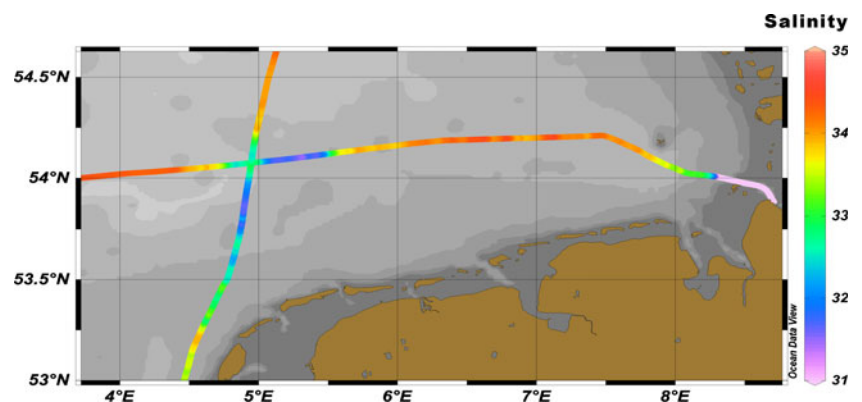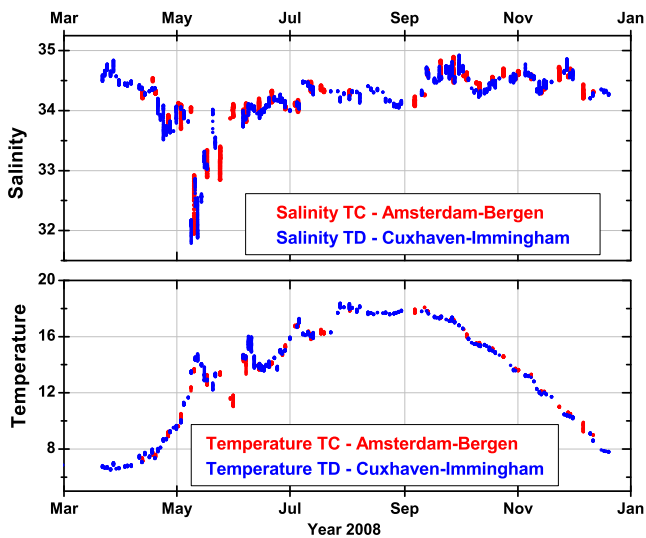
Fig. 9 Time series of salinity and seawater temperature at the cross section (54.04°N and 5.0°E) of the FerryBox routes Amsterdam–Bergen and Immingham–Cuxhaven in 2008

Fig. 11 Uptake of carbon during growing season (March to October) calculated from average oxygen fluxes measured along the transect Harwich–Cuxhaven in 2002, 2004 and 2005

3.4 Estimation of carbon fluxes from continuous oxygen measurements

The release of oxygen during photosynthesis enables the use of dissolved oxygen concentrations as a measure of primary production in aquatic ecosystems. Besides on thermal effect, oxygen fluxes thus reflect net primary production, that is, the excess of total primary production over community respiration. Consequently, the calculation of oxygen fluxes based on observations of oxygen distributions in surface waters and gas-exchange parameterization provides information on carbon fluxes. This, however, requires a measurement error of less than 1% because changes in dissolved oxygen concentrations are relatively small.

A continuous dataset on oxygen concentrations was recorded for the years 2002, 2004 and 2005 along the track from Cuxhaven to Harwich (no data were available in 2003
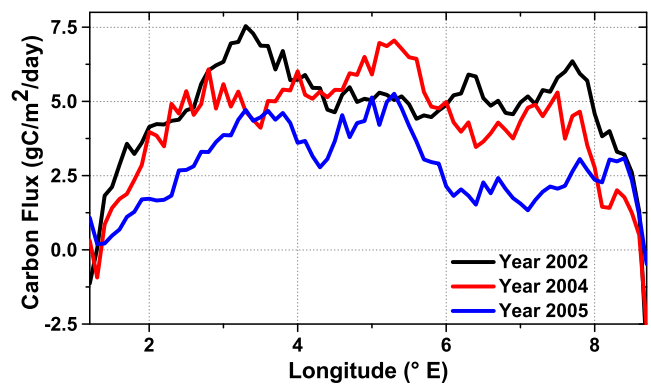
due to a change of ship). Oxygen anomalies calculated according to Eq. 1 were used in combination with wind fields to estimate the oxygen fluxes (Eq. 2) for the respective years. Oxygen fluxes, in turn, were used to derive time series of carbon fluxes (carbon uptake) as an indicator for biological activity neglecting the small thermal component of the calculated oxygen anomaly. Figure 11 depicts the corresponding results for the growing season between March and October. It can be seen that highest average carbon uptake rates (i.e. higher primary productivity) occurred in the English Channel region (~3.2°E), near the Dutch coast (~5.2°E) and in the German Bight around 7.7°E. In accordance to the chlorophyll-a data from 2005 (cf. Fig. 5), the seasonal pattern of these fluxes (not shown) shows high values along the Dutch coast during spring followed by increased uptakes in the English Channel and in the German Bight. This suggests that these regions may act as important carbon sinks due to increased phytoplankton growth. In contrast, close to the shore carbon sea–air fluxes are close to zero or even negative which identifies these areas as a potential source of atmospheric carbon dioxide.

Fig. 10 Resulting final CTH patterns from three different Lagrangian particle transport simulations with PELETS-2D showing the percentage of particles having ever visited a cobweb cell. For each simulation, 500 particles were initialized in the centre of a cobweb structure (circle of 1 km diameter centred at 54.04°N, 5.2°E) on 4th May (a), 16th May (b) and 28th May (c), and trajectories integrated over a 12-day period backward in time
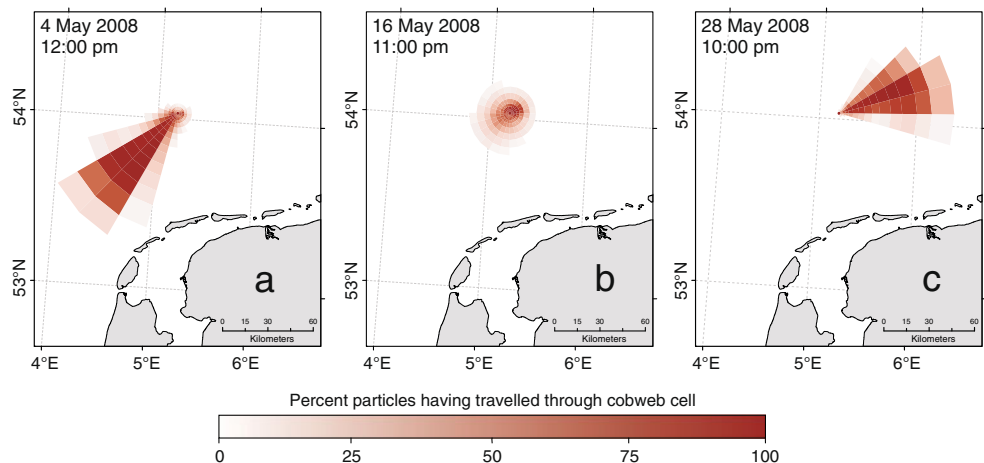
3.5 Large area surveys

Since 1999, the German BSH runs a yearly oceanographic survey during the summer thermal maximum development to monitor the water quality in the North Sea. In 2009, a FerryBox system was used during the 3-week long campaign to continuously record a variety of surface water parameters (salinity, temperature, turbidity, chlorophyll-a

fluorescence, dissolved oxygen, pH, nitrate, o-phosphate, silicate and ammonia). In combination with discrete water sampling and CTD profiling, this database provides an almost synoptic view of the entire North Sea for that time period (Fig. 12). Contour plots produced from the surface water temperature and salinity data show a clear thermal gradient that crosses the North Sea northeast to southwest and the inflow of higher saline water masses from the
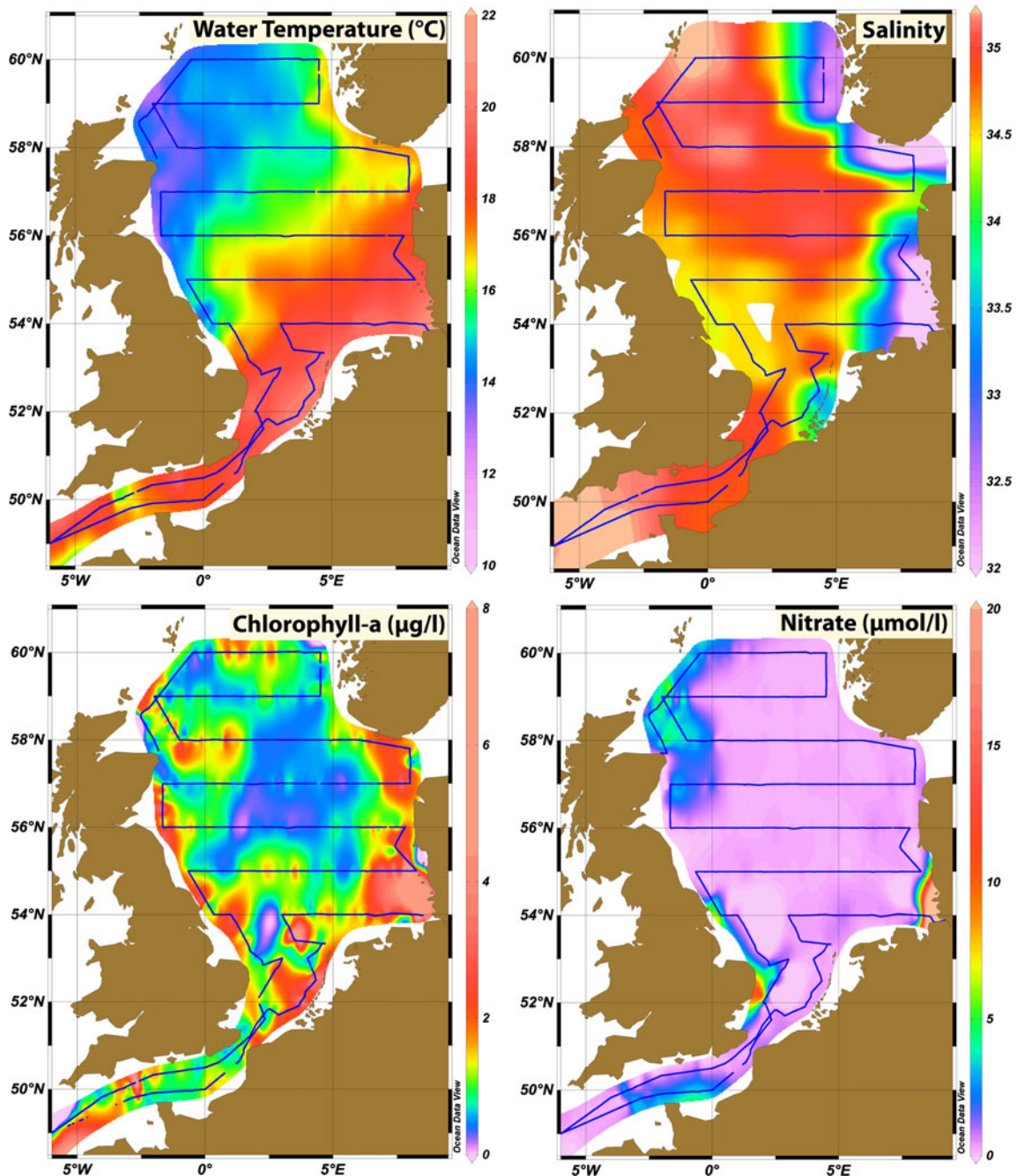

Fig. 12 Contour plots of water temperature, salinity, chlorophyll-a fluorescence and dissolved nitrate from data recorded during a FerryBox survey with the RV Pelagia (20th August to 9th September 2009). The *blue dots* mark the sampling points

Northwest Atlantic and the English Channel, respectively. The chlorophyll-a distribution shows higher values close to the coast but in general is very patchy. This pattern probably results from a complex situation in stratification at that time which could not be resolved by the surface water measurements of the FerryBox alone. Future investigations need to record depth profiles of chlorophyll-a in order to facilitate the interpretation. The distribution of nitrate in surface water mainly reflects river runoff but also the inflow of nutrient rich water from North Atlantic. Highest concentrations are observed in the River Elbe estuary and off the English coast (52.5°N and 54°N) where they most likely result from increased nutrient loads of the River Thames and the River Humber. The River Seine and the River Loire probably contribute to the high nitrate concentrations observed off the French coast.

Using FerryBox systems on regular research cruises in combination with other data collection techniques has several advantages. For example, the infrastructure aboard most research vessels allows the simultaneous analysis of water samples for parameters that cannot be measured automatically and can be used for quality control too. Research ships can also deploy undulating vehicles for recording water column profiles that complement the 2-D measurements of FerryBoxes. Such a technique is currently applied within the Coastal Observation System for Northern and Arctic Seas project managed by the Helmholtz-Zentrum Geesthacht (for further information, visit www.cosyna.de). Here, undulating vehicle (SCANFISH^{TM}) profiles are taken four times a year in areas that are not covered by FerryBox transects to obtain 3D structures of important oceanographic and water quality parameters.

4 Conclusions

FerryBox systems, especially those equipped with an automated cleaning and antifouling device, have reached a high level of performance. Currently, different research institutes and environmental monitoring agencies across Europe (e.g. AWI, DE; DELTARES, NL; CEFAS, UK; SEPA, UK) deploy them on ferries, cargo ships and research vessels (e.g. RV Polarstern, RV Zirfaea, RV Pelagia, RV Endeavour). In comparison to other in situ measurement systems, the reliability and data availability of FerryBoxes is higher and maintenance costs are significantly lower. Moreover, the quasi unlimited power supply and operation-friendly conditions on ships enables the use of new, sensitive sensors and thus widens the spectrum for environmental assessments. This, however, requires routine inspection of the data as well as regular calibration and maintenance of the sensors.

After 8 years of FerryBox research at the Helmholtz Zentrum Geesthacht, we can draw the following conclusions:

New, high-performance sensors for pH, dissolved oxygen, turbidity, chlorophyll, pCO2 and dissolved nutrients, that are otherwise not mature enough or too energy demanding to be deployed on buoys or piles, can now be used to continuously measure biological relevant parameters in situ.

Continuous recordings of physical, chemical and biological parameters on SoO provide better insights into seasonal and long-term dynamics of important ecosystem processes such as primary production and nutrient cycling.

In contrast to the effectiveness of research cruises and stationary systems, FerryBoxes have a higher chance to observe short term or exceptional events due to a high spatial (100–500 m) resolution along the track and a repetition rate of the measurements at a certain point in the range of 2–5 days depending on the frequency of operation on the specific route.

In combination with (operational) hydrodynamic models, information from FerryBox measurements gains a better understanding of the spatial distribution and history of water masses. This, in turn, can be used as an input to more sophisticated models that simulate, for instance, suspended matter transport and biogeochemical cycles.

Regular, high-precision measurements of dissolved oxygen and pCO2 along FerryBox transects can support the estimation of carbon fluxes and net primary production, and thus contribute important information on regional air–sea CO2 exchange (i.e. which areas of the North Sea act as a source/sink for atmospheric carbon dioxide).

With combined efforts from FerryBox measurements, CTD casts, undulating towed vehicles, remote sensing and numerical models a large-scale 3D-image of shelf seas can be obtained.

For these reasons, we encourage the use of FerryBox systems to fill existing gaps in operational observation networks. This will increase the data coverage in space and time and thus lead to a better understanding of the linkage between physical forcing and relevant ecosystem processes.

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