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FerryBox and MERIS - Assessment of Coastal and Shelf Sea Ecosystems by Combining *In-situ* and Remote Sensed Data

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Abstract

An automatic measuring system called "*FerryBox*" was installed on a ferry travelling between Germany (Cuxhaven) and Great Britain (Harwich) enabling on-line oceanographic and biological measurements such as salinity, temperature, fluorescence, turbidity, oxygen, pH, and nutrient concentrations. Observations made along the ferry transect reveal characteristic phenomena such as high salinity inflow through the Channel into the southern Bight, algal bloom dynamics and related oxygen and pH changes. Combination of these on-line observations with remote sensing enhances the spatial resolution of the transect related measurements. Several examples of the synergy between both operational measuring strategies are shown, both for large scale algal blooms in the North Sea as well as for local intense but short term blooms in the German Bight. Coherence of the data sets can be gained and improved by using water transport models in order to obtain synoptic overviews of the remote sensed and *FerryBox* related parameters. Limitations of the currently used algorithms for deriving chlorophyll-a from remote sensing images for coastal and shelf seas (Case-2 water) are discussed, as well as depth related processes which can not be properly resolved on the basis of water intake at a fixed point. However, in mixed coastal waters under normal conditions *FerryBox* data represent average conditions. The importance of future applications of these combination of methods for monitoring of coastal waters is emphasized.

Keywords:, ships-of-opportunity, FerryBox, remote sensing, in-situ monitoring, water quality, chlorophyll-a, primary production, red tides, North Sea,

1. Introduction:

Monitoring of a highly dynamic system such as coastal waters requires dense sampling in space and time in order to catch short-term events which might have a strong impact on the coastal ecosystem, such as exceptional phytoplankton blooms or changes caused by storms. Existing observations mostly lack the spatial coverage and temporal resolution required to determine the state of the marine environment and changes therein. The lack of monitoring systems that provide continuous observations of the marine environment in the coastal areas and shelf seas of Europe is a serious hindrance to understand these systems.

Remote sensing offers the opportunity to get frequent (daily) synoptic estimates of water quality parameters over large areas. The global coverage of satellites allows for the estimation of water quality in remote and inaccessible areas. However, there are also significant limitations of satellite observations. The ability to distinguish between the various constituents of the water is limited to parameters which can be correlated to optical properties. These are concentrations of suspended sediment, phytoplankton and 'Gelbstoff' (yellow substances) whose major part is coloured dissolved organic matter. Data are only available when cloud conditions permit. Sampling depth is limited to near surface waters, varies with the clarity of the water and is not controllable. Open ocean reflectance (Case 1 waters) is mainly affected by chlorophyll and related degradation pigments and allows good estimates of chlorophyll concentrations. In contrast, estuarine and coastal waters (Case-2 waters) are more difficult to characterise by remote sensing because often reflectance is affected by site-specific factors. For instance, it may be difficult to discriminate between chlorophyll and suspended matter if much of the reflectance is not caused by phytoplankton and concentrations of different optically active substances are much higher. Therefore, site specific algorithms have to be developed for these types of waters (Hellweger et al. 2004).

Currently, in situ monitoring is mainly carried out by manual sampling and analysis during ship cruises and autonomous measuring systems on buoys. The latter only allow reliable long-term measurement of standard oceanographic parameters (temperature, salinity, currents). In order to increase the temporal and spatial coverage the use of “ships of opportunity” (SoO) has been promoted by EuroGOOS (Flemming et al. 2002). 60 years ago the "Continuous Plankton Recorder (CPR)" (Reid et al. 1998) has followed the idea of towing scientific equipment by SoO and has produced an impressive data on plankton abundance with time (e.g. Vezzulli & Reid, 2003). Recently, sophisticated systems have been implemented on ferry boats which allow precise measurements of temperature, salinity and chlorophyll (Rantajärvi 2003; Swertz et al. 1999; Harashima and Kunugi 2000, Hydes et al. 2003, Petersen et al. 2003) and even currents by ADCP (Ridderinkhof et al. 1999). In the ”*FerryBox*-Project” supported by the European Union eleven groups work together in order to enhance the use of SoO for operational monitoring of the marine environment (Petersen et al., 2005). SoO on regular routes offer a cheap and reliable measuring platform to obtain continuous and spatial high resolution observations of near surface water parameters. Such systems are able to measure a whole set of oceanographic and biological parameter which are also observed by satellites (temperature, chlorophyll, turbidity, yellow substances). However, the data of *FerryBox* systems are restricted to the transect and to a certain depth (depth of the inlet of the *FerryBox*) which may be problematic in stratified waters.

In order to increase the accuracy of satellite images by ground truth measurements especially in shelf seas on the one hand and to widen the observations of the transect-restricted *FerryBox data* on the other hand, it seems to be logical to combine remote sensing observations with *FerryBox* data. In this way a synergistic effect of both data sources can be accomplished. First examples were shown for the Baltic Sea (Pulliainen et al. 2004, Vepsäläinen et al. 2005).

In this paper we will show how *FerryBox* transect data can be combined with large scale satellite data to improve the quality of monitoring of coastal waters. We focused on two aspects: the measuring accuracy as well as the spatial and temporal resolution of *FerryBox* and remotes sensing data. A specific problem is posed by the temporal difference between the two types of observations which is shown to be solved by using water transport models. A final question which we tried to solve is to which extent these observations can be used to detect and analyse small scale, local and short term algal blooms in specific areas along the transect.

2. Material and Methods

2.1. FerryBox system

The "German *FerryBox*"system consists of an automated flow-through system with different sensors (temperature and salinity (FSI, USA), *in-vivo* fluorescence as a proxy for chlorophyll-a (SCUFA-II, Turner Design, USA), algal group analyser (AOA, bbe-moldaenke, Germany), turbidity (Turner Design, USA and Endress & Hauser, Germany), oxygen and pH (Endress & Hauser, Germany) and automatic wet chemical nutrient analysers (APP, ME-Grisard, Germany) (dissolved inorganic nitrate, ammonia, o-phosphate and silicate) and an additional UV-nitrate detector (ProPS, TRIOS, Germany) for optical detection of nitrate.

In this contribution for chlorophyll-a fluorescence data from the algal group analyser (AOA) were used (exception spring bloom 2004). At certain times water automatically sampled by the *FerryBox* were analyzed by HPCL according to the procedure described by Wiltshire et al. (1998) in order to validate the measured chlorophyll values. It turned out that the ratio between in-vivo chlorophyll-a fluorescence and chlorophyll-a concentration analysed by HPLC shows a seasonal behaviour as the chlorophyll-a fluorescence depends on the species as well as on the physiological status of the algal. In order to make the data comparable for the chlorophyll-a values the calibration of the manufacturer was used. Thus, these values may differ from time to time from measured real chlorophyll-a concentrations in the lab.

The water intake is in front of the ships cooling system at a fixed depth (5 m). The water is pumped continuously along the sensors. The water temperature measured by the *FerryBox* is influences by heating up in the tube to the *FerryBox*. Differences between intake and *FerryBox* were maximally up to 0.4°C based on measurements with a sensor at the intake and the sensor in the *FerryBox*. Data including time and position (latitude, longitude) are automatically transferred to shore and the system can be remotely operated via mobile phone connection (GSM). Spatial resolution of recording is about 100 m with the exception of the data of the chemical nutrient analysers which have a spatial resolution of 6-9 km depending on time needed for the analysis. On shore data enters a SQL database (Oracle) with access from a public web page (*http://ferrydata.gkss.de*). Water samples for subsequent analysis in the laboratory can be taken by an automatic water sampler at predefined positions. The samples are kept refrigerated (4°C) and in the dark. A more detailed description of the system is reported in Petersen et al. (2003).

2.2. Study area:

The German *FerryBox* system is installed on the ferry 'Duchess of Scandinavia' (DFDS Seaways, Copenhagen, Denmark) on the route between Cuxhaven (Germany) and Harwich (Great Britain) since 2002. The ferry travels along the southern part of the North Sea covering the coastal zones of Germany and the Netherlands and crosses the inflow of the English Channel into the North Sea. The map of the route is shown in Fig. 1. The ferry is scheduled to travel daily between the two ports, mainly overnight.

Figure 1: Map of the Southern North Sea and transect of the ferry (Duchess of Scandinavia’s route)

On its route the Ferry crosses several water masses that are separated by permanently existing fronts with only limited water exchanges. Near Cuxhaven the water masses are largely influenced by the outflow of the Elbe river. Despite the low salinities off Cuxhaven the turbidity is not very high since the turbidity zone of the Elbe estuary is located more upstream in the inner estuary. Along the Dutch Wadden Sea lower salinities are found that originate from the fresh water inputs of rivers and the IJsselmeer. In the further course of the route the influence of the riverine input decreases and the water masses are influenced by water masses with Atlantic water properties which reach the track of the ferry through the English Channel. Approaching the English Coast a slight decrease of salinity is observed and the turbidity increases strongly reaching even higher values then in the Elbe estuary due to long term erosion along the English coast.

Due to the strong tidal energy the water column is more or less vertically mixed along the transect throughout the year (e.g. Rodhe, 1998). This justifies the application of a *FerryBox* system although only one water horizon is monitored with the applied system.

2.3. Synoptical correction of data by model

Remote sensing and in-situ measurements are in general not carried out at the same time. The movement of water masses in between can be calculated by application of numerical models. We used the operational model system (Dick et al., 2001) of the Federal Maritime and Hydrographic Agency (BSH).

The model system consists of several computer programmes. On the basis of meteorological and wave forecasts supplied by the German Weather Service (DWD), as well as tide predictions, the model computes forecasts of currents, water levels and temperatures, salinities and ice cover in the North and Baltic Seas (BSH circulation model) and programmes to compute the drift and dispersion of substances (Lagrangian and Eulerian dispersion models).

The Operational Dispersion Models and specific applications have been described in detail by Dick and Soetje (1990), Schönfeld (1995), and Müller-Navarra et al. (1999), both for the North and Baltic Sea. Concerning the Operational Circulation Model, technical reports have been published by Kleine (1993, 1994).

In order to compare the remote sensing data and the measurements of the *FerryBox* the drift of the water masses sampled by the *FerryBox* was estimated by applying the Lagrangian dispersion model. The drift was calculated within the time lag between each *FerryBox* observation and the satellite overpass, thus achieving observations on a ship route synoptic with the remote sensed data.

2.4. MERIS data

The remote sensed data was taken by the MEdium Resolution Imaging Spectrometer Instrument (MERIS) on the ENVISAT satellite launched in 2002. MERIS measures the solar radiation reflected by the earth, at a maximal ground spatial resolution of 300 m, in 15 spectral bands, from the visible to the near infra-red. We used partly 300 m-resolution-data (FR, Full resolution) and due to higher availability 1200 m-resolution-data (RR reduced resolution). MERIS allows global coverage of the earth in 3 days. For medium latitudes on two out of three days MERIS-data are available.

We used Level-1b data, which are among others calibrated radiances at top of the atmosphere, and applied the maximum chlorophyll index algorithm as described by Gower et al. (1999) as a measure for a 'red tide strength'. For Level-2-data, the Meris-level2-products were used which yielded the geophysical data products on total suspended matter, yellow substance and chlorophyll-a concentration. These products are intended for blue open ocean water (Case-1), the product called algal-1 relying mainly on reflectance ratios. For a wider range of concentrations that can be found in coastal waters and which are characterised by higher turbidity and higher yellow substance absorptions the products tsm (total suspended matter), ys (yellow substance) and algal-2 were applied. These case-2 products are determined by an algorithm shortly referred to as a ‘neural-net’, a multiple non-linear regression method (Schiller & Doerffer, 1999). Its coefficients are determined from a table of input variables (water leaving reflectances, angles) and corresponding output variables (concentrations) using a feed forward backpropagation optimisation technique as ‘training’. The table of water leaving radiance reflectances as a function of the concentrations of water constituents and the three angles is produced by radiative transfer simulations using a Monte Carlo transfer model. We used the version as it was distributed by ESA in 2004 and 2005 (IPF 4.04 to IPF 4.10). This comprises the neural-net as it was prepared before launch of Envisat in 2002.

3. Results and Discussion

3.1. Algal dynamics in the Southern North Sea in spring 2004

The observations of single transects with the *FerryBox* can be pooled in a contour plot in order to get an overview of the temporal and spatial variability of a parameter. Figure 2 shows algal dynamics along the route between Harwich and Cuxhaven in spring 2004, represented by the values of in-vivo chlorophyll-a fluorescence. Since the SCUFA-II had several gaps at the spring bloom 2004 the fluorescence signal of the sensor SCUFA-II was used. The data were re-calibrated with measurements from the Algal-Online-Analyser (AOA) to make the results comparable to 2005.

Figure 2: In vivo fluorescence of chlorophyll-a along the transect of the ferry between March and June 2004

A weak spring bloom started in late March 2004 off the Dutch coast (4.5 – 6.2 °E), followed ba a first stronger bloom later in early April between 3.8 °E and 5.8 °E. The bloom spreaded into the German Bight between the end of April and early May, most likely by advective transport with movement of the water masses along the Dutch and German coast. In May, the first strong bloom occured in the water masses that reach the Ferry transect from the English Channel (2.3 – 4.2 °E). It drifted towards the Dutch coast and disappeared in mid-June. After these spring blooms in the Channel and along the Dutch and German coast the chlorophyll concentrations remained low and weak blooms with high spatial patchiness were observed between 5°E and 7.5°E at the end of June. Later on, there was no visible algal activity with exception of a short-term event happening in the German Bight at the beginning of August which will be discussed in detail in the following section.

3.2. Algal dynamics in the Southern North Sea in spring 2005

In 2005 the development of the spring bloom observed along the transect by *FerryBox* is shown on the basis of chlorophyll-a fluorescence data (Fig. 3). In addition, the oxygen saturation index and the pH values are presented.

Figure 3: Contour plots along the transect from March to June 2005: a)in-vivo chlorophyll-a fluorescence, b)oxygen saturation, c) pH

Similar to the bloom dynamics in 2004, weak chlorophyll concentrations were found in March and the first bloom started at the Dutch coast between 4.5°E and 6°E at the end of March 2005. Whilst in 2004 the bloom spread out to the German coast in 2005 the bloom remained on a fixed location and strongly increased at mid of April.

The bloom in the water mass reaching the ferry transect from the English Channel between 3.2°E and 4.2°E initiated earlier (mid of April) than in 2004 and lasted until June with a comparable drift to the Dutch coast as in 2004. Both blooms disappeared end of May and at the beginning of June 2005 respectively. A second bloom appeared later in water masses that reached the ferry transect from the English Channel between 3.2°E and 4.2°E. It started in mid of April and continued until June with a drift to the Dutch coast. Despite of slightly different timing these observations are very similar to the measurements in 2004. Both blooms disappeared at the end of May and at the beginning of June 2005, respectively.

In 2005 again an intensive bloom was observed in the German Bight off the Elbe estuary starting in May and disappearing mid of June 2005. This bloom is characterised by considerably higher chlorophyll concentrations than in 2004 (about1.5 times higher).

The dynamics of the chlorophyll concentrations can be compared to the observed oxygen concentrations. In Fig. 3b the dynamics of the oxygen saturation values along the transect is shown. The major patterns of the chlorophyll fluorescence correspond well with the oxygen dynamics. However, at certain times and on certain parts of the transect high oxygen saturation can be seen without corresponding high chlorophyll values. In particular, this was the case at the German coast near the Elbe estuary (7.5°E – 8.4°E) at the end of April until beginning of May and near the English coast between 1°E and 2°E at the end of May. Similar observations were also found in 2004 (not shown). Most likely, these findings are caused by primary production from algae below the water intake of the ferry and diffusion of the produced oxygen towards the surface. Although the highly energetic environment along the ferry route with its strong tidal motions causes turbulent mixing and therefore a more or less well mixed water column throughout the year (e.g. Rodhe, 1998) patches of low salinity waters entering the route, cause a local and temporary stratification (Schrum, 1997). In these cases algae may accumulate below the pycnocline and produce oxygen which diffuses upstream whereas the algae are trapped below the pycnocline.

At the beginning of June the algal break down was accompanied by an oxygen depletion with saturation values of only 80% along the eastern Dutch coast (between 5.5°E and 6.5 °E).

Consistent with the algal blooms are the observed pH data along the transect as shown in Fig. 3c. The pH increases significantly along the Dutch coast during the plankton bloom in May and pH values up to 8.8 have been found along the German coast in water masses influenced by the Elbe estuary (8 – 8.7 °E).

3.2.1. Spring bloom observed by remote sensing in 2005

In the North Sea the availability of suitable remote sensing images is often restricted by cloud coverage. In 2005 a considerable set of more or less cloud free images could be obtained during spring time. Unfortunately in most part of the scenes water content concentrations are flagged as unreliable. As this flag is known to be extreme restrictive in this product version (IPF 4.x) (pers.com. Roland Doerffer) we did not obeyed the flag fully. The reliability for each part is discussed below in detail. Thus, the spatial distribution of the blooms at the locations observed by the *FerryBox* in 2005 can be extracted from remote sensing images and compared to the data of the *FerryBox*. Figure 4 shows the distribution of derived chlorophyll-a concentrations by MERIS on 11th and 21st of April as well as on 15th and 28th of May. In addition to each image the comparison of the MERIS chlorophyll-a concentrations along the track of the ferry with the *FerryBox* chlorophyll-a fluorescence are shown. Since at the time being no drift corrected *FerryBox* positions were available for 2005, the original positions of the ferry track were taken. For all comparisons *FerryBox* data from the particular cruise starting from Harwich on the day before the image was taken were used. Thus the time difference between the satellite image and the *FerryBox* observation is at maximum 19 hours in the western part but reduces to 2 hours in the eastern part.

Figure 4: Chlorophyll-a concentration derived from ENVISAT-MERIS (algal-2 for case-2 water) for the North Sea (quality flags not obeyed – see text) and comparison with extracted chlorophyll-a fluorescence from the *FerryBox*. Black lines show the tracks (not corrected for drift) of the ferry.
a) 11th of April, b) 21st of April c) 15 of May, d) 28th of May.

On 11th of April a strong bloom along the Belgian and Dutch coast and near shore of the German coast can be distracted from the satellite images. The comparison of the extracted chlorophyll values with the chlorophyll-a fluorescence of the ferry sampled on the cruise from Harwich to Cuxhaven on 10th-11th of April shows good agreement and even the shoulders of the curves fit well from the Channel to the Dutch-German border (6°E). Along the English coast very high suspended matter concentration of 25 to 60 mg/l can be derived from remote sensing. The high signal from suspended matter may introduce the false signal in the chlorophyll result west of 2.2°E. From 6.5°E and eastwards the agreement with the *FerryBox* data degrades. For this part of the image the low-quality flag is raised and remote sensed data should be interpreted with care expecting strong deviations. In addition around 5°E are some smaller clouds which also cause a flagging of the data.

On 21st of April almost no chlorophyll was found in the algal-2 signal from MERIS whereas the *FerryBox* detected enhanced levels up to 22 µg/l chlorophyll-a off the Dutch coast. Almost the whole scene is flagged as unreliable and the disagreement to *FerryBox* confirms the importance of quality flag although this flag is not quantified in the standard product from ESA. Thus, it is difficult to decide which pixel is more or less reliable.

In May a wide spread bloom was observed in the Southern Bight between longitude 3°E and 4°E and a strong bloom with chlorophyll-a concentrations up to 25µg/l is observed along the Dutch coast and in near shore Belgian waters starting from outflow of the Rhine estuary by the *FerryBox*. In the German Bight a bloom was detected which was only touched by the ferry track at its southern edge. In the satellite image of 15th of May the broad peak at 5°E seems to lack the eastern shoulder. The quality flag was raised for the whole scene. We look here into the data anyhow but the agreement at the eastern shoulder is very likely the effect of sun-glint hampering MERIS. It occurs when the sensor is directed more towards the sun and higher winds causing waves to more often reflect direct sun-light towards the sensors. In this scene the glint effect is maximal between longitudes 5°E and 7°E.

Two weeks later on 28th of May the bloom in the Southern Bight region still persists with a small drift to the north. At this time the bloom along the Dutch coast shows a high patchiness indicating the break down of this bloom as also can be seen in the contour plot of the *FerryBox* data (figure 3). The pattern of the bloom is characteristic for the algal species *Phaeocystis* forming recurrent blooms in the North Sea when it approaches its culmination (pers. com. Rüdiger Röttgers) and was also observed by remote sensing in 2003 (Peters et al. 2005). This patchiness of chlorophyll-a fluorescence as measured along the track by the *FerryBox* only partly corresponds with the patterns of chlorophyll-a derived from remote sensing. The scene of this day is strongly influenced by sun-glint with the maximum between 6°E and 8°E. The low-quality flag is raised for almost the whole image. At the end of May the bloom in the German Bight already disappeared.

In general the comparisons showed a good agreement of main features between remote sensed data and *FerryBox* measurements. Some drawbacks are visible. A precise modelling where each water parcel measured by the ferry will be transported by tidal and wind induced currents to the time of the satellite overpass would improve the agreement of sharp rises and slopes but these data were at the time of study not available.

The difference in observed chlorophyll concentrations between *FerryBox* and remote sensed measuring is expectable. The algorithms used to produce the remote sensed standard coastal data are not yet tuned to their optimum. The methods to determine chlorophyll are very distinctive. In the *FerryBox* system a measurement of fluorescence is used to derive chlorophyll concentrations. This is highly influenced by physiological status of the algae. Remote sensing of chlorophyll is always a determination of absorption. The specific absorption is depending on species as well and may easily vary by a factor of two, for instance between the species *Chatonella* and the diatoms. On top of these uncertainties is a profound variation between measurements of chlorophyll in laboratory by means of HPLC in the order of 20% standard deviation possible, as round robin tests with several laboratories showed (Tilstone et al. 2002)

3.3. Algal bloom in the German Bight in August 2004

An extraordinary dense algal bloom was observed by the *FerryBox* in the German Bight in August 2004. As this bloom could be observed by remote sensing as well it is a convincing example how remote sensing data benefits from data of the *FerryBox* and vice versa.

This bloom was characterised by high chlorophyll concentration and extremely high oxygen over-saturation (up to 200%) as well as very high pH values up to 8.65 indicating an algae bloom with high growth rates. By collecting water samples from a ferry from Cuxhaven to Helgoland the dominant species was identified as the planktonic, phototrophic ciliate *Myrionecta rubra* which is well known for its extremely high rate of primary production (Crawford 1989). The water samples within the bloom contained chlorophyll-a concentrations up to 100µg/l measured by HPLC. The remote sensing image of the derived chlorophyll concentrations are shown in Figure 5.

Figure 5: Algal bloom in the German Bight on 3rd of August 2004: standard algal concentration for coastal waters derived from remote sensing images (1200m spatial resolution) taken by MERIS

Since the ferry travels on different routes on its east- and westbound trip (distance approximately 20 km) and the main bloom was observed northwards from the route, the *FerryBox* data during that time period of the algal bloom are shown in two columns (southern route: Harwich-Cuxhaven, northern route: Cuxhaven-Harwich) in figure 6. The ferry passes the shown parts of the transect on the southern route every second day in the early morning between 6:15am and 8:15am UTC and the northern route coming from Cuxhaven every second day between 3:45pm and 5.45pm UTC.

Figure 6: German Bight in August 2004: *FerryBox* observations on salinity, water temperature, chlorophyll fluorescence, dissolved oxygen saturation, nitrate and pH along the transects. Time (UTC) of data sampling: southern route 6 to 8 am, northern route

The comparison of the salinity transects shows higher salinities (32.8) on the southern route and lower values down to 30 on the northern route indicating stronger impact of riverine water with higher nutrient likely caused by the north-west directed outflow of the Elbe river. These observations are also supported by the nitrate data showing low concentrations, sometimes even below the detection limit on the southern route between 7.5 and 8.2°E. On the northern route the nitrate concentrations decrease during the bloom until 4th of August. Thus, on the northern route very strong chlorophyll-a fluorescence peak occur first observed on 28th of July together with corresponding high oxygen and pH values. In contrast, on the southern route a weak chlorophyll peak occurs only on 3rd of August. The measured oxygen and pH data partly show a different behaviour compared to the chlorophyll fluorescence on the transect. For instance, the oxygen peak between 7.7 and 7.9°E on the transect from Harwich to Cuxhaven (left column) on 1st of August is not reflected by a corresponding chlorophyll fluorescence. Similar high oxygen saturation levels up to 190% were detected between 7.5 to 7.7 °E on the route from Cuxhaven to Harwich on 28th of July but the shape of the chlorophyll curve is different with a maximum at 7.75°E on this transect. Whilst chlorophyll fluorescence and oxygen do not always correspond, the shapes of the oxygen and pH curves show a good correspondence.. This different behaviour of chlorophyll fluorescence on the one hand and oxygen and pH on the other hand may be explained by a biological production that takes place below the sampling depth of the *FerryBox*. Therefore, the productivity is not detected in the fluorescence signal of the *FerryBox* but enhanced concentrations are measured as the oxygen produced by primary production diffuses towards the surface. Similar findings were also reported by Hydes et al. (2005). The second reason for the missing correlation between chlorophyll and oxygen may be that the algal bloom already breaks down and sinks to the bottom but oxygen remains in the water column and it takes time (mainly controlled by wind driven atmospheric exchange) until it is in equilibrium with the atmosphere. This holds both for oxygen as well as for CO_2 which controls the pH. A third reason could be a drift of the species *Myrionecta rubra* to the surface after enrichment (driven by the wind) whereas the oxygen and pH signal in the water column still persists. Especially this species is well known for a pronounced surface or near surface aggregation (Crawford et al., 1997).

In order to get a rough estimate about the productivity of this bloom the oxygen anomaly; i.e. the difference between observed dissolved oxygen concentrations and the solubility of oxygen as a function of actual in situ temperature and salinity was calculated. Applying the parametrisation of the relation ship between gas exchange and wind speed from Wanninkhof (1992) the oxygen flux across the air/sea boundary was estimated by using wind speed data from NCEP Reanalysis data provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado, USA, from their Web site at http://www.cdc.noaa.gov. The temporal development of the oxygen anomaly, in combination with the estimation of the oxygen flux across the sea-air boundary was used to derive a measure for the net community production (Najjar and Keeling, 2000). Assuming that the productivity is in the same range within the bloom area (from satellite image estimated: approx. 880 km^2) the productivity adds up to 13.8 g C m^{-2} for the one week lasting *Myrionecta* bloom in August 2004.

Former studies investigating the primary production heading up with values between 240 to 500 g C m^{-2} a^{-1} (van Beusekom and Diel-Christiansen, 1994, observations) and 125 to 260 g C m^{-2} a^{-1} (e.g. Skogen et al., 1995, modelling) for the net community production within the southern German Bight. Thus, within one week of blooming *Myrionecta rubra* approximately 10 % of the annual mean net community production has been produced.. By applying the traditional monitoring methods those blooms are often undiscovered and therefore the productivity of the North Sea may be underestimated.

3.3.1. Remote sensing of the Myrionecta bloom

Myrionecta rubra contains an endosymbiont of cryptomonad identity which is responsible for the primary production associated with “red water” (Crawford, 1989). Therefore, the development of the red tide clearly could be observed by the derived red tide indexes as shown in figure 7 for the days in July and August 2004 during which remote sensing data were available from the German Bight. In the images the red tide first appeared on 30th of July 2004 according to the first high oxygen and chlorophyll-a observations by the *FerryBox*. On 2nd and 3rd of August the bloom expanded and drifted southwards where it passed the northern track of the ferry. On 5th of August the bloom partly disappeared and on 6th of August only a weak signal of the red tide was left. Unfortunately between 6th and 10th of August no *FerryBox* data were available due to a break down of the system. However, in the *FerryBox* data from the first cruise after this event on 11th of August the high chlorophyll and oxygen levels were completely eliminated.

Figure 7: Development of the Red Tide Index estimated from satellite images from 24th and 30th of July as well as 2nd, 3rd, 5th and 6th of August 2004. Time of overpass approximately 10am (UTC)

This red-tide is an example of a short term event (duration approximately one week) which can only be observed by high frequency monitoring such as by *FerryBoxes*. In combination with remote sensing also the spatial distribution can be estimated.

From the images the pixels of the tracks of the ferry can be extracted and compared with the data from the *FerryBox*. However, in such strongly tidal influenced regions as the German Bight the drift of water-masses between measurements by the *FerryBox* and time of satellite overpass has to be calculated. Each position of the *FerryBox* was corrected by a hydrodynamic model and transformed to the time of the satellite image. As an example, figure 8 shows the original position of *FerryBox* data and the drifted position of the tracks (Harwich-Cuxhaven and Cuxhaven-Harwich) at the time of satellite image on 2nd of August 2004.

Figure 8: Original position of *FerryBox* measurements and position of the water masses after correction of the drift by a hydrodynamic model at the point in time the satellite image has been taken (2nd of August 2004, 10:30am UTC)

In case of the transect Cuxhaven-Harwich (start of the ferry in Cuxhaven on 1st of August 3pm) the time lag between the satellite image and the *FerryBox* measurements was between 19 and 22 hours before the satellite image was taken. During the transect Harwich-Cuxhaven (start of the ferry in Harwich on 2nd of August 3pm) the satellite over passed the area between 19.4 and 20.4 hours later. In longitude and latitude the drift of the water masses can be in the range of 0.05° (~ 5.5 km). The main forces of the drift are tide and wind. The correct position of sampled water masses by the ferry is very important in case the track of the ferry touches the edge of the algal bloom.

With the corrected positions of the *FerryBox* measurements the extracted remote sensing data from the satellite image can be compared with the *FerryBox* results. Figure 9 shows the comparison from 3rd of August 2004.

Figure 9: Comparison of chlorophyll-a fluorescence of the *FerryBox* with the extracted chlorophyll-a data (algal-2) from the satellite image at 3rd of August 2004.

The curve of the *FerryBox* data fits good with the curve of the extracted pixel from the MERIS data. The maximum chlorophyll has the same magnitude of about 30 µg/l. The slightly different position and different shape of the peaks may be explained by the time lag between the two data sets (in such a high variable algal bloom changes in chlorophyll values with time are to expected) and uncertainties in the calculated position correction by the drift model. It is noticeable that the shape of the oxygen curve fits slightly better to the algal-2 curve than to the chlorophyll-a fluorescence from the *FerryBox*.

4. Conclusion

FerryBox systems proved to be a cost effective tool for monitoring coastal and shelf seas with an extensive set of water quality parameters (oceanographic as well as biological relevant data e.g. chlorophyll, oxygen, pH and nutrients). The data availability is nearly independent from weather conditions exceptional extreme storm events and a full coverage over space and time can be achieved as in contrast to surveys by research vessels. The high frequent sampling of data allows to detect even short-term events as shown for the red tide in August 2004 which would be not have been detected by conventional monitoring.

The spatial restriction to the transect can be overcome for certain parameters such as chlorophyll-a and suspended matter by combining *FerryBox* measurements with remote sensing. Although the detection methods for chlorophyll-a are different (*FerryBox*: in-vivo fluorescence, remote sensing data: derived from absorption and scattering from the surface layer) the comparisons of the chlorophyll data from *FerryBox* and MERIS show that the results of both methods in most cases are comparable within the limits of the used methods. This is especially remarkable for such difficult regions like the coastal zone of the North Sea with high contents of other constituents influencing the measured reflectance of remote sensing. However, at some specific situations some strong differences between both methods still occur. Thus, the algorithms have to be improved. It can be expected that with the next generation of site specific algorithms for deriving chlorophyll-a concentration from reflectance remote sensing data are even more reliable. Since the *FerryBox* also allows automated sampling of water samples along the track these samples can be used together with the continuous in-vivo chlorophyll-a fluorescence measurements to get a dense data set of ground truth data for calibration and validation of remote sensing. This will provide a considerable improvement in the accuracy of the calculated chlorophyll data. Thus, the spatially covered information can be provided with competent accuracy even for Case 2 waters.

The results obtained in this investigation show that the assimilation of *FerryBox* data along a transect with satellite observations increase the information value compared with the use of either of the two individual information sources. By using *FerryBox* systems on more lines crossing the area of interest on different tracks the information density about the water quality could be significantly improved. In addition, by including the information about many other water quality parameters measured by the *FerryBox* (e.g. nutrients etc.) a much deeper insight in the processes controlling the water quality of coastal waters can be obtained.

The value of such a combination of ship-of-opportunity data with remote sensing can even be improved further by including numerical model data: The assimilation of these data with numerical models can be used to simulate the circulation of the water masses in order to fill the gaps between remote sensing and transect data in time and space. For instance, the disadvantage of the restricted availability of satellite data in areas such as the North Sea due to cloud coverage can be overcome by applying a numerical model with data assimilation which fills the gaps between the satellite passes.. This investigation showed already how important the hydrodynamic models in such strongly tidal influenced areas as the North Sea are for a comparison between different measurements with different spatial resolution at slightly different times. More research has to be carried out in this field, e.g., to include processes such as algal growth and degradation which may occur in the time span between the different measurements.

Since both methods used in this investigation are restricted to the water surface conventional monitoring methods by buoys and research vessels are still necessary at strategic locations.

This will be necessary, for instance, to get information about the change of water constituents within the depth profile.

One of the most important aspects of the relatively new *FerryBox* technology is its role in not only improving remote sensing products but as well fostering the understanding of marine processes: The lack of reliable temporal and spatial high resolved biological data hampered in the past the assimilation into numerical models. With the potentials of the *FerryBox* systems this situation could be improved in future and severe progress will be possible in marine ecosystem modelling resulting in an operational integrated monitoring system by data assimilation of in-situ data as well as remote sensing observations.

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