Wetlabs NTU instrument mounted on rod for deployment on floating buoy.

Photo DHI

CHALLENGES OF OPTICAL BACKSCATTER MONITORING IN MIXED SEDIMENT ENVIRONMENTS

Optical backscatter instruments (OBS) are very popular instruments for measuring suspended sediments in the field. In the following, an analysis of the sensitivity of optical backscatter (OBS) measurements to sediment grain size and the applicability of OBS measurements in mixed sediment environments is given.

In this article, an analysis is given based on laboratory tests, numerical analysis and field measurements. As described in Downing (2006), OBS instruments are simple and effective devices for measuring turbidity. The signal however needs a transfer function to convert turbidity to total suspended matter concentration (TSMC). The transfer function is dependent on several variables, notably the grain size distribution. Downing (2006) states that there is an almost linear relationship between turbidity (e.g. given in NTU) and TSMC for specific sediment properties. However, as demonstrated in Bundgaard et al. (2011), suspended sediment properties may shift in time either due to flocculation or through erosion and deposition, which may result in erroneous results as calibrations are usually made for stationary conditions (Downing, 2006).

The present analysis demonstrates that for stationary sediment properties, there is a linear relationship between turbidity and TSMC, but also that the relation is not linear if the sediment properties shift in time. The conversion factors are shown to tend to an exponential function of median grain size and thus the calibration function between turbidity and TSMC for a mixed sediment environment also becomes exponential. This is demonstrated through thorough analysis of excessive field measurements of suspended sediment dynamics in a mixed sediment non-tidal lagoon on the Baltic coast in southern Denmark.

With the presented findings, it is also shown that for mixed sediment environments, it is not enough to take water samples for conversion during calm weather because the calibration factor will shift with turbulence intensity, causing larger grain sizes to be suspended and affecting the stability and size distribution of flocs. It is therefore necessary to take water samples under a broad range of occurring conditions. The analysis shows that the conversion curve for mixed sediment environments is exponential with growing conversion factors for increasing grain sizes consistent with smaller light scattering. An indicative method for assessing grain sizes based on the calibration factors is given and finally, the findings are validated using an example from the field.

Introduction

Sediment measurements in shallow coastal waters and lagoons are often associated with challenges relating to determining the actual sediment concentration levels. Sediment concentrations can be determined by a range of methods and all applied instruments have both strengths and weaknesses. Some of these are described in literature like Downing (2006) and Sutherland et al. (2000). Generally, all light scattering devices require calibration and they are furthermore sensitive to biofouling. Apart from sediment concentration (TSMC), almost all instruments are also sensitive to shifting grain size distributions, sediment grain shapes, sediment reflectivity, suspended organic material and the colour of the water. Of these, grain size distribution is the most important factor. The effect has previously been documented by various authors (Battisto et al., 1999; Black and Rosenberg, 1994; Conner and De Visser, 1992; Ludwig and Hanes, 1990; Sutherland et al., 2000). In the mentioned studies, only Battisto et al. (1999) used natural mixed sediments while the remaining studies did not include the effect of shifting sediment composition in the water column.

If sampled and treated properly, water samples and subsequent filtrations is the most reliable measure to give the correct sediment concentration. The downside is that physical presence is needed to take the samples which can be costly and challenging in rough weather. Therefore, and to achieve a higher data coverage, it is attractive to setup systems which are self-recording and eventually online, and which can operate in shallow lagoons without the need for physical presence during the campaign. This, however, leads to a new set of challenges as the applied instruments must be able to measure changing sediment concentrations with varying grain size distributions. One of the most applied instruments is the OBS (Downing, 2006; Sutherland et al., 2000). The challenge for this instrument becomes how to make an optimum transfer function between the OBS reading in NTU and the TSMC in mg l^{-1}. The correlation is expected to be linear for fixed sediment properties but if the sediment properties change over time, little is reported on the transfer function to be applied. The present article studies the correlation between grain size distribution and calibration coefficients for OBS measuring devices under static sediment conditions only varying concentration levels and under dynamic conditions, and shows both variations of concentration levels and grain size distributions.

In many studies, the turbidity is obtained from optical instruments, and during recent decades, most notably by optical backscatter (OBS). However, OBS devices do not measure the sediment concentration directly but rather a calibrated unit like NTU or FTU. The calibrated unit must be transferred to true sediment concentrations (TSMC) using manually collected water samples. Turbidity signals obtained from the OBS device are subsequently correlated to the TSMC results from the water samples and from this correlation, a transfer function is obtained (Downing, 2006). The transfer function is not generally valid as it is dependent on several variables including but not limited to: sediment grain size distribution, sediment colour and occurrences of biological substances. The transfer function therefore changes both in time and space, and therefore needs to be updated regularly.

The data used for the study have been gathered partially from an online monitoring system placed in the non-tidal Rødsand lagoon at the coast of Lolland in southern Denmark and partially from experimental geotechnical sampling and investigations in the adjacent Fehmarnbelt related to the planning of the Fehmarnbelt Fixed Link between Denmark and Germany.

The static conditions were studied in the laboratory and transfer functions were developed for different sediment types. This lead to an improved understanding of the expected variation that could be found in situ. The assumption was then validated based on field measurement campaigns from the Rødsand lagoon.

Materials and methods

The laboratory works

A single OBS sensor was tested with several sediment samples in the laboratory. The aim was to establish the response of the sensor to different sediment types with constant grain size distributions.

The test setup consisted of a 10 litre black container filled with 8 litres of saltwater with 8 PSU (practical salinity unit) and a magnetic stirrer. The OBS sensor was mounted centrally in the container. The water was allowed to rest for about one hour before the test began to limit the effects of air bubbles.

TABLE 1

Overview of sediment median diameters (d_{50}) tested.

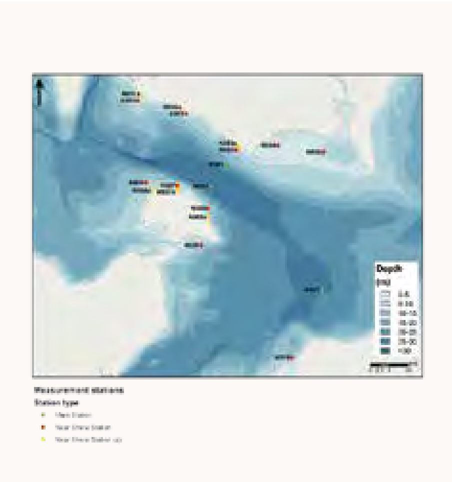
Test ID	d_{50} (mm)
A008	0.002
A014	0.005
A015	0.01
NS06	0.01
NS08	0.02
NS02	0.04
A003	0.05
A002	0.09
A010	0.09
A001	0.1

The magnetic stirrer was started and readings from the OBS in clear water was recorded. As the test progressed, small amounts of sediment was subsequently added and the OBS response was continuously logged. Water samples were taken during the test to establish a transfer function. The grain size distributions of the applied sediment had been established through laser diffraction analysis prior to the test. The OBS response was tested for increasing concentrations of a total of nine different median grain sizes (see Table 1).

After each test, the correlation between turbidity and TSMC was established for the specific sediment. In this way, a curve for conversion factors as function of median grain size was established by plotting NTU against TSMC and establishing a linear correlation.

Field work

A series of measurement campaigns were conducted in Rødsand lagoon in southern Denmark and sediment dynamics were studied using several instruments including Wetlabs NTU, Sequoia LISST-100x and RDI ADCPs. Initially, it was attempted to create transfer functions for the OBS sensors by extracting water samples on planned service visits. Eventually, it was found that service visits were always planned in reasonably calm weather situations and therefore only



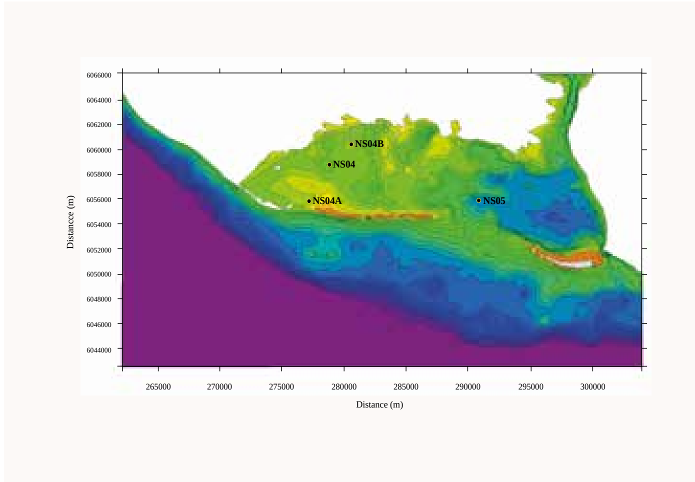


FIGURE 1

The sediment investigations in Rødsand were carried out as part of a larger program in connection with the planning of the Fehmarnbelt fixed link. Studies in Rødsand lagoon were more intensive due to the protection status of the area.

low concentrations were represented in the water samples. To overcome this constraint, it was decided to mount automatic water samplers on each monitoring station. Each water sampler contained 24 one-litre samples. These water samplers were connected to an online system in a way, so the water samples could be extracted based on a message from a remote location. This made it possible to extract water samples based on the NTU signal which could be followed on the online system. In this way, it was possible to extract a total of 144 water samples covering both calm weather and six rough weather events.

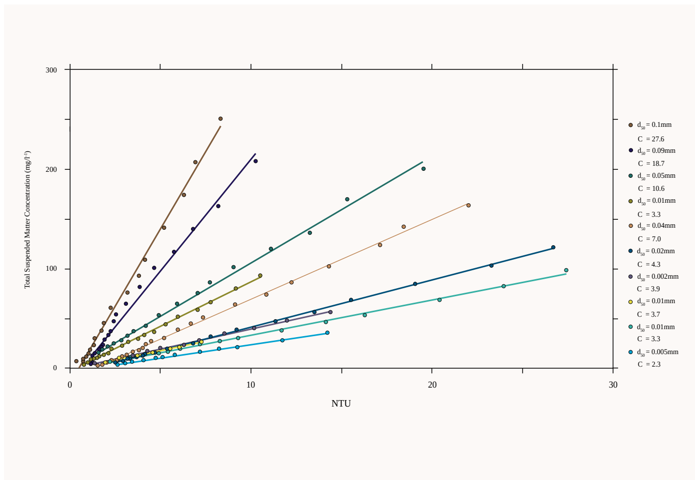


FIGURE 2

Results of applying different grain size distributions to the same OBS device. The slope of the transfer function increase with increasing median grain size. This is important when applying transfer functions in area with varying grain sizes.

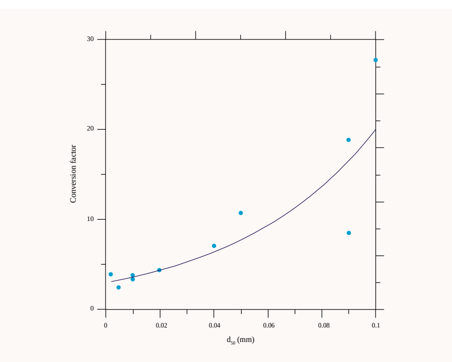


FIGURE 3

The graph shows the interdependency between the correlation factor and the mean grain size. When a range of correlation factors have been obtained with different mean grain sizes it becomes clear that the dependency of grains size is of importance when investigating the output from the sensors.

The water samples thus included a large range of sediment concentrations. All water samples were analysed for TSMC and used for conversion of the OBS measurements. An overview of the measuring stations is given in Figure 1. All the results were plotted as shown in Figure 2 and used to establish correlations between NTU and TSMC during both calm and rough weather situations.

Results

Laboratory results

In Figure 2, a range of analyses are shown. Each colour and line show the result for one specific sediment sample, characterised by its mean grain size which is indicated. The results show that for all specific samples tested, a linear correlation can be used to determine a calibration factor, and that the correlation factor generally increases with increasing median grain size values. Applying d_{50} as a proxy for the grain size distribution of the ten tested sediment types, a function for the correlation factor can be worked out which is shown in Figure 3.

Automatic water sampling

The results of the field tests with the automatic water sampler are evaluated for

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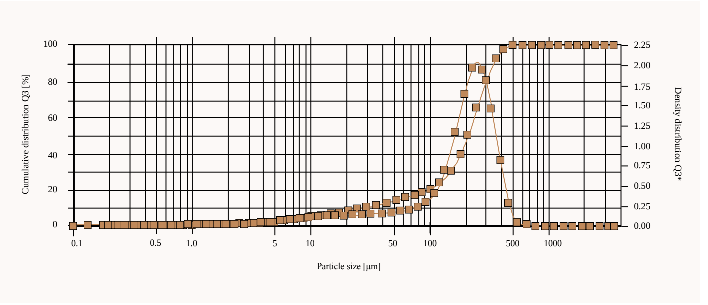

FIGURE 4

At site NS04a, the grain size distribution of the seabed is a mixture between cohesive and coarser material.

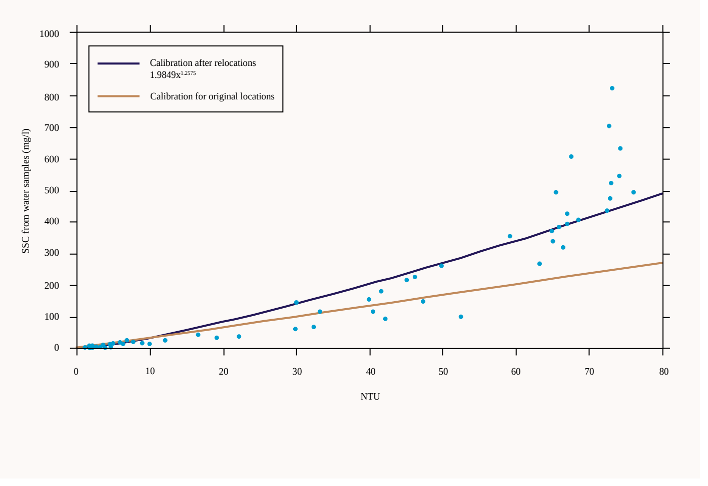

FIGURE 5

Calibration correlation. As expected from the laboratory tests shown in Figure 3, the conversion correlation is exponential which corresponds well with the mixed sediment environment.

position NS04a (see Figure 1). The seabed at NS04a bed is a mixed bed with mainly fine sand but also with coarser materials as well as silt and clay. Figure 4 shows dispersed grain size distribution of a grab sample extracted at the site. This qualifies as a mixed sediment environment as it contains significant parts of both cohesive and non-cohesive material. In the following, the calibration and the measurements made at this station will be used.

Water samples at NS04a in Rødsand lagoon were taken using an automatic water sampler. The samplings were triggered automatically in order to cover a variety of both calm periods and periods with more rough wind and wave conditions. The measured TSMC were plotted against the NTU values from the OBS and the results for station NS04a are given in Figure 5.

To show the variability of the grain size distribution during stormy weather, the grain size distribution was measured at NS04a using a laser scattering LISST-100x instrument (see Figure 6). The grain size measurements show that the grain sizes observed in the suspended sediment vary significantly over time which further supports the need for applying a calibration factor that takes varying grain sizes into account when measuring in a mixed sediment environment.

Discussion

Laboratory tests

If the measured sediment has a fixed and relatively uniform structure with respect to grain size distribution, the conversion from OBS-NTU values to sediment concentrations (TSMC) becomes a linear function. This is supported by Downing (2006). All sediment types show identical near linear behaviour although calibration factors vary, generally showing increasing calibration factors with increasing mean grain sizes of the measured sediment (shown in Figure 2).

The observed increase of the calibration factor with increasing median grain size means that light backscatter is decreasing with increasing grain size. This is consistent with the scattering being a function of the surface area of the sediment (Battisto et al., 1999; Downing, 2006; Ludwig and Hanes, 1990).

Figure 3 and Figure 5 show that the conversion factor can be expressed as an exponential function of the median grain size. This means that if one knows the median grain size or even the characteristics of changing particle sizes of mixed sediments, it is possible to use an exponential transfer function and get a higher accuracy with respect to OBS-based measurements of true suspended sediment concentrations (TSMC).

If the conversion factor for a given location is known and the concentrations are not excessive, the conversion factor might be used to give an indication of the grain size distribution and thereby the amount of fines. The argument for this is that the fines account for most of the light dampening so if very fine material is present at a given site, the conversion factor will be low whereas high

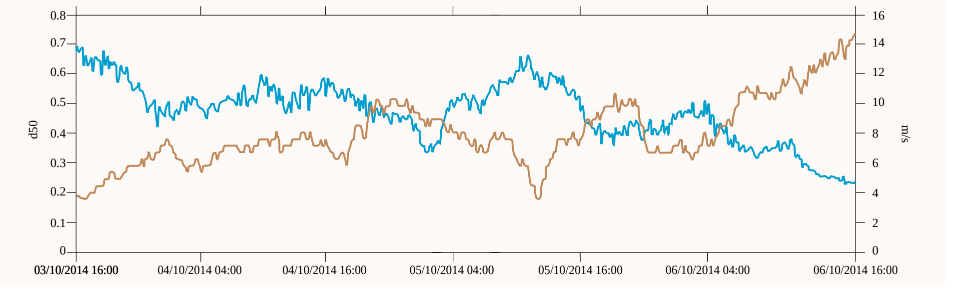

FIGURE 6

Grain size variation and wind speed variation at position NS04a. At this site, the median grain size is inversely correlated to the wind speed. The wave energy destroys the fragile flocs resulting in a decreasing size during rough periods. The flocs reform quickly as the wind speed decreased.

TABLE 2

Interpretation of grain size distributions from calibration factors.

Calibration factor	Material
<5	High amounts of fines
5–10	Medium to low amounts of fines
>10	Well graded sand with low amounts of fines

calibration factors indicate presence of coarse materials. In Table 2, an interpretation of the relation between grain sizes and conversion factors is suggested.

Judging from Table 2 and the calibration curve in Figure 5, the suspended sediment should consist of quite a bit of fines, indicated by the lower parts of the calibration curve, as well as of coarser materials, indicated by the steeper right part of the calibration curve. This is consistent with the found bed composition illustrated in Figure 4 and the observations of sediment being eroded and deposited sequentially during rough weather periods. The variation in conversion factors and the shape of the calibration curve covering the full spectrum of hydrodynamics is of high importance in a mixed sediment environment where the grain size distribution of the suspended sediment varies. In such environments, a varying conversion factor must be considered because amounts of coarser grain sizes will increase substantially with higher currents and wave intensity. Simultaneously, the floc size of cohesive sediments can temporarily decrease due to increasing turbulence levels (Bundgaard et al., 2011). In such an environment, the optimum conversion function will be exponential. Practically, this means that water samples will have to be taken under all occurring conditions to get an optimum calibration. Otherwise, the correlation may be erroneous.

The error will vary from place to place as a function of local sediment characteristics and wave conditions, and the possible error in Rødsand lagoon can be quantified based on data shown in Figure 5. The error will result from the difference between applying a standard linear calibration factor based on standard calm weather water samples (the orange line in Figure 5) and applying the exponential calibration equation based on water samples covering all conditions (the black line in Figure 5). The calculated error in percentage at increasing suspended sediment concentrations is shown in Figure 7.

The error varies with sediment concentrations consistent with the expected change in grain size distribution during storms. The error is significant for larger concentrations and should be considered before choosing the approach for calibrations of the OBS measuring device in mixed sediment environments.

Conclusions

Studies were carried out, including comprehensive sampling and analyses of water samples, to convert NTU signal from OBS sensors to total suspended matter concentration using water samples. The analysis showed that the conversion factor is strongly dependent on grain sizes in suspension. This is consistent with the findings in literature (e.g. Battisto et al., 1999; Black and Rosenberg, 1994; Conner and De Visser, 1992; Downing, 2006; Ludwig and Hanes, 1990)N.C., during October 1997. The distinct scales of resuspension for sand and mud at this location allow concentrations of both size classes to be determined simultaneously from a single OBS time series. For this study, OBSs were calibrated separately using sand and mud collected off Duck, N.C.. OBS voltage gain associated with mud was found to be an order of magnitude larger than that for sand. Based on this calibration, it was shown that the mass concentrations of particles smaller than 63 microns pumped off Duck during October 1997 were consistent with the lowest 1st to 5th percentile of voltage recorded by the OBSs. Calibrated OBS response above this background turbidity was consistent with pumped sand concentration as long as corrections were made for (i. Tests with various natural sediments with varying grain size distributions show that the individual conversion factors for each sediment type are linear functions of concentrations, where the conversion factors themselves are exponential functions of d_{50} for the individual sediments. The precise relation between d_{50} and the conversion factors is most likely a function of specific local sediment characteristics and local wave and current conditions. The conversion factor should therefore be regarded site specific and cannot be generalised. Analysis show in conclusion that for mixed sediment environments, it is not sufficient to extract water samples for conversion during calm weather. The conversion approach has to take into account that during rough weather, substantial amounts of coarser sediment can be mobilised and floc sizes temporarily change. Therefore, the conversion factor will shift with more intense hydrodynamics. To determine a reliable local conversion for an OBS in a mixed sediment environment, samples are needed under a wide and representative range of conditions. The achieved data allow for an indicative method for assessing median grain sizes based on the conversion factors. Disregarding the effects of changing and variable grain sizes of sediments in suspension on the conversion of OBS values, the error is proven significant especially at higher sediment concentrations.

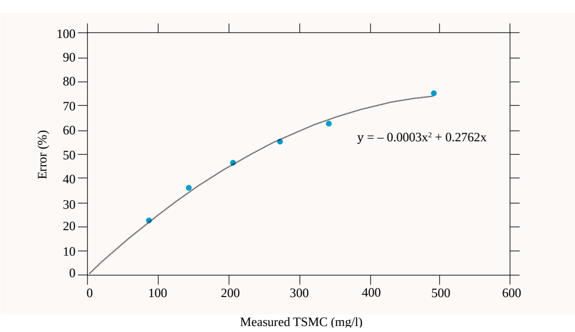

FIGURE 7

Error in % between using a standard calibration equation a more realistic exponential equation.

Summary

Optical backscatter instruments (OBS) are very popular instruments for measuring turbidity and suspended sediments in the field. An analysis of the sensitivity of optical backscatter (OBS) measurements to sediment grain size and the applicability of OBS measurements in mixed sediment environments is given based on laboratory tests, numerical analysis and field measurements.

As described in Downing (2006), OBS instruments are simple and effective devices for measuring turbidity. The signal however needs a transfer function to convert turbidity to total suspended matter concentration (TSMC). The transfer function is dependent on several variables notably the grain size distribution. Downing (2006) states that there is an almost linear relationship between turbidity (e.g. given in NTU) and TSMC for specific sediment properties.

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An indicative method for assessing grain sizes based on the calibration factors is given and finally, the findings are validated using an example from the field.

Klavs Bundgaard
Klavs Bundgaard holds an Msc in civil engineering from Technical University of Denmark specialised in Coastal and Ocean Engineering. He has a strong background working with fine grained sediments and measuring techniques, first as senior hydraulic engineer with DHI and later as team leader, senior consultant, and senior project manager for SWECO and NIRAS. Klavs was the project manager for the spill investigations for the EIA for Europe's largest marine infrastructure project, Fehmarnbelt for DHI and has been involved in numerous marine studies on cohesive sediments in Denmark and around the world, affirming his expertise in modelling and measuring cohesive sediments. Klavs is also a member of CEDA's environmental committee.

Ulrik Lumborg
Ulrik Lumborg started working for DHI in 2005 after finishing a PhD from University of Copenhagen on modelling of cohesive sediment dynamics. In the first years, Ulrik focused on numerical modelling issues. After some years he became involved with survey work and has since studied a number of sites based on a combination of monitored data and numerical modelling. His main works during recent years have been with the environmental impact assessment of the Fehmarnbelt Fixed Link as well as spill monitoring on dredging projects throughout Europe.

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Lotte Nyborg

As a geographer and remote sensing specialist, Lotte Nyborg has broad experience with sediment-related issues and marine mapping in Denmark and around the world. Lotte played an important role in developing the complex QA and filtering procedures used for the OBS measurements in the Fehmarn Belt Study. With more than 15 years in DHI GRAS, she has experience in remote sensing analysis in both terrestrial and marine environments including coastal studies, mapping of suspended sediment as well as marine habitat mapping based on satellite imagery.

Bjarne Holm Jakobsen

Prior to joining Femern A/S in 2011 as an environmental coordinator, Bjarne Holm Jakobsen received his MSc and PhD in Geography and further Master's courses in International and European Environmental Law at the University of Copenhagen. As associate professor, head of department and research station manager, he has been involved in many research and development projects within environmental sciences, focusing on the marine area and land-ocean interactions. He is currently responsible for the transnational coordination of environmental management for planning and construction of the Fehmarn Belt Fixed Link and is part of research activities and methodological studies discussed in the present article.