

CHAPTER 4



All quiet on the sea bottom front? Lessons from the morphodynamic monitoring

Dries Van den Eynde, Matthias Baeye, Robin Brabant, Michael Fettweis, Frederic Francken, Piet Haerens, Mieke Mathys, Marc Sas and Vera Van Lancker

The impact of the construction of the offshore wind farms on the turbidity was local and temporary, with no significant difference between the before and after situation. Erosion pits were formed, both around gravity based foundations and monopiles, though erosion protection provided the necessary stability. Dredging/filling works were more complex than expected. Large volumes of sand were lost and sand pits did not refill naturally. In dune migrating areas the coverage of export cables could not be guaranteed. As a result they are now buried 1 m below the base of the dunes.

INTRODUCTION

Wind turbines may affect the marine environment in various ways (e.g., Petersen and Malm, 2006). For sediment- and morphodynamics this relates mainly to: (1) increases in turbidity; (2) scour around the foundations; and (3) erosion around the cables (e.g., Carroll et al., 2010).

For Belgian waters, the installation of wind farms was new, with large uncertainties in the estimations of environmental impact. The concession zones fall within offshore areas where natural turbidity is relatively low, hence, given the large-scale works, increases in turbidity needed quantification. Formation of scour or erosion pits was expected, because of the installation of gravity based foundations (GBF) for the first six wind turbines on the Thorntonbank. For the Belwind wind farm, consisting of monopiles, erosion

pits around the monopiles were first allowed to develop, and were then filled with an erosion protection. The fact that the formation of erosion pits was accepted, required monitoring of both the erosion pits and turbidity levels.

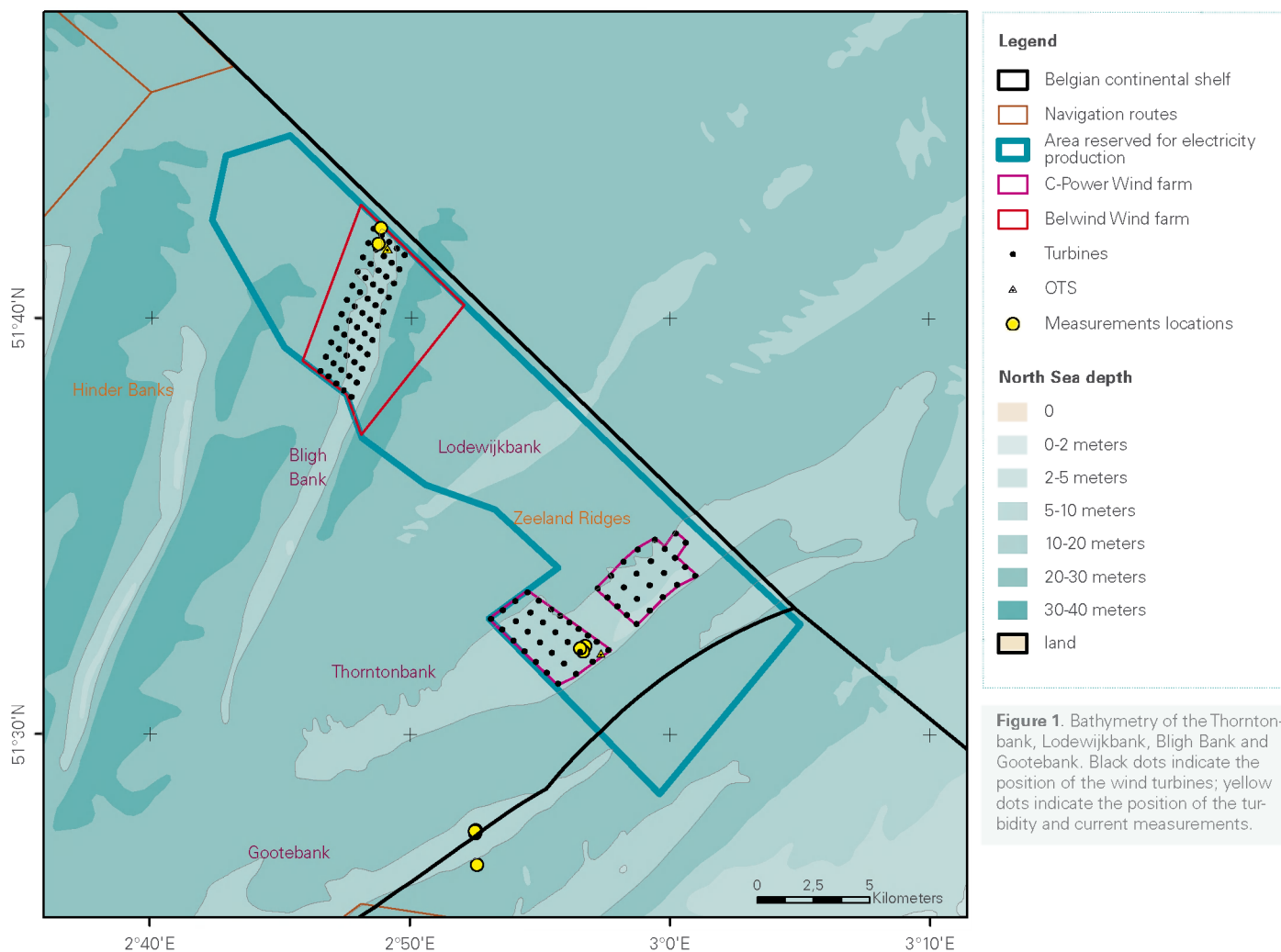
On the Thorntonbank, dredging works were needed for seabed levelling in the areas of large sand dunes. Part of the dredged sand could be re-used to infill the GBF itself, as back-fill of the foundation pit or as backfill of the temporary trench that was dredged for the cable-crossing of the sea-lane. It was expected that, finally, a net amount of 385,000 m³ of sand would be disposed within the concession area. It could be expected that the transport of these sand piles would redistribute the sand towards the possible erosion pits, but monitoring was necessary to study this process.

Finally, the coverage (i.e. 1 m below the seabed) of the export cables to the shore was of concern. Sand dune migration was known to occur (e.g., Lanckneus et al., 2002); hence uncertainty arose on the longevity of coverage of the export cables.

ENVIRONMENTAL SETTING

The Thorntonbank, Lodewijkbank and Gootebank are coast-parallel sandbanks, belonging to the Zeeland Ridges, whilst the Bligh Bank is one of the Hinder Banks, lying more obliquely to the coastline (Figure 1). Minimum water depths are close to -6 m (below the lowest water level) for the Zeeland Ridges and -9 m for the Bligh Bank. In the gullies, -28 m up to -36 m is reached, respectively. Sandbank lengths are 15 to 30 km, while the width varies from 1 km for the Bligh Bank, to up to more than 4 km for the sandbanks of the Zeeland Ridges. Sandbanks are covered with large to very-large dunes with heights varying from 2 m to 6 m (Van Lancker et al., 2007). Median grain sizes of the sandbanks range between 300 μm and 350 μm (Verfaillie et al., 2006).

The hydrodynamics in the area are dominated by semi-diurnal tides with a spring tidal range of 4 to 5 m. Tidal current ellipses are elongated, with a southwest-northeast axis. Flood and ebb peak currents are oriented towards the northeast and the southwest, respectively. Surface peak currents reach up to 1 m/s; flood and ebb currents are competitive in strength, though the ebb period lasts longer. Flood currents are strongest along the southern slope of the Zeeland Ridges, whilst the ebb is strongest along the steep side of the Bligh Bank. An ebb oriented sand transport is observed along the gentle slope of the Zeeland Ridges, though preceding hydro-meteorological conditions may alter sand transport directions consistently (Lanckneus et al., 1993).



MONITORING TURBIDITY

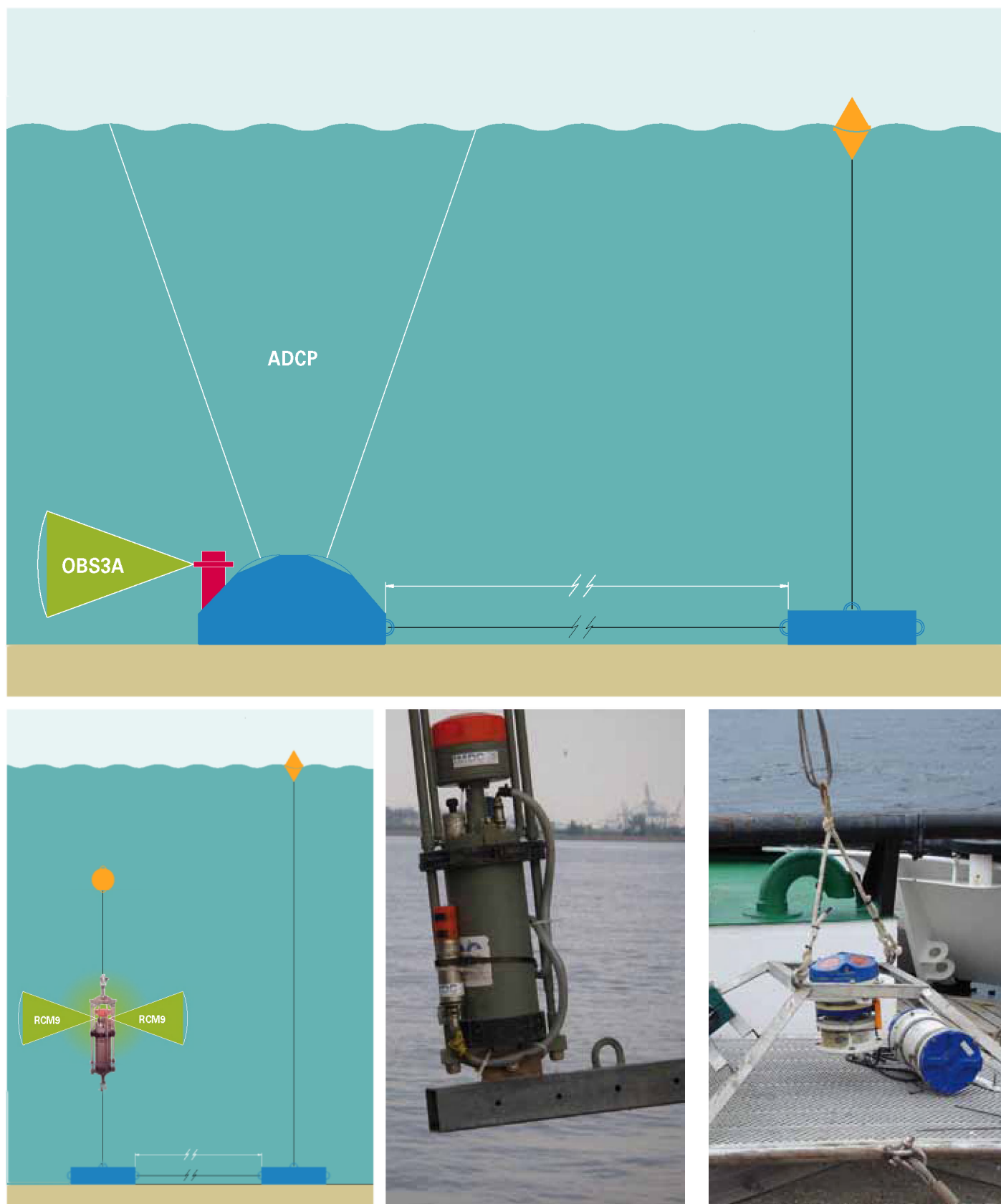
The first part of the monitoring aimed at evaluating increases in turbidity, due to the installation works (e.g., of the GBFs on the Thorntonbank) or during the operation of the wind farms (e.g., as a result of the dynamic erosion protection in the Bligh Bank wind farm). From the monitoring specifications, measurements of currents, waves and turbidity were mandatory near the wind turbines before, during and after the works. Similar measurements were carried out at a nearby non-affected site, for which the Gootebank was chosen. A period of at least 15 days was chosen to cover a spring-neap tidal cycle. International Marine and Dredging Consultants (IMDC) executed the monitoring for the C-Power wind farm; RBINS-OD Natural Environment the one for Belwind. On the Thorntonbank and on the Gootebank, measurements were performed using a bottom-mounted Acoustic Doppler Current Profiler (ADCP) (IMDC 2008a; 2008b; 2008c; 2009a)

(Figure 2). This device measured current profiles over the entire water column, water level and wave heights. An optical back scatter sensor (OBS), measuring turbidity, was mounted on the ADCP at about 0.7 m above the bottom. Furthermore, an RCM9 current meter (Figure 2) was used as backup for current, turbidity and water level measurements. To convert the values from the OBS into material in suspension in mg/l, the instrument was calibrated in the laboratory using fine material from the harbour of Oostende. To estimate the effect of the construction works of the first phase on the suspended particulate matter (SPM) concentration, three measuring campaigns were executed: before (February-March 2008), during (June-July 2008) and after the works (June-July 2009). The positions of the measurements were indicated in Figure 1. The instruments were deployed along the gentle slope or on the top of the sandbanks in water depths of around -16 to -17 m.

Statistical analyses of wave, current and SPM concentration data was performed (IMDC, 2009b). Results showed that SPM concentration was low, both on the Thorntonbank and Gootebank. During the winter period, the median SPM concentration was 9 mg/l on the Gootebank and 4 mg/l on the Thorntonbank. High turbidity was generally correlated with higher wave conditions. During the summer periods, the median SPM concentration on the Thorntonbank and Gootebank was very low (1 to 2 mg/l). Overall,

the range of SPM values was similar for both the Thorntonbank and Gootebank. No clear influence from the dredging works or from the installation of the GBF foundations was found in the data.

Figure 2. ADCP and RCM9 as deployed on the Gootebank in water depths of -17 m (IMDC, 2010).



On the Bligh Bank and on the Gootebank, two tripods (Figure 3) were used for measuring SPM concentration, suspended particle size distribution, salinity, temperature and current velocity. Water depths were around -26 m on the Bligh Bank, around -24 m on the Gootebank. An Acoustic Doppler Profiler (ADP) measured the velocity profile from the top of the tripod to the bottom; an Acoustic Doppler Velocimeter (ADV) measured the velocity near the bottom with a high frequency; a CTD conductivity sensor system measured temperature, salinity and water depth; two OBS sensors measured turbidity at 0.2 m (SPM1) and 2 m (SPM2) above the bottom; finally a LISST 100C measured the particle size of the material in suspension. The ADP housed an altimeter, to measure the distance from the measuring point to the bottom, hence providing information on seabed evolution and

thus indirectly on sediment transport. Furthermore, from the backscatter of the ADP, also SPM concentration profiles were derived. To measure current profiles from the bottom to the water surface, a bottom-mounted ADCP was deployed nearby the tripod. Water samples were taken and filtered to obtain SPM concentration, further used for the calibration of the OBS measurements.

Measurements were done before (June-July 2009), during (October-December 2009) and after the works (June-July 2010 and March-April 2012). Measurements before and during the works were executed simultaneously on the Bligh Bank and on the Gootebank. After the works, only measurements at the Bligh Bank were performed.

Figure 3. Two tripods and two ADCPs ready for deployment on the Bligh Bank and the Gootebank (RV Belgica).



Figure 4 shows SPM mass and volume concentrations, transmission, median particle size, temperature and salinity at the Bligh Bank, before the start of the construction works. Also the significant wave height at the Zuidwest Akkaert (Meetnet Vlaamse Banken, Flanders Hydrography) is shown. Figure 5 shows SPM concentration profiles (from the backscatter of the ADP) and seabed evolution (from the ADP altimeter), after the execution of the construction works at the Bligh Bank. SPM concentrations were very low ($< 5 \text{ mg/l}$) at both locations and during almost all campaigns (Van den Eynde et al., 2013). SPM concentrations showed a clear correlation with spring-neap tidal cycle variation, without a clear visible influence of wave activity. This is also shown in the scatter plot between significant wave height and SPM concentration on the Bligh Bank after the works (Figure 6). Remark that before and after the works, the significant wave heights were relatively low, with waves up to 2.2 m, before the works, and up to 2.0 m,

after the works. Only during the works, wave heights were higher from November, 14th until December, 1st, 2009, with peaks higher than 3 m on December 1st.

Altimeter data showed a seabed variation of several tens of centimetres, probably due to migrating bed forms. During spring tide, the bottom is lower than during neap tide, possibly caused by higher erosion.

At the Bligh Bank and Gootebank variations in SPM concentrations were tidally-driven. The mean SPM concentration was higher at the Gootebank than at the Bligh Bank. At the Bligh Bank, the mean was somewhat higher after the works than before the works. However, no indication was found that the construction works resulted in a significant increase in turbidity.

Figure 4. Variation in SPM concentration (from the OBS sensors); SPM volume concentration, median particle size and transmission (from LISST); and temperature and salinity (from CTD sensor) at the Bligh Bank (-26 m water depth) from June, 24th, 2009 until July, 14th, 2009. Wave height at Zuidwest Akkaert (from Meetnet Vlaamse Banken, Flanders Hydrography). SPM1 at 29 cm above the bottom, SPM2 at 234 cm above the bottom.

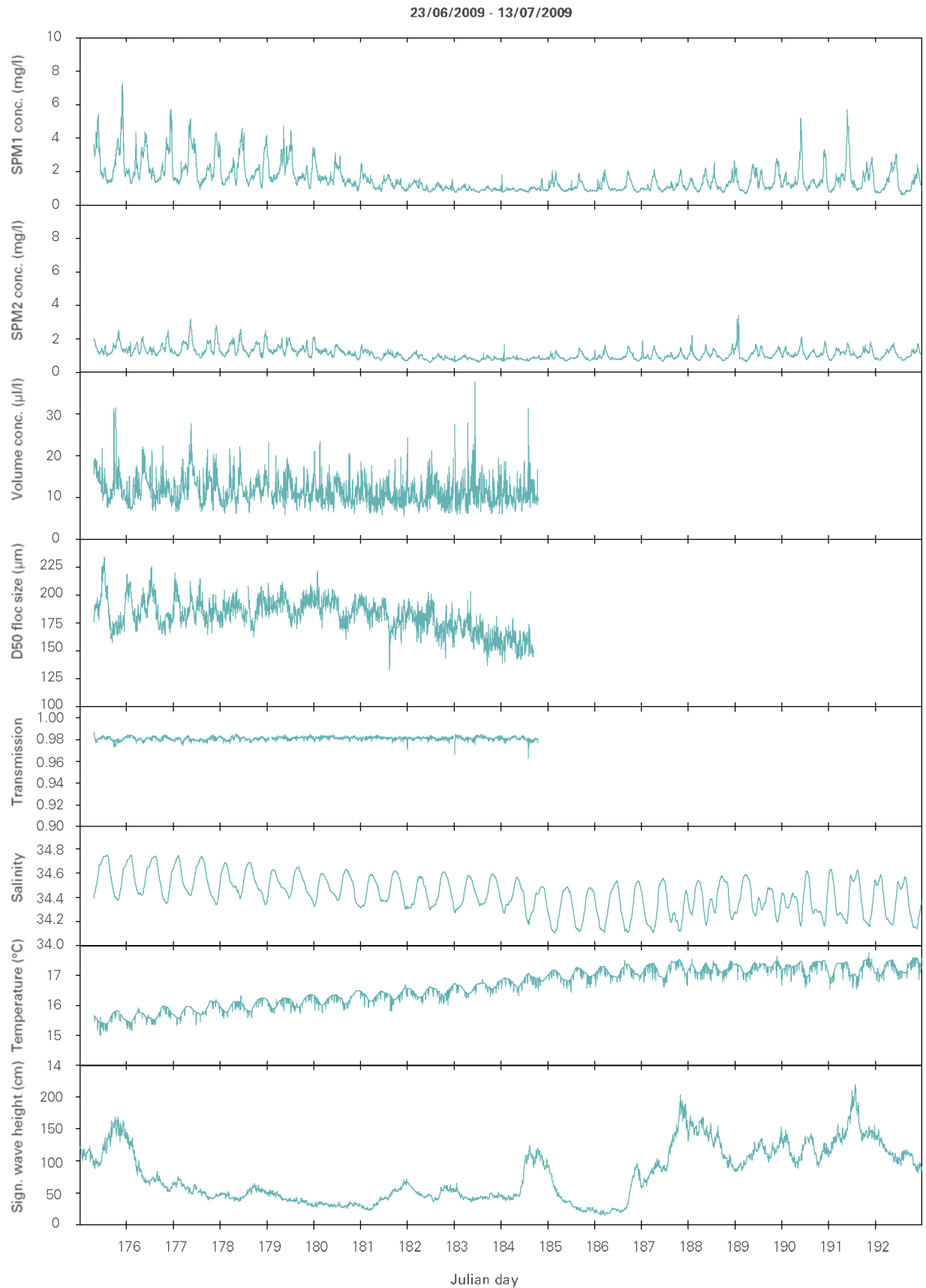


Figure 5. Measurements of SPM concentration in the lowest 1.5 m above the bottom, derived from the backscatter of the ADP, together with the seabed evolution from the ADP altimeter, at the Bligh Bank from May, 5th, 2010 till June, 3th, 2010.

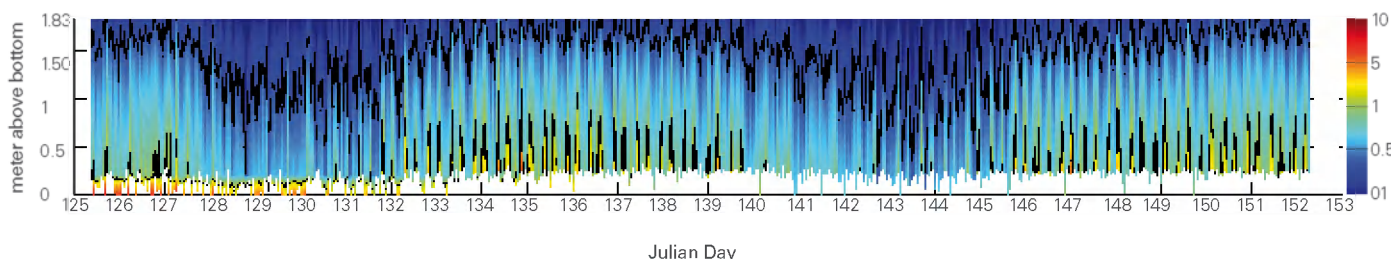
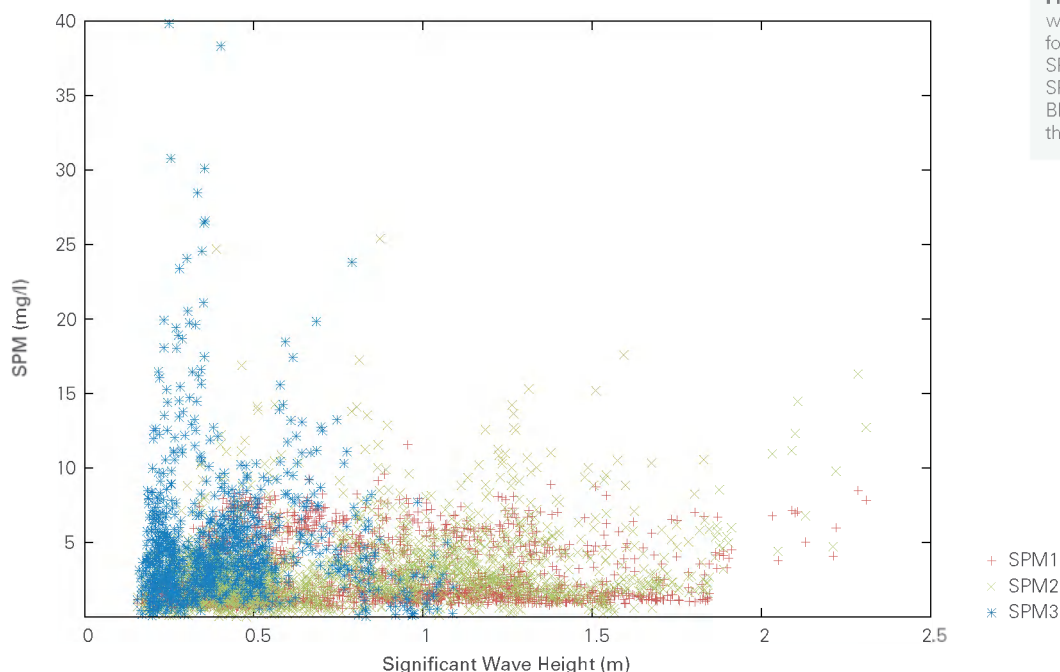


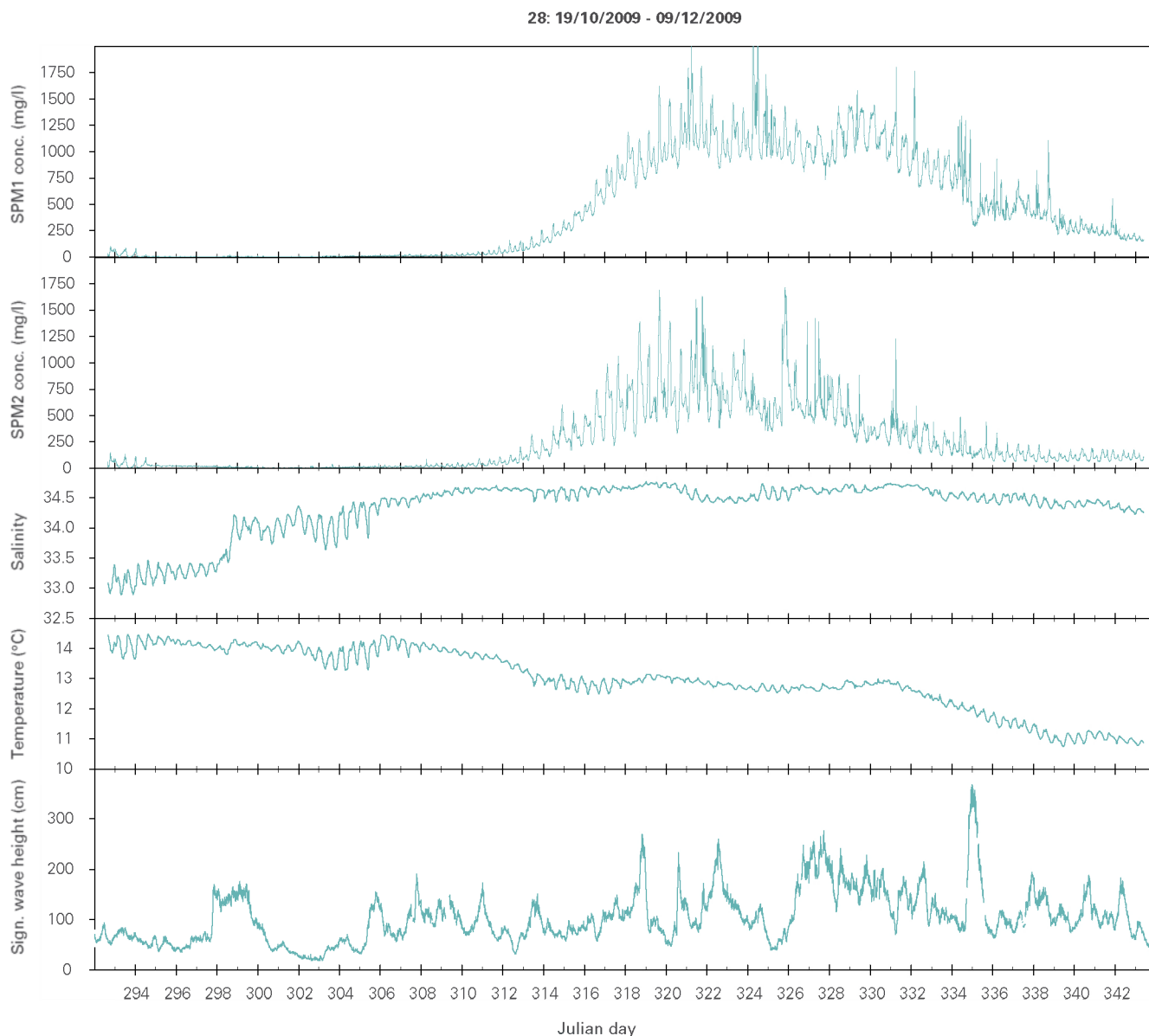
Figure 6. Scatter plot of significant wave height and SPM concentration for SPM1 (0.2 m above the bottom), SPM2 (2 m above the bottom) and SPM3 (1 m above the bottom) at the Bligh Bank (-26 m water depth), after the works.



While the SPM concentrations remained low during most of the measuring campaigns at the Bligh Bank and the Thorntonbank, this was clearly not the case at the Gootebank (Figure 7). At the Gootebank, from November 1st, 2009 onwards, the SPM concentrations increased considerably to high values up to 2000 mg/l close to the bottom, and 1700 mg/l at 2 m above the bottom. This was a result of a long period of prevailing southerly winds (Van den Eynde et al., 2013) that can cause an offshore shift of the coastal turbidity maximum (Baeye, 2012) and the introduction of associated high concentration mud suspension layers at the measuring location as observed in the ADV altimetry time series. These findings indicate that the Gootebank is not a good reference station for the Bligh Bank and/or Thorntonbank. Under varying conditions or events, SPM dynamics might differ between these locations. Therefore longer time series

should be used for the evaluation of effects of anthropogenic impacts on the turbidity. Such time series can be statistically analysed, and the significance in turbidity changes can then be determined before and after the construction works. Such an approach was successfully used for the assessment of turbidity changes due to disposal experiments of dredged material from the port of Zeebrugge (Fettweis et al., 2011).

Figure 7. SPM concentration (SPM1 at 29 cm above the bottom, SPM2 at 234 cm above the bottom), temperature, salinity at the Gootebank from October 19th, 2009 to December 9th, 2009. Significant wave height at Zuidwest Akkaert (Meetnet Vlaamse Banken, Flanders Hydrography).



In a first attempt to use longer time series to evaluate the effects of the wind farms on turbidity, satellite images were used from the MODIS and MERIS multi-spectral sensors on the EOS-PM and ENVISAT satellites (Van den Eynde et al., 2013). The spectral bands of these sensors can be used to estimate the SPM concentration at the water surface. Using the MUMM/GRIMAS tool (Vanhellemont et al., 2011) the SPM concentration time series was extracted at a point central on the Bligh Bank. These satellite data are available since 2002 and consist of one image per day, taken around noon. However, almost 86 % of the measurements are disturbed by clouds, resulting in 559 good values of surface SPM concentration at the Bligh Bank from the MODIS satellite and 397 good values from the MERIS satellite. The surface SPM showed a very clear seasonal cycle, resulting in higher surface SPM concentration values in winter months

(3-4 mg/l) and lower SPM concentration values in summer months (< 1 mg/l). Since the good values are not evenly distributed over the years and the months, the monthly values were calculated first, replacing the missing values by the climatological monthly means, before calculating the yearly mean values of the surface SPM concentrations. These monthly and yearly means from the MODIS sensor are presented in Figure 8. Student's T-test indicated that the yearly mean surface SPM concentration before the works (2002-2009) were not significantly different from the yearly mean surface SPM concentrations after the works (2010-2013). Also the monthly means did not differ significantly in most cases before and after the construction works. Only for a few months the differences were significant, but these results could be related to meteorological events, rather than to the construction and operation of the wind farms.

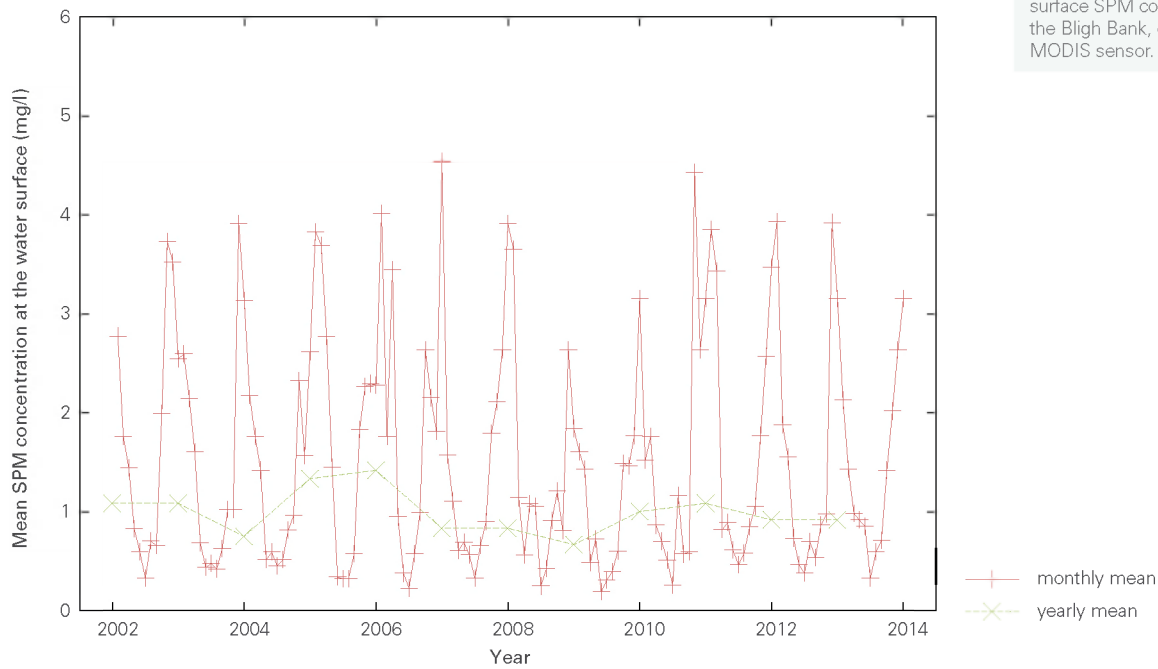


Figure 8. Monthly and yearly mean surface SPM concentration values at the Bligh Bank, calculated from the MODIS sensor.

Conclusion

Both at the Thorntonbank and the Bligh Bank, no indication could be found of an increased turbidity due to the construction of the wind farms. Furthermore, it was shown that the Gootebank was clearly not a good reference site for these measurements. To investigate the effects of anthropogenic impacts on the marine environment, statistical analyses of long time series is more appropriate. Finally, also long time series of satellite-

derived surface SPM concentrations were analysed to look at possible impacts of the wind farm on turbidity at the Bligh Bank. No significant differences of the yearly (and monthly) mean surface SPM concentrations before and after the installation of the wind farm could be demonstrated. Possible effects of the construction and operation of the wind farms on the turbidity are presumed to be local and temporary.

BATHYMETRICAL SURVEYS OF SCOUR AND DREDGED PITS

Multibeam-based bathymetry allowed studying the formation of scour or erosion pits around turbine foundations. During the construction of six GBFs on the Thorntonbank, the morphological evolution of the construction site was intensively monitored (C-Power, 2009a). Surveys were done prior to the installation works, after the dredging of the foundation pits, after installation of the gravel bed, prior to the installation of the filter layer and after the installation of the GBFs. Since then, five surveys were conducted to monitor the condition of the scour protection. The results of these surveys were compared with the bathymetry after the installation of the GBFs (C-Power, 2012b).

In some cases, small areas were found where erosion exceeded a pre-set alarm level. This was mostly levelled out by natural sedimentation, apart from one location where rocks were deposited (northeast of GBF D1, see figure 9), preventing erosion at the foundation.

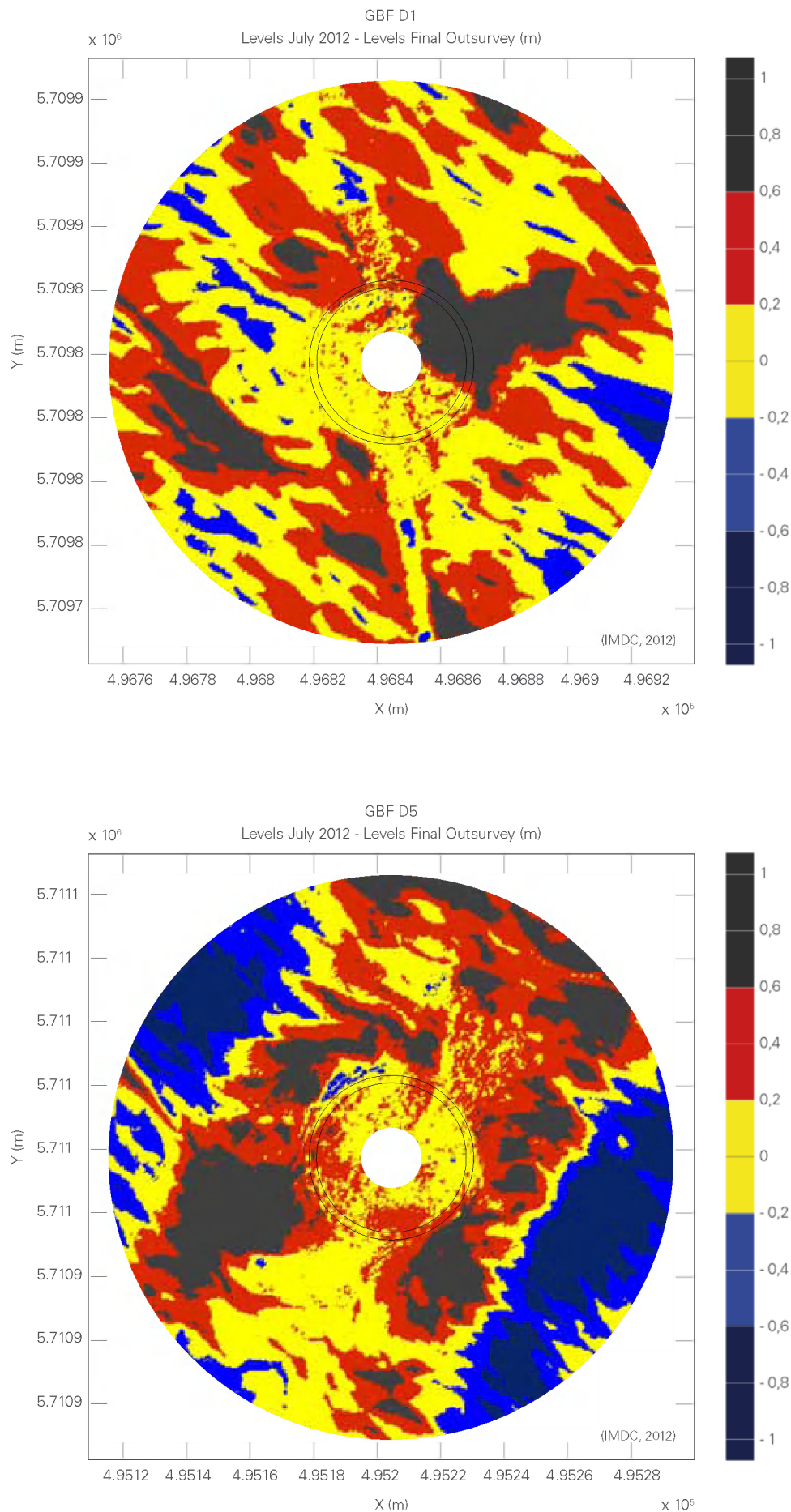
Overall, sedimentation occurred in the dredged pits (e.g., GBF D5, see figure 9). Around the erosion protection, similar seabed levels occurred, though important erosion or deposition was also observed. The erosion protection functioned without any secondary erosion.

To monitor scour around the foundations on the Bligh Bank, three bathymetric surveys were performed around 6 monopiles. Differential bathymetry maps were produced with the bathymetry before the installation as a reference (Belwind, 2010).

The results showed erosion pits ranging from 2 to 6.5 m, below the original seabed level. This was below the expected dimensions of erosion pits, as reported in den Boon et al. (2004). For monopiles with a diameter of about 5 m, their model predicted erosion pits of about 8.75 m.

Since 2010, 5 monopiles were monitored on a yearly basis: at the four corners of the wind farm, and at the monopile of the transformer station located in the centre of the wind farm where the seabed is most shallow. Results show that the scour protection was sufficient with erosion never below the alarm level. The rocks of the scour protection deposited in the erosion pits remained in place (Belwind, 2012).

Figure 9. Difference maps of the bathymetry around GBF D1 and GBF D5, comparing the bathymetry after installation against the situation in July 2012 (C-Power, 2012a).



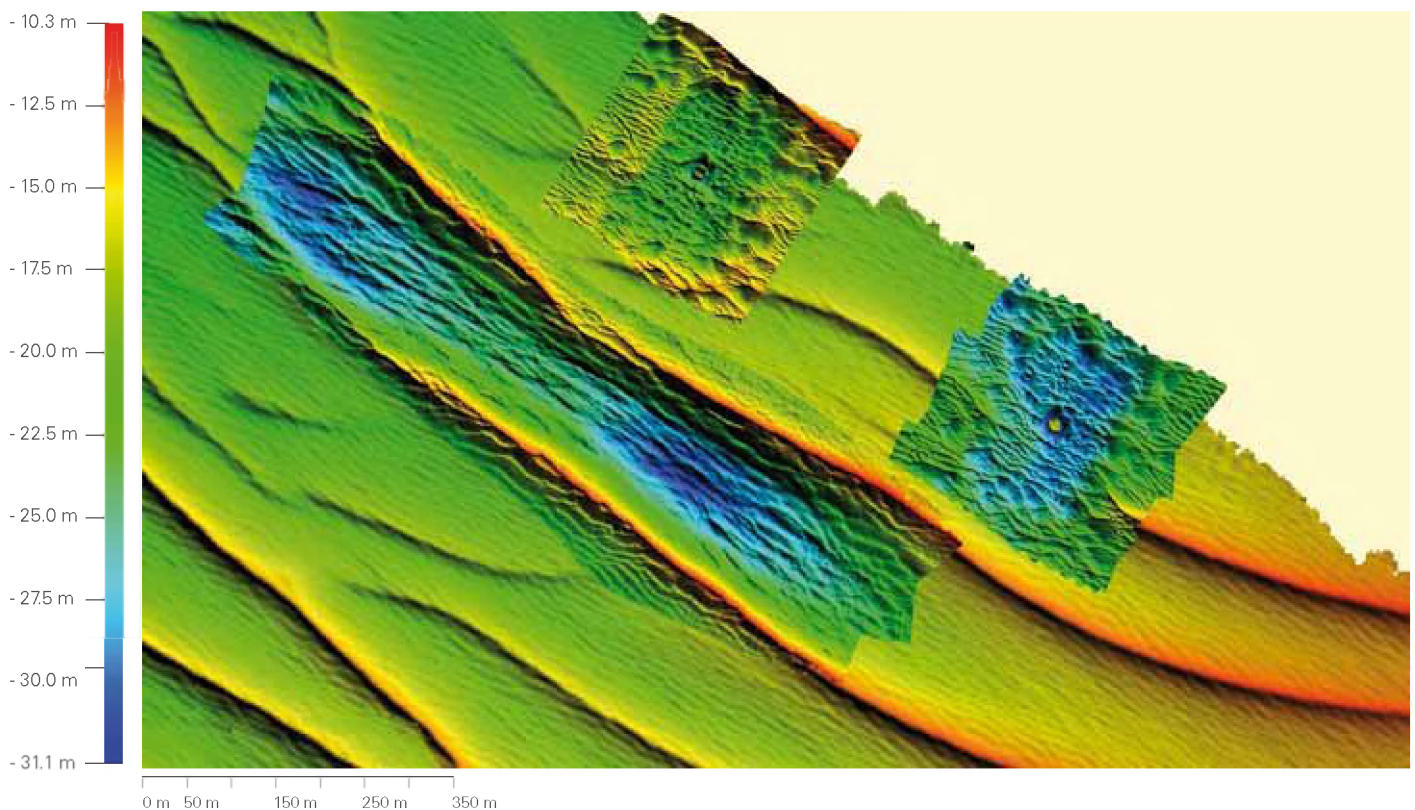
BATHYMETRICAL SURVEYS OF THE SAND STOCK/DREDGING PITS

Before the GBF installation on the Thorntonbank, large sea bed preparation works were necessary, involving dredging of an important amount of sand. It was expected that an excess volume of 385,000 m³ sand had to be stored within the concession area. Three disposal sites were defined within the perspective that natural sand transport would replenish the construction pits. Given the large uncertainties on natural sand transport rates and on the behaviour of such sand stocks, the evolution of these sand piles was monitored.

However, first surveys revealed large losses during the dredging and dumping activities (IMDC, 2009c). From the dredging of 579,000 m³ sand to construct the foundation pits, only about 400,000 m³ was found back at the disposal sites. On the other hand, for backfill of the foundation pits, infill of the GBFs, correction disposals and backfilling of the fair channel, some 868,000 m³ was extracted again from these dumping

sites, from which some 588,000 m³ was used effectively for the backfill and infill operations. IMDC (2009c) concluded that the sand was mostly lost during dredging (10 %) and disposal works (20-25 %). Due to these losses, no excess material was found at the disposal sites after the construction of the foundation pits and the backfill and infill operations, but instead 480,000 m³ sand was extracted. The bathymetry of one of these sand pits is shown in Figure 10.

Figure 10. Depression generated in the C-Power concession area. Background bathymetry is from 2006 (FPS Economy).



Compared to October 2008, the continued monitoring of the depressions showed that in June 2009, 471,000 m³ was still missing, indicating that over a period of 8 months only 9,000 m³ were naturally deposited in the depressions (Figure 11). Between September 2009 and April 2010, some deposition resulted in a volume increase of 45,000 m³, but due to dune migration the material almost entirely disappeared again in February 2011. In February-March 2011, the sand pits were filled again, by using material from the foundation pits that were dredged for the installation of jacket foundations (second phase of the C-Power wind farm). The difference between the original sites and June 2011 amounted -18,000 m³. The last survey of July 2012 showed some additional deposition in the area, resulting in a total difference of +5,000 m³.

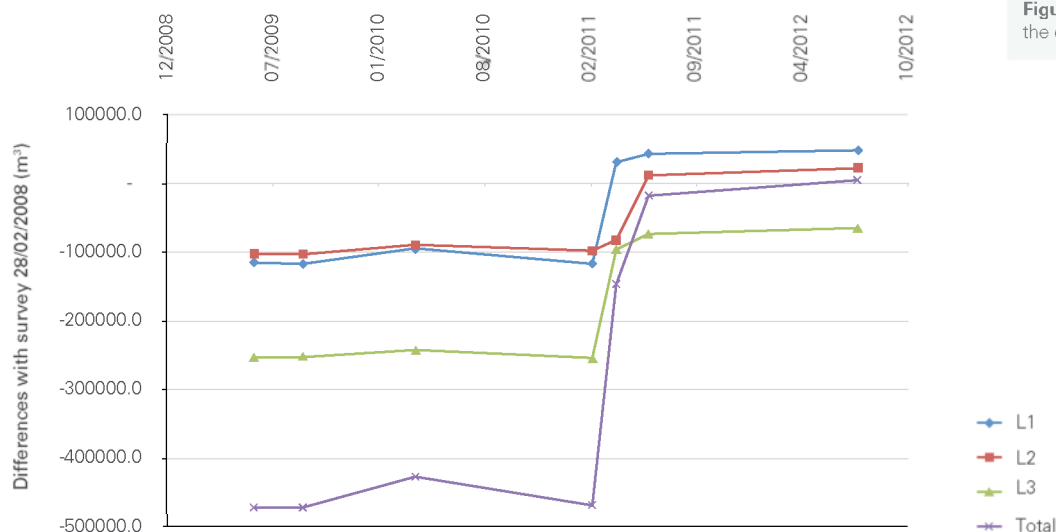


Figure 11. Evolution of the material in the disposal areas (C-Power, 2012a).

To conclude, substantial losses (30 to 35 %) of material during the dredging and dumping works were revealed. Furthermore, it appeared that the sand pits generated by the dredging works are quite stable over a longer period, despite the natural variation imposed by dune migration. Similar results, showing stability of sand pits, were found after severe aggregate extraction (Van Lancker et al., 2010).

BATHYMETRICAL SURVEYS OF THE EXPORT CABLES

To assure that the export cables remained buried, their coverage was verified on a regular basis. Along the entire length of the 150 kV (A) export cable from the C-Power wind farm to the cable landing at Oostende, a burial depth of 2 m was aimed for. In some areas, due to clay layers, only 1 m burial depth was reached (Figure 12) with a much deeper burial around km 14 where the cable crosses the navigation channel 'Scheur'. This was required in the environmental permit for safety reasons. At km 24, a surface communication cable was crossed and gravel was disposed to protect the cable. Verification of the depth of burial (DOB) of the cable showed

that at some areas, especially near the GBF D1 and at the Scheur, the DOB was less than 1 m. At three locations, the cable was exposed at the seabed and needed re-burial. This was due to sand dune migration (Figure 13). Remediation works were executed to assure that the cable remains covered. From this, C-Power decided that the second export cable (B) would be buried 1 m below the base of those sand dunes. Similar difficulties were encountered with the export cables from the the Belwind wind farm to shore. Rocks were deposited on the locations where the cable was exposed.

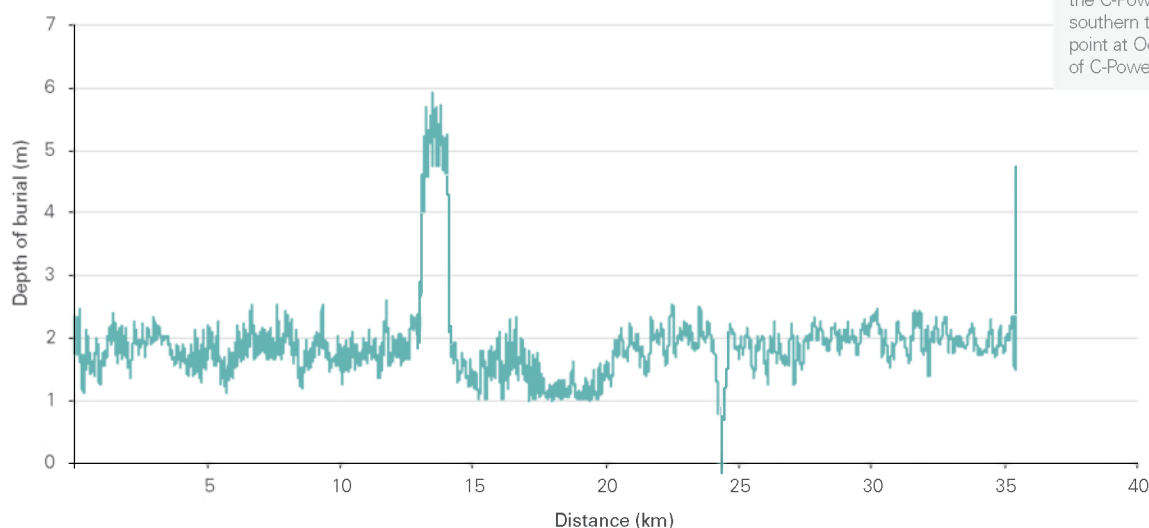


Figure 12. Original depth of burial (January 2009) of the export cable from the C-Power wind farm from the most southern turbine (km 0) to the landing point at Oostende (km 36) (From data of C-Power, 2009b).

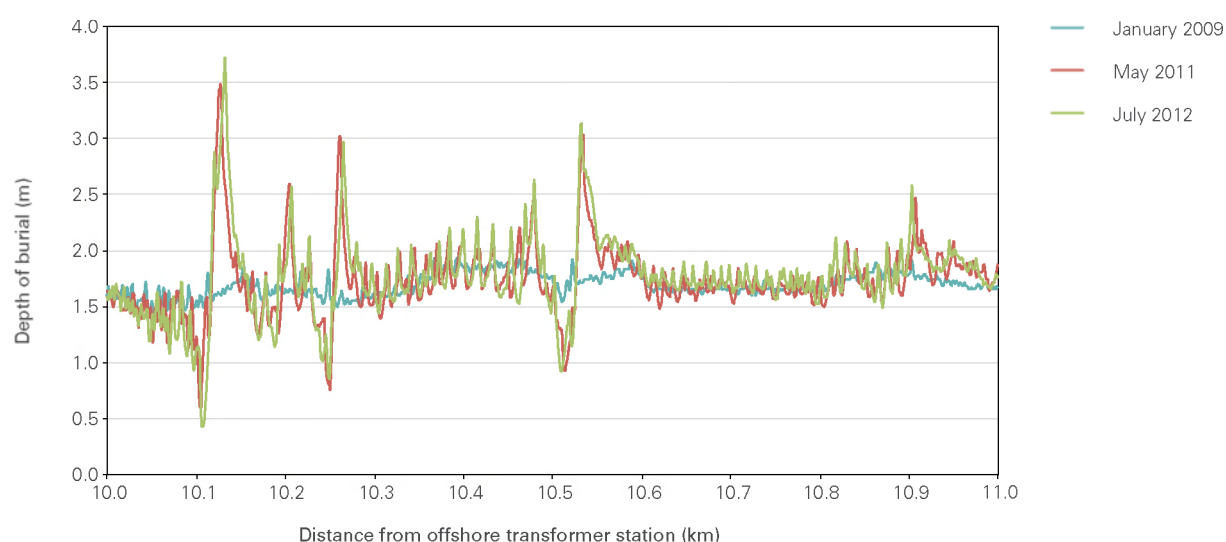
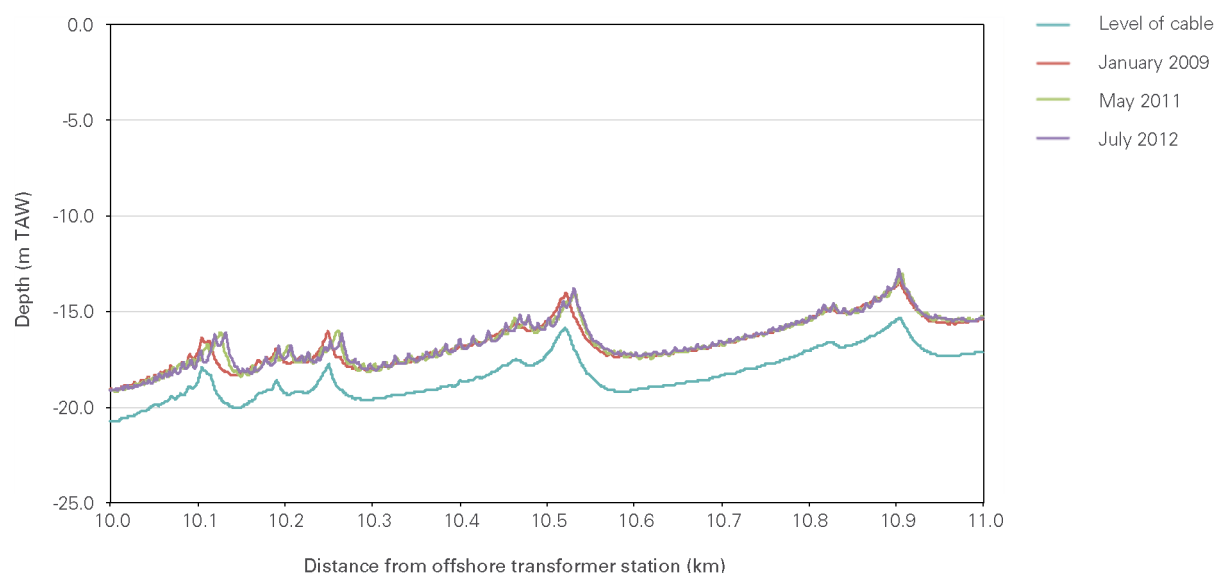


Figure 13. Bathymetry during different surveys and depth of burial of the 150 kV cable from the C-Power wind farm between km 10 and km 11 (From data of C-Power, 2012a).

In the North Sea, exposure of cables, due to moving sand dunes, could be expected based on experiences with pipelines (e.g., Morelissen et al., 2003). Model results and measurements showed that in the North Sea, sand wave migration occurs at a rate of 10 m per year (Van Dijk and Kleinhans, 2005). Within the wind farm areas, Bolle et al. (2013) quantified a dune migration of 1 to 7 m/year. Furthermore, Galagan et al. (2005) showed that cables could be uncovered after 6 to 18 years, using a migration velocity of only 1 to 3 m per year and a depth of burial of the cable of 1.8 m. For higher migration rates and smaller depths of burial, less time is expected. In areas of migrating sand dunes, the monitoring of the export cables remains important.

CONCLUSIONS

Related to the installation and exploitation of wind farms on the Belgian Continental Shelf, the monitoring of changes in sediment- and morphodynamics consisted of four parts:

1. Monitoring of the effect on the turbidity. No important effects were measured along the Thorntonbank, Bligh Bank and at a reference station at the Gootebank. Firstly, due to a higher variability in turbidity and different SPM dynamics, it was shown that the Gootebank was not a good reference site for the Bligh Bank and Thorntonbank. Nevertheless, measurements showed that the effects of the works at the wind farms and the wind turbines have a local and temporary effect on the turbidity. This was confirmed by the analysis of longer time series of satellite data for the Bligh Bank.
2. Monitoring of erosion pits. Surveys around the GBFs for the C-Power wind farm and the monopiles of the Belwind farm showed no secondary erosion and the erosion protection remained stable. Only at one GBF, an additional rock dumping was needed, when depths were below the alarm level. The monitoring of the dynamic erosion protection was executed around six monopiles. The depth of the erosion pits varied between 2.0 m and 6.5 m, in the north of the wind farm. The variation indicated that the erosion pit depth possibly depended on seabed sediments, geological substratum and prevailing hydrodynamics. A continuous monitoring of the foundations remains necessary.
3. Monitoring of sand piles and dredged pits. For the installation of the GBFs, it was shown that during the dredging and dumping works important sand losses of about 30 to 35 % occurred. Monitoring the sand pits, generated during these works during several years, showed that the sand pits were relatively stable and that no natural filling of the sand pits occurred.
4. Monitoring of the depth of burial of the export cables to the shore. Results showed that the cable can become exposed due to the migration of sand dunes. For both the Thorntonbank and Bligh Bank, some remedial rock dumpings were needed to ensure the burial of the cables. This led to the recommendation that in areas of migrating sand dunes, the cable should be buried 1 m below the base of the sand dunes. A regular control of the coverage of the cables remains necessary.

