Monitoring of hydrodynamic and morphological changes at the C-Power and Belwind offshore windmill sites-A synthesis

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Chapter 3. Monitoring of hydrodynamic and morphological changes at the C-Power and the Belwind offshore wind farm sites – A synthesis

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Abstract

In 2008 the first six wind mills of the C-Power farm were installed on the Thornton Bank using gravity based foundations (GBF). The use of GBFs implies important dredging works to prepare the sea bed, whereby sand piles were stored in the concession area. The construction of 110 turbines on monopiles at the Bligh Bank for the Belwind farm started in 2009. Dynamic erosion protection was chosen around the monopiles, allowing the development of an erosion pit around the monopiles; later this pit is refilled with material ensuring protection against erosion. The effects of the installation of the wind turbines, especially of the GBFs and of the dynamic erosion protection, on the turbidity and the morphodynamics of the sand banks is not well known; therefore assessment of possible impacts is necessary, based on a sound monitoring programme.

The monitoring includes: (1) measurements of currents, waves and turbidity, near the wind mill parks and at a reference site, before the works, during the works and after the works; (2) the control of the possible erosion and generation of erosion pits around the foundations of the turbines; (3) monitoring of the coverage of the cables from the farms to the shore; and (4) monitoring of the movement and evolution of the sand piles or pits, which were generated, during the construction of the GBFs.

Measurements of the turbidity, currents and waves were executed on the Thornton Bank before the works, during the works and after the works by International Marine and Dredging Consultants (IMDC) and at a reference site, located at the Goote Bank. Although biofouling of the OBS sensors disturbed some of the measurements, the analysis of the results showed that no significant increase in turbidity could be demonstrated. Measurements on the Bligh Bank were executed before the works by MUMM. The measurements during and after the works are foreseen in 2010 and 2011.

The sea bed around the GBFs was intensively monitored. In the final survey, the scour protection is clearly visible. No indication of secondary scour is apparent. The monitoring of the dynamic erosion protection at the Bligh Bank was executed around six monopiles. In the north of the farm, an erosion pit of 6.5 m was developed.

The depth of burial of the cable of the C-Power farm to the shore was monitored during the jetting and the ploughing of the cable. The cable lies most of the time 2 m below the sea bed, although at some sections with clay layers, only 1 m was obtained.

Finally, the monitoring showed that, during the installation of the GBFs, an important amount of sand was dredged at the concession area for the backfill of the foundation pits and the fair channel, and that some sand pits were created. It appeared that more material was dredged and used than was expected. During backfill, most of the sediment was lost during disposal. Monitoring of these sand pits, during several months, showed that the sand pits are relatively stable and that no natural filling of the sand pits occurs.

Samenvatting

In 2008 werden de eerste zes windturbines voor het C-Power windpark gebouwd op de Thorntonbank, gebruik makend van gravitaire funderingen. Het gebruik van deze gravitaire funderingen impliceerde belangrijke baggerwerken om de zeebodem voor te bereiden, waarbij zandhopen gecreeërd werden in het concessiegebied. Voor het Belwind park startte de constructie van 110 turbines op monopile funderingen in 2009. Rond de monopiles werd gekozen voor een dynamische erosiebescherming, waarbij de ontwikkeling van een erosieput wordt toegelaten, alvorens deze put te vullen met materiaal, die de bescherming tegen erosie moet garanderen. Het effect van deze windmolens, vooral door het gebruik van gravitaire funderingen en van dynamische erosiebescherming, op de turbiditeit en de morfodynamica van de zandbanken is nog niet voldoende gekend, zodat een monitoring werd opgelegd, om de impacten in te schatten.

Deze monitoring omvat: (1) metingen van stromingen, golven en turbiditeit ter hoogte van het windmolenpark, en op een referentiesite, voor de werken, tijdens de werken en na de werken; (2) de controle van het ontstaan van erosieputten rond de funderingen van de turbines; (3) de controle van de bedekking van de kabels van de parken naar de kust; en (4) de monitoring van de bewegingen en de

evolutie van de zandhopen of -putten, die werden gegenereerd als gevolg van de gravitaire funderingen.

Metingen van de turbiditeit werden uitgevoerd op de Thorntonbank voor, tijdens en na de werken door International Marine and Dredging Consultants (IMDC), evenals op een referentiesite op de Gootebank. Ondanks het feit dat begroeiing van de OBS sensoren de metingen verstoorden, kon de analyse van de resultaten geen significante verhoging van de turbiditeit, als gevolg van het windmolenpark aantonen. Voor de Blighbank, werden metingen van de turbiditeit voor de werken uitgevoerd door BMM. De metingen tijdens en na de werken zijn voorzien in 2010 en 2011.

De zeebodem rond de gravitaire funderingen werd intensief opgemeten. In de finale meetcampagne is de erosiebescherming rond de funderingen duidelijk zichtbaar. Er was geen aanduiding van de aanwezigheid van secundaire erosieputten. De monitoring van de dynamische erosiebescherming werd uitgevoerd rond zes monopiles. In het noorden van het park werden erosieputten tot 6,5 m opgemeten.

De diepte van de kabel onder de zeebodem van het C-Power park, naar de kust, werd opgemeten tijdens de installatie van de kabel. De kabel ligt over het gehele traject op een diepte van ongeveer 2 m, uitgezonderd in enkele secties met harde kleilagen, waar slechts een diepte van 1 m werd bereikt.

Gedurende de installatie van de gravitaire funderingen werd een belangrijke hoeveelheid zand gebaggerd en vervolgens gestockeerd als zandhopen voor het heropvullen van de funderingsputten en de vaargeul. Op deze locaties toonde de monitoring echter depressies aan en bleek veel meer materiaal weggebaggerd, dan oorspronkelijk begroot. Dit is wellicht te wijten aan verliezen tijdens de bagger- en stortwerken, alsook aan natuurlijke erosie. Monitoring van de zandputten, over verschillende maanden, toonden aan dat de putten relatief stabiel zijn, en dat er weinig natuurlijke opvulling van de putten optreedt.

3.1. Introduction

3.1.1. Context

A worldwide climate strategy was agreed upon in the framework of the 1992 United Nations Climate Change Convention and its 1997 Kyoto Protocol. One of the essential components to renewable energy is the use of offshore windmills. Permits were given to the consortia C-Power NV, Belwind NV and Eldepasco NV to build and exploit offshore wind farms. The C-Power farm comprises 60 windmills and is constructed 27 km from Zeebrugge on the Thornton Bank. The water depth varies between 12 and 27 m MLLWS (mean lowest low water during spring tide). The wind farm will have a total power of 300 MW. In 2008 the first six windmills were installed on the Thornton Bank. The Belwind wind farm lies 42 km offshore on the Bligh Bank and is, today, the world’s most offshore wind farm. Water depth varies between 20 and 35 m MLLWS. The farm will have a total power of 330 MW. The construction of 110 turbines started in 2009. The start of the construction of the Eldepasco wind farm on the Bank Zonder Naam is foreseen in 2011.

In the Environmental Impact Report (Ecolas, 2003; 2005; 2007) and the Environmental Impact Assessment (EIA) (MUMM, 2004; 2006; 2007a; 2007b), the possible effects of the construction and the exploitation of the wind farm on the marine environment are discussed. For the hydrodynamic and morphological aspects, main effects to be expected are: (1) increase in turbidity; (2) formation of erosion pits around the foundations; and (3) erosion around the cables. Specifications of this monitoring, methodological approach and first results are presented in the next sections.

Due to the water depth and geology of the Thornton Bank, gravity based foundations (GBF) were used. Because of the large sand dunes on the Thornton Bank, a seabed levelling was required before the GBFs could be placed. A foundation pit was dredged removing the loose sand and creating a flat surface on dense sand. Part of the sand could be re-used to infill the GBF itself, as back-fill of the construction pit or for the 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 had to be disposed within the concession area, situated in the troughs between the large dunes.

To ensure that the height of the sand piles was restricted to the height of the sand dunes (*i.e.* about 5 m), three disposal sites were defined. These sites had to be located in the concession zone where the sand transport would redistribute the sand towards the possible erosion pits around the GBFs. To define the best possible position for these disposal sites, information from MUMM (2006) was used, giving a general overview of the estimated sediment transport, based on numerical modelling and bedform asymmetries. The latter were derived from multibeam bathymetry maps (Roche and Degrendele, Federal Public Service Economy, SME's and Energy, unpublished). From the bedform asymmetries, sand transport direction to the northeast was derived for the southern part of the Thornton Bank. Model results (Van den Eynde, 2005) did confirm a dominance of the northeast sand transport; as such, it was decided to define three sand disposal sites southwest of the constructed wind turbines. Monitoring is required to follow-up of the evolution of these sand piles.

For the Belwind wind farm, dynamic erosion protection was chosen around the monopiles. This means that an erosion pit around the monopiles was allowed to develop. This pit then was refilled with erosion protection. The fact that the formation of erosion pits was accepted, could have important implications on the increase in turbidity in the area.

Overall, it was considered that important uncertainties still exist on the possible effects on the hydrodynamics and morphodynamics in the area, especially considering the fact that GBF and dynamic erosion protection were used, and therefore an appropriate monitoring campaign was set up.

3.1.2. Environmental setting

The Thornton and Goote Bank, as also the Bank Zonder Naam, are quasi coast parallel sandbanks, belonging to the Zeeland Ridges, whilst the Bligh Bank is one of the Hinder Banks, lying more obliquely to the coastline (see Figure 1). Minimum water depths are close to -6 m MLLWS for the Zeeland Ridges and -9 m for the Bligh Bank. In the swales, -28 m up to -36 m is reached, respectively. Sandbank length is about 15 km for the Goote Bank, 30 km for the Thornton Bank and 24 km for the Bligh Bank. Widths vary from 1 km for the Bligh Bank, up to more than 4 km for the Zeeland Ridges. Sandbanks are covered with large to very-large dunes (*senso* Ashley, 1990) with a wavelength of several hundreds of meters, a crest length of several tens of metres and heights varying from 2 m to 6 m. Their asymmetry varies according to preceding hydro-meteorological conditions (Lanckneus et al., 2001). The cross-section of the sandbanks is clearly asymmetrical, with the steeper side (slope ~3 %) facing south-east for the Zeeland Ridges and Bligh Bank. The gentle slopes of the banks are less than 1%. The topography of the Goote Bank is the least pronounced. Medium sands characterise the sandbanks with a median grain size between 300 µm and 350 µm. The geological substratum consists of alternating sand and clay layers of the Tertiary.

Semi-diurnal tides of macrotidal range (4-5 m at spring tide) characterise the hydrodynamics. Average tidal movement corresponds to an elongated current ellipse, with a southwest-northeast axis. Flood and ebb peak currents are oriented towards the northeast and the southwest, respectively. Tidal currents are rotating counter clockwise around the Zeeland Ridges; clockwise around the Bligh Bank. Surface peak currents reach up to 1 m/s; flood and ebb currents are competitive in strength, thought the ebb period lasts longer. Sand transport directions are linked to the tidal currents. 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 (Van Lancker et al., 2007). Mostly, an ebb oriented sand transport is observed along the gentle slope of the Zeeland Ridges, though dependent on preceding hydro-meteorological conditions.

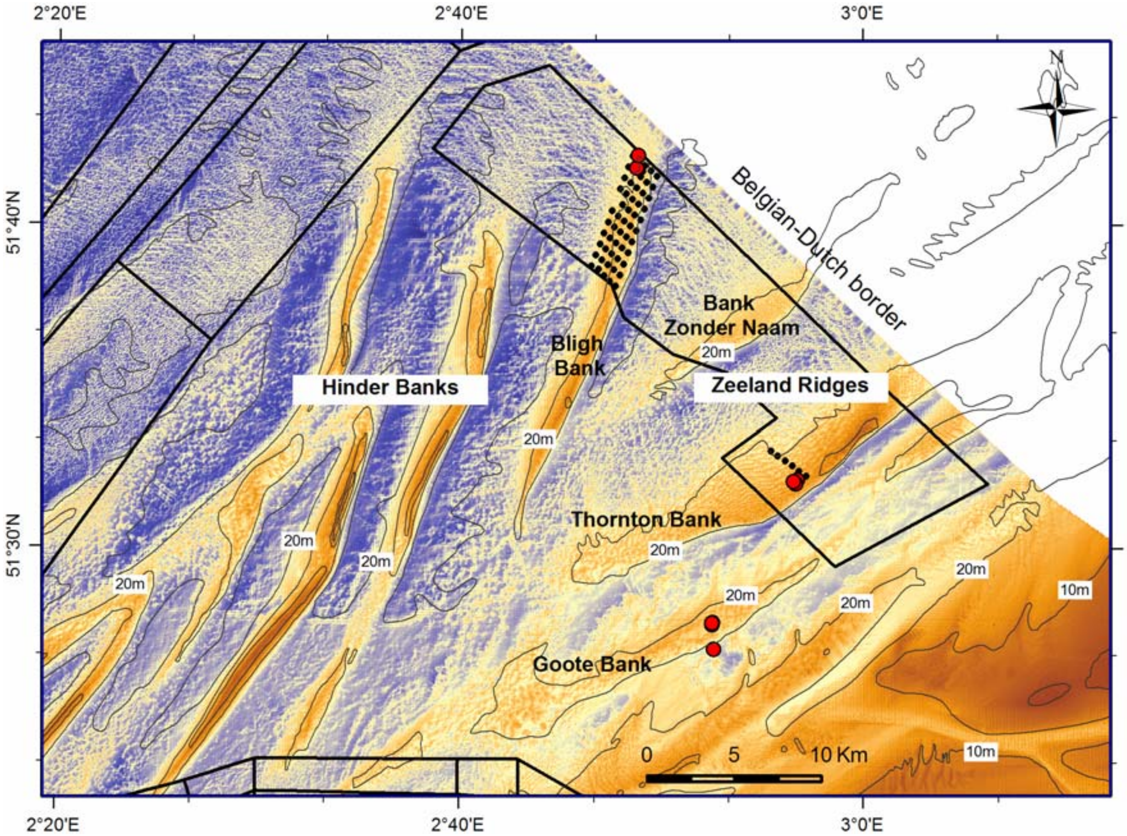

Figure 1: Bathymetry of the Thornton Bank, Bank Zonder Naam, Bligh Bank and Goote Bank. The black dots indicate the position of the windmills, the red dots indicate the position of the turbidity and current measurements.

3.2. Material and methods

3.2.1. Monitoring

The monitoring comprises four sections. First of all, measurements of currents, waves and turbidity were specified near the wind farms. To investigate the effects of the works and of the exploitation of the windmills, measuring campaigns were set up before, during and after the works. It was expected that meteorological effects could have significant effects on turbidity also; therefore simultaneous measurements were done near the windmills and at a nearby reference site. As reference site, the Goote Bank was chosen. The measuring campaigns had to be executed for a period of at least 15 days, to cover a spring-neap tidal cycle. International Marine and Dredging Consultants (IMDC) executed the monitoring for the C-Power wind farm; MUMM the one for Belwind.

A second part of the monitoring consists of bathymetrical surveys to identify erosion and formation of erosion pits around the foundations of the turbines. Based on numerical sediment transport studies (Van den Eynde, 2005; 2007), and on maps of median sand grain size of the Belgian part of the North Sea (BPNS) (Van Lancker et al., 2007), some specific sites were selected for the measurements, *e.g.* on the top of the sand bank. The bathymetrical surveys had to be carried out 1 month after the installation of the foundation, one month after the construction, after a severe storm in the area and one month after this storm during the first year. Additionally, a yearly control of the erosion pits had to be executed.

Further, the coverage of the cables in the wind farms and from the farms to the shore needs regular verification. To ensure a burial of 1 m, as requested by the environmental permit, the cable is buried, where possible, at two meter below the sea bottom. However, in some sections with clay layers, only 1 m is reached. Monitoring is important to assure that the cable will remain buried. These control measurements have to be executed after a severe storm in the area and one month after this storm. Additionally, a yearly control is needed.

Finally, an additional monitoring was defined in the case GBFs were used (C-Power wind farm). As indicated above, it was expected that an excess volume of 385,000 m³ sand had to be stored in the concession zone. In the EIA it was specified, that this storage of sand should occur in piles, with a maximum height of the same order of the sand dunes in the area, *i.e.* 5 m height, and preferably at such a place that the natural sand transport will use this sand to fill the construction pits. However, there are still large uncertainties on natural sand transport on these sand banks and on the behaviour of such sand piles. Therefore, it was specified that the movements of the stored sand had to be monitored with the same frequency, as the control of the erosion pits.

3.2.2. Measurements of the turbidity

Monitoring of currents, waves and turbidity were executed on the Thornton Bank and on the Goote Bank (reference site) (IMDC, 2008a; 2008b; 2008c; 2009a). For current profiles, water level and wave heights, an Acoustic Doppler Current Profiler (ADCP) from RD Instruments was used. An optical back scatter sensor OBS3A (Campbell Scientific) was mounted on the ADCP at about 0.7 m above the bottom (mab). Furthermore, an RCM9 current meter (Aanderaa) was used as backup for current, turbidity and water level. The RCM9 was deployed at 2 to 3.8 m above the bottom. A laboratory calibration, using fine material from the harbour of Oostende, was performed relating OBS readings in Nephelometric Turbidity Units (NTU) to the actual material in suspension in mg/l. Fine material was used for this calibration, since measurements with a Laser In-Situ Scattering and Transmissometry sensor (LISST) showed that on the Kwinte Bank, a sand bank 15 km offshore, the material in suspension consists of fine-grained cohesive material (Fettweis, 2008). To estimate the effect of the works on the suspended particulate matter (SPM), three measuring campaigns were executed: before (IMDC, 2008b), during (IMDC, 2008c) and after the works (IMDC, 2009a). In table 1 the period of the measurements and the position of the ADCP and OBS3A sensor are indicated.

Table 1
Location and period of deployments of the ADCP and OBS3A for C-Power monitoring.

Thornton Bank			
Before	51°32’08.4”	2°56’44.8”	18/02/2008 - 03/03/2008
During	51°32’00.8”	2°56’40.0”	17/06/2008 - 17/07/2008
After	51°32’05.1”	2°56’32.6”	05/06/2009 - 03/07/2009
Goote Bank			
Before	51°27’38.6”	2°52’30.7”	14/02/2008 - 03/03/2008
During	51°27’42.9”	2°52’32.3”	17/06/2008 - 24/07/2008
After	51°27’41.8”	2°52’30.5”	05/06/2009 - 14/07/2009

During the summer campaigns biofouling on the OBS sensors started after about 14 days of deployment on the OBS sensors and the Thornton Bank RCM9 and after 26 days on the Goote Bank RCM9. During the last campaign, the OBS sensor on the Goote Bank was lost.

MUMM monitored currents and turbidity on the Bligh Bank. Two tripod benthic bottom landers were deployed by the *RV Belgica* on the Bligh Bank and on the Goote Bank (reference site), respectively. The tripod measuring system was developed to monitor SPM and current velocity. Mounted instruments include a SonTek 3 MHz Acoustic Doppler Profiler (ADP), a SonTek 5 MHz Acoustic Doppler Velocimeter (ADV Ocean), a Sea-Bird SBE37 CT conductivity sensor system, two OBS sensors (one at about 0.2 m above the bottom, the other one at about 2 m above the bottom), and two SonTek Hydra systems for data storage and batteries. The ADV Ocean includes an altimeter, measuring the distance from the measuring point to the bottom. This can provide information on the movement of the bottom, and thus indirectly of sediment transport near the bed. On the tripod system, deployed on the Bligh Bank, also a LISST-100X, together with an additional OBS, were mounted. This LISST measures particle size of the material in suspension. Furthermore, an ADCP was deployed nearby the tripod, to measure current profiles.

To calibrate the OBS sensors, field calibration was executed at a location nearest to the tripod location using the *RV Belgica*. During a tidal cycle, a Niskin bottle was closed every 20 or 30 minutes, resulting in about 30 to 40 samples per tidal cycle. Three sub samples were filtered on board using pre-weighted filters (Whatman GF/C). After filtration, filters were rinsed with Milli-Q water to remove salt, and dried and weighted to obtain the SPM concentration. A linear correlation between OBS readings and SPM concentrations was established. Remark that measuring SPM concentration is associated with uncertainties. The uncertainties due to filtration and consequently also on SPM concentration derived from OBS, are relatively higher in clearer waters due to a relatively higher systematic error. Fettweis (2008) showed that tidal cycle measurements, taken in low turbide waters, include a systematic error of 4.5 mg/l.

The ADV data have been used to calculate the bottom shear stress, based on turbulent kinetic energy, which can be obtained for the variance of the velocity fluctuations (Fettweis et al., 2010). Since the measurements are executed in water depths of about 25 m, and waves were limited, no wave correction was applied in this case.

MUMM executed one measuring campaign before, during and after the works. In table 2, the location and period of the deployments are given. A joint measuring campaign with IMDC, for the Eldepasco monitoring, is being executed in May 2010, with tripods deployed simultaneously on the Bank Zonder Naam, Bligh Bank and Goote Bank.

Table 2
Location and period of deployments of the ADCPs and tripods for the Belwind monitoring.

Bligh Bank			
Before	51°41’47.5”	2°48’44.4”	24/06/2009 - 14/07/2009
During	51°42’10.4”	2°48’49.6”	21/10/2009 - 09/12/2009
Goote Bank			
Before	51°27’00.6”	2°52’40.2”	23/06/2009 - 13/07/2009
During	51°26’53.2”	2°52’35.2”	19/10/2009 - 09/12/2009

For the Bligh Bank campaign, before the works, the recordings with the LISST were limited to 2 days, and those of the ADP to 18 days. Due to technical problems the CTD, ADV and OBS did not work properly during the works on the Bligh Bank and only data from the ADP, LISST-100X and OBS are available. Therefore a second measuring campaign, during the works on the Bligh Bank, was set-up in May 2010. Biofouling started deteriorating the OBS data quality after about 9 days on the Goote Bank (before) and 14 days on the Bligh Bank and Goote Bank (during).

3.2.3. Bathymetric measurements

Bathymetric measurements were performed using a Reson Seabat 8125 multibeam for the monitoring of erosion pits in the C-Power farm by Dredging International. GEOxyz executed the bathymetric measurements for the Belwind consortium, using a Simrad EM2003 multibeam.

During the construction of the GBFs, the morphological evolution of the construction site was intensively monitored (C-Power, 2009). For each of the 6 GBFs, five surveys were executed. A survey prior to the works was executed from February 28 to 29, 2008. A survey after the dredging of the foundation pits and one after installation of the gravel bed were executed in April 2008; a survey, prior to the installation of the filter layer in September 2008, and a final survey, after the completion of the works, in June 2009.

Three measuring campaigns at 6 monopiles have been executed by Dredging International: A10 in the southwest corner of the farm, C05 and D06 in the middle of the farm, and F03, F04 and F05 in the north of the farm. Surveys were executed on January 6, January 15 and February 8, 2010.

Differential bathymetry maps were produced with respect to reference bathymetry, obtained in August 2009 (Belwind, 2010).

For the 150 kV cable of the C-Power wind farm to the cable landing at Oostende, a monitoring has been executed during jetting and ploughing of the cable. The cable laying ended on September 29, 2009.

On February 27-28 2008, a reference survey of the bathymetry at the disposal sites in the concession area was executed. Further, five bathymetric surveys in 2008 and two in 2009 were carried out. A first campaign was executed on April 22, 2008, after the dredging of the foundation pits.

3.3. Results

3.3.1. Hydrodynamics and SPM concentration measurements

In figure 2 the measurements during the works on the Thornton Bank of currents, waves and SPM are presented as an example (from IMDC, 2009b). It can be observed that after about 14 days, OBS3 measurements halted, due to biofouling on the sensors.

Waves were higher during the campaign in February 2008, in the winter period, than during the campaigns in June-July 2008 and June-July 2009, occurring in summer time. Around March 1st, 2008, a storm passed by, with significant wave heights higher than 3.5 m at the Thornton Bank.

Statistical analyses of wave, current and SPM concentration data was performed (IMDC, 2009b). The analysis showed that SPM concentration was low, on the Thornton Bank and Goote Bank. During the winter period, the median SPM concentration was 9 mg/l on the Goote Bank and 4 mg/l on the Thornton Bank. The analyses showed that high turbidity was correlated with higher wave conditions. However, during periods of high waves, low concentrations occur as well, indicating that wave action is not the only driving factor. During the summer periods, the median concentration of SPM on the Thornton Bank and Goote Bank was very low (1 to 2 mg/l). The measurements showed a similar behaviour of SPM concentration on the Thornton Bank and Goote Bank.

In Figure 3, the measurements at the Bligh Bank, before the works, are presented. The SPM concentrations at the Bligh Bank during June-July 2009 show a clear correlation with spring-neap tidal cycle variation, and almost no influence of wave activity is visible. SPM concentrations are low (< 5 mg/l) at both locations, except during autumn 2009 when the SPM concentration was surprisingly high on the Goote Bank (see Table 3). The tidal cycle measurement, during the same period, indicated mean values of 32 mg/l and a maximum of 58 mg/l; data from the tripod confirmed these values during the first days of deployment. SPM concentration decreased again a few days later.

During the measurement periods, significant wave heights of up to 2.2 m were recorded. Median significant wave heights were lower during the measurements (62 cm: June-July 2009; 64 cm: October-November 2009) than during the corresponding season of 2009 (66 cm, 95 cm). Mean SPM concentration was only slightly higher during periods with significant waves higher than 1.5 m on the Goote Bank (0.2 mab: 5.5*/1.0; 2 mab: 5.4*/1.2) and on the Bligh Bank (2 mab: 3.2*/1.2; 2 mab: 3.2*/1.3), both for June-July measurements (compare with Table 3). During the October-November measurements, no correlation was found and highest SPM concentrations occurred during lower wave conditions.

Altimeter data combine information of bed level changes and vertical movements of the tripod itself, due to settling. During the deployment the bed level changed during spring tide, possibly due to moving ripples or erosion/deposition events. During neap tide, no sediment transport at the bottom is apparent and the bed level remained nearly constant for about 5 days.

Current profiles at the Bligh Bank, during the works, are shown over the first 13 m above the bottom in Figure 4. Since no ADCP was available for deployment during this first campaign at the Goote Bank, an ADCP was used from Afdeling Maritieme Dienstverlening en Kust, Afdeling Kust. Unfortunately, no ADCP data were available during the second campaign.

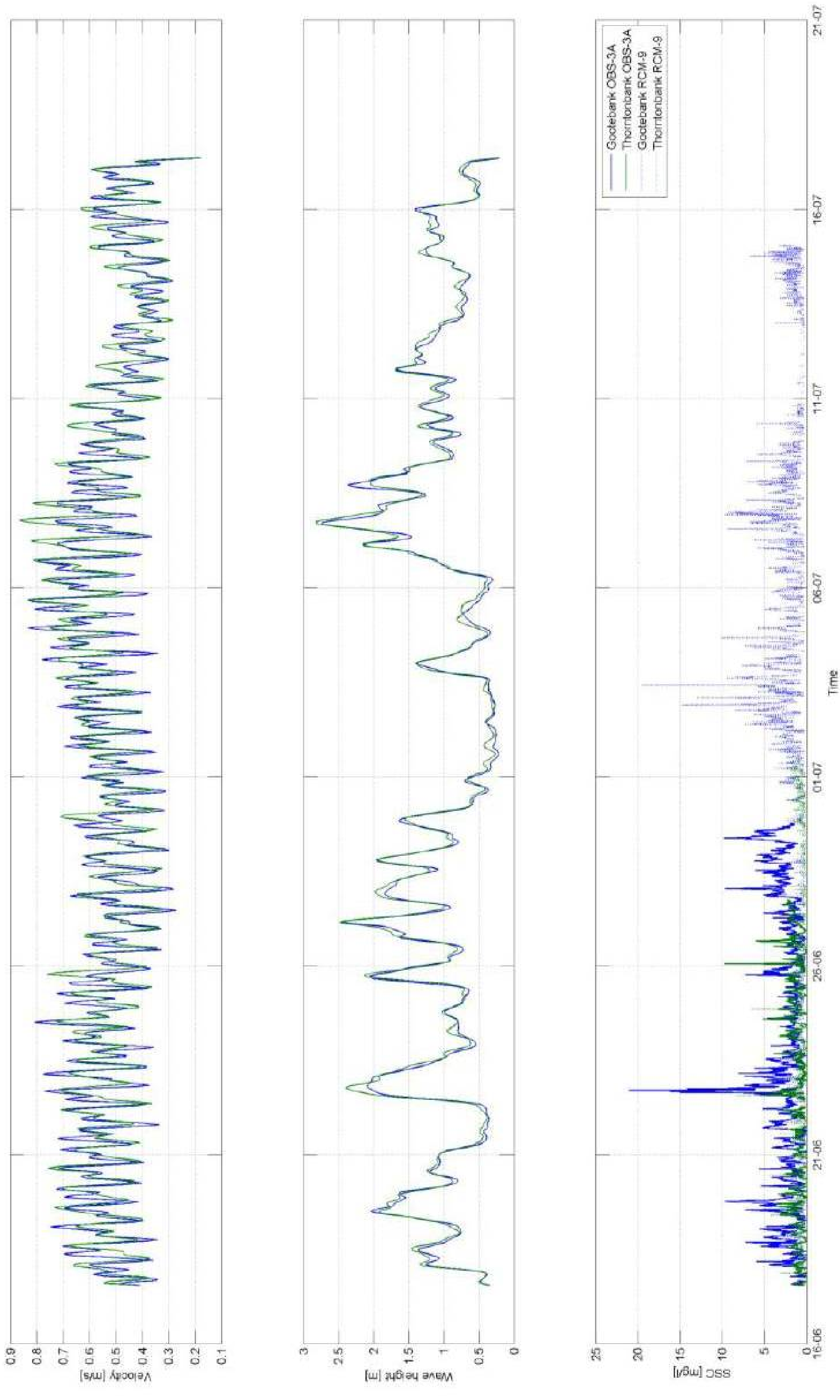

Figure 2: Measurements at the Thornton Bank and the Goote Bank in June-July 2009. Top: currents; middle: wave height; bottom: SPM measurements (from IMDC, 2009b).

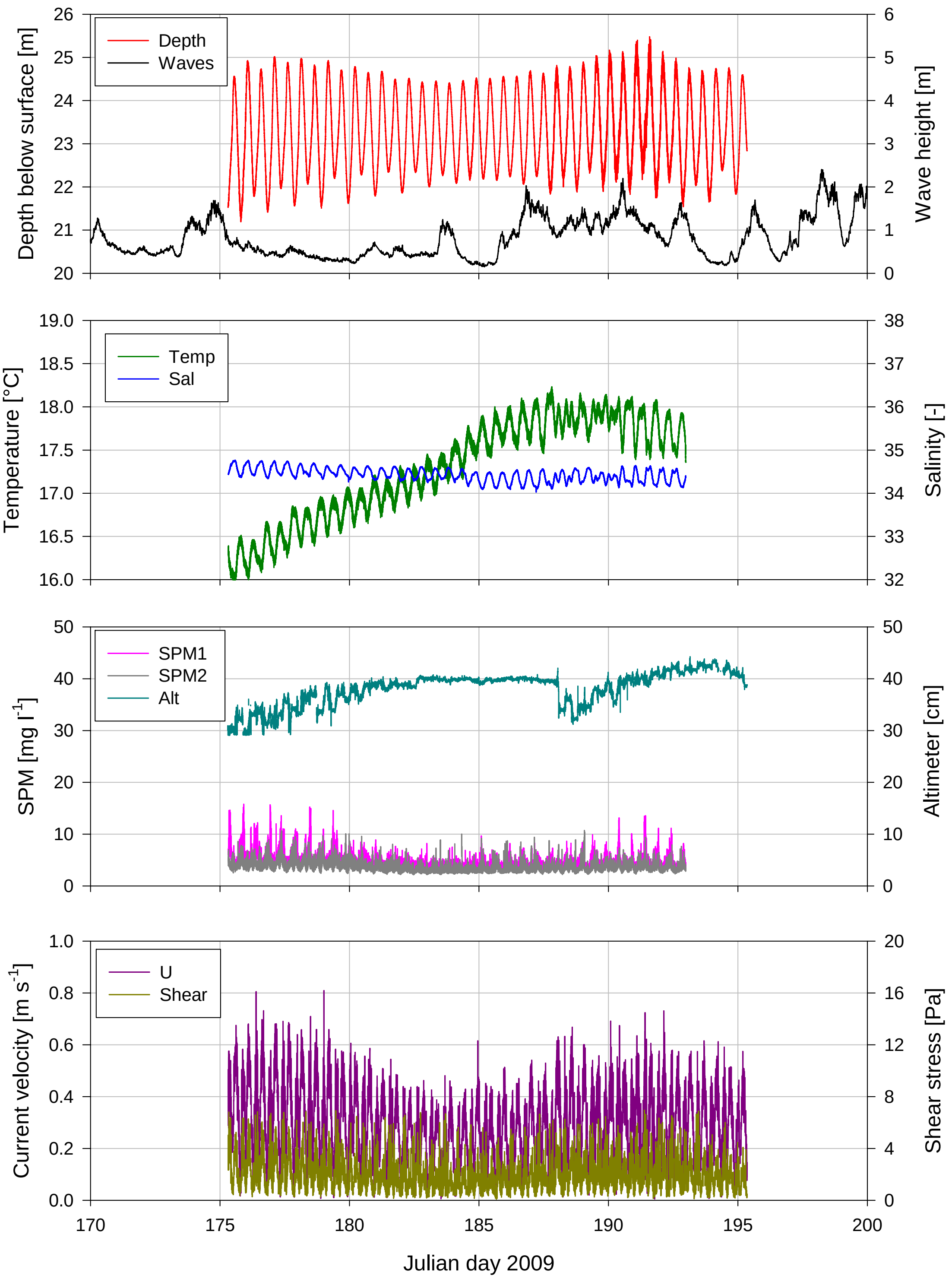

Figure 3: Measurements at the Bligh Bank (MUMM), during the Belwind monitoring campaign, before the works. Significant wave height data are from Akkaert Zuid (Meetnet Vlaamse Banken, Agentschap Maritieme Dienstverlening en Kust, Afdeling Kust); upper middle: temperature and salinity; lower middle:. SPM1: SPM concentration at 0.2 m above bottom, SPM2: SPM at 2.0 m above bottom, Alt: distance between ADV measuring volume and sea bottom; bottom: current velocity from the ADV and calculated bottom shear stress.

Table 3: Mean SPM concentration (mg/l) during tidal cycle and tripod measurements on Goote Bank and Bligh Bank. For the tidal cycle data the standard deviation, due to natural variability, is shown, whereas for the tripod data the multiplicative standard deviation is shown.

Location	Period	Type	Measuring height (m above bed)	SPM concentration (mg/l)
Goote Bank	25-26/06/2009	Tidal cycle	3.0	5.1±0.9
	23/06-3/07/2006	Tripod	0.2	5.2*/1.1
	23/06-3/07/2006	Tripod	2.0	5.1*/1.1
	19-20/10/2009	Tidal cycle	3.0	31.9±13.2
	19/10-6/11/2009	Tripod	0.2	14.4*/1.9
	19/10-6/11/2009	Tripod	2.0	11.2*/1.8
Bligh Bank	24/06/2009	Tidal cycle	3.0	4.0±0.7
	24/06-3/07/2009	Tripod	0.2	3.1*/1.3
	24/06-3/07/2009	Tripod	2.0	3.1*/1.2
	20-21/10/2009	Tidal cycle	3.0	4.5±0.8
	21/10-7/11/2009	Tripod	2.0	4.3*/2.2

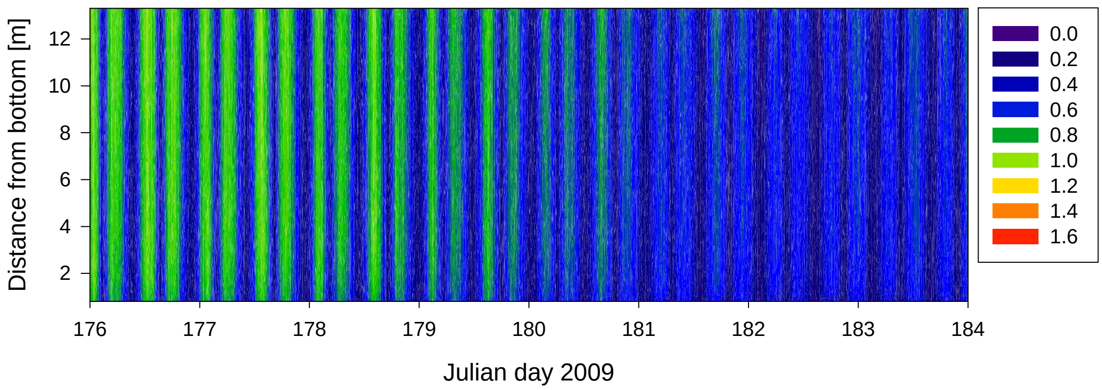

Figure 4: ADCP measurements at the Bligh Bank, during the Belwind monitoring campaign, before the works.

Finally, the average particle size, as measured by the LISST, are shown for the same campaign in Figure 5. The measurements, with a frequency of 1 Hz, show large variability. A 10 minutes running mean shows that the average flock size is around 250 µm during spring tide, decreasing to 200 µm during neap tide.

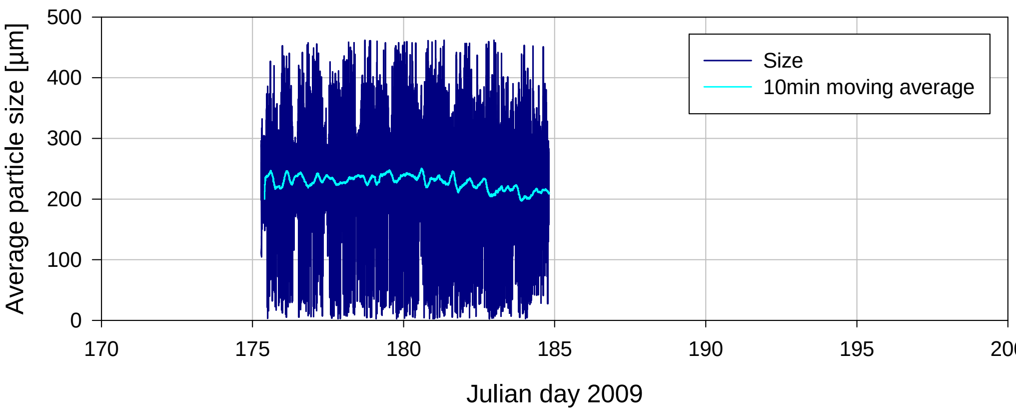

Figure 5: LISST measurements at the Bligh Bank, during the Belwind monitoring campaign, before the works, with a 10 minutes moving average.

3.3.2. Bathymetric measurements of erosion pits

In Figure 6, the results of four surveys around one of the GBFs, *i.e.* GBF2 at (51°32’24.63”N, 2°56’49.75”E), are presented. The bathymetry before the works, after the dredging of the foundation pit, prior to the installation of the filter layer and after the works, are shown. The foundation pit is clearly visible. However, after the installation of the erosion protection, no indication of secondary scour is found.

The erosion pits around the monopiles, during the dynamic erosion protection on February 8, 2010, were relatively limited and varying between 2 m (A10), 2.7 m (C05 and D06), 4-4.5 m (F04 and F05) and 6.5 m of depth (F03) (see Figure **7**).

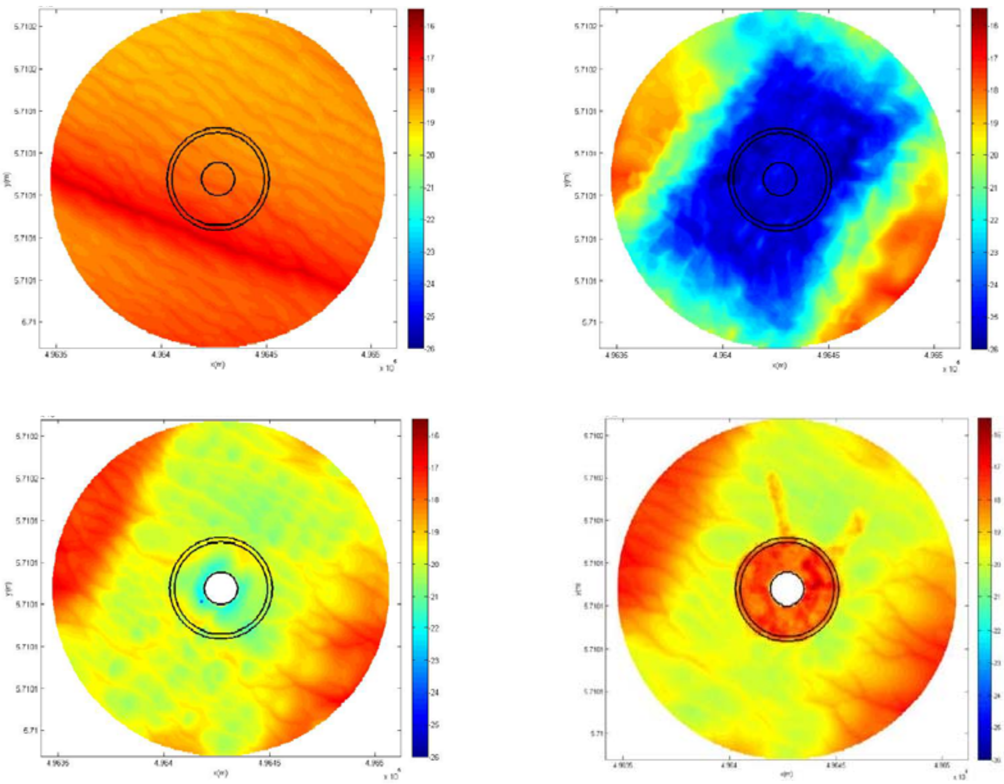

Figure 6: Depth variation near GBF2 (51°32’24.63”N, 2°56’49.75”E). Upper left: prior to the works; Upper right: after the dredging of the foundation pit; Lower left: prior to the installation of the filter layer; lower right: final survey after completion of the works (from: C-Power, 2009).

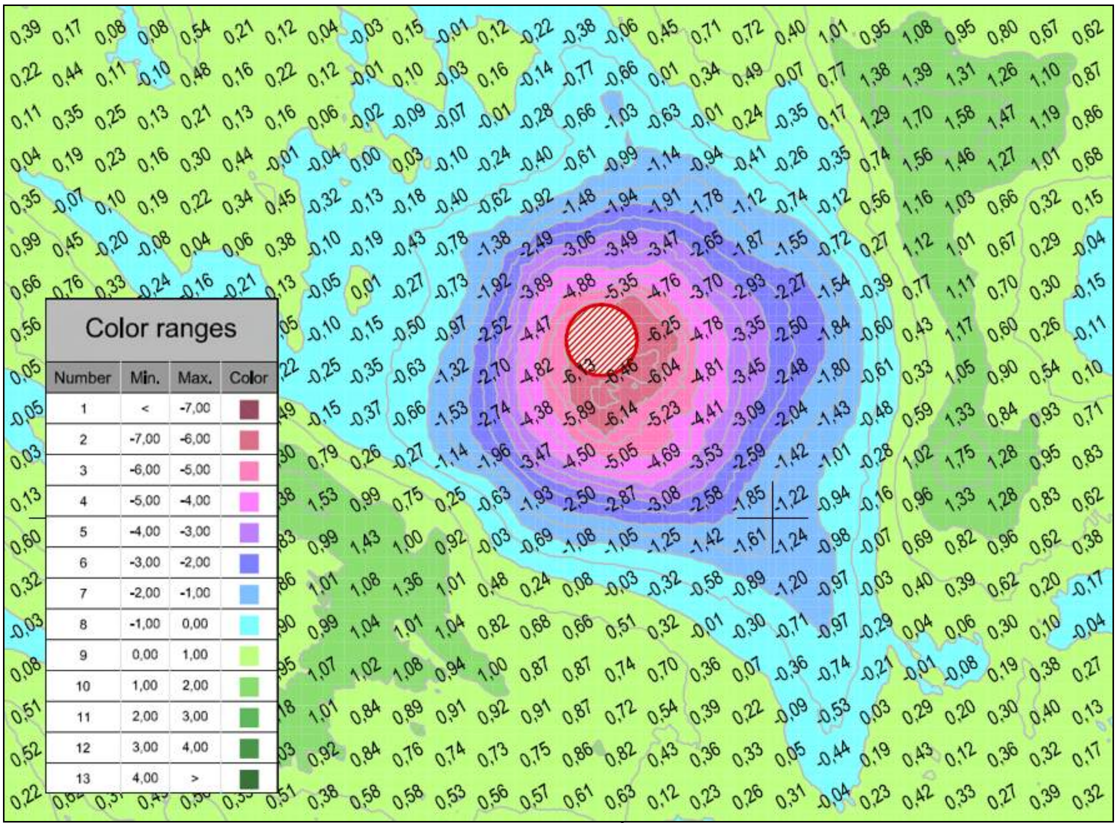

Figure 7: Differential bathymetry map between February 8th, 2010 and the reference situation, measured in August 2009. Monopile F03 in the Belwind wind farm (from: Belwind, 2010).

3.3.3. Bathymetric measurements of cable coverage

Over the entire length of the cable, a depth of burial of around 2 m was aimed for. In some cases, due to clay layers, only 1 m depth of burial was reached (Figure 8). Note that around km 14, a much deeper burial was observed, because of crossing of the navigation channel. This was required in the environmental permit for safety reasons. At km 24, a surface communication cable was crossed. At that place, gravel was disposed to protect the cable.

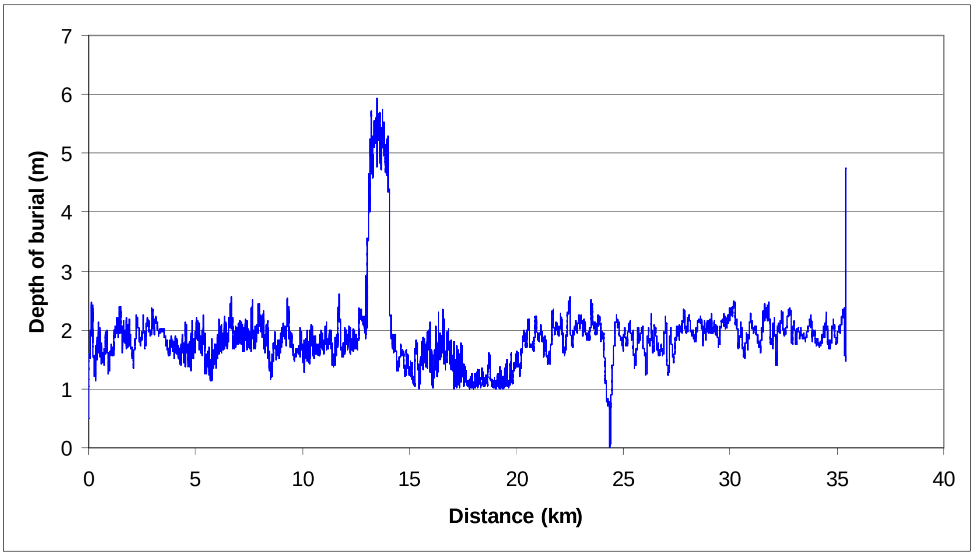

Figure 8: Depth of burial of the 150 kV cable from the C-Power wind farm from the most southern turbine (km 0) to the landing points at Oostende (km 36) (Figure prepared from data of C-Power, 2009b).

3.3.4. Bathymetric measurements of sand piles

Different surveys were executed on the disposal sites. They revealed that after the dredging of the foundation pits, only about 400,000 m³ was found on the disposal areas, although almost 579,000 m³ has been removed to construct the foundation pits.

In the following months, sand was used for backfill of the foundation pits, infill of the GBFs, correction disposals and backfilling of the fair channel. During the works, it appeared that more sand was necessary for the backfill of the foundation pits and the fair channel. After all the works, a total of 468,000 m³ sand was removed from the disposal site, causing three depressions (Figure 9). This means that a total of 868,000 m³, *i.e.* 400,000 m³ that was at the disposal sites and 468,000 m³ that was missing after the works, has been dredged; from this only 588,000 m³ were effectively found to be disposed for the backfill and infill operations.

In 2009, two additional surveys were executed to monitor the evolution of the depressions. Compared to October 2008, in June 14 2009, still 471,000 m³ was missing, indicating that over a period of 8 months only 9,000 m³ were naturally deposited in the depressions.

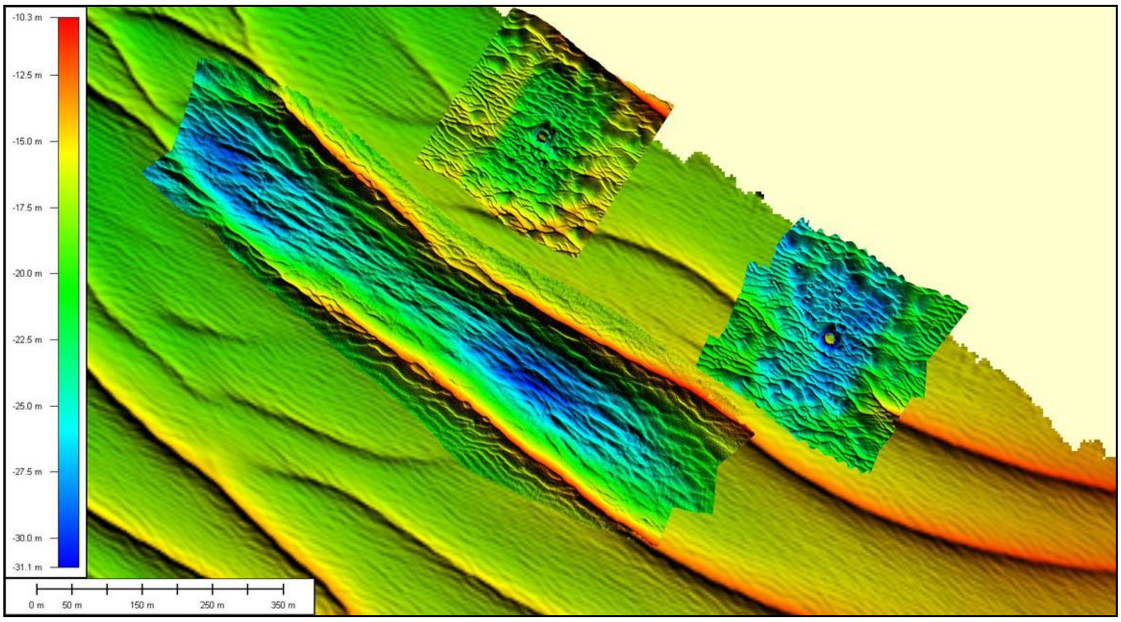

Figure 9: Example of 2 foundation pits with associated depression (2009 bathymetry). In the depression, sand from the GBF location was temporarily stored, though after infill of the GBFs and backfill of the cable, a sand deficit was encountered. This resulted in major depressions. (data: C-Power; visualization: M. Baeye UGent/MUMM). Background bathymetry is from 2006 (FPS Economy, SME's, Self-Employed and Energy).

3.4. Discussion

3.4.1. Hydrodynamics and SPM concentration measurements

SPM concentration variation during the measurements was mainly controlled by currents (spring-neap cycle). Most of the time, high concentrations were related to high waves. However, during periods of high waves, low concentrations occur as well, indicating that wave action is not the only driving factor.

At the reference site, Goote Bank, high SPM concentration was correlated with low salinities (±33 psu). This was due to persistent easterly winds, generating offshore advection of SPM and fresh water from the coastal area. To our knowledge, it is the first time that such an increase in SPM concentration was observed on the Goote Bank. However, as no long term data series are available, it remains unclear, if such an event is exceptional or common. These findings indicate also that the

Goote Bank is possibly not a good reference station for the Bligh Bank and/or Thornton Bank, as SPM dynamics might differ for these locations under varying conditions or events.

For the assessment of construction induced turbidity changes, natural variability needs quantified first. Indeed, Orpin et al. (2004) argue that the natural variability of the system could be used to define the initial limits of acceptable turbidity levels. Such an approach assumes that a short-term increase (several hours) that falls within the range of natural variability will not have any significant ecological effect. For at least coral communities, very sensitive to turbidity, they showed that changes in species density or faunal community may be due to changes in sediment composition and increased SPM concentration.

Building further on this, a methodology has been developed comparing variations of statistical parameters during the data collected during the field experiments. It is assumed that SPM concentration is log-normally distributed (Fettweis & Nechad, 2010). By using frequency distributions of different data sets, calculations can show whether (or not) two distributions are drawn from the same distribution function, using standard statistic tests. If the data, collected during different sampling periods, have similar log-normal distributions, geometric means and standard deviations, it can be concluded that - within the range of natural variability and measuring uncertainties - similar sub-samples from the whole population are obtained and no changes have occurred due to external disturbances. At present, there are no indications of a construction induced increase of turbidity, during nor after the works.

3.4.2. Bathymetric measurements of erosion pits

Around the GBFs, erosion protection was installed and no secondary erosion was observed.

During the installation of the dynamic erosion protection, erosion pits were allowed to develop around the monopiles at the Bligh Bank. Depth measurements of these pits indicated a variation of 2 to 6.5 m. This range is still below the values reported in den Boon et al. (2004), where information is given on the expected dimension of erosion pits, based on physical models. Results indicate that monopiles, with a diameter of about 5 m, will generate an equilibrium erosion pit of about 8.75 m. Still, according to Sumer & Fredsøe (2001), the development of the erosion pit is a fast process, as such monitoring remains important.

The fact that the depth of the erosion pit varies between 2 m and 6.5 m, indicates that there can be a large variation in the depth of erosion pits, depending possibly on the seabed sediments, geological substratum and prevailing hydrodynamics. More research is needed to gain more insight in these differences. The observed variation does indicate that for some other turbines, the erosion pit could be even larger.

3.4.3. Bathymetric measurements of cable coverage

Morelissen et al. (2003) showed that pipelines in the North Sea could be uncovered by movements of sand dunes. In some cases even erosion underneath the pipelines occurred. Model results and measurements showed that in the North Sea, sand wave migration occurs of about 10 m per year (Van Dijck & Kleinhans, 2005). Using a migration velocity of only 1 to 3 m per year and a depth of burial of the cable of 1.8 m, Galagan et al. (2005) showed that cables could be uncovered after 6 to 18 years. For higher migration rates and smaller depths of burial, less time is expected. The cable from the C-Power wind farm to the shore is buried at a depth of about 2 m, and less (1m) in areas with clay layers. Therefore it is clear that the coverage of the cable has to be verified regularly, *i.e.* after a severe storm and one month after this storm, and from then, every year.

3.4.4. Bathymetric measurements of sand piles

From the measurements, it appeared that much more sand was dredged, than was effectively used for backfill or infill operation. From a detailed analysis of the results (IMDC, 2009b), it was concluded that losses were most probably due to dredging (10%), disposal works (20-25%) and natural erosion processes (8%). These estimates result in a closed sand balance and showed that a larger quantity of sediment was dredged than was originally disposed on the three temporary disposal sites; this would explain the three depressions, as found in the concession area.

The fact that over a period of 8 months only a very limited amount of material was filling up the sand pits, that were generated, agrees with other research, where the stability of sand pits, after severe aggregate extraction, was demonstrated (for an overview see Van Lancker et al., 2010). Specifically, for the Kwinte Bank, a sandbank 12 km offshore, a depression of 5 m in depth was created. Degrendele et al. (2010) showed that after cessation of marine aggregate extraction, this depression remained stable and no recovery of the depression occurred. Also in the SANDPIT project (Walstra et al. 2003), the stability of sand pits was demonstrated (MUMM, 2007).

3.5. Conclusions

The natural turbidity regime and a first assessment of the effects of the construction of windmills on sediment dynamics are presented. The results remain preliminary, since monitoring is still on-going and only short-term effects can be discussed. However, collected data allowed evaluating the monitoring procedure. Initially, it was designed that the monitoring should include *in situ* measurements before, during and after the construction and this during two simultaneous measurements, at two locations, for at least 14 days. One location was defined as reference station, not influenced by impacts of construction sites. However, data have shown that the natural variability at the Goote Bank and the Thornton Bank is rather high, whereas at the Bligh Bank no significant variations have been observed during the deployments.

Despite similar geographic, sedimentary and hydrodynamic conditions the turbidity data suggest that the Goote Bank is possibly not a good reference site for the Bligh Bank and the Thornton Bank for the monitoring of turbidity. This is due to the higher variability in SPM concentration observed at the Goote Bank and the fact that SPM dynamics might be different on the three sites. The data suggest that SPM concentration on Thornton Bank and Bligh Bank is mainly influenced by waves and current resuspension, whereas on the Goote Bank, situated closer to the shore, advection of coastal water masses with higher turbidity and lower salinity are also responsible for the observed SPM concentration variability (see Fettweis et al., 2010).

Data so far demonstrate that, due to spatial variations in turbidity, the use of a reference site is not advised. Therefore, it is recommended to limit the monitoring to the construction sites only, but to extend the duration of the measurements (a few months, distributed over different seasons) in order to have sufficient data for meaningful statistical analysis. Long time series at one location have the advantage that natural variability can be assessed and that impact of construction works can be identified with higher probability. Such an approach was successfully used for the assessment of turbidity changes due to disposal experiments of dredged material from Zeebrugge harbour (Lauwaert et al., 2009).

The sea bed around the GBFs was intensively monitored. In the final survey, the scour protection is clearly visible, but no indication of secondary scour has been observed. 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 farm. This is in agreement with the expected maximum depths of 8.7 m. The variation however indicates that the erosion pit depth possibly depends on seabed sediments, geological substratum and prevailing hydrodynamics.

The depth of burial of the cable of the C-Power farm to the shore was monitored during the jetting and the ploughing of the cable. The cable lies most of the time 2 m below the sea bed, although, where clay layers occur, only 1 m was obtained. Due to movement of sand dunes, these cables could become unburied; a regular control of the coverage of the cables is therefore necessary.

Finally the monitoring showed that, during the installation of the GBFs, an important amount of sand was dredged at the concession area for the backfill of the foundation pits and the fair channel, which resulted in the creation of some sand pits. Calculation showed that 868,000 m³ was dredged (IMDC), while only 588,000 m³ were effectively found to be disposed for the backfill and used for the infill operations. These losses are due to dredging and disposal works and, to a lesser extent, to natural erosion processes. Monitoring of these sand pits during several months showed that the sand pits are relatively stable and that no natural filling of the sand pits occurs.

3.6. Acknowledgements

The staff and the crew of *RV Belgica* are acknowledged for their skilful mooring and recovery of the tripods. Measurements would not have been possible without technical assistance of A. Pollentier, J.-P. De Blauwe and J. Backers (measuring service of MUMM, Oostende). G. Dumon of the Agentschap Maritieme Dienstverlening en Kust, Afdeling Kust is acknowledged for making wave measurements available (Meetnet Vlaamse Banken). Hans Poppe, Agenschap Maritieme Dienstverlening en Kust, Afdeling Kust, is thanked for the deployment of an ADCP on the Goote Bank and making these measurements available.

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