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ORIGINAL

In situ observations of suspended particulate matter plumes at an offshore wind farm, southern North Sea

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Abstract Suspended particulate matter (SPM) plumes associated with the monopile foundations of the Belgian offshore wind farm (OWF) Belwind I were acoustically profiled by means of a Doppler current profiler (ADCP). Together with the analysis of a bottom lander dataset of optical and acoustic backscatter sensors (OBSs and ADPs respectively), the spatiotemporal SPM plume dynamics were inferred. The fieldwork comprised (1) near-bed measurements of hydrodynamics and SPM concentrations in the direct vicinity of the wind turbines, by means of a bottom lander over a spring–neap cycle in May 2010; this dataset represents a typically tide-driven situation because there was no significant meteorological forcing during the measurement period; (2) additional vessel-based measurements conducted in May 2013 to capture the SPM plumes inside and outside the OWF over part of a tidal cycle. Both in situ datasets revealed that the SPM plumes were generated at the turbine piles, consistent with aerial and space-borne imagery. The SPM plumes are well aligned with the tidal current direction in the wake of the monopiles, concentrations being estimated to reach up to 5 times that of the background concentration of about 3 mg/l. It is suggested that the epifaunal communities colonizing the monopile surface and the protective rock collar at the base play a key role as source of the suspended matter recorded in the plumes. The organisms filter and trap fine SPM from the water column, resulting in predominant accumulation of SPM, including detritus and (pseudo-) faeces, at the base of the piles. When tidal currents exceed a certain velocity, fine particles in the near-bed fluff layer are re-suspended and transported downstream in the wake of the piles.

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Introduction

The development of offshore wind farms (OWFs) is continually expanding in Europe (EWEA 2013). The impact of OWFs on the marine environment can be both negative and positive (Punt et al. 2009). During the construction phase, drilling of turbine foundations, scouring around the foundations as well as trenching of inter-platform cables and export cables (OSPAR 2004) are considered to have adverse effects, as these activities are likely to increase the natural background levels of suspended particulate matter (SPM) in the water column (Degraer et al. 2013). However, as construction activities are relatively short and localized, the overall increase in SPM concentration is limited. Regarding potential impacts during the operational phase of the OWF (minimum 20 years), recent satellite observations of a UK OWF (Vanhellemont and Ruddick 2014) and aerial photographs in a Belgian OWF (Fig. 1) have shown that the individual wind turbines induce SPM plumes with concentrations that are considerably higher than in ambient waters. The observed turbidity increase is a sign of change in hydrological, seafloor and/or biological conditions. It is therefore to be expected that further expansions of OWFs in the North Sea (EWEA 2013) could affect the marine ecosystem over larger areas (e.g. Van den Eynde et al. 2013).

The occurrence of turbid plumes associated with coastal defence works, land reclamation, dredging and disposal operations, sand extraction, and large-scale aquaculture facilities has received increasing interest worldwide over the last decade (e.g. Fredette and French 2004; Orpin et al. 2004; Bolam et al. 2006; Ware et al. 2010; Fettweis et al. 2011; Mostafa 2012; Borst et al. 2013). Offshore structures and construction

Fig. 1 Aerial photograph (SE view perspective) of the Belwind OWF (southern North Sea) on 18th March 2014 (01.30 p.m. UTC, altitude about 500 ft, RBINS-OD Nature flight), showing SPM plumes in the wakes of the turbine piles around maximal flood current at spring tide (full moon phase). Photograph taken by MUMM, RBINS-OD Nature

activities impose local changes in hydrodynamics and sediment transport, and affect turbidity, fine-grained sediment dynamics and bed shear stress (de Vos et al. 2011; Whitehouse et al. 2011; Nielsen et al. 2013). Indeed, these effects have been identified as being significant in the EU Marine Strategy Framework Directive of 2008, in particular with regard to descriptors 6 (seafloor integrity) and 7 (hydrographical conditions; also see European Commission 2010).

It should be noted, however, that many of the abovementioned activities are located in near-shore waters where natural SPM concentrations are already quite high (cf. Fettweis et al. 2012a, 2012b). The increase in turbidity in these areas are thus of less concern than in more offshore waters where natural SPM concentrations are low. Most of the new OWF developments in the North Sea, however, are concentrated in these latter areas where (for example) (epi-) benthic communities are more sensitive to changes in turbidity (Orpin et al. 2004; Degraer et al. 2008).

Considering the situation outlined above, the influence of OWFs on water column turbidity during the operational phase is clearly an environmental topic requiring urgent attention. The present study, which is based on in situ measurements after the construction of the Belwind OWF in the southern North Sea, aimed at characterizing the SPM plumes and investigating their origin (i.e. determining the source of the SPM in the plumes). The results of the investigation served to test the hypothesis of Vanhellemont and Ruddick (2014) who suggested that scouring of the seabed at the base of the turbines could be the cause of the elevated SPM concentrations.

Study area

The study area is located in the southern North Sea 46 km off the Belgian coast in the allocated Belgian zone for offshore renewable energy production (Fig. 2), and within the 17 km^2 area of the Belwind I OWF in the northern part of the Bligh Bank sandbank (T010 orientation). The Bligh Bank environment is characterized by low-turbidity, high-salinity English Channel waters, with a very limited influence of the more turbid and lower-salinity coastal waters (Lacroix et al. 2004). The overall SPM concentration is thus very low in this area (a few mg/l; Fig. 2), the Secchi disk depth being about 10 m (A. Norro, pers. comm.).

The southern North Sea is characterized by an amphidromic point with a counter-clockwise rotating tidal wave (Proudman and Doodson 1924). In Belgian waters, major axes of semidiurnal tidal current ellipses are oriented mainly northeast (flood)–southwest (ebb). The tidal range varies between 2.5 and 5 m, and depth-averaged current velocities easily reach 1 m/s. The dominant direction of wind-generated waves is from the southwest. Water depths in the OWF area range between 15 and 37 m. The seabed consists of medium-sized sands with diameters ranging between 289 and 364 μm. The mud fraction (silt+clay) in the sand matrix is about 1% (Van Lancker 2009).

The wind turbines are arranged in five rows of 11 turbines each placed 650 m apart. The five rows are 500 m apart and aligned SSW–NNE. All wind turbines (and the offshore high-voltage station) have similar monopile foundations of 5 m diameter with a scour protection (rock collar) about 15 m wide and 1.4 m high around each foundation. The construction started in September 2009 and was finalized by February 2010. It should be noted, however, that nine monopiles had already been installed in the northern rows by the end of September 2009. The submerged sections of the piles, which have a surface area of about 16 m^2 per meter water depth, and their scour protection collars, which have surface areas of 200 m^2 and more, are intensively and rapidly (within weeks) bio-fouled during spring, summer and fall (Kerckhof et al. 2012 and Fig. 3). The physical and biological impacts of the OWF on the marine environment are being monitored according to an environment-friendly OWF management policy (Degraer et al. 2013).

Materials and methods

Near-bed optical and acoustic data

Between 17 and 31 May 2010 (i.e. 3 months after finalization of the OWF), a bottom lander was equipped with a SonTek® 5 MHz acoustic Doppler velocimeter (ADV) and a D&A Instruments OBS-3 (optical backscatter point sensor), co-located about 20 cm above the mobile sand bed in a water depth of 25 m MLLWS (mean lower low-water spring tide). The measurement period covered a full neap–spring cycle (first quarter and full moon lunar phase) and was characterized by a general absence of any significant meteorological forcing.

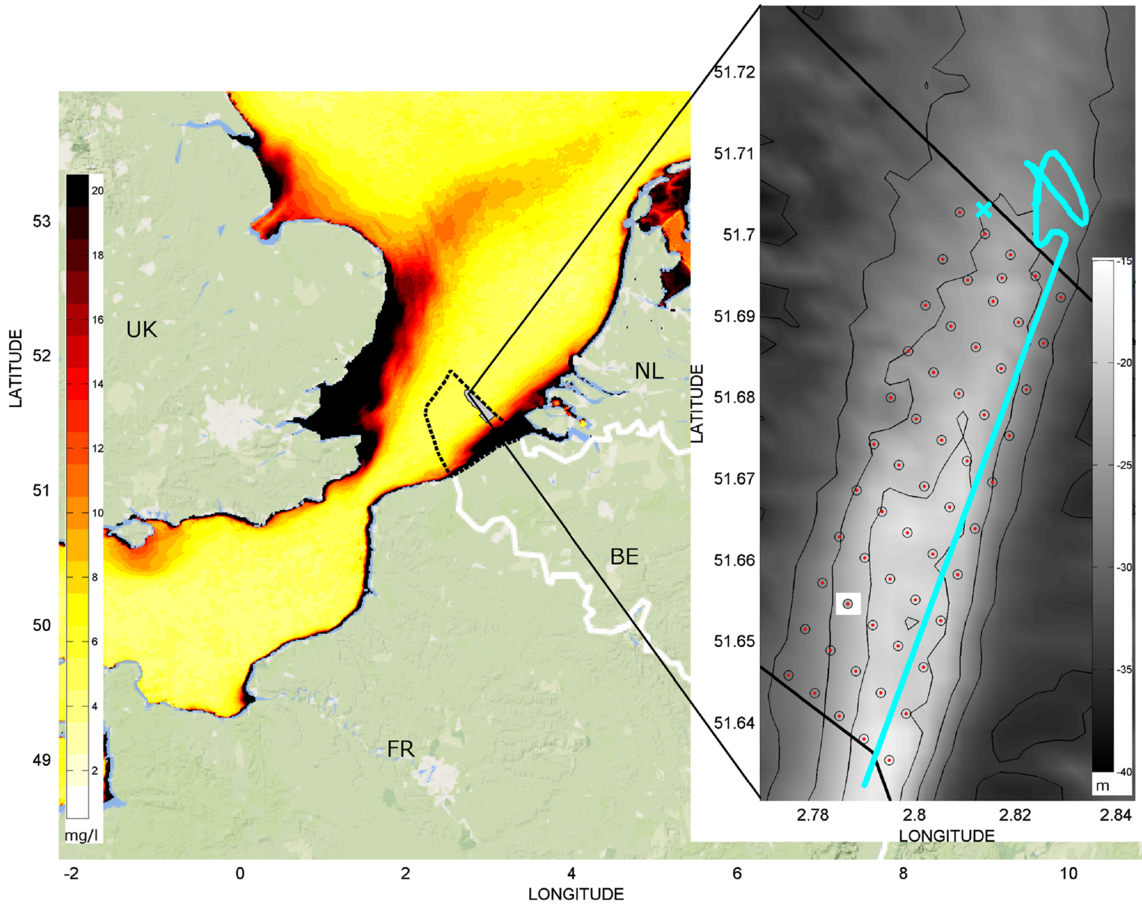

Fig. 2 *Left* Location of the study area in the southern North Sea, in Belgian waters within the allocated zone for offshore renewable energy production (*grey filled polygon*). The background is MODIS Aqua water surface SPM concentration (Fettweis et al. 2012a). *Right* The Belwind OWF, with locations of the 55 monopiles (red/black bullets) in one sector. *Blue cross* Location of bottom lander measurements, *blue line* ship's track. The monopile highlighted in the white box (B8) has been filmed (see Fig. 3). Grey scale background is bathymetry (mean lower low water springs)

Calibration of the OBS was first conducted in the laboratory by converting the OBS voltage readings into normalized turbidity units (NTU) using standard Formazine solutions. The next step involved converting the NTU values into SPM mass concentrations through calibration against filtered in situ water samples. The ADV measures current direction and speed in a non-intrusive way and also stores backscatter signal amplitudes that were subsequently correlated with the OBS-derived SPM concentrations (Fig. 4), typically encompassing a linear relationship between log ($SPMC_{OBS}$) in mg/l and ADV amplitude in dB (e.g. Voulgaris and Meyers 2004). The least squares best-fit coefficient of determination R^2 was 0.65, although there are periods in which the correlation is slightly weaker or stronger (cf. Results).

Fig. 3 Freeze-frame from the underwater video of the B8 monopile (for location, see Fig. 2) at the Belwind I OWF on 2nd June 2010, 7 months after piling. Bio-fouling is mainly by the hydroid *Tubularia larynx* (F. Kerckhof, pers. comm.). In the water column, marine snow or fine-grained flocs are visible. Scale bar 15 cm. Photograph taken by A. Norro, RBINS-OD Nature

Water column acoustic profiling

On 7 May 2013 (between the last quarter and new moon lunar phases), hull-mounted Teledyne RD Instruments® acoustic Doppler current profiler (ADCP) recordings were conducted in and around the OWF under fair-weather conditions. The main purpose was to profile the SPM plumes at the highest vertical and temporal resolution (experimental ADCP settings with a bin size or vertical

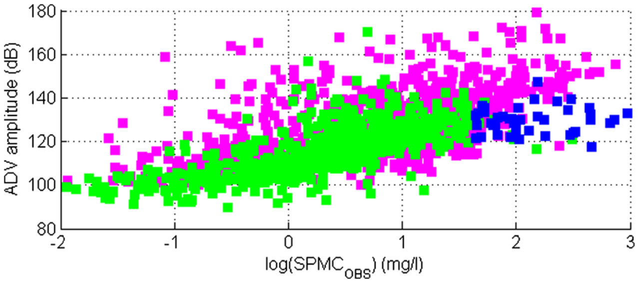

Fig. 4 Correlation between log (SPMC$_{OBS}$) in mg/l and ADV amplitude in dB. *Magenta* Spring tide, *green* neap tide, *blue* exceptionally high SPMC$_{OBS}$ peaks during neap tide. R^2 for all data pooled is 0.65, for spring tide 0.55 and for neap tide 0.71

resolution of 25 cm). Given the operating system frequency of 300 kHz, the quality of the hydrodynamic data is relatively low. The raw ADCP echo intensity data were used as a proxy for SPM concentration (SPMC$_{ADCP}$), a common practice widely applied in various settings worldwide (e.g. Holdaway et al. 1999; Gartner 2004; Kim et al. 2004; Jourdin et al. 2014; Nauw et al. 2014). The echo intensity is a function of the instrument and of the sediment and water properties. Instrument properties are frequency, source level power, receiver sensitivity and slant range, the latter being the distance between the transducer face and the ensonified volume. Sediment characteristics relate to size, type and concentration of the particles in the water column. The conversion of echo intensity to SPM concentration is based on the general sonar equation (Urick 1983; Medwin and Clay 1998):

$$E = P - T + S$$

where E is the echo intensity, P the source level power, T the transmission loss and S the target strength.

The transmission loss is due mainly to spherical beam spreading and the attenuation of sound in the water. A typical attenuation value for water alone is 0.069 dB/m at an acoustic frequency of 300 kHz (Deines 1999). Sound attenuation due to particles in the water is regarded as negligible when SPM concentrations are low (Tessier 2006). The target strength S will eventually represent the suspended particles in the ensonified volume. Deines (1999) applied the sonar equation for RDI®ADCP:

$$S_v = C + 10\log_{10}\left(TR^2\right) - 10\log_{10}(L) - 10\log_{10}(P) + 2\alpha_w R + K_c(E - E_r)$$

where S_v is the volume backscattering strength (dB), T the temperature of the transducer, R the slant range (m), L the transmit pulse length, α_w the absorption coefficient of water (dB/m), K_c the received signal strength indicator scale factor (for converting counts into dB), E_r the received noise (counts), E the echo intensity (counts) and C a constant that combines all other non-measurable parameters such as noise power and transducer efficiency (Thorne and Hanes 2002; Kim et al. 2004). The parameters C and K_c cannot be measured directly and are hence derived from the SPM mass concentrations obtained from filtered in situ water samples (SPMC$_{Niskin}$) collected over several tidal cycles at different stations in Belgian waters in order to cover a wide range of SPM concentrations. As hydrodynamic turbulences might also affect the acoustic backscatter (Nauw et al. 2014), the measurements for calibration purposes and those in the OWF corresponded to high turbulent intensities (i.e. Kolmogorov eddy length scales smaller than the wavelength of the sound wave):

$$SSC_v = 10\log_{10}(SPMC_{Niskin}) - 10\log_{10}\left(TR^2\right) + 10\log_{10}(L) + 10\log_{10}(P) - 2\alpha_w R$$

In all, 296 sediment mass concentrations and their concurrent echo intensities (E–E_r) were used in the linear regression analysis (R^2=0.91), resulting in a best-fit (least squares) line with corresponding K_c and C coefficients of respectively 0.45 (slope) and –83.27 (y-intercept; Fig. 5). K_c is within the range suggested by Deines (1999). Depth-averaged currents calculated by means of the 3D hydrodynamic COHERENS model applied to the Belgian continental shelf (Luyten 2011) were used to illustrate the overall hydrodynamics on the sandbank.

Results

Near-bed SPMC: optical and acoustic data

SPM concentrations recorded by the OBS (SPMC$_{OBS}$) and the ADV (SPMC$_{ADV}$) range between 0 and 20 mg/l over the course of the full neap–spring tidal cycle (about 14 days; Fig. 6). Maximum concentrations were reached mainly during spring tide before day 139 and after day 146, corresponding to the times when ebb and flood currents reach maximum speeds near the seabed (up to 0.5 and 0.4 m/s respectively). The blue bars in Fig. 6 illustrate a quarter-diurnal signature of SPM concentration.

During neap tide (days 139–146), SPMC$_{OBS}$ values were generally low except for three events between days 139–141. Intriguingly, these increases in concentration (up to 20 mg/l) did not coincide with periods of maximum current speed, but occurred during slack water (when current velocities were about 0.1 m/s). Also, the events were not captured by the ADV (see red bars). The correlation between the SPMC$_{OBS}$ and ADV signal is weaker (R^2=0.55) during spring tide (Fig. 4, magenta squares) than during neap tide (green and blue squares, R^2=0.71).

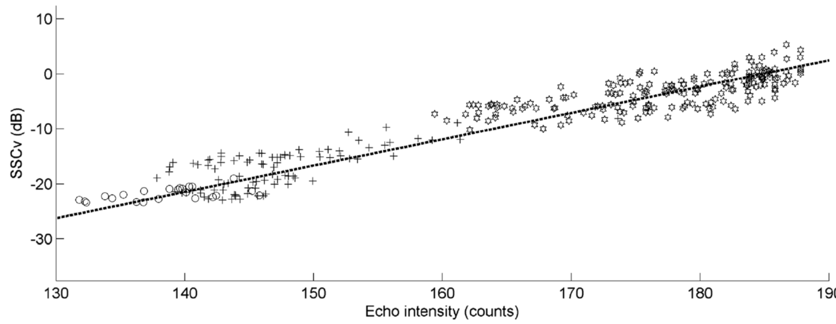

Fig. 5 ADCP linear regression scatter plot with best-fit line $SSC_v = K_c(E - E_r) + C$ where K_c is 0.45 and C is –83.27 (R^2=0.91). Different symbols represent different stations

Acoustic water column profiling

Hull-mounted ADCP measurements were conducted inside and outside the Belwind OWF 2 days prior to spring tide (7 May 2013). Figure 7 shows a transectional contour plot of the $SPMC_{ADCP}$ time series over ~1 h during low water slack tide (see Fig. 8, top left). The vessel entered the OWF from the SSW heading towards the NNE (T020), and passed several monopiles on both port and starboard sides. The tidal current was directed towards the E (beginning of flood phase) and reached a depth-averaged speed of 0.5 m/s. In Fig. 7 (bottom, 1 and 2), the increases in $SPMC_{ADCP}$ in the 4 minute subset (between day 127.409 and 127.4115) reached 6 mg/l, which is about 3 times that of the background value. The quasi-circular spots of high SPM concentrations are positioned at a water depth of 16 m, i.e. about 5–10 m above the seafloor, and are about 50 m wide. Outside the OWF (Fig. 8, bottom), these features are up to 100 m wide. At that particular time and location, the NE-directed flood current increased up to 0.8 m/s. The maximum $SPMC_{ADCP}$ was 10 mg/l, which is about 5 times that of the background concentration.

Discussion

SPM concentration is generally controlled by hydrodynamics, the availability of fine seabed sediments and biological activity (e.g. Fettweis et al. 2014, southern North Sea). Changes in SPM concentration at a certain location would therefore largely be related to those parameters. The hydrodynamics vary with meteorological conditions, neap–spring tide and intra-tidal phases. Except for the meteorological forcing (which was insignificant during the present measurement period), this is readily represented by both the acoustic and optical data of this study (Fig. 6). In essence, the SPMC reached maximum values at highest current speeds at spring tide and minimum values during slack water and neap tides. While this accords with expectations, it does not explain the peaks in the OBS-derived SPM concentrations observed at slack water just after low water (i.e. at the onset of the flood phase; Fig. 6). In addition, there is a lack in coherence between the optical and acoustic data at those instances. These observations together with the ADCP profiling results strongly suggest that the bio-fouled monopile foundations and associated sediment characteristics were responsible for the occurrences of SPM plumes in the Belwind I offshore wind farm.

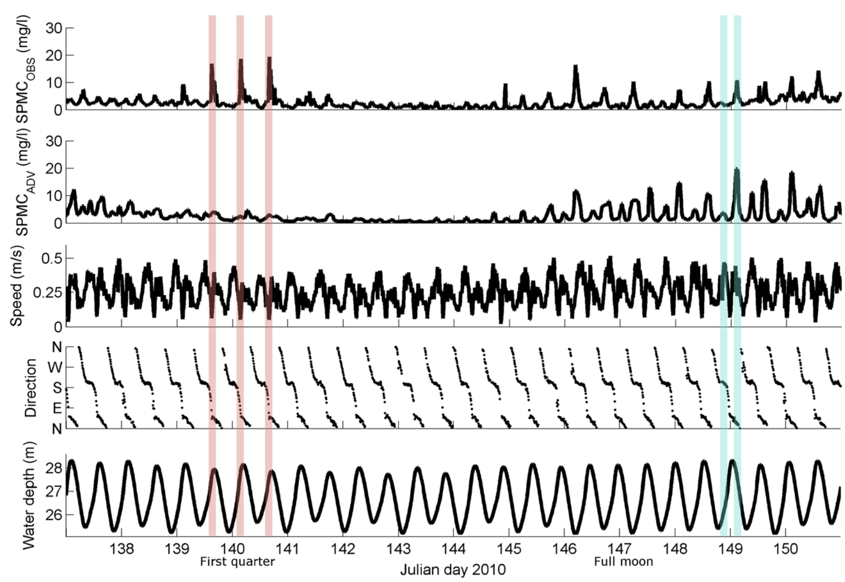

Fig. 6 Neap–spring time series between 17th May and 31st May 2010 showing (from top to bottom) $SPMC_{OBS}$, $SPMC_{ADV}$, ADV-based current speed, ADV-based current direction, and water depth. *Red bars* $SPMC_{OBS}$ peaks during slack current. *Blue bars* Ebb (SW direction) and flood (NE direction) current-induced re-suspension of sand particles; this is representative for all the other SPMC peaks in the time series, except around day 140 (red bars)

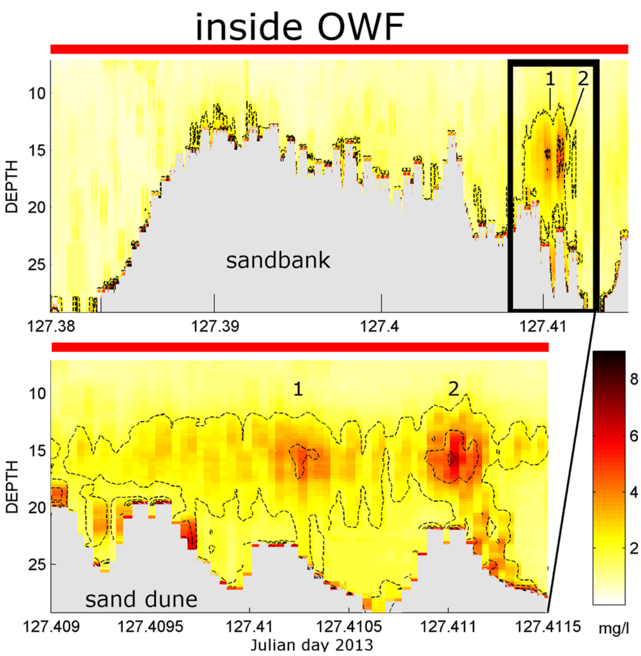

Fig. 7 *Top* Transectional $SPMC_{ADCP}$ concentrations on 7th May 2013 when the ship was sailing inside the OWF (see also Fig. 8, top, red line). *Bottom* SPM_{ADCP} concentrations between 127.409 and 127.4115 showing the cross-section of two separate SPM plumes (1 and 2; see also Fig. 8, top). *Grey shading* Sand bank and superimposed sand dunes

Pile epifaunal colonization

The installation of the OWF monopile foundations and the scour protection by rocks around the piles has created large areas of hard substrates in an otherwise soft bottom environment. These hard substrates provide a new habitat to various fouling communities such as amphipods, hydroids and bivalves not previously established in the area (for the present study region, see De Mesel et al. 2013). A consequence of this increase in hard substrate epifauna is the production and accumulation of detritus, faecal and pseudo-faecal pellets around the OWF turbine piles (McKindsey et al. 2011; Coates et al. 2014). Pseudo-faeces are rejected mucus-bound pellets of fine-grained material produced by filter feeders to discard unwanted material from their filtering surfaces (Maar et al. 2009; Ysebaert et al. 2009; McKindsey et al. 2011). Other organisms such as the amphipod *Jassa herdmani* and various species of the hydroid *Tubularia* filter the water column and build tube-like structures that trap SPM (for the present study region, see De Mesel et al. 2013 and Fig. 3). In these offshore areas, the SPM typically consists of fine mineral and organic particles that aggregate into larger flocs (e.g. Fettweis et al. 2006) with settling velocities of generally less than 1 mm/s (Manning et al. 2011). In contrast, pseudo-faecal pellets have settling velocities of a few cm/s (Giles et al. 2009; McKindsey et al. 2009). This results in high deposition rates

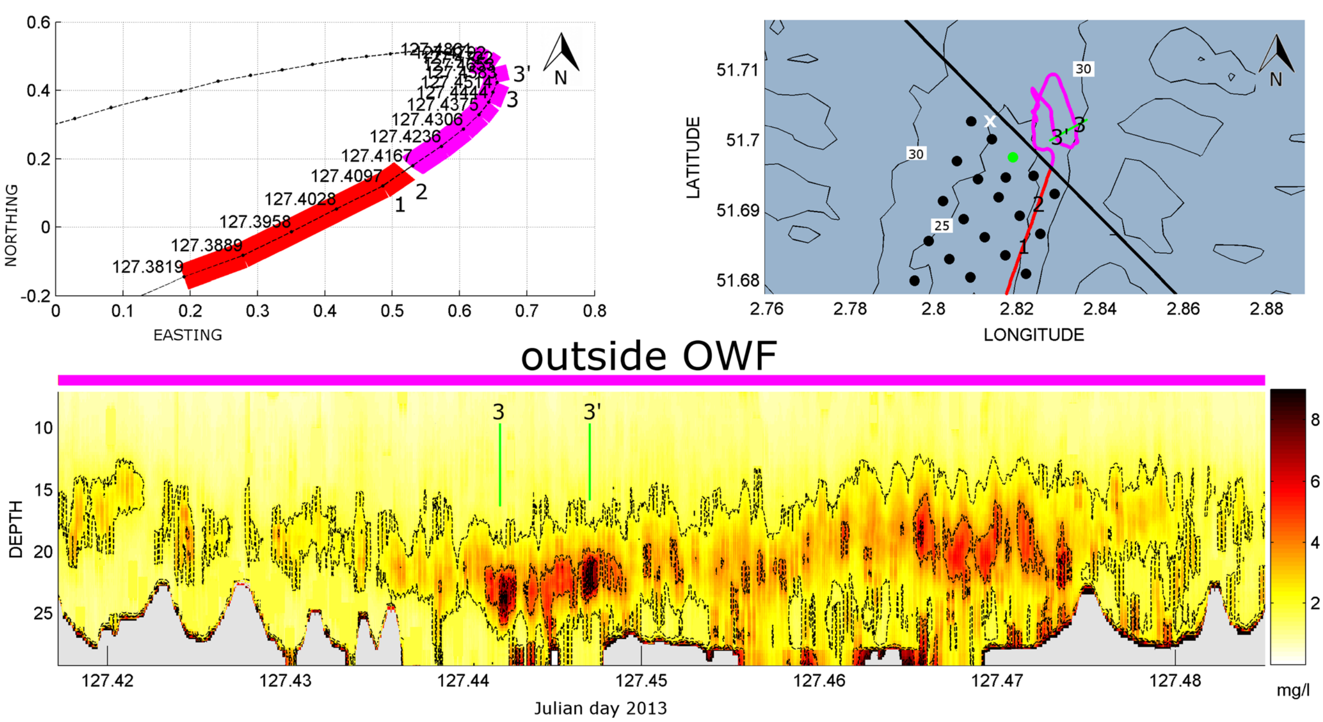

Fig. 8 *Top left* Tidal current ellipse on 7th May 2013 a.m. (more specifically, between 127.38 and 127.49) generated by the hydrodynamic numerical model COHERENS V2.0 (Luyten 2011): *red* transect sailed inside the OWF, *magenta* outside the OWF. *Bottom* SPM_{ADCP} concentrations when the ship was outside the OWF. The green bars (3 and 3') accentuate one particular SPM plume that was recorded twice (see ship's track in magenta on map at *top right*), very likely associated to the monopile indicated in green, according to the current direction at that time. *White cross* Bottom lander's position, *black lines and labels* bathymetry MLLWS

at the base of the turbine piles, causing a fining of the sediment and enrichment in organic matter at the seabed (Coates et al. 2014). Orvain et al. (2003) defined this organic matter-enriched bed layer associated with aquacultures, consisting of fine sediments and (pseudo-) faeces, as biogenic fluff. This fluff favours the establishment of a benthic community dominated by opportunistic deposit feeders, in turn substantially contributing to the deposition of organic matter (Dumbauld et al. 2009; Forrest et al. 2009). In the North Sea, Krone et al. (2013) observed that wind turbine foundations concentrated 35 times more macrozoobenthos biomass per square meter seafloor than was the case for the reference soft bottom sediments (i.e. the footprint of the turbine foundation vs. the non-affected seafloor).

SPM plume spatiotemporal dynamics

The increases in $SPMC_{ADCP}$ correspond to the plumes originating from the monopiles. For example, between day 127.44 and 127.45 the same SPM plume was profiled twice, as depicted by the green lines in Fig. 8 (bottom, 3 and 3'). Based on the current direction, the plume can be linked to the monopile highlighted in green in Fig. 8 (top right), situated 1.2 km upstream of the vessel.

It is well known that scour pits, caused by horseshoe and lee-wake vortices, may form around monopiles (Den Boon et al. 2004; Høgedal and Hald 2005; Whitehouse et al. 2011; Chen et al. 2014). To guarantee stability of the piles, the scour pits at the Belwind OWF have been filled with stones in a radius of 7 m around the pile. Bathymetric surveys in the study area revealed limited secondary scour around the scour protection (Belwind 2012) and thus only limited erosion of the surrounding seabed. It is therefore not likely that sand particles are the source of the SPM in the plumes because these have large settling velocities (>1 cm/s) and would thus be transported mainly in bedload. The fine-grained material (fluff), on the other hand, would remain in the water column for much longer periods and over greater distances (1 to 2 km) because of their low settling velocities (<1 mm/s). Precisely this can be inferred from the $SPMC_{ADCP}$ data, namely elongated SPM plumes at the mid-water level. The faecal and pseudo-faecal pellets accumulate in the depositional areas around the monopile foundations (Coates et al. 2014). These faecal and disintegrated pseudo-faecal pellets can easily be re-suspended and broken up (Widdows and Navarro 2007; Giles et al. 2009). The larger (not yet disintegrated) particles are not transported in the plumes, but remain in the wake of the monopile. From the vessel-mounted ADCP measurements, the observed SPM plumes (e.g. during day 127.44–127.45) are located at a depth of about 22 m—at the piles, this corresponds to the depth of the rock collar (scour protection), thus indicating re-suspension of the fluff from the rocky base of the piles. Taking into account the good water clarity, the plumes probably do not actually reach the water surface, as intuitively (and maybe wrongly) inferred from Fig. 1. The Secchi disk depth of about 10 m implies that submerged SPM plumes could well be visible from the surface during strong currents, as shown in Fig. 1.

Furthermore, the plumes depicted in Fig. 7 were recorded when the current was still relatively weak but nevertheless strong enough to re-suspend the fluffy material. Regarding the bottom lander data and the out-of-phase $SPMC_{OBS}$ vs. $SPMC_{ADV}$ peaks, the SPM plume evidently reached the bottom lander, as it was sensed to a much lesser extent by the acoustic signal (ADV) that is typically affected by sediment type, size and composition (Thorne et al. 1991; Fugate and Friedrichs 2002; Voulgaris and Meyers 2004; Ha et al. 2009; Bian et al. 2015). On the other hand, OBSs are most sensitive to clay- and silt-sized particles, the grain-size effects being an order-of-magnitude lower than those of concentration, flocculation effects being even smaller (Downing 2006). The bottom lander occasionally measured the plume during the onset of three consecutive flood phases. In Fig. 2, the northernmost monopile evidently was the upstream source of the SPM that was eventually sensed by the OBS.

Conclusions

For the Belgian offshore wind farm Belwind I, the main findings of this study are that (1) there is a linkage between the SPM plumes and the turbines in the OWF, (2) it is possible to visualize and determine the dimensions of submerged plumes, and (3) the origin of the SPM plume material is associated with bio-fouling on the turbine piles and the scour protections. The findings clearly argue against scouring of the seabed at the base of the turbines being the main cause of the elevated SPM concentrations.

The results raise numerous questions warranting further research. In particular, longer time series with bottom landers, gliders and/or profilers are required in order to capture the impacts of meteorological forcing, spring–neap cycles and seasonality on SPM plume dynamics. Such continuous measurements would throw light on the effect of seasonal variations in bio-fouling on plume occurrence and intensity. In order to better characterize the SPM plumes and their cause, data on the composition and particle size of the SPM should be included in future monitoring. Despite their limited duration, further ship-based measurements and sampling campaigns are needed to enable chemical analyses of suspended material within and outside the SPM plumes.

The rapid expansion of OWFs in the North Sea in the course of the next decades calls for studies that account for the impacts of artificial hard substrates on the wider ecosystem. The considerations outlined above should be integrated in the future monitoring of OWFs in the North Sea as part of the EU Marine Strategy Framework Directive, in particular with regard to descriptors 6 (seafloor integrity) and 7 (hydrographical conditions; see European Commission 2010).

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Conflict of interest The authors declare that they have no conflict of interest.

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