ENVIRONMENTAL IMPACTS OF OFFSHORE WIND FARMS IN THE BELGIAN PART OF THE NORTH SEA

LEARNING FROM THE PAST TO OPTIMISE FUTURE MONITORING PROGRAMMES

Edited by
Steven Degraer
Robin Brabant
Bob Rumes

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INTRO

EXECUTIVE SUMMARY AND CONTEXT SETTING

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CHAPTER 1

Executive summary

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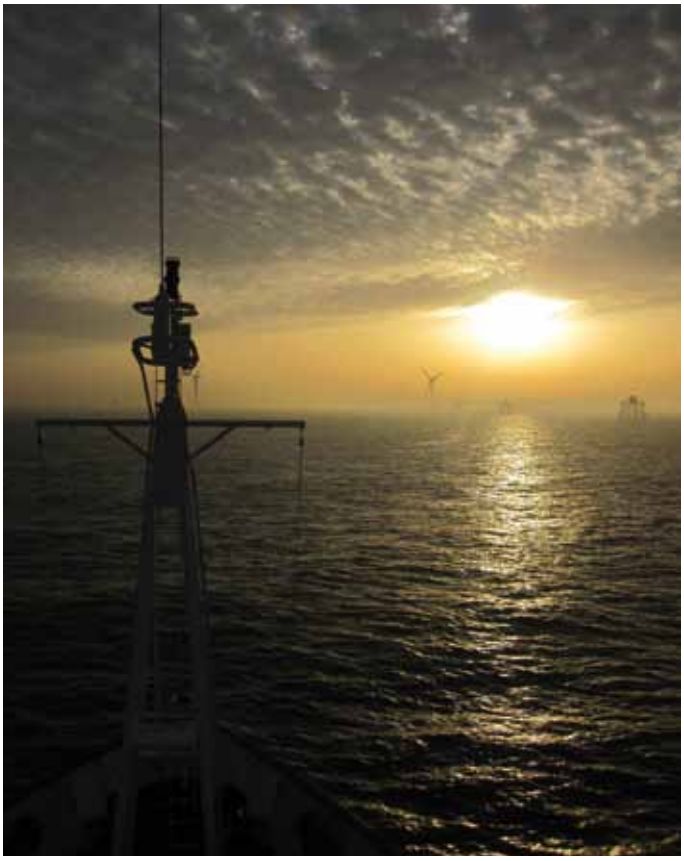
THE BELGIAN OFFSHORE WIND FARM MONITORING PROGRAMME

Belgium has allocated a 238 km zone in the Belgian part of the North Sea (BPNS) to offshore renewable energy production, for example offshore wind farms (Chapter 2). The first wind turbines were built in 2008. At present (October 2013), 109 turbines are operational in the BPNS. The installed wind turbines differ in foundation type and generated power: while the first six wind turbines have gravity based foundations (GBF), the majority are monopiles (55) followed by jacket foundations (48). The power that can be generated ranges between 3 and 6.15 megawatt (MW) per wind turbine. In the next few years, several hundreds of turbines will be up and running. The offshore wind farms are expected to contribute for about 43% of the Belgian 2020 targets for renewable energy.

Prior to construction, a developer needs to obtain a domain concession and an environmental permit. The latter includes a number of terms and conditions to minimise or mitigate the environmental impact of the wind farm project. This imposes a monitoring programme to assess the potential impacts on the marine environment. These assessments enable the authorities to impose mitigation measures or even halt the activities in case of extreme damage to the marine ecosystem. The monitoring programme equally allows understanding and evaluating the underlying ecological processes in support of an environment-friendly offshore wind farm policy and management. The programme started in 2005 and targets physical (hydro-geomorphology and underwater noise), biological (epifouling community on the hard substratum, macro- and epibenthos of the soft substratum, fish, seabirds and marine mammals), as well as socio-economic (seascape perception and offshore renewables appreciation) aspects of the marine environment. The Management Unit of the North Sea Mathematical Models (MUMM), a Scientific Service of the Operational Directorate Natural Environment (OD Nature) of the Royal Belgian Institute of Natural Sciences (RBINS) coordinates the monitoring programme. To cover all necessary scientific expertise MUMM collaborates with several institutes: the Research Institute for Nature and Forest (INBO), the Institute for Agricultural and Fisheries Research (ILVO-Bio-Environmental research group), Ghent University (Marine Biology Research Group and INTEC), International Marine and Dredging Consultants (IMDC) and Grontmij Belgium NV.

This report presents an integrated overview of all scientific findings of the Belgian offshore wind farm monitoring programme, with the specific aim of drawing lessons from these findings to optimise future monitoring programmes. A series of anticipated negative and positive impacts are covered, but the report also targets an insight in the underlying ecological processes. The report further elaborates on context setting and nuancing the results, and ends with some reflections to optimise the future monitoring programme.



ANTICIPATED NEGATIVE IMPACTS

Anticipated negative impacts on the marine environment also affect social acceptance of offshore wind farm developments (Chapter 3). The lack of social acceptance is actually considered one of the most important challenges of energy project developers worldwide. The social acceptance of offshore wind farms in Belgian waters was investigated through questionnaires in 2002 and 2009, i.e. prior to and after the first wind turbines had been constructed in 2008. The research demonstrated an increasing positive attitude towards offshore wind farms with 68% in support of the initiatives in 2009 versus 53% in 2002, and only 8% opponents in 2009 versus 21% in 2002. More than 90% of the 2009 respondents considered wind energy to be a good alternative to non-renewable energy sources. In Belgium, offshore wind farm siting is socially and environmentally more acceptable than onshore wind farms, even when seascape is taken into account. Interestingly, getting informed on environmental impacts of offshore wind farms was valued highest by the public. A follow up study on social acceptance is proposed when the wind farms closest to the coast are constructed.

Anticipated negative ecological impacts cover the risks of increased turbidity, increased sediment erosion and surfacing of the electricity export cable (Chapter 4). Detailed morphological investigations found that increases in turbidity are mainly due to meteorological events rather than to the construction and operation of the wind farms. Sediment erosion stayed within acceptable limits: the erosion protection around GBFs wind turbines functioned without any secondary erosion, while the monopile erosion pits ranging from 2 to 6.5 m were adequately confined by an erosion protection layer. However, there were substantial sediment losses (30 to 35 %) during the dredging and dumping activities to install the GBFs, leaving a series of dredging pits that have been refilled by using sand from the second phase of wind farm development. Electricity export cables further proved susceptible to exposure because of the dynamic sand dune migration. A continued monitoring of turbidity using satellite images is advised. The follow-up with multibeam of erosion near the foundations, wind turbine stability and cable burial, should be continued...

Negative impacts on seabirds through habitat change, habitat loss, barrier-effects and collision are major environmental concerns (Chapter 5). While some species avoided the wind farms (i.e. northern gannet *Morus bassanus*, common guillemot *Uria aalge* and razorbill *Alca torda* at the most offshore Bligh Bank, and common gull *Larus canus* at the most onshore Thorntonbank), other species seemed to be attracted (i.e. lesser black-backed gull *Larus fuscus* and herring gull *Larus argentatus* at the Bligh Bank, and little gull *Hydrocoloeus minutus*, great black-backed gull *Larus marinus*, Sandwich tern *Sterna sandvicensis* and common tern *Sterna hirundo* at the Thorntonbank). Large gulls were often seen flying at rotor height (15-22%). Based on daytime observations, each year up to about 1300 birds, mainly gulls, are expected to collide with the turbines once all wind farms will be operational in the BPNS. During strong migration periods, thrush *Turdus* spp. collisions can reach 200 victims during a single night. Visual census combined with radar observations will aid a future accurate bird mortality assessment. Future monitoring of the local seabird distribution will further increase the likelihood of displacement effect detection and will allow discerning possible habituation effects.

Increased noise levels generated by wind farms, may harm the marine environment (Chapter 6). For example, the maximum detected above water sound pressure level during pin piling activities for the installation of jacket foundations, reached 145 dB(A). The operational sound pressure level mainly generated by the blades passing through the air, amounted to 105-115 dB(A) at wind speeds higher than 12 m/s and could hence be detected up to a distance of 10 km. Underwater noise generated during the installation of gravity based foundations (about 115 dB re 1 Pa root mean square) was close to ambient noise levels. In contrast, monopile piling produced excessive underwater noise levels of 179-194 dB re 1 Pa (zero to peak level at 750 m), attenuating to ambient noise levels at a distance of up to 70 km. For pin piling (jacket foundations) lower noise levels of 172-189 dB re 1 Pa were measured, but the total number of blows per megawatt installed is 57% higher than for a monopile. When in operation, steel monopile sound pressure is double of that emitted by a jacket foundation turbine, in its turn twice the sound pressure of the background or GBF foundation turbine. Future monitoring will mainly target continuous underwater noise measurements, which can be compared with other types of human-induced noise in the marine environment.

Piling noise in fact is a major concern to marine mammals and fish (Chapter 7). For the harbour porpoise *Phocoena phocoena* occurring in Belgian waters with densities of up to 2.7 ind./ km , aerial surveys during a piling event showed a distance of disturbance of porpoises of up to at least 20 km from the piling location. A model allowed reproducing the porpoise displacement in a wide area around the piling zone, but outside this area larger differences between the observations and the model were detected. The latter difficulties may be caused by the spatial variability in food availability or seasonal movements. Further fine tuning and testing of the model in different piling conditions and based on aerial surveys and passive acoustic monitoring data, is therefore advised. The impact of construction and operational noise on fish eggs and larval development in Belgian waters only started recently, and needs more attention in the future monitoring programme. These 'passive drifters' cannot actively escape from the exposure to human-induced noise. Especially fish with a swim bladder, for which the European sea bass *Dicentrarchus labrax* will be used as a model species, will be targeted through an experimental study.

ANTICIPATED POSITIVE IMPACTS

The protection against fishing activities inside the wind farms is undoubtedly the main anticipated positive impact of offshore wind farms on the marine environment (Chapter 8). Based on VMS data (Vessel Monitoring System), it can be concluded that fishing vessels - mainly trawlers - are virtually everywhere in Belgian waters, except in the wind farms. A moderate increase in fishing activities, mostly from Dutch fishing vessels, is noted in the zone surrounding the wind farm concessions. Recreational anglers, mostly targeting pelagic and bentho-pelagic fish, first concentrated close to the gravity-based foundations at the Thorntonbank, but recently seem to have almost left the area.

Combined with a possible reef effect, the exclusion of fisheries was expected to have a significant positive impact on the soft sediment benthos. A macrobenthic *Nephtys cirrosa* community was found at the Thorntonbank and Gootebank, corresponding to a typical sedimentology with a median grain size between 331 m and 410 m (Chapter 9). The community is dominated by a few species, like the polychaetes *N. cirrosa* and *Spiophanes bombyx*, the mysid shrimp *Gastrosaccus spinifer* and the amphipod *Urothoe brevicornis*. A natural inter-annual variability in densities between about 200 and 800 ind./m , was detected. While the macrobenthic community structure was similar in the control and concession sites before construction, significant differences were found in 2008. In this year, i.e. shortly after major construction works, high densities (dominated by *S. bombyx*) were detected. However, no large-scale effects could be detected, as the differences between control and impact sites disappeared again after two years. The Benthic Ecosystem Quality Index (BEQI) confirmed the recovery of the community after the construction works. Long-term and larger-scale effects could hence not be detected. Future monitoring will focus on the fisheries exclusion and smaller-scale enrichment effects (Chapters 8 and 13), and aim at detecting these effects at the scale of a complete wind farm.

Demersal fish, benthopelagic fish and epibenthos from soft sediments may be positively impacted as well (Chapter 10). For example, epibenthos biomass and length of whiting *Merlangius merlangus* slightly increased at the edge of the Thorntonbank, while (temporarily) increased abundances of sole *Solea solea* and dab *Limanda limanda* were observed at the edge of the Bligh Bank. Inside the wind farms, several local and temporal impacts were detected. At the Thorntonbank, increases in dab mean length (2012), epibenthos biomass (2009) and number of demersal fish species (2009) were observed. At the Bligh Bank, densities of the common starfish *Asterias rubens* and sole increased over the monitoring period, and several 'larger' plaice *Pleuronectes platessa* and turbot *Psetta maxima* were noted. Some short time construction effects were seen shortly after the start of the piling activities, like increased sandeel *Ammodytes tobianus* densities and decreased densities in dab, ophiuroids *Ophiura ophiura*, squid *Allotheutis subulata* and dragonet *Callionymus lyra*. A continued monitoring, taking into account the high natural spatio-temporal variability, will ensure an increased power of impact detectability.

Some fish may be directly attracted to the artificial hard substrata, in search for food or shelter (Chapter 11). The offshore wind turbine fish community (near the gravity-based foundations) was dominated by pouting *Trisopterus luscus* and cod *Gadus morhua*, while also other species such as poor cod *Trisopterus minutus*, saithe *Pollachius virens* and black seabream *Spondyliosoma cantharus* were exclusively detected close to the turbines. Cod and pouting catches were up to 12 and 30 times higher, respectively, compared to the wrecks, and up to > 100 times higher compared to the nearby sandy areas. The density peaks of both species (May-November for cod and September-December for pouting), probably reflect a seasonal spawning migration. Young individuals dominated the local cod and pouting populations. Future monitoring will focus on the representativeness of GBF wind turbines compared to steel monopile turbines, the latter having a smaller erosion protection layer and are positioned in more offshore waters.

Fouling organisms colonising artificial hard substrata, increase the local species richness (Chapter 12). Different communities can be detected along the depth gradient: the marine splash midge *Telmatogeton japonicus* dominated the splash zone; the intertidal fringe was characterised by barnacles and the blue mussel *Mytilus edulis*; a *Jassa-Tubularia*-Actiniaria community in the subtidal zone was dominated by the amphipod *Jassa herdmani* (up to 3 10^5 ind./m) and the hydroids *Tubularia indivisa* and *T. larynx* (up to 90% coverage). The patterns in species richness, density and coverage were best illustrated at the Thorntonbank, where they showed an increase mainly during the first two to three years, after which they stabilised. These long-term dynamics are superimposed by seasonal dynamics with highest densities (generally ranging between 1-1.5 10^5 ind./m) and coverage (on average 60-70%) in spring and summer. In addition to the settling of new species, competition and predation are important biological processes shaping hard substrata communities. Future monitoring will focus on a better understanding of the spatial heterogeneity, the dynamics along the onshore-offshore gradient, and the use of the artificial reefs by larger invertebrates, such as crabs and lobsters.

UNDERSTANDING ECOLOGICAL PROCESSES BEHIND THE OBSERVED PATTERNS

A proper understanding of the ecological processes underlying the observed impacts is indispensable to deliver science-based advice for an environment-friendly design of future wind farms. For example, understanding the effects of organic enrichment on soft sediment macrobenthos at a small scale, allows extrapolating these small-scale effects to large-scale and long-term impacts (Chapter 13). Lower median grain sizes of the sediment and increased organic matter levels were found close to the gravity based foundations at the Thorntonbank. These phenomena could be linked to a macrobenthic community evolving away from the typical *N. cirrosa* community in this area. Close to the turbines, elevated macrofaunal densities (up to 11500 ind/m^2), biomasses (up to 9540 mg/m^2) and number of species (up to 32 spp.) were found, especially along the Northwest and Southwest transects. Juvenile common starfish *A. rubens*, the sand mason *Lanice conchilega*, the bee spionid *S. bombyx*, and the typical hard substrate species *Monocorophium acherusicum* and *J. herdmani* tend to dominate in this enriched environment. The local enrichment was detectable to a distance of 50 m from the turbines. Future monitoring will target the spatial extension of this effect through time and at other types of wind turbine foundations.

Zooming into fish habitat use in Belgian offshore wind farms, mainly young individuals of Atlantic cod and pouting were clearly attracted nearby the wind turbines as was observed by divers and by line fishing. Demersal fish species were however not found to be consistently attracted at larger distances (minimum 180 m) from the turbines (Chapter 14). So far, no clues of increased recruitment or growth in demersal species were detected at larger distance. However a number of larger individuals of plaice *Pleuronectes platessa* were caught at the Bligh Bank. Dab on the other hand occurred in lower numbers, but remarkably had a fuller stomach inside (mean Fullness Index, FI: 0.15) than outside (FI: 0.05) the area. Similarly to cod, pouting showed feeding mainly upon epifouling species, such as *J. herdmani* and *Pisidia longicornis*. Cod indeed showed an attraction to the artificial hard substrata with about 90 % of the individuals staying within a 40 m range from the wind turbines. Future monitoring will focus on attraction and production mechanisms other than food availability, but will also aim at including a wider set of fish species and an energy profiling of their prey species.

Recent sightings of European shag *Phalacrocorax aristotelis*, a seabird species favouring cliffs and rocky shores, in Belgian wind farms and black-legged kittiwakes *Rissa tridactyla* starting to breed on North Sea gas platforms, all point towards the attraction-production potential of offshore wind farms for seabirds (Chapter 15). Whether birds are attracted to wind farms from a sheer physical point of view, with the wind farm functioning as a stepping stone or a resting place (attraction), or whether they already learned to exploit the possibly increased food availability (production), remains to be investigated. Black-legged kittiwakes were already regularly observed foraging inside the Bligh Bank wind farm, with the percentage of kittiwakes actively foraging inside the wind farm being much higher than in the control area (5.9% versus 0.3%). Also high numbers of lesser black-backed gulls were foraging close to the Thorntonbank jacket foundations. Future monitoring will pay attention to the behaviour and foraging-related activities of seabirds, and to pelagic fish as the most important prey species for seabirds.

Within the attraction-production debate of offshore wind farms we also investigated whether marine mammals were attracted to the increased fish abundance close to wind turbines or rather repulsed by the increased noise levels (Chapter 16). Harbour porpoises showed an uneven spatio-temporal distribution in Belgian waters, with a shift from the northern and north-eastern part of the Belgian waters towards the south-west and west between February and April. As the offshore wind farms are relatively small compared to the area that can be covered in a short time period by this highly mobile species, differences in distribution of harbour porpoise within and outside wind farms are probably inferior to seasonal variations within the southern North Sea caused by movements to find suitable prey resources. In addition to continued aerial surveys, future monitoring will target small-scale passive acoustic monitoring (PAM) to investigate the potential use of offshore wind farms by harbour porpoises. Attention will also be paid to disentangle the complex link between PAM data and species densities.

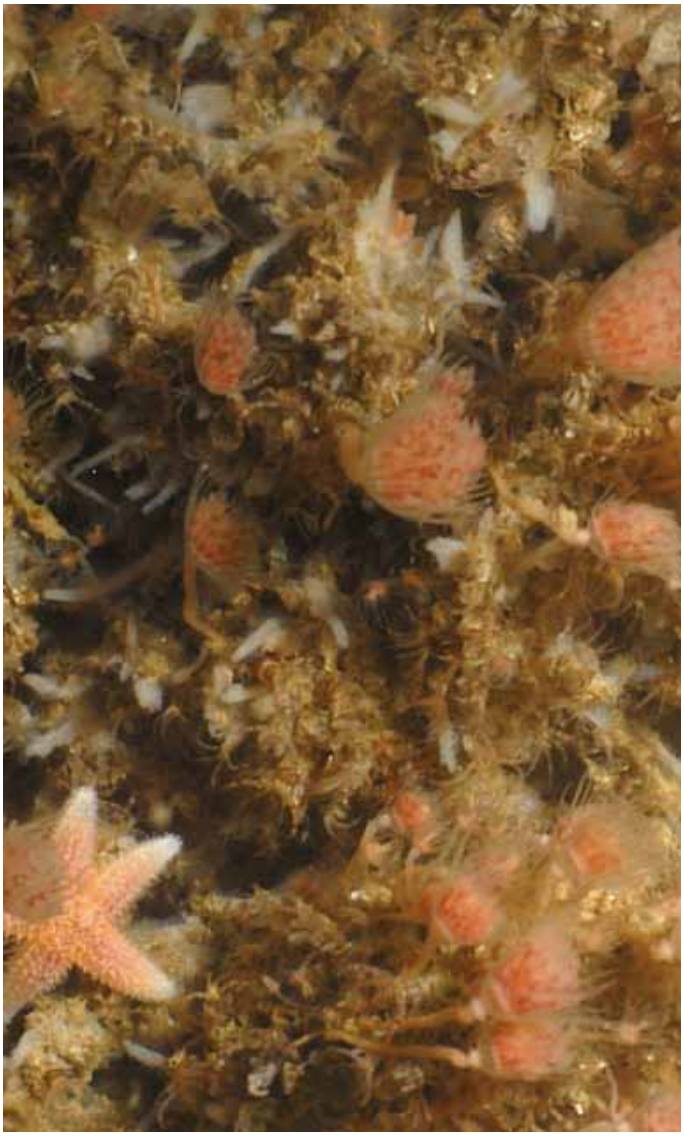
NUANCING EFFECT INTERPRETATION

Several impacts have been identified in the Belgian offshore wind farms, varying from seemingly negative to seemingly positive impacts (Chapter 17). Species richness increased because hard substrata (wind turbine foundations and erosion protection layers) were introduced. However, offshore wind farms may also increase the risk of invasions in the North Sea, as non-indigenous species (NIS) may now find more suitable place to survive and hence strengthen their competitive position in the North Sea. More than half of the hard substratum intertidal species (e.g. the invasive Pacific oyster *Crassostrea gigas*) in the wind farms can be categorised as NIS. Pouting is attracted to wind farms, but we do not know yet whether these offshore wind farms act as an ecological trap. However, pouting is significantly larger inside than outside the wind farms, their stomach is filled more and their condition is similar, so no evidence was obtained to assume that the habitat quality of offshore wind farms does not fulfil the functional needs of pouting. Preliminary extrapolation of bird collisions (at North Sea population scale) to future expansions of offshore wind farms showed that the existing adult mortality for instance of lesser and great black-backed gull might exceed the accepted threshold of 5%. Future monitoring will take account of the need for up scaling to species population levels and the expansion of offshore wind farms in the North Sea.

Increased species richness, densities and biomass further can be evaluated in different spatial settings, for instance at turbine level or at the level of a wind farm or even the Belgian part of the North Sea (Chapter 18). The species pool of soft sediment fish and squid did not change drastically, but the number of hard substrate associated fish species increased from 2 to 8 inside the wind farm concession area. The number of benthic species in the concession area more than doubled, from 91 to 264 species, since the installation of the first turbine foundations, mainly because of the increase of hard substratum species from 10 to 100. Autumn benthic biomass increased ~4000 times at the scale of a single gravity based foundation from 0.6 kg ash-free dry weight (AFDW) before construction to ~2500 kg after construction, with the major part of the biomass at the scour protection (89%) and the intertidal *M. edulis* zone (10%). For the entire Thorntonbank wind farm, the autumn biomass increased about 14 times from about 5 to 70 ton AFDW. The offshore wind farms may contribute about 3% of the total biomass in the BPNS. Future monitoring will focus on a validation of the fouling biomass estimates for jacket and monopile foundations.

REFLECTIONS FOR AN OPTIMISATION OF FUTURE MONITORING PROGRAMMES

Six years of monitoring triggered a reflection on how to best continue the monitoring programme, building on both basic and targeted monitoring contexts (Chapter 19). The basic monitoring should be rationalised at the level of the likelihood of impact detection, related to research effort and impact size. The meaningfulness of impact size deserves our attention and should be aligned with the current implementation of European Directives, such as the Marine Strategy Framework Directive. Future basic monitoring finally needs to consider the representativeness of the current findings, so far largely focused on GBFs. Within a targeted monitoring context, the artificial reef effect will undoubtedly play a key role in the future monitoring programme. It already received a lot of attention in the monitoring so far, but various cause-effect relationships, mainly linked to the attraction-production hypothesis, remain yet to be tackled, preferably through international scientific collaboration. A major challenge however is to achieve a reliable assessment of cumulative impacts and to upscale locally observed impacts to the larger scale at which ecological processes take place. This will require a close collaboration between scientists, industry stakeholders and administrators, preferably across countries bordering the North Sea.



CHAPTER 2

Monitoring offshore wind farms in the Belgian part of the North Sea: Setting the scene

Robin Brabant*, Steven Degraer* and Bob Rumes

*shared first authorship

Offshore wind farms are expected to contribute for about 43% of the Belgian 2020 targets for renewable energy. Today, 109 turbines are operational in the Belgian part of the North Sea. In the next few years, several hundred of turbines will be up and running. With 238 km reserved for offshore wind farms, major ecological impacts may however be expected. These impacts both positive and negative, triggered an environmental monitoring programme focusing on various aspects of the marine ecosystem components, but also on the human appreciation of offshore wind farms. This report targeting marine scientists, policy makers and managers, provides an overview of the major scientific achievements of six years of monitoring.

OFFSHORE WIND FARMS IN BELGIUM

The European Directive 2001/77/EC on the promotion of electricity produced from renewable energy sources in the internal electricity market, imposes a target figure for the contribution of the production of electricity from renewable energy sources upon each Member State. For Belgium, this target figure is 13% of the total energy consumption, which must be achieved by 2020. Offshore wind farms in the Belgian part of the North Sea (BPNS) are expected to make an important contribution (ca. 43%, assuming 2000 MW installed capacity by 2020) to achieve that goal.

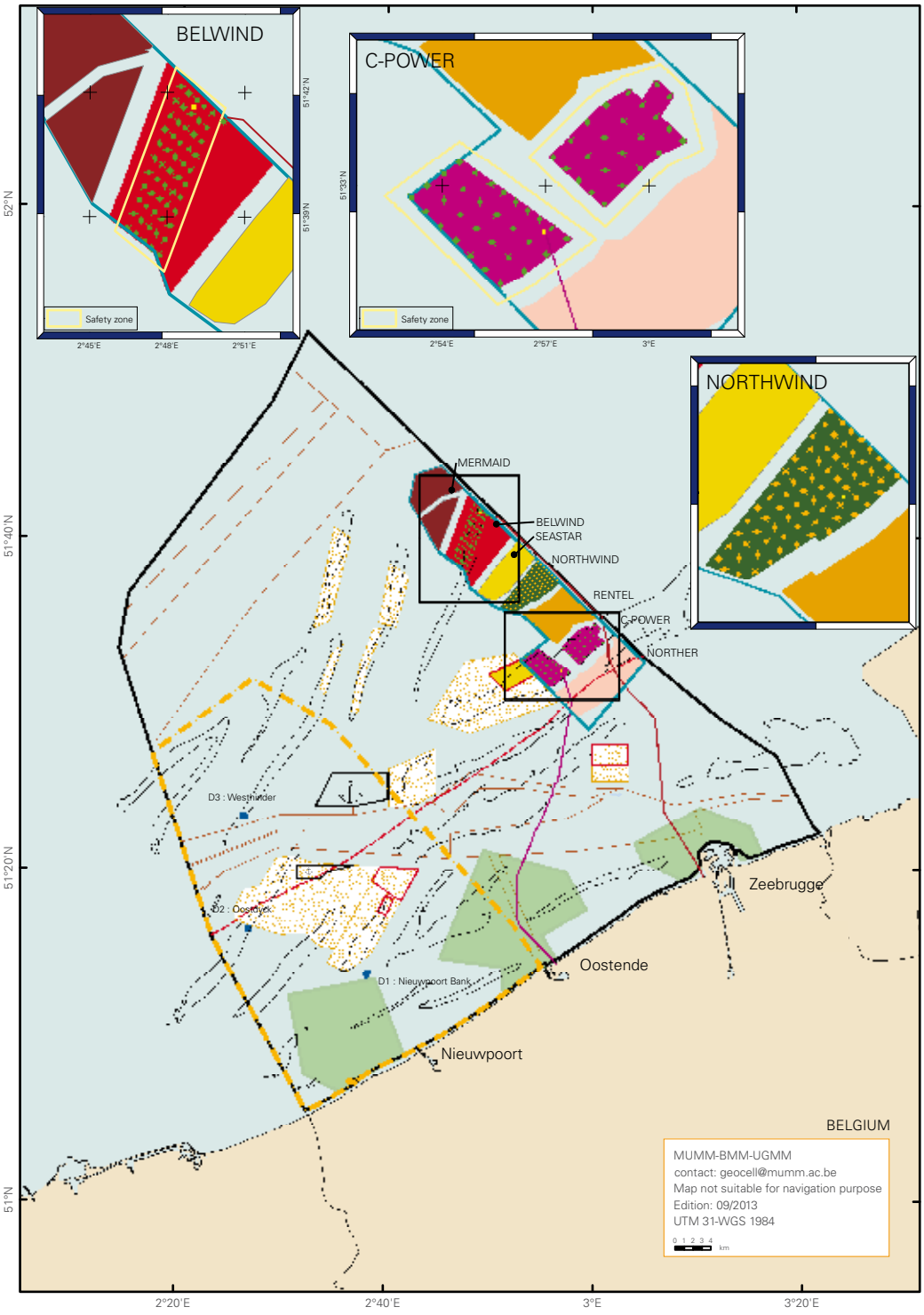
With the Royal Decree of 17 May 2004, a 264 km area within the BPNS is reserved for the production of electricity from water, currents or wind. It is located between two major shipping routes: the north and south traffic separation schemes. In 2011, the zone was adjusted on its Northern and Southern side in order to ensure safe shipping traffic in the vicinity of the wind farms. After this adjustment the total surface of the area amounted to 238 km .

Prior to installing a wind farm, a developer must obtain (1) a domain concession and (2) an environmental permit. Without an environmental permit, a project developer is not allowed to build and exploit a wind farm, even if a domain concession was granted.

When a project developer applies for an environmental permit an administrative procedure, mandatory by law, starts. This procedure has several steps, including a public consultation during which the public and other stakeholders can express any comments or objections based on the environmental impact study (EIS) that is set up by the project developer. Later on during the permit procedure, the Management Unit of the North Sea Mathematical Models (MUMM), a Scientific Service of the Operational Directorate Natural Environment (OD Nature) of the Royal Belgian Institute of Natural Sciences gives advice on the acceptability of expected environmental impacts of the future project to the Minister responsible for the marine environment. MUMM's advice includes an environmental impact assessment (EIA), based on the EIS. The Minister then grants or denies the environmental permit in a duly motivated Decree.

The environmental permit includes a number of terms and conditions intended to minimise and/or mitigate the impact of the project on the marine ecosystem. Furthermore, as required by law, the permit imposes a monitoring programme to assess the effects of the project on the marine environment.

At present, five projects were granted a domain concession and an environmental permit (from South to North: Norther, C-Power, Rentel, Northwind & Belwind). Two additional projects were granted a domain concession, one of which has submitted its application to obtain an environmental permit in summer 2013 (Table 1).



Map of the Belgian part of the North Sea with an indication of the human activities. A 238 km area (blue polygon) is reserved for the production of renewable energy by the Royal Decree of 17 May 2004, as adjusted by the Royal Decree of 3 February 2011 (http://www.mumm.ac.be/EN/Management/Atlas).

Human activities in the Belgian marine area

- Belgian continental shelf
- Territorial sea limit
- Anchorage area
- Navigation route
- Area reserved for electricity production
- Operational wind turbine
- Turbine under construction
- Offshore transformer station
- Export cable Belwind
- Export cable C-Power
- Reference zone for Wind farm monitoring
- Mineral resources extraction zone
- Zone closed for mineral resources extraction
- Mariculture area
- Site of Community Importance (Habitat Directive) "Vlaamse banken". New Special Area of Conservation
- Special Protection Area (Birds Directive)

Table 1. Overview of wind farms in the Belgian part of the North Sea (situation on 30th of September 2013)

*number of turbines and/or total capacity still to be decided

**20 MW wave energy

Project		Number of turbines	Capacity (MW)	Total capacity (MW)	Concession obtained	Environmental permit obtained	Status
C-Power	phase 1	6	5	325	YES	YES	Phase 1 completed in 2009
	phase 2&3	48	6.15		YES	YES	Entire wind farm completed in 2013
Belwind	phase 1	55	3	330	YES	YES	Phase 1 completed in 2011
	phase 2	55	3		YES	YES	Phase 2 construction foreseen to start in 2014
	demo	1	6		YES	YES	Alstom Haliade demo turbine installed in 2013
Northwind		72	3	216	YES	YES	Construction ongoing
Norther		47 – 100*	3-10	258 – 470*	YES	YES	Construction foreseen to start in 2014
Rentel		47 – 78*	4-10	289 – 468*	YES	YES	Construction foreseen to start in 2016-2017
Seastar		41*	4-10	252 – 540*	YES	NO	Construction foreseen to start in 2016-2017
Mermaid		75*	6*	450*+ 20**	YES	NO	No information

C-Power's onshore construction site of the gravity based foundations in Ostend.

TIMELINE WIND FARMS DEVELOPMENT

2008

The C-Power project is located on the Thorntonbank sandbank, located at 27 km off the Belgian coast. In 2008, C-Power started with the construction of the first phase of its project, i.e. six turbines on gravity based foundations (GBF). A GBF is a hollow, concrete structure that is filled with sand once it is placed on the seabed. Due to its weight, it remains stable. Before the GBF can be placed, the seabed needs to be prepared to create a flat surface on dense sand.

Transport of a gravity based foundation from the port of Ostend to the C-Power site at the Thorntonbank.

Assembly of a C-Power phase 1 turbine on the Thorntonbank.

2009

The six turbines of C-Power's first phase were commissioned and producing electricity by May 10th, 2009.

Phase 1 turbines on the Thorntonbank.

Pile driving of monopiles (MP) for the Belwind project on the Bligh Bank started on September 8th 2009. The 56th and last monopile of the first phase was installed on February 5th 2010.

Piling vessel (with red and white hammer) at the Belwind site on the Bligh Bank.

2010

A transition piece (TP) was installed on every Belwind monopile. The TP makes the connection between the MP and the wind turbine. In 2010, Belwind installed 55 wind turbines and one offshore high voltage station. The entire phase 1 of Belwind was fully operational from December 31st 2010 onwards.

Belwind Phase 1 wind turbines on the Bligh Bank.

2011

The construction of phase 2 and 3 of the C-Power project (i.e. 48 turbines and one offshore transformer station) started in spring 2011. The foundation type for the phase 2 and 3 turbines is different from the pilot phase since jacket foundations, instead of the GBFs, were installed. These foundations consist of a steel jacket with four legs. The foundations were installed using the pre-piling concept: four pin-piles were driven into the seabed and the legs of the foundation were grouted on the pre-piles.

Phase 3 jacket installation at the C-Power site.

The C-Power offshore transformer station was installed on March 17th, 2012. On the background the six phase 1 turbines and ongoing jacket installation.

The construction of the Northwind project on the Lodewijkbank started in spring 2013. The wind farm is expected to be fully operational by spring 2014.

2012

Vessel on its way to the Nortwind site on the Lodewijkbank with two monopiles and two transition pieces.

In the summer of 2013 the entire C-Power wind farm was finalised and producing energy. The wind farm was officially inaugurated on September 17th, 2013.

2013

Partial view of the C-Power wind farm.

OFFSHORE WIND FARM MONITORING AND RESEARCH STRATEGY

The monitoring programme started in 2005 with the investigation of the pre-impact condition of the ecosystem and the search for appropriate reference sites, but it was continued only from 2008 onwards when the first six wind turbines were installed onto the Thorntonbank. The monitoring programme targets physical (i.e. hydro-geomorphology and underwater noise), biological (i.e. hard substratum epifauna, hard substratum fish, soft substratum macrobenthos, soft substratum epibenthos and fish, seabirds and marine mammals), as well as socio-economic (i.e. seascape perception and offshore renewables appreciation) aspects of the marine environment. MUMM coordinates the monitoring and covers the socio-economic aspects of the monitoring. OD Nature further adds its expertise in hydro-geomorphology, underwater noise, hard substratum and non-indigenous epifauna, marine mammals and radar detection of seabirds. Further collaborations complete the necessary expertise in the following domains: seabirds (Research Institute for Nature and Forest), soft substratum epibenthos and fish (Institute for Agricultural and Fisheries Research), soft substratum macrobenthos, hard substratum fish (Marine Biology Research Group, Ghent University), above water noise (INTEC, Ghent University), seabed morphology (IMDC) and seascape (Grontmij).

With the monitoring programme, MUMM and its partners (1) assess the extent of the anticipated impacts on the different aspects of the marine ecosystem and (2) aim at revealing the processes behind these impacts. The first objective is basically tackled through the basic monitoring, focusing on the *a posteriori*, resultant impact quantification, while the second monitoring objective is covered by the targeted or process monitoring, focusing on the cause-effect relationships of *a priori* selected impacts. As such, the basic monitoring deals with observing rather than understanding impacts and hence leads to area-specific results, which might form a basis for halting activities. In this study, basic monitoring generally follows a before-after, control-impact or BACI design, in which ecological changes at the impact site are compared with the ecological condition before the impact and in non-impacted reference or control sites. Targeted monitoring on the other hand deals with the understanding of the processes behind the impacts of a selected set of hypothesised cause-effect relationships highly relevant to the wind energy sector. This step is not only a prerequisite for an effective regulatory application, but also permits (1) current and future impact mitigation, (2) better prediction of future impacts, as well as (3) moving away from site-specific observations to more generic knowledge. More details on this topic can be found in Degraer and Brabant (2009).

SIX YEARS OF MONITORING AND RESEARCH

In addition to a set of early scientific reports presenting the baseline condition at future impact and reference sites (De Maersschalck et al., 2006; Henriet et al., 2006; Vanermen et al., 2006), an overview of the major achievements of the monitoring programme has been presented in a series of yearly published, integrated reports.

In 2009 (Degraer and Brabant, 2009), we reported on the lessons learnt and recommendations from the first two years of environmental monitoring. This report more specifically evaluated the appropriateness of the selected reference sites and reference conditions for both the C-Power and the Belwind projects. It further introduced the various environmental data under surveillance, including a preliminary evaluation of the impacts linked to the construction of the first six turbines at the Thorntonbank. Its main importance however is found in its advices for future monitoring at the level of technicalities, scientific design, as well as research focus and strategies.

Degraer et al. (2010) then focused on the early and or localised environmental impacts of the GBF wind turbines (C-Power) and or monopiles (Belwind), as well as on the natural spatio-temporal variability (i.e. dynamic equilibrium). Early impacts were detected for the geophysical environment of both the GBF wind turbines at the Thorntonbank and the monopile wind turbines at the Bligh Bank, the establishment of hard substratum biota on and close to the GBF wind turbines at the Thorntonbank, and the social attitude towards offshore renewables. The natural spatio-temporal variability was investigated for the soft substratum macrobenthos, soft substratum epibenthos, soft substratum fish and marine mammals.

In 2011 (Degraer et al., 2011), a selection of targeted monitoring results was presented for the first time, from which we attempted to construct a hypothesis-driven impact scenario, including presumed cause-effect relationships between the various ecosystem components. The integration of the monitoring findings obtained so far, already allowed for some preliminary speculation on the long-term impact processes within the Belgian wind farm zone. Those were a prolonged organic enrichment of a naturally relatively poor environment, an increased food availability for epibenthic and fish predators and the improved seabird and marine mammal habitat quality. The Benthic Ecosystem Quality Index (BEQI) was further applied to evaluate the deviation in macrobenthic density, number of species, species composition and biomass between the benthic data collected in the impact area and the reference area, both from the period before and after the construction of the first wind turbines.

The 2012 report (Degraer et al., 2012) continued building on a common understanding of the environmental impacts of offshore wind farms. This included the cause-effect relationships of observed impacts within the benthos, a strengthening of the visual detection of impacts on seabirds and getting prepared for going offshore with the bird radar, and a quantification of harbour porpoise *Phocoena phocoena* disturbance by piling activities.

THIS REPORT

This report finally presents an integrated overview of all scientific findings of the Belgian offshore wind farm monitoring programme, with the specific aim of drawing lessons from these findings to optimise future monitoring programmes. The report as such covers a series of anticipated negative (Part I) and positive impacts (Part II), but also targets an understanding of the ecological processes behind observed impacts (Part III). Further considerations on context setting, nuancing and reflections on future monitoring are further presented in Parts IV and V, respectively.

Part I reports on the anticipated negative impacts, with:

- the disruption of a previously unspoiled seascape by offshore wind farms visible from the coast (Chapter 3); altered sediment characteristics and increased erosion of the natural sandy sediments around wind turbine foundations because of accelerating currents next to the foundations (Chapter 4);
- a major disturbance of seabirds because of avoidance and collision by seabirds (Chapter 5);
- increased construction and exploitation noise levels and the associated impact on marine mammals and fish (Chapters 6 and 7).

Part II targets a set of anticipated positive impacts, with:

- an enrichment of the soft-substratum macro-, epibenthos and fish as a result of e.g. the exclusion of fisheries from the wind farms (Chapters 8, 9 and 10);
- an attraction of fish by the introduced hard substrata (Chapter 11);
- an increased species richness because of the introduction of hard substrata (i.e. wind turbine foundations) and a consequent fouling by hard substrata invertebrates (Chapter 12).

Part III focuses on the results from the targeted monitoring, hence shedding a light onto cause-effect relationships behind the observed changes in the ecosystem (e.g. artificial reef, refugium and ecological trap effects; see Box), with:

- a local enrichment in soft sediment macrobenthos close to wind turbines (Chapter 13);
- a (possible) attraction of fish, seabirds and marine mammals as a consequence of habitat alterations (Chapters 14, 15 and 16).

Part IV aims at putting all findings into a wider context, as such nuancing anticipated positive and negative effects, with:

- an introduction to ecological pitfalls and unintended consequences in non-indigenous biofouling organisms, attracted fish and colliding seabirds (Chapter 17);
- a context setting of the locally observed increase in biodiversity and biomass (Chapter 18)

Part V finally reflects on the optimisation of the future offshore wind farm monitoring (Chapter 19).

While providing an overview of all major scientific findings, this report also serves as a feedback moment after six years of monitoring and research. Such feedback moment necessitates the attention not only of scientists, but also of the offshore wind energy sector as well as marine policy makers and managers, and the public at large. As its target audience hence is very wide we have chosen to restrict the scientific details to that level needed to comprehend our major findings. The report may and should hence be read as a non-specialist document. We fully understand some readers would however be interested in getting more detail, for which we refer to the integrated scientific reports introduced above (Degraer and Brabant, 2009; Degraer et al., 2010, 2011, 2012), all downloadable from www.mumm.ac.be. Alternatively, those readers may directly want to get in touch with the authors of the chapters, whose contact details may be found at page 239.

BOX:

The ecological hypothesis-derived terms artificial reef effect, refugium effect and ecological trap effect are commonly used throughout this report. The following definitions ascertain the reader to be clear on what is meant by these terms.

2 Artificial reef / reef effect (Langhamer, 2012)

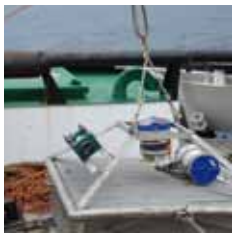
When introduced into the marine environment, wind turbines together with their associated scour protection, constitute an artificial reef which means that the surfaces are readily colonised by a typical and broadly predictable assemblage of organisms, reflecting zonation patterns observed in adjacent rocky shore communities. Although the scientific literature mostly agreed that there is likely to be a positive effect on fish and crabs, the extent and nature of the effect is heavily dependent on the nature of the reef created, the location, and the characteristics of the native populations at the time of introducing the artificial reef.

2 Refugium effect / no trawling zone (Langhamer, 2012)

Establishing offshore wind farms facilitates the creation of no-trawling zones, covering hundreds to thousands square kilometres. As such, wind farms may prevent fisheries-induced stirring up of bottom sediments and loading suspended solids into the water column, as well as a direct reduction in vulnerable species, biodiversity, production and biomass in general. These no-trawling zones as such mitigate habitat losses and degradation. In these areas juvenile fish will have a higher chance to survive. Even older, larger fish will have increased survival rates and in this way offshore wind farms may contribute to a spill over effect. A consequent higher fishing pressure at the edge of the wind farms may counteract this anticipated positive effect.

2 Ecological trap (Robertson and Hutto, 2006)

In suddenly altered ecosystems as is the case for the construction of offshore wind farms, ecological traps may arise. When an organism is attracted to, and preferably settles in a habitat with suboptimal conditions relative to other available habitats, it is caught in a so-called ecological trap. Ecological traps are thought to occur when the attractiveness of a habitat increases disproportionately relative to its value for survival and reproduction. Habitat choices are a consequence of natural selection and are based upon a number of ecological cues which indicate the quality status of a habitat. An ecological trap may occur when changes in the environment act to uncouple the cues used to assess habitat quality from the true quality of the environment.



PART I

EVALUATING ANTICIPATED « NEGATIVE » ENVIRONMENTAL EFFECTS

CHAPTER 3
CHAPTER 4
CHAPTER 5
CHAPTER 6
CHAPTER 7

CHAPTER 03

Seascape: final results of a socio-economic study

Marisa Di Marcantonio, An Vanhulle, Rik Houthaeve and Bob Rumes

In 2002 and 2009 two sociological seascape surveys took place in Belgium. These surveys focused on both the visual and overall experience. People's general opinion on wind energy and on the local planned wind farms were asked. Results show that in 2002 there was already a majority in favor of wind farms and this number still increased by 10% in 2009. A future survey is proposed to take place in the summer after the first wind turbines of the wind farms closest to the land have been installed. At that time at least three other wind farms will also be operational.

INTRODUCTION

Feenstra (2013) mentions that the lack of social acceptance also called NIMBY (Not In My Backyard) has become the third most important challenge of energy project developers worldwide, in addition to financial and regulatory issues. The NIMBY label is heavily discussed in research: where in the early years of wind farm development the NIMBY attitude – preferring technical siting elsewhere- was frequently used to explain opposition to new developments, more recent research has focused on looking for the reasons underlying opposition or support (Devine-Wright, 2008; Firestone et al. 2009; Haggett, 2011 and Wolsink, 2000 and many more). As part of the licensing conditions for the first offshore wind farms in the Belgian part of the North sea, a socio-economic study was conducted. This research focuses on people's opinion on renewable energy in general and opinions on specific projects in the Belgian part of the North sea. It tries to get an insight on underlying reasons for people's attitudes towards renewables and offshore wind energy in particular.

RESEARCH STRATEGY

When did we survey?

Since Belgium has little experience with sociological land(sea)scape studies, a research methodology was used that is very well known in other countries (Krohn and Damborg, 1999 and Wolsink, 1996) where a long experience exists of measuring perceptive effects of infrastructural works within a certain landscape.
This particular sociological survey focuses on both the visual experience and "total experience" of the perception of the surroundings and landscape. This kind of survey usually has a wide scope and will investigate the (changes in) quality of the life of the respondents and will attempt to relate this to several effects simultaneously.

In 2002 a first sociological seascape survey (WES, 2002; WES, 2003) took place in Belgium to study acceptance and assessment of renewable energy and more specifically of offshore wind farms in Belgium. For this purpose 405 persons (137 coastal residents, 67 second residents, 13 coastal workers and 188 tourists) were interviewed face to face at the coast. During the summer of 2009 a public inquiry (Houthaeve and Vanhulle, 2010) was held to check for comparable results since 2002. Similar to the study of 2002, the methodology of the 2009 study included a public inquiry of 1000 persons, particularly coastal inhabitants (235), tourists (257 daytrip tourists, 244 overnightstay tourists), second residents (222), sailors and coastal workers (42). Researchers wanted to know if eventually acceptance changes as wind farms are constructed (integration of perception/acceptance). Respondents were asked their opinion on the construction of offshore wind farms and the results were compared to the results of 2002 (Figure 1).

Six wind turbines were already built in 2008.To investigate the impact of these already built wind turbines at sea simulations of the offshore wind farms, as well as the actual view from the coastline, were used. Photomontages were used for calibration purposes.

For these montages a real view picture base layer was used, whereas for the photo simulation a base layer of a neutral sea picture was used. On this base layer a simulation of the wind turbines was added digitally to give an impression on what the situation would look like with real wind turbines. Using this technique a large number of viewpoints and angles can be simulated taking into account different wind farm configurations, turbine types,... The use of a neutral base layer is important because the simulations are used in the inquiries for the sociological landscape study and the evaluations made by the interviewed people may not be influenced by random distractions on the photo like e. g. ships, objects on the beach, etc. Sunny weather conditions were used on all simulations. Respondents were asked to evaluate four different simulations (presented on high quality paper photographs with a 20x30 cm format): a first one showing wind turbines of the three permitted projects, followed by a simulation of the Belgian wind farm area fully occupied with wind turbines (worst cases scenario) (Figure 7). Also a simulation of a night view and a simulated situation at sea (at a distance of 2 km from the wind farm) were shown.

What did we ask to the people?

To find out how people think about a certain subject the selection of the questions asked during the enquiry are of utmost importance and lot of effort is spent in selecting the questions to be asked during the survey. Questions used in the 2009 survey were based on the previous study of 2002. The questionnaire had six different parts, each linked to a specific objective:

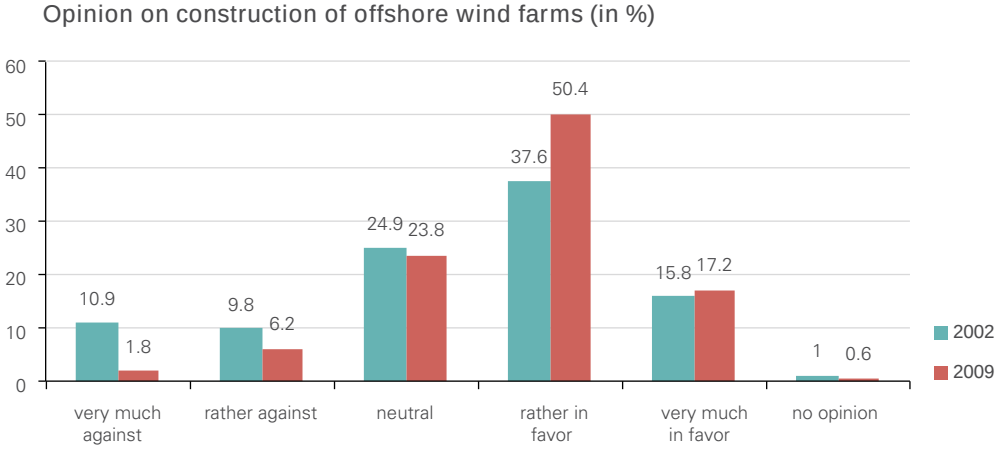
- the first part of the questionnaire focused on the relation of the respondent with the coast side in order to determine the frequency with which the respondent is in contact with the view of offshore wind farms e.g. "how many times do you visit the coast";
- the second part examined the social relevance of sustainable development by proposing a number of statements on wind farms and wind energy in general; this in order to gage the respondents opinion on this matter and see if the people's opinion had changed according to the previous survey in 2002;
- the third part sounded the experience of the actual wind farm, how the visual impact is appreciated from the dyke, what the impact was of the turning blades what the impact of lights in bad weather conditions or at night are;
- the fourth part of the questionnaire looked into the effects the wind farm has on the behavior of people (perception, acceptance,...) e.g. "will you still visit the coast if this wind farm is to be built?";
- the fifth part focused on the cumulative impact of the second and third wind farm planned in the wind farm area; photo simulations were used for this part;
- the last part focused on socio demographic information of the respondents (age, education level, etc.).

RESULTS

Did people's opinion change in time?

Figure 1 shows that, in 2009, more than half of the respondents (50%) said to be rather in favor of the construction of offshore wind farms and 17% is even very much in favor thereof. A small minority of 8% is (rather) against offshore wind farms. The number of persons with a positive attitude has risen by 10% in comparison with 2002. Generally, people still find the quality of the seascape very important: the wide sea view and the openness, naturalness and the tranquility of the sea. Kuehn et al. (2005) mentions that interviewers for the Horns Rev wind farm in Denmark revealed that many of the opponents modified their views after construction of the farm. Ladenburg et al. (2005) gives the figures for this statement: two years after the construction, 12 % of residents felt the wind turbines negatively impacted the view and 89% supported new offshore developments in Denmark. A survey conducted in 2005 in USA for the Cape Cod offshore wind farm showed that a majority of the Cape Cod residents (55%) were opposed to the project (and 44 % supporters). A more recent survey conducted in 2007 showed that the project has been gaining support amongst residents with 61% of residents supporting the development of the Cape Cod offshore wind farm and 36% opposing (2% unsure) (Firestone et al, 2009) .

Figure 1. Opinion on construction of offshore wind farms, survey 2009 compared to survey 2002 (in %).



Age doesn't matter, gender does

People living at the coast and sailors are less in favor of construction of offshore wind farms than people living further inland, but both groups still remain predominantly positive. Firestone (2009) mentions comparable conclusions for the Cape Cod and Delaware projects in USA. Age did not matter in the opinion on offshore wind farms but gender did, with men being slightly more positive than women. Also more people are in favor when they had a higher education. As the higher educated people are more represented in the respondents group this opinion on the construction of offshore wind farm is globally too positively presented. Nevertheless similar results were found for the Cape Cod wind farm where the supporters of wind farms had higher educational background attainment (Nordman, 2011).

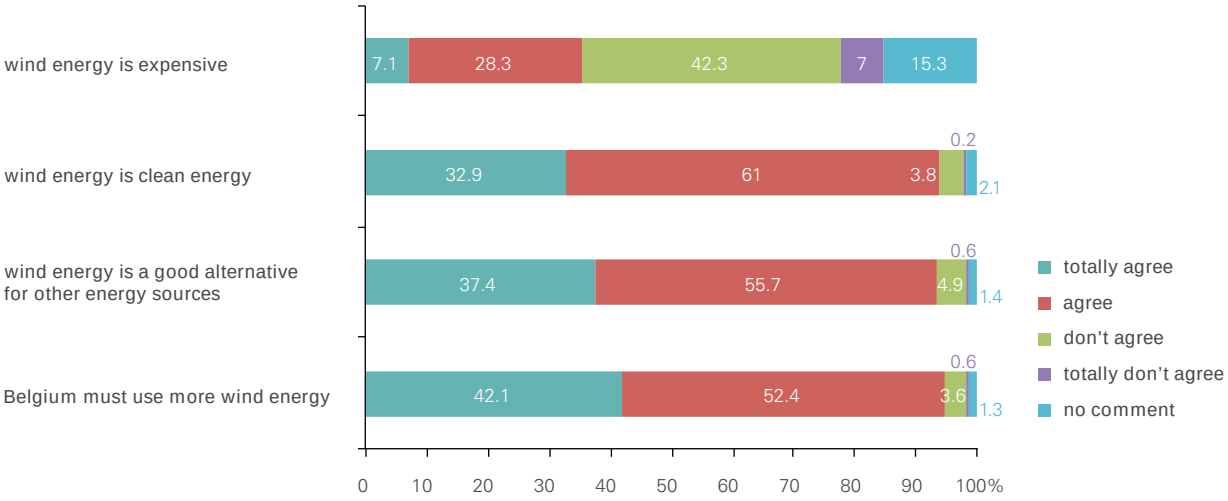
Opinion about wind energy

Here we look at people's opinion about wind energy in general and offshore wind energy in particular.

Wind energy in general and applicability of wind energy

Following statements on **general wind energy subjects** were proposed to the people.

Figure 2. Agreement / disagreement with the statements on wind energy in general, survey 2009 (in %).

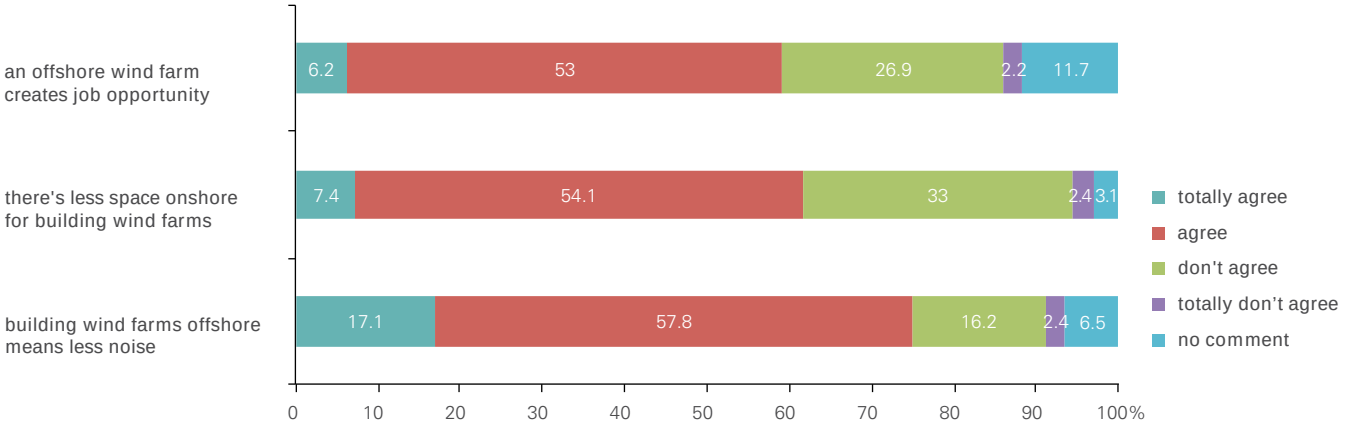


Almost everyone (95 % of the respondents) is strongly convinced that Belgium should use more wind energy, almost 94% agrees that wind energy is a clean energy. Almost everyone (93%) also agrees that wind energy is a good alternative for other classic energy sources; about 6% doesn't agree (totally), 1% has no opinion. It's striking how much people agree with these statements on wind energy in general.
The last statement gathers information on the financial implications of wind energy. It is notable that on this statement opinions are divided. More than one out of three agrees that wind energy is expensive. Quite a lot of people (15%) do not have an opinion on this subject; half of the respondents (49%) do not agree (totally) that wind energy is expensive.
The above results indicate that while the respondents in general considered wind energy to be a clean and sustainable energy source there is still uncertainty about the costs.

Offshore wind energy

Three statements sound people's opinion on the **advantages** of an offshore wind farm.

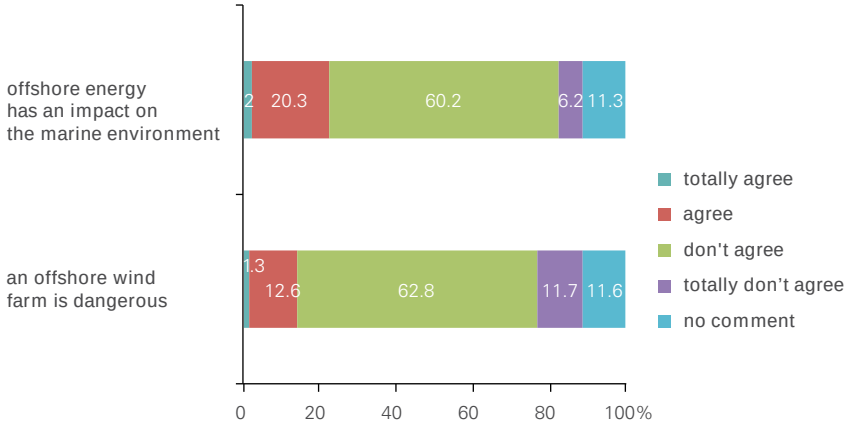
Figure 3. Agreement / disagreement with the statements about advantages of an offshore wind farm, survey 2009 (in %).



Globally a fairly positive perception of the siting on wind farm offshore rather than onshore is set forward. Almost of the respondents is convinced that at sea there's little or no burden of noise from a wind farm and more than 61% thinks moreover that more space is available for wind farms offshore than onshore. Still one out of three does not agree with this statement. Almost 60% of the respondents think that an offshore wind farm will bring more work to the region whereas less than 30% is in (total) disagreement with this statement. For this particular advantage respondents hesitated the most (almost 12% 'no opinion'). Nevertheless, since 2012, the harbour of Ostend (Belgium) which reoriented strategically to an energy port has experienced that a wind farm developer brings lots of side activities to a harbour (maintenance companies, electrical companies, boat transfer companies…). Due to the offshore industry in general 956 people were working in the front part of the harbour (where the wind farm industry is localized). This number is without counting for all temporally workers for the building of the wind farm, nor for the crew on the vessels in the building area. The wind farm industry doubled the number of ship transfers in/out the port to 4500 movements in 2012. A survey conducted one year after construction of the Nysted offshore wind farm (Denmark) indicated that 86% of respondents were supportive of new offshore wind farms in Denmark as a new turbine manufacturing plant brought jobs to the area, which had relatively high unemployment (Ladenburg et al., 2005).

Two statements sound people's opinion on the **disadvantages** of an offshore wind farm.

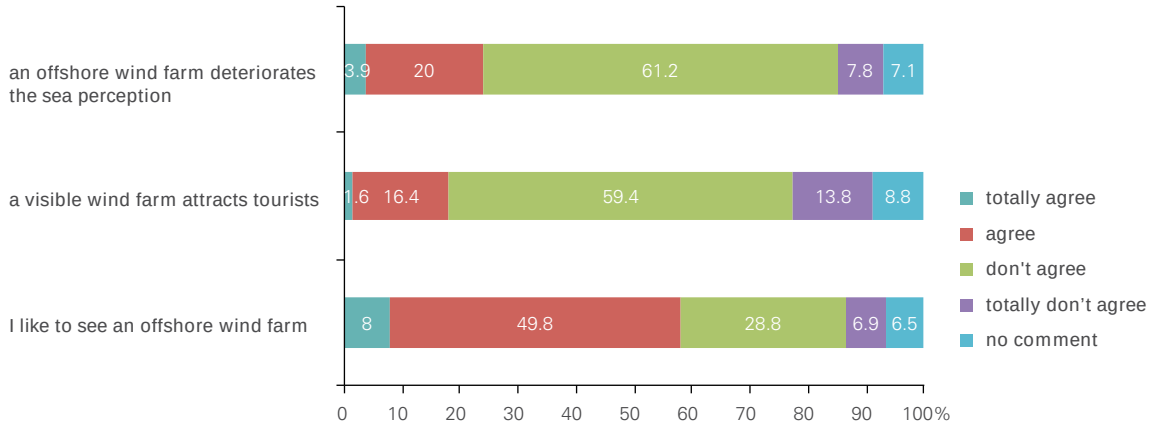
Figure 4. Agreement / disagreement with the statement about the disadvantages of an offshore wind farm, survey 2009 (in %).



Almost th of the respondents do not believe (at all) that an offshore wind farm could be dangerous, although almost 12% has no opinion. The wording of this questions could have been better chosen: replacing 'dangerous' by 'risky' probably would give other responses. 2 out of 3 respondents expect that a wind farm does not affect the marine environment. Almost 25% of the respondents think that a wind farm affects nature although it is not specified if this effect would be positive or negative. Gee (2010) described in a similar German study that 15% of all arguments employed, were arguments on nature conservation and these were mostly exclusively used to object to offshore wind farms. In that study the nature conservation category was very diverse with arguments covering indistinct fears that offshore farms will harm the marine ecosystem and also fear of very specific negative impacts on bird and marine mammal species. The category also comprises indirect impacts, such as oil spills resulting from tanker collision with a wind farm.

Assessing people's **opinion on how the visibility** of an offshore wind farm **affects acceptance** was done by using following statements:

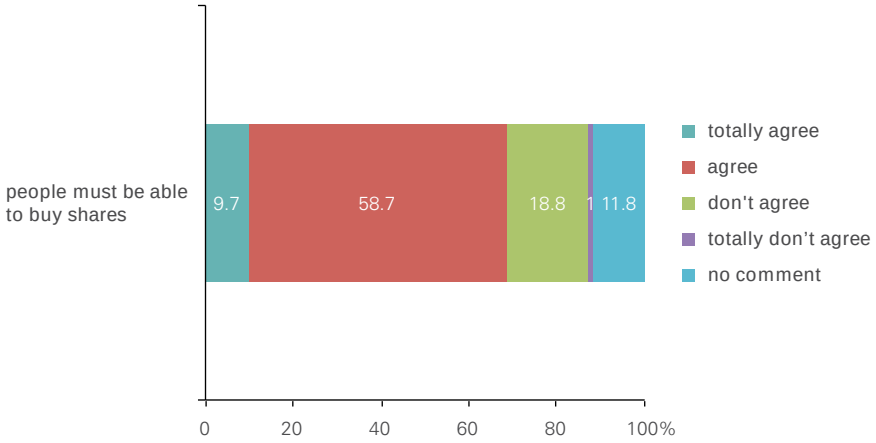
Figure 5. People's opinion on the view of an offshore wind farm, survey 2009 (in %).



More than half of the respondents (58%) (totally) would like to see an offshore wind farm. More than 1/3rd of the respondents (totally) would not like to look at a wind farm at sea.
A comparable, more generally formulated statement generates more positively results: almost 70% (totally) don't agree with the statement that a wind farm at sea will affect the 'sea perception', and only 24% agree. A majority of the respondents don't think that a visible offshore wind farm will attract more tourists, only 18% agrees (totally) with this statement.

Finally people's opinion on the **possibility of buying shares** of wind farms was surveyed.

Figure 6. People's opinion on the possibility of buying shares of an offshore wind farm, survey 2009 (in %).



More than 60% of the respondents (totally) agree that citizens should be able to buy shares of a wind farm. About 12% has no opinion about this and almost 1 out of 5 (totally) doesn't agree with this statement. Currently, at least one offshore wind farm in Belgium offers the possibility of participation by buying shares.

Photo simulations and photo montages

Worst case: Belgian wind farm area completely built[1]

After viewing a photo simulation in which the entire Belgian wind energy zone is operational (Figure 7), respondents were asked if the distance from the wind turbines to the beach is acceptable (i.e. large enough). More than 62% of respondents think this distance is acceptable with 13% finding it a rather acceptable. However 20% of respondents found the distance unacceptable, (in addition to 5% having no opinion). People indicating finding the distance unacceptable were asked under which conditions this fully built area would become acceptable. For 84% of those respondents it would become more acceptable if the wind farms were less visible, 69% wanted the wind farms to have another (less visible) orientation/set up, 56% would find it more acceptable if the wind farms would provide them with cheap energy, 53% if there's no harm for nature, 43% if the wind farms would provide economic growth and employment, 23% if people could buy shares and finally 20% if the park could be visited.

In general the results of the survey are similar to those published in the international literature regarding the perception of wind farms. Nordman et al. (2011) states that the researchers for the Cape Cod project (USA) found following patterns: residents expected positive impacts on job creation, electricity rates and air quality; many respondents would increase their support if Cape Cod received the electricity, if electricity rates decreased, if local fishing was helped and if air quality improved. The location of turbines and their visibility from the shore is clearly an important factor. In a coastal region of Germany, where 54% of coastal residents disagreed with a planned offshore project aesthetics was cited as the most common reason for opposition, while energy was the primary reason for support (Gee, 2010). Ladenburg et al. (2005), Firestone et al. (2009), Devine-Wright P. (2008) and H bner and Pohl (2013) found that people consistently prefer wind farms located further from shore. However, the benefit that people perceived from moving a hypothetical wind farm an additional mile offshore diminishes with distance. That is, people are more sensitive to the difference between a wind farm at six versus seven miles from shore, than when comparing a wind farm at 12 versus 13 miles (Ladenburg et al., 2005).

From the before mentioned results it can be concluded that the perception value of the sea is influenced by the wind turbines at sea. In addition, the degree of visibility was found to influence acceptance. In our survey variations in the distance offshore, the orientation as seen from the coastal towns and the number of visible wind turbines were simulated. When the wind turbines were simulated at a sufficiently large distance and/or are limited in number, a fundamental change in this perception is prevented, which added to the acceptance. Aside from these visual factors, ecological and economic factors also play a rather important role in the degree of acceptance.

[1] **Other cases** are described in (Vanhulle, A. et al, 2010)

Figure 7. Simulation of the fully occupied wind farm area seen from the dyke in Blankenberge (Simulation and montage: Grontmij, 2010).

What do people want to be informed of?

As a last question respondents were asked on which aspects of offshore wind energy they would like to be informed. The most common answers given are shown in figure 8.

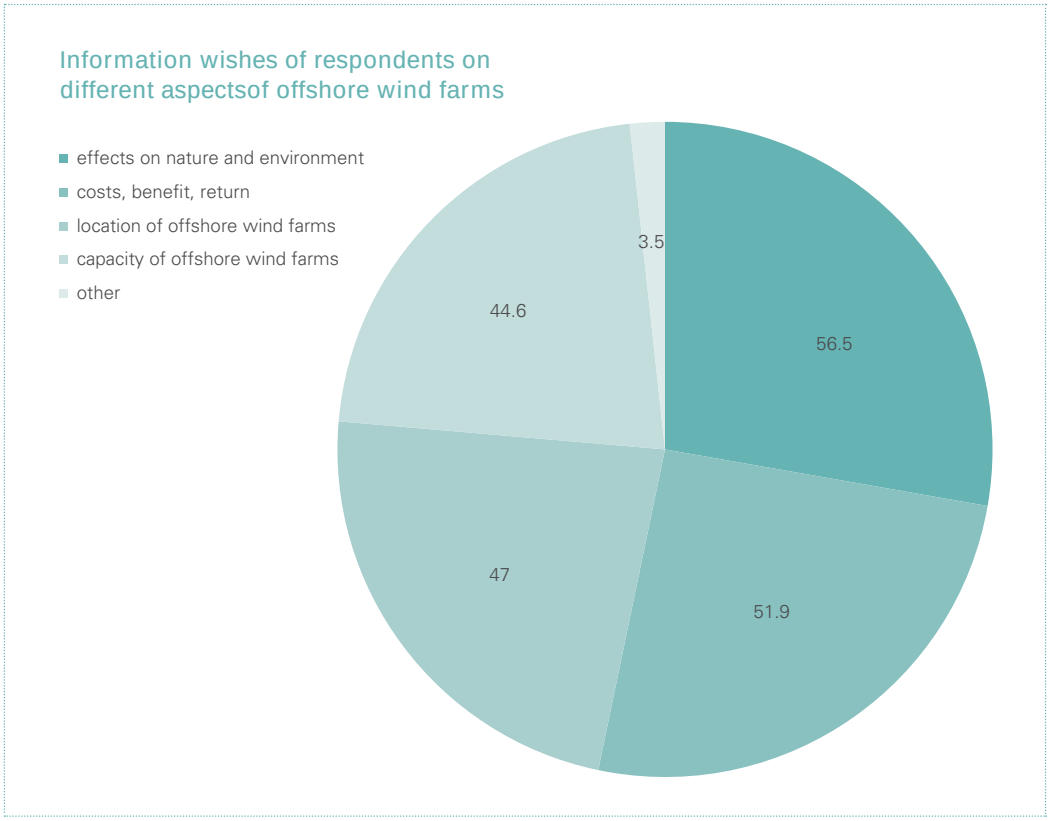


Figure 8. Information wishes of respondents on different aspects of offshore wind farms, survey 2009 (in %).

FUTURE MONITORING

Determining how peoples' perception has changed five years after the initial study could be the subject of a new socio-economical study in the (near) future. This study could focus on changes in people's opinion now that a number of parks are operational. The wind farms closest to the coast are visible and real time view on the offshore wind farms can now be used to validate photo simulations. The impact of the works on local lives (visual perception but also opportunities for local work) can be included and finally, as utility bills are rising, it would be interesting to see if and how people link this fact to local offshore wind projects. Such a follow up study is proposed to be done the summer after the first wind turbines of the wind farms closest to the land have been installed. At that time at least three other wind farms will also be operational.

With 53.2% of the people indicating that the worst-case scenario (fully occupied zone) would become acceptable if there is no damage to the marine environment and with results of the survey indicating (Figure 8) that the most important thing people want to be informed about is the effects on nature and environment one could say that the Belgian government was correct in implementing an extended monitoring programme when permitting the first wind farm. The following chapters describe the results of the different research programmes related to the environmental impacts of offshore wind in the past 5 years. These aim to provide the general public and the scientific community with a more robust knowledge on the possible impacts and allow the reader to develop his/her own opinion on the effects of offshore wind farms.

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 m 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).

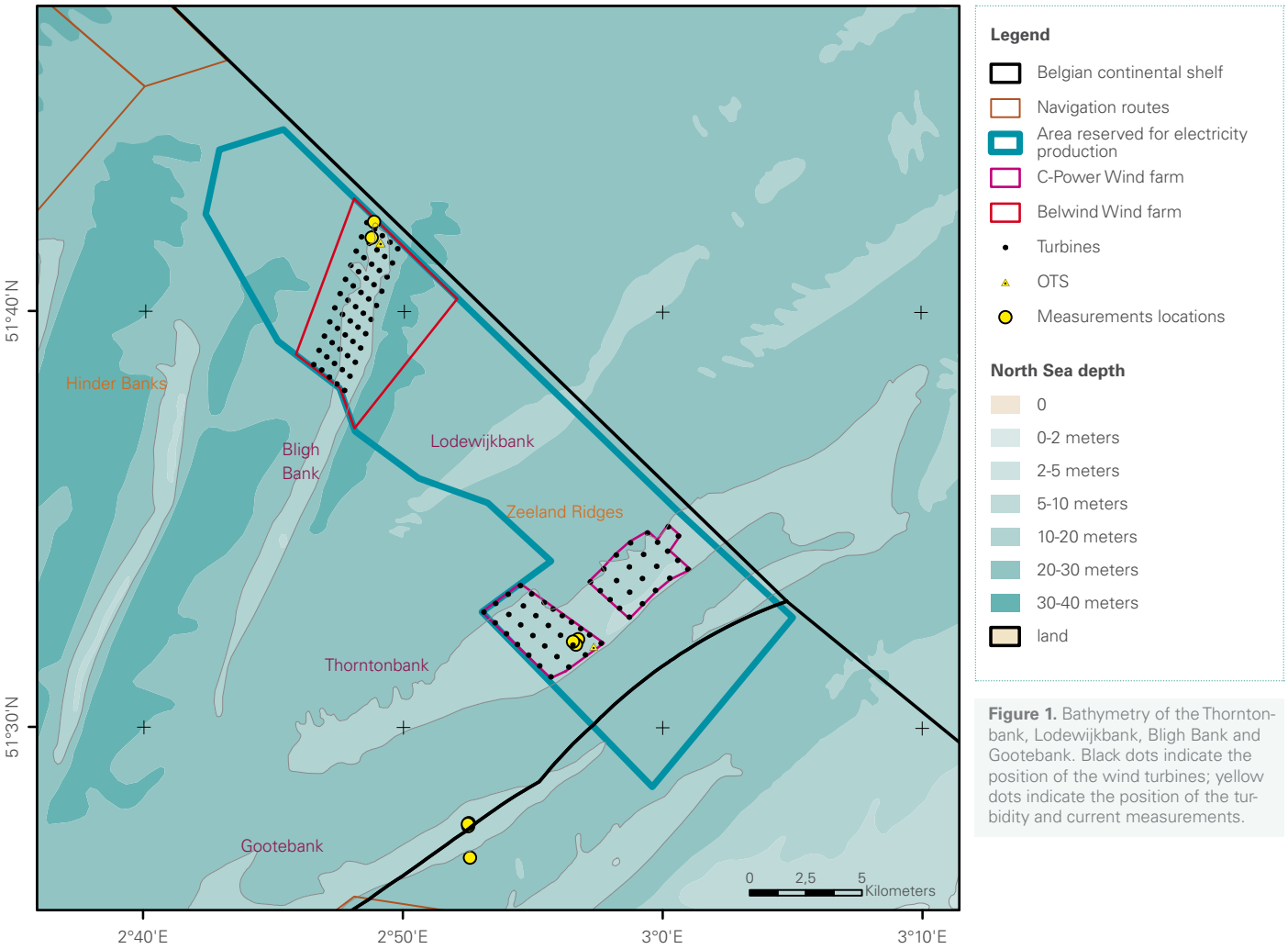


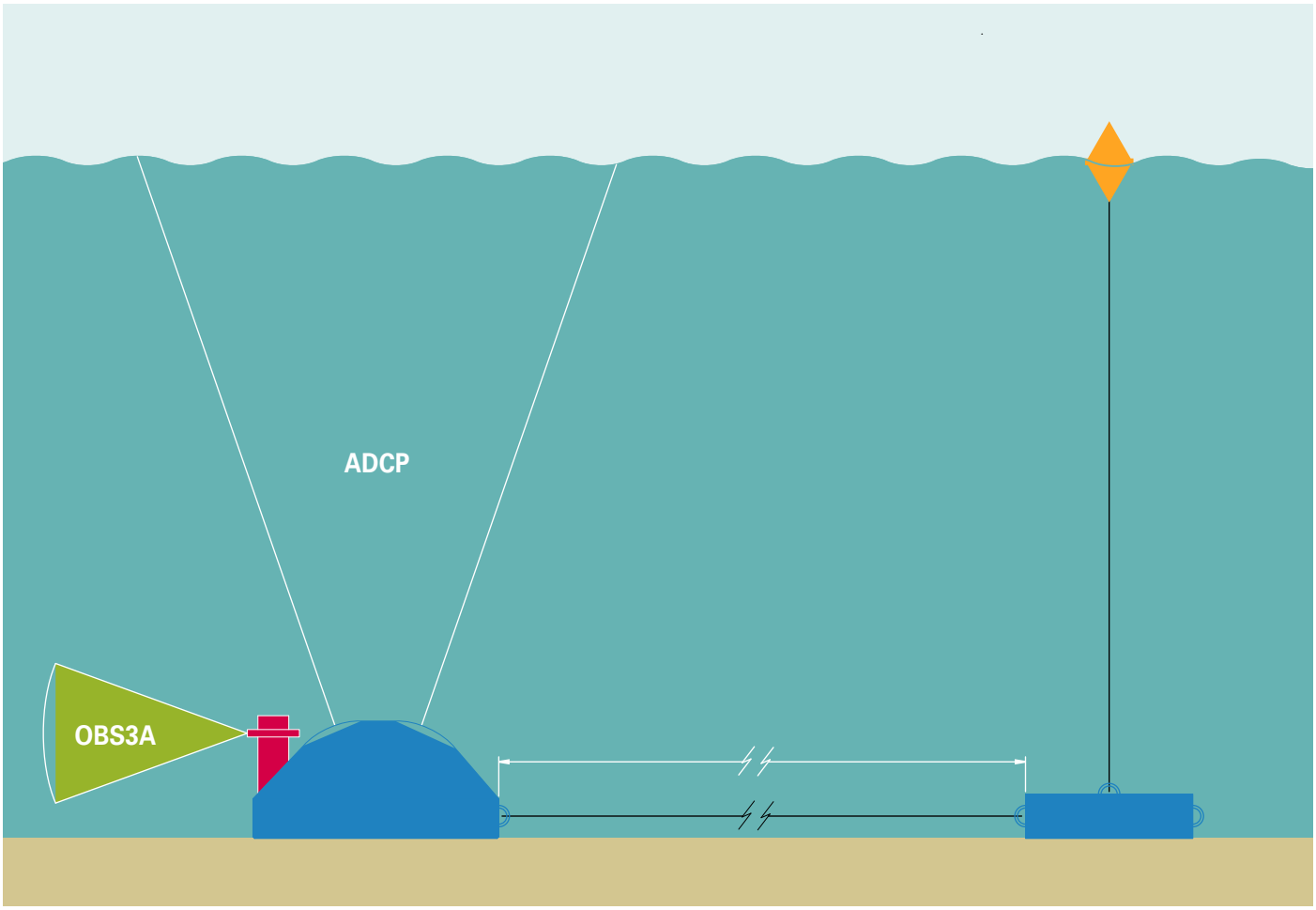
Figure 1. Bathymetry of the Thornton-bank, Lodewijkbank, Bligh Bank and Gootebank. Black dots indicate the position of the wind turbines; yellow dots indicate the position of the tur-bidity and current measurements.

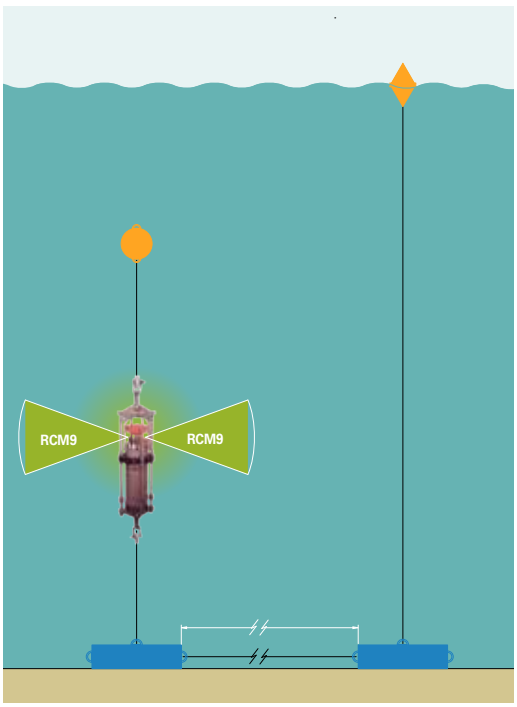
MONITORING TURBIDITY

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 are 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 -24m 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 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.

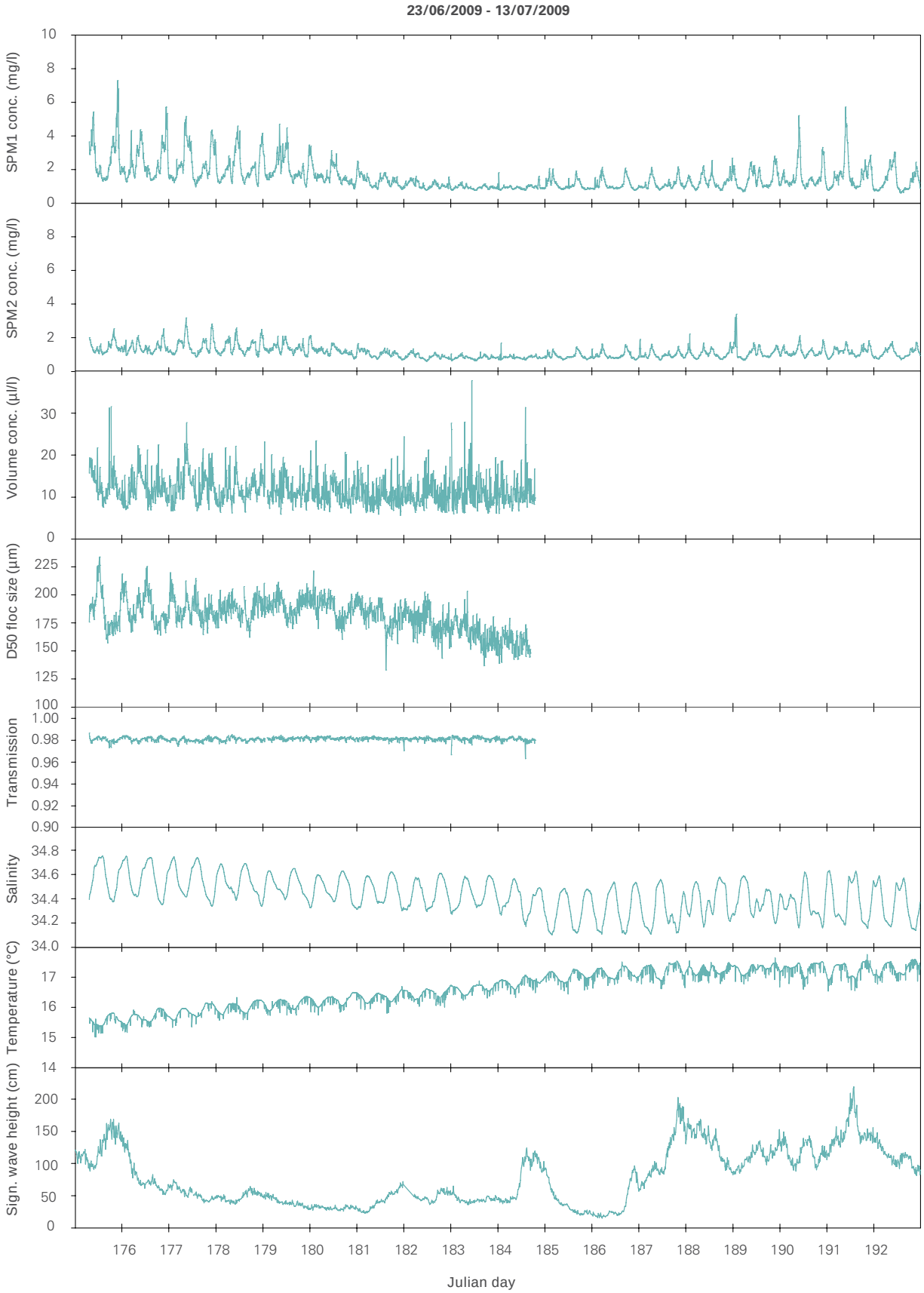


Figure 5. Measurements of SPM concentration in the lowest 1.5 m above the bottom, derived from the backscatter of the ADP, together with the seabed evolution from the ADP altimeter, at the Bligh Bank from May, 5th, 2010 till June, 3th, 2010.

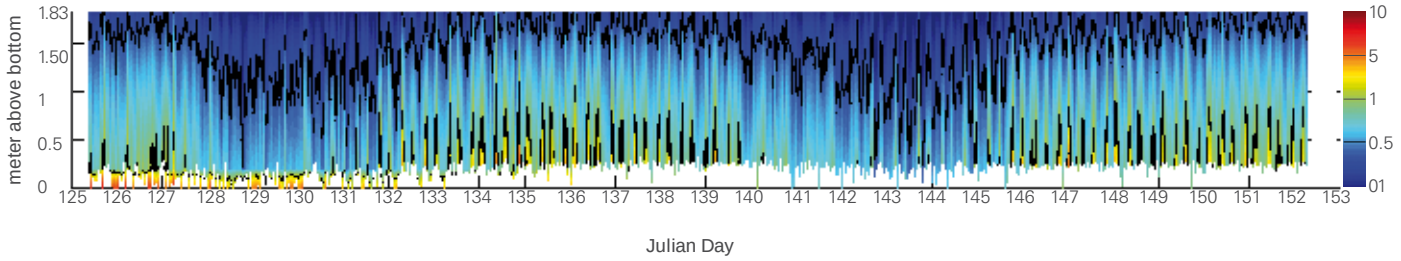
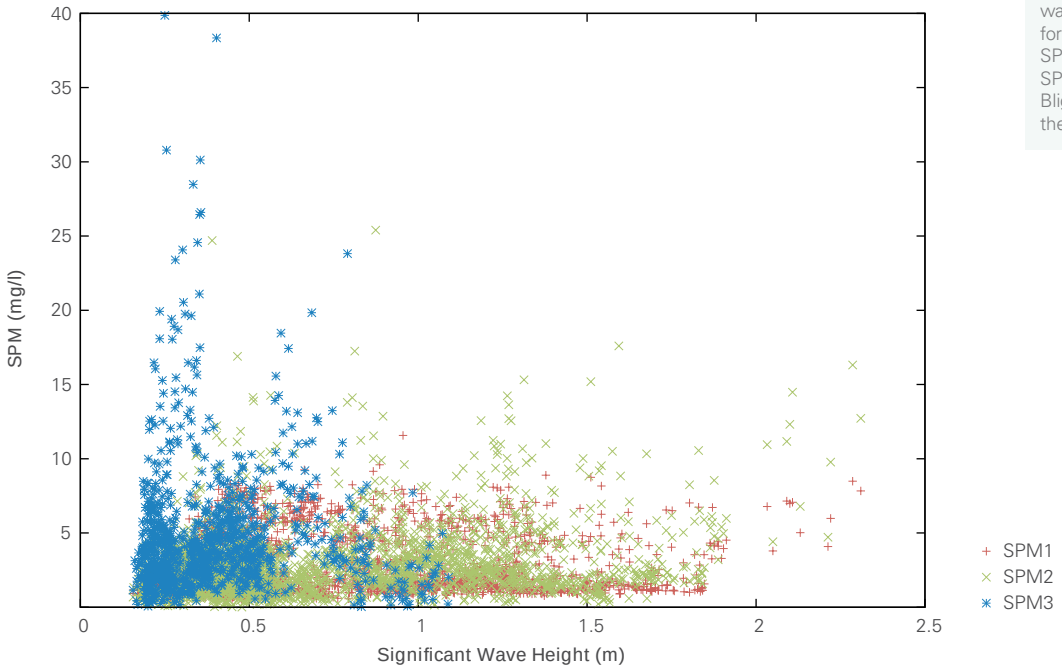
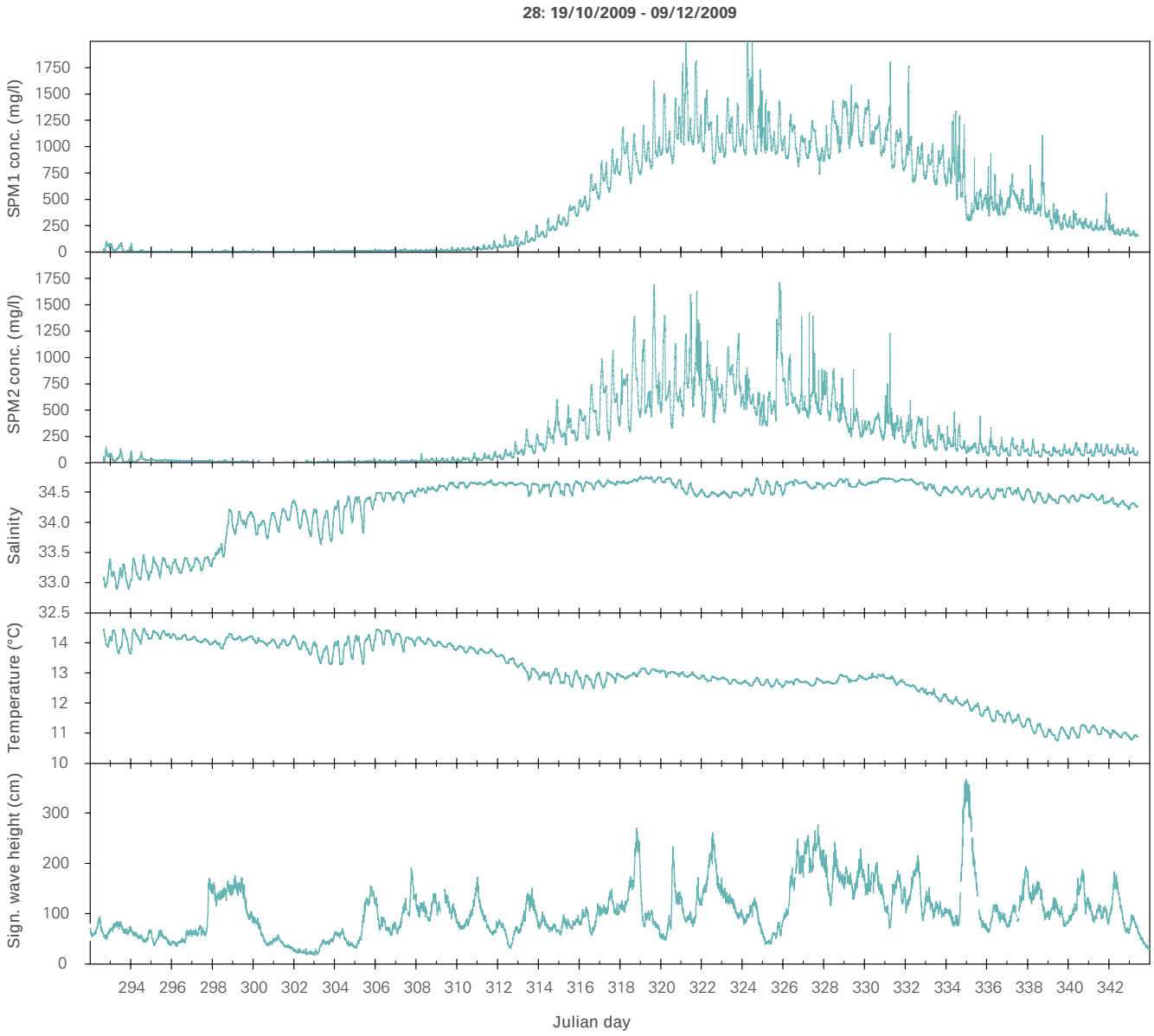


Figure 6. Scatter plot of significant wave height and SPM concentration for SPM1 (0.2 m above the bottom), SPM2 (2 m above the bottom) and SPM3 (1 m above the bottom) at the Bligh Bank (-26 m water depth), after the works.



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.

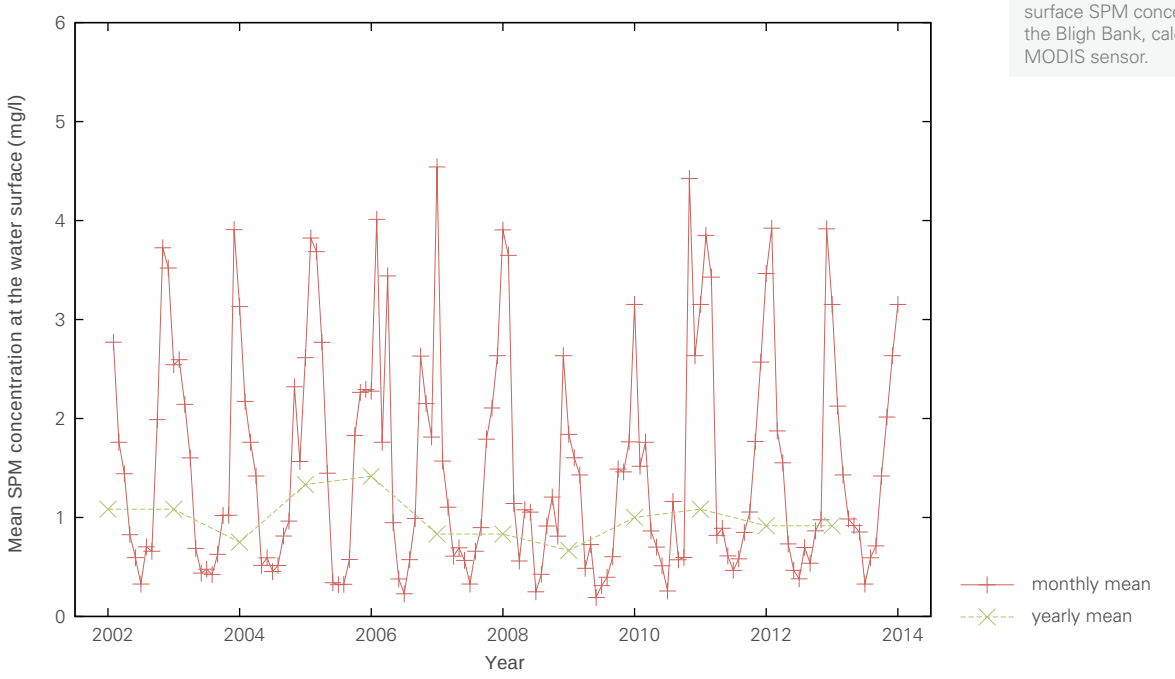


Figure 8. Monthly and yearly mean surface SPM concentration values at the Bligh Bank, calculated from the MODIS sensor.

Conclusion

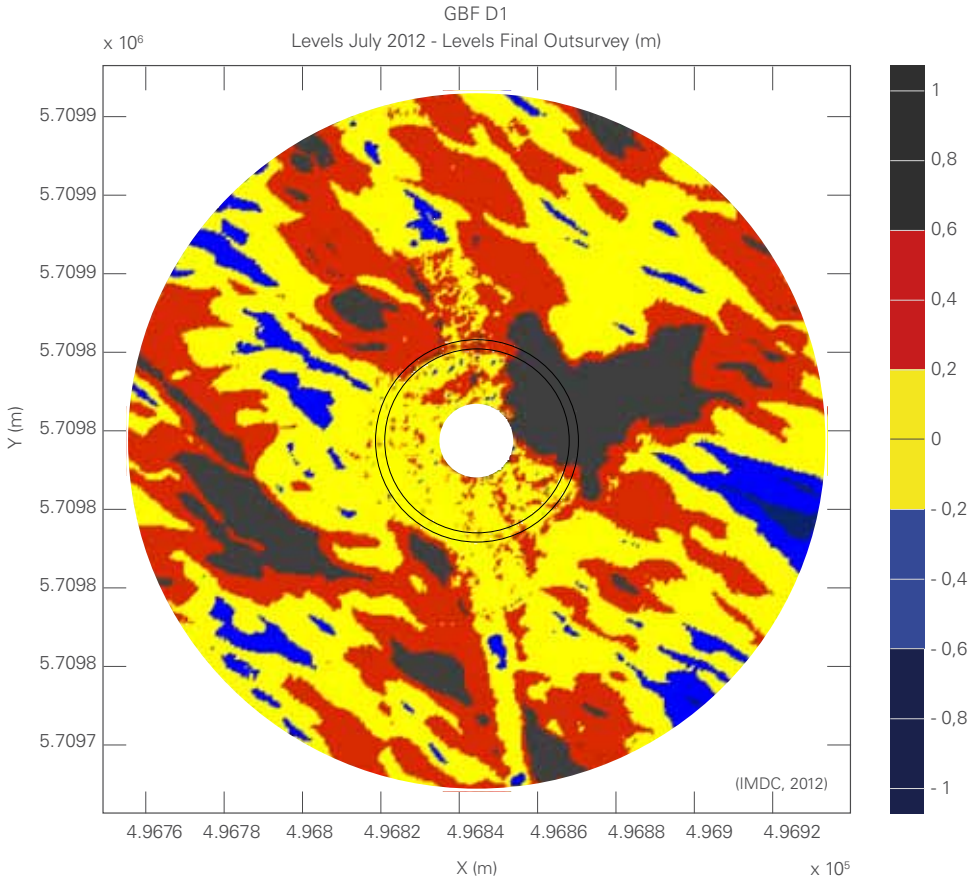
Both at the Thorntonbank and the Bligh Bank, no indication could be found of an increased turbidity due to the construction of the wind farms. Furthermore, it was shown that the Goote-bank was clearly not a good reference site for these measurements. To investigate the effects of anthropogenic impacts 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.

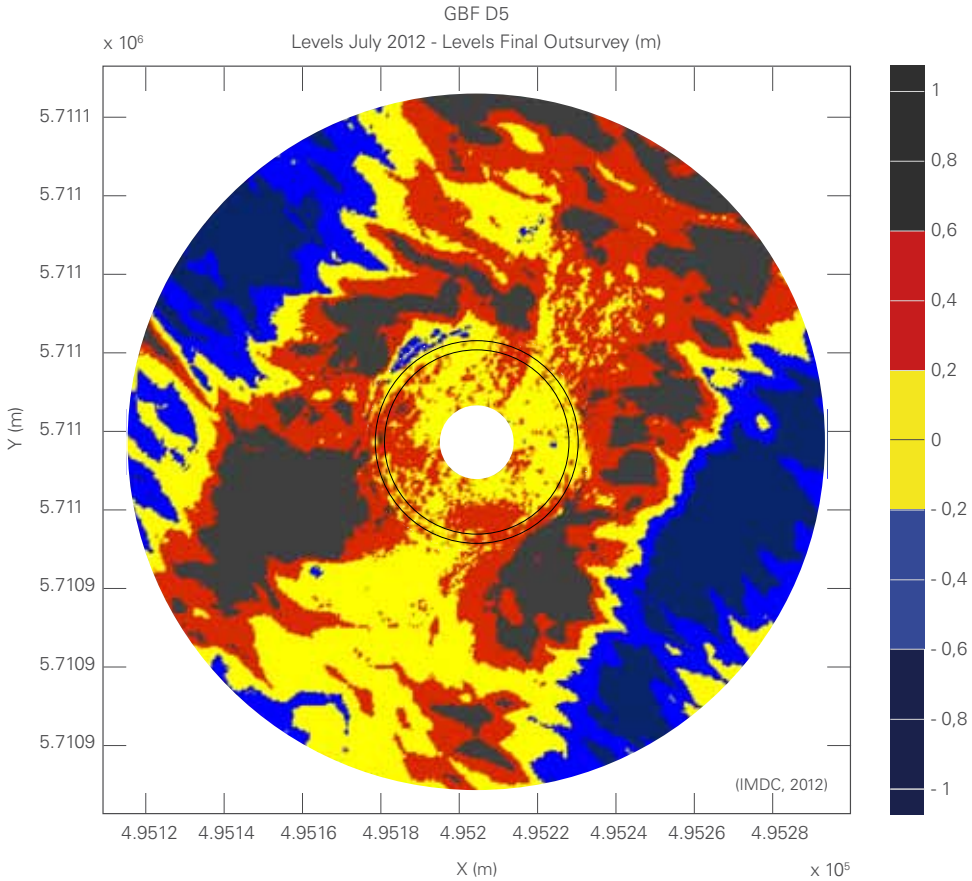
BATHYMETRICAL SURVEYS OF SCOUR AND DREDGED PITS

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).



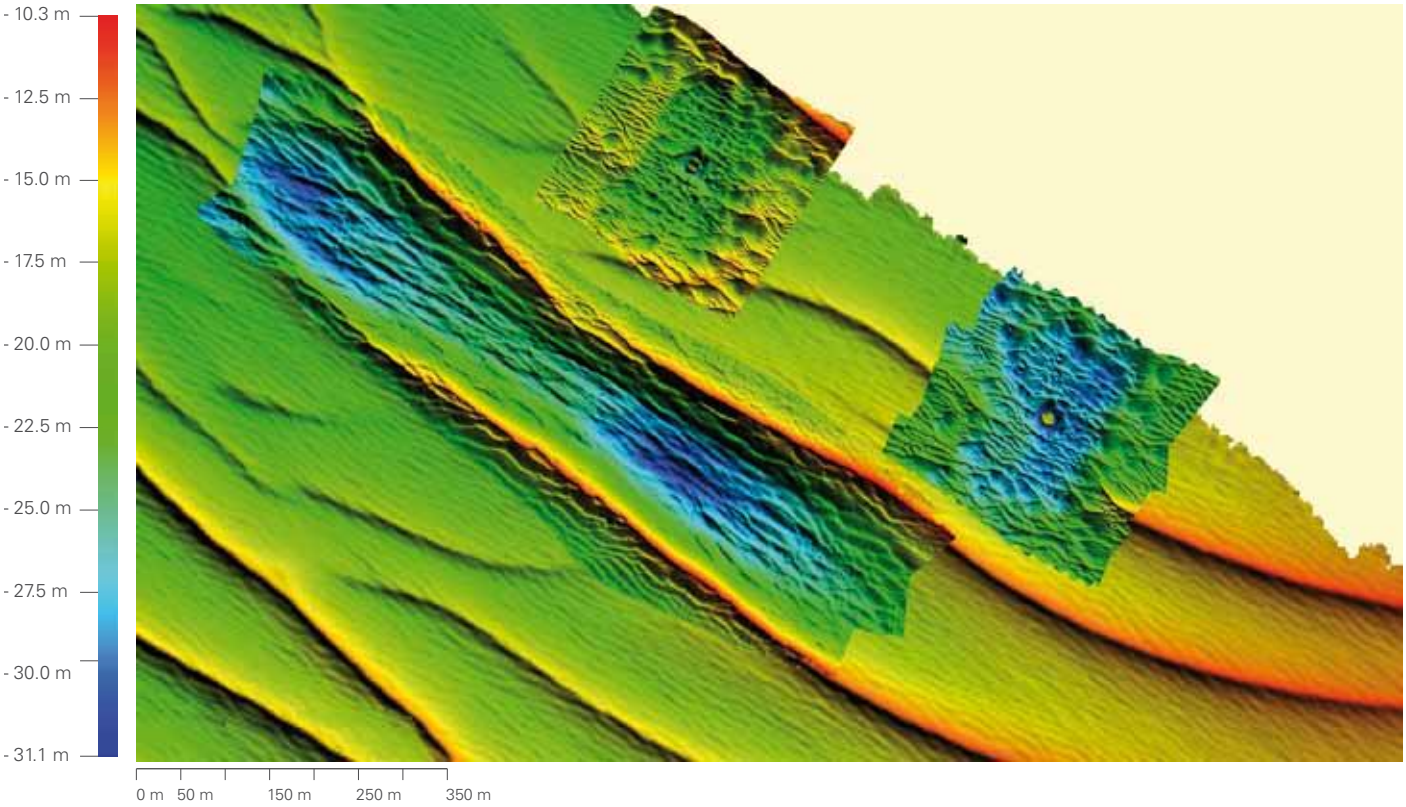


BATHYMETRICAL SURVEYS OF THE SAND STOCK/DREDGING PITS

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 m 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 m sand to construct the foundation pits, only about 400,000 m 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 m was extracted again from these dumping sites, from which some 588,000 m 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 m 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 m was still missing, indicating that over a period of 8 months only 9,000 m were naturally deposited in the depressions (Figure 11). Between September 2009 and April 2010, some deposition resulted in a volume increase of 45,000 m , 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 m . The last survey of July 2012 showed some additional deposition in the area, resulting in a total difference of +5,000 m .

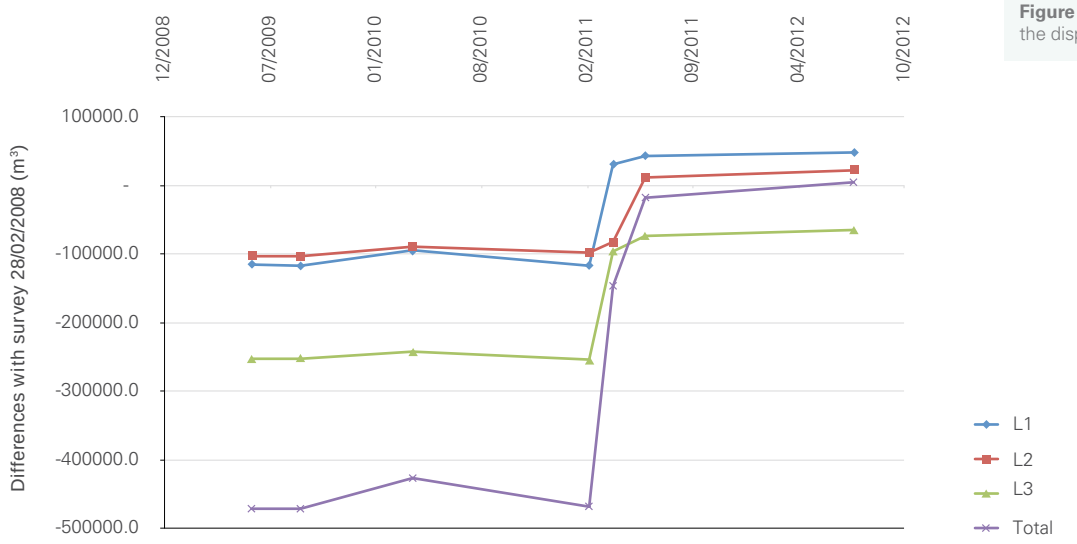


Figure 11. Evolution of the material in the disposal areas (C-Power, 2012a).

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).

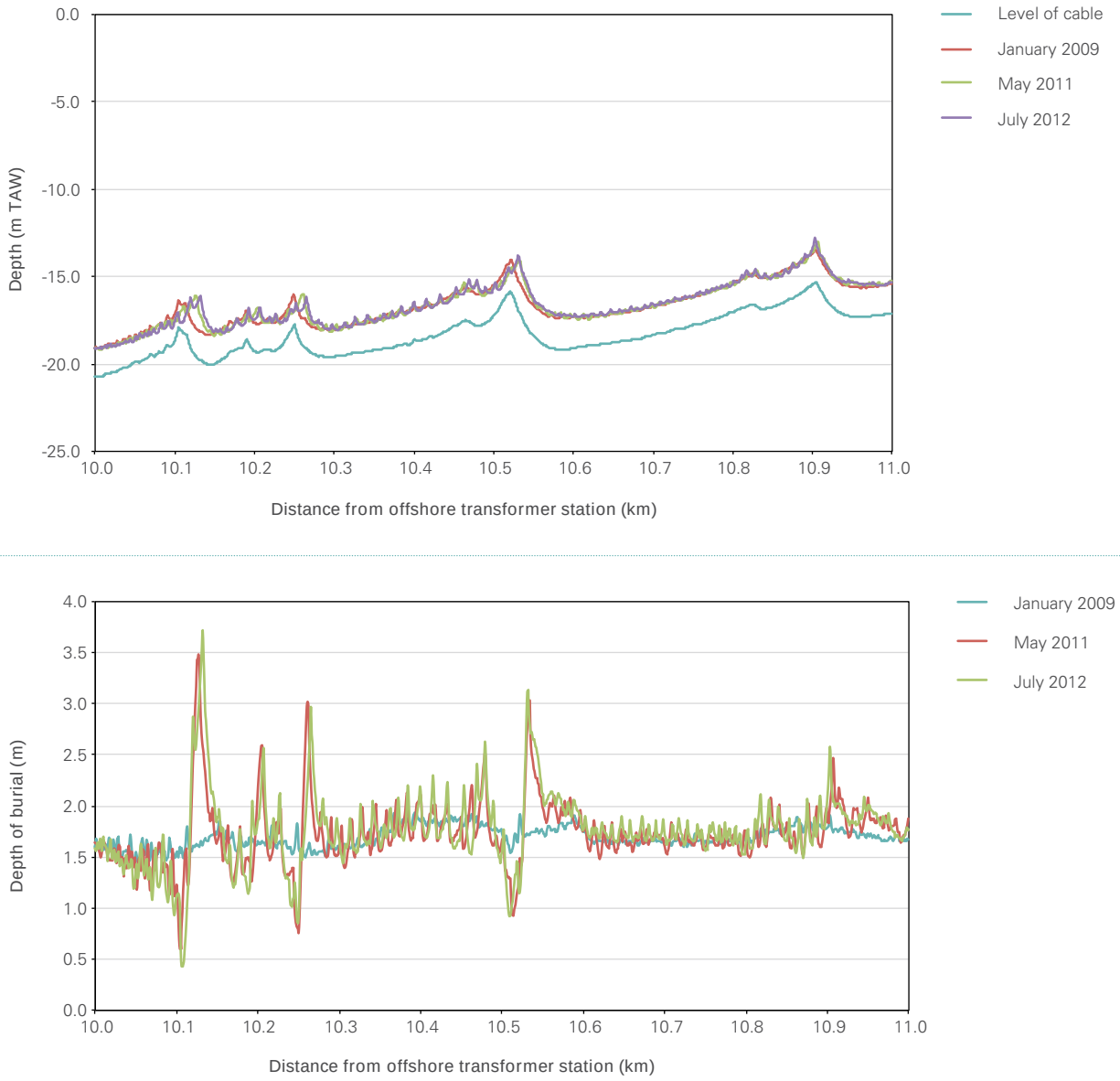


Figure 13. Bathymetry during different surveys and depth of burial of the 150 kV cable from the C-Power wind farm between km 10 and km 11 (From data of C-Power, 2012a).

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 Dijck 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.

CHAPTER 05

Bird monitoring at the Belgian offshore wind farms: results after five years of impact assessment

Nicolas Vanermen, Robin Brabant, Eric Stienen, Wouter Courtens, Thierry Onkelinx, Marc Van de walle, Hilbran Verstraete, Laurence Vigin and Steven Degraer

To monitor the impact on birds following the construction of two offshore wind farms in the Belgian part of the North Sea, a twofold strategy was followed. Monthly ship-based seabird surveys allowed for a detailed displacement effect assessment, while radar research aimed at studying avoidance behaviour and barrier effects. Both methods provided input data for collision risk modelling in order to assess bird collision rates. Three years after the completion of the wind farm at the Bligh Bank, it showed that northern gannet, common guillemot and razorbill avoid the wind farm, while numbers of lesser black-backed and herring gull increased significantly. Collision risk modelling learned that gulls in particular are at risk of colliding with the turbine blades, with up to 2.4 bird strikes per turbine per year.

INTRODUCTION

Despite its limited surface, the Belgian part of the North Sea (BPNS) holds internationally important numbers of seabirds. Its specific importance to seabirds varies throughout the year. During winter, maximum numbers are present with over 46,000 seabirds, of which more than 20,000 auks. Offshore, the wintering community is dominated by common guillemots *Uria aalge*, razorbills *Alca torda* and black-legged kittiwakes *Rissa tridactyla*. Meanwhile, large numbers of grebes, scoters and divers reside inshore. In summer, fewer birds are present (on average 15,000), but high numbers of terns and gulls exploit the area in support of their breeding colony located in the port of Zeebrugge. During autumn and spring, the BPNS makes part of a very important seabird migration route through the Southern North Sea and an estimated number of no less than 1.0 to 1.3 million seabirds annually migrate through this 'migration bottleneck' (Stienen et al., 2007). For a number of species, the BPNS hosts more than 1% of the biogeographical populations involved, i.e. northern gannet *Morus bassanus* (autumn), little gull *Hydrocoloeus minutus* (spring), lesser black-backed gull *Larus fuscus* (summer), great black-backed gull *Larus marinus* (winter) and common tern *Sterna hirundo* (summer) (Vanermen et al., 2013).

Possible effects of offshore wind farms on seabirds range from indirect effects (habitat change, habitat loss and barrier-effects) to direct mortality through collision (Exo et al., 2003; Langston and Pullan, 2003; Fox et al., 2006; Drewitt and Langston, 2006). The installation of an offshore wind farm indeed changes the impacted area drastically, not only because of the impressive physical appearance in the wide open seascape, but also due to the underwater changes following the introduction of hard substrates in a soft-bottom marine ecosystem. On the one hand, some seabirds can be expected to avoid the huge vertical structures in much the same way as they avoid the coast or are scared off by ship traffic. As such, seabirds can be displaced out from an area which was used for foraging prior to the construction of the wind farm, resulting in habitat loss. In an offshore context, the impacted area is generally surrounded by a huge surface of turbine-free marine habitat, which however does not necessarily include equally suitable feeding grounds. Birds bound to shallow waters are thus the most at risk of losing large areas of valuable and irreplaceable habitat, since wind farms too are generally built on shallow sandbanks. On the other hand however,

there are numerous examples of seabirds being attracted to offshore constructions, as for example gas platforms. Mostly, this attraction effect is hypothesised to result from increased food availability and roosting possibilities (Tasker et al., 1986; Wiese et al., 2001). The same of course can be expected to happen at offshore wind farms. But with wind farms acting as a magnet to seabirds, more birds face the risk of colliding with the turbine blades. Importantly, as seabirds are long-lived species with a delayed maturity and small clutch size, even the smallest change in adult survival may have a substantial impact at a population level (Stienen et al., 2007).

Wind farms may finally also act as barriers for local flight movements as well as for migration, resulting in longer flight paths and an increased energy expenditure. Petersen et al. (2006) and Krijgsveld et al. (2011) demonstrated birds to change their flight direction as they approach a wind farm (i.e. macro-avoidance). The extent of this effect is yet unknown but might be particularly important in case of wind farms oriented perpendicular to the main migration direction, as is the case in the BPNS.

Based on data collected during the first six years of offshore wind farm monitoring at the BPNS, this chapter addresses (1) the displacement effects of offshore wind farms, (2) the possible barrier-effect and (3) the expected number of birds colliding with the turbines.

RESEARCH STRATEGY

Two techniques were used in this investigation. Visual censuses from research vessels aimed at estimating local seabird densities, allowing to assess seabird displacement effects as well as to predict bird collision rates. This method provides a high taxonomic resolution and direct information on seabird behaviour, but is restricted to daylight and good weather conditions only. Radar research complemented the visual census data with continuous observations, and aimed to study barrier effects and – again – bird collision rates, yet with a significantly lower taxonomic resolution. While visual censuses are already at full maturity allowing for an in depth impact assessment, radar research first had to cope with various technical and analytical problems, some of which are addressed in this chapter.

Displacement

Since 2005, three years before the construction of the first offshore wind turbine, seabird displacement effects were investigated performing monthly BACI-designed seabird surveys across impact and control areas. Seabird surveys were conducted according to the internationally applied European Seabirds at Sea (ESAS) method (Tasker et al., 1984). The focus is on a 300 m wide transect along one side of the ship's track. While steaming, all birds in touch with the water (swimming, dipping, diving) located within this transect are counted ('transect counts'). In contrast, the density of flying birds was assessed through so-called 'snapshot counts': right at the start of each minute, the number of birds flying within a quadrant of 300 by 300 m inside the transect is counted. Taking account of the distance travelled, these count results can be transformed to seabird densities.

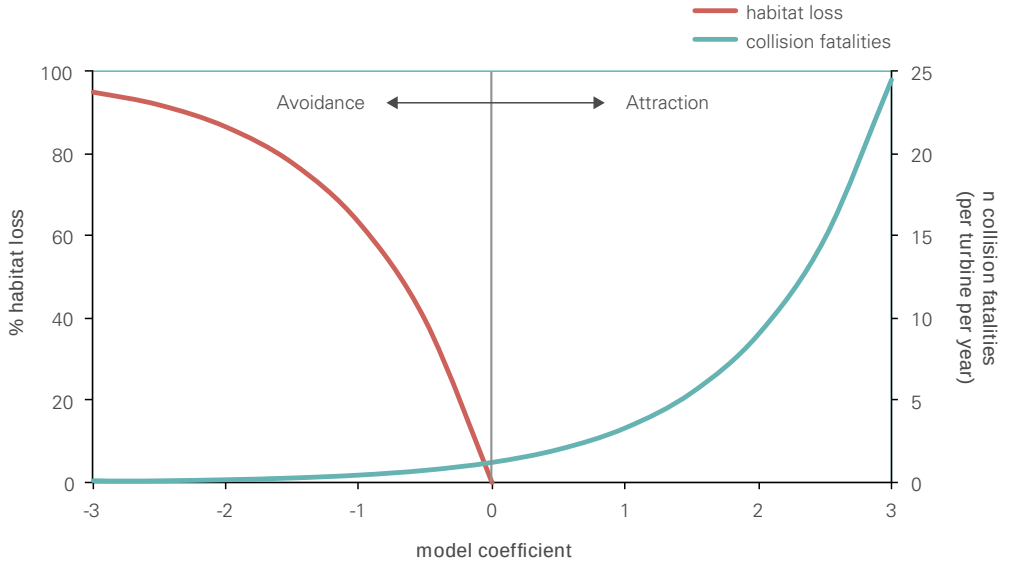
Based on the results gathered during the Danish pilot project on seabird displacement effects at offshore wind farms (Petersen et al., 2006), we surrounded the future wind farm areas by a buffer zone of 3 km to define the impact areas, being the zones where effects of turbine presence can be expected (Figure 1). Next, a more or less equally large control area was delineated, harbouring comparable numbers of seabirds, showing similar environmental conditions and enclosing a high number of historical count data (Vanermen et al., 2010). Considering the large day-to-day variation in observation conditions and seabird densities, the distance between the control and impact area was chosen to be small enough to be able to survey both areas on the same day by means of a research vessel. To minimise overall variance and in order to avoid pseudo-replication resulting from autocorrelation between subsequent ten-minute counts, the applied unit in our seabird database, count data were summed per area (control/impact) and per monitoring day (Stewart-Oaten et al., 1986). Only those days during which both areas were surveyed, were used in this study.

Seabird survey from the RV Belgica at the Thorntonbank.

Figure 1. Location of the impact and control areas for the Thorntonbank and Bligh Bank wind farms, with indication of the monitoring route sailed in the course of 2012.

Seabirds mostly occur strongly aggregated in (multi-species) flocks, inducing count results with a high proportion of zeros and relatively few but sometimes very high positive values. To correctly handle this inherent over-dispersion and excess in zero values, a zero-inflated negative binomial (ZINB) model was used (Zeileis et al., 2008). This type of model consists of two parts, (1) a 'zero component' modelling the chance of not encountering birds with a logistic regression, and (2) a 'count component' modelling the data according to a negative binomial (NB) distribution. Seasonality was added to the models as a covariate and was modelled as a cyclic sine curve, which can be described through a linear sum of a sine and a cosine term (Stewart-Oaten and Bence, 2001). Next, we included the two-level factor variable BA (before/after wind farm construction) and, depending on the outcome of the model selection process, CI (control/impact area) or T (turbines absent/present). The wind farm displacement effect is then estimated by the coefficient of the interaction between BA & CI or by the coefficient of the factor variable T. How the value of this coefficient relates to the impact of wind farm presence on seabirds is illustrated in Figure 2. A negative model coefficient value indicates that birds are avoiding the wind farm, resulting in habitat loss yet a decreasing number of collision fatalities, while a positive value suggests attraction of seabirds and increased bird mortality. The exponential relation between the model coefficient and the number of collision fatalities is explained by the logarithmic link between the response and the linear regression equation incorporated in the NB model structure.

Figure 2. Relation between the displacement-related model coefficient and the anticipated negative impact on seabirds (estimation of collision fatalities being based on the characteristics of lesser black-backed gull and a hypothetical density of 0.02 birds/km at rotor height).



BOX:
Radar systems as a tool to study large scale effects of offshore wind farms on birds

The Merlin radar system (DeTect Inc., Florida, USA) consists of two identical solid state S-band radar antennas, one scanning in the horizontal pane and one in the vertical. The horizontal scanning radar (HSR) is rotating 360° in the horizontal pane and provides information on flight tracks and therefore on the possible avoidance behaviour of birds around the wind farm. By rotating in the vertical pane, the vertical radar (VSR) creates a 'radar screen' that registers all targets moving through that screen. As this 'radar screen' is fairly narrow, every registration can be seen as one (or a group of) target(s) passing through that area. This way of data collection allows deriving the flux of birds through the area. It also provides data on the flight altitudes.
The range of the radars can be specified in the system's settings. The radars are usually operated at a range between two and four nautical miles for the HSR and 0.75 – 1 nautical mile for the VSR. This type of system records birds continuously year-round and is remotely manageable. The Merlin software of the radar is designed to record and track moving objects. The objects of interest are in this case obviously birds. When the radar energy reflects on a bird and this is received by the radar antenna, an echo appears on the raw radar screen. If the echo meets certain (plotting) criteria (e.g. minimum size, intensity of the echo, etc.) it will be plotted on the processed Merlin screen. If the radar detects the same echo in four consecutive scans, it is considered as a confirmed 'track' and will be written to the database, together with its own, unique track identification code. The radar further registers over 40 variables (e.g. time, location, speed, heading, size) for every record.

Figure 3. Unprocessed data during the fall migration of 2012. Upper panel: 15 minutes of horizontal radar data from October 22nd (8:45 – 9:00 pm). The horizontal radar range is set at 4 NM (7408 m); lower panel: one hour of vertical radar data from October 6th (11 to 12 am). The vertical radar range is set at 1 NM (1852 m). On both figures some bird tracks are notable, but also wind turbines, rain, etc. Certain areas have few or no detections at all, due to some issues with the detectability of the radar signal, which have been improved now. The direction in which an object is moving is indicated by the color.

After a test-phase in the port of Zeebrugge, the radar system was moved to the transformer platform on the Thorntonbank, about 25 km from the coast. The radar antennas are installed on the top deck, about 36 m above the sea-surface, on the south-western side of the platform.

Merlin dual radar system installed on the top deck of the transformer platform of the C-Power wind farm at the Thorntonbank.

Obviously not only birds are recorded by the radar; this also happens for rain, waves, boats, wind turbines, etc. These unwanted echoes are being referred to as 'clutter'. For offshore studies the biggest source of clutter is the sea surface (further referred to as 'sea clutter'). The VSR is typically less vulnerable to sea clutter than the HSR. A first challenge in radar data analysis was to effectively remove this clutter from the radar database. Based on visually ground truthed radar observations during the test phase at Zeebrugge, we quantified the differences in echo characteristics between birds and other objects (e.g. vessels, sea clutter, etc.). A good example of a differentiating variable is the track length of a target. With a mean track length of about five records, the track length of sea clutter was found to be significantly shorter than the tracks for birds and vessels (Figure 4). Combining radar data variables and extensive ground truthing will hence allow us to further filter birds from the radar data for future seabird investigations.

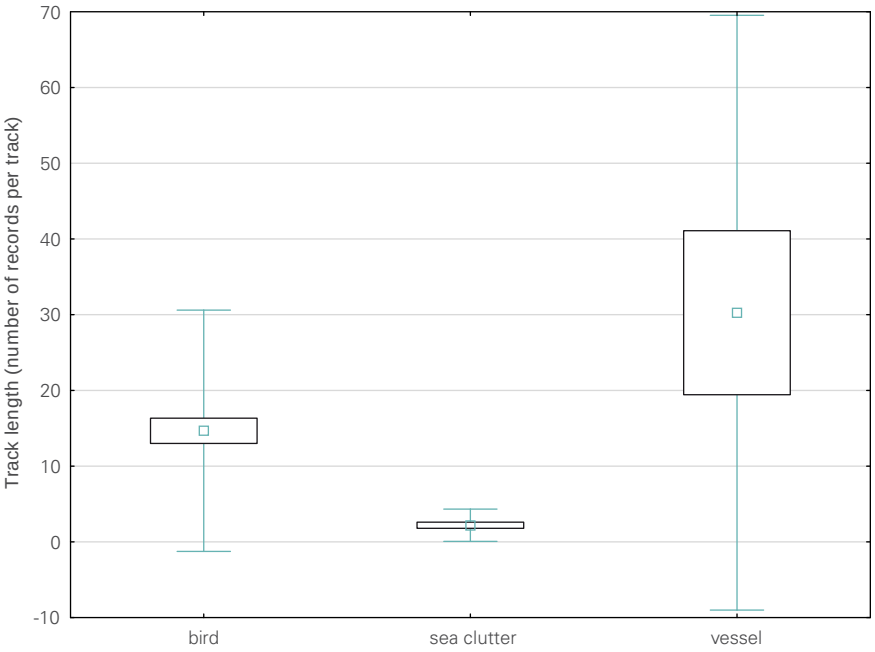


Figure 4. Track length of ground truthed tracks assigned to sea clutter, vessels and birds. Mean ± standard deviation (whiskers) and 95% confidence intervals (box).

Barrier-effect

Radar observations provide continuous data on flight movements over a wide area, allowing to assess barrier effects and avoidance behaviour on a large scale. Radars have been used for similar offshore research programs abroad, for instance in Denmark (Desholm, 2006) and the Netherlands (Krijgsveld et al., 2011). GIS processing of horizontal radar data allows to determine changes in seabird flight directions as they approach the wind farm (i.e. avoidance) and at what distance from the wind farm they show this avoidance behaviour. Although successfully applied in the tern breeding colony at the harbour of Zeebrugge (presented in Brabant et al., 2012a), we were not yet able to run such analysis for the offshore wind farm environment due to issues with the radar signal detectability.

Collision rate

Collisions of birds with fixed and rotating structures of wind turbines have been recorded in numerous wind farms on land (Everaert and Stienen, 2007; Barclay et al., 2007; etc.). For obvious reasons it is more difficult to assess the number of collision victims at an offshore wind farm, and at this point, actual data on offshore collision rates are lacking. Band (2012) however developed a (theoretical) collision risk model (CRM) to estimate the bird collision risk based on technical turbine specifications and wind farm configuration, combined with bird-related parameters. In this study, data on wingspan and flying speed were taken from Cramp (1977-1985) and Alerstam et al. (2007). The CRM also includes a micro-avoidance rate, accounting for last-minute avoidance actions. This factor is hard to assess, but is considered to be very high and is generally set to at least 95% (Chamberlain et al., 2006). Importantly, the number of estimated victims is proportional to the percentage of birds that ***does not*** perform avoidance actions (= 1 - % micro-avoidance). A seemingly small difference in avoidance rate between 95% and 99.5% therefore results in a factor 10 difference in terms of estimated collision victims. To estimate collision rate in this study, we applied the micro-avoidance value of 97.6% as found by Krijgsveld et al. (2011) based on their extensive radar research.

The 'snapshot counts' as performed during the seabird surveys allowed estimating densities of flying birds within the Bligh Bank wind farm, which were used as input for the CRM. Meanwhile, the flight height of all observed seabirds was categorised as 'in', 'under' or 'above' the rotor sweep zone (30-150 m). Radar observations too were used to determine bird densities, which were deducted from the flux of birds through the vertical radar beam. As the radar does not differentiate between individual and flocks of birds, the flux is expressed as the number of (groups of) birds/hr/km. The flux and estimated number of collisions were calculated for two days during the fall migration of 2012 (October 21st and 22nd 2012) and for two days in the winter of 2013 (January 22nd and 23rd 2013).

Lesser black-backed gull approaching the rotor sweep zone in the Bligh Bank wind farm.

DISPLACEMENT EFFECTS REVEALED

Because the large difference in configuration between the wind farms at the Bligh Bank (five rows of 11 turbines) and the Thorntonbank (a single row of six turbines at the time of the surveys) can be expected to trigger different displacement effects, we analysed both areas separately.

Bligh Bank

Three species significantly avoided the Bligh Bank wind farm, i.e. northern gannet and both auk species (Figure 5). For razorbill, this effect was limited to the wind farm area itself, but northern gannet and common guillemot also avoided the area up to at least 3 km from the nearest turbines. Little gull numbers decreased after the wind farm construction, but this change was not statistically significant. The distribution maps show that the avoidance by northern gannet (Figure 6, upper panel) was almost absolute while common guillemot (Figure 6, lower panel), despite its avoidance behaviour, was regularly observed inside the wind farm.

Figure 5. Seabird displacement effects at the Bligh Bank wind farm based on the results of 63 surveys before and 30 surveys after the turbines were built and indicated by the displacement-related model coefficient (blue bars indicate significance: . ~ p<0.1, * ~ p<0.05, ** ~ p<0.01, *** ~ p<0.001).

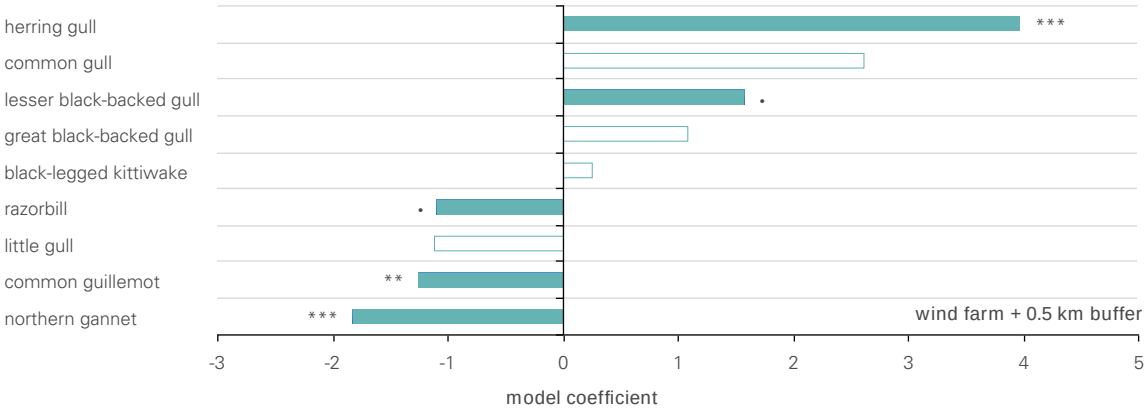


Figure 6. Observations of northern gannet and common guillemot during the seabird monitoring program at the Bligh Bank after wind farm construction.

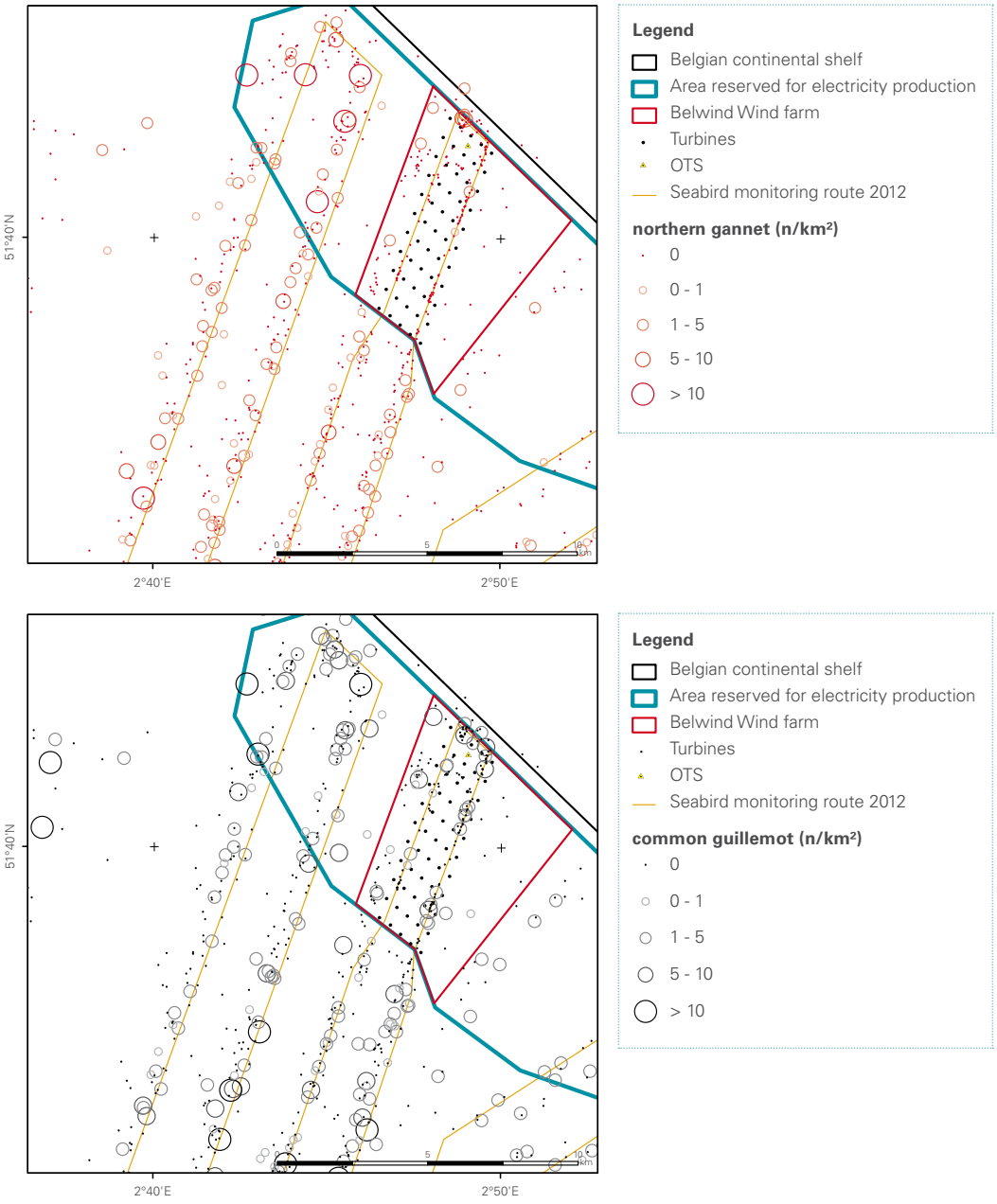
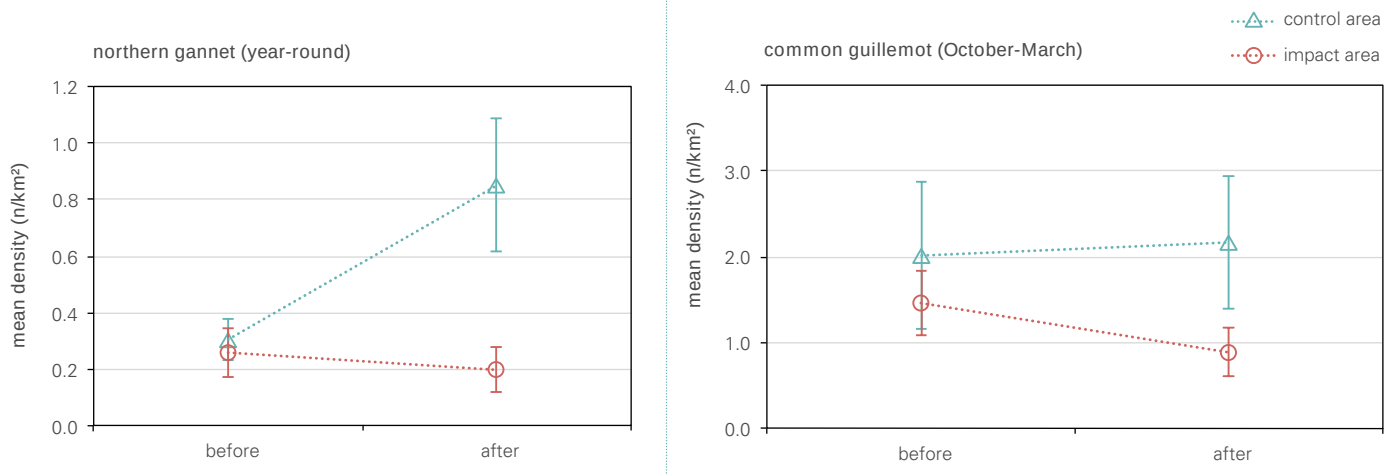


Figure 7. Densities of northern gannet and common guillemot at the Bligh Bank study area before and after wind farm construction.



Lesser black-backed gulls and herring gulls *Larus argentatus* on the other hand showed a significant increase in numbers after the wind farm was constructed (Figure 5, see also Chapter 15 – Figure 1). For lesser black-backed gull the attraction effect was significant for up to at least 3 km from the wind farm, which was not the case for herring gull. The attraction of herring gulls is nicely illustrated by the distribution pattern in Figure 8 (lower panel), with high numbers being observed exclusively near or inside the wind farm. In contrast, the distribution pattern of lesser black-backed gull (Figure 8, upper panel) suggests indifference rather than attraction. Lastly, an increase in numbers was observed in three other gull species: common gull *Larus canus*, great black-backed gull and black-legged kittiwake, but these effects were not found to be statistically significant.

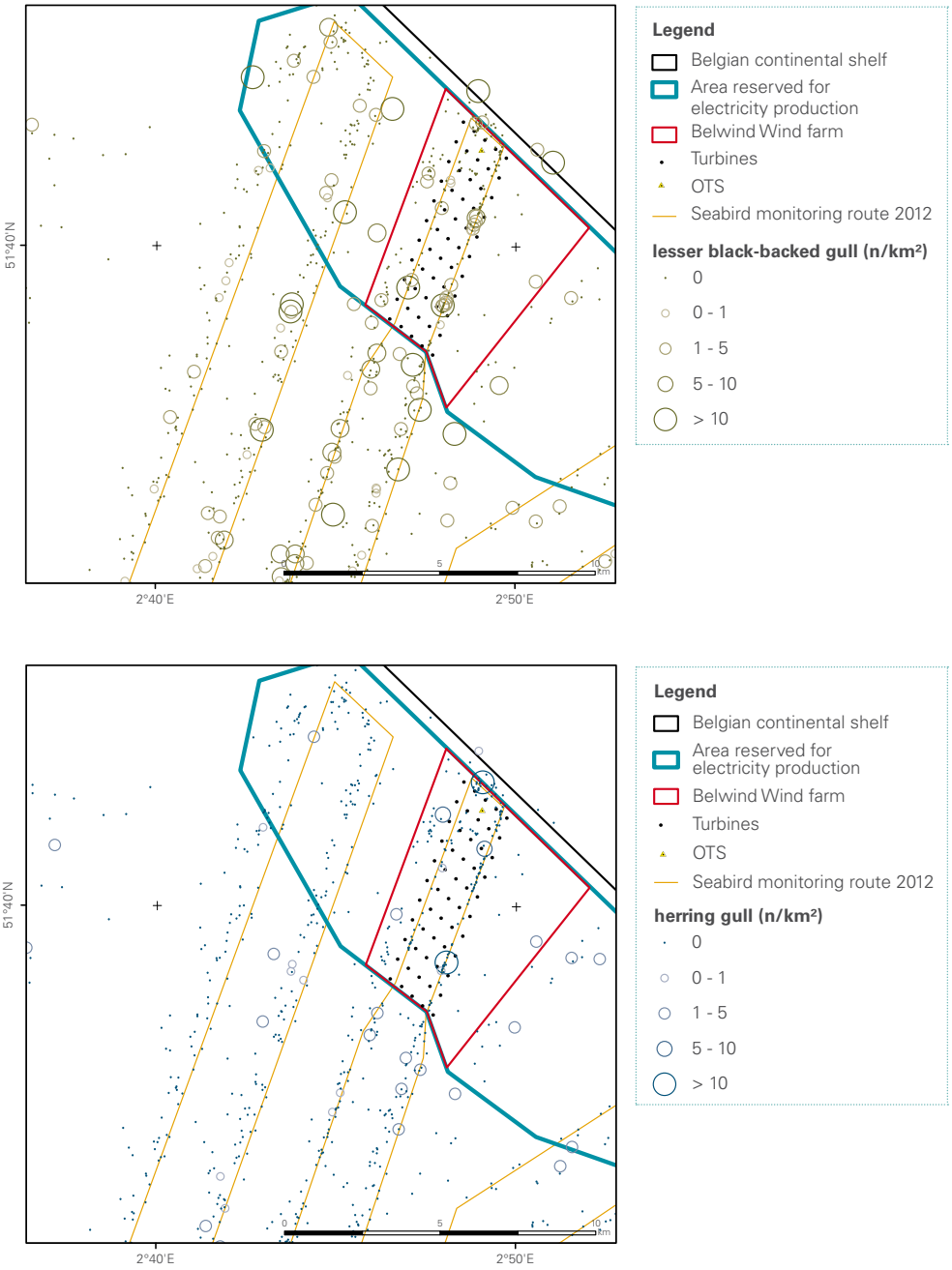
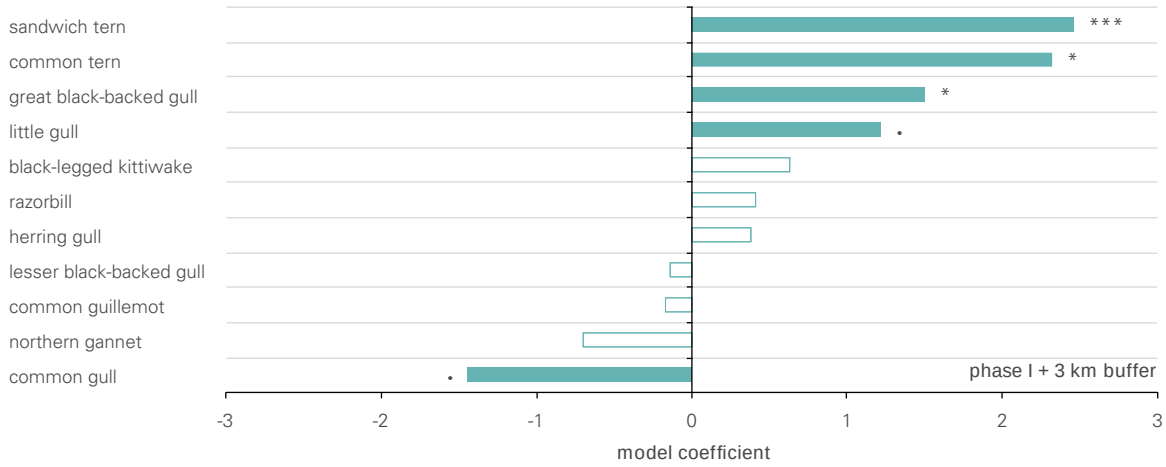


Figure 8. Observations of lesser black-backed and herring gull during the seabird monitoring program at the Bligh Bank after wind farm construction.

Thorntonbank

Four species occurred in significantly higher numbers after the construction of the first six turbines (phase I), i.e. little gull, great black-backed gull, sandwich tern *Sterna sandvicensis* and common tern (Figure 9). Common gull however avoided the area during the time of our research, opposite to what was found at the Bligh Bank. Data collected in 2012, i.e. during the construction period of phases II & III, showed significantly higher numbers of sandwich tern to occur in and around the wind farm under construction.

Figure 9. Seabird displacement effects at the Thorntonbank wind farm based on the results of 66 surveys before and 33 surveys after the turbines were built and indicated by the displacement-related model coefficient (blue bars indicate significance: . ~ p<0.1, * ~ p<0.05, ** ~ p<0.01, *** ~ p<0.001).



Razorbill

Seabird avoidance and attraction!

The wind farm monitoring programme revealed significant attraction of large gulls towards offshore wind farms at the BPNS. This was rather surprising since in contrast, no clear-cut attraction effects were found for large gulls during the Danish and Dutch monitoring programs (Petersen et al., 2006; Leopold et al., 2011). In general, at-sea gull distribution is strongly determined by the presence of fishing trawlers. The main anticipated effect of wind farms on gull distribution patterns was thus a decrease in densities resulting from the prohibition for trawlers to fish inside the farm boundaries. Yet, we found an increase in numbers, which can be caused by increased resting and feeding opportunities (see Chapter 15). For common gull and black-legged kittiwake results did not show unambiguous effects. Both species were however regularly observed between the turbines, suggesting indifference towards wind farm presence. On the other hand, three species displayed avoidance, being northern gannet, common guillemot and razorbill. Interestingly, strong avoidance by gannets and auks is reported by the Dutch researchers at the OWEZ wind farm (Leopold et al., 2011; Krijgsveld et al., 2011) and avoidance by auks was also found by Petersen et al. (2006) at the Horns Rev wind farm in Denmark.

Furthermore, we found significant attraction effects of three Annex I species (i.e. little gull, common tern and sandwich tern) to the operational phase I at the Thorntonbank. Importantly, high proportions of these species' biogeographical populations migrate through the Southern North Sea (Stienen et al., 2007).

Clearly it is impossible to count 'inside' a one-dimensional farm of six turbines, and the revealed attraction effects account for the wind farm ***buffer*** zone, rather than the wind farm area itself. This finding nevertheless agrees well with findings done by the Danish researchers Petersen et al. (2006), who observed a significant post-construction increase in numbers of little gull just outside the Horns Rev wind farm boundaries (up to 2 km), and a slight (non-significant) increase in numbers inside the wind farm. The same authors found a clear post-construction increase in numbers of common tern in the immediate vicinity of the farm (1 to 8 km), opposed to a total absence of the species inside the wind farm up to 1 km of its boundaries. Similarly, increased presence of sandwich terns foraging on the borders of the OWEZ wind farm was observed by our Dutch colleagues. Apart from this, Krijgsveld et al. (2011) report both tern species and little gull to regularly enter the wind farm, with little gull being observed in higher numbers inside compared to outside OWEZ. Unfortunately, densities of all three species were mostly too low to draw firm conclusions on displacement effects (Leopold et al., 2011).

Two common guillemots near the Bligh Bank wind farm

BIRD COLLISIONS

Visual census results

The species-specific flight height is of large influence on the expected collision risk, and forms a crucial input for the CRM. Table 1 shows our results of flight height estimations as performed during ship-based seabird surveys. While large gull species were seen flying at rotor height quite frequently (15-22%), common guillemots and razorbills were never observed flying above 30m.

Based on the densities of flying seabirds assessed during our ship-based surveys in the Bligh Bank wind farm and the corresponding CRM results, we expect one or more casualties per year for five seabird species (all gulls) at this specific location, up to more than one victim per turbine per year for lesser black-backed gull (see Table 2). For all other seabird species occurring in the study area, the density of individuals flying at rotor height was close to zero and the number of expected collision fatalities is regarded to be insignificantly low. In total, the number of gull victims is estimated at 134 per year (2.4 per turbine), which is almost half the number obtained by Poot et al. (2011), reporting an estimated 243 gull victims at the OWEZ wind farm (6.8 per turbine). This substantial difference in estimated collision rate can partly be explained by the far more offshore location of the Bligh Bank compared to the OWEZ wind farm, respectively 40 versus 10 km from the coast, which is inevitably reflected in lower gull densities.

Table 1. Species-specific percentages of birds flying at rotor height (30-150 m) as observed during seabird surveys at the BPNS.

	% at rotor height
northern gannet	5
little gull	2
common gull	15
lesser black-backed gull	22
herring gull	15
great black-backed gull	20
black-legged kittiwake	9
sandwich tern	2
common tern	1
common guillemot	0
razorbill	0

Table 2. Estimated collision victims based on observed densities of flying birds inside the Bligh Bank wind farm and an assumed micro-avoidance rate of 97.6%.

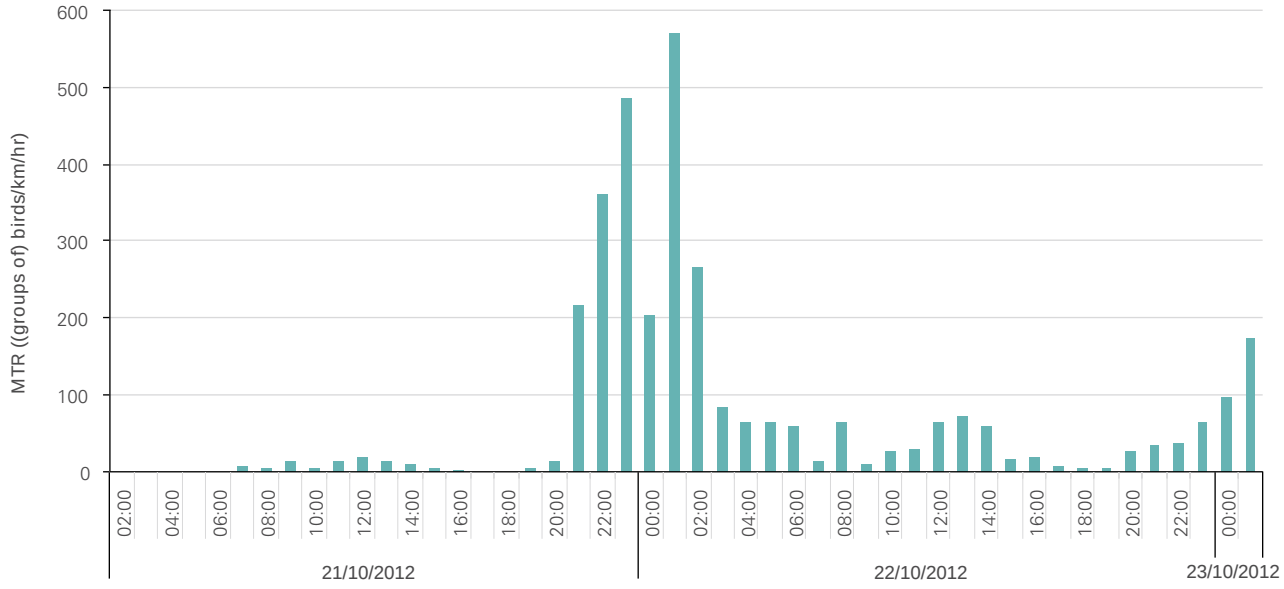
	common gull	lesser black-backed gull	herring gull	great black-backed gull	black-legged kittiwake
winter	3	0	3	3	19
spring	0	40	3	4	10
summer	0	22	0	0	0
autumn	0	3	0	21	3
number/year	3	65	6	28	32
number/ (turbine*year)	0.05	1.18	0.11	0.51	0.58

Radar results

On October 21st, 1,176 (groups of) birds were recorded at rotor height in 17 hrs, with an average flux of 69.3 (groups of) birds/hr/km. The flux went up as high as 570 (groups of) birds/hr/km around midnight (Figure 10). On October 22nd, 1,864 (groups of) birds flew on rotor height in 24 hrs, with an average flux of 77.7 (groups of) birds/hr/km.

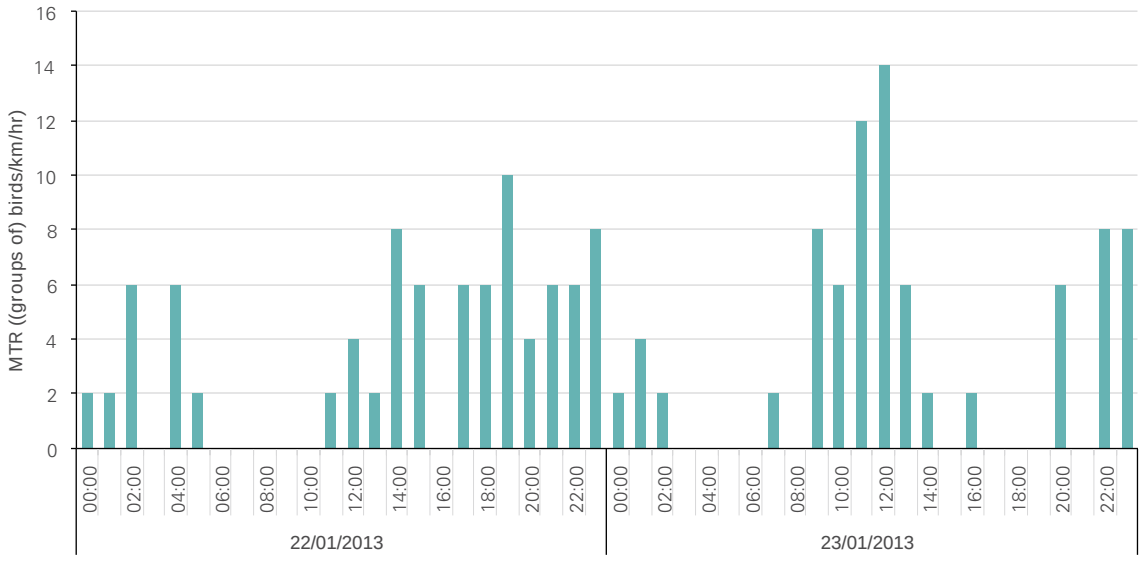
Isolating the radar results obtained during the night of October 21st and 22nd (sunset to sunrise), we observed an average flux at rotor height of no less than 204 (groups of) birds/km/hr. This massive night time bird movement can without doubt be assigned to thrush migration, the more considering the visual observation of large numbers of thrushes arriving at the port of Zeebrugge during the early morning of October 22nd. Wind conditions during that time were E-NE and thus favourable for southwest bound migration. Applying the CRM results in an estimated number of 21 collision victims during that specific night at the Thorntonbank (micro-avoidance rate set at 97.6%).

Figure 10. Bird flux (groups of birds/hr/km) at rotor height for October 21st and 22nd 2012.



Under normal circumstances however, less birds frequent the study area. For example, on January 22nd and 23rd, respectively 86 and 82 (groups of) birds/km were recorded at rotor height (Figure 11), resulting in an average flux of 3.5 (groups of) birds/km/hr. Applying the CRM results in an estimated 58 collision victims during the winter months December, January and February (micro-avoidance rate of 97.6%). Based on the known species-spectrum occurring at the Thorntonbank in winter, these collision victims are most likely to be common gulls, lesser black-backed gulls, herring gulls, great black-backed gulls and black-legged kittiwakes.

Figure 11. Bird flux (groups of birds/hr/km) at rotor height for January 22nd and 23rd 2013.



Extrapolating and nuancing bird collision estimates

Current plans are to construct seven wind farms at the BPNS, with a maximum number of turbines of 530. Extrapolating the earlier results leads to an estimated 209 thrushes to collide with offshore turbines at the BPNS during a single night with comparable migration (micro-avoidance rate 97.6%). Based on daytime observations, each year up to 1,291 birds are expected to collide with the turbines (micro-avoidance rate 97.6%), for the major part gulls. Such extrapolations should be handled with care as the results presented here are yet based on flux and density measurements collected during small time frames. While ship-based visual censuses were limited to a single daytime visit each month, it allows for a large spatial coverage. In contrast, radar observations are bound to one location but provide continuous measurements when fully operational. Applying both techniques is therefore invaluable for an integrated assessment of bird mortality at the Belgian concession zone for wind energy.

FUTURE MONITORING

With the wind farms at the BPNS being operational since the end of 2009 (Thorntonbank) and 2010 (Bligh Bank), the results presented here are still based on a relatively limited impact dataset. Power analyses showed that even for quite substantial changes in seabird densities (e.g. a decrease of 75%), up to ten years of monitoring may be needed to obtain sufficient statistical power (Vanermen et al., 2012). Indeed, at both wind farms we saw numbers of several seabird species to have changed, without the difference in density being statistically significant. With more years of monitoring ahead of us, our data will allow to better distinguish between true displacement and indifference. Long-term monitoring at the various wind farm sites is also needed to anticipate the possible habituation of seabirds to the presence of wind turbines (temporal variation) or the fact that displacement effects might differ between wind farm sites (spatial variation). The results from the Dutch and Danish research programs further show that the occurrence of increased numbers just outside an offshore wind farm (as was found near the single row of turbines at the Thorntonbank) cannot be extrapolated to the wind farm area itself. Continuing the monitoring of seabird presence in the now fully operational (and two-dimensional) Thorntonbank wind farm is therefore highly important. Clearly, if the attraction effects as found in this study persist during the coming years, the associated increased collision risk is of serious conservational concern considering the involved species' high protection status.

The main technical challenges currently being tackled in close collaboration with the radar developers are (1) the negative correlation between seabird detectability and distance and (2) the substantial shadow effects created by individual wind turbines. Once these issues are solved, the radar research will further focus on the barrier and collision effects, using a similar approach as was demonstrated above and taking account of radar data filtering. Also, Chamberlain et al. (2006) showed how small differences in estimated avoidance rates result in proportionally large changes in estimated mortality. To improve the outcome of the CRM, radar observations should be combined as much as possible with simultaneous visual observations at the spot, to assess species-specific flight heights and avoidance rates, taking account of differing bird behaviour under a range of conditions. The CRM however remains a theoretical model, and to know actual collision rates, devices that measure collisions of birds with turbines are still needed. Finally, the construction of a new wind farm in the area south of the radar location in the near future will provide an ideal opportunity for the comparison of pre- and post-impact patterns, which was not possible for earlier projects.

Northern gannet

CHAPTER 6

Qualifying and quantifying offshore wind farm-generated noise

Alain Norro, Dick Botteldooren, Luc Dekoninck, Jan Haelters, Bob Rumes, Timothy Van Renterghem and Steven Degraer

The construction, operation and dismantling of offshore wind farms generate noise both above and under water that may be of environmental concern. The maximum detected sound power level of the above water pin piling noise for example, reached 145 dB(A), while the operational sound power level amounted to 105-115 dB(A) at high wind speed. Underwater construction noise was close to ambient noise levels for gravity based foundations (about 115 dB re 1 µPa RMS), while pin piling and especially monopile piling produced excessive levels of underwater noise up to 194 dB re 1 µPa (zero to peak level at 750m), attenuating to ambient noise levels at a distance of up to 70 km. Whether or not such noise levels are to be considered acceptable will depend on the future implementation of proposed regulations into the Belgian legislation.

INTRODUCTION

In the past decade, the potential impact of underwater noise pollution has been increasingly recognised at the international level, with several intergovernmental bodies, including the UN General Assembly and the UN Convention on Migratory Species, calling for multilateral efforts to minimize the risk of adverse effects on the marine environment. (European Parliament, 2004) (Marine Mammal Commission, 2007) (International Fund for Animal Welfare, 2008), (International Maritime Organisation, 2009), At the European level, the new EU Marine Strategy Framework Directive has identified noise as one of the pressures that need to be controlled to achieve the 'good environmental status' of European marine waters (Anonymous, 2012a). The Belgian part of the North Sea (BPNS) hosts numerous human activities generating noise, including sand and gravel extraction, the installation of pipelines and cables, military exercises as well as intense shipping. As a recent activity, offshore wind farm construction and operation now contribute to the human-induced noise in the BPNS.

Four different phases, each with specific noise emitted, should be distinguished during a wind farm life cycle (Nedwell and Howell, 2004): (1) the reference situation before the start of the construction, (2) the construction phase, (3) the operational phase and (4) the dismantlement phase. Noise emissions associated with the construction phase include e.g. increased shipping traffic, dredging activities, cable trenching, the installation of the scour protection and pile driving. During the operational phase of a wind farm, various kinds of lower level, yet chronic (at least 20 years), noise is expected to propagate above and under water, among which machine noise, self noise generated by the blades passing through the air, noise due to inflow turbulence and noise generated by vibration of the turbine propagating into the water through the foundation. No information is available about the noise during the wind farm dismantling phase as this activity has yet to take place.

This chapter focuses on the qualification and the quantification of wind farm generated noise both above and under water during the construction and operational phase.

MONITORING STRATEGY

Above water noise

The above water or airborne noise level generated by the hammer during a pin pile piling event (jacket) was measured at a short distance (at about 284 m). The source power levels obtained from measurements during piling were used to estimate the impact distance of construction activities in the vicinity for different meteorological conditions using the parabolic equation numerical technique (Dekoninck and Van Renterghem, 2012).
Source power measurements of the operational phase of an offshore turbine are problematic due to the instrument unfriendly conditions. Two approaches were tested. At the one hand, measurements were made from a RHIB at various distances of the wind farm and at the other hand, continuous noise monitoring was set up on the platform of an operational turbine. Measurement conditions in a RHIB are highly limited due to safety issues for the persons on board (wave height) and due to the disturbing noise of waves breaking against the RHIB. Wind turbines at high production and hence high noise emission conditions cannot be monitored with this technique, but a good reference for the offshore background noise levels could be established. One of the remarkable findings was the presence of low frequency background noise related to engines of large ships at long distance. Long term measurements at the wind turbine platform of a 5 MW turbine of C-Power (at approximately 15 m above the water surface and at a minimum 30 m distance from the blade tip) proved to be a useful technique to evaluate the noise emission of a wind turbine in operational conditions.

Underwater noise

Before the construction the background or ambient noise, with both a natural and a human induced component (eg. shipping, rain, waves…), was measured at the Thorntonbank and the Bligh Bank respectively by Henriet et al. (2006) and by Haelters et al. (2009). Construction and operational noise were measured at both the Thorntonbank and the Bligh Bank. Real time noise recordings of maximum 20 minutes each were performed from a RHIB drifting in silent mode with a Br el & Kjær hydrophone (type 8104) deployed at 10 m depth. A Br el & Kjær amplifier (Nexus type 2692-0S4) allowed for an amplification of the signal, prior to its recording with an MARANTZ Solid State Recorder (type PMD671), operated at the highest possible sampling rate of 44.100 Hz. All signals recorded were post-treated for detecting maximum peak levels (zero to peak $L_{z\text{-}p}$), used to characterise impulsive noise events (Betke, 2008). Raw measurements were normalised to a distance of 750 m, taken as a standard distance for e.g. German and Belgian underwater noise measurements (M ller and Zerbs, 2011; Anonymous, 2012; see Ainslie et al., 2010). The third octave spectrum was used to identify the spectral window of the noise. Other parameters are also computed and more information on the standardized protocol could be found in Norro et al. (2013). We finally used the collected information on $L_{z\text{-}p}$ to estimate offshore wind farm-generated noise propagation in the shallow water environment of the BPNS. A simple propagation model (regression) was fit through the data collected at different distances, which together with the addition of an attenuation term allowed for underwater noise propagation modelling (for details: see Norro et al. 2013).

The three foundation types used in the Belgian waters.

WIND FARM-GENERATED NOISE FEATURES

Above water noise characteristics

The maximum detected source power level of the above water noise during piling was 145 dB(A), but the source power level was highly dependent on the progress of the piling (Figure 1). Firstly, an increase is detected while the piling power is gradually reaching its maximum. While the pile is driven into the seabed, the noise emission drops when the largest section of the pile is below the water surface. Piling activities could be detected in low background noise conditions at a distance of up to 10 km from the source and hence cannot be heard from the coast.

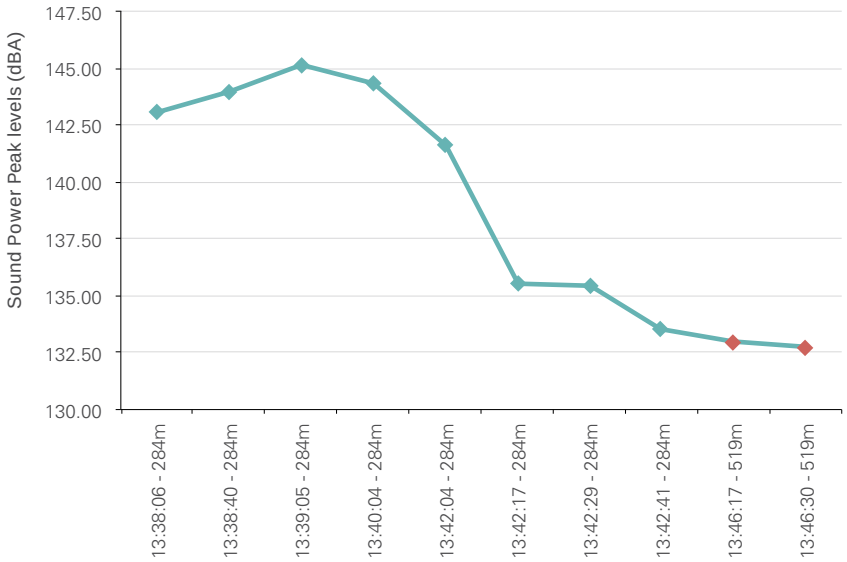
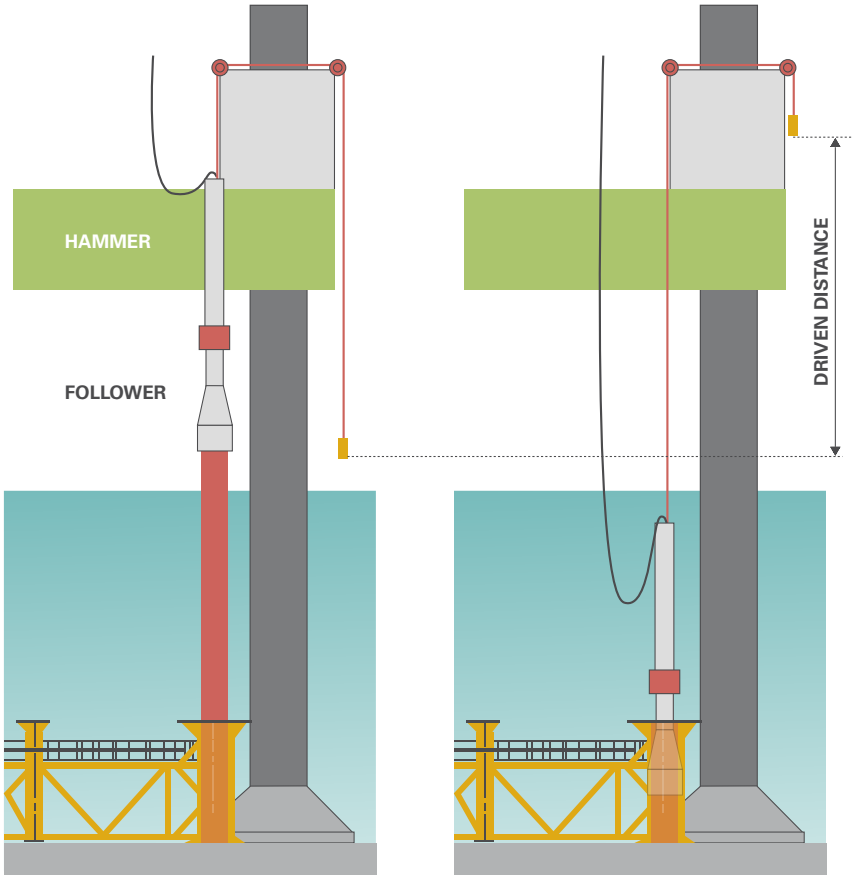


Figure 1. Sound power of the peak levels of piling activity change during the piling progress. Blue points are based on measurements at 280 m distance from the pile, red points at 520 m.



Self noise generated by the blades passing through the air, was detected to be the most important source of sound during operation in modern horizontal axis wind turbines. It occurs when boundary layer turbulence passes the trailing edge of the blade and increases when the boundary layer separates or vortex shedding occurs. Atmospheric conditions could affect the generated sound power in different ways. Boundary layer wind gradients may result in non-optimal inflow conditions for some of the blade positions and inflow turbulence may differ depending on the weather. It can be expected that offshore conditions are more stable than onshore conditions. Noise measurements were evaluated against wind speed at hub height and production data (Figure 2). For very low wind speeds and correspondingly low production, noise levels increase with wind speed but as soon as production is above 2 MW or wind speed is over 9 m/s at hub height, a plateau is reached. Only when production reaches 4.5 MW, which roughly corresponds to wind speeds of 12 m/s at hub height, the noise level starts to rapidly increase again. This could be explained by the changing blade pitch that is used to limit the rotation speed at very high wind speeds, but it could also be caused by the interaction of the wind with the microphone or by secondary sources such as breaking waves. The overall A-weighted sound power level calculated backward from these measurements amount to 102-105 dB(A) for wind speeds between 8 and 12 m/s at hub height and to 105-115 dB(A) for wind speeds higher than 12 m/s. Meteorological effects on sound propagation are limited to a few hundred meters – typically of relevance for onshore operations – because of the height of the source. Long distance propagation over several kilometres over the sea surface depends on meteorological conditions.
Spectral data showed a faint tonal peak at low frequencies that increases with production (and rotation speed), which is expected to have a mechanical origin. This indicates that the mechanical noise generated by e.g. the gearbox and the generator may be less carefully encapsulated for these offshore wind turbines compared to onshore wind turbines, in which a significant effort is put into noise reduction. The main contribution is however broad band noise centred between 300 and 800 Hz for the most significant operational range. This spectrum corresponds to what can be expected for such large wind turbines (Møller et al., 2011).

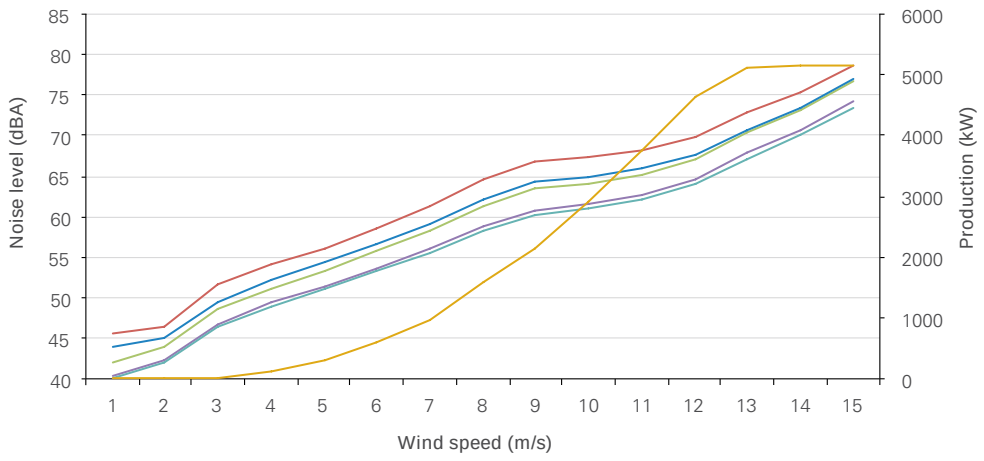


Figure 2. Noise level on the wind turbine platform as a function of wind speed and production.

Underwater noise characteristics

The ambient underwater noise amplitude ranged from 95 to 110 dB re 1 Pa in the 20 Hz to 3 kHz frequency window. The amplitude decreased to 80 dB re 1 Pa at 10 kHz. Slightly higher values were found at the Thorntonbank site (see Henriet et al., 2006), where also a peak at 100 Hz was detected. Both the increase in amplitude and the extra peak may be attributed to the location of the interconnector pipeline and/or the shipping route that are closer to the Thorntonbank than to the Bligh Bank.

Jacket pin pile (left) and monopile (right) driving preparation at the Thorntonbank and Bligh Bank.

As the installation of gravity based foundations (GBF) do not require piling, the construction of GBF wind turbines may be considered relatively silent as most of the noise is derived from an increase of shipping and dredging operations with RMS noise levels of about 115 dB re 1 Pa, i.e. little higher than the ambient noise level (Haelters et al., 2009). Piling events however are known to produce much higher peaks in noise levels. The piling of 5 m diameter monopiles at the Bligh Bank for example produced an $L_{z\text{-}p}$ of 179 to 194 dB re 1 Pa as measured and normalized at a distance of 750 m from the piling location, while piling 1.8 m diameter pin piles for the jacket foundations at the Thorntonbank showed $L_{z\text{-}p}$ levels ranging from 172 to 189 dB re 1 Pa at the same distance (Norro et al., 2013). Even if these emissions are limited in time, they have to be considered of the same order of magnitude as those produced by airguns (ESF. 2008). While piling pin piles seemed to generate less noise than piling larger monopiles, this could not be statistically underpinned. The total number of blows and hence the piling time required for the installation of one jacket, is however higher than for a monopile. When normalized to the installed power, 57% more blows/MW installed were needed for the construction of an average jacket foundation than for a monopile foundation. Most of the energy during piling is present in the 50 Hz to 1 kHz frequency window (computed for several strokes), where several foundation-specific peaks may be discerned (Figure 3).

When normalised to 750 m for the source (Ainslie et al., 2010), the piling of a 5 m diameter monopile and a 1.8 m diameter pin pile generated a maximum $L_{z\text{-}p}$ of 194 dB re 1 Pa, respectively 189 dB re 1 Pa. As comparison, same normalisation is applied to the literature data presented in Nehls et al. (2007), $L_{z\text{-}p}$ ranged from 185 dB re 1 Pa for a 3.3m diameter pin piling event at FINO 2 (Germany) to 196 dB re 1 Pa for a 4.2 to 4.7 m diameter monopiling event at North Hoyle, Scroby Sands and Barrow (UK), and FINO 3 (Germany). A normalised 200 dB re 1 Pa at 750 m was finally obtained for the piling of a 4.7 m diameter monopile at the Q7 wind farm (de Jong and Ainslie. 2008).

Parvin et al. (2006) cited by Nehls et al (2008) derived a relation between $L_{z\text{-}p}$ and the diameter of the pile. When applied for pile of 5m and 1.8 m diameter the $L_{z\text{-}p}$ values obtained at 750 m are respectively 197 dB re 1 Pa and 190 dB re 1 Pa. Good agreement is obtained even if energy produced by the hammer as well as the nature of the sediment are not taken into account explicitly.

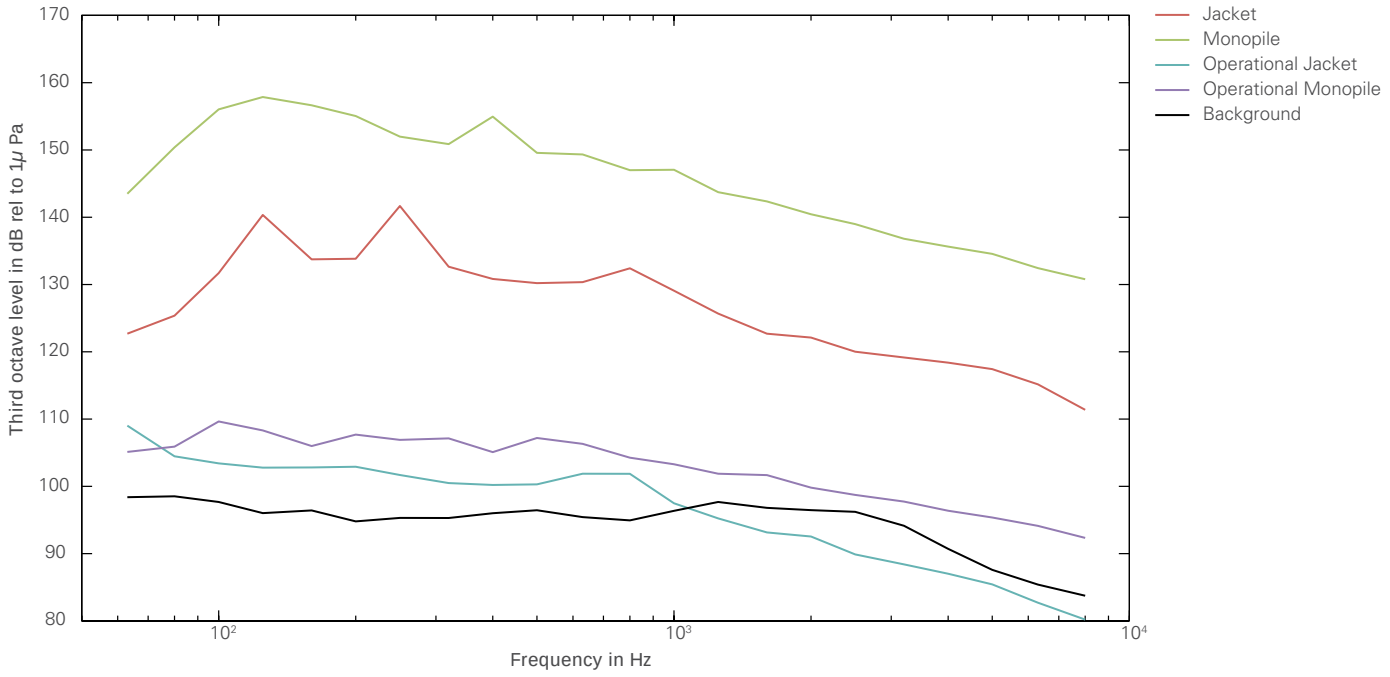


Figure 3. 1/3 octave spectra of ambient noise at the Bligh Bank (black), as well as noise emitted during the construction and operation of offshore wind farms. Jacket for a 6,15 MW turbine: construction (red) and operation (blue); monopile for a 3 MW turbine: construction (green) and operation (pink).

The propagation model indicates that noise generated by monopiling attenuated to ambient noise levels at 70 km from the source, while this distance is shorter for pin piling noise (i.e. 50 km; Figure 4). When considering the noise level of major disturbance for harbour porpoises *Phocoena phocoena* of $L_{z\text{-}p}$ 149 dB re 1 µPa (Bailey et al., 2010), according to this model this species would suffer major disturbance up to a distance of 8 km for pin piling and 16 km for monopiling.

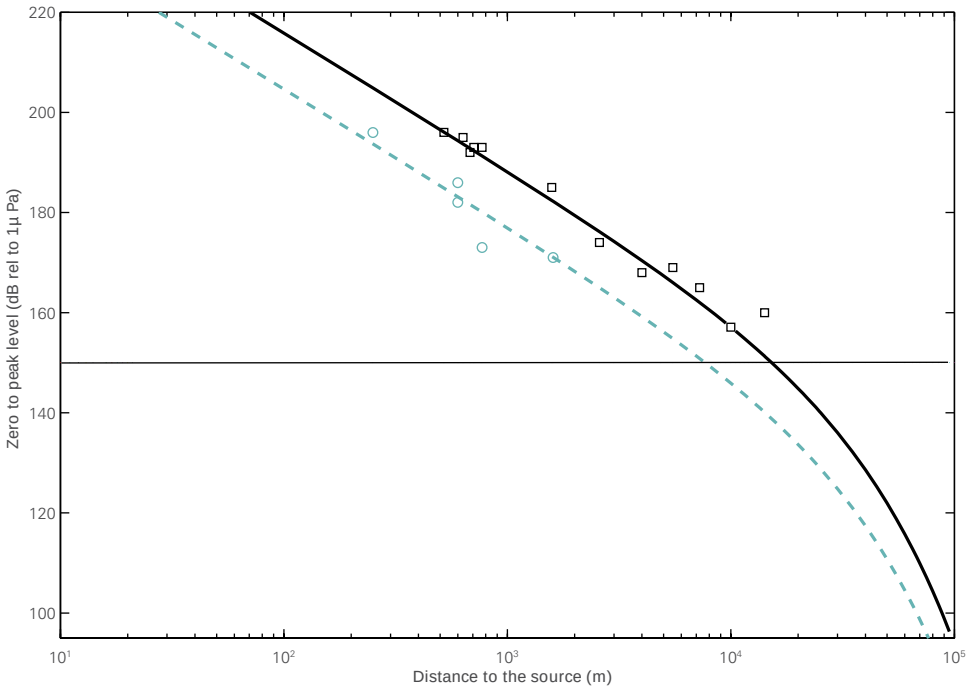


Figure 4. Propagation model derived from pin piling (dashed line) and monopiling (plain line). Squares and circles are the measured $L_{z\text{-}p}$ for monopiles (squares) and jackets (circles) respectively, while the horizontal line at 149 dB re 1 Pa indicates the level ($L_{z\text{-}p}$) for major harbour porpoise disturbance (Bailey et al., 2010).

Because of the expectation of a more limited impact of relatively low level operational noise compared to construction noise, less data exist on the operational noise emitted by operational wind turbines, especially large ones (5 MW or more). Tougaard et al. (2009) based on measurements taken close to the foundation (14 and 20 m) demonstrated an increase above the ambient noise of 10 to 20 dB re 1 Pa at 125 Hz for 2 MW wind turbines, while no increase was detected at other frequencies. Betke (2006) however reported an additional peak in the 1/3 octave spectrum at 150 Hz. In our study, operational noise was measured both for the GBF and jacket foundation wind turbines at the Thorntonbank and the monopile foundation turbines at the Bligh Bank. A 3 MW monopile wind turbine typically generated a sound pressure twice as high as that of a 6.15 MW jacket foundation turbine (i.e. 6 dB re 1 µPa (RMS) higher throughout the 1/3 octave spectrum; Figure 3), in its turn emitting higher noise levels than a 5 MW GBF wind turbine (by 6 dB RMS). Note that during the measurements sea states ranged from 2 to 3, and/or a wind force of 4-5 Beaufort.

LEGISLATION AND NOISE LEVEL LIMITS

With regards to operational above water noise, environmental noise limits for onshore wind turbines are given in VLAREM, in which noise limits depend on the time of the day (i.e. day, evening, night) and the type of area. In the most restrictive conditions (i.e. residential area) the noise should not exceed 39 dB(A) at night. A decision on how to measure onshore wind turbine-generated noise is under construction by the Flemish government. However, detailed calculation guidelines are available. These are based on ISO9613, adverse meteorological conditions, and equivalent levels. If these regulations would be applied to the offshore wind turbines studied, the minimal distance for siting a residence to a single wind turbine would need to be higher than 500 m (at wind speeds below 12 m/s). For a park of 100 wind turbines, this distance would need to be increased to at least 3-4 km. We should however mention that the residential areas nearest to the offshore wind farms are located at a distance of 30 km at present and 21 km when the whole Belgian wind farm zone will be developed. Residents along the Belgian coast will hence never experience noise pollution from the offshore wind farms.

For underwater generated noise, limits are not yet fully implemented in Belgian legislation, but a maximum $L_{z\text{-}p}$ of 185 dB re 1 Pa at 750m from the noise source has been recommended in the framework of the implementation of the Marine Strategy Framework Directive (MSFD) (Anonymous, 2012). These underwater noise level limits are of course not directly related to human welfare, but rather to its disturbance of marine life, with currently special attention to marine mammals. Given the seasonally high density of harbour porpoises in Belgian waters (up to more than 2 ind./km on average), the possible impact of excessive noise on this species is explored in Chapter 7.

FUTURE MONITORING

Next to the weather limitations to perform *ad hoc* noise measurements from an RHIB at sea, the most critical issue to monitor construction noise is the ability to be on site when work is undertaken. At several occasions during the first years of monitoring the piling work was cancelled at short notice, forcing the monitoring team to return to the harbour without performing any measurements. To overcome the above-mentioned difficulties, the future construction noise monitoring will also be performed using moored instruments. These instruments record long time series of underwater noise covering one or more complete sequences of piling. The instruments will also be used for operational noise recordings throughout a wide range of weather conditions, currently problematic given the limitation of a sea-state of 2-3 and/or a 4-5 Beaufort wind force.

Also some questions regarding above water noise produced by large offshore wind turbines remain unsolved. The influence of inflow turbulence on (low frequency) noise emission could be worth studying. For offshore wind turbines, it is expected that it is mostly relevant in the presence of upwind turbines. Slow fluctuations in noise levels may be an issue when it comes to estimating the perception of wind turbine noise. The directivity of this component of the noise is not known very well. Piling noise propagation was calculated using linear propagation models. However, levels are high and propagation distance is long so mild non-linear effects may occur. Measurements at larger distance could validate this influence.

Finally, to comply with the newly proposed guidance document for monitoring underwater noise in European seas (Dekeling et al. 2013), a register of sources and levels of noise should be compiled. The future offshore wind farm noise monitoring programme will therefore start developing a register for underwater noise sources and levels in the BPNS, which will facilitate setting a context for underwater noise interpretation and evaluation.

CHAPTER 7

The effects of pile driving on marine mammals and fish in Belgian waters

Jan Haelters, Elisabeth Debusschere, Dick Botteldooren, Val rie Duli re, Kris Hostens, Alain Norro, Sofie Vandendriessche, Laurence Vigin, Magda Vincx, Steven Degraer

Pile driving generates very high levels of low frequency impulsive underwater noise, with possible consequences for marine mammals and fish. To describe the effects of pile driving on harbour porpoises we developed a model based on the results of aerial surveys, which clearly pointed at disturbance effects. Especially fish with a swim bladder can be affected by piling operations, but the investigation of sub-lethal effects and the sensitivity of different fish species and life stages is complex. A multidisciplinary study is proposed to investigate these effects in the field and under controlled laboratory conditions.

INTRODUCTION

The installation of numerous offshore wind farms across the North Sea has triggered a range of questions regarding its impact on the marine ecosystem. In most cases, wind turbine foundations are hammered into the seafloor. This activity is known to produce low frequency impulsive underwater noise (see chapter 6; ICES, 2010). Underwater sound travels at a speed of 1500 m/s, and can travel up to considerable distances. For pile driving, sound pressure levels (peak to peak, SPL_{p-p}) of up to 200 dB re 1 µPa at a distance of 750 m from the noise source have been measured or estimated (Madsen et al., 2006; Norro et al., 2010; 2012). Such noise levels can have consequences on living organisms ranging from masking, behavioural disturbance, physiological stress, hearing loss (temporary or permanent), and even to injury or death (Popper et al., 2004; Hastings and Popper, 2005; Wahlberg and Westerberg, 2005). Given such consequences, noise is increasingly considered as an important form of pollution. One of the aims of the European Marine Strategy Framework Directive (MSFD; 2008/56/EC) is to establish a framework for community action in the field of marine environmental policy, with anthropogenic underwater noise at levels that do not adversely affect the marine environment. To implement the MSFD, Belgium adopted an interim criterion of a maximum zero to peak noise level (L_{z-p}) of less than 185 dB re 1 µPa at 750 m from the source for anthropogenic impulsive sounds (Anonymous, 2012a).

The impact of noise is of particular concern for marine mammals and fish, which utilise sound in their everyday lives. To assess the effects of pile driving on marine mammals, the research has focused on the harbour porpoise *Phocoena phocoena*, as this is by far the most common cetacean in European, including Belgian, waters (Haelters et al., 2011). Harbour porpoises use sound production and reception for foraging, spatial orientation and social interactions. Sound has essentially taken over many of the roles normally requiring vision. Therefore, this species may be heavily impacted by excessive underwater noise, an impact not yet fully understood. Around a pile driving site, areas can be defined where exposure to the noise can lead to injury, permanent and temporal hearing threshold shifts (PTS; TTS), masking of the animal's sonar system, behavioural reactions (possibly leading to stress) and audibility of the noise to the harbour porpoise (Lucke et al., 2009).

At the very start of bio-acoustic research, marine mammals were the main target group. Later, researchers took an interest in fish, as sound enables them to communicate, forage, find a mate, orientate, avoid predators, defend their territory and express aggression (Hastings and Popper, 2005; Kikuchi et al., 2010).

Underwater sound consists of two components: particle motion, indicating the movement of the molecules in the

medium due to the sound waves, and sound pressure. Particle motion moves through a fish's body and is detected by the inner ear, which acts as a biological accelerometer and enables fish to hear (Popper and Fay, 1999; Wysocki et al., 2009). Fish rely especially on particle motion in their response to sounds from different directions. In contrast to fish without swim bladders, those with gas-filled swim bladders will respond to sound pressure waves because of the higher compressibility of gas compared to seawater (Thomsen et al., 2006). These compressions may be transmitted to the inner ear whereby sound pressure is transformed into particle motion and will give them an auditory advantage, with information on sound characteristics such as distance and location.

Only for a limited number of fish species the hearing range is known, and although it varies greatly between species, frequencies from below 50 Hz up to 500-1500 Hz are detectable by the majority of them (Thomsen et al., 2006; Popper and Hastings, 2009; Andersson, 2011). A few species, including the Atlantic herring *Clupea harengus*, can perceive sound above 1500 Hz (Wysocki et al., 2009). The hearing range of the harbour porpoise stretches from 250 Hz to 160 kHz, while it is most sensitive between 100 and 140 kHz (Kastelein et al., 2002).

RESEARCH STRATEGY

One of the aims of the Belgian wind farm monitoring programme is to investigate the ecological impact of noise on marine mammals and fish. While the research on marine mammals already made some major achievements, the investigation of the effect of underwater noise on fish only recently started and its description here is limited to a scientific justification of what is and will be done.

Harbour porpoise *Phocoena phocoena*

Harbour porpoises are notoriously difficult to study in the wild because of their elusive nature and the technical difficulties related to the environment they live in. Our knowledge of the impact of piling on harbour porpoises is limited to exposure studies of individual animals in captivity with extrapolations to the marine environment, simple predictions of disturbance distance such as made in environmental impact assessments and a few studies at construction sites (ICES, 2010; Murphy et al., 2012). To describe and predict the impact of pile driving, we developed a model based on anticipated harbour porpoise behaviour. We compared the model results with changes in the in situ distribution patterns of harbour porpoises due to pile driving.

Before and during the piling of jacket foundations at the Thorntonbank in 2011, we performed a number of standardised aerial line transect surveys (Buckland et al, 2001), making observations in a predefined pattern consisting of parallel tracks 5 km apart and approximately covering the Belgian marine waters (Haelters, 2009). To assess possible effects of piling on the distribution and abundance of harbour porpoises, observations were transferred to a fine-scale density map, in which the density in unvisited areas was extrapolated from observations using inverse distance weighting.

As it is difficult to objectively qualify and quantify the impact of piling based on maps from aerial surveillance data, a model was developed describing the fundamental phenomena at the basis of the harbour porpoises' redistribution. We presumed that the speed of a harbour porpoise may be described as a combination of a directional movement and random dispersal. Close to the impact area and during piling, we presumed that a porpoise would exclusively head away from the piling location at a speed which would decrease as a function of disturbance, i.e. the noise level the animal is exposed to. In the absence of piling or at a distance where the piling noise is tolerated, harbour porpoises would – at least over the short time frame as applicable in this study – move more slowly and in random directions (i.e. random dispersal).

The model was first applied to hypothetical data, described by an even distribution of harbour porpoises throughout the area (1 animal/km). The resulting density pattern after a first period of disturbance (piling), without taking account of random motion, can be described as an area near the impact location where the density is lower than average (due to animals moving away), surrounded by an area with a higher density (due to movement of individuals away from the piling zone), and an area with no change in density (i.e. the area beyond the influence of the pile driving activity). In the case of short, consecutive pile driving periods, the areas described above would systematically shift further away from the impact location (Figure 1).

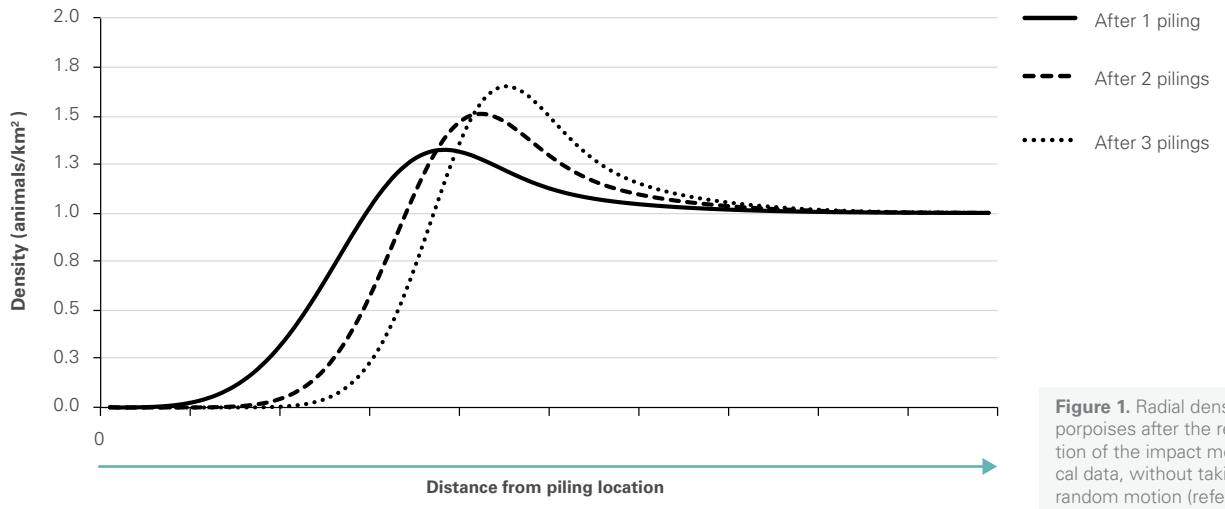


Figure 1. Radial density of harbour porpoises after the repeated application of the impact model to hypothetical data, without taking account of random motion (reference density = 1 animal/km).

To apply the model to real data, we made several assumptions. The density distribution on 29 March 2011 was used as a reference situation. We used a particle tracking approach to simulate the displacement of harbour porpoises. As an average and maximum swimming speed we used respectively 0.9 and 4.3 m/s (after Otani et al., 2001). For the random dispersal during periods or in areas without disturbance, we ignored water currents. We modelled one impact phase that lasted for two hours and was followed by a quiet period of two hours. In the model, we used 19 km as the distance from the noise source where a noise level (L_{p-p}) of 140 dB re 1µPa is reached (Norro et al., 2013). Tougaard et al. (2011) consider 140 dB re 1µPa as the discomfort noise level for harbour porpoises. We did not take account of a different reaction of individual harbour porpoises to noise: e.g. some animals may be tolerant to higher noise levels than others and some may remain in a noisy area because of good feeding opportunities, less competition with other porpoises or fewer predators.

Fish

Most of the energy emitted by the construction and operational noise of offshore wind farms is at frequencies below 1 kHz, which is well within the hearing range of fish (Figure 2). The actual effects of noise depend on the physical characteristics of the sound and the environment, and on the characteristics of the fish itself, such as size, life stage and species-specific hearing capabilities. All these factors make bio-acoustic research a complex matter.

The variables used to describe impulsive sounds generated through piling are the sound exposure level to a single strike (SEL_{ss}), the cumulative sound exposure level (SEL_{cum}) and the number of strikes (Slabbekoorn et al., 2010). The first results on the effects of low and mid frequency impulsive noise on fish showed that SEL_{ss} >176 dB re 1 µPa s and SEL_{cum} >207 dB re 1µPa s are needed to induce significant tissue damage in juvenile and adult roundfish (Halvorsen et al., 2012; Casper et al., 2012). Something more difficult to assess is the disturbance of the natural behaviour of fish or the masking of the communication and orientation signals due to exposure to lower noise levels (Hastings and Popper, 2005; Thomsen et al., 2006; Walhberg and Westerberg, 2005; Mueller-Blenkle et al., 2010). On average, SEL_{ss} of 163 dB re 1 µPa s at 750m and SEL_{cum} of 196 dB re 1µPa s at 750m were measured at the Bligh Bank during monopile-driving (Norro et al., 2013).

In a controlled environment, Bolle et al. (2012) exposed newly hatched sole *Solea solea* larvae to noise resembling piling noise at 100 m. No difference in immediate mortality or mortality up to 7 days after exposure was observed between the control and exposed groups. However, the few studies concerning fish larvae leave many questions unanswered (Booman et al., 1996; Govoni et al., 2006; Bolle et al., 2012). Defining the sound level thresholds causing mortality, injury, hatching failure, and delayed or abnormal development should have priority. Particular developmental stages which are more vulnerable than others should be identified. Overall, the ecological impact of these effects should be assessed and, if significant, taken into account by policy makers.

Given the scarcity of data on the impact of noise on fish and fish larvae, criteria for underwater noise or accompanying legislation in relation to fish are rare. The US Fisheries Hydro-acoustic Working Group formulated interim criteria for the maximum noise levels that fish could be exposed to without causing non-auditory tissue damage. The interim criterion for maximum SEL_{cum} for fish of 2 grams or more is set at 187 dB re 1µPa s, and for fish less than 2 grams at 183 dB re 1µPa s (Oestman et al., 2011).

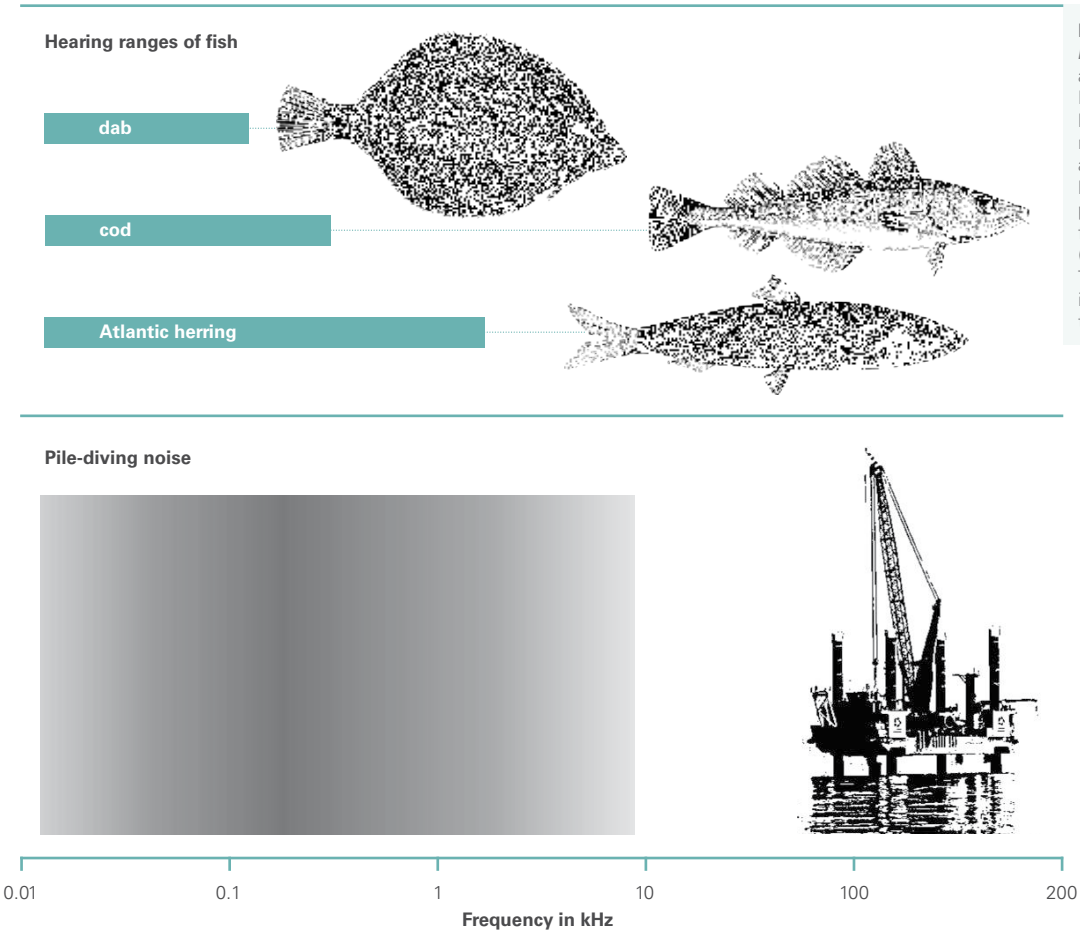


Figure 2. Hearing ranges of dab *Limanda limanda*, cod *Gadus morhua* and Atlantic herring *Clupea harengus*. Dab has no swim bladder and therefore has a narrow hearing range. The hearing range of cod is slightly wider as it has a swim bladder, and Atlantic herring has a wide hearing range due to a pair of elongated gas ducts extending from the swim bladder to the inner ear (based on Slabbekoorn et al., 2010). The grey scale represents the energy intensity level in the frequency range of the piling noise.

HARBOUR PORPOISES: SENSITIVE TO PILE DRIVING?

The estimated average densities of harbour porpoises over the surveyed area on 29 March (pre-piling phase) and 16 April (piling phase) were respectively 2.7 and 1.3 animals/km (Haelters et al., 2012a). Before piling, harbour porpoises were unevenly distributed throughout Belgian waters, with the highest densities in the western and northern part (Figure 3a). During the piling event, no harbour porpoises were observed in a zone around and north of the piling location (Figure 3b). The results of the application of the model to the reference situation indicate a similar zone void of harbour porpoises (Figure 3c). While the model is able to reproduce the porpoise displacement in a wide area around the piling zone, outside of this area there are larger differences between the situation observed and the one modelled.

Both the results of the aerial surveys and the application of the model to a reference situation during pile driving indicated an apparent distance of disturbance of harbour porpoises of around 20 km in Belgian waters. This is consistent with the results of similar research (Brandt et al., 2011; 2012; Tougaard et al., 2009; 2011), and it is likely that a similar disturbance occurred in the adjacent Dutch waters. The observed disturbance distance could be the consequence of repeated piling events: as observed by Thompson et al. (2010), the distance over which harbour porpoises are disturbed becomes larger with each piling event.

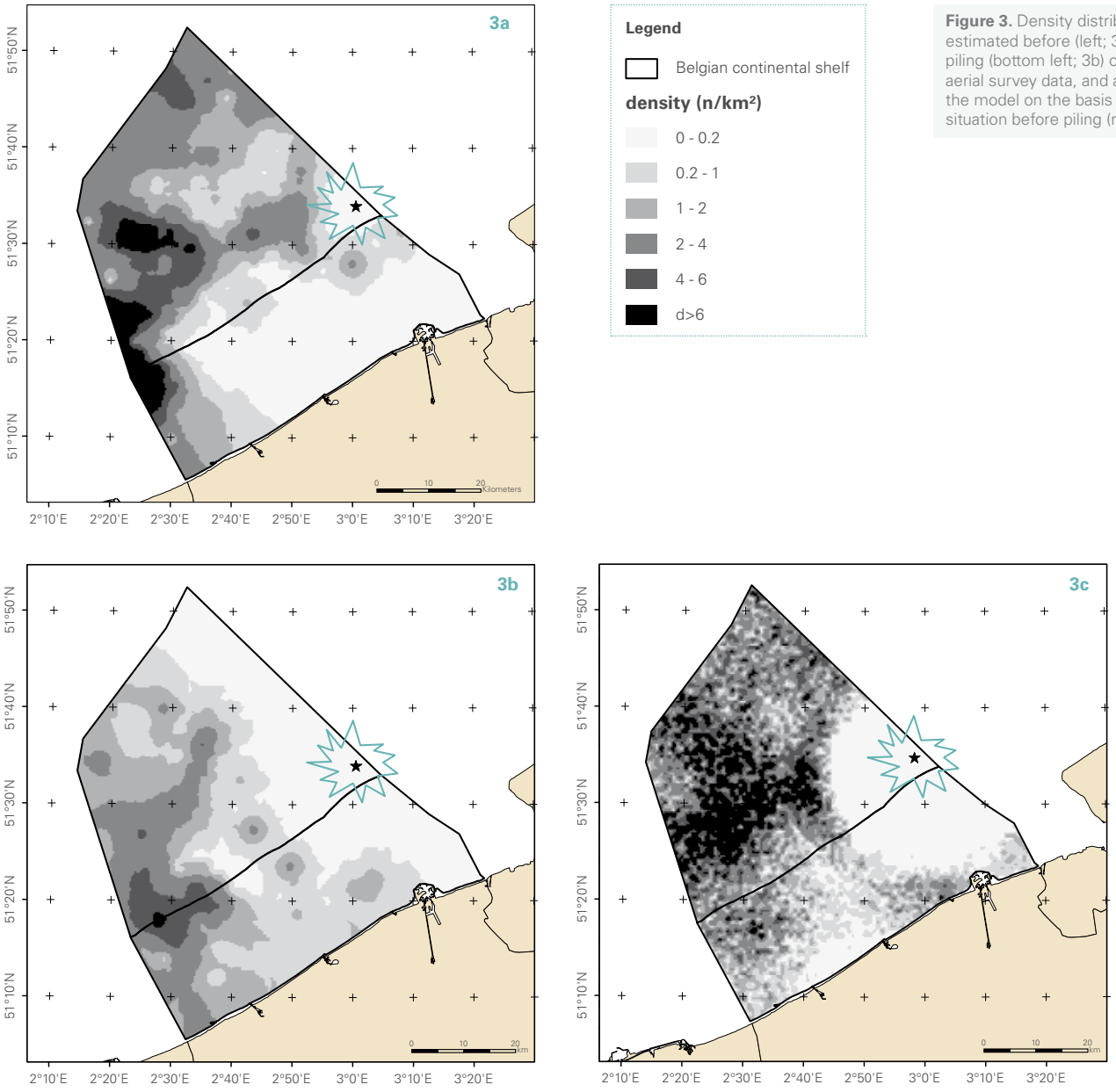


Figure 3. Density distribution maps: estimated before (left; 3a) and during piling (bottom left; 3b) on the basis of aerial survey data, and application of the model on the basis of the situation before piling (right; 3c).

The deviation between the model predictions and the density distribution estimates during piling outside the 20 km distance range indicate that there were likely other factors than piling that played a role in the spatial shifts of harbour porpoises between the reference survey and the survey performed during the piling. These could be food availability or seasonal movement. While harbour porpoises were very common in the survey area at the end of March 2011, their average density had halved by mid-April, probably due to a combination of disturbance by pile driving over a large part of this area and the onset of a general seasonal movement out of Belgian waters.

Harbour porpoises need to feed on a regular daily basis. Therefore prey availability is an important factor determining their distribution. Undoubtedly, pile driving disturbs harbour porpoises over a large area, with the population level consequences remaining unknown. Given the seasonally high densities of harbour porpoises in Belgian waters, thousands of these protected animals could be affected. The sub-lethal effects on individual harbour porpoises, with possible consequences at the population level (through effects on breeding frequency and longevity), and the cumulative effects due to the construction at several sites in the Southern North Sea, remain poorly understood.

Independent of construction operations, harbour porpoises have shown important shifts in their overall distribution pattern within the North Sea during the last decades (Hammond et al., 2013). Next to the effects of construction operations, it is therefore necessary to have a good understanding of such natural background shifts. They need to be taken account of, as the current management measures include a temporal exclusion of piling activities based on seasonal harbour porpoise densities.

FUTURE MONITORING
Harbour porpoises

We presented a model to simulate the disturbance effects observed during pile driving in 2011. However, any extrapolation of the model should be treated with care. The piles driven in 2011 for example, were relatively small (jacket foundations) and it can be expected that the piling of larger piles (monopiles) leads to increased disturbance distances due to increased noise levels. It is therefore advisable to test the model during different piling conditions with different noise levels, but also with different recurrences in the disturbance events. A model extension should further aim at comprising the effects of noise mitigation techniques and the effects of simultaneous piling at several sites within e.g. the southern North Sea.

Next to data from aerial surveys, data collected using an array of passive acoustic monitoring devices, moored following the gradient of noise level, could help to better understand the disturbance effects. It is evident that the investigations of the impact of piling on harbour porpoise distribution and abundance need to be combined with acoustic measurements.

For piling operations at the different wind parks, amongst others the floating crane SVANEN was used.

Fish

A multidisciplinary study combining biology, acoustics, physiology and biochemistry has been designed to examine the impact of the construction and operational noise of offshore wind farms on fish in Belgian waters. The focus will be on the impact of impulsive noise on fish eggs and larvae, since these 'passive drifters' cannot actively escape the exposure. The European sea bass *Dicentrarchus labrax* (Figure 4) has been chosen as a model species for round fish, especially for the physoclist fish which are lacking a connection between their gut and swim bladder. Sea bass is a commercially important species in the Southern North Sea, and eggs, larvae and fry are year-round available from the Ecloserie Marine de Gravelines (France), which makes it an excellent model species.
The first part of the study deals with the impact of pile driving noise. The worst case scenario will be analysed on board of a piling platform (Figure 5), while the impact at 500 m will be examined from a rigid-hulled inflatable boat (RHIB). In parallel, noise exposure experiments will be carried out under controlled conditions in the laboratory. The embryonic and larval development of fish exposed to different noise levels will be monitored and compared with control groups through different replicates.

In the second part of the study, the impact of long-term exposure to operational noise will be studied under controlled conditions in the laboratory. During their embryonic and larval development, fish will be exposed to different operational noise recordings. Possible chronic effects of operational noise on growth, weight, physiological stress, morphology, survival, and behaviour will be examined.

Figure 4. European sea bass *Dicentrarchus labrax* juvenile.

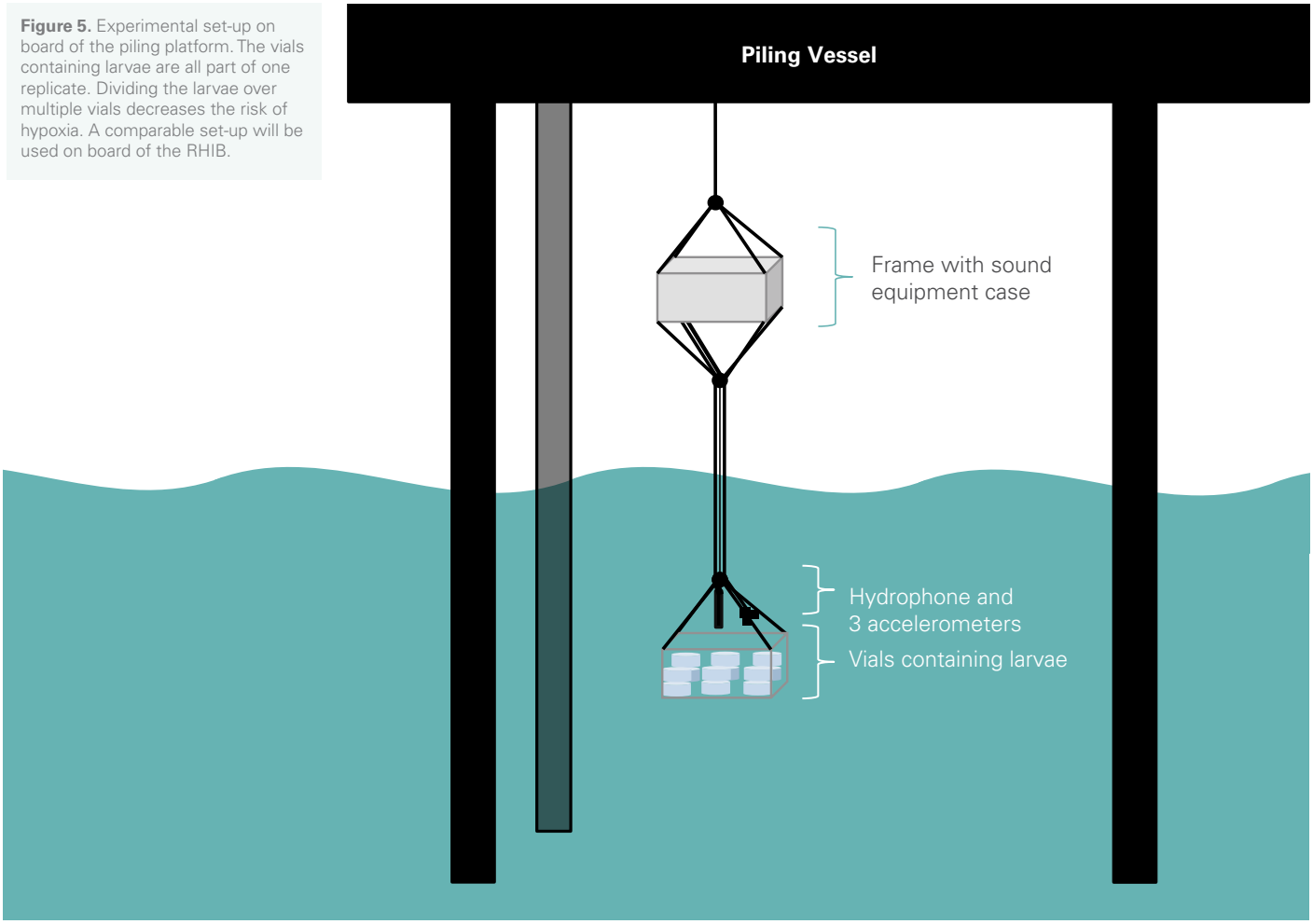


Figure 5. Experimental set-up on board of the piling platform. The vials containing larvae are all part of one replicate. Dividing the larvae over multiple vials decreases the risk of hypoxia. A comparable set-up will be used on board of the RHIB.

The harbour porpoise is the smallest and most common cetacean of the North Sea.

PART II

EVALUATING ANTICIPATED « POSITIVE » ENVIRONMENTAL EFFECTS

CHAPTER 8
CHAPTER 9
CHAPTER 10
CHAPTER 11
CHAPTER 12

CHAPTER 8

Fisheries activities change in the vicinity of offshore wind farms

Sofie Vandendriessche, Kris Hostens, Wouter Courtens and Eric Stienen

Changes in fisheries activity in the vicinity of the wind farms were described based on Vessel Monitoring System (VMS) data of commercial vessels and ship-based survey data of recreational fishing vessels for the period 2010-2011. The VMS density maps show increases in the number of registrations north of the Thorntonbank Phase 3, west of the Thorntonbank Phase 2, and south of the operational turbines at the Bligh Bank. A slight decrease was seen south of the Thorntonbank. Concentrations of recreational fisheries activity at the wind farms were reduced in 2010-2011: observations of anglers decreased and the link with wind farms seemed mostly gone.

INTRODUCTION

In the Belgian part of the North Sea (BPNS), the construction of offshore wind farms has given rise to the establishment of areas closed to commercial fishing activity. Following such closures, different effects on both the ecosystem and on patterns of fishing activity have been observed (e.g. Murawski et al, 2000; Grizzle et al, 2009) and can therefore also be expected to manifest themselves in the BPNS. These effects comprise (1) the establishment or recovery of spawning and nursing grounds, (2) the recovery of benthic communities and diversity within the area, and (3) edge effects[1] (also known as fringe effects) along the borders resulting from displacement of fisheries activities and changes in fishing intensity (Anonymous, 2004). The latter effect can be evaluated using VMS data of trawlers and ship-based survey observations of recreational fisheries originating from the Belgian part of the North Sea.

VMS data originate from a fishing vessel monitoring system (VMS), which is a program of fisheries surveillance in which satellite transmission equipment installed on fishing vessels provides information about the vessels' position and activity. This is different from traditional monitoring methods, such as surface and aerial patrols, on-board observers, logbooks or dockside interviews. VMS data constitute a cost-effective tool for the successful monitoring, control and surveillance of fisheries activities. In this respect, they are an excellent tool for monitoring compliance with closed-area regulations and for investigating changes in fisheries distribution and effort in the vicinity of such closed areas. Since 2005, all European Community vessels automatically transmit vessel identification, date, time, position, course and speed either hourly or every 2 hours.

Recreational and small-scale fisheries (vessels <15m) are not subject to VMS surveillance. Since these fishery types have been estimated to represent a meaningful proportion of total fishing effort in the BPNS (Depestele et al, 2008; Lescrauwaet et al, 2013), other ways of estimating fishing effort by these small vessels have to be considered. In this respect , visual surveys are complementary to VMS data, since they can provide an estimate of the spatial distribution and the presence of hot spots of small scale fishing activities (Maes et al, 2005; Goffin et al, 2007; Depestele et al, 2008).

The aim of the described analysis was to investigate changes in fisheries activity in the vicinity of the existing wind farms at the BPNS based on Vessel Monitoring System (VMS) data and ship-based survey data.

[1] **Edge effects** relate to the influence that a habitat edge can have in determining species composition and processes within a habitat. Edge effects can be considered as, or to influence, patterns in biological and physical parameters such as species richness, predation, food availability, disturbance and temperature (Murcia, 1995)

Fishing vessel trawling near a wind farm

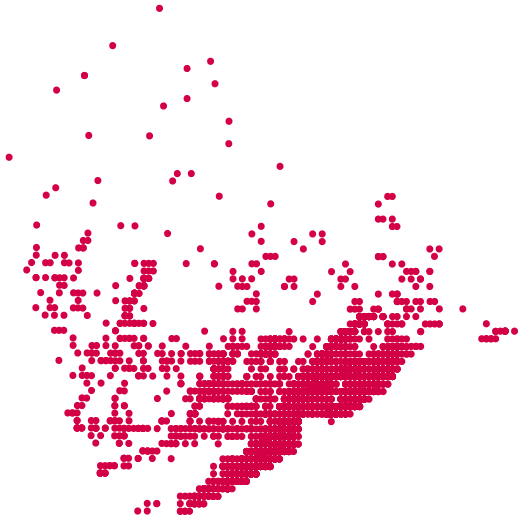
DATA SOURCES AND ANALYTICAL METHODS

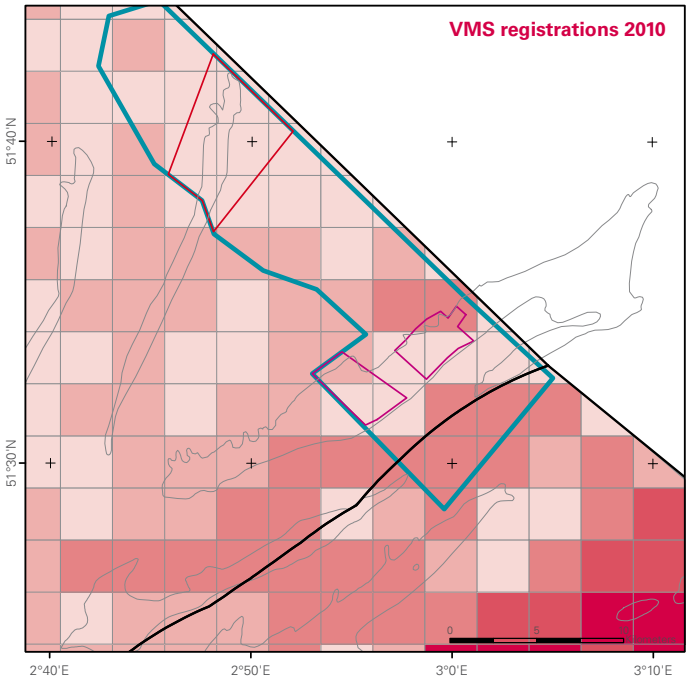
Aerial and ship-based surveys show that especially Belgian and Dutch, but also French, British and Danish fishing vessels operate within the Belgian Part of the North Sea (Depestele et al, 2008). These are mostly trawlers, but gill and trammel netters, long liners and bottom seiners were also observed in the area. Recently, Belgian Vessel Monitoring System (VMS) data (2006 – 2011) have been made available by the Belgian Sea Fisheries Service[2] for scientific research related to fisheries management. British data (2007 – 2011) were made available by the British Marine Management Organization, and Dutch data (2010 – 2011) were made available by the Dutch Ministry of Economic Affairs. Danish and French data were not available, but since they mainly reflect pelagic and trammel net fisheries (Depestele et al, 2008), their absence will not have a significant impact on the results.

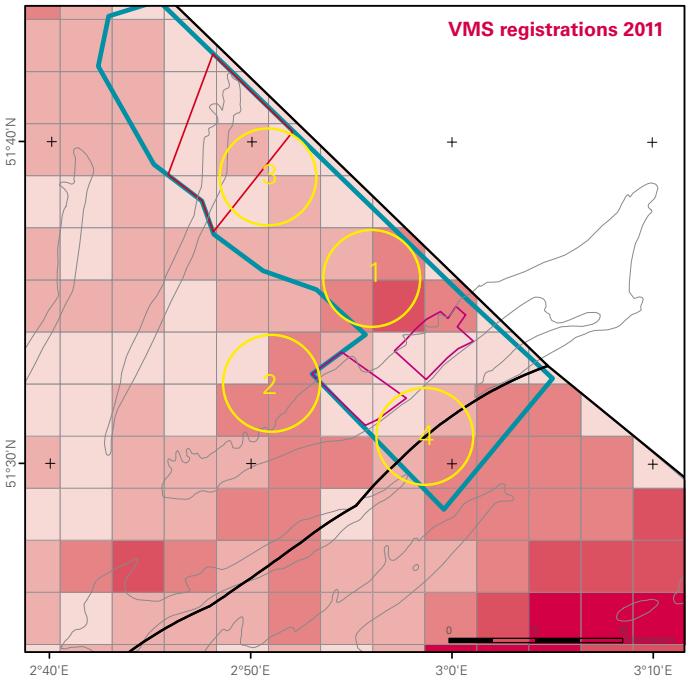
Since metadata about fishing gear and engine power were not available for the majority of the data, speed filters could not easily be applied and no distinction could be made between fishing, steaming or other activities. Consequently, the analysis is limited to "fishing vessel presence" rather than representing "fishing intensity". Only the results on the years 2010-2011 are presented.

All data were plotted on BPNS maps representing the number of VMS registrations per 3 km grid cell, since this proved to be an adequate resolution for VMS data with a 2 hour interval (Mills et al, 2007). The data were processed and visualized using Microsoft Access and ArcView 10.0 (ESRI Inc, 2010). The data on small-scale and recreational activities originate from intensive ship-based seabird surveys performed by the Research institute for Nature and Forest (INBO). During these surveys, observation records of vessels are standardized,. For more details on the methodology see chapter 5. All data were again plotted on BPNS maps per 3 km grid cell.

[2] All primary data on vessels sailing under the Belgian flag were supplied by the Department of Agriculture and Fisheries – Sea Fisheries Service / Departement Landbouw en Visserij – Dienst Zeevisserij







Legend

- Belgian continental shelf
- Area reserved for electricity production
- C-Power Wind farm
- Belwind Wind farm

Number of VMS registrations per grid cell per year

- 1 - 50
- 51 - 100
- 101 - 200
- 201 - 400
- 401 - 800