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Displacement of seabirds by an offshore wind farm in the North Sea

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ABSTRACT: The number of offshore wind farms in Europe and elsewhere has substantially increased in recent years. This rapid development has raised concerns about potential impacts on marine wildlife, particularly on seabirds, as these can be negatively affected through collision and displacement. While collision risk has been the focus of a number of studies, information about displacement of seabirds is scarce. Here we present data from an extensive survey program that aimed at determining the effects on seabirds of the first German offshore wind farm, 'alpha ventus'. Data were collected by line transect surveys during the first 3 yr of operation. We found significant displacement of 5 species with 75–92% lower abundance inside compared to outside the wind farm. For 3 species, the response distance to the outermost turbines was estimated to exceed 1 km. Two gull species were attracted to the wind farm site. Our results and a review of the available literature revealed good agreement with respect to the sign of the response (avoidance vs. attraction) but considerable differences in the strength of the response and the spatial extent of the disturbance outside the footprint of wind farms. While it seems unlikely that small-scale displacement by single wind farms would have an impact at the population level, the extent of the proposed development of offshore wind energy warrants further research into cumulative effects and their biological significance for seabird populations.

KEY WORDS: Common guillemot · Displacement · Habitat loss · Little gull · Offshore wind farms · Red-throated diver · Response distance · Seabirds

INTRODUCTION

Concerns about global climate change have led to efforts to reduce CO_2 emissions in many countries worldwide. This has triggered the rapid development of offshore wind farms in recent years, particularly in the North and Baltic Seas in Europe, where >30 offshore wind farms (OWF) are fully commissioned, and a large number of projects are planned or under construction. Such large-scale development of offshore wind energy has raised concerns about potential impacts on marine wildlife, particularly seabirds. Several potential effects on birds have been identified (Drewitt & Langston 2006), of which collision risk and displacement due to disturbance may have the strongest impact. While collision risk has been the focus of a number of studies (e.g. Desholm & Kahlert 2005, Larsen & Guillemette 2007), much less information, particularly from peer-reviewed literature, is available on the potential displacement of birds at sea and resultant habitat loss (Vanermen et al. 2015). In addition, the available studies, usually conducted as part of environmental impact assessments, have often reported inconclusive results (e.g. Gill et al. 2008, Walls et al. 2013). Hence, there is still considerable uncertainty regarding the impact of offshore wind farms on seabird abundance and spatial distribution.

Changes in abundance of birds at wind farms may be caused by noise and visual disturbance (moving rotor blades) or merely by the presence of these vertical structures. The disturbance may be intensified by maintenance activities such as increased vessel movement and human activity at the turbines. Difficulties in determining displacement effects are likely

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related to the large spatiotemporal variability of seabird abundance at sea. This variability has been attributed to the dynamic environment of seabirds, especially the ephemeral nature and patchy distribution of prey (Weimerskirch 2007). Consequently, distribution models of seabirds at sea often have little explanatory power, even when information about important environmental factors including prey resources is available (Fauchald 2009, Hovinen et al. 2014). Such stochastic variability substantially hampers attempts to detect directional changes in seabird abundance, particularly at small spatial scales (Maclean et al. 2013). Identification of small-scale changes in abundance, however, is essential in determining the effects of offshore wind farms on seabirds.

Studies on the displacement of seabirds at wind farms are often based on a comparison of distribution patterns before and after the construction of a wind farm (e.g. Walls et al. 2013, Petersen et al. 2014). The conclusions drawn from these studies usually are weakened by the challenge of distinguishing among changes due to large-scale temporal trends, stochastic variability and the actual effects of the wind farm (e.g. Guillemette et al. 1998, Lindeboom et al. 2011). Additional challenges include differences in survey methods employed before and after wind farm construction (Webb et al. 2015). Moreover, relatively few studies have attempted to determine the avoidance distance from wind turbines at sea (Petersen et al. 2014). This is unfortunate since knowledge of the response/avoidance distance to OWFs is important in gauging the total area potentially impacted. For example, given a medium-sized OWF of about 30 km^2, the potentially affected area would be approx. 6 times larger than the actual footprint of the wind farm if an avoidance distance of 4 km is assumed.

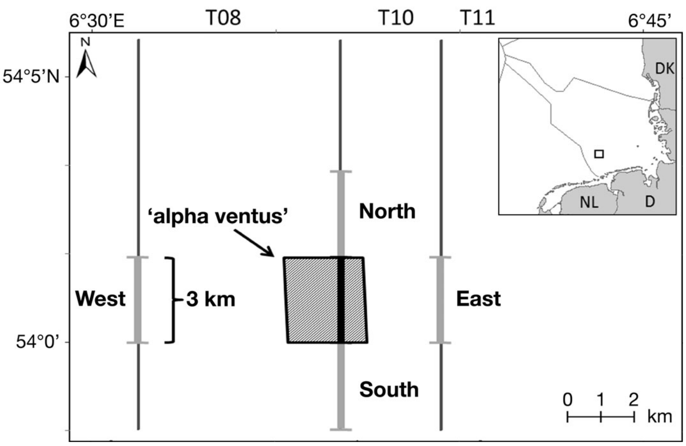

Fig. 1. Location of the wind farm 'alpha ventus' and the transects of the ship-based surveys. The 3 km segments of the transects used for data analyses are highlighted

'Alpha ventus', located in the southern North Sea, was the first German OWF to be fully commissioned. It was designed as a test site to gain experience in the construction and operation of offshore wind turbines and to determine potential effects on the marine environment. Here we use data from an extensive seabird survey program to determine the displacement of seabirds during the first 3 yr of operation of the wind farm and to estimate the response distance to wind turbines at sea. We used a novel approach to identify small-scale differences in the spatial distribution of seabirds resulting from the presence of an OWF without the inclusion of pre-construction data. We created a 'natural experiment' comparing the total number of observations of a given species across all surveys within the wind farm to adjacent areas of similar size outside the wind farm. This approach helped to compensate for the low sighting rates often reported in single surveys, to minimize total variance and to circumvent problems arising from the generally high spatiotemporal variation of seabird distribution at sea (Maclean et al. 2013, Vanermen et al. 2015). A subsequent analysis of the spatial gradient of the abundance of birds in relation to the OWF allowed us to estimate displacement distances for a number of seabird species.

MATERIALS AND METHODS

The OWF 'alpha ventus' is located in the western German Bight about 45 km north of the Frisian island of Borkum (Fig. 1) at a water depth of approximately 30 m. The wind farm comprises 12 turbines, with a capacity of 5 MW each and a maximal height above the waterline of between 148 and 155 m. It covers an area of about 4 km^2, with a distance of approximately 800 m between turbines. The wind farm was constructed between April and December 2009; the operational phase started in 2010. Data on seabird distribution and abundance were collected during ship-based, line-transect surveys between January 2010 and March 2013. The data used in this study were collected within a larger monitoring program as part of an environmental impact assessment issued by the German Federal Maritime and Hydrographic Agency.

Ship-based surveys

Ship-based surveys were conducted along 11 fixed line-transects of 13.6 km length, aligned in a north–south direction and equally spaced at 3 km intervals across the study area. A total of 77 complete surveys were carried out over the study period. Transects were sampled at least once per month, with an increased sampling frequency of up to 3 times per month in spring (March–May) and fall (September–November). Sampling took place at wind speeds <5 Beaufort (Bft) and sea states <Level 5.

The surveys followed the standardized sampling protocol as outlined in Tasker et al. (1984) and Camphuysen et al. (2004). In short, all birds occurring in an area of 300 m perpendicular to the keel line of the vessel and 300 m in front of the bow of the ship were recorded at a constant cruising speed of approximately 10 knots. Flying birds were recorded using the 'snapshot method' (Tasker et al. 1984). Birds were recorded on both sides of the vessel, usually by 2 observers on each side. In order to detect species known to respond to approaching vessels at greater distances, 1 observer regularly searched the area up to 2.5 km in front of the ship using binoculars. Observations were done from the flying bridge of the vessel at a height of about 7 m above the water line; an 'observation box' minimized the effects of inclement weather. The location of the ship was continuously recorded by GPS, and weather conditions were recorded every hour.

Data analysis

Out of the 115 bird species identified during the study period, we selected the 10 most common seabird species or taxa for statistical analysis (Table 1). Not all birds belonging to these taxa could be identified to species level. This was true for alcids, divers and terns, which were therefore not analyzed on the species level. Data from observations with identification on the species level indicated that alcids were dominated by common guillemots (*Uria aalge*; 78.7%). Divers were mainly red-throated divers (*Gavia stellata*; 92.9%). Within the group of terns, sandwich terns (*Thalasseus sandvicensis*) were slightly more common (54.8%) than common/arctic terns (*Sterna hirundo* and *S. paradisaea*; 45.1%). The proportion of individuals identified to species level was 50, 73 and 86% for divers, terns and alcids, respectively.

The footprint of the wind farm was defined as the perimeter of the outer turbines including a buffer of 300 m. This was done to reflect the spatial resolution of the bird observation data.To determine the response of these species to the wind farm, we selected the data of five 3 km transect segments: (1) for Transect 10, crossing the area of the wind farm on a south–north axis, we selected the 3 km segment that covered the length of the wind farm, as well as 2 segments of similar length directly north and south of the wind farm; (2) for Transects 8 and 11, we selected a 3 km segment directly west and east of 'alpha ventus', respectively (Fig. 1). The transect segments were selected to create a study design with no systematic differences in environmental variables known to affect seabird distribution at sea (e.g. bathymetry, sediment structure, distance to shore, or geographic position (potential east–west or north–south gradients in seabird distribution in the German Bight) between segments inside and outside the wind farm, except for the presence of the wind farm itself. Mean water depth varied only marginally between segments inside (28.6 m) and outside (range: 27.4–30.5 m) the wind farm. The sediment structure, dominated by

Table 1. Statistics of generalized linear models comparing the total number of individuals (divers, gannet, alcids) and clusters (all other species) within the wind farm 'alpha ventus' to adjacent transect segments. Data were collected during 77 ship-based surveys. Positive *z*-values indicate higher abundance outside the wind farm; negative *z*-values indicate higher abundance inside the wind farm. Bold print: $p < 0.05$

	N	Comparison wind farm vs. adjacent transect segments							
		South		North		West		East	
		z	p	*z*	p	*z*	p	*z*	p
Divers	41	2.47	**0.01**	1.66	0.10	1.82	0.07	2.55	**0.01**
Gannets (*Morus bassanus*)	60	0.70	0.48	1.83	0.07	2.66	**0.008**	3.54	**<0.001**
Little gulls (*Hydrocoloeus minutus*)	99	2.35	**0.02**	2.68	**0.007**	4.40	**<0.001**	3.25	**0.001**
Common gulls (*Larus canus*)	138	–0.13	0.90	–0.93	0.36	0.00	1.00	–1.21	0.23
Lesser black-backed gulls (*Larus fuscus*)	417	–4.27	**<0.001**	–3.81	**<0.001**	–3.74	**<0.001**	–4.04	**<0.001**
Herring gulls (*Larus argentatus*)	53	–0.58	0.57	1.50	0.13	2.12	**0.03**	0.50	0.62
Great black-backed gulls (*Larus marinus*)	93	–2.47	**0.01**	–1.23	0.22	–2.31	**0.02**	–2.95	**0.003**
Kittiwakes (*Rissa tridactyla*)	249	0.46	0.65	0.68	0.50	3.69	**<0.001**	1.98	**0.048**
Terns	87	3.29	**0.001**	3.19	**0.001**	2.88	**0.004**	1.65	0.10
Alcids	546	5.50	**<0.001**	7.36	**<0.001**	9.51	**<0.001**	4.65	**<0.001**

fine sand, was uniform across the study area (Schuchardt et al. 2008). As the nearest shore is south of 'alpha ventus' (Fig. 1), the mean distance to shore was similar for transect segments within and outside the wind farm. The same was true of differences along the east–west gradient.

All observations of the respective species in these segments were summed up over all surveys. As we were interested in relative differences, we used the raw counts in statistical analyses and did not correct for the decreasing detection probability with increasing distance from the transect line. In our analysis, such a correction, which is essential for the calculation of absolute bird densities, would have been necessary if the detection function had varied systematically between transect segments inside and outside the wind farm. Sample size of birds inside the wind farm was too low to test for differences empirically. However, as observation conditions, indicated by sea state, were similar (mean ± SE; inside: 2.6 ± 0.1; outside: 2.6 ± 0.05), and the difference in mean cluster size (flock size) was <1 individual cluster^{-1} between inside and outside for all species, it seems unlikely that differences in detection probability caused a bias in our data.

To test for differences in abundance within and outside the wind farm, we compared the total number of birds summed up over all surveys within the 3 km segment covering the wind farm to the counts for the transect segments directly south and north of the wind farm on Transect 10 and the segments east and west of the wind farm on Transects 8 and 11, using a generalized linear model (GLM) with a Poisson error distribution and 'segment identity' as the only explanatory variable.

In an additional step, we estimated the disturbance distance to the wind turbines, i.e. the maximum distance from the outer turbines of the wind farm to which bird abundance was affected. Only species for which the first analysis indicated displacement by the wind farm (except for gannets [*Morus bassanus*] for which sample size was too low) were included in this analysis. For these species, observations from Transect 10 were grouped into 300 m segments starting from the center of the wind farm to 3000 m (6000 m for alcids) outside the outer turbines of the wind farm. Data from south and north of the wind farm center were pooled. As we expected a non-linear relationship but had no *a priori* expectation of the shape of the function between bird counts and the distance to the wind turbines, we fitted generalized additive models (GAM) with a Poisson error distribution to the data.

For species that usually occurred as single individuals or in small groups, the total number of individuals was used as the response variable in all models (alcids, divers, gannet). As all other study species often occur in highly variable flock sizes, we used the number of observations (clusters) as the response variable. Thus we avoided a potentially large impact of single clusters on model outcomes for these species.

We used R 3.1.0 and the package mgcv (R Development Core Team 2014) in all statistical analyses.

RESULTS

There was evidence of displacement of divers, gannets, little gulls, terns and alcids from the wind farm (Fig. 2, Table 1). The abundance was, on average, 90% (divers), 79% (gannet), 92% (little gull), 76% (terns) and 75% (alcids) lower inside compared to outside the wind farm.

The GAMs suggested that bird abundance increased with increasing distance from the wind farm until a species-specific asymptote or threshold (undisturbed distance) was reached (Fig. 3; exception: terns). Diver abundance reached an asymptote of about 2.5 birds per 300 m at a distance of 1.5–2 km from the outermost wind turbines (Fig. 3B). However, due to low sample size, model uncertainty was large and the smooth term only marginally significant (GAM; $\chi^2_{3.5,\,4.3} = 9.5$, $p = 0.06$, adjusted $R^2 = 0.37$). The effect on little gulls extended up to a distance of approximately 1.5 km, where the number of clusters per 300 m line transect reached an asymptotic value of about 3 (Fig. 3C; GAM: $\chi^2_{2.4,\,3.0} = 9.7$, $p = 0.02$, adjusted $R^2 = 0.50$). Alcid numbers reached an asymptotic level of about 17 ind. per 300 m transect segment at a distance of approximately 2.5 km compared to 2 observations per 300 m within the wind farm (Fig. 3A; GAM: $\chi^2_{3.6,\,4.5} = 59.4$, $p < 0.001$, adjusted $R^2 = 0.71$). The GAM of the response distance of terns showed an increase from close to zero clusters per 300 m transect segment within 'alpha ventus' to about 7 clusters per 300 m at a distance of approximately 1.3 km (Fig. 3D), yet cluster numbers decreased again at larger distances from the wind farm (GAM; $\chi^2_{3.0,\,3.8} = 19.0$, $p < 0.001$, adjusted $R^2 = 0.63$).

No clear pattern was evident for kittiwakes (*Rissa tridactyla*). While the number of clusters of kittiwakes within the wind farm was, on average, 32% lower than in adjacent transect segments, statistically significant differences were only found in comparison to

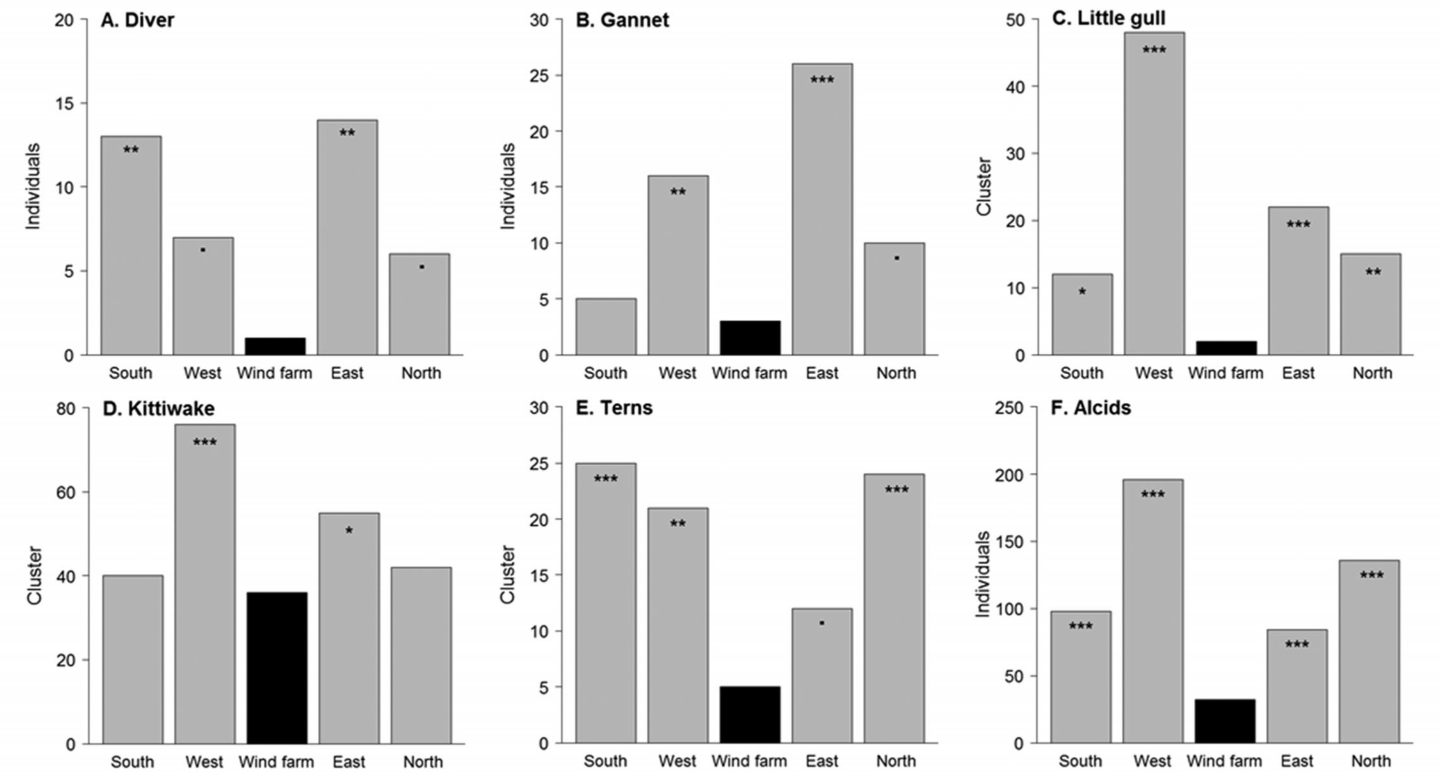

Fig. 2. Abundance of 6 different seabird taxa within the footprint of the offshore wind farm 'alpha ventus' (black bars) and in areas of similar size south, west, east and north of the wind farm (grey bars). Data were collected during 77 ship-based surveys between 2010 and 2013. Each bar represents data of transect segments of 3 km length. Panels A, B & F show the cumulative number of individuals of divers, gannets and alcids, respectively; Panels C, D & E show the cumulative number of clusters of little gulls (*Hydrocoloeus minutus*), kittiwakes (*Rissa tridactyla*) and terns. See 'Materials and methods' for details. Significance: *$p < 0.05$; **$p < 0.01$; ***$p < 0.001$

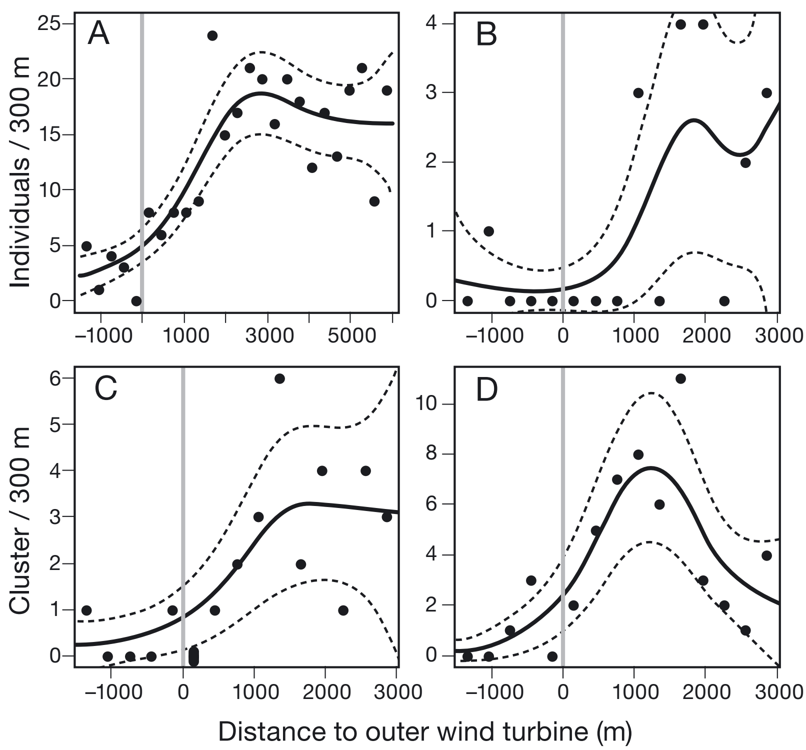

Fig. 3. Generalized additive models (GAM) of the (A,B) number of individuals and (C,D) clusters of 4 seabird taxa in relation to the distance from the outermost wind turbines of the wind farm 'alpha ventus'. Grey line indicates the location of the outermost wind turbine, dashed lines, the 95% confidence interval of the GAM. Data were collected during 77 ship-based surveys between 2010 and 2013. Observations were summed over 300 m transect segments: (A) alcids; (B) divers; (C) little gull and (D) terns

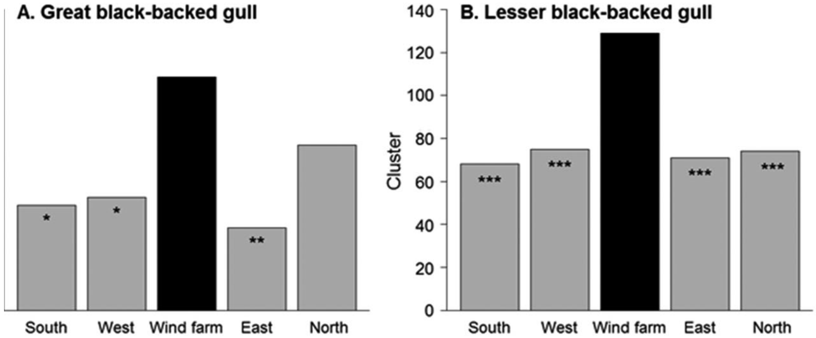

Fig. 4. Number of clusters of (A) great (*Larus marinus*) and (B) lesser black-backed gull (*Larus fuscus*) within the footprint of the offshore wind farm 'alpha ventus' (dark bars) and in areas of similar size south, west, east and north of the wind farm (light bars). Data were collected during 77 ship-based surveys between 2010 and 2013. Each bar represents data of transect segments of 3 km length. See 'Materials and methods' for details. Significance: $^{*}p < 0.05$; $^{**}p < 0.01$; $^{***}p < 0.001$

transect segments east and west of the wind farm (Fig. 2, Table 1). The abundance of common gull (*Larus canus*) and herring gull (*Larus argentatus*) clusters were not affected by the wind farm (Table 1).

For 2 species, lesser and great black-backed gull (*Larus fuscus* and *Larus marinus*), a significantly higher number of clusters was found within the wind farm compared to in the neighboring areas (Fig. 4, Table 1). On average, the number of clusters within the wind farm was 79 and 100% higher than in adjacent transect segments for lesser and great black-backed gulls, respectively.

DISCUSSION

Our data strongly suggest displacement of several seabird species at the OWF 'alpha ventus' in the North Sea. We found significantly reduced numbers of 5 species of seabirds within the footprint of the wind farm. Two species were attracted to the wind farm. None of the species showed complete displacement; the proportion of birds displaced varied between 75 and 90%. The disturbance effect extended to a distance between approximately 1.5 and 2.5 km beyond the outermost turbines of the wind farm.

The study site 'alpha ventus' consists of only 12 turbines, and, as a consequence, only 1 survey transect traversed the wind farm area at a length of 3 km, resulting in low sample sizes despite the large number of surveys (77). Nevertheless, our approach yielded sufficient data to analyze effects on 10 species (taxa).

Studies to determine displacement by offshore wind farms are often based on before–after (pre-construction vs. post-construction) comparisons or a before–after–control–impact (BACI) design (Underwood 1992). BACI studies have been criticized mainly based on the fact that it is impossible to find a control site that does not differ in any (environmental) variable other than the impact. Hence, differences between control and impact sites may be caused by the impact or any other variable differing between sites or simply by chance (Hurlbert 1984, Underwood 1992). Due to the large spatiotemporal fluctuations in the abundance of seabirds at sea, even detailed before–after studies with large sampling effort may remain inconclusive (Petersen et al. 2014, but see Vanermen et al. 2015). Incorporation of information on food availability may help interpret results of BACI studies (Guillemette et al. 1998, 1999). However, information on food availability is difficult to obtain, and the explanatory power of models on seabird distribution is usually small even if food availability and other physical covariates are taken into account (Ainley et al. 2005, Fauchald 2009).

Our study design was based on differences in seabird abundance within and outside and thus indepepent of temporal fluctuations. In addition, by comparing the wind farm area to several 'control' sites surrounding the impact area, systematic differences along potentially important spatial gradients such as distance to shore were avoided. Due to the close proximity and small spatial extent of impact and control sites, other abiotic factors such as bathymetry, sediment structure, or water characteristics did not vary systematically between sites (see 'Materials and methods'). Hence, we are confident that systematic differences between the wind farm and all 4 control sites are causally related to disturbance by the wind farm and cannot be attributed to differences in other environmental factors. However, it needs to be noted that our estimates of displacement distance are conservative, because our 'control' sites north and south of the wind farm bordered directly on the footprint of 'alpha ventus' which may have reduced seabird numbers in those areas (see Fig. 3). Also, observations were only done in calm to moderate weather conditions (wind force max.: 5 Bft). Whether seabirds respond to offshore wind farms in a similar way in stronger winds remains to be tested.

Despite the inconsistencies between studies with respect to the species-specific effect of OWFs on sea-

Table 2. Response of seabirds to offshore wind farms and estimated response distance (i.e. distance from the wind farm to which birds are affected) as reported in the peer-reviewed and 'grey' literature in comparison to the results of this study; '–' and '+' signs indicate statistically significant negative and positive effects on abundance, respectively; '0' indicates no detected effect. Symbols in parentheses indicate no statistical effect, but response suggested by the authors. The list is not exhaustive; purely descriptive reports have not been included. Empty cells: no information available

	Response	Estimated response distance	Offshore wind farm	Reference
Divers	–	1.5 km	Alpha ventus	Present study
	–	2–6 km	Lincs	Webb et al. (2015)
	–	1 km[a]	Kentish Flats	Percival (2014)
	–	5–6 km[b]	Horns Rev II	Petersen et al. (2014)
	– / –		Egmond aan Zee / Princess Amalia	Leopold et al. (2011, 2013)
	–	0 km	Thanet	Percival (2013)
	(–)		Robin Rigg	Walls et al. (2013)
	–/(–)	2 km	Horns Rev I / Nysted	Petersen et al. (2006), Petersen & Fox (2007)
Gannets	(–)		Alpha ventus	Present study
(*Morus bassanus*)	–		Lincs	Webb et al. (2015)
	(–) / –	3 km	Thorntonbank / Bligh Bank	Vanermen et al. (2013, 2015)
	– / –		Egmond aan Zee / Princess Amalia	Leopold et al. (2011, 2013)
	0		Thanet	Percival (2013)
	(–)		Robin Rigg	Walls et al. (2013)
	0		Kentish Flats	Gill et al. (2008)
	(–)		Horns Rev I	Petersen et al. (2006)
Little gulls	–	1.5 km	Alpha ventus	Present study
(*Hydrocoloeus minutus*)	0		Lincs	Webb et al. (2015)
	(+) / (–)		Thorntonbank / Bligh Bank	Vanermen et al. (2013, 2015)
	– / –		Egmond aan Zee / Princess Amalia	Leopold et al. (2011, 2013)
	–		Horns Rev I	Petersen & Fox (2007)
	0		Horns Rev I	Petersen et al. (2006)
Common gulls	0		Alpha ventus	Present study
(*Larus canus*)	(–) / 0		Thorntonbank / Bligh Bank	Vanermen et al. (2013, 2015)
	0 / 0		Egmond aan Zee / Princess Amalia	Leopold et al. (2011, 2013)
	0		Thanet	Percival (2013)
Lesser black-backed gulls	+		Alpha ventus	Present study
(*Larus fuscus*)	0		Lincs	Webb et al. (2015)
	0 / +		Thorntonbank / Bligh Bank	Vanermen et al. (2013, 2015)
	– / 0		Egmond aan Zee / Princess Amalia	Leopold et al. (2013)
	0		Thanet	Percival (2013)
	0		Kentish Flats	Gill et al. (2008)
Herring gulls	0		Alpha ventus	Present study
(*Larus argentatus*)	0 / +		Thorntonbank / Bligh Bank	Vanermen et al. (2013, 2015)
	0 / 0		Egmond aan Zee / Princess Amalia	Leopold et al. (2013)
	0		Thanet	Percival (2013)
	(+) / 0		Horns Rev I / Nysted	Petersen et al. (2006)
Great black-backed gulls	+		Alpha ventus	Present study
(*Larus marinus*)	+ / 0		Thorntonbank / Bligh Bank	Vanermen et al. (2013, 2015)
	0 / 0		Egmond aan Zee / Princess Amalia	Leopold et al. (2013)
	0		Thanet	Percival (2013)
	0		Kentish Flats	Gill et al. (2008)
Kittiwakes	(–)		Alpha ventus	Present study
(*Rissa tridactyla*)	– / 0		Egmond aan Zee / Princess Amalia	Leopold et al. (2013)
	0 / 0		Thorntonbank / Bligh Bank	Vanermen et al. (2013, 2015)
	0		Thanet	Percival (2013)
	0		Robin Rigg	Walls et al. (2013)

[a]No statistical effect outside wind farm, 1 km suggested by author; [b]Statistical effect up to 13 km — authors suggest effect up to 5–6 km;

Table continued on next page

Table 2 (continued)

	Response	Estimated response distance	Offshore wind farm	Reference
Terns	–	1.5 km	Alpha ventus	Present study
	0		Lincs	Webb et al. (2015)
	–[c] / 0		Egmond aan Zee / Princess Amalia	Leopold et al. (2013)
	+[d] / 0		Thorntonbank / Bligh Bank	Vanermen et al. (2011, 2013)
	0		Kentish Flats	Gill et al. (2008)
	(–)		Horns Rev I	Petersen et al. (2006)
Alcids	–	2.5 km	Alpha ventus	Present study
	–	4 km	Lincs	Webb et al. (2015)
	– / –[e]	3 km	Bligh Bank	Vanermen et al. (2015)
	– / –[e]		Egmond aan Zee / Princess Amalia	Leopold et al. (2011, 2013)
	(–)		Thanet	Percival (2013)
	(–)		Robin Rigg	Walls et al. (2013)
	0		Kentish Flats	Gill et al. (2008)
	0		Thorntonbank	Vanermen et al. (2013)
	–	2 km	Horns Rev I	Petersen et al. (2006), Petersen & Fox (2007)

[c]Effect found for common/arctic terns; [d]Effect found for common and sandwich terns; [e]Significant negative effect in common guillemots and razorbills

birds, a review of the available literature together with the results of this study reveals a clear pattern for most species (Table 2). For example, there is strong evidence across studies that alcids, gannets and, particularly, divers are displaced by OWFs (Table 2). However, estimated response distances vary especially for divers, where studies reported distances varying from zero (no displacement) to 13 km (Percival 2013, Petersen et al. 2014). It seems likely that discrepancies of this magnitude are, at least partly, due to differences in study designs and data analyses, as well as the confounding effect of spatiotemporal variation in seabird populations at sea. For example, Petersen et al. (2014) found lower abundance of divers post- versus pre-construction at 'Horns Rev II' and a displacement distance of 13 km. The authors, however, concluded that a response distance of this magnitude was unrealistic and likely related to factors other than the wind farm (Petersen et al. 2014).

In agreement with our results, earlier studies mostly reported no displacement of *Larus*-gulls (Table 2; but see Leopold et al. 2013), while 3 studies suggested attraction (Petersen et al. 2006, Vanermen et al. 2013, 2015). Most *Larus*-gulls are known to be attracted by human activities at sea, mainly fishing vessels (Garthe & Hüppop 1994), and are usually assumed to be insensitive to anthropogenic disturbance (Garthe & Hüppop 2004, Furness et al. 2013). Gulls may also benefit from foraging opportunities on hard substratum benthic species and fish species known to increase substantially within OWFs (Lindeboom et al. 2011, Reubens et al. 2013, Stenberg et al. 2015).

There is considerable uncertainty on the response of terns to OWFs (Table 2). A number of studies did not report displacement of these species (Gill et al. 2008, Leopold et al. 2011, Lindeboom et al. 2011), yet Petersen et al. (2006) reported results suggestive of displacement at 'Horns Rev I'; Leopold et al. (2013) found tern displacement at the Dutch wind farm 'Egmond aan Zee'. In contrast, results for 'Thorntonbank' suggest an attraction effect on both common and sandwich terns (Vanermen et al. 2013). Our data provide evidence of displacement at 'alpha ventus', with the number of tern clusters reduced by about 75% within the wind farm. However, our attempt to determine the response distance of terns remained inconclusive, as tern numbers showed a maximum at 1–1.5 km from the wind farm, yet decreased again at larger distances.

There are several factors that may cause differences in the sign and magnitude of the response of seabirds between different wind farms. These may be related to the specific location, size and configuration of the wind farm, or the size of the turbines. For example, the density of wind turbines has been suggested to cause differences in displacement at Dutch wind farms (Leopold et al. 2011). In addition, habituation may mitigate displacement at wind farms in operation for longer time periods. Clearly, more research is needed to determine the influence of these factors on the displacement of seabirds.

Our results indicate that the impact on seabirds of operating wind farms is not necessarily comparable to the effects of other human disturbances at sea. We found good correspondence between vulnerability to displacement by OWF and sensitivity indices based on vessel and helicopter traffic (Garthe & Hüppop 2004, Furness et al. 2013) in species considered to be susceptible to anthropogenic disturbance (e.g. divers, alcids). Yet our data suggest that species previously classified as relatively insensitive to human disturbance at sea may be displaced by OWFs (e.g. gannet, little gull, terns).

Furthermore, there is virtually no information available on the potential consequences of displacement for an individual bird and the potential propagation of effects on a population level (Topping & Petersen 2011). The biological significance of displacement may depend on a number of factors, such as the availability of suitable habitat outside the wind farm or the degree of inter- and intra-specific competition in these areas. Also, changes in the behavior of birds, such as foraging activity within an OWF, remain unstudied. It is unknown whether behavioral changes or habitat loss due to displacement may ultimately affect the vital rates of individuals and hence population size. Given the size of most offshore wind farms it seems unlikely that displacement at single wind farms may cause adverse effects on seabirds beyond the individual level. However, the scale of planned offshore wind developments raises questions about multiplicative effects on seabirds and warrants further research into cumulative effects.

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