CHAPTER 7

LESSER BLACK-BACKED GULL DISTRIBUTION IN AND AROUND THE THORNTON BANK OFFSHORE WIND FARM USING GPS LOGGER DATA

VANERMEN Nicolas, COURTENS Wouter, DAELEMANS Robin, VAN DE WALLE Marc, VERSTRAETE Hilbran & STIENEN Eric W.M.

Research Institute for Nature and Forest, Havenlaan 88, bus 73, 1000 Brussels, Belgium

Corresponding author: nicolas.vanermen@inbo.be

Abstract

We analysed GPS data of lesser black-backed gulls (*Larus fuscus*) caught and tagged in the colonies at Ostend and Zeebrugge. After exploring general patterns in at-sea presence and behaviour, we performed three modelling exercises to study the response of lesser black-backed gulls towards the C-Power turbines at the Thornton Bank offshore wind farm (OWF) in more detail. These exercises confirmed that much more time was spent roosting on outer than on inner turbines. Next, we found a significant and gradual increase in the number of logs of flying birds going from the centre of the wind farm up to 2000 m from the wind farm edge, beyond which the response seemed to stabilise. For non-flying birds too, the model predicted a minimum number of logs in the centre of the wind farm and a flattening of the smoother at about 2000 m, yet with a highly increased presence right at the wind farm's edge, representing birds roosting on the outer turbine foundations. The last model, aiming to assess temporal variation in the presence of lesser black-backed gulls in and around the Thornton Bank OWF, showed that the birds were increasingly wary of entering the wind farm during times of strong winds with fast moving rotor blades. The results of this study illustrate that the response of lesser black-backed gulls towards OWFs can be subject to both temporal and (within-OWF) spatial variation, which in turn can be of high value in refining collision risk modelling.

1. Introduction

In this chapter we will analyse GPS data of lesser black-backed gulls (*Larus fuscus*) caught on the nest and tagged in the colonies at Ostend and Zeebrugge. GPS data have the major advantage of providing detailed information on the movements of individual birds, without being limited to specific time frames or environmental conditions as is the case with seabirds-at-sea monitoring. Moreover, when enough individuals of a specific colony or population are included, the cumulative data no longer reflect individual birds' preferences but allow for a general characterisation of their behaviour and distribution. First we will explore the dataset looking for general patterns in at-sea presence and behaviour, comparing these with the patterns observed in and around the C-Power offshore wind farm (OWF) at the Thornton Bank. Next, we will turn to three modelling exercises for a detailed study of the response of the tagged lesser black-backed gulls towards the Thornton Bank OWF.

2. Material and methods

2.1. Overall data selection

From 2013 to 2017, 133 lesser black-backed gulls breeding in Zeebrugge (77 birds), Ostend (6 birds) and Vlissingen (50 birds) have been equipped with an UvA-BiTS tracker (Bouten *et al.* 2013). As the colony of Vlissingen is located over 40 km from the Thornton Bank OWF, we only considered birds tagged in Zeebrugge and Ostend, and further selected all at-sea GPS logs at least 1 km from the shoreline and within 80 km from the colony of origin (fig. 1). Because the Thornton Bank OWF was only fully operational from the summer of 2013 onward, we further discarded all 2013 data from the analyses.

Resulting from differing needs and priorities of the GPS data end users, tracking resolution varied strongly from 10 to 3600 seconds. To obtain a balanced dataset, we selected one data point per 20 minutes for tracks with a higher resolution and deleted tracks with a resolution lower than 20 minutes. The choice for this 20-minute boundary was based on the fact that it is the original resolution for about half of the total tracking time in the regarded dataset. Meanwhile, by bringing down the tracking resolution, we avoided temporal correlation between records (Ross-Smith *et al.* 2016). This data selection was applied in all calculations except when assessing the actual time spent in a certain area.

About 40% of the birds from Ostend and Zeebrugge (34 individuals) were recorded inside the Thornton Bank OWF at least once (fig. 2), allowing for a characterisation of their presence and behaviour inside the wind farm compared to the surrounding or wider area. The tagged birds visited the further offshore Northwind and Belwind wind farms to a far lesser extent and interaction with these wind farms was therefore not considered in this chapter.

Furthermore, 48 herring gulls were equipped with a UvA-BiTS tracker, 37 in Ostend and 11 in Zeebrugge. Herring gulls generally stayed closer to the shore compared to lesser black-backed gulls, and never ventured far enough offshore to encounter the wind farms currently present in the Belgian part of the North Sea (BPNS) (fig. 3). Because of this lack of interaction with offshore turbines, herring gulls were not considered further on in this report.

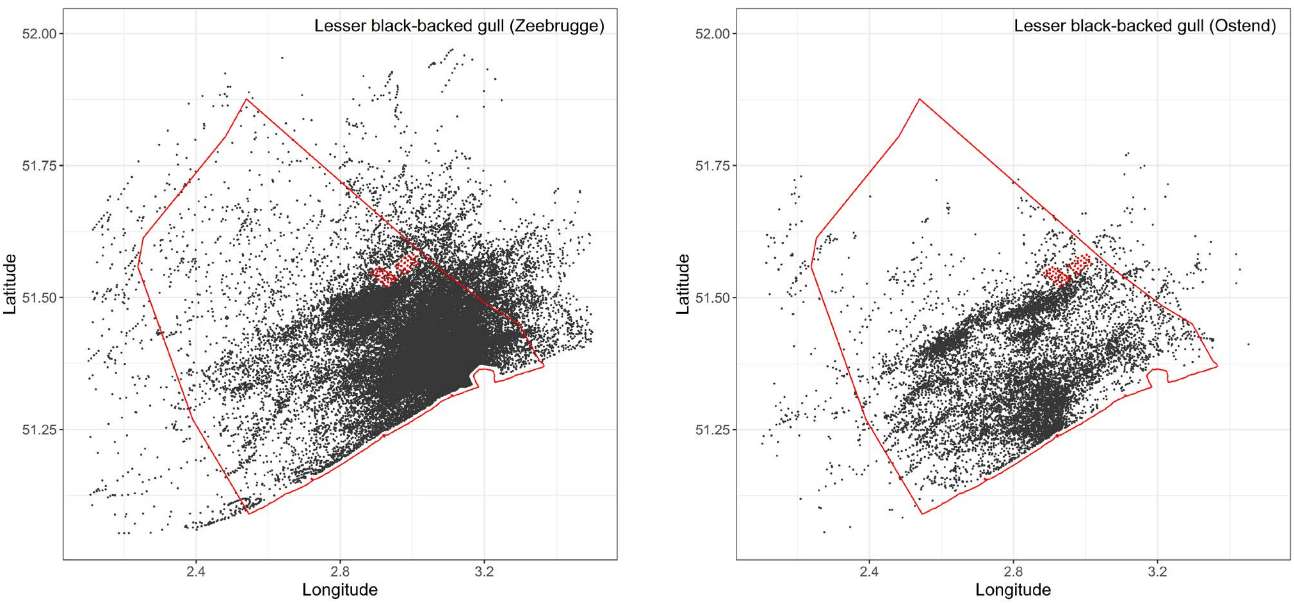


Figure 1. Twenty-minute interval GPS logs of lesser black-backed gulls (period 2014-2017) originating from Zeebrugge and Ostend; the Belgian North Sea border and the turbines at the Thornton Bank are indicated in red.

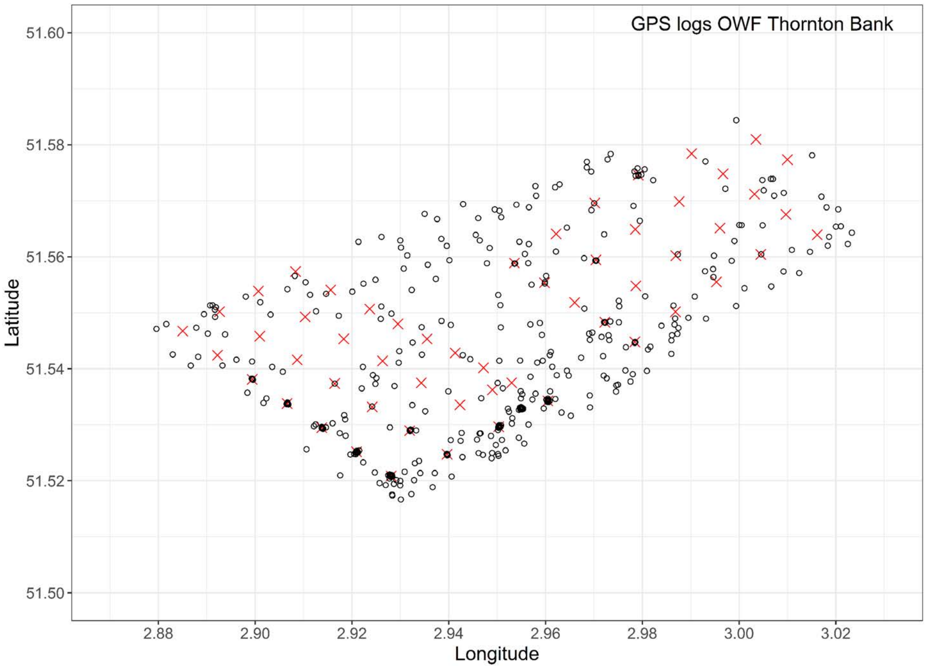


Figure 2. Twenty-minute interval GPS logs of lesser black-backed gulls (period 2014-2017) inside the Thornton Bank OWF; the turbines are indicated in red.

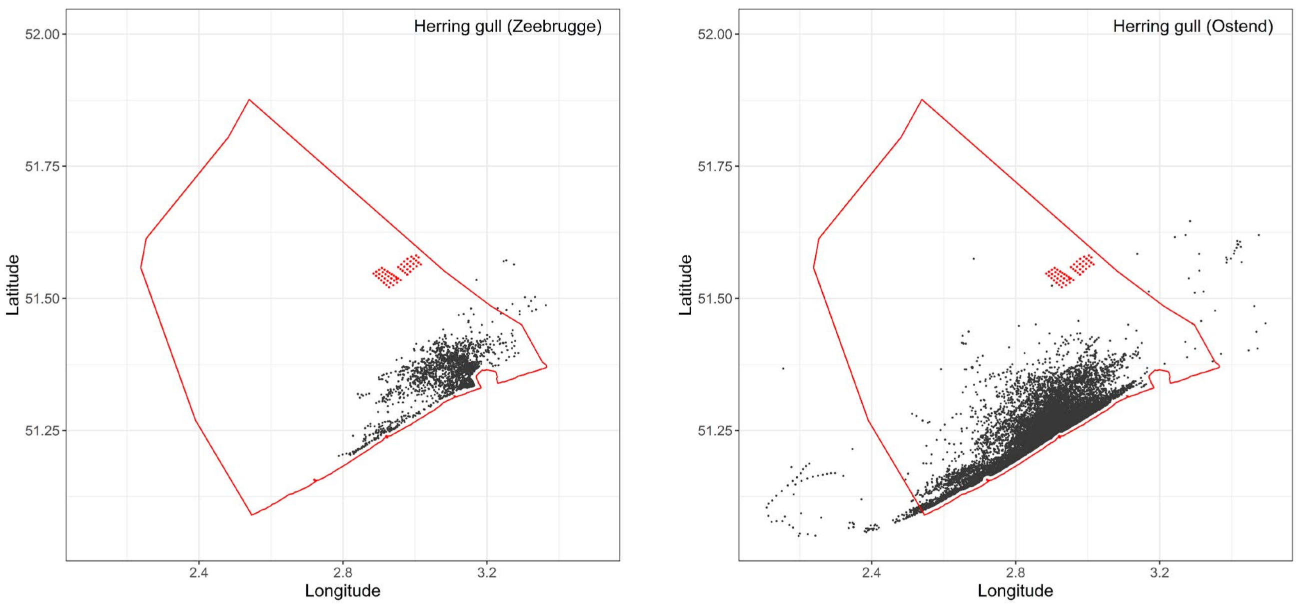


Figure 3. Twenty-minute interval GPS logs of herring gulls (period 2014-2017) originating from Zeebrugge and Ostend; the Belgian North Sea border and the turbines at the Thornton Bank are indicated in red.

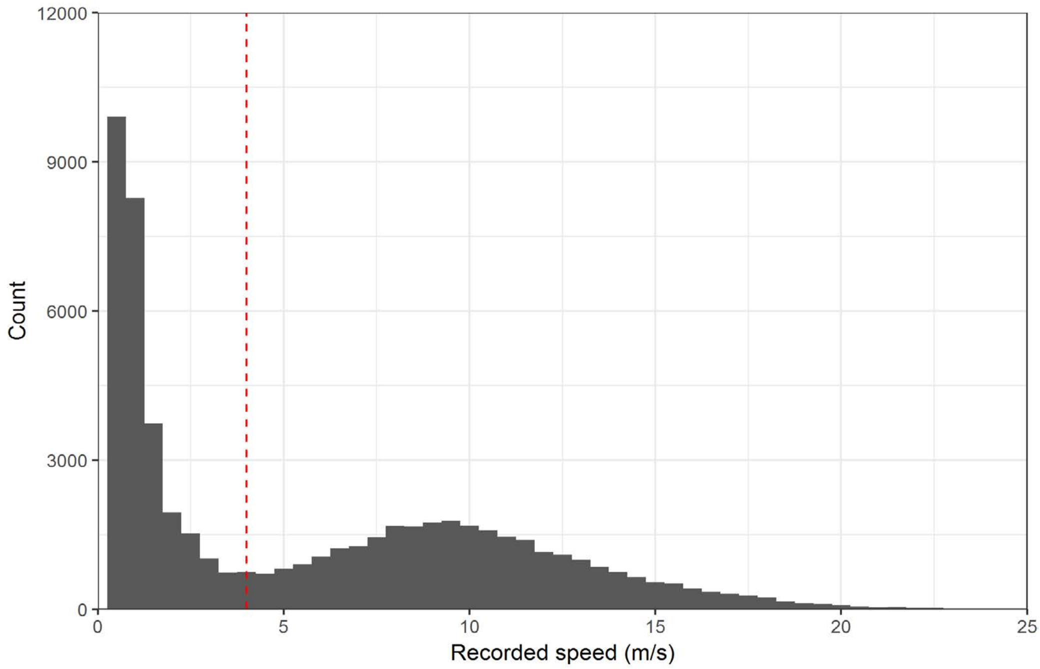


Figure 4. Histogram of the recorded ground speeds.

2.2. Data exploration

Based on the resulting dataset of 59,493 GPS logs, we explored how flight height, direction and activity related to the time of day, tidal height, wind velocity and wind direction, and investigated whether the patterns found varied across the BPNS. Birds were considered flying when their recorded ground speed exceeded 4 m/s, a cut-off speed coinciding with the minimum indicated in the bimodal histogram displayed in fig. 4. This value appears to be on the high side, as Gyimesi *et al.* (2017) applied a cut-off of 2.5 m/s, while Ross-Smith *et al.* (2016) used a value of only 1.1 m/s (4 km/h). Because tidal currents in the BPNS may already reach 1 m/s or more (Ruddick & Lacroix 2006), the latter seems to be an absolute minimum for birds logged at sea. On the other hand, Baert *et al.* (2018) used a measured ground speed of 4.5 m/s to discern active flight from a variety of behaviours (standing, resting, walking, floating, soaring and tortuous flight). Anyhow, knowing that the GPS speed measurements are subject to considerable error (Bouten *et al.* 2013) and based on the strongly bimodal pattern in fig. 4, the value of 4 m/s seemed to be the best possible guess in the framework of this study.

Data on tide and wind conditions were queried from the Monitoring Network Flemish Banks by means of the LifeWatch Data Explorer (http://rshiny.lifewatch.be/MVB%20data/). The variables 'mean wind velocity' and 'mean wind direction' are based on offshore measurements at the Westhinder station, while 'tidal height TAW (cm)' measurements originate from the Ostend station, all with a sample period of 60 minutes.

When comparing general at-sea gull behaviour to the behaviour recorded in or around the Thornton Bank wind farm, we often made subsets of data as illustrated in fig. 5. These selections were based on the same before-after control-impact (BACI) polygons used in the displacement analyses in previous reports (*e.g.*, Vanermen *et al.* 2017), being a wind farm area (the turbine-built zone surrounded by an initial 0.5 km buffer), a buffer zone (the area 0.5-3.0 km from the nearest turbines) and a control area at a comparable distance to the shore and including the SW part of the Thornton Bank as well as the Goote Bank.

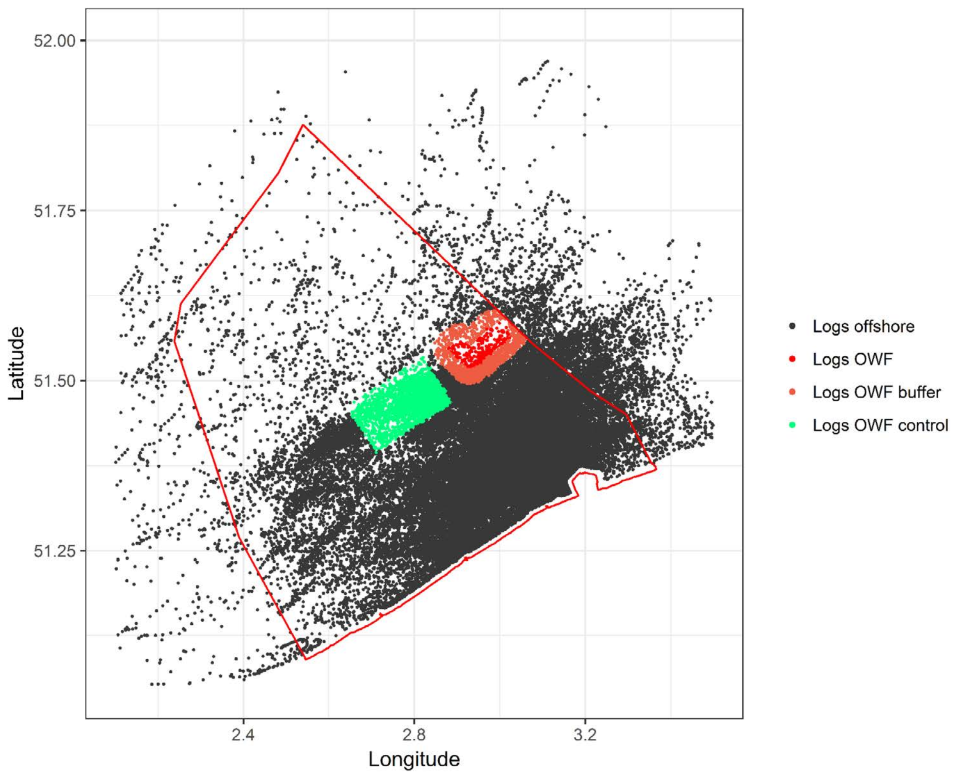


Figure 5. Data selection for comparison of bird behaviour inside versus outside the Thornton Bank OWF.

2.3. Modelling exercises

2.3.1. Association with turbine foundations

In order to explore the gulls' roosting behaviour on turbine foundations, we calculated the time spent in (1) 100 m wide buffer areas around the turbines and (2) the OWF as a whole by summing the time intervals between the first and last GPS log of each visit to these respective areas. This implies that single 'isolated' logs were not taken into calculation, but also that we assume birds to stay within the area boundaries between two subsequent logs inside these areas. Next, we modelled whether the time spent on a turbine foundation is affected by the distance from that turbine to the wind farm edge.

2.3.2. Modelling the effect of distance

To study the effect of distance to the wind farm on the presence of lesser black-backed gulls, we built a grid of 500x500 m cells up to a distance of 3250 m to the nearest turbine (fig. 6). Extending this distance was not feasible due to the presence of the Northwind wind farm just north of the Thornton Bank. For each grid cell, the distance from its centroid to the wind farm edge was calculated. We then modelled the effect of distance to the wind farm edge on the number of logs per grid cell applying a smoother, both for flying and swimming/resting birds.

2.3.3. Modelling temporal variation

To study the temporal variation in the presence of lesser black-backed gulls in and around the Thornton Bank OWF, we defined eight 5x5 km grid cells aligned with the Thornton Bank. The two middle cells include the wind farm (the 'impact' cells), the other six cells being 'control' cells (fig. 7). We then generated a dataset with one line for each hour and each grid cell in the months of March to August in the years 2014 to 2017, resulting in 141,128 rows. The dataset was thus limited to the spring and summer period, but note that only 0.3% of our 59,493 at-sea GPS logs within 80 km from the colony (2.1) was logged in the months of

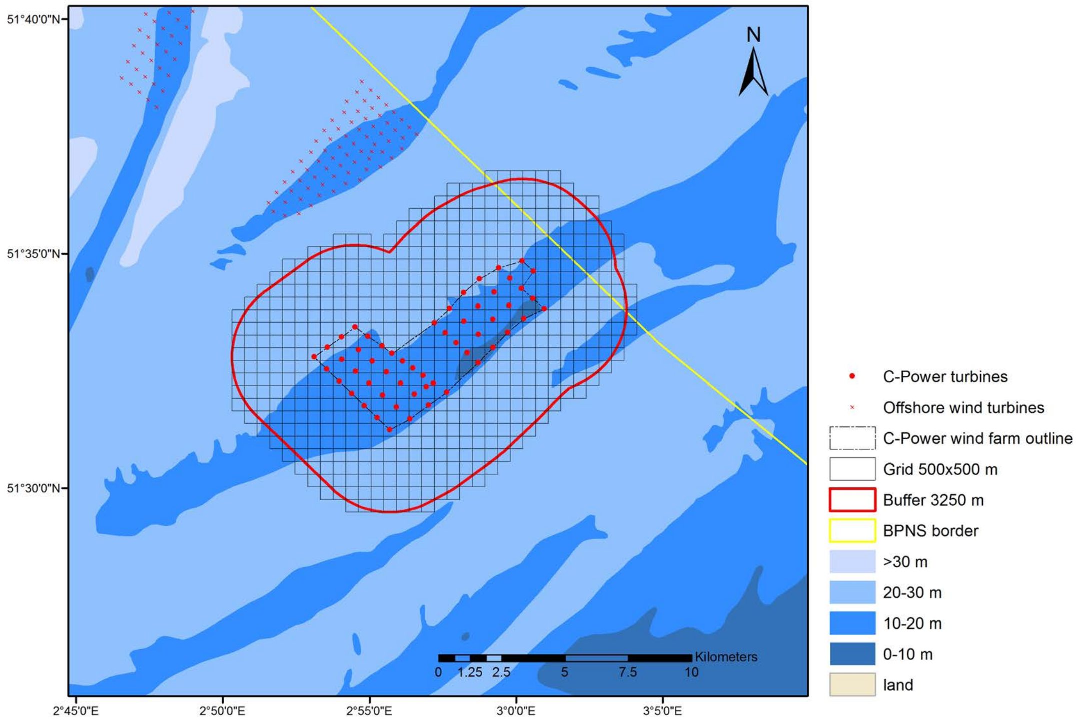


Figure 6. Grid of 500x500 m cells for modelling the effect of distance to the OWF edge on the number of lesser black-backed gull logs per grid cell.

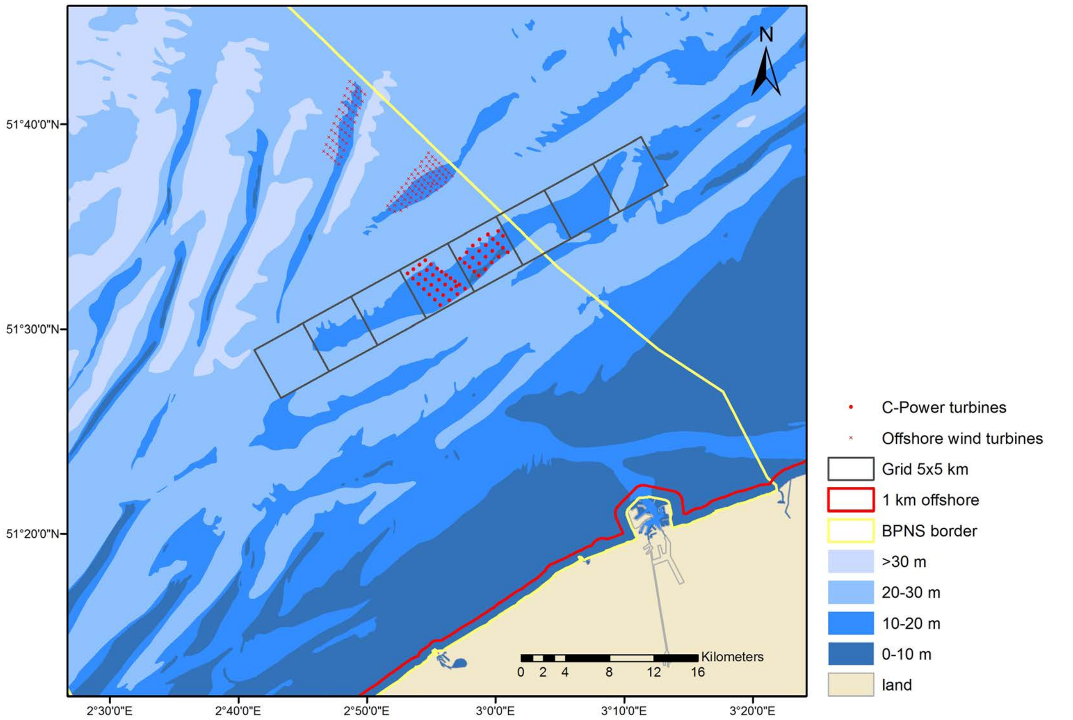


Figure 7. Grid of eight 5x5 km cells for modelling temporal variation in the presence of tagged lesser black-backed gulls in and around the OWF at the Thornton Bank.

September to February. Next, the response variable was calculated by aggregating the number of GPS logs per grid cell and per hour. The explanatory variables included in the dataset were wind speed, tidal height and hour of the day, next to the factor variables weekend/week and control/impact. Finally, this dataset was modelled using an information-theoretic approach, first to select the appropriate data distribution, and next to perform a backward model selection.

2.4. Statistics

All data processing and analyses were performed in R version 3.4.2 (R Core Team 2017) using RStudio (RStudio Team 2016) and the following packages (in alphabetical order):

- data.table (Dowle & Srinivasan 2017)
- ggplot2 (Wickham 2009)
- MASS (Venables & Ripley 2002)
- mgcv (Wood 2017)
- plyr (Wickham 2011)
- pscl (Zeileis *et al.* 2008)
- reshape (Wickham 2007)
- rgdal (Bivand *et al.* 2017)
- rgeos (Bivand & Rundel 2017)
- spatialEco (Evans 2017)
- sp (Pebesma & Bivand 2005)

3. Results

3.1. Data exploration

3.1.1. Distribution patterns

Figure 1 already illustrated that the Thornton Bank OWF falls within the normal at-sea distribution of lesser black-backed gulls breeding in Zeebrugge and Ostend. We can further illustrate this by plotting the cumulative proportion of the number of logs against the distance to the colony of origin. This shows that for both colonies, 95% of the offshore records occurred within about 38 km from the colony (fig. 8), while the OWF at the Thornton Bank is located at respectively 25 and 32 km from Zeebrugge and Ostend.

Up to a distance of 10-15 km, flight directions of lesser black-backed gulls breeding in Zeebrugge are mostly oriented perpendicular to the shoreline, either straight to the sea (-60°) or directed towards land (120°) (fig. 9, panel at the top). Gradually, flight orientations become more evenly spread over all directions, indicating a shift from directed commuting flights from and to the colony to less oriented flights in search of food. Accordingly, the proportion of birds flying is strongly affected by the distance to the colony, dropping steeply from about 90% close to the colony to 50% at a distance of 10 km. From there on, the proportion of birds flying decreases more

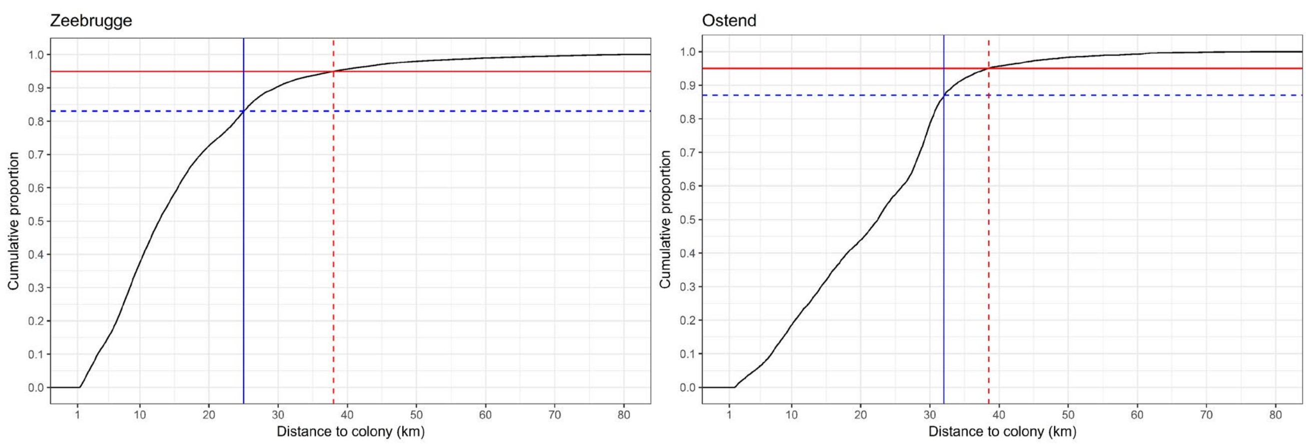


Figure 8. Cumulative proportion of the number of at-sea GPS logs against the distance to the colonies of origin in Zeebrugge and Ostend; the distance to the nearest turbine at the Thornton Bank is indicated in blue, while the 95% boundary is indicated in red.

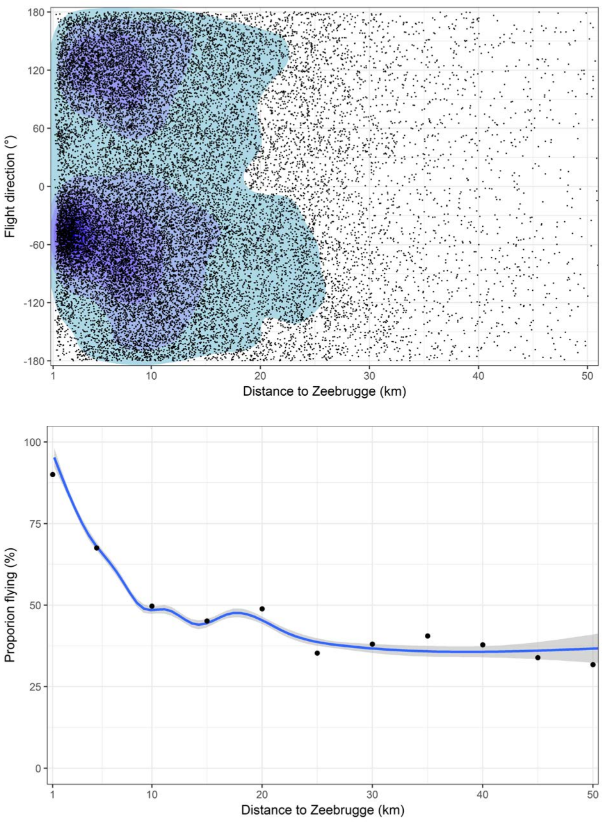


Figure 9. Flight directions in relation to the distance to Zeebrugge with a heat map in the background (panel at the top) and the relation between the proportion of birds flying and the distance to Zeebrugge (panel below).

gradually and stabilises at about 32% beyond a distance of 25 km.

Distribution patterns of birds from Zeebrugge appear to be very similar when comparing different years or seasons (see Annex 1). On the other hand, tagged lesser black-backed gulls showed a much lower at-sea presence during weekends compared to weekdays (fig. 10). By means of example and accounting for birds from Zeebrugge, our dataset holds 17,510 at-sea logs recorded on Wednesdays and Thursdays, compared to only 8423 records on Saturdays and Sundays. Birds thus appear to be present at sea twice more likely during weekdays, which is probably related to reduced fishery activities during the weekend, as was already reported for lesser black-backed gulls breeding on Texel in the Netherlands (Tyson *et al.* 2015).

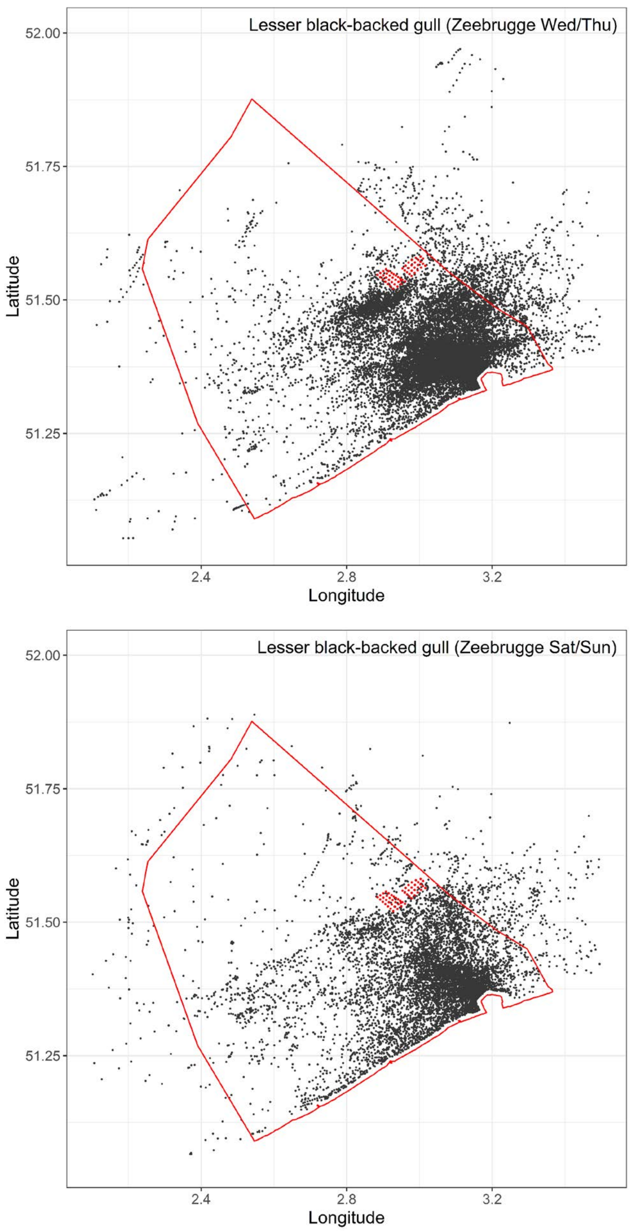


Figure 10. Distribution patterns of birds from Zeebrugge during weekdays (Wednesday/ Thursday) and weekend days (Saturday/Sunday).

3.1.2. Diurnal patterns

The diurnal presence of lesser black-backed gulls at sea is characterised by a double-peaked pattern, with lowest numbers around midnight, highest numbers in early morning (3 am) and a secondary peak in the evening (7 pm) following a somewhat lower presence in between (fig. 11, panel at the top). However, when splitting up the data per month, there appear to be considerable differences between months. In March and April

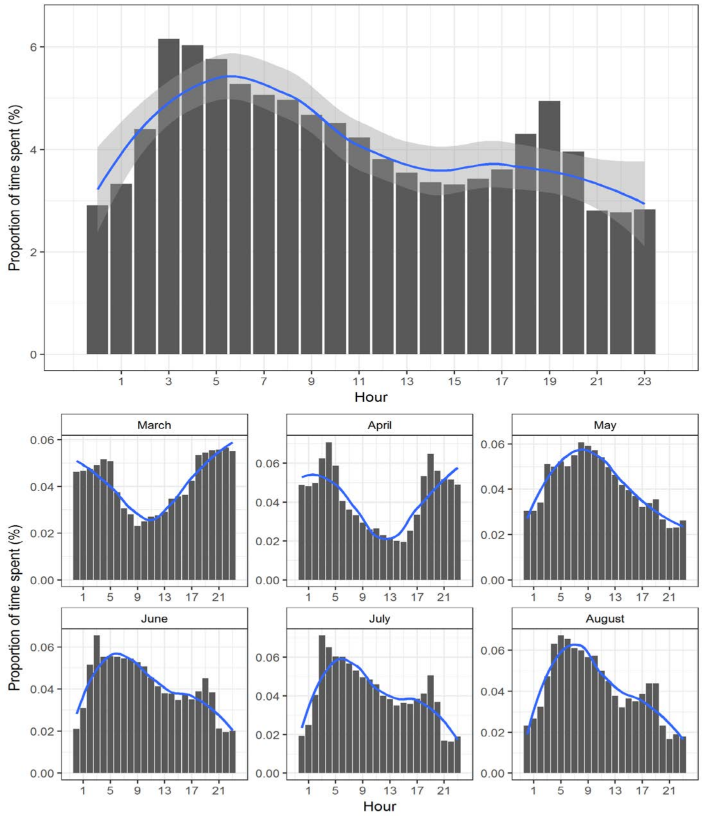


Figure 11. Diurnal rhythm in the time spent at sea by tagged lesser black-backed gulls for all data (panel at the top) and split up per month (panel below).

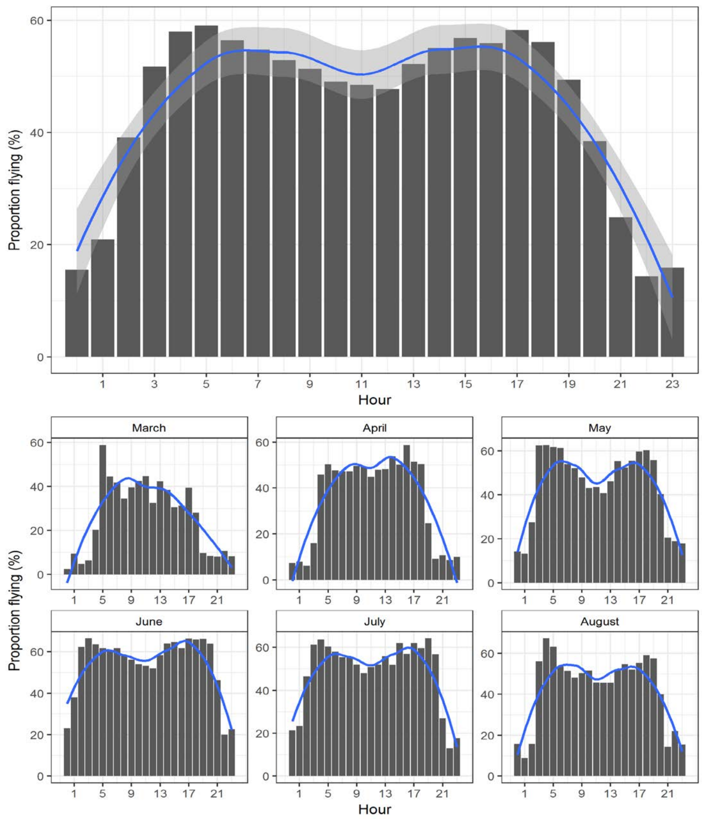


Figure 12. Diurnal rhythm in the proportion of birds flying for all data (panel at the top) and split up per month (panel below).

(pre-breeding period), highest presence rates occur from 6 pm to 5 am, with a considerably lower presence during the day. In contrast, from May to August (incubation, chick rearing and early post-breeding periods), the gulls spend most of their time at sea roughly between 3 am and midday, with a moderate secondary peak around 7 pm, while comparatively much less time is spent at sea around midnight (fig. 11, panel below).

Looking at the diurnal rhythm in the proportion of birds flying, we see a highly symmetrical and double-peaked pattern, with highest flight activity occurring at 5 am and again at 5 pm, and a slight dip in flight activity in between. Around midnight, flight activity drops below 20% (fig. 12, panel at the top) and birds are mainly resting. Again, there is a seasonal aspect to this, in the sense that flight activity is lowest from March to April, highest in the period May to July and decreasing again in August. When, for example, comparing the flight activity in March to that in May, the period of low flight activity during the night is longer, while the proportion of birds flying throughout the day is lower. It seems that during the pre-breeding period, relatively more lesser black-backed gulls prefer to spend the night resting at sea.

The diurnal presence of birds in the wind farm study area differs from the overall at-sea pattern. The morning peaks in presence inside the OWF and its control area come later, respectively at 7 and 10 am, compared to 3 am for all at-sea data compiled. In accordance to the pattern for all data compiled, there is a moderate evening peak in the OWF at 6 pm, yet at the same time there is no increased evening presence in the control area (fig. 13).

In the wind farm control area, there is less flight activity (35%) compared to the wider offshore area (52%) (fig. 14, panel at the top), which is in line with the decreasing flight activity with increasing distance to the coast as illustrated in fig. 9. Flight activity is lower still in the OWF (25%), and thus below what could be expected based on the aforementioned general inshore-offshore pattern. This comparatively low flight activity inside the wind farm might indicate that birds come to the area to rest rather than to forage.

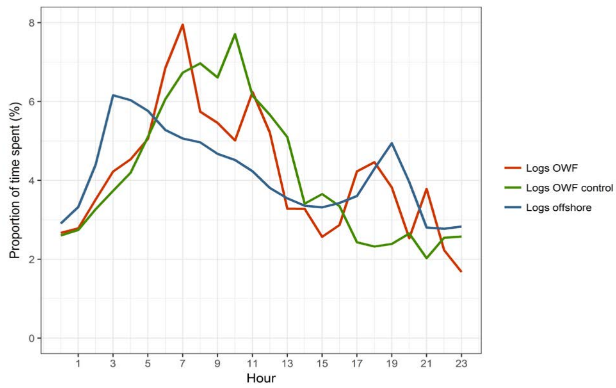


Figure 13. Comparison of the diurnal rhythms in presence of tagged lesser black-backed gulls in the OWF at the Thornton Bank, the nearby control area and at sea in general.

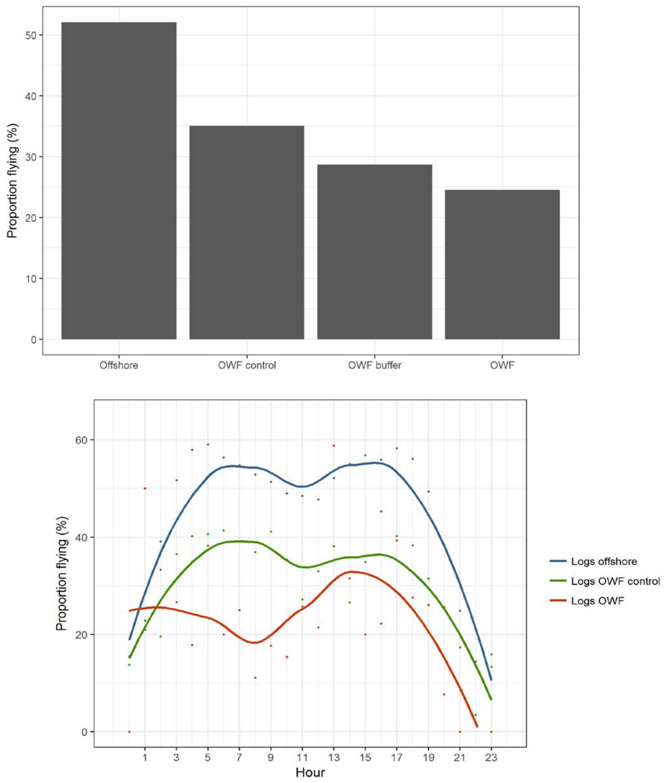


Figure 14. Bar plot of the proportion of birds flying per sub-area (panel at the top) and diurnal rhythm in flight activity in the OWF and its control area compared to the pattern observed in all data (panel below).

3.1.3. Flight heights

The UvA-BiTS trackers measure altitude, which allowed studying the proportion of birds flying at rotor height under different circumstances. Unfortunately, the altitude measurements are not without error, especially at higher measurement intervals (Bouten *et al.* 2013; Ross-Smith *et al.* 2016), illustrated by the rather large amount of negative altitudes (see figs 15 & 16). Nevertheless, they do give a good indication of overall height. A good example hereof is the difference between the altitude histograms of non-flying birds in the OWF and the control area. Next to the expected and most dominant cohort of birds logged at altitude zero (birds on the water) which is present in both histograms, we see an obvious second cohort of birds at altitudes of about 20 m in the OWF histogram, representing birds roosting on the turbine foundations (fig. 15).

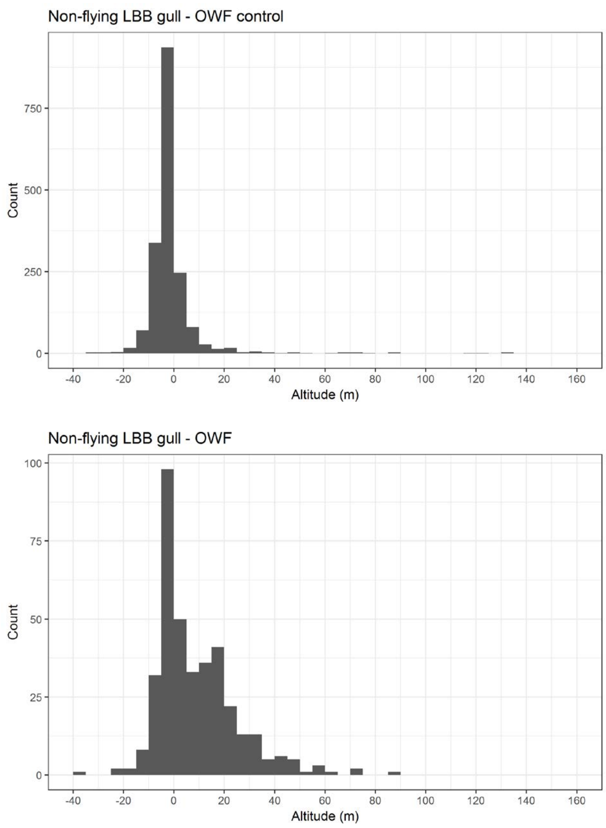


Figure 15. Histograms of recorded altitudes of non-flying lesser black-backed gulls in the control area (panel at the top) and the wind farm at the Thornton Bank (panel below).

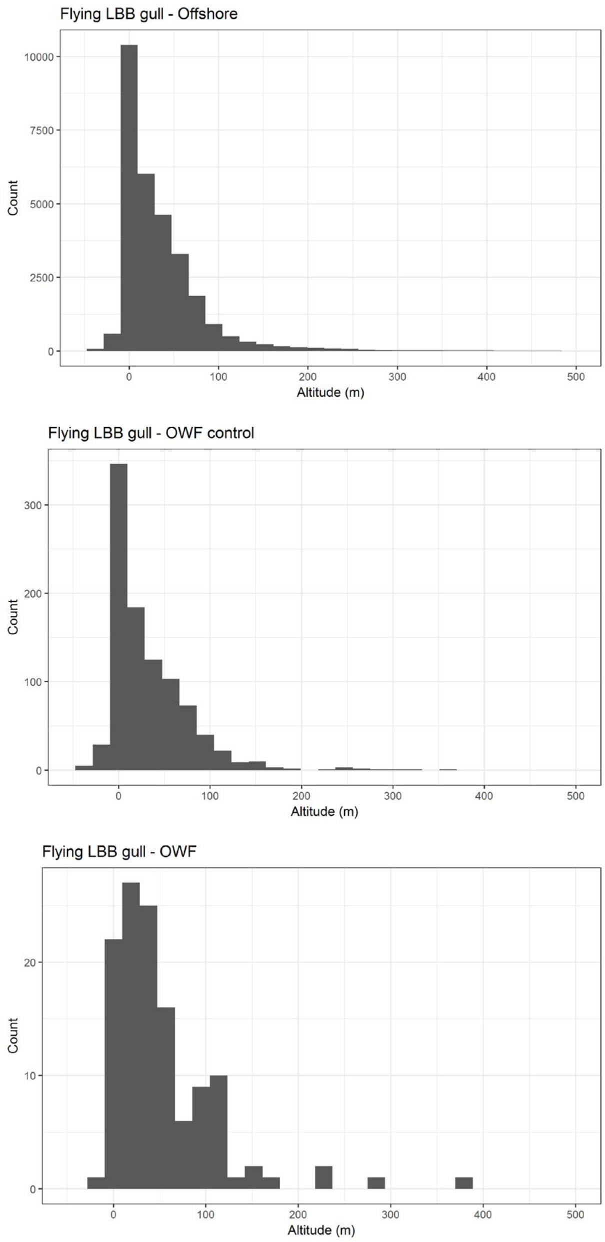


Figure 16. Histograms of recorded altitudes of flying lesser black-backed gulls in the offshore range under consideration (first panel), the OWF control area (second panel) and the Thornton Bank OWF area (third panel).

For flying birds, altitude histograms for all at-sea data and the control area are highly similar, with a peak occurrence of logs with a measured altitude of around zero (fig. 16, first and second panels). Flight altitudes recorded inside the OWF, on the other hand, show a clearly different histogram, with comparatively fewer measurements around zero, a higher weight for altitudes between

10 and 70 m and a secondary cohort of altitudes around 100 m (fig. 16, third panel). Note that this latter histogram is based on a limited amount of logs (n = 126) and may therefore not be fully representative.

When calculating the proportion of birds flying at rotor height (between 31 and 157 m), this leads to a percentage of 37% for both the full dataset and the logs inside the control area. In the wind farm area this percentage increases to 49% (fig. 17). Again, this difference might be coincidence due to the limited number of records involved. But on the other hand, logs recorded inside the OWF coincide with lower wind speeds than in the control area (median 5.3 m/s versus 6.2 m/s respectively) and, as we will see in 3.1.4, low wind speeds typically induce higher flight heights. It would thus be interesting to investigate whether the response of lesser black-backed gulls towards wind turbines varies with wind conditions, indirectly inducing this deviating altitude proportioning.

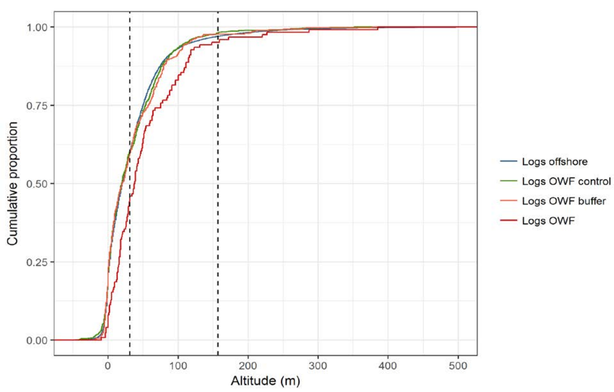


Figure 17. Cumulative proportion of recorded altitudes for the full offshore dataset, next to the OWF and its buffer and control areas, with the rotor swept zone between 31 and 157 m indicated by the vertical dashed lines.

3.1.4. *Effect of wind and tide*

The overall presence of lesser black-backed gulls at sea seems to be largely unaffected by tidal height and wind direction, but is negatively affected by wind velocity. For example, while the median wind velocity in the regarded period was 8.3 m/s, the median wind velocity coinciding with birds GPS logs was only 6.4 m/s. Meanwhile, wind velocity clearly affects flight height, which drops from a 30 m median at low wind speeds (0-5 m/s) to close to sea level during wind speeds of over 15 m/s (fig. 18, panel at the top). Flight height is further determined by the relative wind direction, as birds tend to fly higher during back winds compared to head winds. This effect becomes more pronounced with increasing wind velocities (fig. 18, panel below).

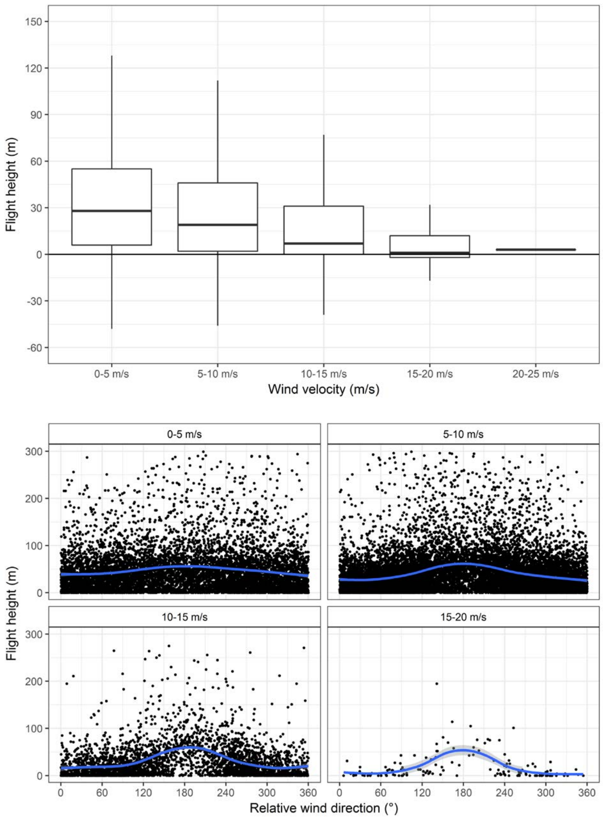


Figure 18. Boxplots of recorded flight heights for five wind velocity categories (panel at the top) and interaction between flight height, wind velocity and relative wind direction (180° representing back wind) (panel below).

Comparing the wind speeds coinciding with offshore GPS logs of lesser black-backed gulls (blue line in fig. 19, panel at the top) with the hourly wind speed measurements in the months of March to August in the years 2014 to 2017 (grey bars in fig. 19, panel at the top), low wind speeds (< 5 m/s) occurred more often than expected, while the opposite is true for high wind speeds (> 10 m/s). The gulls thus clearly favour calm conditions when going offshore, and seem to prefer to stay on land during strong winds. These preferences are even more pronounced in the Thornton Bank OWF. Standardising the number of logs in the wind farm with the total number of logs recorded at sea per wind velocity category, we see the chance of visiting the wind farm decreasing linearly with increasing wind velocity (fig. 19, panel below). The latter also applies for the OWF control area, yet to a lesser extent, suggesting that this pattern is only partly related to the presence of the wind farm.

When doing the same exercise for tidal height categories, we see that there is no

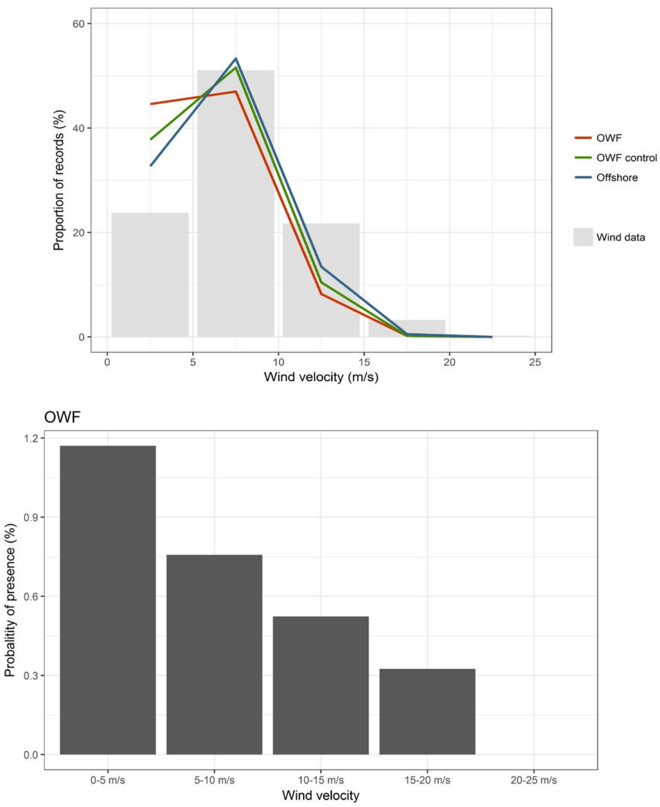


Figure 19. The proportion of GPS logs (coloured lines) and hourly wind speed measurements (grey bars) per wind velocity category (panel at the top) and the effect of wind velocity on the probability of lesser black-backed gulls visiting the Thornton Bank OWF (panel below).

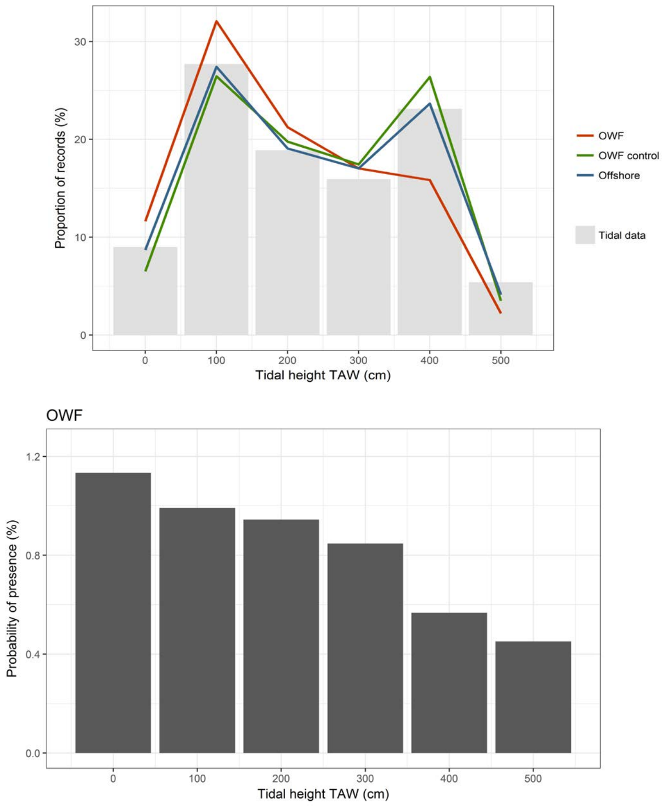


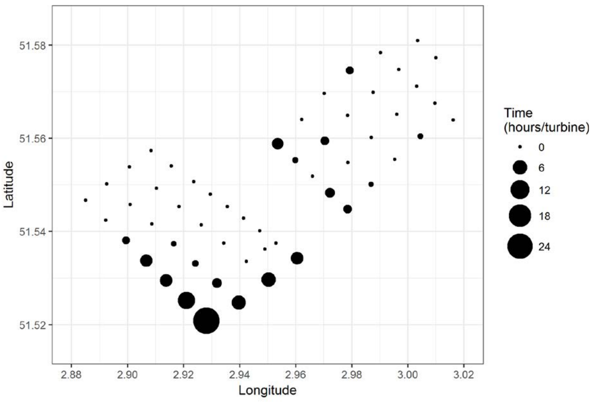
Figure 20. The proportion of GPS logs (coloured lines) and hourly tidal height measurements (grey bars) per tidal height category (panel at the top) and the effect of tidal height on the probability of lesser black-backed gulls visiting the Thornton Bank OWF (panel below).

clear pattern of preference in case of all offshore logs neither for logs inside the control area, yet a clearly deviating pattern for logs inside the OWF (fig. 20, panel at the top). Coinciding with the latter, tidal heights below 300 cm occurred more often than expected, opposed to an under-representation of tidal heights above 300 cm. Resulting, the chance of lesser black-backed gulls visiting the wind farm at the Thornton Bank decreases with increasing tidal height (fig. 20, panel below).

3.2. Modelling exercises

3.2.1. Association with turbine foundations

As could already be deducted from figures 2 and 15, lesser black-backed gulls were often logged on or near the turbine foundations in the Thornton Bank OWF, with a



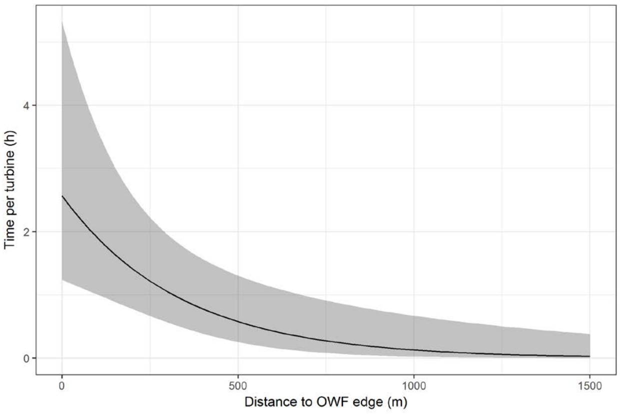


Figure 21. Actual time spent per turbine by lesser black-backed gulls tracked inside the Thornton Bank OWF (panel at the top), and the model prediction of the relation between the time per turbine and the distance to the edge of the wind farm (panel below).

clear preference for the south corner of the wind farm. The birds also seemed to prefer outer to inner turbines. Apart from this, they were more often found resting in the wind farm area compared to the nearby buffer and control areas, and the wider area in general (fig. 14).

In order to explore this apparent preference to turbine foundations, we first calculated the proportion of the time spent in (1) 100 m wide buffer areas around the turbines and (2) the OWF as a whole. Exploring the characteristics of the records comprised within these 100 m turbine buffer zones (n = 635), we see that most (96%) indeed refer to non-flying birds logged at a mean height of 14 m above sea level. Based on this exercise, we estimate that lesser black-backed gulls spend 49% of their time inside the Thornton Bank wind farm resting on the jacket foundations. When simply calculating the proportion of the number of (20-minute resolution) logs within the 100 m turbine buffer areas *vs*. the number of logs inside the OWF as a whole, we obtain a very similar result of 48%. Considering the huge difference in surface between the OWF footprint area and the turbine buffer areas, it is clear that lesser black-backed gulls show high preference towards the turbine foundations. Figure 21 (panel at the top) illustrates the total time spent per turbine, a variable which was further used to test the hypothesis that birds prefer outer to inner turbines. Based on the Akaike information criterion (AIC), a negative binomial distribution performed better compared to the Poisson or zero-inflated alternatives, and distance modelled linearly was preferred over distance modelled as a smoother. In doing so, distance to the wind farm edge was found to have a significant and negative effect on the time spent per turbine (fig. 21, panel below). The model summary can be consulted in Annex 2.1.

3.2.2. Modelling the effect of distance

An overlay of the 595 grid cells of 500x500 m with the GPS records of lesser black-backed gulls from Zeebrugge and Ostend resulted in a selection of 2601 logs, 72% of which were categorised as non-flying and 28% as flying. The logs concentrate in the south corner of the study area (fig. 22), close to the most favoured turbines (fig. 21). For each grid cell we determined the distance from its centroid to the wind farm edge, and assigned negative distances to centroids that fall within the wind farm boundaries. Distance was used as a smoother to model its effect on the number of logs per grid cell, considering both a Poisson and negative binomial distribution. We performed separate aggregates for non-flying and flying birds, in order to model both categories.

Both for flying and non-flying birds, the AIC was in strong favour of a

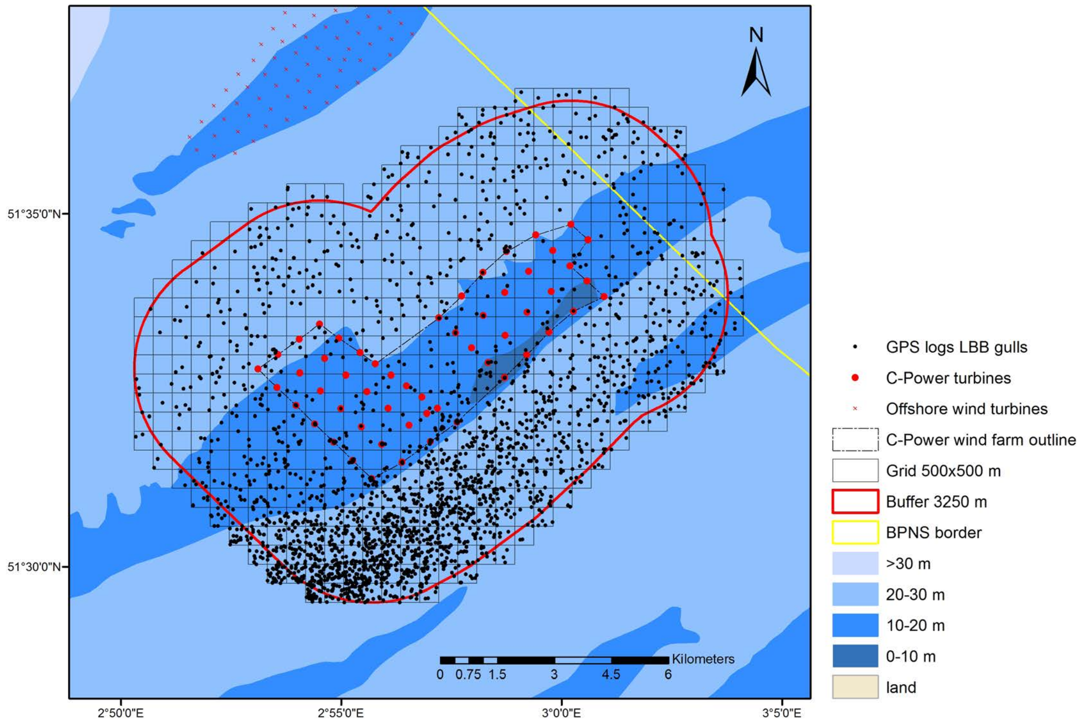


Figure 22. Selected GPS logs for the analysis of the effect of distance to the wind farm edge on the presence of lesser black-backed gulls.

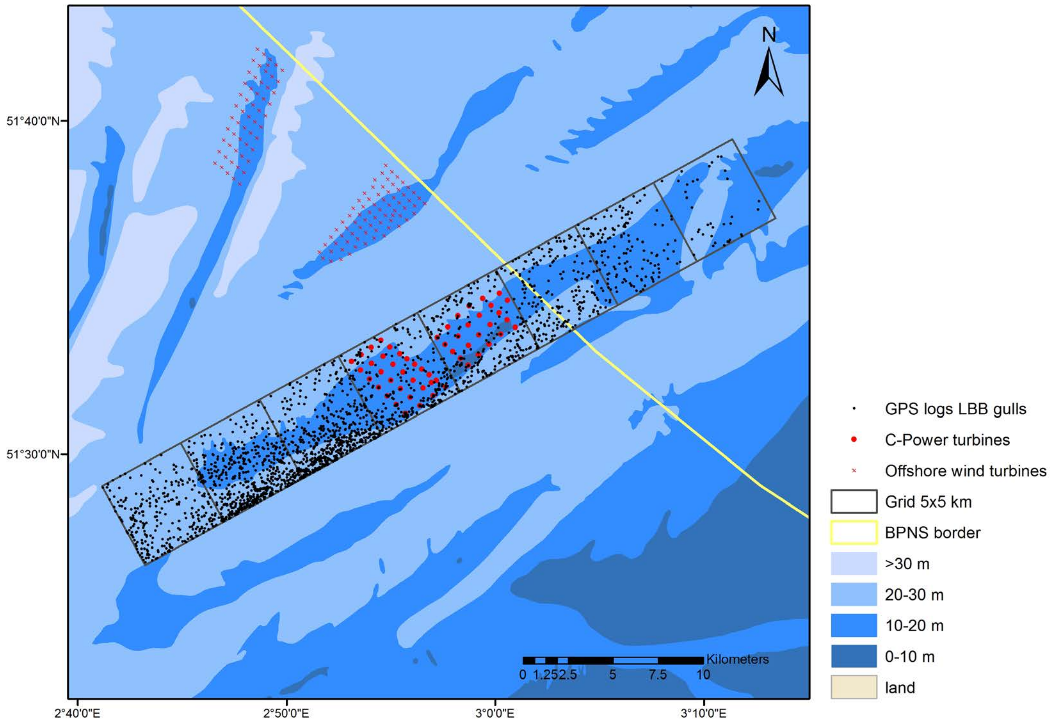


Figure 23. Selected GPS logs for modelling temporal variation in the presence of tagged lesser black-backed gulls in and around the OWF at the Thornton Bank.

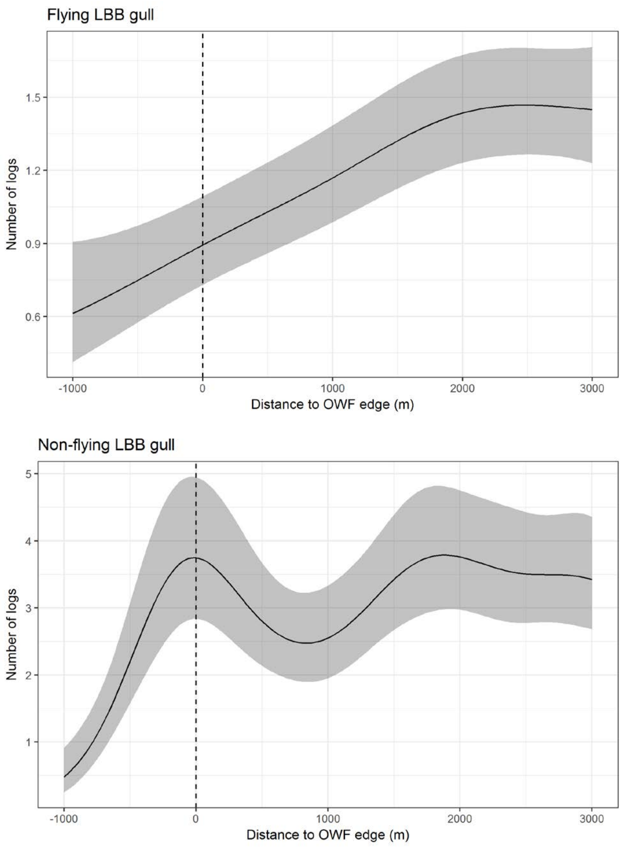


Figure 24. Model predictions of the effect of distance to the OWF edge on the number of logs per 500x500 m grid cells for flying birds (panel at the top) and non-flying birds (panel below).

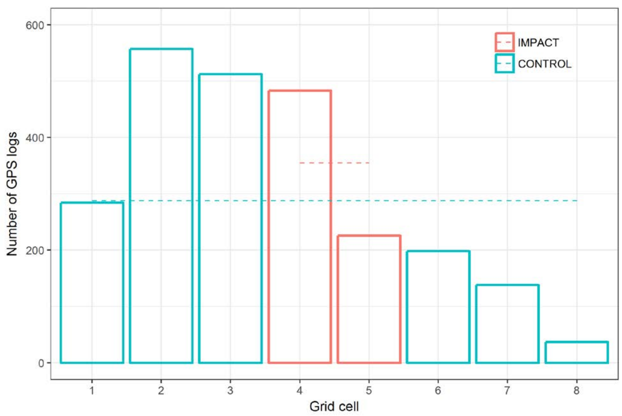


Figure 25. Number of selected logs in the eight 5x5 km grid cells, with the mean for the control-impact groups indicated by the dashed horizontal lines.

negative binomial distribution, and the distance smoother appeared to be highly significant in both cases ($P < 0.001$, also see Annex 2.2). Moreover, the model predictions show interesting patterns (fig. 24). First of all, there is a clear positive effect of distance on the number of logs per grid cell, with the response variable reaching a ceiling at about 2000 m for both flying and non-flying birds, indicating avoidance of the wind farm and its immediate surroundings. In case of non-flying birds, however, there is a strong secondary peak in predicted numbers right at the edge of the wind farm, representing birds roosting on the outer turbine foundations.

3.2.3. Modelling temporal variation

We analysed the temporal variation in presence of tagged lesser black-backed gulls in and around the Thornton Bank OWF making use of the generated dataset as described in Material and methods. Exploring the dataset learned that the eight 5x5 km grid cells include 2435 logs of tagged lesser black-backed gulls, which are quite unevenly distributed (fig. 23, see the previous page, and fig. 25). The four SW grid cells for example hold more than twice as many logs than the four NE grid cells, and based on the bar plot in fig. 25, one could suspect a SW-NE gradient in presence. Apart from this, the mean number of logs appears to be slightly higher in impact cells compared to control cells.

No fewer than 734 logs (30%) occurred in the relatively short period of June to July 2016, representing only 8% of the timeframe considered. Limiting the analysis to this specific timeframe offers some major advantages, considering the increased proportion of non-zero counts and the fact that there is less need to account for temporal random effects. Doing so, we investigated the effect of wind, tide and diurnal patterns on the presence of lesser black-backed gulls in the study area in general, and the wind farm in particular.

We regarded two types of distribution (Poisson and negative binomial) and chose following full models:

- N_records ~ CI * (WEEKEND + WIND + TIDE) + s(HOUR, bs = “cc”, by = CI, k = 8)

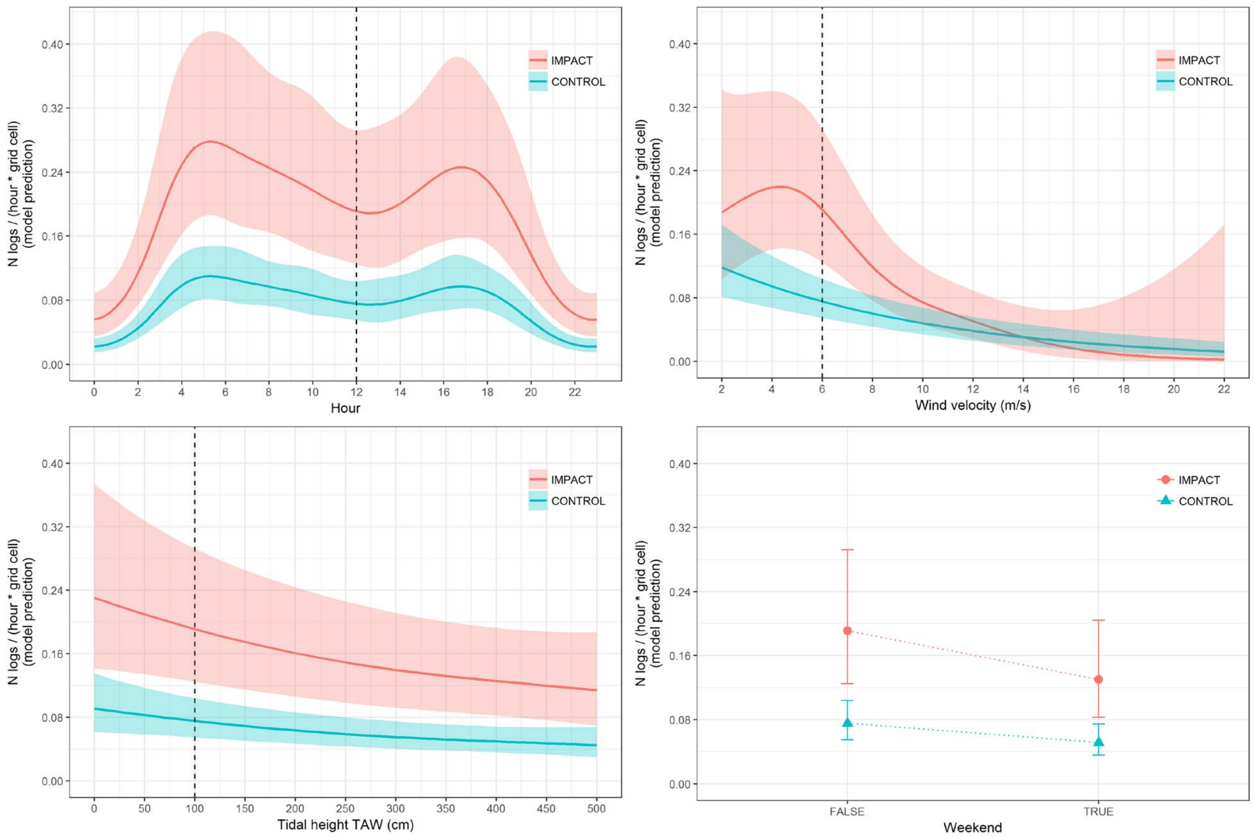


Figure 26. Model predictions of the number of logs per grid cell per hour for all coefficients included in the model (control/impact factor, true/false weekend factor, wind velocity, tidal height and hour of the day), each time keeping all other variables constant at the levels indicated by the vertical dashed lines.

- N_records ~ CI * WEEKEND + s(WIND, by = CI, k = 8) + s(TIDE, by = CI, k = 8) + s(HOUR, bs = "cc", by = CI, k = 8)

In which:

- N_records = the number of records in a certain grid cell in a certain hour
- CI = a factor variable assigning the grid cells to 'control' (n = 6) or 'impact' (n = 2)
- WEEKEND = TRUE/FALSE factor variable for weekend versus weekdays
- WIND = the mean wind velocity (m/s) per hour as measured at the Westhinder station
- TIDE = the mean tidal height TAW (cm) per hour as measured at the Ostend station
- HOUR = hour of the day

The two full-model options only differ in the way we model TIDE and WIND effects, *i.e.,* either linearly (yet with a log link) or through smoothers. For HOUR, a cyclic smoother was applied in both full-model options. In all cases, the smoothers' basic dimension k was limited to 8 to avoid over-fitting. As the 'treatment' of the grid cells in terms of prevailing wind, tidal conditions and hour of the day is the same for all eight grid cells, we specifically looked for interactions between the factor CI, on the one hand, and WIND, TIDE, WEEKEND and HOUR on the other hand.

Based on AIC, a negative binomial distribution was by far the preferred distribution (ΔAIC's of 1183.0 and 1140.4), with a slight advantage for the option with WIND and TIDE modelled by smoothers (ΔAIC of 3.4). Applying a stepwise and backward model selection based on the AIC led to the selection of the following model:

- N_records ~ CI + WEEKEND + s(WIND, by = CI, k = 8) + s(TIDE, k = 8) + s(HOUR, bs = "cc", k = 8)

All main terms were retained in the model, as well as the interaction between CI and WIND. Despite the high proportion of zero's in the dataset (96.4%), these were all accounted for by the included variables, as model overdispersion was estimated to be 0.99 by dividing the residual deviance by the residual degrees of freedom. The model summary is given in Annex 2.3.

Model predictions in relation to the included co-variables are shown in fig. 26. The results are in line with the patterns observed during the explorative analyses: a double-peaked diurnal pattern and negative correlations between presence and both tidal height and wind velocity. Following the positive CI and negative WEEKEND coefficients, the number of records is expected to be highest in the impact grid cells during the week under most circumstances, indicating a preference to the wind farm cells despite the local absence of fishery activities. Interestingly, the model predicts a highly different effect of wind velocity on the presence of lesser black-backed gulls between control and impact grid cells. Comparing the model prediction graphs in the right upper panel of fig. 26, we see a strong preference for impact cells during low wind speeds, followed by a steep decrease in the number of impact cell records at wind speeds of > 5 m/s, eventually resulting in a (slight) preference for control cells from wind speeds of > 14 m/s on. This is in line with the pattern observed in fig. 19, confirming that lesser black-backed gulls are increasingly wary of entering the wind farm during strong winds.

4. Discussion

Exploring the at-sea GPS data of tagged lesser black-backed gulls showed that most birds (95%) from Zeebrugge and Ostend were logged within a distance of about 38 km from the colony of origin. The proportion of gulls recorded in flight was found to decrease with distance to the coast, dropping from 90% close to Zeebrugge and stabilising at about 30% beyond a distance of 25 km from the colony. Flight activity was lower still in the OWF at the Thornton Bank (25%), which might be an indication of an increased preference for roosting between or on the turbines. Strikingly, the gulls were twice more likely to explore the offshore areas around the colonies during the week compared to the weekend, which is most probably related to the much reduced fishing activity during the weekend (Tyson *et al.* 2015). This immediately highlights our most important missing variable when aiming to study the observed distributional patterns of lesser black-backed gulls in relation to the Thornton Bank OWF. The inclusion of Vessel Monitoring System (VMS) data would therefore be a huge step forward.

In our dataset, the overall percentage of birds flying at rotor heights (set between 31 and 157 m) was 37%, but this percentage amounted to 49% inside the Thornton Bank OWF. The latter percentage, however, is based on a limited number of data, and should therefore be interpreted with care. Apart from this, the birds' flight height was strongly determined by wind velocity, with a median flight altitude of 30 m at wind speeds below 5 m/s, opposed to sea-level flight heights in wind speeds of over 15 m/s. Interestingly, there appears to be an over-representation of low wind speeds at times when lesser black-backed gulls were logged between the turbines, suggesting that the birds were more inclined to enter the turbine-built area during calm conditions. Nevertheless, this over-representation of low wind speeds (inducing increased flight heights) alone cannot explain the major difference in flight height proportioning inside compared to outside the wind farm, which might therefore indicate a behavioural response towards the turbines. This has already been suggested by Camphuysen (2011) at Dutch OWFs and is something to keep an eye on when more GPS data of birds flying between offshore turbines become available.

Finally, we performed three modelling exercises. In the first exercise we analysed the time spent roosting on turbine foundations. Our results showed that lesser black-backed gulls strongly prefer the turbines along the edge of the wind farm to roost, especially those situated closest to the colonies. This result is different from the one presented in our previous report (no effect of distance to the wind farm edge was found by Vanermen *et al.* 2017), but note that the latter result was based on a dataset including the 2013 data, when all turbine foundations were already present, but not all of them were carrying turbines. The fact that gulls favour outer rather than inner turbines is interesting as it points towards a conflict of the opposing forces of avoidance and attraction right along the wind farm edge.

This is further illustrated in our second modelling exercise where we aimed to assess the effect of distance to the wind farm edge on the number of logs up to a distance of 3250 m. This showed that flying birds avoided the wind farm up to a distance of 2000 m, while the number of non-flying (roosting) birds peaked at the wind farm's edge, but also largely avoided the inner part of the OWF. Note that in previous reports and based on BACI analyses of at-sea survey results (Vanermen *et al.* 2016 & 2017), we could not detect an effect of the Thornton Bank wind farm on overall lesser black-backed gull densities, while a significant attraction effect was found in the more offshore Bligh Bank wind farm, despite the fact that the Bligh Bank turbines are installed on monopile foundations which offer much less roosting possibilities. The marked difference in response between both sites might be an illustration of the Bligh Bank OWF functioning as a stepping stone, allowing birds to colonise areas that are otherwise off limits (Leopold *et al.* 2013). Such an effect is likely to be far more prominent outside the birds' normal distribution, as is the case for the Bligh Bank. Whatever the reason, all this at least shows that the response of birds can be subject to spatial variation, not only when comparing wind farms or regions, but also on a smaller 'within-OWF' scale.

In the third and last modelling exercise, we analysed the temporal variation in presence in eight 5x5 km² grid cells along the Thornton Bank, two of which include the wind farm and the other six representing control cells. This showed that the presence of lesser black-backed gulls in the area is driven by diurnal and tidal patterns as well as by wind velocity. The model further showed a decreased presence during the weekend and a preference for the impact cells including the wind farm. As there are no pre-construction GPS data available, we cannot assign this preference to an attraction effect. Yet, this preference for the wind farm is striking, considering the fishery activities in the surrounding area and the fact that the gulls seem to avoid the wind farm interior as illustrated in the previous modelling exercises. Interestingly, the wind farm cells were preferred at wind speeds below 5 m/s but avoided during wind velocities above 14 m/s. Lesser black-backed gulls thus seem to be increasingly wary to enter the wind farm during times of high winds with fast moving rotor blades, which is a clear indication of temporal variation in their response towards OWFs.

Gaining more knowledge on the spatio-temporal variation in the response of seabirds towards offshore wind turbines is considered to be a major challenge for reliable impact assessments. The results of this study can therefore be of high value in refining collision risk modelling for lesser black-backed gull, a species which may potentially suffer from population impact due to increased mortality following large-scale exploitation of offshore wind in the North Sea region (Brabant *et al.* 2015).

Acknowledgements

We wish to thank all offshore wind farm concession holders for financing the environmental monitoring, as well as Steven Degraer and Robin Brabant from the Royal Belgian Institute of Natural Sciences (RBINS) for assigning the seabird monitoring part to INBO. The bird tracking network was funded by LifeWatch and was realised in close cooperation with Ghent University (Luc Lens and Hans Matheve), University of Antwerp (Wendt Müller), VLIZ (Francisco Hernandez) and the LifeWatch team at INBO (Peter Desmet and Bart Aelterman).

References

Baert, J.M., Stienen, E.W.M., Heylen, B.C., Kavelaars, M.M., Buijs, R.-J., Shamoun-Baranes, J., Lens, L. & Müller, W. 2018. High-resolution GPS tracking reveals sex differences in migratory behaviour and stopover habitat use in the Lesser Black-backed Gull *Larus fuscus*. *Scientific Reports* 8 (5391): 1-11.

Bivand, R., Keitt, T. & Rowlingson, B. 2017. rgdal: Bindings for the 'Geospatial' Data Abstraction Library. R package version 1.2-16. Available online at: https://CRAN.R-project.org/package=rgdal

Bivand, R. & Rundel, C. 2017. rgeos: Interface to Geometry Engine – Open Source (GEOS). R package version 0.3-22. Available online at: https://CRAN.R-project.org/package=rgeos

Bouten, W., Baaij, E.W., Shamoun-Baranes, J. & Camphuysen, C.J. 2013. A flexible GPS tracking system for studying bird behavior at multiple scales. *Journal of Ornithology* 154: 571-580.

Brabant, R., Vanermen, N., Stienen, E.W.M. & Degraer, S. 2015. Towards a cumulative collision risk assessment of local and migrating birds in North Sea offshore wind farms. *Hydrobiologia* 756: 63-74.

Camphuysen, C.J. 2011. Lesser Black-backed Gulls nesting at Texel – Foraging distribution, diet, survival, recruitment and breeding biology of birds carrying advanced GPS loggers. NIOZ Report 2011-05. Texel: Royal Netherlands Institute for Sea Research, Marine ecology department.

Dowle, M. & Srinivasan, A. 2017. data.table: Extension of 'data.frame'. R package version 1.10.4. Available online at: https://CRAN.R-project.org/package=data.table

Evans, J.S. 2017. spatialEco. R package version 0.0.1-7. Available online at: https://CRAN.R-project.org/package=spatialEco

Gyimesi, A., Middelveld, R.P., Grutters, B.M.C., Stienen, E.W.M. & Fijn, R.C. 2017. Effects of offshore wind farms on the behaviour of Lesser Black-backed Gulls. Report commissioned by Eneco. Report n° 17-175. Culemborg: Bureau Waardenburg.

Leopold, M.F., van Bemmelen, R.S.A. & Zuur, A. 2013. Responses of local birds to the offshore wind farms PAWP and OWEZ off the Dutch mainland coast. Report C151/12. Texel: Imares.

Pebesma, E.J. & Bivand, R.S. 2005. Classes and methods for spatial data in R. R News 5 (2). Available online at: https://cran.r-project.org/doc/Rnews

R Core Team. 2017. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. Available online at: https://www.R-project.org/

Ross-Smith, V.H, Thaxter, C.B., Masden, E.A., Shamoun-Baranes, J., Burton, N.H.K., Wright, L.J., Rehfisch, M.M. & Johnston, A. 2016. Modelling flight heights of lesser black-backed gulls and great skuas from GPS: a Bayesian approach. *Journal of Applied Ecology* 53 (6): 1676-1685.

RStudio Team. 2016. RStudio: Integrated Development for R. RStudio, Inc., Boston, MA. Available online at: http://www.rstudio.com/

Ruddick, K. & Lacroix, G. 2006. Hydrodynamics and meteorology of the Belgian Coastal Zone. In V. Rousseau, C. Lancelot & D. Cox (eds), *Current status of eutrophication in the Belgian Coastal Zone.* Brussels: Université libre de Bruxelles/Belgian Science Policy, pp. 1-15.

Tyson, C., Shamoun-Baranes, J., Van Loon, E.E, Camphuysen, K.(C.J.) & Hintzen, N.T. 2015. Individual specialization on fishery discards by lesser black-backed gulls (*Larus fuscus*). *ICES Journal of Marine Science* 72 (6): 1882-1891.

Vanermen, N., Courtens, W., Van de walle, M., Verstraete, H. & Stienen, E.W.M. 2016. Seabird monitoring at offshore wind farms in the Belgian part of the North Sea – updated results for the Bligh Bank and first results for the Thorntonbank. Report INBO.R.2016.11861538. Brussels: Research Institute for Nature and Forest.

Vanermen, N., Courtens, W., Van de walle, M., Verstraete, H. & Stienen, E.W.M. 2017. Seabird monitoring at the Thorntonbank offshore wind farm – Updated seabird displacement results and an explorative assessment of large gull behavior inside the wind farm area. *Reports of the Research Institute for Nature and Forest* 2017 (31). Brussels: Research Institute for Nature and Forest.

Venables, W.N. & Ripley, B.D. 2002. *Modern Applied Statistics with S. Fourth Edition*. New York: Springer.

Wickham, H. 2007. Reshaping data with the reshape package. *Journal of Statistical Software* 21 (12): 1-20.

Wickham, H. 2009. *ggplot2: Elegant graphics for data analysis*. New York: Springer.

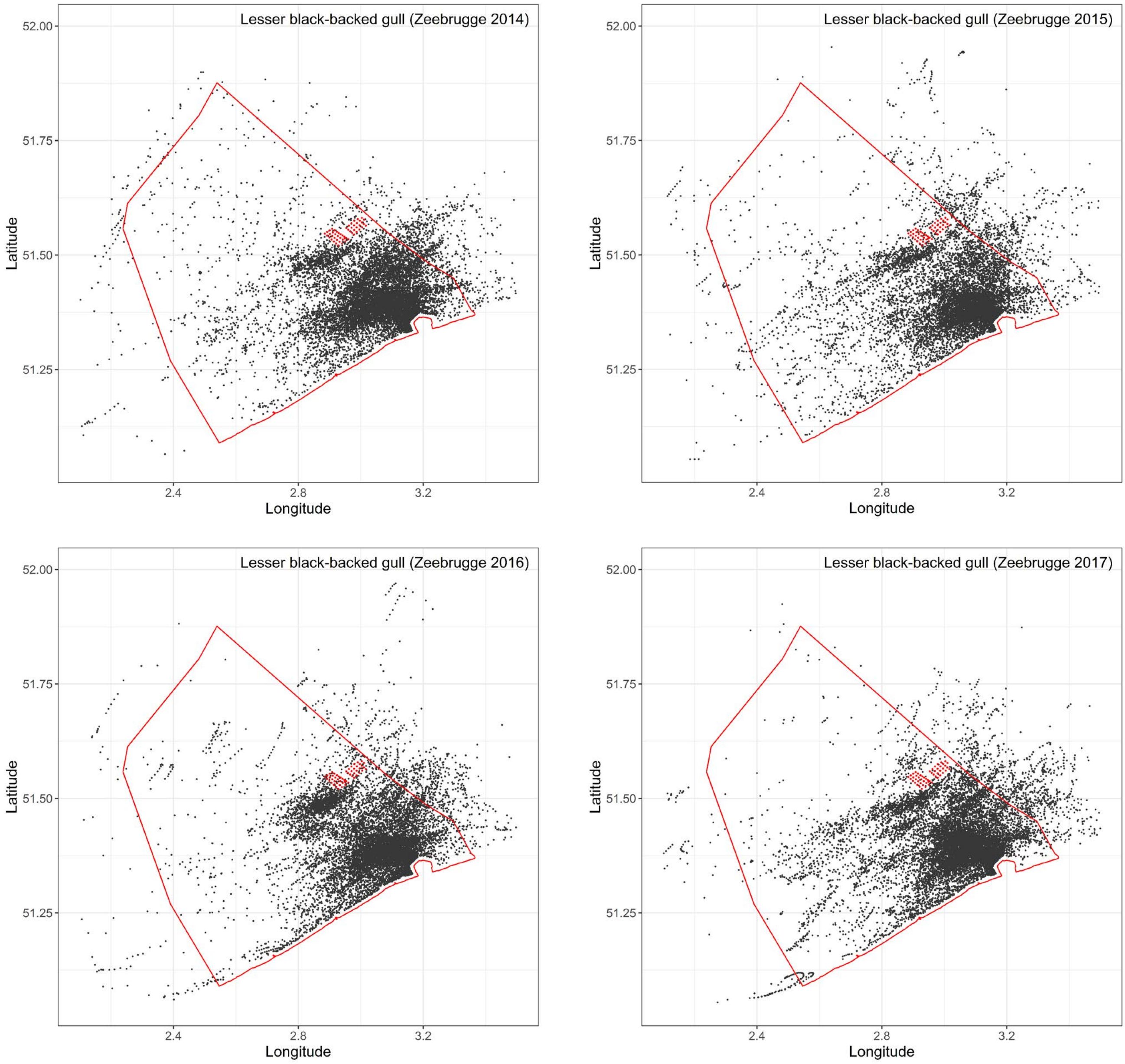
Wickham, H. 2011. The split-apply-combine strategy for data analysis. *Journal of Statistical Software* 40 (1): 1-29.

Wood, S.N. 2017. *Generalized Additive Models. An Introduction with R (2nd edition)*. London: Chapman and Hall/CRC.

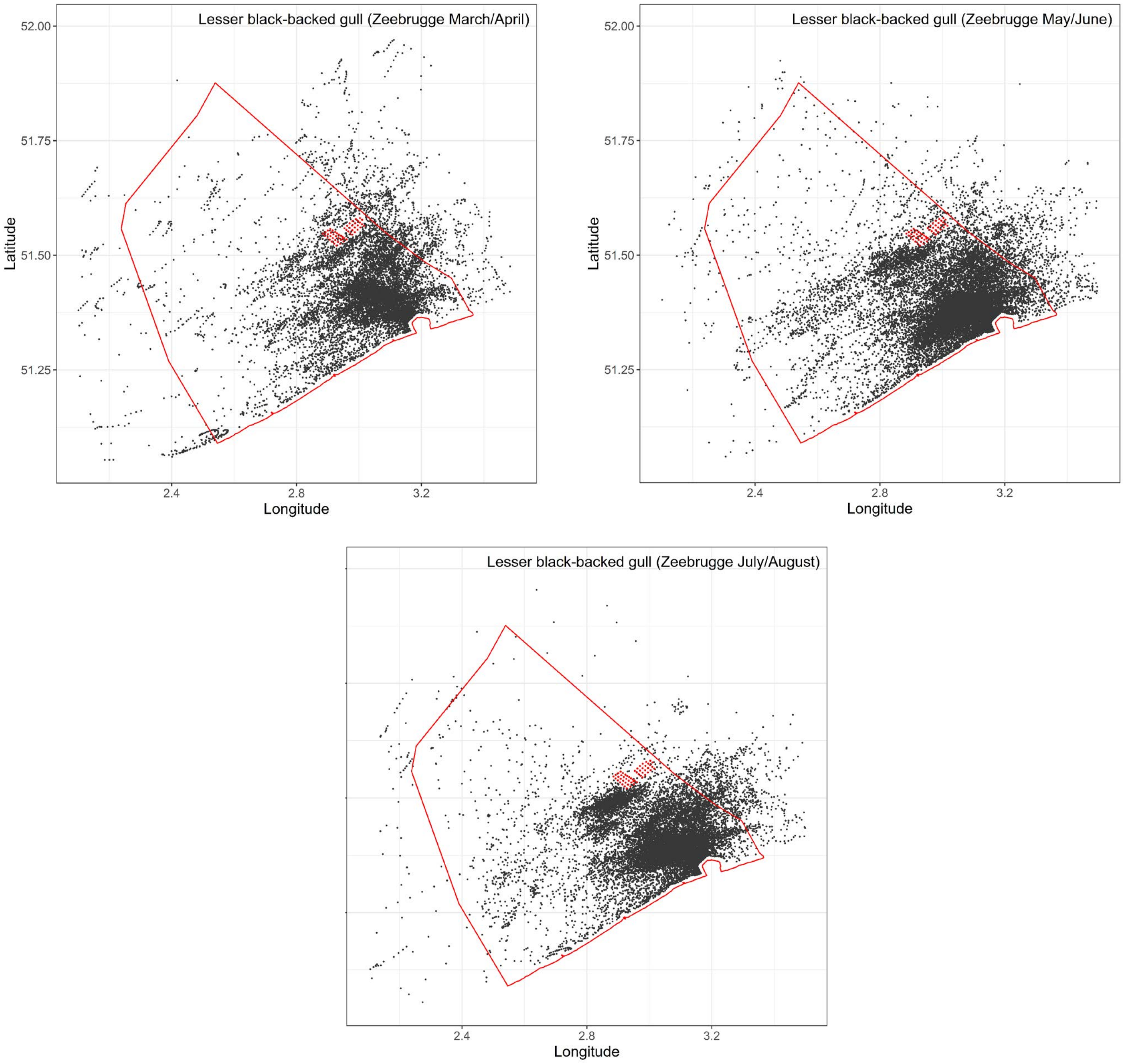
Zeileis, A., Keibler, C. & Jackman, S. 2008. Regression models for count data in R. *Journal of Statistical Software* 27 (8): 1-25.

Annex 1

Distribution figures



Yearly distribution patterns of birds from Zeebrugge.



Seasonal distribution patterns of birds from Zeebrugge.

Annex 2

Model summaries

2.1. Association with turbine foundations

```
Deviance Residuals:
     Min        1Q    Median        3Q       Max
-1.11087  -1.11087  -0.66867   0.05869   1.86667

Coefficients:
              Estimate Std. Error z value Pr(>|z|)
(Intercept)  0.9427338  0.3717886   2.536  0.01122 *
distance    -0.0029789  0.0009926  -3.001  0.00269 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Dispersion parameter for Negative Binomial(0.2577) family taken to be 1)

    Null deviance: 48.118  on 54  degrees of freedom
Residual deviance: 39.524  on 53  degrees of freedom
AIC: 157.19

Number of Fisher Scoring iterations: 1

              Theta:  0.2577
          Std. Err.:  0.0860

 2 x log-likelihood:  -151.1910
```

2.2. Modelling the effect of distance

```
Family: Negative Binomial(0.694)
Link function: log

Formula:
number ~ s(Distance, k = 8)

Parametric coefficients:
            Estimate Std. Error z value Pr(>|z|)
(Intercept)  1.06831    0.05551   19.24   <2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms:
              edf Ref.df Chi.sq  p-value
s(Distance) 5.731    6.5  38.97 1.59e-06 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) =  0.0147   Deviance explained = 6.59%
-REML = 1333.5  Scale est. = 1         n = 595
```

```
FLYING LBB
Family: Negative Binomial(1.155)
Link function: log

Formula:
number ~ s(Distance, k = 8)

Parametric coefficients:
            Estimate Std. Error z value Pr(>|z|)
(Intercept)  0.18140    0.05389   3.366 0.000762 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms:
              edf Ref.df Chi.sq  p-value
s(Distance) 2.331  2.908  19.58 0.000234 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) =  0.0236   Deviance explained = 3.42%
-REML = 909.53  Scale est. = 1         n = 595
```

2.3. Modelling temporal variation

```
Family: Negative Binomial(0.053)
Link function: log

Formula:
records ~ CI + weekend + s(Mean.wind.velocity, by = CI, k = 8) + s(hour, bs = "cc", k = 8) +
s(Tidal.height.TAW, k = 8)

Parametric coefficients:
            Estimate Std. Error z value Pr(>|z|)
(Intercept) -3.12260    0.08248 -37.857  < 2e-16 ***
CIIMPACT     0.57746    0.13401   4.309 1.64e-05 ***
weekendTRUE -0.38418    0.13459  -2.854  0.00431 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Approximate significance of smooth terms:
                                edf Ref.df Chi.sq  p-value
s(Mean.wind.velocity):CICONTROL 1.006  1.012 29.401 6.63e-08 ***
s(Mean.wind.velocity):CIIMPACT  2.916  3.661 27.528 1.09e-05 ***
s(hour)                         5.141  6.000 57.777 3.82e-12 ***
s(Tidal.height.TAW)             1.383  1.669  9.827  0.00351 **
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

R-sq.(adj) =  0.0197   Deviance explained =   12%
-REML = 2223.9  Scale est. = 1         n = 11600
```