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Preface

This report includes the results on fluxes, avoidance and flight behaviour of birds in offshore windfarm Borssele and the shipping lane within, based on measurements by a dedicated bird radar and visual observations. The work was commissioned by Rijkswaterstaat (RWS). Jos de Visser has coordinated the project with input from Dagmar van Nieuwpoort. Jos also provided useful comments on the setup of the research and together with Ingeborg van Splunder helped arranging the fieldwork. Joris Diehl and Koen Lim (RWS-CIV) gave assistance around technical issues with the bird radars and the radar databases. Tony ‘t Mannetje from the Rijksrederij arranged vessels for the bird counts. We thank him and all the crew members for their help and care during the fieldwork. Rene Somer (Robin Radar Systems) provided support from the radar manufacturer. We thank Marjolein Hormes and Alain Segberts from Ørsted for admitting the fieldwork within the wind farm, and all the planners for their cooperation. Marin van Regteren and Sander van der Horst from Eneco provided weather data measured in the wind farm. The study profited from fruitful discussions with Maja Bradaric and Jens van Erp (both University of Amsterdam).

The project team of Waardenburg Ecology consisted of the following field team: Elisa Bravo Rebolledo, Jacco Leemans, Koen Kuiper, Daniel Beuker, Nienke Heida, Job de Jong, Abel Gyimesi and Youri van der Horst, whose efforts made the collection of all the data possible. Data analysis was carried out by Jacco Leemans, Koen Kuiper, Nienke Heida, Rob van Bemmelen, Hannah Madden and Gerben IJntema. Abel Gyimesi had the overall responsibility as project manager and Ruben Fijn provided advice on the setup of the fieldwork and conducted the quality control. Robert Middelveld, Marije Stokkers and Tom Raats assisted with the figures in this report. We thank them all for their contribution.

Jorg Welcker (BioConsult SH), Roel May (NINA), Henri Zomer en Martine Graafland (both Rijkswaterstaat) provided comments on the concept version of this report. We thank them fort heir valuable contribution.

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Executive summary

Aim and scope

The main aim of this project was to carry out measurements on bird numbers and bird behaviour in relation to an offshore wind farm. More specifically, based on field observations and radar measurements we collected information on bird fluxes, flight behaviour, meso-avoidance and area use, in particular to any differences within a shipping lane inside the wind farm. The ultimate goal was to gain new insights that help to better understand the effects of offshore wind farms on birds.

Species composition (§3)

Species composition during daytime in and around the wind farm was determined through visual observations following two observations protocols: boat surveys and flux measurements. The most common species in winter were black-legged kittiwake, common gull, common guillemot and razorbill. Regular but less frequent species present in winter included northern gannet, great black-backed gull and herring gull. During spring migration sandwich tern and lesser black-backed gull were found to be the most numerous species in the wind farm. In late spring and early summer, during the breeding season, few birds were present and species composition was almost solely comprised of lesser black-backed gull. Through late summer and autumn numbers of lesser black-backed gull were highest. During autumn migration most different species were encountered. Migrant species regularly seen in this time were sandwich tern, black-headed gull and little gull alongside returning common winter visitors. Note that the presented species compositions are only representing bird activity during daylight, as visual observations during night-time could not be carried out.

General flux patterns (§4)

This chapter presents the results of visual flux measurements of local birds and more than four years of radar measurements.

Visual fluxes

Fluxes based on visual measurements were determined as the number of birds flying through an area per km per hour. Average fluxes were determined for all birds, all seabirds and on species level for the two most common species, lesser black-backed gull (n = 138) and black-legged kittiwake (n = 48). Fluxes were not different in the corridor compared to the wind farm for all seabirds nor all observed bird species together, except when comparing number of birds for all bird species instead of number of observations. This is likely caused by higher numbers of non-seabird species (for example starlings on migration) by chance crossing the field of observations in the corridor, although those birds could have just as well been observed in the wind farm. Average fluxes were about two times higher in the morning than in the afternoon for all investigated groups. Expectedly, average fluxes for lesser black-backed gull were highest in spring and summer and fluxes for black-legged kittiwake were highest in autumn and winter as these species occur seasonally in the area. Lowest average fluxes for all birds and seabirds were found in spring and highest fluxes were found in autumn. Note that the amount of collected data on visual fluxes is limited and variation in data is high. Also note that visual fluxes only represent the situation during daylight.

Radar fluxes

In the study period from the 1st of October 2019 to the 31st of December 2023, on average 28 and 120 bird targets per km per hour (day and night together) were recorded in wind farm Borssele by the horizontal radar and the vertical radar respectively. Exceptionally high fluxes of more than 500 bird targets per km per hour were recorded by the horizontal radar in 9 out of 9,449 hours (0.1%), and by the vertical radar in 284 out of 9,833 hours (2.8%). These peak hours mostly occurred during the night in March, October and November, and hence mostly consisted of nocturnally migrating birds. The vertical radar generally recorded higher mean traffic rates (MTRs) than the horizontal radar. Even considering only vertical radar tracks up to an altitude of 300 m (which is approximately the altitude range of the horizontal radar), the number of tracks detected by the vertical radar is mostly higher than the horizontal radar. Possibly, both radars differ in performance in terms of their capability to detect birds. However, as the two radars are of a different type (horizontal S-Band vs vertical X-Band radars), and also the method to derive fluxes was different for both radars, it is difficult to assess to what extent the difference in the recorded fluxes is a result of these technical or methodological differences .

The temporal variation in the hourly average number of tracks per km showed a roughly similar pattern each year, with peak fluxes in early spring (March) and autumn (October and November). These patterns were recorded by both radars, although the peaks in spring were less noticeable based on the horizontal radar. Higher MTRs in March, October and November were generally recorded in each year of the study period, with the exception of March 2020 (possibly due to a lack of data remaining after filtering). The extent to which these peaks were recorded by the radars slightly differs between each year. During the peak seasons, the main flight directions were easterly in spring and south-westerly in autumn.

Flight activity in Borssele was not constant during the day. The radar measurements revealed that during the migration periods in spring and autumn the number of birds passing through the area was peaking at the start of the night. During the night, the numbers steadily decreased to daytime levels. In winter, the number of birds were the highest during the daylight period, with slightly elevated numbers just after sunrise. In summer, no clear differences were recorded in the MTR throughout the day. The relative percentage of tracks during day and night (corrected for number of hours of day/night) showed a clear pattern with an increasing proportion of night-time tracks during spring and autumn migration in their respective peak months March and October (77% of tracks at night). Relatively most tracks during daytime were recorded in January and December (61-68% at daytime). Flight direction during the peak hours in autumn slightly differed throughout the night. During autumn birds generally fly towards the (south)west. However, around sunrise these directions divert towards south and even to southeast. This may indicate nocturnal migrants making correction flights towards land. Around sunset in autumn birds fly more (north)west.

The temporal patterns in fluxes throughout the year (i.e. highest fluxes during migration in March and October) and seasonal patterns throughout the day were in line with the patterns in fluxes measured earlier in wind farms OWEZ (Krijgsveld *et al.* 2011) and Luchterduinen (Leemans *et al.* 2022b). When applying the monthly species composition of birds in flight measured during ship-based surveys on the average bi-monthly radar fluxes during daylight, we found that the highest species-specific fluxes (of lesser black-backed gull and black-legged kittiwake) in Borssele were somewhat lower than the species-specific fluxes measured in wind farm Luchterduinen. On the other hand, for several species (black-headed gull, common gull, herring gull, little gull, common guillemot, razorbill, common tern and Sandwich tern) the highest flux in Borssele was in at least one bi-monthly period higher than in Luchterduinen.

Effect weather on fluxes (§5)

This chapter presents the effects of local wind speed and direction on the radar fluxes in Borssele. Mean traffic rates of more than 500 tracks/km/hour were recorded with wind speeds between roughly 1 and 15 m/s (*i.e.* 1-7 Bft). The highest MTRs during peak migration were generally with wind speeds between roughly 3 and 6 Bft. In spring, these peaks occurred with on average lower wind speeds (3-4 Bft) than in autumn (5-6 Bft). Bird flight activity (of local birds) during the day in summer and winter was not significantly affected by wind speed.

Wind direction, in combination with wind speed (expressed by an eastern and a northern component), significantly affected bird flight activity in all seasons. Bird flight activity (of local birds) during the day in both summer and winter was higher with winds with a strong northern component and a strong eastern component. Furthermore, the model predicted elevated bird activity during the day in summer with strong southwestern winds. In winter, a strong eastern wind component always resulted in higher predicted MTRs than strong western components, regardless of the south-north component.

When only considering peak migration hours with more than 500 birds per km per hour, we found that spring migration mainly occurred with southern and especially south-western winds, while the highest MTRs during autumn migration were found with north-eastern and eastern winds. MTRs were significantly higher with more tailwind in spring, while this relation was not significant in autumn. However, note that the hours in autumn with the highest MTRs are lacking horizontal radar data. As such, these hours were not included in the analysis as data on the average hourly flight directions from horizontal radar data were necessary to calculate the amount of tailwind per hour.

Occasionally, migration peaks in both spring and autumn may occur during hours with sidewind or even winds going towards headwind. Remarkedly, five of the peak nights recorded by the horizontal radar in autumn were with relatively unfavourable wind directions, while all peak nights recorded by the vertical radar were with predominantly tailwinds. One hypothesis is that with more headwind, birds tend to fly lower, and therefore larger numbers fly within the altitude range of the horizontal radar. This might also explain why all peak nights measured by the horizontal radar were recorded in autumn, as migration in autumn generally occurs at lower altitudes.

The analysis of the effect of weather on bird radar fluxes in Borssele was largely restricted to periods with relatively calm weather due to the sensitivity of the radars to wave and rain clutter. Furthermore, as we lack rain measurements at the radar location, we were not able to directly link radar fluxes to the amount of precipitation. Potential weather effects on bird fluxes were also explored by looking into the fluxes obtained through visual flux measurements. However, as field days were limited to calm weather conditions due to safety regulations and to ensure carrying out reliable visual observations, we were not able to collect enough field data under varying weather conditions to conduct meaningful analyses on fluxes measured during visual observations.

Corridor use (§6 and §7)

As described in chapter 6, no differences in bird density were found between the corridor and inside the wind farm based on ship-based survey data. The studied species (lesser black-backed gull, black-legged guillemot, northern gannet, razorbill, common guillemot and common gull) do not seem to prefer the corridor over the rest of the wind farm. We did find less northern gannets and more lesser-black backed gulls in the border of the wind farm than inside of it. These densities were used in chapter 7 to estimate flux using the collision rate model (sCRM). When comparing those fluxes to the fluxes measured in the field, these (largely) differed from each other, but neither a systematic over- nor underestimation was detected. The input used to calculate flux has a large influence on the results, which shall directly translate into large differences in the final estimates of the number of collisions.

Flight height (§8)

This chapter presents data on the flight height of birds in wind farm Borssele. First, vertical radar data is used to show general patterns in flight height throughout the year and during the day and then relate these patterns to (weather) circumstances. Then, we present species compositions of local seabirds in different height classes as observed during visual flux measurements and boat surveys, and statistically analyse whether species-specific flight heights differ between different areas in the wind farm (*i.e.* corridor, inside wind farm or edge wind farm) or between seasons.

Radar flight heights

The highest number of bird tracks was measured at altitudes between 5-10 and 20-30 meters. Above 30 meters, the number of detected tracks steadily decreased with altitude. The altitude profiles were relatively similar between each season. Most noticeable were the relatively high numbers of tracks at higher altitudes in spring, which were not recorded in the other seasons. In peak hours with more than 500 tracks/km/hour, the proportion of tracks above rotor height was significantly higher in spring and summer (median ≈ 0.8), than in autumn and winter (median ≈ 0.4-0.5). On the other hand, the proportion of tracks at rotor height in spring was significantly lower than in winter and autumn. The proportion of tracks below rotor height was highest in winter.

The median flight height was in each season significantly lower during the day than in the night. At night, the median flight height was higher in spring than in the other seasons, while during the day, the median flight height was lower in winter compared to the other seasons. The median flight height during peak hours with more than 500 tracks/km/hour in spring was nearly always higher than during peak hours in autumn. In peak migration nights in spring, flight heights were on average somewhat higher between sunset and midnight, while in autumn, flight heights were higher at the start and end of the night, especially around sunset, compared to the rest of the night.

The median flight height seemed to show a positive correlation with wind speed, suggesting that birds tend to increase their flight height with stronger winds. However, we cannot exclude that some clutter related to wave height that may have remained in the dataset also affected this correlation, as prior to filtering we also found a strong positive correlation between flight height and wave height. In peak migration nights in spring and autumn, no effect of wind speed on the proportion of tracks above, at or below rotor height was found. We found no correlation between wind direction and median flight height. However, flight heights were generally higher with more tailwind, especially in autumn. Lastly, the proportion of tracks at rotor height during peak hours in autumn was significantly lower during construction and operation (median of approx. 0.5), than during piling (median just above 0.6). These results suggest that birds have generally increased their flight height after the erection of wind turbines, as the proportion of tracks above rotor height have increased. It must be noted, however, that the data during piling is only based on one season.

Species-specific flight heights
Apart from the flight heights recorded by the radar we also analysed flight heights of local seabirds through two types of visual observations: flux measurements and boat-based observations. We tested the effects of the seasons and of the area of the wind farm where the bird was observed in (within the farm, on the border or in the corridor) on flight heights. We found statistically significant effects of both season and the area, especially for the black-legged kittiwake. Kittiwakes seemed to fly more often at collision risk height in winter than in spring. We speculate that this effect may be due (e.g. naïve young birds) birds that arrive in late autumn, habituate to the presence of turbines in the course of the seasons. Given these differences in flight height in kittiwakes, more research is suggested to determine whether changes in flight height over the seasons also cause a higher collision mortality. The descriptive results suggest that black-legged kittiwakes fly lower inside the corridor compared to inside the wind farm. Lastly, while we also found significant effects of season and area on larger aggregations of species (species groups), these effects may be largely influenced by a single species that was most present in such species groups (e.g. the species group of small gulls consisted mostly of kittiwakes).

Flight speed (§9)

In this chapter, we present data on the flight speeds of birds in wind farm Borssele. Here, flight speed refers to the ground speed, which is the speed of a flying bird relative to the ground and is therefore not corrected for wind. Horizontal radar data is used to show general patterns in flight speeds throughout the year and during the day and then relate these patterns to weather circumstances. The average flight speed of all radar tracks (*i.e.* all birds combined) that was measured by the horizontal radar in the study period was 13 m/s. Flight speeds did not substantially differ between the seasons, with the exception of summer, in which the average flight speed was significantly lower than in the other seasons. Generally, the average flight speed was significantly higher during the night than during day, most notably in winter and spring. Only in autumn the average flight speed was not significantly different between night and day. The highest average ground speeds per hour were often recorded in hours with relatively high fluxes, which indicates that bird migration occurs at on average higher flight speeds (m/s) than the flight speeds of local birds.

Flight speeds were directly influenced by wind speeds, although the extent of this influence depends on the difference between flight direction and wind direction. At lower flight speeds (up to roughly 16 m/s), no correlation was found between flight speed and wind speed. However, higher average flight speeds were almost exclusively recorded in hours with higher wind speeds (3 Bft or higher). Furthermore, the highest average flight speeds were recorded during the night with winds from the east, northeast, southwest or west, which matches with the wind directions with which nocturnal bird migration in spring and autumn mainly occurs. The average ground speed showed a clear positive correlation with the amount of tailwind, especially in spring.

The eleven most tagged species(groups) were used to analyse species-specific flight speeds. Results showed highest flight speeds for common starlings and northern gannets. All gull species showed similar flight speeds, except little gull which showed a reasonably lower flight speed. Variation within species could be the result of varying wind direction and wind speed but also different kind of flights, *e.g.* commuting versus foraging flights. As little gulls were often seen in foraging flights at low altitudes above the sea level, we argue that this behaviour was captured within the flight speeds of the tagged birds (n=5). Remarkedly, the flight speed of each species was lower in Borssele than the flight speed measured by radar in wind farm Luchterduinen. Possibly, birds in Borssele may show on average more foraging behaviour and thus lower flight speeds than in Luchterduinen.

Meso-avoidance (§10)

Integrated Step Selection Functions (iSSFs) have recently been used to estimate macro-avoidance of offshore wind farms by birds, based on GPS-tracks of individual birds, which opens up the possibility to use iSSFs to estimate meso-avoidance. In chapter 10, we apply iSSFs to estimate horizontal meso-avoidance using radar tracks. In contrast to more commonly applied methods to estimate meso-avoidance, this approach allows inclusion of track-level covariates, such as species identification. Using iSSFs also directly models bird movement behaviour. We applied this method to two radar track data sets: 1) tracks observed and identified to species level in the field and 2) six autumn nights with intense southbound migration. Our estimates of meso-avoidance at the species- or species-group-level were associated with considerable uncertainty, which is likely attributable to the low sample sizes. Overall, the tagged tracks indicate an meso-avoidance rate of 27%. Meso-avoidance estimate during nights with intense migration suggested a much higher avoidance of 63%, which varied among nights between 43% and 73%. Finally, we highlight potential applications of this model for further study of meso-avoidance and formulate several recommendations for improvements of the model and its estimates.

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1 Introduction

1.1 Background

The world cannot cope with climate change without a global energy transition. As burning fossil fuels is the main cause of climate change, a sustainable energy supply helps to combat climate change. The rollout of offshore wind farms is indispensable for the Dutch energy transition to achieve the goals of the Paris Climate Agreement (Macquart *et al.* 2023). However, the development of offshore wind energy is also expected to have negative effects on nature (Akerboom *et al.* 2021, Piet *et al.* 2021).

Also the cumulative assessments within the Framework for Assessing Ecological and Cumulative Effects (in short KEC; cf. the Dutch abbreviation), financed by the Dutch governmental body Rijkswaterstaat (RWS), showed the intended developments of offshore wind energy may lead to cumulative effects on bird species (Potiek *et al.* 2022). Due to these expected effects, the Dutch Ministry of Economic Affairs commissioned RWS to deploy an integrated research programme to reduce the knowledge gaps with regard to the effects of offshore wind farms on the North Sea ecosystem, which was named the Offshore Wind Energy Ecological Programme (Wozep).

Measuring species-specific bird fluxes, collisions and avoidance behaviour is an essential research focus of Wozep. The aim is to generate knowledge that reduces uncertainties of input parameters of models that are used in assessments of future wind farms, and hence Wozep research projects often have a direct application. One of the uncertainties in wind farm assessments concerns the determination of the numbers of casualties that is currently done in the Netherlands by using the Stochastic Collision Risk Model (sCRM), which is based on the Band model (Band 2012). This model heavily relies on assumptions about avoidance behaviour, bird fluxes, flight speeds and flight altitudes. In order to collect more in-field measurements on these parameters, specialized bird radars, cameras and visual observations are currently the best available data collection methods.

To contribute to the collection of such data, RWS has purchased six Robin 3D Fixed Radars, consisting of a horizontal and vertical radar (in short: RWS bird radar). One of these radars was installed on the Alpha platform of Borssele wind farm (BSA). Subsequently, RWS commissioned Waardenburg Ecology to carry out research on bird fluxes, flight- and avoidance behaviour in offshore wind farm Borssele. More specifically, the research in BSA was also intended to investigate whether a so-called shipping lane (further in this report referred to as ‘corridor’) is also recognised by birds as a safe passage route through the wind farm, and hence occur there in different numbers or show different behaviour.

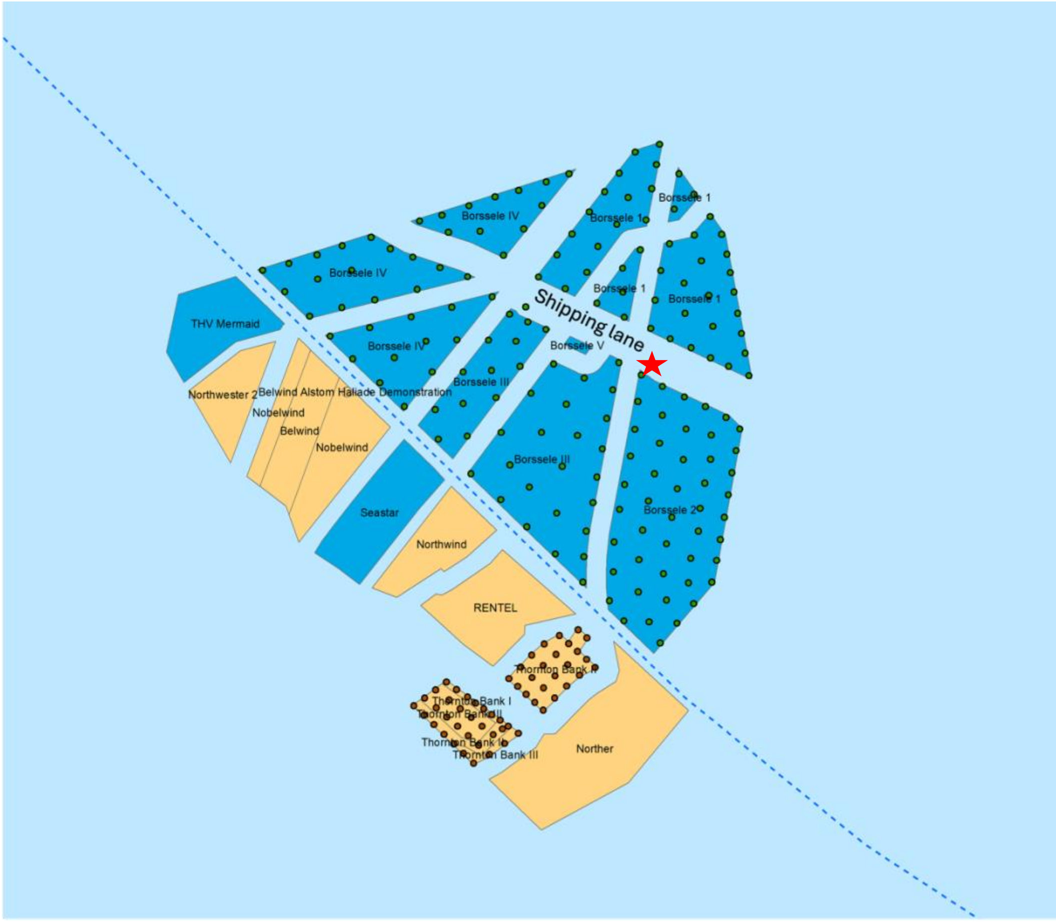

Figure 1.1 *The five plots (Borssele 1, 2, 3, 4 and 5) and the turbine locations of offshore wind farm Borssele along the Dutch - Belgian border (dotted line) and the adjacent Belgian wind farms. Also the east-west oriented shipping lane in the middle of wind farm Borssele is indicated. The radar location is indicated with a red star.*

1.2 Aim and scope

The first priority of the RWS bird radar in BSA was to measure fluxes, meso-avoidance and corridor use of birds. As RWS wanted to have species-specific information, the research questions were formulated as which species, and in what numbers, occur in the offshore wind farm, and do they adjust their flight path in the wind farm in relation to the presence of the corridor? The goal was to focus on 4-6 bird species, including at least the three most common gull species and nocturnal migratory birds.

In specific, the current project aimed to gather knowledge on the following research topics:

1. Flux, group size and flight height of species.
2. Relationship of these fluxes to bird densities reported in previous monitoring studies.
3. Use of corridors by birds within the wind farm.
4. Species- and season-specific meso-avoidance.
5. Factors affecting the above variables, such as season, diurnal rhythm and weather.
6. Understanding the origin of uncertainties in the results.

The results gathered during this study, in combination with the results of other Wozep projects, can lead to new insights both into avoidance behaviour and empirical collision risks, which can be used directly in collision risk models. With these results, the effects of new offshore wind farms can be studied in much greater detail in the future. Later on, also the results of model calculations can be validated against actual measured collisions. The data collected can also be used for other purposes: flux data for example for the development of a bird warning system for (future) offshore wind farms or to operationalize a stop/start procedure (shutdown-on-demand). Moreover, the experiences gained during this project on the corridor use of birds in wind farm Borssele will shed light on whether a corridor in an offshore wind farm could be an efficient mitigation measure, which could help the spatial design of wind farms at other locations.

2 Data collection

2.1 Study area

Offshore wind farm Borssele is located in the southeastern tip of the Dutch Continental Shelf (NCP) against the border with the territorial waters of Belgium. The water depth in the wind farm ranges from 14m to 36 m. The total area is 344 km^2 and divided into four subplots. Our field observations on fluxes mainly took place in Plot I (63 km^2) and Plot II (60 km^2), the two eastern plots of the wind farm, owned by Ørsted and Plot III (75 km^2) in the middle of the wind farm owned by Blauwwind. These plots lie along the Dutch coast of Zeeland, the closest point being 23 km and the farthest point 39 km from Westkapelle, and approximately 100 km from the coast of Southeast England. Furthermore, the width of the corridor is approximately 2 km, while the average distance between turbines in wind farm Borssele is almost 1.3 km.

The construction of the wind turbines in wind farm Borssele started in the last quarter of 2019 (that of Plot I and II in 2020) with piling foundations, while the first towers and blades were installed in April 2020. Construction of all turbines was completed in November 2020. Plot I and II were officially opened in September 2021. The wind farm consists altogether of 173 turbines of 8-9.5 MW, of which 94 turbines are located in Plot I and II of Borssele and 77 turbines in Plot III and IV. These latter wind turbines are of the type Siemens Gamesa, with a rotor diameter of 167 m, and heights of the lower and upper rotor tip of respectively 25 and 192 m. The blade length of these turbine is 81.4 m, and hence the swept area of each turbine is 21,900 m^2. In Plot III and IV there are 77 V164-9.5 Megawatt turbines produced by Vestas. The heights of the lower and upper rotor tip of these turbines are respectively 25 and 189 m.

2.2 Radar measurements

2.2.1 Radar specifications

On platform Borssele Alpha ('BSA') (Figure 2.5) Rijkswaterstaat installed a so-called Robin 3D Fixed bird radar system, consisting of a horizontal Furuno magnetron-based S-band radar and a fixed vertical Furuno magnetron-based X-band radar. The system is developed by Robin Radar Systems as a dedicated radar to detect flying birds. The horizontal radar was installed on the Utility Deck (39.5 metres above sea level) and the vertical radar was installed on the Roof Deck (47.6 metres above sea level) of BSA (Figure 2.1). The installation of the radars was carried out in August 2019 and the radars were calibrated in September 2019.

In theory, the horizontal radar emits radiation 360 degrees round, but to ensure health safety of humans working at the platform, to protect the platform itself from radiation, and to minimize false radar echoes caused by the platform, a blank sector is created to avoid radiation towards the platform. As the horizontal radar is located at the southwest corner of the platform, the blank sector covers the area northeast of the platform. The blank area is 124° wide, which is 34.4% of the complete circle around the radar. The horizontal radar emits radiation vertically with an angle of 25° (12.5° upwards and 12.5° downwards, thus touching the sea water surface at around 178 m from the platform (Figure 2.1). The longer wavelength of the S-band means that the horizontal radar has reduced sensitivity to smaller objects, which then reduces the detection of small birds and the potential contamination of the radar database by echoes caused by rain and waves. The combined effect of the detection and clutter suppression capabilities of the S-band radar is an improved detection of medium- and large-sized birds within the scanned range of 6 km. The horizontal radar can detect birds up to altitudes of roughly 300 m.

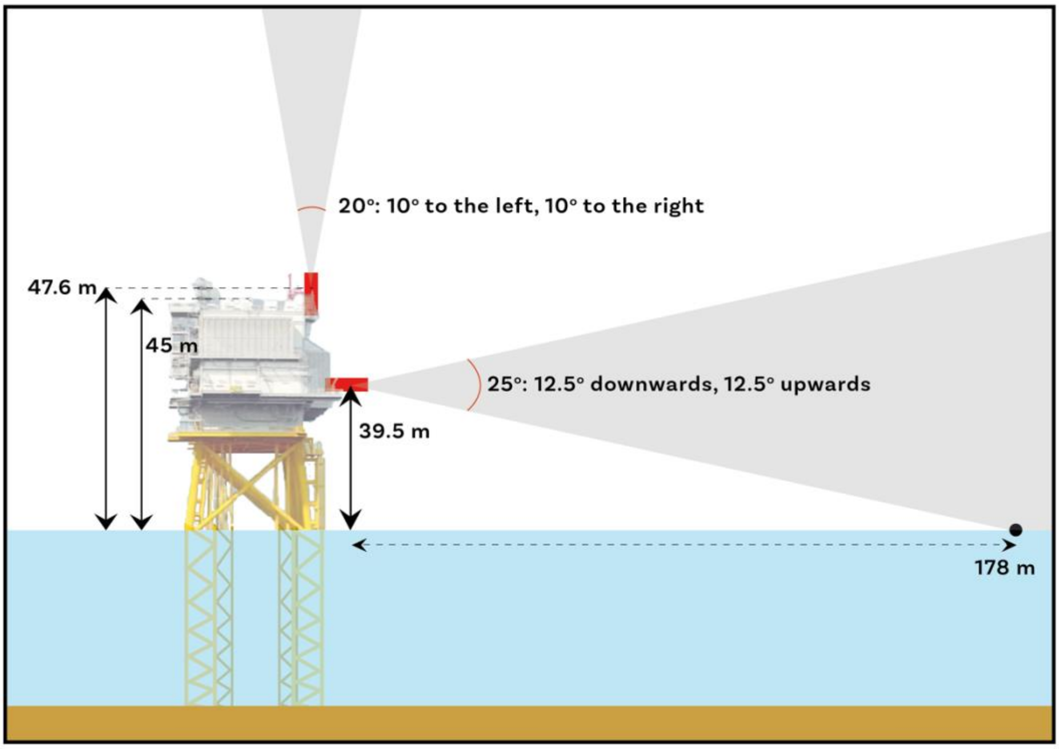

Figure 2.1 *Position of the vertical (upper red rectangle) and horizontal (lower red rectangle) radar on BSA, together with the heights of the radars above mean sea level and the widths of the radar beams.*

The vertical radar works in a similar way to the horizontal radar but tilted 90 degrees, resulting in a rotation of the radar in the vertical plane. Emission of the vertical radar is blanked downwards to prevent superfluent clutter (*i.e.* unwanted back-scattered signal), reflection from the water and the platform components beneath the radar. The vertical beam is rather narrow, and hence the radiation field resembles a 'bow-tie' shape when viewed from above. The vertical radar is orientated from the northwest to southeast, which is perpendicular to the main migration direction of birds in this part of the North Sea in autumn (see Figure 4.1). The vertical radar can detect birds up to altitudes of roughly 3-4 km. Radar tracks detected by both the horizontal and vertical radar are combined by the radar software into a 3D track, containing information both on the horizontal position in space and the altitude. As the radar system was developed to detect flying birds, whenever we report radar results on bird activity, these always consider birds in flight, i.e. bird flight activity.

2.2.2 Data filtering

Prior to the analyses of the data collected by the radar, several steps were taken to filter the dataset to prevent as much as possible any non-bird tracks entering the calculations. First of all, in all our radar analyses, we included all radar data from 1 October 2019 until 31 December 2023, unless indicated otherwise in the methods section of a chapter. Some of the further filtering steps were only applied to the data of one of the radars, as the two radars differ in their sensitivity for different clutter sources. Namely, the different radar types and the different wavelengths mean that the sensitivity to clutter induced by waves and precipitation also differs significantly between the two radar types. All filter steps are outlined in this paragraph, where we indicate between brackets to which radar dataset we applied the described steps. For the vertical radar, most filter steps were in line with an earlier Wozep study carried out with an offshore bird radar in offshore wind farm Luchterduinen (Leemans *et al.* 2022b), while for the horizontal radar, most filter steps were following the methods of van Erp *et al.* (2023).

Rain showers (vertical radar)

In rainy weather, the vertical radar is susceptible to record rain showers as bird targets. When this happens, rain showers may introduce large amounts of clutter into the database in short periods of time (Figure 2.2). Possibly, these rain showers develop too fast to activate the dynamic radar filters on time. If so, the radar usually classifies these showers as birds. The large number of tracks in the database created by rain showers could severely distort the flux calculations. Therefore, we aimed to filter out all hours of which we had any indication that it could be raining in Borssele. The nearest location for which rain measurements were available is located near the shore. As rain showers may occur very locally, we did not find these data useful to effectively carry out rain filtering of the dataset. Hence, we applied other filtering steps in which we indirectly identified periods with rain (clutter). By carrying out these steps, we could effectively filter out the hours with the most intensive rain showers.

First of all, we used data from the radar database that indicate the percentage of each radar image where rain filtering was active. We determined per minute how many vertical radar images were more than 5% affected by the rain filter. If this threshold applied to more than half of the radar images in a minute, then this minute was marked as a ‘rain minute’. If one hour consisted of more than 9 ‘rain minutes’, then this hour was marked as ‘rain hour’. Subsequently, all ‘rain hours’ were filtered out from the dataset. The main purpose of this filtering step is to identify hours with a 'negative observation bias' (van Erp *et al.* 2023). If the dynamic radar filtering is activated by rain, it prevents rain clutter from entering the database. However, at the same time, it also reduces the detection of bird tracks.

As mentioned above, rain showers could still enter the database due to the delay in the activation of the dynamic radar filtering. Therefore, we applied two additional filtering steps, in which we identified these rain showers. One step is based on the properties of each track, which are assigned to each track by the radar software. Tracks of rain showers are often assigned the property ‘in blob formation’ (Leemans *et al.* 2022b), which is a property that is assigned by the radar software to targets with multiple reflection centres, assumed to originate from different tracks that are detected at (very) close distance to each other but not distinguishable by the tracker of the radar as individual tracks. On the contrary, in hours with intensive bird migration, the property ‘in blob formation’ occurs considerably less often. Therefore, we filtered out all hours in which more than 100 tracks were assigned as ‘in blob formation’ and at least 15% of all tracks during that hour were assigned as such. For this, we used all tracks that intersected with a flux line of one kilometre (see §4).

Rain showers may introduce large amounts of clutter into the database in short periods of time. Hence, in the last filtering step, we determined the number of vertical radar tracks per five minutes. We then identified all five-minute periods with at least 100 tracks and at least three times more tracks than in the previous period (again using all tracks that intersected a flux line of one kilometre). All hours in which this threshold was (at least once) met, were filtered out from the dataset.

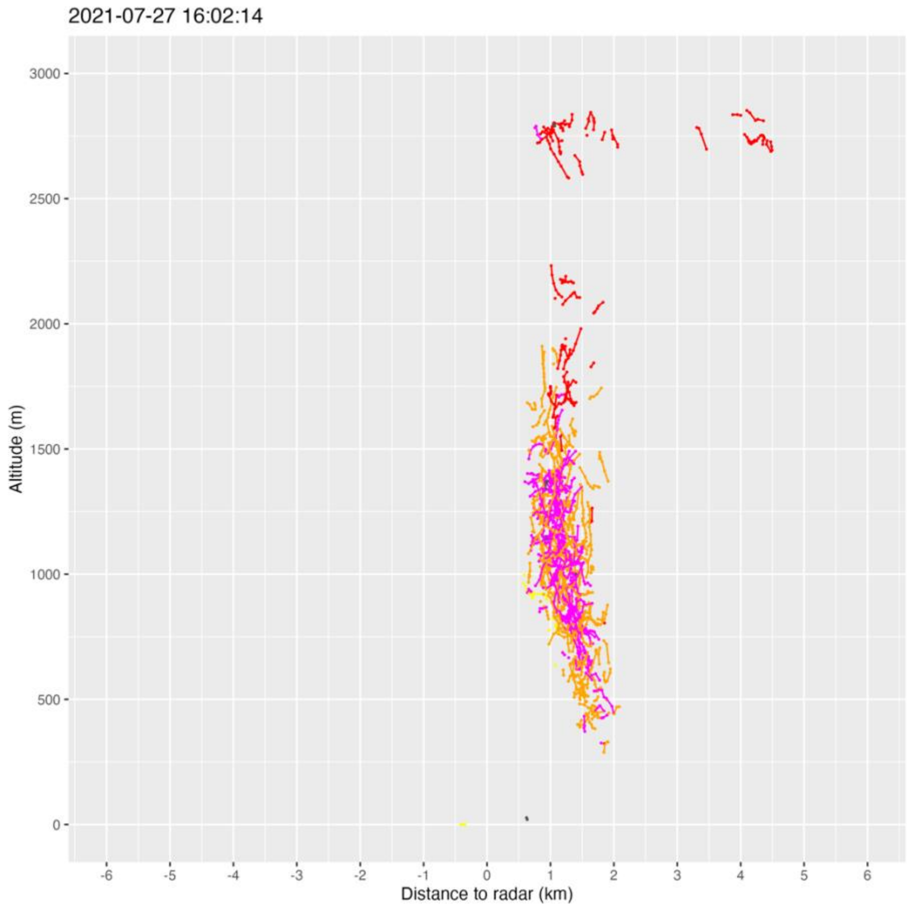

Figure 2.2 *Typical example of a rain shower registered by the vertical radar. Different colours represent different radar classifications.*

Wave clutter (horizontal radar)

In a similar way to rain, sea clutter may in theory also contaminate the radar dataset with non-bird targets, while at the same time, a high filter activity caused by waves may also hamper the detection of birds and thus introduce a negative observation bias (Mateos-Rodriquez 2009). For example, Krijgsveld *et al.* (2011) showed that birds could not be recorded by a bird radar at wave heights more than 1.80 m (corresponding to 3 Bft. wind from the west). Radar validation of the radars at BSA showed that at wave heights between 0.5-1 m, the detection probabilities of smaller birds within 2 km of the radar are already decreasing (Leemans *et al.* 2022a). Due to their smaller size and corresponding smaller radar signal strength, songbirds are expected to suffer earlier from being lost in sea clutter than larger birds. Therefore, in order to prevent the calculation of unrealistic bird fluxes due to superfluous radar filtering or a high number of sea clutter entering the database as birds, we removed all hours with an average 'land mask' filtering above 0.14. The land mask value indicates the percentage of each radar image on which filtering is active due to, for example, wave clutter. The threshold was determined following the methods of van Erp *et al.* (2023), in which we modelled the average hourly land mask value against the hourly number of tracks with a Generalized Additive Model (GAM). Then we determined at which land mask value the first derivative of the model was at its minimum (*i.e.* at which land mask value the decline in tracks is the steepest) and took this value as the threshold.

Wave clutter (vertical radar)

In comparison to the vertical radar in wind farm Luchterduinen (Leemans *et al.* 2022b), the vertical radar at BSA seems to be more susceptible to wave clutter (Leemans *et al.* 2022a). More specifically, the number of tracks detected by the vertical radar showed a strong positive correlation with wave height (Figure 2.3), which is suggestively a result of wave clutter. However, other explanations, like clutter from spinning rotor blades, cannot be ruled out. We had to apply several additional steps to remove this clutter from the database. First of all, we removed all tracks with an average altitude below 3 m. Then, we looked at which characteristics of tracks had a (strong) correlation with wave height and identified three radar characteristics that were useful for filtering. Firstly, we found that with increasing wave height, the altitude of tracks decreased generally stronger during their lifetime. Secondly, with increasing wave height, tracks were on average much shorter. Lastly, with increasing wave height, the average direction of tracks generally became less clear (note that tracks detected by the vertical radar could only move towards or away from the radar, as this radar has no information on movement direction in the horizontal plane). We expressed this as the 'ratio of directions', in which '1' means that all tracks go in the same direction, while '0' means that the number of tracks that move towards the radars is equal to the number of tracks that move away from the radar.

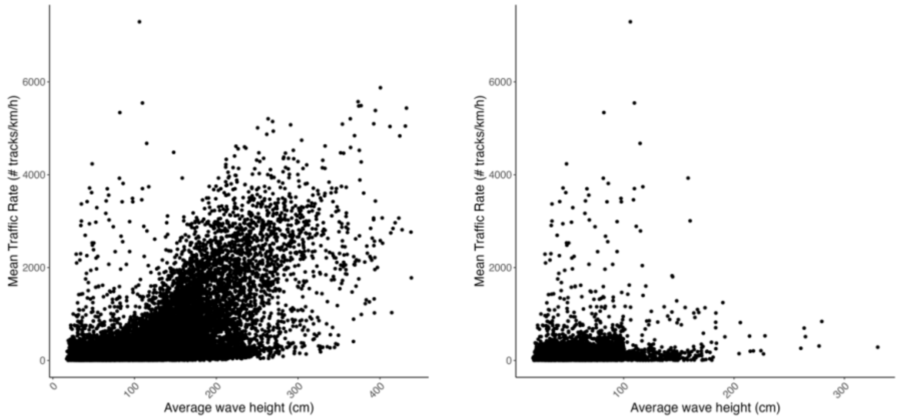

Figure 2.3 *Average hourly wave height (cm) vs the number of tracks per km per hour before wave filtering (left) and after wave filtering (right).*

Based on these findings, we determined thresholds with the aim of removing the hours with falsely high traffic rates, while retaining hours with (most likely) bird migration. We first filtered out all hours with an average track elevation or a median track elevation of -0.05 (radians) (Figure 2.4). Subsequently, hours with a mean traffic rate of at least 100 tracks/km/hour and a ratio of directions of less than 0.125 were also filtered out. Lastly, we filtered out all hours with a wave height of at least 100 cm and a ratio of direction lower than 0.7, unless the average track length in that hour was more than 250 m.

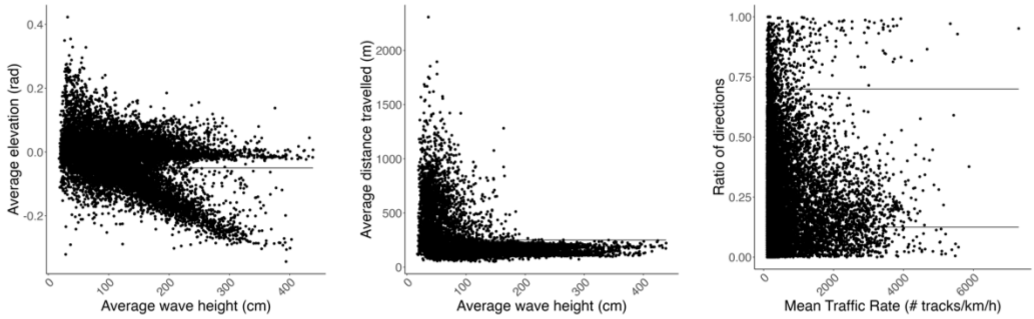

Figure 2.4 *Left: average hourly wave height (cm) vs average elevation (radians) indicating the threshold of -0.05 radians. Middle: average hourly wave height (cm) vs average track length (m) (i.e. distance travelled) indicating the threshold of 250 m. Right: number of tracks per km per hour vs the ratio of directions indicating the thresholds of 0.125 and 0.7.*

Classification (both radars)

The radar software classifies each track, based on certain radar echo characteristics. Tracks could, for example, be classified as small bird, medium bird, or large bird or as a bird flock. Likewise, airplanes or boats detected by the radar enter the database with their own classification. We only considered bird tracks in our calculations. For the vertical radar, it became evident that in some cases birds may be classified as 'slow targets'. Therefore, for this radar we also included tracks that were classified as such, as long as their median radar cross-section (RCS) fell within the limits that are applied for birds by the radar manufacturer (-50 to 5).

Non-bird tracks (horizontal radar)

After filtering on waves and classification, still some clutter may remain in the dataset (van Erp *et al.* 2023). For example, reflections of the radar beam on stationary objects like wind turbines or ships may induce stationary clutter that could be classified as birds. These clutter tracks have a stationary character, *i.e.* the track moves only a limited distance in a relatively long period. Therefore, we calculated for each track its straight-line displacement over time (*i.e.* distance between start of track and end of track divided by the duration of the track), and subsequently filtered out all tracks within the lowest 0.1% percentile of straight-line displacement over time (van Erp *et al.* 2021). Another feature of clutter tracks is that they are often short and tortuous tracks. Hence, we also filtered out all tracks within the lowest 0.1% percentile of straightness, which was calculated as the (shortest) distance between start - and endpoint of a track divided by the total track length. Lastly, we filtered out all tracks with biologically unrealistic airspeeds lower than 5 m/s or higher than 30 m/s, as recommended by van Erp *et al.* (2023).

Periods without radar coverage (both radars)

Alongside all periods that we filtered out of the dataset, the radars in Borssele were not operational during certain periods, for example due to maintenance. The hours in which the radars were (partially) not operational were identified for both radars separately and subsequently filtered out.

Table 2.1 provides an overview of the percentage of hours in each month of the study period that remained in the database after all filter steps were applied. On average, the percentage of hours that remained in the dataset was 25.3% for the horizontal radar and 26.4% for the vertical radar. For the vertical radar, 7%, 29% and 37% of hours were filtered out due to respectively radar downtime, rain clutter and clutter related to wave height. For the horizontal radar, 4.5% of hours is missing due to radar downtime, while roughly 70% of hours is filtered out due to wave clutter.

Table 2.1 Overview of the percentage of hours in each month of the study period that remained in the database after all filter steps were applied.

	2019		2020		2021		2022		2023	
month	**HR**	**VR**	**HR**	**VR**	**HR**	**VR**	**HR**	**VR**	**HR**	**VR**
January	-	-	16.8	30.8	10.1	9.9	25.5	23.8	10.8	8.3
February	-	-	6.3	10.3	29.3	25.1	5.4	10.3	26.9	25.4
March	-	-	2.8	5.4	37.1	19.2	54.0	52.3	4.2	17.2
April	-	-	17.1	8.8	17.9	12.6	31.8	31.0	13.5	29.4
May	-	-	27.7	12.4	44.1	28.9	56.9	40.7	20.6	33.1
June	-	-	50.1	15.8	64.7	51.4	47.5	45.7	24.3	43.5
July	-	-	44.5	52.7	48.1	38.0	53.1	47.7	12.8	22.0
August	-	-	50.0	39.0	24.1	22.4	52.8	49.2	14.9	35.6
September	-	-	28.9	28.3	45.3	34.2	34.6	29.0	32.8	41.3
October	12.1	27.8	8.9	12.6	9.4	16.3	29.2	39.1	7.7	18.3
November	13.1	37.2	28.1	31.3	18.2	22.9	18.3	15.1	1.7	8.5
December	14.1	26.9	10.5	23.7	19.1	16.9	13.3	12.4	1.5	4.0

2.2.3 Weather circumstances during radar measurements

Analyses of radar measurements were carried out on data collected from 1 October 2019 until 31 December 2023. Based on information from the Royal Netherlands Meteorological Institute (www.knmi.nl) we give in this chapter a short summary of the weather circumstances of each season of the study period, to provide a description of the conditions in which the measurements took place.

Autumn 2019
The autumn of 2019 was quite mild, quite sunny and wet. At the end of October, it became dry, sunny and cool and the first frost of the winter half-year was recorded. The weather in November was mostly variable and a little too cold.

Winter 2019/2020
December and January were very mild, very sunny and rather dry. February was still extremely mild, the second mildest February month since 1901. However, it also rained a lot, national records in the amount of rain were broken. On February 9, a southwest storm passed by.

Spring 2020
Spring as a whole was mild, with a record amount of sunshine. However, the first half of March was still variable and wet, just like February. After that, it was dry and very sunny. Although March as a whole was mild, at the end of the month still some frost could occur. April also began cold, but the rest of the month was mild. In May a few nights of frost occurred between May 11 and May 14. The month was dry and very sunny.

Summer 2020
The summer was very warm, characterized by an alternation of very hot and cooler periods. The amount of precipitation was quite normal.

Autumn 2020
Autumn was very mild, and also sunny. All months were too warm, especially November. The coastal area of the Netherlands was much wetter than normal.

Winter 2020/2021
December was mild and also wet. January was wet with rather normal temperatures. February was sunny and dry.

Spring 2021
The spring of 2021 was very cold and wet.

Summer 2021
Until June 18 the summer began as the warmest ever. The heat ended with heavy thunderstorms, after which the rest of the summer was wet and increasingly cool.

Autumn 2021

Autumn was mild, sunny and on the dry side. All months were too warm, especially September. At the end of November, the first signs of winter appeared in the form of frost and snow on a larger scale.

Winter 2021/2022

December was often (very) mild, especially at the end of the month and also dry. January and February were also mild and featured four storms: on January 31 and three other in the period of February 16 - 21.

Spring 2022

March was milder than normal and the sunniest March since measurements began. The first 10 days of April were cold with occasional light frosts at night, but it was sunny, and precipitation was around normal. May started also cool with locally light frosts. However, halfway the month it became for five days became warm, followed by thunderstorms around May 19 and 20.

Summer 2022

The summer was one of the warmest and sunniest ever since measurements began in 1901, and it was also very dry.

Autumn 2022

The first half of September was warm, and the second half cool. The month was also wet. In contrary, October was very mild and very dry. At the end of the month, it became exceptionally warm for the time of year. November was also mild, but on November 19 and 20 it became cold with moderate frosts at night. On the west coast it became very wet.

Winter 2022/2023

December was colder than normal, especially due to a colder period from December 8 to 18. After that, it was generally very mild. Colder days with occasional snow occurred only temporarily in mid-January, but these periods were brief and the mild weather prevailed.

Spring 2023

The spring was exceptional in the large amount of rain that mainly fell in March and April.

Summer 2023

The summer of 2023 entered in the top-10 warmest summers since records began in 1901. It was also a very sunny summer.

Autumn 2023

Autumn was exceptionally mild. Thanks to a very wet October and November, autumn was also particularly wet.

Winter 2023

December was very mild, although it began with a week of frost at night and temperatures a few degrees above zero during the day. In the rest of the month the weather was mild and variable.

2.3 Field observations

2.3.1 Study period

Fieldwork in wind farm Borssele was carried out over the course of two years. It started in December 2021 and ended in December 2023. During this period two different types of observation protocols were carried out: boat surveys and flux measurements from a fixed point. Boat surveys were planned once a month, however due to weather circumstances some surveys had to be cancelled. The most important factor determining whether field trips could be realized was wave height. When wave height exceeded 1m, trips were usually cancelled as it was not possible to confidently count all birds under such circumstances. In total 20 surveys were conducted of the 24 originally planned (Table 2.2). Especially in 2023 several long periods with unfavourable weather conditions occurred which led to the cancellation of trips. In November boat surveys had to be cancelled during both years. Flux measurements were carried out during the second year (2023) of the fieldwork. These measurements were either carried out from a ship or from a turbine. The methods used were the same from both observation platforms. Altogether 14 field trips were conducted during which flux measurements were collected (Table 2.3).

Table 2.2 Date, direction in which the transects were sailed (from point A to J, or the other way around, see Figure 2.5) and weather conditions during the boat surveys.

Date	Direction	Sea state	Wind	Temperature	Visibility
14-12-2021	A > J	2-3	SW4	10	>10 km
25-01-2022	J > A	1	N3	4	2-5 km
09-03-2022	A > J	2-3	S4	11	>10 km
22-04-2022	J > A	4-5	NE6	11	>10 km
31-05-2022*	A > J	2	W3	13	>10 km
21-06-2022*	J > A	2	NE3	15	6-9 km
29-07-2022	A > J	2	N3	18	>10 km
26-08-2022	J > A	3	N4	18	>10 km
30-09-2022	A > J	2-3	SW5	15	>10 km
14-10-2022*	J > A	2	SW4	15	>10 km
06-12-2022	A > J	3	N4	8	>10 km
08-02-2023	A > J	2	S3	5	>10 km
14-02-2023	J > A	2	S2	8	6-9 km
17-03-2023	A > J	1-2	S3	12	>10 km
27-05-2023	J > A	3	NE4	12	>10 km
13-06-2023	A > J	2-3	NE5	21	>10 km
11-07-2023	J > A	3	SW5	19	>10 km
15-08-2023	A > J	2	SW3	18	>10 km
06-09-2023	J > A	1	E2	25	>10 km
01-12-2023	A > J	2-3	E4	3	>10 km

*Both sides of ship counted

Table 2.3 Date, observation platform and weather conditions during flux measurements.

Date	Platform	Wind	Temperature	Sea state	Cloud cover	Visibility
06-02-2023	L01	NE2	6	2	2	>10 km
07-02-2023	ship	E2	5	2	0	>10 km
15-02-2023	ship	SW3	8	2	2	8 km
26-04-2023	L01	NE1	8	1	6	>10 km
14-06-2023	ship	NE3	17	2	0	>10 km
15-06-2023	ship	E3	18	2	0	>10 km
29-06-2023	ship	W4	17	3	8	6 km
30-06-2023	ship	SW4	16	3	1	>10 km
30-06-2023	L01	SW4	16	3	1	>10 km
14-07-2023	ship	S3	16	3	7	7 km
17-08-2023	ship	NE4	23	5	0	>10 km
14-09-2023	ship	S2	17	2	2	>10 km
16-11-2023	L01	SE3	10	2	8	>10 km
02-12-2023	ship	SW1	2	2	6	>10 km

2.3.2 Boat surveys

Data were collected during ship-based surveys from the Rijkswaterstaat (RWS) vessel ‘Scheldestroom’, following the European Seabirds At Sea (ESAS) protocol (Camphuysen *et al.* 2004). This standardized methodology uses a transect with a width of 300 metres diagonally placed in front of the boat. It was attempted to sail at a constant speed of around 9.7 knots (about 18.0 km/h) as much as possible. This results in a transect length of 300 meters every minute. Observers were located on top of the ship, at about 10 metres above sea level. In ESAS terminology, the “Full transect method with snapshot” was applied. The “Full transect” method dictates that birds are recorded both inside and outside the transect. In other words, birds sitting on the water, or shortly dipping into the water inside the transect are recorded as ‘in transect’. All others are recorded as “outside transect”. The “Snapshot” part refers to flying birds. Each minute a snapshot of the transect is recorded and all flying birds that are inside the transect at that moment are noted as “in transect”. Outside the snapshot moment all flying birds are recorded as “outside transect”. Observations were carried out by naked eye, binoculars were only used for identification. Depending on whether two or three observers were present on the boat, one or two sides of the boat were counted, respectively. Both sides of the ship were counted on three occasions. The altitude of flying birds was recorded with a Laser Range Finder (LRF) whenever possible. When this was not possible, flight altitude was noted in height classes (0-2 m, 3-10 m, 11-25 m, 25-50 m, 50-100 m, 100+ m). Distance of swimming birds to the ship was noted in distance bands (0-50 m, 51-100 m, 101-200 m, 201-300 m, 300+ m). A standard order of transects was sailed each survey, alternating in direction per survey (A>J or J>A) (Figure 2.5). The different transects were located either a) inside the wind farm, b) in the corridor, or c) along the border of the wind farm. The sailed route was tracked using a GPS and metadata about the weather were noted at the starting point of each transect.

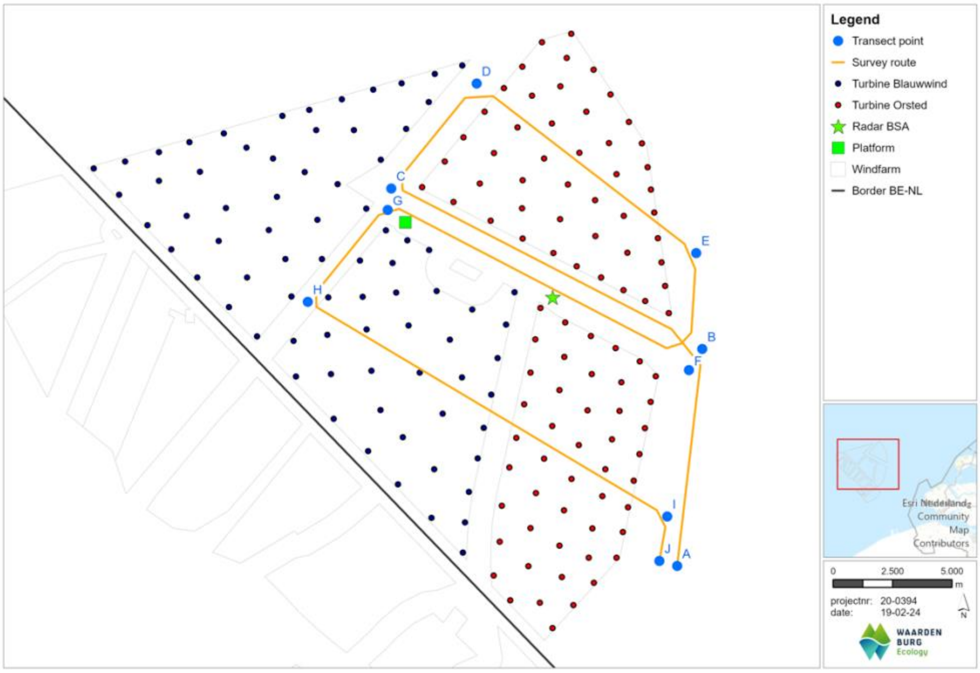

Figure 2.5 *Sailed route during boat surveys around wind farm Borssele. Transects were sailed in alternating sequences (A>J or J>A).*

2.3.3 Flux measurements

Flux measurements were either executed from the Rijkswaterstaat vessel 'Scheldestroom' or from turbine L01 located close to Borssele Alpha. When measurements were done from the vessel two locations were used during the day. The first location (location 1) was in the middle of the corridor at 0.6 km northwest from Borssele Alpha. This was located in the beam of the vertical radar. The second location (location 2) was at 1.5 km west from Borssele Alpha at the border between the wind farm and the corridor. The starting location was alternated between surveys. During flux measurements, an observer was looking in the direction of a predetermined wind turbine and counted all flying birds crossing the line between the observer and the wind turbine during a predetermined timeframe. Observations were done with the naked eye and binoculars were only used for identification. When a bird was seen crossing the line, information on species, number of birds, distance and flight altitude were recorded. In addition, it was attempted for every bird to collect exact information on distance and flight altitude with the LRF. However, this was not always possible and in such cases distance and flight altitude were estimated in classes. For flight altitude the same classes were used as during the boat surveys. For distance, birds were allocated to the following classes: 0-100 m, 101-250 m, 251-500 m, 501-1000 m, 1000+ m. At location 1, flux measurements were always done towards the northwest in line with the beam of the vertical radar. At location 2 flux measurements were executed in alternating directions, either towards the inner side of the windfarm or towards the corridor. When flux measurements were done from turbine L01, observations were also done in alternating directions either towards the inner side of the windfarm or towards the corridor, as this turbine is located on the border between the wind farm and the corridor.

Additionally, if time allowed it, as many radar tracks as possible were tagged during the flux measurements, as these observations were mainly carried out within the range of the radar.

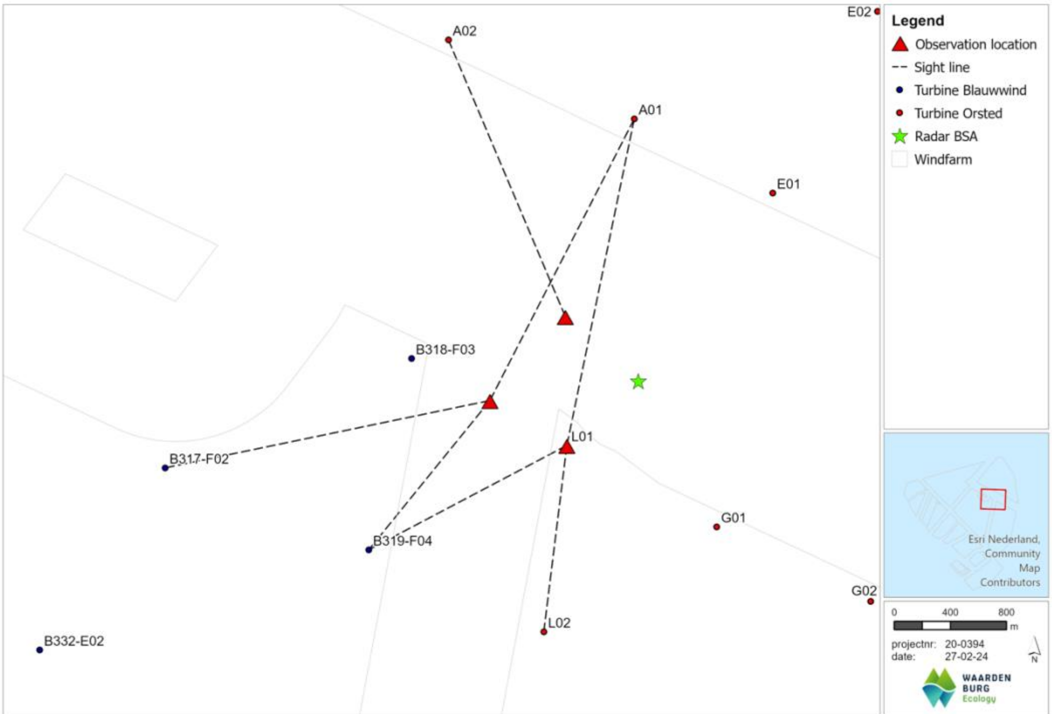

Figure 2.6 *Positions from where flux measurements were done and the sight lines indicating the direction in which the flux measurements were done.*

3 Species composition

Species composition in the study area influences all measurements carried out during the study. Therefore, we systematically recorded species composition during the boat surveys and the flux measurements. In this chapter, we present data on these observations, and also describe additional species occurring in the study area during radar observations.

3.1 Methods

In this chapter, data are presented on the species composition that was observed during the boat surveys and the flux measurements in and around wind farm Borssele. The species composition was calculated separately based on both observation protocols.

3.1.1 Boat surveys

A species composition of birds in and around the wind farm was calculated based on the observations during the boat surveys. In this chapter, no differentiation was made between observations that were done either in the corridor, in the wind farm or along the border of the wind farm. First, results are presented on the average number of individuals per species that were observed during boat surveys over bimonthly periods. Additionally, we also investigated the species composition based on percentages per month and the number of observations versus the total number of individuals per species.

Birds were divided in two categories: seabirds and non-seabirds. Species were considered to be seabirds when they utilize the habitat to forage, rest or as daily commute between breeding/resting places and foraging areas. Species were considered to be non-seabirds when they are only assumed to visit the habitat during their seasonal migration in spring and autumn.

3.1.2 Flux measurements

Species composition was also calculated based on the flux measurements. It was calculated in two different ways, based either on the number of individuals seen or on the number of observations of a certain species and was expressed as the number of birds seen per hour. In these calculations no correction was made for the detection rate of birds by the observers. This will be done in §4, where results on the fluxes of birds are presented.

3.1.3 Tagged radar tracks

An overview is given of the number of tagged radar tracks and the species that corresponded to those tracks. No true species composition was calculated with this information as tracks were often tagged opportunistically, whenever time and weather circumstances allowed for it, and detection rates by the radar for different species are variable.

3.2 Results

3.2.1 Boat surveys

Number of individuals

During all boat surveys a total of 3,247 individual birds were observed. Large fluctuations were observed during boat surveys in the total number of birds present in the area throughout the year. Most birds were present in the winter. Especially during January, many birds were observed as the number of individuals exceeded 400 per survey. During other winter months the number of observed birds fluctuated around 200 individuals per survey. Least birds were present in May and June, when less than 30 individuals were seen per boat survey. In the remaining months during spring and late summer to autumn, when migration occurs, absolute numbers of birds observed were lower than in winter, but higher than in late spring and early summer (Table 3.1). During winter, the most frequently encountered species during the boat surveys included the guillemot (n = 378), razorbill (n = 506), black-legged kittiwake (n = 645) and common gull (n = 261), although their relative abundances fluctuated throughout winter (Table 3.3). Other regular, but less frequent, winter visitors included northern gannet (n = 131), great black-backed gull (n = 45) and herring gull (n = 58). In April, during spring migration, a big shift in the species composition occurred. In this period, large numbers of Sandwich tern (n =176) and lesser black-backed gull (n = 555) were present, whilst most winter visitors were gone. Through May and June, during the peak of the breeding season, lesser black-backed gull was the only species regularly present. Numbers of this species peaked in August, after the breeding season, when autumn migration started. Other regular species during autumn migration were black-headed gull (n = 83), little gull (n = 48), common tern (n = 24) and Sandwich tern (less abundant than in spring), whilst the first common winter visitors also returned to the area.

In total, 19 species of seabirds (excluding lumped species) were observed during boat surveys. Species richness was highest during autumn migration in September when 16 of those species were recorded. In winter, species richness was relatively high with around 10 to 12 species present in the wind farm. In contrast, species richness in late spring and summer was generally low and only a couple of species were recorded.

Table 3.1 *Average number of individuals of species of seabirds observed in Borssele wind farm during boat surveys grouped in bimonthly periods. Highlighted fields (in grey) mean a species was seen during that two-month period. Non-highlighted fields mean no observations were done of a species in that two-month period.*

Species	**Dec/ Jan**	**Feb/ Mar**	**Apr/ May**	**Jun/ Jul**	**Aug/ Sep**	**Oct/ Nov**
black-headed gull	0.5	0.5	0	0.2	17.8	3.5
black-legged kittiwake	90.0	65.8	0.5	0	0.8	8.5
common guillemot	55.0	36.8	0	0	2.8	0
common gull	10.8	47.0	1.0	0.4	6.0	0
common scoter	0.3	0.5	0	0	0.3	0
common tern	0	0	0	0.6	5.3	0
european shag	0	0	0	0	0	0.5
european storm-petrel	0	0	0	0	0.3	0
great cormorant	0	0.5	0.3	0	0.3	0
great black-backed gull	7.0	2.3	0	0	2.0	0
herring gull	3.8	7.8	0	0.2	2.0	1.5
large gull sp.	3.3	0.8	0.8	0.2	1.5	5.5
lesser black-backed gull	2.5	10.8	22.0	25.0	64.5	15.5
little gull	3.0	0.3	1.0	0	3.8	8.0
northern gannet	10.3	14.3	0.3	1.0	1.5	7.5
arctic skua	0	0	0	0	0.5	0
Razorbill	53.8	46.8	0	0.2	8.3	35.0
red-throated diver	0.5	0	0	0	0	0
sandwich tern	0	3.3	26.8	9.0	2.8	0
tern sp.	0	0	0	0	5.3	0
yellow-legged gull	0.8	0.5	0.5	0	0.3	0.5
razorbill/guillemot	7.0	1.3	0	0	1.5	0
small gull sp.	0.8	0.3	0	0	0	0
Total	249	239	53	36.8	127	86

A number of species of non-seabirds were also observed during the boat surveys (Table 3.2). All species of non-seabirds occurred generally only incidentally. Some species in this list were observed in a certain month in relatively high numbers (e.g. common starling), but such cases can be attributed to groups of birds of a certain species and such species were only recorded on a few occasions. Species richness of non-seabirds was highest in September during autumn migration but could generally be considered low. However, as migration for many species largely occurs during nighttime it is likely that some species of non-seabird are more common in the wind farm than found in this study.

Table 3.2 *Average number of individuals of non-seabirds observed in Borssele wind farm during boat surveys grouped in two-month periods. Highlighted fields mean a species was seen during that two-month period. Non-highlighted fields mean no observations were done of a species in that two-month period.*

species	Dec/ Jan	Feb/ Mar	Apr/ May	Jun/ Jul	Aug/ Sep	Oct/ Nov
barn swallow	0	0	0.25	0	0	0
brambling	0	0	0	0	0.25	0
brent goose	0	0	0	0	4.5	0
carrier pigeon	0	0	0.25	0	0	0
common chiffchaff	0	0	0	0	0.25	0
common kestrel	0	0	0	0.2	0	0
common ringed plover	0	0	0.5	0	0	0
common starling	14.75	0.25	0	1.2	0	0
common swift	0	0	0	0.2	0	0
eurasian oystercatcher	0	0	0.25	0	0	0
eurasian skylark	0.75	0	0	0	0	0
eurasian teal	0	0	0.5	0	1	0.5
eurasian robin	0	0	0	0	0.25	0.5
fieldfare	3.25	0	0	0	0	0
great crested grebe	0	0.25	0	0	0	0
gr. white-fronted goose	0.25	0	0	0	0	0
grey wagtail	0	0	0	0	0.25	0
greylag goose	1.25	0	0	0	0	0
hen harrier	0	0	0.25	0	0	0
meadow pipit	0	0	0	0	1	0
pipit sp.	0	0	0	0	0.5	0
ruddy turnstone	0	0	0	0	1	0
song thrush	0	0	0	0	0.25	0
songbird sp.	0	0	0.25	0	0	0
whimbrel	0	0	3.25	0	0	0
white wagtail	0	0.5	0	0	0	0
Total	20.25	1	5.5	1.6	9.25	1

Table 3.3 *Species composition in wind farm Borssele based on percentages of the total number of individuals observed during boat surveys. Non-seabirds were lumped into species groups. Highlighted fields mean a species was seen during that two-month period. Non-highlighted fields mean no observations were done of a species in that two-month period.*

species	Dec/Jan	Feb/Mar	Apr/May	Jun/Jul	Aug/Sep	Oct/Nov
black-headed gull	0.2	0.2	0	0.5	13.0	4.0
black-legged kittiwake	33.4	27.4	0.9	0	0.6	9.8
common guillemot	20.4	15.3	0	0	2.0	0
common gull	4.0	19.6	1.7	1.0	4.4	0
common scoter	0.1	0.2	0	0	0.2	0
common tern	0	0	0	1.6	3.9	0
European shag	0	0	0	0	0.0	0.6
European storm-petrel	0	0	0	0	0.2	0
great cormorant	0	0.2	0.4	0	0.2	0
great black-backed gull	2.6	0.9	0	0	1.5	0
herring gull	1.4	3.2	0	0.5	1.5	1.7
large gull sp.	1.2	0.3	1.3	0.5	1.1	6.3
lesser black-backed gull	0.9	4.5	37.6	65.1	47.3	17.8
little gull	1.1	0.1	1.7	0	2.8	9.2
northern gannet	3.8	5.9	0.4	2.6	1.1	8.6
arctic skua	0	0	0	0	0.4	0
razorbill	20.0	19.5	0	0.5	6.1	40.2
razorbill/guillemot	2.6	0.5	0	0	1.1	0
red-throated diver	0.2	0	0	0	0	0
sandwich tern	0	1.4	45.7	23.4	2.0	0
small gull sp.	0.3	0.1	0	0	0	0
tern sp.	0	0	0	0	3.9	0
yellow-legged gull	0.3	0.2	0.9	0	0.2	0.6
ducks/geese/grebes	0.6	0.1	0.9	0	4.0	0.6
raptors/falcons	0	0	0.4	0.5	0	0
songbirds	7.0	0.3	0.9	3.1	2.0	0.6
waders	0	0	6.8	0	0.7	0
other	0	0	0.4	0.5	0	0

Table 3.4 *Species composition in wind farm Borssele based on percentages of the total number of individuals **in flight** observed during boat surveys. Non-seabirds were lumped into species groups. Highlighted fields mean a species was seen during that two-month period. Non-highlighted fields mean no observations were done of a species in that two-month period.*

species	Dec/Jan	Feb/Mar	Apr/May	Jun/Jul	Aug/Sep	Oct/Nov
black-headed gull	0.01	0.01	0	0	0.21	0.06
black-legged kittiwake	0.44	0.33	0	0	0	0
common guillemot	0.09	0	0	0	0	0
common gull	0.06	0.23	0.02	0	0.01	0
common tern	0	0	0	0	0.06	0
common/arctic tern	0	0	0	0	0.02	0
great black-backed gull	0.04	0.01	0	0	0.02	0
herring gull	0.07	0.10	0	0.06	0.02	0.06
large gull sp.	0.01	0	0	0	0.01	0
lesser black-backed gull	0.01	0.10	0.37	0.76	0.52	0.18
little gull	0.04	0	0.02	0	0	0.29
northern gannet	0.14	0.15	0.02	0	0	0.12
razorbill	0.02	0.04	0	0	0	0.24
razorbill/guillemot	0.06	0.01	0	0	0	0
sandwich tern	0	0.01	0.55	0.12	0.03	0
songbirds	0	0	0	0	0.03	0
waders	0	0	0	0	0.05	0
raptors/falcons	0	0	0	0.06	0	0
other	0	0	0.02	0	0	0

Figure 3.1 shows the number of observations *vs*. the number of individuals of the most common species observed in the wind farm during boat surveys. For most species the total number of individuals observed is only slightly higher than the total number of observations. These species mainly occurred singly or in small groups. Interestingly, the number of observed individuals of razorbill was higher than the number of observed common guillemot, however, common guillemots were observed more often. This means razorbill generally occurs in larger groups than the common guillemot in the wind farm. This is also shown by comparing average group sizes of razorbill (2.66) and common guillemot (1.48). Another species that tended to occur in relatively larger groups than most other species was the Sandwich tern. Especially in July, several groups of ten to twenty birds were present in the wind farm. These birds congregated around buoys used for resting in between feeding.

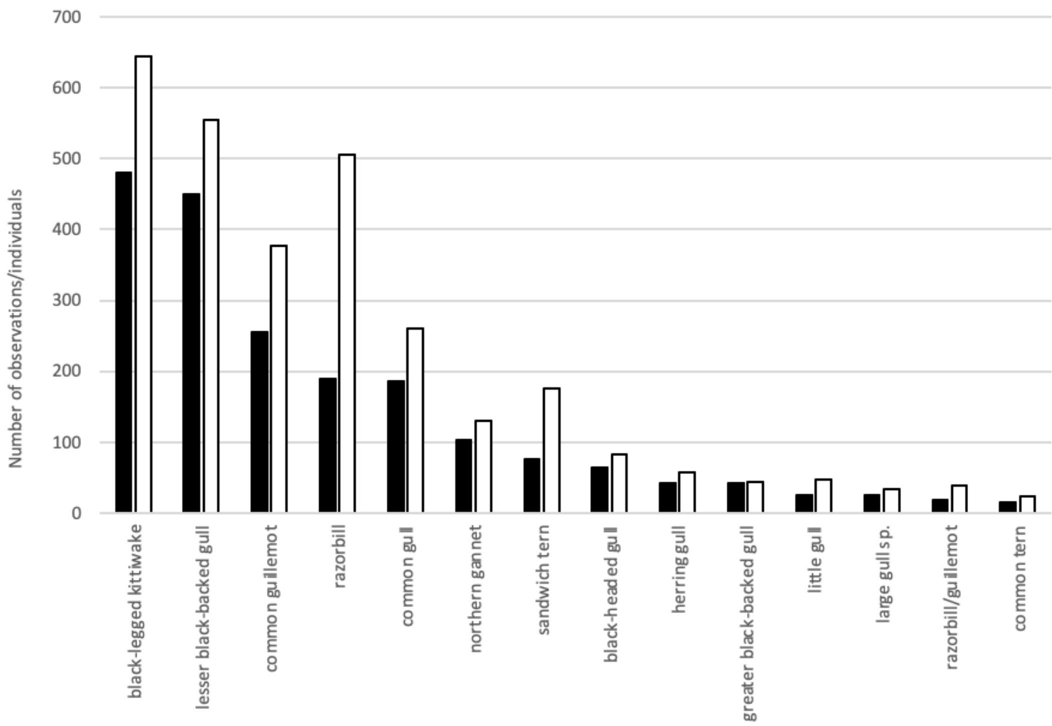

Figure 3.1 *Number of observations (black) and number of individuals seen (white) during boat surveys in Borssele wind farm. Only species with more than 15 observations are shown.*

Table 3.5 shows the differences in species observed along the three different transect types (corridor, inside windfarm, outside windfarm) differentiated during the study. Both the total number of individuals observed along a transect type and the relative abundance along a transect type (percentage) are reported. One should note that the length of the different transect types was not similar. Relative occurrence in the corridor compared to relative occurrence inside the windfarm was very similar for most species, however for some species differences were noted. Both razorbill and sandwich tern showed higher abundance in the corridor than inside the windfarm. Remarkably, the relative abundance of lesser black-backed gull was twice as high in the windfarm compared to the corridor. Larger differences can be noted when comparing occurrence outside the windfarm with the two other transect types. Most remarkable is the occurrence of the sandwich tern, which shows much higher abundance outside than inside the windfarm. Other species that were relatively seen more often outside than inside the windfarm include black-headed gull, little gull and lesser black-backed gull.

Table 3.5 *Species composition in wind farm Borssele differentiated between the* ***corridor, inside the windfarm*** *and* ***outside the windfarm****. Non-seabirds were lumped into species groups.*

Species	**corridor**		**inside WF**		**outside WF**	
	N	%	N	%	N	%
arctic skua	0	0.00	0	0.00	2	0.24
black-headed gull	20	1.49	29	2.87	34	4.09
black-legged kittiwake	303	22.61	216	21.39	126	15.14
common guillemot	165	12.31	113	11.19	100	12.02
common gull	124	9.25	95	9.41	42	5.05
common scoter	2	0.15	0	0.00	2	0.24
common tern	6	0.45	13	1.29	5	0.60
european shag	0	0.00	0	0.00	1	0.12
european storm-petrel	1	0.07	0	0.00	0	0.00
great cormorant	1	0.07	1	0.10	2	0.24
great black-backed gull	23	1.72	18	1.78	4	0.48
herring gull	21	1.57	21	2.08	16	1.92
large gull sp.	20	1.49	12	1.19	5	0.60
lesser black-backed gull	144	10.75	208	20.59	203	24.40
little gull	9	0.67	10	0.99	29	3.49
northern gannet	51	3.81	57	5.64	17	2.04
Razorbill	265	19.78	145	14.36	96	11.54
red-throated diver	2	0.15	0	0.00	0	0.00
sandwich tern	59	4.40	14	1.39	103	12.38
tern sp.	15	1.12	2	0.20	4	0.48
yellow-legged gull	5	0.37	4	0.40	0	0.00
razorbill/guillemot	20	1.49	13	1.29	6	0.72
small gull sp.	2	0.15	1	0.10	1	0.12
ducks/geese/grebes	19	1.42	13	1.29	0	0.00
raptors/falcons	0	0.00	2	0.20	0	0.00
Songbirds	62	4.63	8	0.79	28	3.37
Waders	1	0.07	15	1.49	4	0.48
Other	0	0.00	0	0.00	2	0.24

3.2.2 Flux measurements

During all flux measurements 924 individual birds were observed across 414 observations. All observations were done in 2023 across eight different months. The highest number of birds were observed in November and December. In these months about 20 observations per hour were done. The number of birds in these months was much higher than during all other months, but this was mainly caused by several groups of common starling (Figure 3.2). In other months, the number of observations of flying birds per hour were relatively low, between 4 to 10 observations per hour. In winter, the most common species observed were the black-legged kittiwake (n = 82) and the common gull (n = 43). In summer, the lesser black-backed gull (n =151) dominated the species composition. All other species were observed on fewer than 25 occasions (Table 3.6).

Table 3.6 Overview of the number of observations of birds per hour in Borssele windfarm during flux measurements. Between brackets the number of individuals.

Species	Dec/Jan	Feb/Mar	Apr/May	Jun/Jul	Aug/Sep	Oct/Nov
black-headed gull	0	0.1 (0.1)	0	0.2 (6.3)	0	0
black-legged kittiwake	10.1 (10.7)	3.0 (3.1)	0	0	0	6.2 (6.5)
carrier pigeon	0	0	0	0	0.2 (0.2)	0
caspian gull	0	0	0.2 (0.2)	0	0	0
common gull	2.4 (2.4)	3.7 (4.2)	0	0	0	0
common scoter	0	0	0	<0.1 (0.1)	0	0
curlew sp.	0	0	0.2 (0.7)	0	0	0
diver sp.	0	0	0.2 (0.2)	0	0	0.4 (0.7)
eurasian curlew	0	0.1 (0.1)	0	0	0	0
gr. black-backed gull	0.5 (0.5)	0.1 (0.1)	0	<0.1 (0.1)	0	1.8 (1.8)
guillemot	0	0.1 (0.1)	0	0	0	0
herring gull	0.5 (0.5)	0	0.2 (0.2)	0	0.2 (0.2)	1.1 (1.1)
large gull sp.	0.8 (0.8)	0.4 (0.4)	0	<0.1 (0.1)	0.2 (0.2)	1.1 (1.1)
le. black-backed gull	0	0.1 (0.1)	1.1 (1.1)	4.9 (5.3)	4.6 (5.1)	0
little gull	1.6 (1.9)	0	0	0	0	2.2 (2.2)
mediterranean gull	0	0	0	<0.1 (0.1)	0	0
northern gannet	0	1.1 (1.1)	0.9 (0.9)	0	0	0.4 (0.4)
razorbill/guillemot	0	0.2 (0.2)	0	0	0	1.1 (1.5)
sanderling	0	0	0	<0.1 (0.1)	0	0
sandwich tern	0	0	5.3 (6.9)	0	0	0
small gull sp.	0.5 (0.5)	0.7 (0.7)	0	<0.1 (0.1)	0.2 (0.2)	0
songbird sp.	0	0	0	0	0.2 (0.2)	0
tern sp.	0	0	0.2 (0.2)	0	0	0
wader sp.	0	0	0	0	0.2 (0.3)	0
common starling	3.4 (100)	0	0	<0.1 (0.1)	0	3.6 (33.5)

Figure 3.2 shows the number of observations versus the total number of individuals of the species most frequently seen during flux measurements in wind farm Borssele. Only species that were observed at least 15 times were included. This graph shows that, although the total number of observations of common starling was comparatively low, based on the number of individuals it was the most abundant species observed. For the other species the number of individuals is almost similar to the number of observations, meaning that these species usually occurred singly or in small groups.

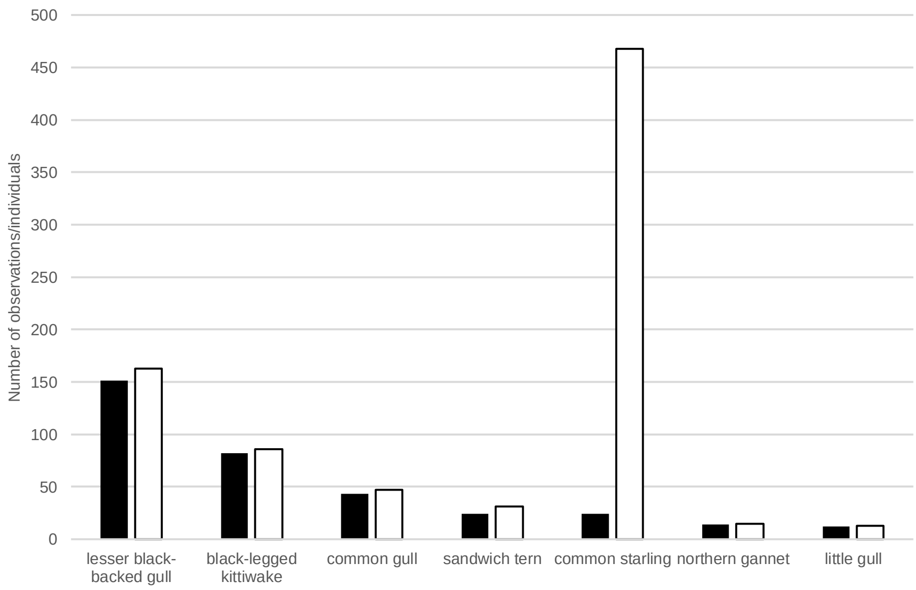

Figure 3.2 Number of observations (black) and number of individuals seen (white) during flux measurements in Borssele wind farm. Only species with more than 15 observations are shown.

3.2.3 Tagged radar tracks

Over the course of the project 557 tracks that were detected by the bird radars were tagged (Table 3.7). These tracks comprised of 22 different species (groups). The most abundant species was the lesser black-backed gull, with almost twice as many tagged tracks as the second most abundant species, the black-legged kittiwake. Other seabirds which were tagged relatively often include common gull, great black-backed gull, large gull sp., northern gannet, and Sandwich tern.

Two species of non-seabirds were also tagged relatively often: common starling and meadow pipit. All tracks of meadow pipit were tagged on just one day (21-09-2021) with strong migration of this species. Similarly, most tracks of common starling stem from just two days in November and December of 2023.

Table 3.7 *All tagged radar tracks that were detected by either the horizontal radar or the vertical radar or both. Per species the number of tracks assigned to that species is given.*

Species	N tracks	species	N tracks
black-headed gull	8	little gull	5
black-legged kittiwake	71	meadow pipit	39
black-throated diver	1	northern gannet	39
common gull	46	razorbill	1
common starling	51	razorbill/guillemot	3
goose sp.	1	red-throated diver	2
great cormorant	4	sandwich tern	33
great black-backed gull	40	small gull sp.	10
herring gull	14	songbird sp.	11
large gull sp.	41	wader sp.	1
lesser black-backed gull	135	yellow-legged gull	1

3.3 Discussion

Species composition was presented based on two different observation protocols: boat surveys and flux measurements. During the boat surveys, areas inside the wind farm, in the corridor and along the border of the wind farm were sampled, whilst flux measurements were only done near the platform Borssele Alpha, in the corridor and inside the wind farm. Furthermore, species composition based on the flux measurements focuses solely on flying birds. Species composition based on the boat surveys encompasses all birds, resulting in large differences in calculated species composition as some species spend much more time in flight than other species. Also, be aware that the presented species composition here is only representative for daylight hours and under relatively favourable weather conditions. Also note that the species composition was based on a relatively scarce number of visits spread as evenly as possible across the year, as carrying out offshore field observations is challenging and strongly weather dependent. As circumstances offshore can substantially vary on a daily basis, the presented composition comes with a significant uncertainty. Especially for migratory birds that can pass the area in large numbers but within a short timeframe. Spatiotemporal variation in the distribution of seabirds is also common (Cleasby *et al.* 2015, Chimienti *et al.* 2017). For example, this is illustrated by the number of lesser black-backed gulls seen during boat surveys in August. In the first year (2022) 141 birds were seen during the survey, whilst in the second year (2023) 38 individuals of this species were seen in August.

The species composition calculated was comparable for most species of seabirds between the different methods. The largest differences between methods occurred within the group of the alcids (razorbill and common guillemot). These species made up a large part of the species composition during boat surveys but were rarely registered during flux measurements. This is unsurprising as alcids typically spend much more time on the water than most other species of seabirds (Dall'Antonia *et al.* 2001, Buckingham *et al.* 2023), which results in low numbers observed when doing flux measurements. In addition to these species, lesser black-backed gull, black-legged kittiwake, common gull, northern gannet, and Sandwich tern come to the forefront as being the most common species in the area during at least part of the year. Less common but also regular species in the area during parts of the year include great black-backed gull, herring gull, black-headed gull and little gull.

Between 2003 and 2013 boat surveys using similar methods were done in the Belgian part of the wind farm (Vanermen *et al.* 2013). This study was also used as input to in the MER for Borssele windfarm to estimate bird densities and collisions. When comparing the species composition determined back then to the results of our study some differences and similarities in species composition can be remarked. Note that densities for most species were higher pre-construction (2003-2008) *vs* post-construction (2009-2013) in the Belgian part of the windfarm. Both common guillemot and razorbill were found to be relatively common, but numbers of common guillemot were two to three times higher than numbers of razorbill throughout winter. In our study we found both species to be equally common. Amongst gulls lesser black-backed gull, common gull and black-legged kittiwake were the most numerous species in our study. This is in line with the Belgian study. However, we found lower numbers of great black-backed gull, which was amongst the most common winter visitors, especially pre-construction. The density of herring gulls in the area was relatively low in earlier studies and similarly so in this study, although we recorded the species regularly. Generally, herring gulls are found more commonly near the coast. In our study, we found high numbers of sandwich tern relative to earlier studies. Most observations of sandwich tern were done in the migration period and may have coincided with a peak in migration of this species. A similar pattern can be observed for common tern and black-headed gull which are also seasonal migrants in the area. In contrast, little gull shows a reversed pattern and especially in spring the numbers we found were relatively low. Possibly, we missed the migration peak of this species which occurs in April. Densities of northern gannet were much lower post-construction compared to pre-construction. In our study northern gannets were recorded regularly in winter and during migration and interestingly, most observations were done inside the windfarm and corridor compared to outside the windfarm. Northern fulmar and great skua were regular species in the area, especially pre-construction, though never abundant. In our study neither species were observed. This is in line with declining general population trends of both species in the Netherlands and the assumption that both species likely show rather strong macro-avoidance to windfarms (Furness 2015, Dierschke *et al.* 2016).

4 General flux patterns

One of the main aims of the study was to determine species-specific fluxes in the study area. influences all measurements carried out during the study. For these purposes, we carried out dedicated visual observations in the field and also analysed radar measurements. In this chapter, we present data on both of these kinds of observations.

4.1 Methods

In this chapter, data are presented on the fluxes of birds flying through wind farm Borssele. The flux was calculated through two different methods. Firstly, flux calculations were done based on the flux measurements done during visual observations. Secondly, fluxes were calculated through filtered radar data. For both methods fluxes were determined as the number of birds flying per km per hour to enable comparisons between the methods.

4.1.1 Flux measurements

The first way in which fluxes were calculated was by extrapolating the data collected during flux measurements done in the field by visual observers (§2). This data was solely collected during the daytime and mainly focuses on seabirds. To translate the collected data into the number of flying birds per kilometre per hour, one first needs to calculate the detection curve of the visual observers by carrying out a distance analysis. This analysis corrects for imperfect detection. We assumed a minimum number of 60 observations per species to carry out distance analysis. Only two individual species met this requirement, the black-legged kittiwake, and the lesser black-backed gull. Additionally, a detection curve was also calculated for all birds, independent of species.

These detection curves are defined by a detection function. Detection functions consist of a key function, and either adjustment terms or covariates. For each species, 6-10 functions were fitted (depending on the number of covariates and adjustment terms included): including half normal and hazard rate key functions, with cosine and hermite adjustment terms with the half normal key functions, and simple polynomial adjustment terms with the hazard rate key function. Season (in this case winter/spring or summer) and survey date were tested as covariates as proxy for weather conditions, as sample sizes were too small to use weather conditions like sea state or wind. These covariates were tested combined with both hazard rate and half normal key functions. The best-fitting model per species was selected based on the lowest Akaike Information Criterion (AIC) value. This 'best' model was used to calculate Effective Strip Widths (ESW). Distance analyses were carried out using the MRDS package in R (Laake *et al.* 2023) using Rstudio version 2023.12.1 (Posit team 2024) and R version 4.2.2 (R Core Team 2023).

Once the ESWs the observed bird numbers can be extrapolated to calculate the number of birds flying per kilometre per hour. In this way, a flux was calculated for each separate flux measurement. Overall fluxes were calculated by taking the average of separate flux measurements. Several different fluxes were explored and compared. Firstly, we looked at the difference between the flux of birds inside the wind farm compared to the corridor. Secondly, we looked at monthly and seasonal differences in fluxes of birds. We also looked into the difference in fluxes during the morning and the afternoon. The fluxes calculated for the visual observations can only be applied to daytime hours.

Fluxes inside the corridor were compared statistically to fluxes inside the wind farm using a Generalized Linear Mixed Model (GLMM) with a negative binomial or poisson distribution using the INLA package in R (Rue *et al.* 2009, Lindgren & Rue 2015). The following model formula was used:

N ~ zone + (1|observation_location) + (1|survey) + offset(log_duration)

with the variables:

N:	Number of birds or number of observations
zone:	Either inside OWF or in the corridor. Inside the OWF was the base level
observation_location	Location used during the survey, either from a ship or a turbine. From a ship was used as the base level
survey:	Identifier for the survey day
log_duration	Log of the duration of the survey (in minutes)

Random intercepts were included per survey and observation location, and the offset of the log of the duration of the survey was used, so differences in specific days and different durations were modelled as well. Only observations carried out from locations where both the corridor as well as the OWF was surveyed were used, to prevent bias.

Analyses were carried out in using the INLA package (Rue *et al.* 2009, Lindgren & Rue 2015). INLA is used for Bayesian statistics, meaning the model outcome provides no p-value or significance results. Instead, Bayesian statistics provide a posterior distribution, from which a 95% credible interval and a mean covariate estimate can be calculated. This posterior distribution represents the distribution of values that the covariate may have, given the data. If 0 is not within the entire 95% credible interval, the covariate most likely had an effect on the response variable. However, if the credible interval spans over 0, the covariate could have a negative as well as a positive effect, meaning that the evidence for an effect is absent or weak; the result can therefore be regarded as inconclusive (van de Schoot *et al.* 2021). The INLA package uses credible intervals of 95%

4.1.2 Radar fluxes

The radar system operating at platform Borssele Alpha is developed to detect flying birds. Therefore, when we report in this study radar results on bird activity, these always consider birds in flight, i.e. bird flight activity. The radar fluxes were calculated using two different methods based on the filtered datasets of the vertical radar data and the horizontal radar data (see §2.2.2). The advantage of using vertical radar data is that it enables determining fluxes at different altitude levels. At the same time, the vertical radar can detect birds up to much higher altitudes than the horizontal radar (respectively roughly 3-4 km vs 300 m). Both radars at BSA suffer severely from wave clutter. However, the vertical radar is more susceptible to rain clutter than the horizontal radar. The horizontal radar also provides more information of for example horizontal flight speeds and - directions. Each radar thus has its (dis)advantages, hence the choice was made to determine radar fluxes for each radar separately (see below).

Overall patterns of fluxes are described, which give an insight in the variations throughout the study period, including variation between months and at different times of day and night. Additionally, the fluxes were differentiated for different weather circumstances (§5) and for different altitude levels as below, at and above rotor height (§8).

The nocturnal activity was determined for each month, by dividing the absolute number of tracks between tracks during day and tracks during night based on the local sunrise and sunset times retrieved from the R package 'suncalc' (Thieurmel & Elmarhraoui 2019). Also, we determined for each month the number of daylight and night-time hours that were present in the filtered dataset. We then calculated the relative percentage of tracks per day and night by correcting for the number of daylight and night-time hours in each month.

Species-specific fluxes were calculated for each month based on 1) the average flux per km per hour during daytime in that month, using for the flux measured by the vertical radar between 3 and 192 m (*i.e.* rotor tip height), and 2) the monthly species compositions based on the number of individuals in flight during ship-based surveys (see Table 3.4). Note that the species-specific fluxes during night-time could not be determined, as the species compositions are only representing bird activity during daylight.

Flux calculation vertical radar

Based on the detection capabilities of the vertical radar, flux lines were drawn from 500-1,000 meters from the radar at both the north-western and south-eastern side of the radar (cf. Fijn *et al.* 2015a), for the sake of using a balanced spatial coverage (Figure 4.1). At these distances, the vertical radar has the best detection capabilities, while we also avoid potential clutter from a wind turbine located on the south-eastern side at a distance of approximately 1,200 meters. Fluxes were determined as the number of tracks per km per hour (also referred to as 'mean traffic rate' (MTR)). Hence, fluxes were calculated by summing all tracks per hour that intersected with the two flux lines of 500 meters to get the number of tracks per km per hour, which means that all tracks within the full altitude range of the vertical radar (up to altitudes of roughly 3-4 km) were taken into account.

Flux calculation horizontal radar

For the horizontal radar, we used the same method to calculate the MTR as was carried out for Luchterduinen by Bradarić (2022) and Kraal *et al.* (2023). Since the horizontal radar resembles a bird eye view of the study area, a density-based approach was used. For this, a 'donut'-shaped polygon around the radar was drawn, excluding the blanking sector towards the northeast. The inner border of the donut is at a distance of 1,000 meters and the outer border at 2,000 meters from the radar (Figure 4.1). The surface area of the donut is 6.18 km^2. Every track with its centroid inside the donut area was used for the analysis.

All tracks involved have a feature which is called the 'number of plots'. The number of plots stands for the number of times the bird is recorded by the radar. Therefore, if the number of plots of all tracks within a certain hour are summed and divided by the number of radar rotations within that hour, one gets the average number of birds recorded by the radar on each rotation. As only the tracks within the donut area are involved, the number of birds on a certain moment divided by the surface of the donut area leads to the average number of birds per km^2 for a certain hour.

The number of birds within a certain area is called the density. The density of birds can be converted into the MTR by multiplying it with the average ground speed (in km/h) of all bird tracks that are used in the analysis in that hour. Note that the horizontal radar does not provide altitude measurements. Therefore, these MTRs only visualise the bird activity in the lower few hundred metres of the air layer.

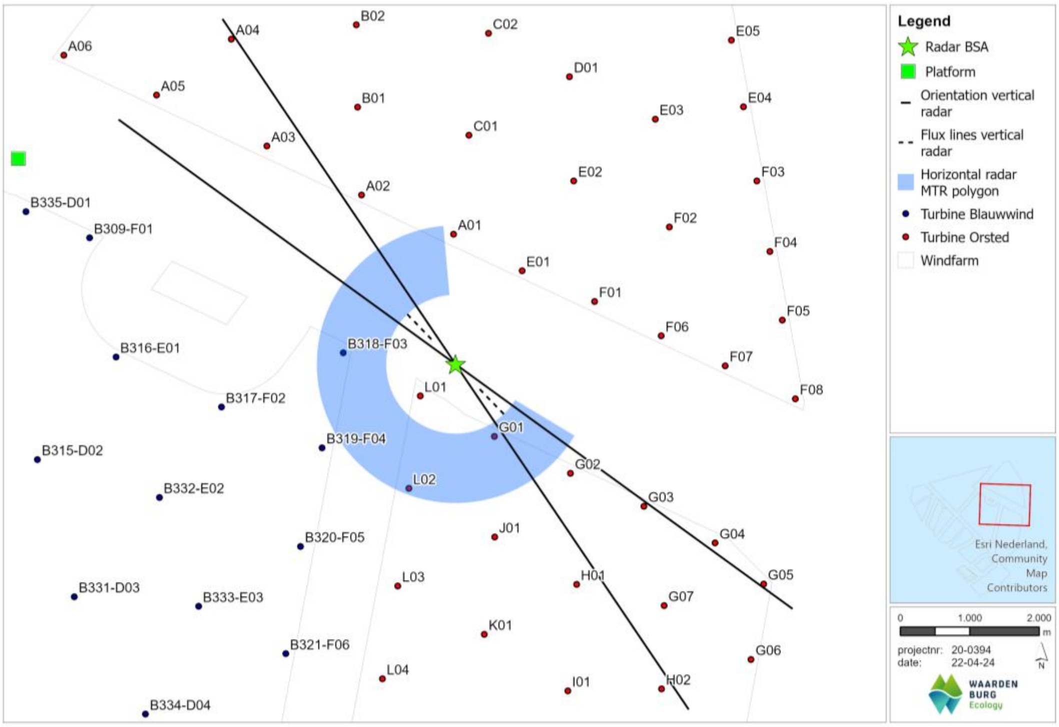

Figure 4.1 *Overview of the orientation and the flux lines of the vertical radar, and the polygon in which the MTRs for the horizontal radar was calculated.*

4.2 Results

4.2.1 Flux measurements

In total 3,000 minutes (60 hours) of flux measurements were done. In this period, a total of 658 birds were observed of which 330 were seabirds. Almost all non-seabirds observed were common starling that passed by in several large groups. The largest group consisted of 150 individuals. Lesser black-backed gull (N = 138) and black-legged kittiwake (N = 47) were the most numerous seabirds.

For the selected species, the best fitting models were as follows. Lesser black-backed gull had the smallest Estimated Strip Width (ESW) of 557 meters and black-legged kittiwake the largest with an ESW of 751 meters (Table 4.1). Adding a covariate (season) resulted in a better model only for all observed species together. Survey date had no significant influence on the detection probability for either of the species or all species together. Adding adjustment terms did not result in a better model.

*Table 4.1 Best fitting models per species in the distance analysis, including resulting Estimated Strip Width (ESW). * ESW of 536 in summer and 802 in winter/spring.*

species	function	adjustment term	covariates	ESW (m)
lesser black-backed gull	halfnormal	None	none	557
black-legged kittiwake	halfnormal	None	none	751
all species together	halfnormal	None	season	536-802*

Figure 4.2 shows the calculated flux of birds per kilometre per hour in the wind farm compared to the corridor. Fluxes were not different in the corridor compared to the wind farm for all seabirds nor all observed bird species together, except when comparing number of birds for all bird species instead of number of observations (Table 4.2). Sample sizes for black-legged kittiwake and lesser black-backed gull were too small to test statistically. Possibly there are non-seabird species that are present in higher numbers in the corridor than in the windfarm, for example starling. Note that the visual data were collected only by day, so this does not say anything about nocturnal migration.

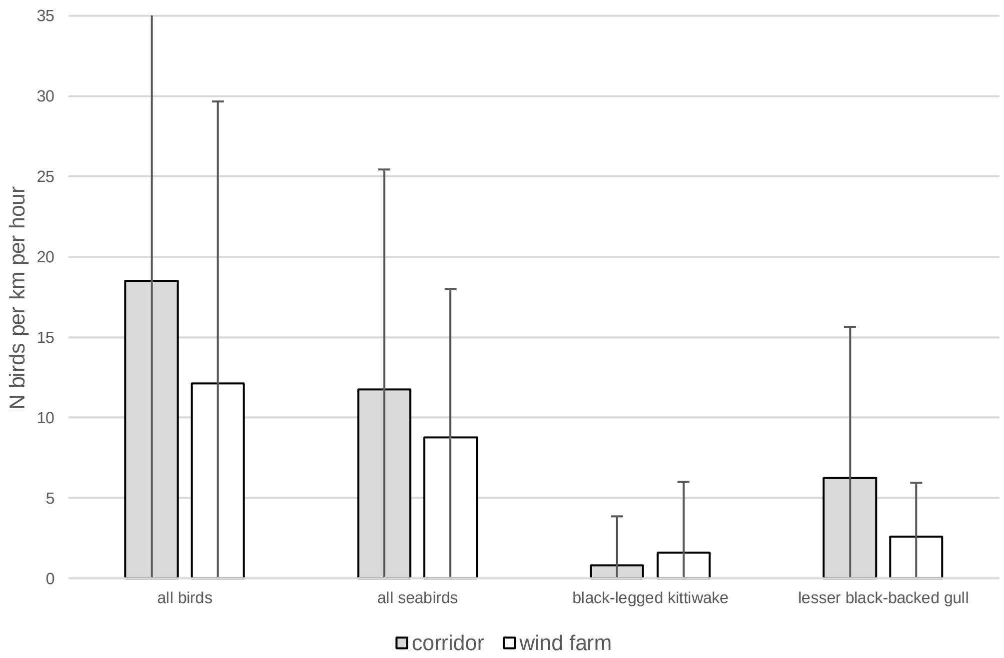

Figure 4.2 *Average fluxes of birds in corridor versus wind farm per km per hour based on visual observations. Error bars represent standard deviation. Fluxes are presented for all birds, all seabirds, black-legged kittiwake and lesser black-backed gull.*

Table 4.2 *Mean, standard deviation, and lower and upper boundary of the 95% credible interval of model estimates of the negative binomial GLMM on the flux data, both on number of observations and number of birds observed. Intercept is the estimate for flux inside the OWF estimated from a ship, corridor is estimate of the difference with inside the OWF. *credible interval does not span zero and is not the intercept.*

	All species - observations			
	mean	*SD*	*lower*	*upper*
Intercept	-2,79	0,13	-3,04	-2,54
Corridor	0,22	0,18	-0,12	0,57
	All species - number of birds			
	mean	*SD*	*lower*	*upper*
Intercept	-2,48	0,20	-2,85	-2,08
*Corridor**	1,08	0,27	0,55	1,61
	Only seabirds - observations			
	mean	*SD*	*lower*	*upper*
Intercept	-2,19	0,24	-2,68	-1,73
Corridor	0,21	0,19	-0,18	0,55
	Only seabirds - number of birds			
	mean	*SD*	*lower*	*upper*
Intercept	-1,89	0,22	-2,30	-1,44
Corridor	0,18	0,31	-0,43	0,78

Figure 4.3 shows the fluxes for birds during different seasons. The flux for all bird species was highest in autumn and winter, but these high fluxes are mainly caused by groups of common starlings that flew through the wind farm during this period. For the group of

seabirds, the differences between the seasons were much smaller. Fluxes were relatively low in spring, but no obvious differences occurred during the other seasons. Black-legged kittiwake only occurred during autumn and winter. Fluxes of the species were equal during these seasons. Lesser black-backed gull occurred during all seasons but was rare in winter. Fluxes of lesser black-backed gull were highest in summer after the breeding season.

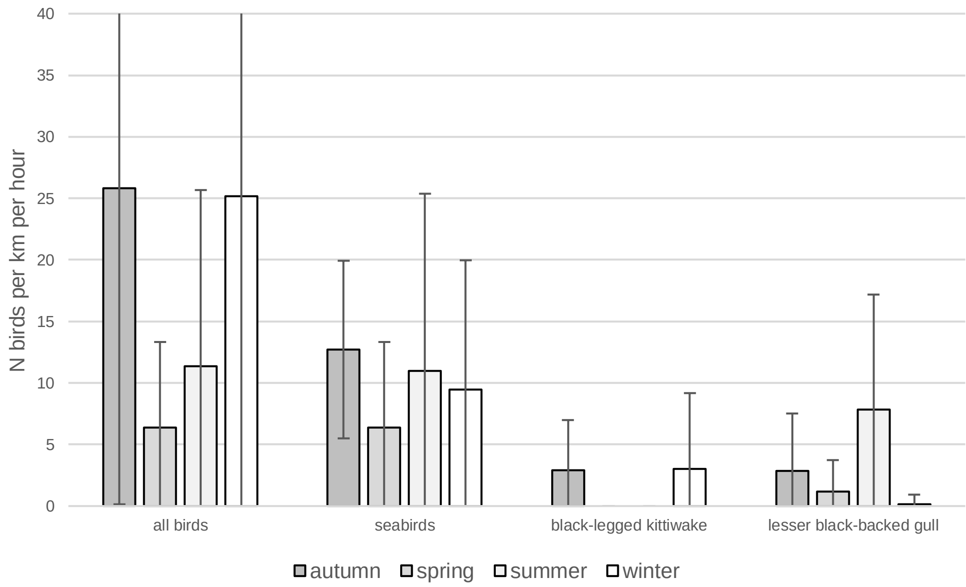

Figure 4.3 *Average fluxes of birds in different seasons per km per hour over entire study period based on visual observations. Error bars represent the standard deviation. Fluxes are presented for all birds, all seabirds, black-legged kittiwake and lesser black-backed gull.*

Figure 4.4 shows the difference in fluxes of birds between the morning and the afternoon. For all groups, the flux of birds was about twice as high in the morning compared to the afternoon.

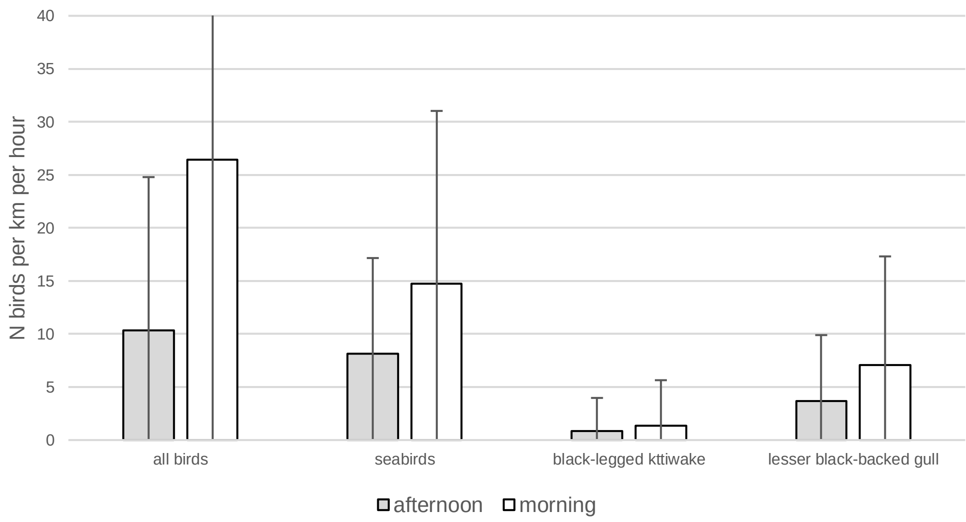

Figure 4.4 *Average fluxes of birds during morning versus afternoon per km per hour over the entire study period based on visual observations. Error bars represent the standard deviation. Fluxes are presented for all birds, all seabirds, black-legged kittiwake and lesser black-backed gull.*

The fluxes calculated based on visual observations are subject to much variation in the data. There is a relatively high number of hours in which very few flying birds were recorded passing the observation line, whilst during some hours the number of birds passing the observation line was much higher. This leads to uncertainty in the resulting flux calculations. Also note, that the effort in flux measurements was not the same throughout the year. Flux measurements were done across eight different months and most hours were invested in summertime. Furthermore, the presented fluxes only represent daytime hours under relatively favourable weather conditions.

4.2.2 Radar fluxes

In the study period from the 1st of October 2019 to the 31st of December 2023, on average 28 and 120 bird targets per km per hour were recorded in wind farm Borssele by the horizontal radar and the vertical radar respectively. The average fluxes recorded during the day were 22 and 82 bird targets per km per hour by the horizontal radar and the vertical radar respectively, while during the night these were 37 and 167 birds/km/hour respectively. The vertical radar generally recorded higher mean traffic rates (MTRs) than the horizontal radar (Figure 4.5). Relatively low fluxes of less than 25 bird targets per km per hour were recorded during respectively 70% and 19% of the hours for the horizontal radar and the vertical radar. Exceptionally high fluxes of more than 500 bird targets per km per hour were recorded by the horizontal radar in 9 out of 9,449 hours (0.1%), and by the vertical radar in 284 out of 9,833 hours (2.8%). The hours with MTRs of more than 500 bird targets mostly occurred *during the night* in March, October and November (Figure 4.6). *During the day*, hours with MTRs of more than 500 bird targets were not recorded in February, May and June. The highest fluxes were measured during the autumn migration on the 16th of October 2023, when between 19:00 and 21:00 (GMT) respectively 7,293 and 5,544 bird targets per km per hour were measured by the vertical radar (also see §5).

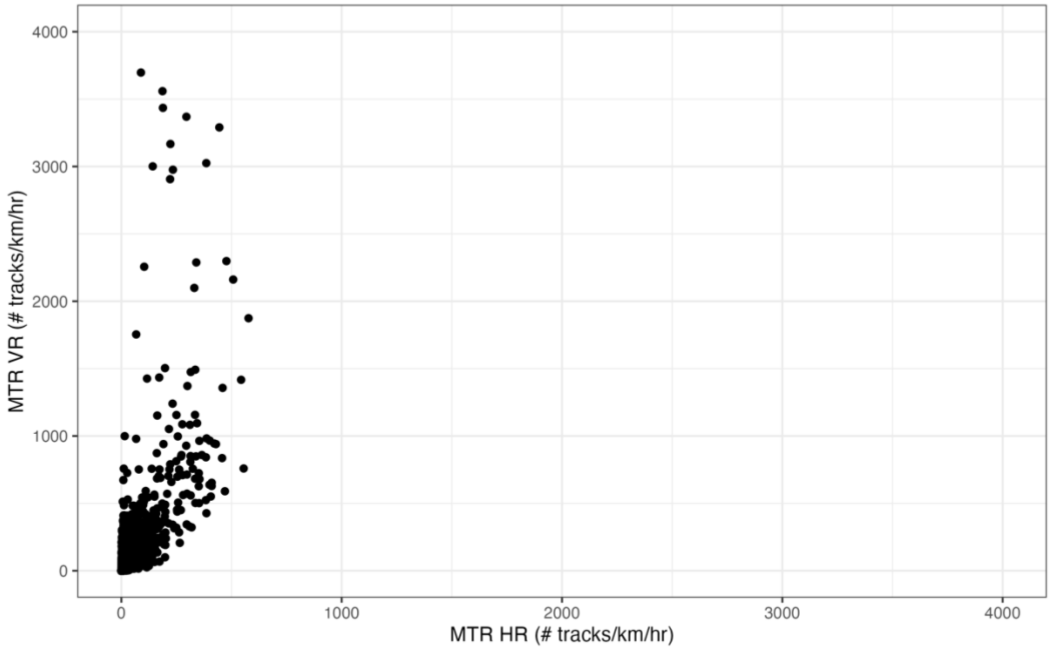

Figure 4.5 *Mean traffic rates measured by the horizontal radar versus the mean traffic rates measured by the vertical radar in the same hour.*

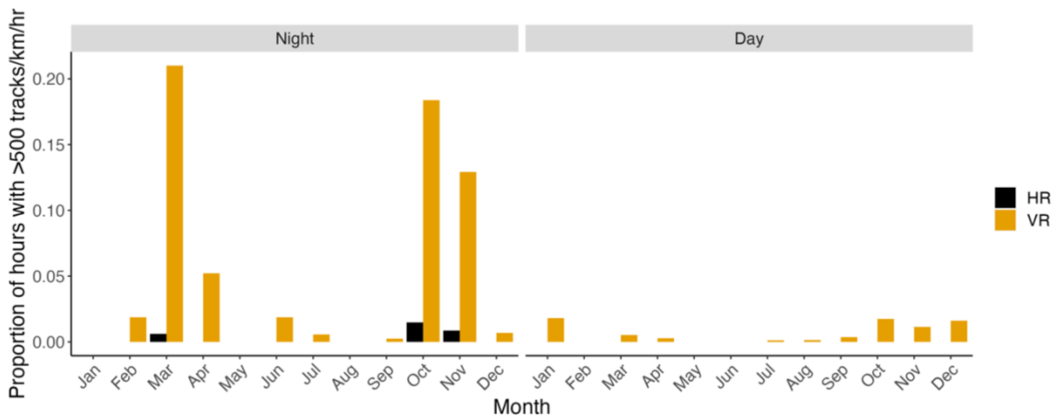

Figure 4.6 *The proportion of hours per month during day (right) and during night (left) in which the horizontal radar (black) and the vertical radar (orange) recorded fluxes of more than 500 tracks per km per hour.*

Temporal variation in fluxes

During daylight, the temporal variation in the monthly average number of tracks per km showed no large differences (Figure 4.7 above). In March and October, both radars recorded on average higher MTRs during daylight, while in July both radars recorded on average the lowest MTR during daylight. On the contrary, during the night, clearly higher fluxes were recorded in spring (March) and autumn (October and November) (Figure 4.7 below). During these seasons, the main flight directions were easterly in spring and south-westerly in autumn (Figure 4.8). On average the lowest fluxes during the night were recorded from May to August. These patterns were recorded by both radars, although the peaks in spring are less noticeable based on the horizontal radar.

Higher MTRs in March, October and November were generally recorded in each year of the study period, with the exception of March 2020 (possibly due to a lack of data remaining after filtering) (Figure 4.9). The extent to which these peaks were recorded by the radars slightly differs between each year. For example, the peaks in 2021 and 2022 were lower than in other years, while some exceptionally high peaks were recorded in autumn 2020 and autumn 2023. In spring, the highest MTRs were generally recorded in the second and third week of March, while in autumn the peaks seem to occur between the first week of October (2020) and the first week of November (2022).

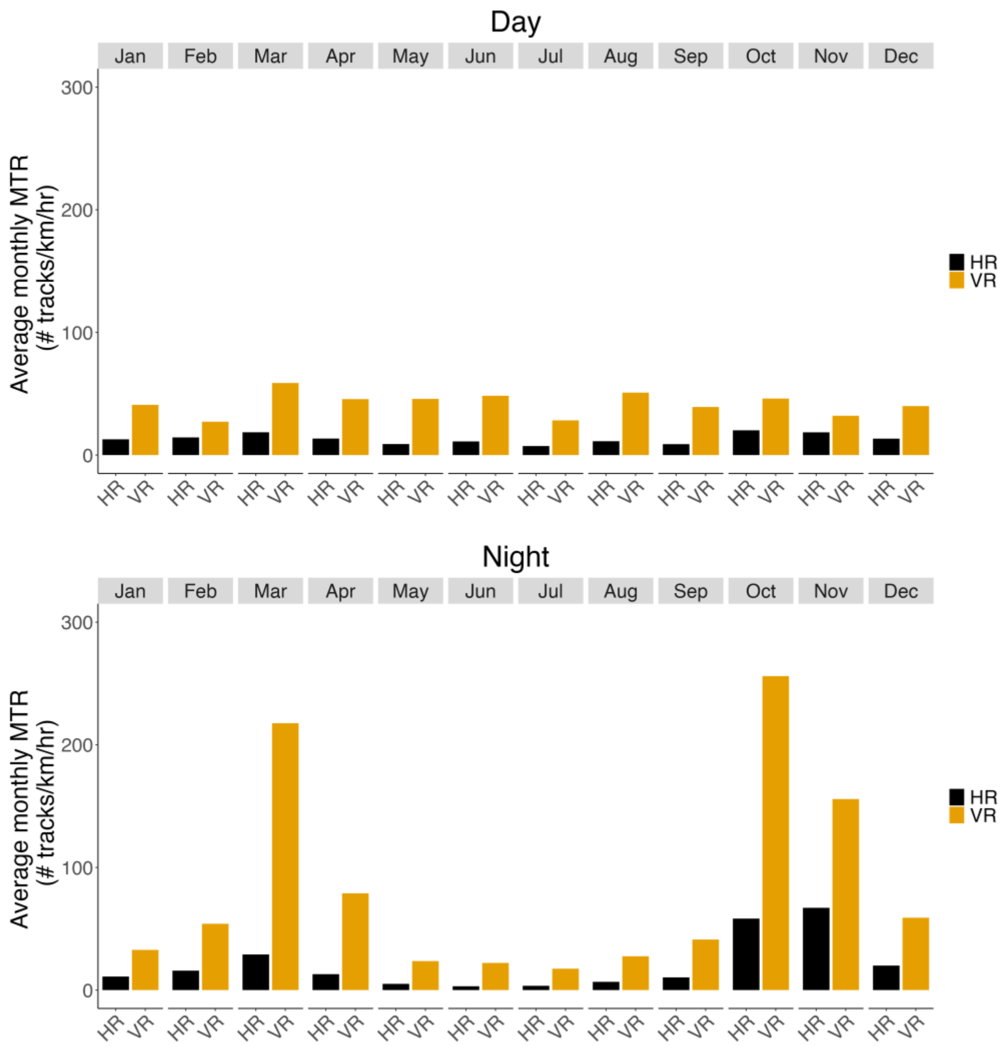

Figure 4.7 *Monthly variation in the average MTR measured by the horizontal radar ('HR') and the vertical radar ('VR') in Borssele during daylight hours (above) and during night-time (below). Each bar indicates the average MTR during each month.*

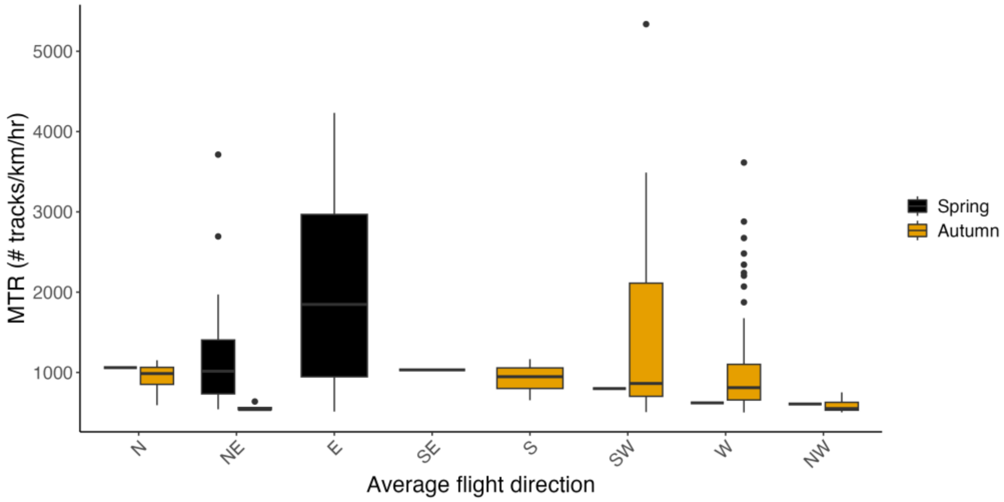

Figure 4.8 Flight direction versus MTR in spring and autumn during peak hours (MTR>500).

Figure 4.9 *Weekly variation in the average MTR in Borssele for each year of the study period, for either the horizontal radar (black) or vertical radar (orange).*

Daily flux patterns

Flight activity in Borssele was not constant during the day. The radar measurements revealed that during the migration periods in spring and autumn the number of birds passing through the area was peaking at the start of the night (Figure 4.10). During the night, the numbers steadily decreased to daytime levels. These patterns were most visible in the vertical radar data. In winter and summer, such patterns were not observed. During winter, the number of birds were the highest during the daylight period, with slightly elevated numbers just after sunrise. In summer, no clear differences were recorded in the MTR throughout the day.

The relative percentage of tracks during day and night showed a clear pattern with an increasing proportion of night-time tracks during spring and autumn migration in their respective peak months March and October (77% of tracks at night), and to a lesser extent in April and November (65-67% of tracks at night) (Figure 4.11). In January and December, more than 61-68% of the tracks were detected during daytime. In the remaining months, the number of tracks during day and night were roughly equal (46-56%).

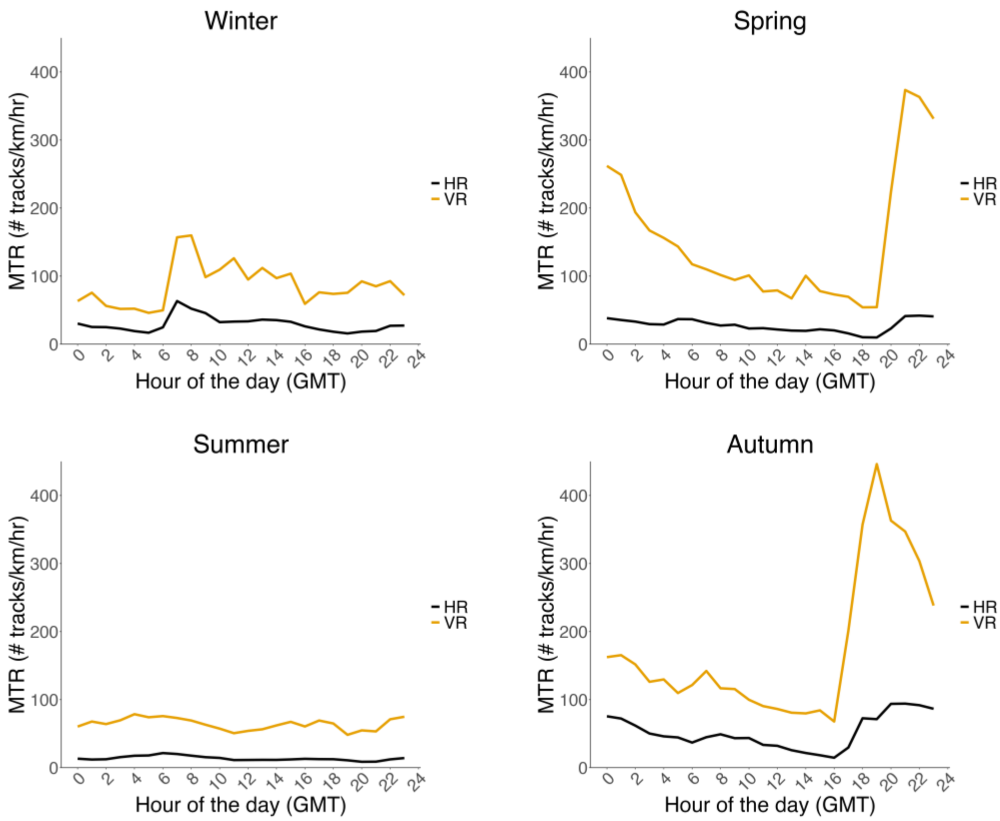

Figure 4.10 *Seasonal patterns of the variation in flight intensities during the day. Flight intensity is presented on the y-axis as the average MTR per hour, for either the horizontal radar (black) or vertical radar (orange).*

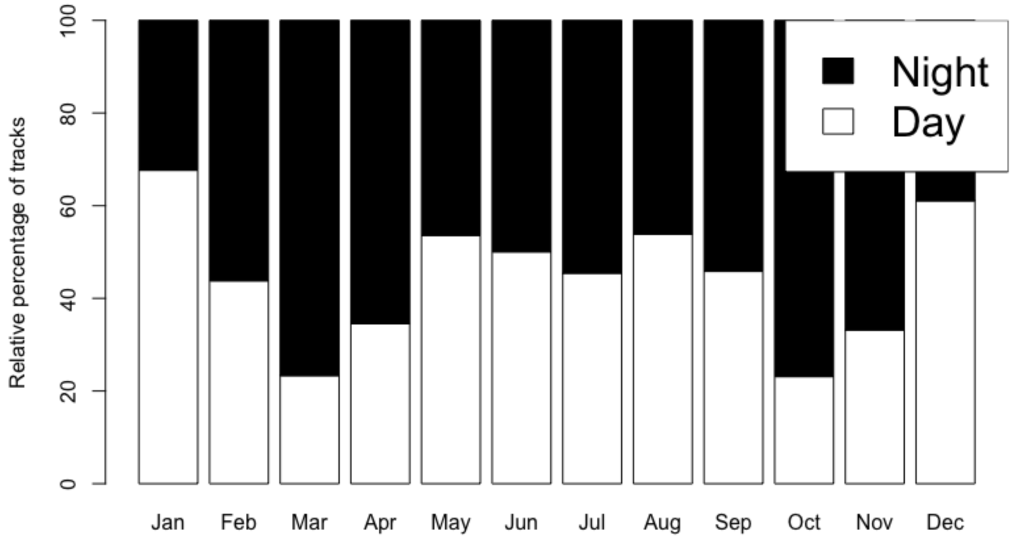

Figure 4.11 *Percentage of tracks during night (black) and day (white) in each month corrected for the monthly numbers of daylight and night-time hours.*

Flight direction during the peak hours (MTR>500) differed also per season. On Figure 4.12 these flight directions are depicted during the day. The figure clearly shows that birds in spring follow an easterly flight direction. On the contrary, during autumn birds generally fly towards the (south)west. However, around sunrise these directions divert towards south and even to southeast. This may indicate nocturnal migrants making correction flights towards land, i.e. birds above sea deciding not to continue their migratory journey during the daytime but take a rest on land. Around sunset in autumn birds fly more (north)west.

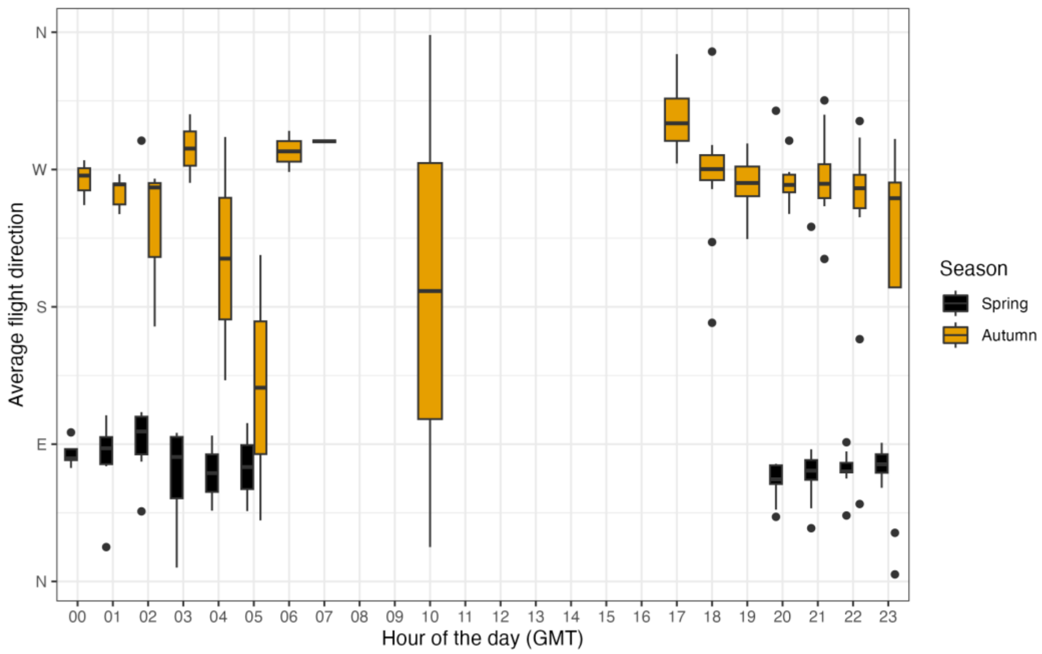

Figure 4.12 *Flight directions during hours of high flight intensity (MTR>500) in spring and autumn.*

Species-specific radar fluxes

When applying the monthly species composition of birds in flight measured during ship-based surveys on the average bi-monthly radar fluxes during daylight, we found that the highest fluxes during daylight are calculated for black-legged kittiwake with on average 43 birds per km per hour in December/January, followed by lesser black-backed gull with around 31 birds per km per hour in June/July and August/September (Table 4.3). Other species with on average more than 10 birds per km per hour in one month were Sandwich tern (April/May) and little gull (October/November). Among the migrant species groups, most numerous were songbirds and waders in August/September and raptors/falcons in June/July. Note, however, that a large number of migrants fly during the night, while the presented fluxes are merely based on daytime observations.

Table 4.3 Average species-specific fluxes per km per hour during daylight in each bimonthly period based on radar measurements and the monthly species composition of birds in flight measured during ship-based surveys, for local birds (above line) and migrants (below line).

species	Dec/Jan	Feb/Mar	Apr/May	Jun/Jul	Aug/Sep	Oct/Nov
black-headed gull	1.02	0.88			12.20	4.25
black-legged kittiwake	42.86	21.01				4.25
common guillemot	9.18					
common gull	6.12	14.88	1.07		0.68	
common tern					3.39	
common/arctic tern					1.36	
great black-backed gull	4.08	0.88			1.36	
herring gull	7.14	6.13		2.40	1.36	4.25
large gull sp.	1.02				0.68	
lesser black-backed gull	1.02	6.13	19.27	31.16	30.50	12.76
little gull	4.08		1.07			21.27
northern gannet	13.27	9.63	1.07			8.51
razorbill	2.04	2.63				17.02
razorbill/guillemot	6.12	0.88				
sandwich tern		0.88	28.90	4.79	2.03	
songbirds					2.03	
waders					2.71	
raptors/falcons				2.40		
other			1.07			

4.3 Discussion

One of the main objectives of the project was to determine species-specific fluxes in wind farm Borssele based on measurements by the bird radars. The current report presents the results of more than four years of radar measurements. The temporal patterns in fluxes throughout the year (*i.e.* highest fluxes during migration in March and October) and seasonal patterns throughout the day were in line with the patterns in fluxes measured earlier in wind farms OWEZ (Krijgsveld *et al.* 2011) and Luchterduinen (Leemans *et al.* 2022b). Also, the number of hours with a mean traffic rate of more than 500 birds per km per hour in Borssele was similar to OWEZ and Luchterduinen. Krijgsveld *et al.* (2015) reported 40 of such hours per year in OWEZ, while 62-92 of these hours were measured in Luchterduinen (Leemans *et al.* 2022b). In Borssele, the bird radars recorded 44-96 hours per year (excluding the remaining months of 2019) with a mean traffic rate of more than 500 birds per km per hour.

It took several steps to filter the dataset of the bird radars in Borssele from the large amount of non-bird tracks caused either by rain or by waves, or from periods in which the dynamic filtering of the radar software may have led to a negative observation bias (*i.e.* falsely low fluxes (van Erp *et al.* 2023)). The sensitivity of the bird radars to clutter caused by rain or waves and hence the extensive filtering that is required to come to a 'clean' dataset of bird tracks, was also reported for the same radar system operational in wind farm Luchterduinen (Leemans *et al.* 2022b). The radar systems at the two locations, however, differ in the sensitivity of the vertical radars for clutter related to wave height. We found a strong positive correlation between wave height and the number of tracks detected by the vertical radar in Borssele. This correlation suggests that the clutter is caused by waves. However, other explanations, like clutter from spinning rotor blades, cannot be ruled out. For the vertical radar in Luchterduinen, only the lowest altitude levels above the sea surface were found to be likely contaminated with wave clutter (Leemans *et al.* 2022b), while for the Borssele radar, tracks in periods with high waves were recorded up to altitudes of several hundreds of meters (Figure 4.13). The cause of this difference in response to wave height is yet unknown to us. All the filter steps we had to apply to come to realistic MTR estimates imply that the unfiltered radar data is not yet directly applicable to produce MTR estimates.

To avoid contamination just above the sea surface, we excluded in our analyses all tracks with an altitude below 3 meters. The downside of this filtering is that several species of seabirds prefer to fly at these low altitudes. Filtering out all tracks just above sea level may therefore reduce the contamination of wave clutter, but at the same time we may also lose most tracks of some species. Also, the strong filtering of periods with rain or waves inherently means that the presented results merely reflect periods with relatively quiet weather. Hence a point of further investigation should be whether the filtering can be improved, in order to prevent more data loss than necessary, especially considering that rain (and similar adverse weather circumstances with lower visibility) may lead to increased collision risk (Hüppop *et al.* 2006, Hüppop *et al.* 2016). For example, actual rain measurements at the radar location itself could already facilitate much more precise filtering of rainy periods. Furthermore, a promising method to reduce the impact of clutter on radar performance could be using machine learning to identify clutter tracks and ultimately improve the classification of tracks. The first results on the automatic classification of wave clutter developed by Waardenburg Ecology for the Max 3D radar of Robin Radar are very promising. Similar methods may be applied to Robin Radar Flex/Fixed systems in offshore wind farms in the future. Ultimately, if this results in improved filtering of clutter, it may allow to lower the strength of the dynamic filtering of the radar software, thus increasing the detection of birds during a larger array of circumstances, and subsequently increase post-processing filtering.

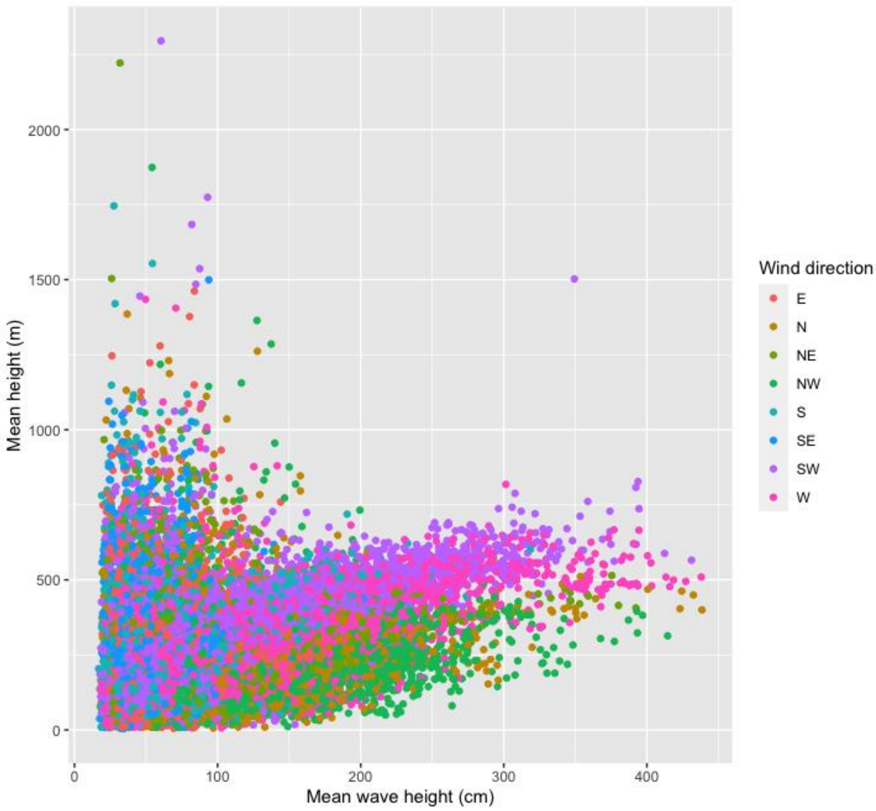

Figure 4.13 *Correlation between average hourly wave height (cm) and average hourly track height (m) given for each wind direction before filtering of the dataset.*

Nocturnal activity was highest during the peak migration in March and October (77% of tracks at night), and to a lesser extent in April and November (65-67% of tracks at night) Outside these months, we found relatively high proportions of nocturnal activity. In January and December, more than 61-68% of the tracks were detected during daytime. In the remaining months, the number of tracks during day and night were roughly equal (46-56%). The remarkable high nocturnal activity outside migration periods may either be explained by local birds being more active at night than was so far assumed, or otherwise some methodological issue may be influencing these results. Possibly, an unknown source of clutter may be continuously generating tracks that remained in the dataset even after all the filter steps applied. If this would be the case, then clutter from wind turbines (that are continuously present) could the most likely cause. This could potentially also explain why nocturnal activity in the summer months is relatively higher than in the winter months. In summer, turbine downtime during the day is generally higher than in winter during the day, due to the more favourable circumstances to perform maintenance to the wind turbines. Wind turbines under maintenance are not operational and hence do not induce radar clutter. However, the exact cause of the relatively high nocturnal activity remains to be further examined.

All the different steps of filtering led to deleting altogether roughly 75% of all hours for both the horizontal radar and the vertical radar. When looking at both radars combined, approximately 63% of all hours were filtered out. The vertical radar generally recorded higher MTRs than the horizontal radar. Hence in practice, when using the highest MTR per hour, we mostly relied on vertical radar data. A possible reason for this difference, and at the same time a strong advantage of using vertical radar data, is that the vertical radar is able to detect tracks up to much higher altitudes than the horizontal radar. However, even considering only vertical radar tracks up to an altitude of 300 m (which is approximately the altitude range of the horizontal radar), the number of tracks detected by the vertical radar is mostly higher than the horizontal radar (Figure 4.14). Possibly, both radars differ in performance in terms of their capability to detect birds. The validation studies of the bird radars in Borssele also suggest such difference, as a lower false negative rate was found for the vertical radar compared to the horizontal radar (Leemans *et al.* 2021, Leemans *et al.* 2022a). However, as the two radars are of a different type (horizontal S-Band vs vertical X-Band), and also the method to derive fluxes was different for both radars, it is difficult to assess to what extent the difference in the recorded fluxes is a result of differences in the detection capabilities of both radars.

A potential disadvantage of using vertical radar data is that we cannot change the orientation of the flux lines used to calculate the fluxes. The vertical radar beam covers areas to the northwest and the southeast from the radar, and hence also the flux lines lay in these directions. If the flux of birds goes in a perpendicular direction to these flux lines (*i.e.* towards southwest or northeast) the calculated fluxes per length of the flux lines are genuine. However, the length of the 'effective flux lines' decreases if the birds are mainly flying in different directions (Figure 4.15). In such situations, fluxes per kilometre will be underestimated (Kleyheeg-Hartman & Potiek 2020), and large deviations in measured fluxes may occur (Leemans *et al.* 2022b). This underestimation may mostly be relevant for migratory birds that in large numbers cross the area in a certain direction in a short period of time. The effect might be small during autumn migration, as migrating birds mainly follow a northeast-southwest direction during their seasonal migration (*i.e.* roughly perpendicular to the vertical radar beam). In spring, the direction of migration over the North Sea often has a more easterly component (see Figure 4.12), when birds from the United Kingdom make the crossing (Bradarić *et al.* 2020). However, in our study, we did not find evidence that this issue affected the general patterns in fluxes. More specifically, we found no hours in which intense migration was recorded by the horizontal radar but not by the vertical radar (considering the hours that were not filtered out in the vertical radar dataset). We therefore did not correct the flux calculations of the vertical radar for the main flight direction of tracks in that hour.

For local birds, the above-mentioned issue is less relevant, as local birds will not consistently cross the radar beam in a certain direction. Hence large deviations with the actual flux will not occur and temporal patterns are not affected as deviations are more or less consistent throughout the year. Note that an individual local bird may cross the flux line multiple times, and hence fluxes must not be interpreted as the number of individuals present in the area. Multiple crossings of the same individual are, however, not likely for migrating birds that pass the area on their seasonal migration. Furthermore, the warning to infer species-specific fluxes based on radar measurements holds in a general sense, as the calculations also rely on tracks classified as 'flocks' by the radar, which indisputably means that more than one target was measured, but the exact number is not known.

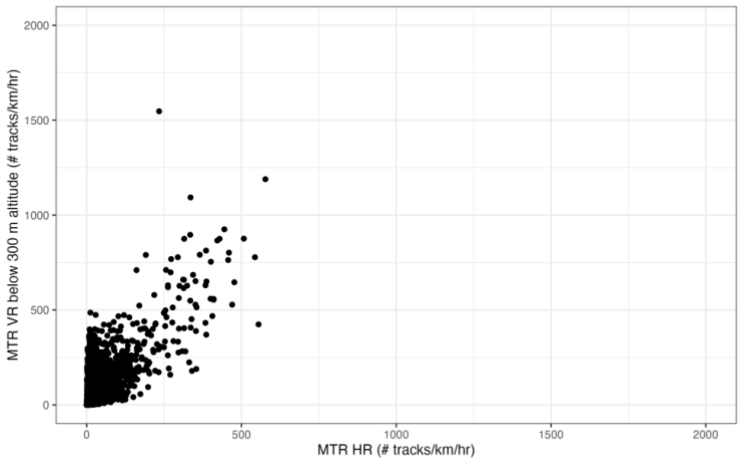

Figure 4.14 *Mean traffic rates in the same hour measured by the horizontal radar versus the vertical radar up to an altitude of 300 m.*

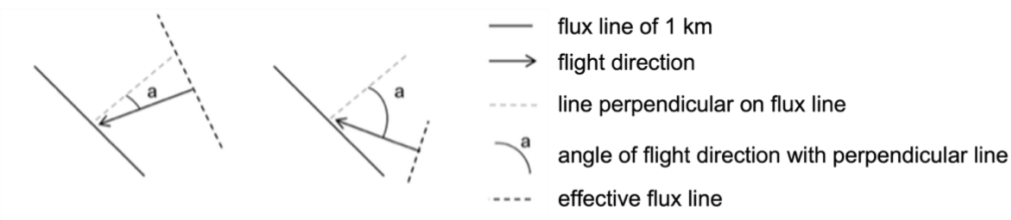

Figure 4.15 *The length of the 'effective flux line' will be smaller than 1 km if the bird's flight direction is not perpendicular to the flux line. The larger the angle of flight direction with the perpendicular line, the smaller the 'effective flux line' will be. Adjusted from (Kleyheeg-Hartman & Potiek 2020).*

The species-specific fluxes based on radar data presented in this chapter are mainly meant to give an indication of the order of magnitude of the fluxes for each species in each month. The highest species-specific fluxes in Borssele were somewhat lower than the species-specific fluxes measured in wind farm Luchterduinen (Leemans *et al.* 2022b). In Luchterduinen, the highest fluxes during daylight were calculated for lesser black-backed gull (49 birds/km/hour in July) and black-legged kittiwake (48.8 birds/km/hour in December), while in our study the highest fluxes were respectively 31.1 and 42.9 birds/km/hour for those species. Furthermore, for several species (black-headed gull, common gull, herring gull, little gull, common guillemot, razorbill, common tern and Sandwich tern) the highest flux in Borssele was in at least one bi-monthly period higher than the highest flux in Luchterduinen, while the highest fluxes were lower in Borssele for other species (great black-backed gull, northern gannet, arctic skua, great skua, common eider, common scoter and great cormorant). Amongst migrants, we found higher fluxes during daytime of waders (August/September) and raptors/falcons (June/July) than in Luchterduinen. It must be noted, however, that the sample size on which we based the species composition of birds in flight in the months June/July and October/November was rather low (n = 17), thus the species-specific fluxes in these months should be taken with extra care.

5 Effect of weather on fluxes

Offshore wind farms are a potential threat to birds, causing increased mortality due to collisions. As collision rates will inevitably increase with intensity of bird movements, it is important to understand when events of intense migration can be expected, so that mitigation measures can be designed and successively taken. Intensity of bird migration and its direction are strongly dependent on the season (*e.g.*, pre- or post-breeding migrations) but also on weather conditions (wind direction and speed) (Newton 2010). In this chapter, we present the effects of wind speed and direction on fluxes measured by the radars in Borssele.

5.1 Methods

Radar data

The effect of weather on fluxes was analysed using the filtered datasets of the horizontal radar and the vertical radar (see §2.2.2). Fluxes (expressed as mean traffic rates, MTRs) were calculated using the same methods as described in §4.1.2.

Weather data

Wind data at 100m above sea level from 2019 and 2020 were taken from the ECMWF database, using the closest grid cell to Borssele Alpha in the ECMWF dataset. Wind data from 2021, 2022 and 2023 were measured on top of the nacelle of nine different turbines close to BSA, and subsequently averaged per hour. The wind components *u* (west to east, referred to as 'eastern component') and *v* (south to north, referred to as 'northern component') were transformed to wind direction and wind speed (in m/s) (for the 2019-2020 data), and vice versa (for the 2021-2023 data), in R using the 'rWind' package (Fernández-López & Schliep 2019). Tail-/headwind per hour was calculated as the absolute difference between the average wind direction and average flight direction in that hour.

Wave height data were retrieved from waterinfo.rws.nl, which were measured locally at 'Schouwenbank 2' (up to 8 Feb 2020) and at Borssele Alpha (from 8 Feb 2020 onwards).

Statistical analysis

The effects of wind on bird fluxes were estimated in R using Generalised Linear Models (GLMs), assuming a Gaussian distribution of the response variable. Models included either wind speed, or the interaction between the eastern and northern wind components and season as linear fixed effects. To test the effects of wind on local bird activity, we took a subset of the data only including daylight hours in winter and summer, to minimise the likelihood that hours with bird migration were present in the dataset. The filtering steps we had to take to remove clutter from the vertical radar dataset at increasing wave heights aimed to remove the hours with falsely high traffic rates, while retaining hours with (most likely) bird migration. Consequently, hours without peak bird migration had a greater chance of being filtered out at increasing wave heights, which could introduce a bias in the analysis of wind speed on bird activity of local birds. Hence, for local birds, we only used horizontal radar data.

5.2 Results

Mean traffic rates of more than 500 tracks/km/hour were recorded with wind speeds between roughly 1 and 15 m/s (*i.e.* 1-7 Bft), although the highest MTRs during peak migration were generally with wind speeds between roughly 4 and 13 m/s (*i.e.* 3-6 Bft) (Figure 5.1). Bird activity (of local birds) during the day in summer and winter was not significantly affected by wind speed (GLM: F = 0.002; P = 0.61, Figure 5.2). In spring, the peak (migration) hours with more than 500 tracks/km/hr occurred with on average lower wind speeds than in autumn. Numbers peaked in spring with wind speeds of 3 and 4 Bft, while in autumn peaks were recorded with 5 and 6 Bft (Figure 5.3).

Wind direction, in combination with wind speed (expressed by an eastern and a northern component, see methods), significantly affected bird activity in all seasons. Bird activity (of local birds) during the day in both summer and winter was higher with winds with a strong northern component (GLM: F = 0.021; P < 0.0001) and a strong eastern component (GLM: F = 0.010; P < 0.05) (Figure 5.4, Figure 5.5). Furthermore, the model predicts elevated bird activity during the day in summer with strong southwestern winds. In winter, a strong eastern wind component always results in higher predicted MTRs than strong western components, regardless of the south-north component.

When only considering hours with more than 500 tracks/km/hr, we found that in spring the highest fluxes occurred with southern and especially southwestern winds, and only exceptionally with (north)eastern winds (Figure 5.6). Model predictions also show significantly lower MTRs in spring with northern (GLM: F = -0.035; P < 0.0001) and eastern winds (GLM: F = -0.044; P < 0.0001) (Figure 5.7). This pattern is reversed in autumn where the numbers mainly peak with east and north-eastern winds, and only exceptionally with western winds (Figure 5.6). Here, model predictions also show significantly higher MTRs in autumn with a strong eastern wind component (GLM: F = 0.087; P < 0.0001), while the effect of the northern wind component is not significant (GLM: F = 0.008; P = 0.25) (Figure 5.7). In all other cases, peak hours in spring and autumn occasionally occur but to a much lesser extent. Lastly, MTRs were significantly higher with more tailwind in spring (GLM: F = 0.032; P < 0.05), while this relation was not significant in autumn (GLM: F = 0.005; P = 0.69) (Figure 5.8). Figure 5.9 shows that such tailwinds cause high numbers of birds flying towards southwest when wind direction is northeast. In spring, higher fluxes were in some cases also found with wind from the side (Figure 5.8). On Figure 5.9, this is visible from the high flight intensity towards the east by a mainly southwestern wind direction.

The top 10 hours with the highest MTRs were all recorded at night in March, October or November, for both the horizontal radar and the vertical radar (Table 5.1). The peak hours on the vertical radar were all recorded with winds of 4-6 Bft from either the (south)west or east and in hours at which the horizontal radar data was filtered out. The peak hours on the horizontal radar were all recorded with winds of 1-4 Bft from a variety of wind directions. Two peak hours in autumn were accompanied with southwestern winds of 1-2 Bft. During five of these hours, the vertical radar also recorded more than 500 tracks/km/hr.

On average, the top 10 nights with the highest MTRs recorded by the vertical radar were all in March or October (Table 5.2), while for the horizontal radar all of these nights were in autumn (four in October and six in November). The peak nights on the vertical radar were all recorded with average winds from an (north- or south)-eastern direction in autumn and a south or southwestern direction in spring. On the other hand, the peak nights recorded by the horizontal radar in autumn were in four cases with an average southernly wind, and once with a north-western wind.

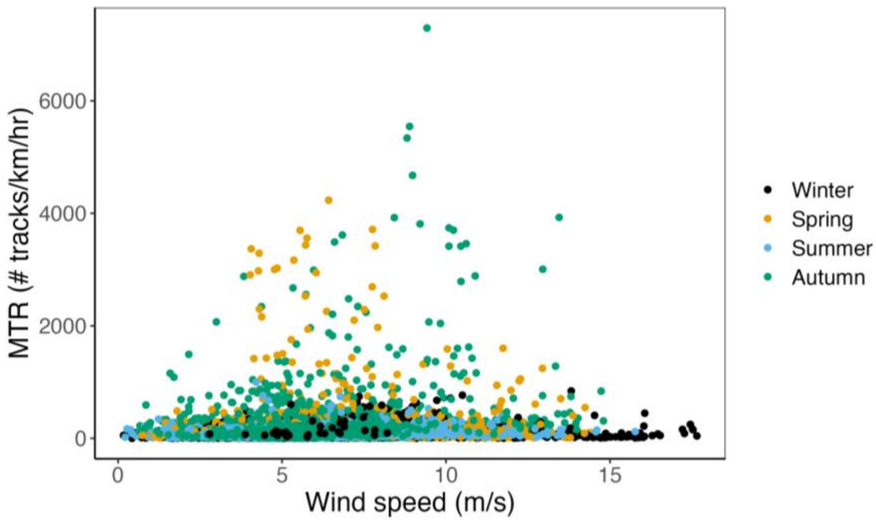

Figure 5.1 Hourly mean traffic rate (MTR) versus the hourly mean wind speed (m/s), in each season. Vertical radar measurements were used as MTR.

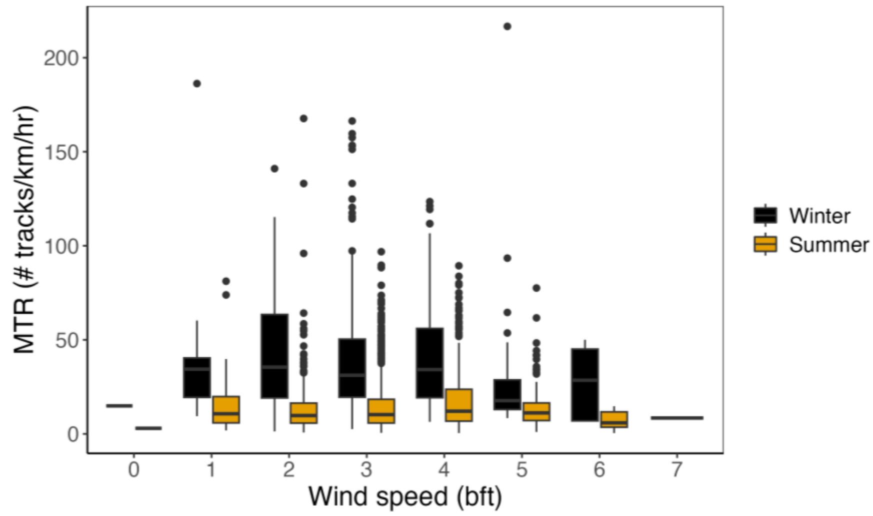

Figure 5.2 Hourly mean traffic rate (MTR) versus the hourly mean wind speed (Beaufort), during the day in winter and summer (to include (mostly) local birds). Horizontal radar measurements were used as MTR.

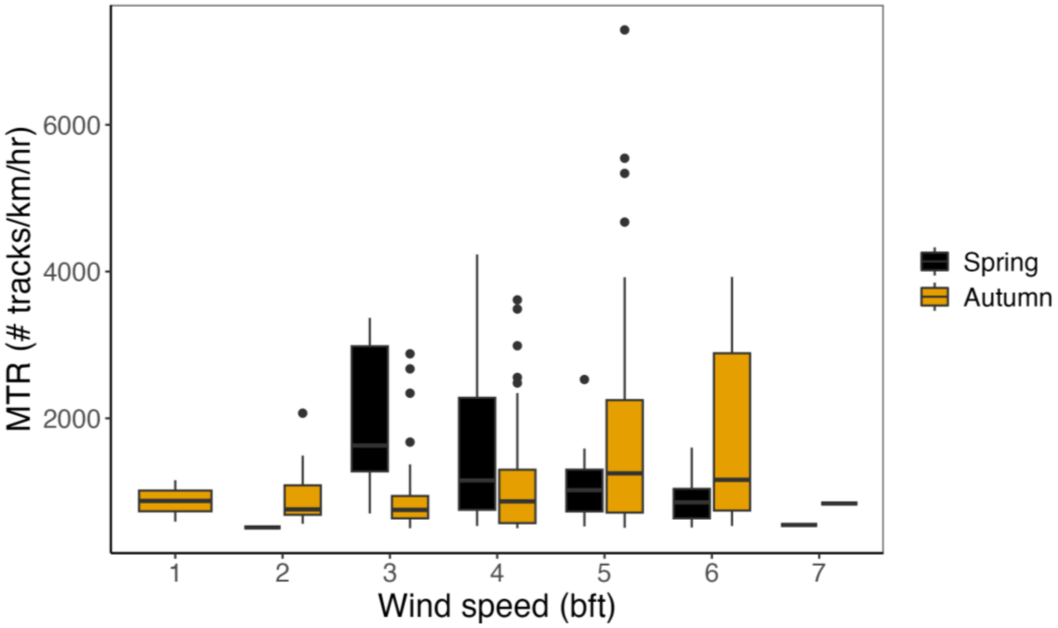

Figure 5.3 *Hourly mean traffic rate (MTR) versus the hourly mean wind speed (Beaufort), in spring and autumn for the hours with an MTR of more than 500 tracks/km/hr (to include (mostly) migratory birds). Vertical radar measurements were used as MTR.*

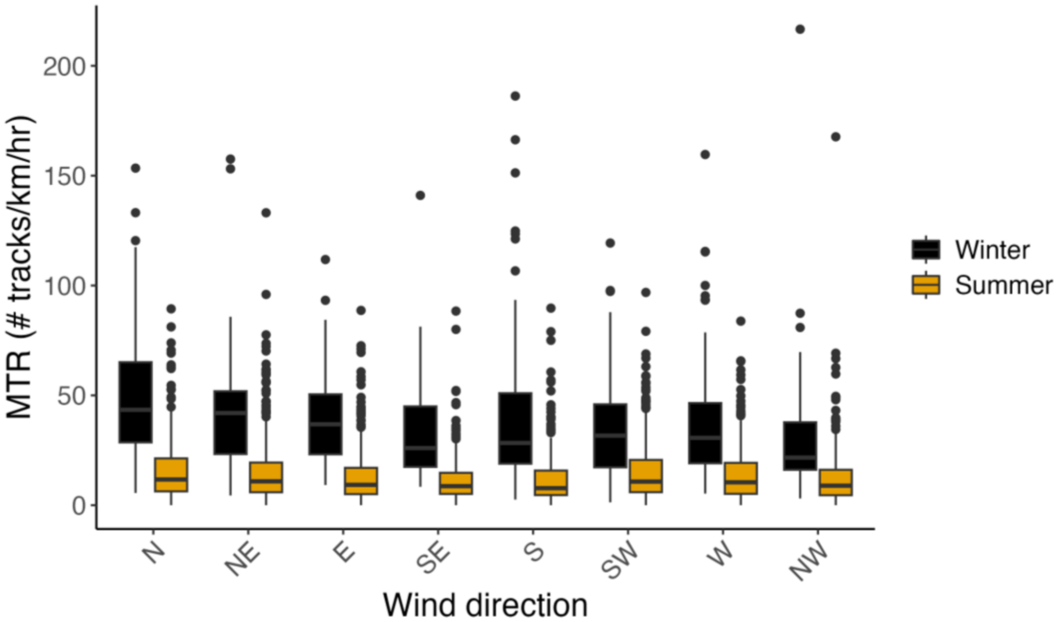

Figure 5.4 *Hourly mean traffic rate (MTR) versus the hourly mean wind direction, during the day in winter and summer (to include (mostly) local birds). Horizontal radar measurements were used as MTR.*

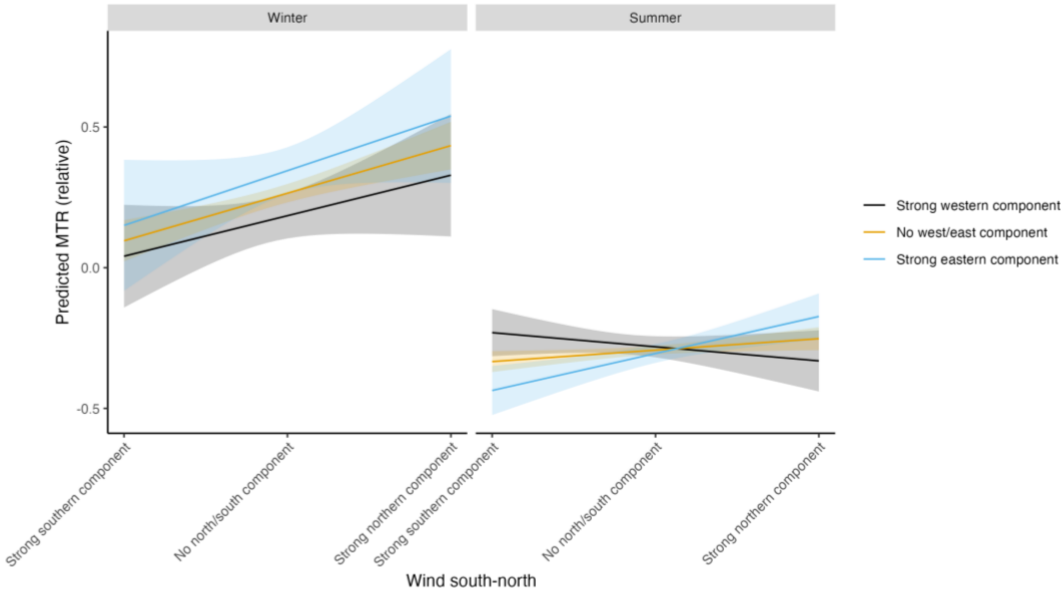

Figure 5.5 *Predicted (GLM) relative hourly mean traffic rate (MTR) based on horizontal radar data, during the day in winter and summer (to include (mostly) local birds), under different wind conditions. Model (GLM) predictions are shown with lines and shaded areas indicating the 95% confidence intervals.*

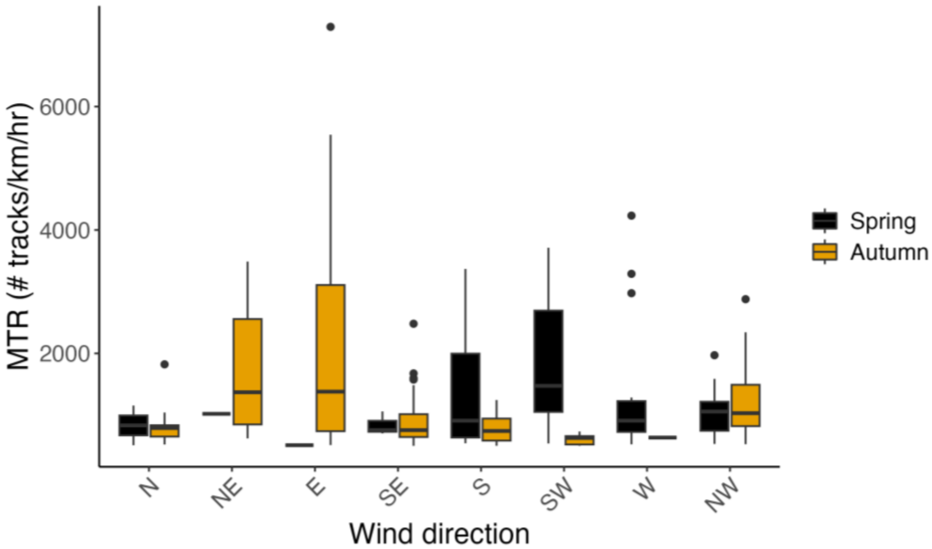

Figure 5.6 *Hourly mean traffic rate (MTR) versus the hourly mean wind direction for the hours with an MTR of more than 500 tracks/km/hr, in spring and autumn (to include (mostly) migratory birds). Vertical radar measurements were used as MTR.*

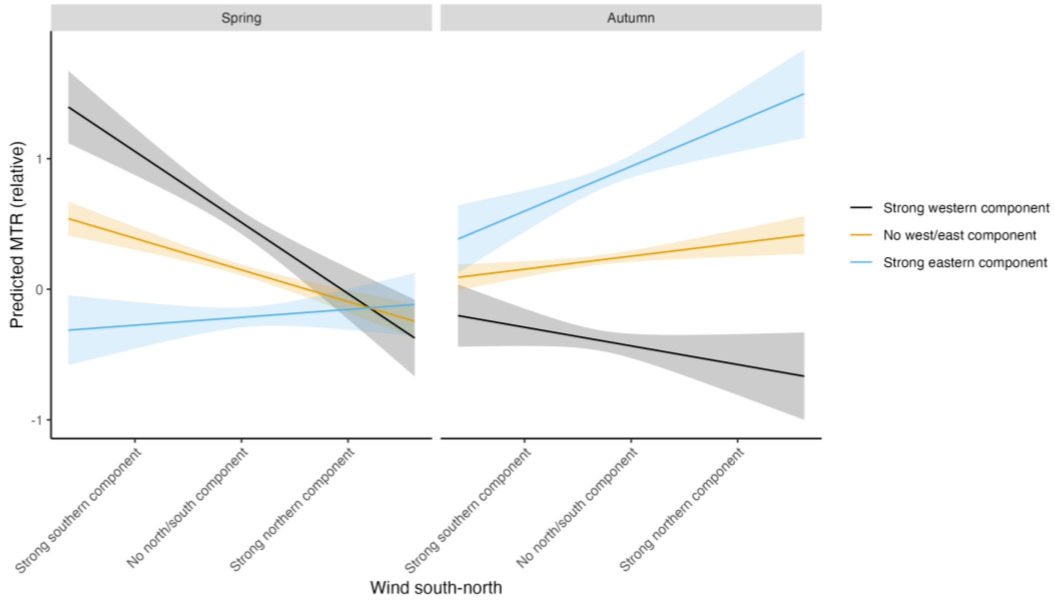

Figure 5.7 *Predicted (GLM) relative hourly mean traffic rate (MTR) in spring and autumn under different wind conditions based on vertical radar data. Model (GLM) predictions are shown with lines and shaded areas indicating the 95% confidence intervals.*

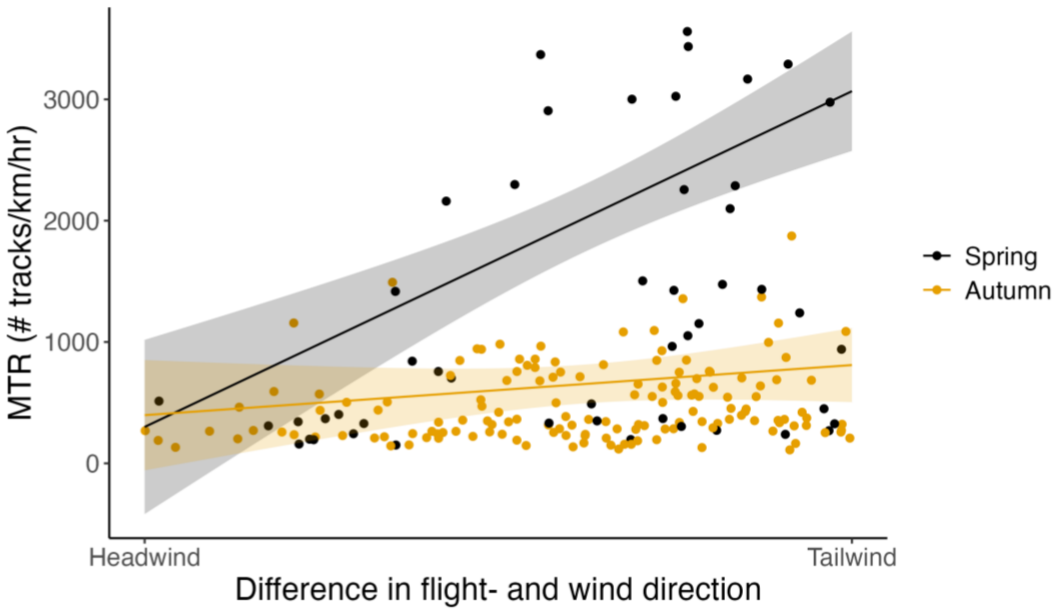

Figure 5.8 *Hourly mean traffic rate (MTR) versus the amount of headwind and tailwind in spring and autumn (dots). Model (GLM) predictions are shown with lines and shaded areas indicating the 95% confidence intervals. Only hours with an MTR of more than 100 tracks/km/hr measured by both the horizontal and the vertical radar were included. Note that the hours in autumn with the highest MTRs are lacking horizontal radar data and hence these hours are not depicted in this figure.*

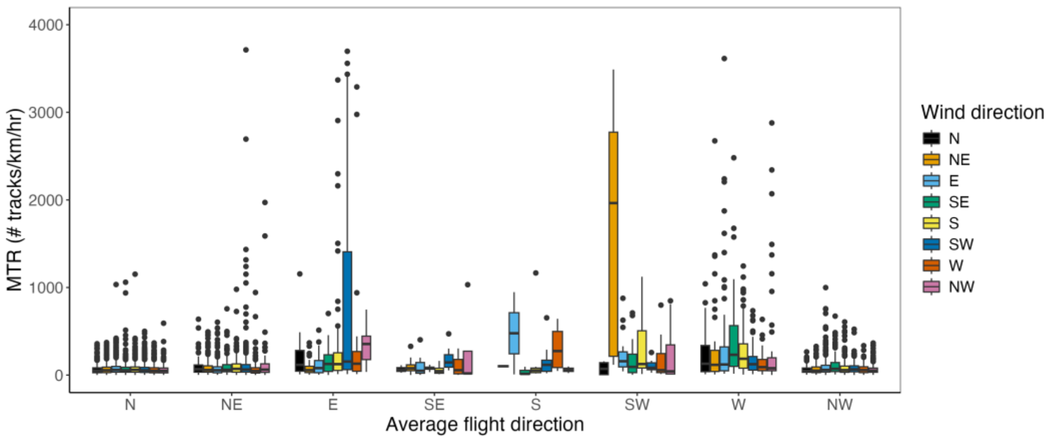

Figure 5.9 *Effect of wind direction on flight direction. Vertical radar measurements were used as MTR. Note that the y-axis is cut off at 4,000 for clarity.*

Table 5.1 *Overview of the top 10 hours with the highest MTRs for the vertical radar (above line) and the horizontal radar (below line) and the weather circumstances during that hour. A dash (-) in the MTR columns indicates that this hour was filtered out for that radar.*

hour (GMT)	MTR VR	MTR HR	wind direction	wind speed (bft)	wave height (cm)
2023-10-16 19:00:00	7,293	-	E	5	106
2023-10-16 20:00:00	5,544	-	E	5	110
2019-10-29 18:00:00	5,338	-	E	5	82
2023-10-16 21:00:00	4,674	-	E	5	115
2022-03-14 01:00:00	4,233	-	W	4	48
2022-10-19 18:00:00	3,927	-	E	6	158
2019-10-29 17:00:00	3,923	-	E	5	82
2019-10-29 19:00:00	3,811	-	E	5	86
2023-10-16 22:00:00	3,740	-	E	5	117
2023-03-18 23:00:00	3,713	-	SW	4	45
2019-10-22 18:00:00	-	705	SW	1	58
2023-11-17 01:00:00	-	613	NW	2	63
2022-10-18 18:00:00	1,874	577	E	4	41
2021-10-07 20:00:00	-	559	S	3	40
2021-10-08 20:00:00	-	559	E	4	34
2019-11-10 18:00:00	759	555	SE	2	63
2022-03-15 02:00:00	1,417	544	S	3	32
2022-03-15 01:00:00	2,161	508	S	3	33
2023-11-17 02:00:00	-	500	SW	2	57
2022-03-15 00:00:00	2,298	477	S	3	34

Table 5.2 Overview of the top 10 nights with on average the highest MTRs for the vertical radar (above line) and the horizontal radar (below line) and the average weather circumstances during that night. A dash (-) in the MTR columns indicates that this night was completely filtered out for that radar.

Night	avg. MTR VR	avg. MTR HR	wind direction	wind speed (bft)	wave height (cm)
2023-10-16 to 17	3,575	-	E	5	110
2020-10-13 to 14	2,952	-	E	5	107
2019-10-28 to 29	2,383	-	NE	4	93
2022-10-19 to 20	2,180	-	SE	5	129
2022-03-13 to 14	1,861	71	SW	4	49
2022-03-17 to 18	1,842	159	SW	3	67
2019-10-29 to 30	1,702	-	E	5	89
2021-03-20 to 21	1,694	197	SW	4	59
2023-03-18 to 19	1,578	85	SW	4	49
2022-03-14 to 15	1,514	230	S	3	32
2023-11-16 to 17	254	408	S	3	69
2021-10-08 to 09	-	337	E	3	45
2022-10-18 to 19	1,395	321	E	5	75
2021-10-07 to 08	-	320	S	3	38
2020-11-07 to 08	573	312	SE	4	38
2022-11-12 to 13	735	290	SE	3	31
2019-11-10 to 11	184	280	S	5	87
2020-11-04 to 05	1,111	265	NW	2	74
2019-11-06 to 07	204	259	S	4	83
2019-10-22 to 23	107	250	SE	2	48

5.3 Discussion

This chapter presents insights on the effects of wind speed and wind direction on bird activity. For this, we used hourly wind data that were either modelled for the wind farm location or locally measured in the wind farm, and thus represent the local conditions. However, bird activity inside the wind farm may also be affected by weather conditions at locations further away, especially in the case of migration events which are strongly dependent on the upstream conditions at departure locations. An analysis of the effects of such upstream conditions on the bird activity inside Borssele wind farm was out of scope of this study.

The highest MTRs during peak migration were generally with wind speeds between roughly 3 and 6 Bft. In spring, these peaks occurred with on average lower wind speeds (3-4 Bft) than in autumn (5-6 Bft; (cf. Bradarić 2022)). The peak hours on the vertical radar were all recorded with winds of 4-6 Bft from either the (south)west or east and in hours at which the horizontal radar data was filtered out. This raises the question whether besides bird migration, some wave clutter may be remaining in the dataset in these hours, which would mean that the actual bird fluxes were somewhat lower.

Wind direction, in combination with wind speed (expressed by an eastern and a northern component, see methods), significantly affected bird flight activity in all seasons. Bird activity (of local birds) during the day in both summer and winter was higher with strong northern and eastern wind components. Additionally, bird activity was higher with strong southern and western components in summer. However, these results on the effect of wind speed on bird flight activity based on the radar measurements should be considered with care, as wind speed also affects the detection capabilities of the radar. As discussed in Chapter 4.3 the amount of clutter in the radar measurements correlates with wave height. Although we cannot rule out that this clutter development is not influenced by reflections from spinning rotor blades as well, both wave height and rotor speed are related to wind speed. As clutter development governs the functioning of the dynamic filters of the radar, different clutter levels and corresponding filtering define the capabilities of the radar to detect bird tracks. Therefore, clutter development in certain seasons may lead to higher (or lower) filtering levels by certain wind directions and hence influence radar results on bird flight intensities.

When only considering peak migration hours with more than 500 birds per km per hour, we found that spring migration mainly occurs with southern and especially south-western winds, while the highest MTRs during autumn migration were found with north-eastern and eastern winds. These results are in line with, for example, Bradarić *et al.* (2020). These peaks at different wind directions reflect the general flight direction of birds during spring migration (mostly towards east) and autumn migration (mostly towards southwest). Nonetheless, our results show that migration peaks in both spring and autumn occasionally occur during hours with sidewind or even winds going towards headwind. MTRs during autumn were not significantly affected by the amount of tailwind. However, note that the hours in autumn with the highest MTRs are lacking horizontal radar data. As such, these hours were not included in the analysis as data on the average hourly flight directions from horizontal radar data were necessary to calculate the amount of tailwind per hour.

Remarkedly, five of the peak nights recorded by the horizontal radar in autumn were with relatively unfavourable wind directions: in four cases with an average southerly wind, and once with a north-western wind, while all peak nights recorded by the vertical radar were with predominantly tailwinds. One hypothesis is that with more headwind, birds tend to fly lower (also see §8), and therefore larger numbers fly within the altitude range of the horizontal radar. This might also explain why all peak nights measured by the horizontal radar were recorded in autumn, as migration in autumn generally occurs at lower altitudes (see §8), when tailwinds occur less often and birds tend to choose to fly in headwinds more often (Bradarić 2022).

The analysis of the effect of weather on fluxes measured by the bird radars in Borssele was largely restricted to periods with relatively calm weather due to the sensitivity of the radars to wave and rain clutter. Furthermore, as we lack rain measurements at the radar location, we were not able to directly link fluxes to the amount of precipitation. In some hours that were filtered out in the vertical radar dataset due to rain filtering, the horizontal radar recorded relatively high MTRs during the migration periods. This suggests that bird migration does occur in periods with at least some precipitation, although it is widely believed that migration intensity is reduced during rainy periods (e.g. Manola *et al.* 2020).

Potential weather effects on bird fluxes were also explored by looking into the fluxes obtained through visual flux measurements. However, as field days were limited to calm weather conditions due to safety regulations and to ensure carrying out reliable visual observations, we were not able to collect enough field data under varying weather conditions to conduct meaningful analyses.

6 Corridor use

To study corridor use of birds both flying, and on the water, data from ship-based surveys was used to calculate densities inside the wind farm, just outside the windfarm and in the corridor. These densities were compared between the wind farm itself and inside the corridor or outside the wind farm, to see if birds prefer one of these areas. In the corridor, spacing between the turbines is twice as wide compared to the rest of the wind farm. Transects outside the wind farm were between 0.9 and 2.6 kilometres from the nearest wind turbine at the edge of the wind farm (Figure 2.5).

6.1 Methods

To study corridor use, ship-based surveys have been carried out. Field methods used are described in paragraph 2.3.

6.1.1 Distance analysis

Distance sampling analyses were carried out to correct for imperfect detection at larger distance from the observer. This analysis was only carried out for birds sitting on the water. as under the ESAS protocols all flying birds within 300 meters are assumed to be detected. Distance models were fitted for each species separately, but only for species with a sufficiently large sample size. A rule of thumb for distance analysis is that 60 observations are needed for a distance analysis, and 60 more for each level of a covariate (Buckland *et al.* 2004). Detection functions consist of a key function, and either adjustment terms or covariates. For each species, 8-12 functions were fitted (depending on the amount of covariates included): including half normal and hazard rate key functions, with cosine and hermite adjustment terms with the half normal key functions, and simple polynomial adjustment terms with the hazard rate key function. Log of group size, sea state and observer team were tested as covariates with both hazard rate and half normal key functions. The best-fitting model per species was selected based on the lowest Akaike Information Criterion (AIC) value. This ‘best’ model was used to calculate Effective Strip Widths (ESW). The ESW is then used to calculate density $D_{swimming}$ of the species, assuming perfect detection at the transect line, using this formula;

$$D_{swimming} = N_{swimming} / (ESW * \text{transect length})$$

with the ESW and transect length in km. To calculate the density of flying birds D_{flying}, the entire transect width can be used, which is 300 meters in case of ESAS counts.

$$D_{flying} = N_{flying} / (\text{transect width} * \text{transect length})$$

To be able to use the number of birds as a ‘count’ response in later modelling, assuming a negative binomial in the GLMM (see next paragraph), we calculated an ESW weighted for the proportion of flying and swimming birds as follows:

ESW average = (N_{total} / ($D_{swimming}$ + D_{flying})) / transect length.

This weighted ESW was then used to calculate the effectively surveyed area corresponding to the summed densities of swimming and flying birds. Distance analyses were carried out using the MRDS package in R (Laake *et al.* 2023). Common guillemot and razorbill were combined for the distance analysis as these species show similar behaviour and this would gain a bigger sample size for this group.

6.1.2 Modelling the number of birds

Between December 2021 and December 2023, 20 boat surveys have been carried out (see 2.3.2 for methods). Because most of the bird species involved do not occur year-round in the study area, not all surveys were used for all species. Which surveys were used for which species was determined by the presence of a species inside the transect during the survey (Table 6.1). Based on this data availability six bird species were selected for analysis: common guillemot, razorbill, black-legged kittiwake, lesser black-backed gull, northern gannet and common gull.

Transects were classified in one of three zones: a) inside the wind farm, b) in the corridor, or c) along the border of the wind farm (Table 6.2, Figure 2.5).

To investigate whether there was a difference in bird densities for these species between the zones, the following generalized linear mixed model (GLMM) using a negative binomial distribution was fitted using the INLA package in R (Rue *et al.* 2009, Lindgren & Rue 2015). The following model formula was used:

N ~ zone + (1|survey) + offset(log_area)

with the variables:

N:	Number of birds
zone:	Either inside OWF, in the corridor, or at the border of the OWF. Inside the OWF was the base level.
survey:	Identifier for the survey day
log_area	Log of the effectively surveyed area that was counted in the transect (in km^2), calculated using the weighted ESW for flying and swimming birds

Random intercepts were included per survey and the offset of the log of the surveyed area was used, so that effectively densities were modelled. Surveyed area was calculated based on the weighted ESW and the length of the transect. During two surveys, the start coordinates of one of the transects was accidentally not recorded, so this coordinate was filled in using the coordinates of another survey. Because the start and end points of transects are more or less at the same location every survey, and the bird numbers are not very high, this is not expected to influence the results.

Table 6.1 *Overview of which surveys were used in the analysis of the selected bird species. In months marked in grey no survey was carried out. In February 2023 two surveys took place.*

2021	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Common guillemot												x
Razorbill												x
Lesser black-backed gull												
Black-legged kittiwake												x
Common gull												
Northern gannet												x
2022	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Common guillemot	x		x						x			x
Razorbill	x		x						x	x		x
Lesser black-backed gull					x	x	x	x	x	x		
Black-legged kittiwake	x		x							x		x
Common gull			x					x				
Northern gannet	x		x							x		x
2023	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Common guillemot		2x	x						x			x
Razorbill		2x	x						x			x
Lesser black-backed gull					x	x	x	x	x			
Black-legged kittiwake		2x	x									x
Common gull		2x										
Northern gannet		2x	x									x

Table 6.2 *Distribution of the different transects over different areas of Borssele OWF.*

Zone	Transects
Inside OWF	DE, GH, HI
Corridor	BC, CD, FG
Border OWF	AB, EF, IJ

Analyses were carried out in R using Rstudio version 2023.12.1 (Posit team 2024) and R version 4.2.2 (R Core Team 2023), using the INLA package (Rue *et al.* 2009, Lindgren & Rue 2015). INLA is used for Bayesian statistics, meaning the model outcome provides no p-value or significance results. Instead, Bayesian statistics provide a posterior distribution, from which a 95% credible interval and a mean covariate estimate can be calculated. This posterior distribution represents the distribution of values that the covariate may have, given the data. If 0 is not within the entire 95% credible interval, the covariate most likely had an effect on the response variable. However, if the credible interval spans over 0, the covariate could have a negative as well as a positive effect, meaning that the evidence for an effect is absent or weak; the result can therefore be regarded as inconclusive (van de Schoot *et al.* 2021). The INLA package uses credible intervals of 95%.

6.2 Results

6.2.1 Distance analysis

For the selected species, the best fitting models were as follows. Lesser black-backed gull had the smallest Estimated Strip Width (ESW) of 179 meters and common guillemot/razorbill the largest (for some observers), with an ESW of almost 300 (Table 6.3, Appendix I for corrected ESWs per survey). Only for razorbill/guillemot it turned out that adding a covariate resulted in a better model. Group size had no significant influence on the detection probability for either of the species. Sea state could only be tested as a covariate for guillemot/razorbill, as for the other species the sample sizes were too low for different sea states. For guillemot/razorbill, sea state did not influence detectability.

Table 6.3 Best fitting models per species in the distance analysis, including resulting Estimated Strip Width (ESW).

species	Function	adjustment term	covariates	ESW
lesser black-backed gull	hazard rate	none	none	179.6
black-legged kittiwake	halfnormal	cosine	none	196.9
common guillemot/razorbill	hazard rate	none	observers	116-300
common gull	hazard rate	none	none	286.3

6.2.2 Bird numbers

For all species except the lesser black-backed gull, a negative binomial distribution was used to model bird densities in the zones of the wind farm. For lesser-black backed gull a zero-inflated negative binomial was chosen, based on the Watanabe–Akaike information criterion (WAIC) value.

For northern gannet and lesser black-backed gull, the 95% credible intervals for the border of the windfarm do not span over zero. This indicates a difference between bird numbers in the wind farm and the border of the windfarm. For northern gannet, less birds were in the border zoned compared to inside to the windfarm, whereas for lesser black-backed gull, there were more birds in the border zone (Figure 6.1. Table 6.4). For northern gannet, the lower densities in the border can also be seen in the boxplot of the raw density data, for lesser black-backed gull the effect seems to be mostly caused by an outlier of around 100 birds per km^2 (Figure 6.2. Figure 6.3). This outlier was during a short transect with a large group of gulls, which gives a high density of birds, especially for this relatively short transect. When excluding this outlier, the 95% credible interval for the border of the wind farm does span 0 (Table 6.5. Figure 6.4).

For the three other selected species (common guillemot/razorbill, black-legged kittiwake and common gull), all credible intervals span over 0, and hence we have no evidence of a difference in bird numbers between the OWF and the corridor or between the OWF and the border of the wind farm (Figure 6.1. Table 6.4). In the raw data, no clear difference can be seen either (Figure 6.2).

Table 6.4 *Mean, standard deviation, and lower and upper boundary of the 95% credible interval of the model estimates of the GLMM on ship-based count data, Intercept is the estimate for inside the OWF, and border and corridor are estimates of the difference with OWF. *credible interval does not span zero and is not the intercept.*

		Common guillemot		
	mean	*SD*	*lower*	*upper*
Intercept	0.76	0.33	0.16	1.45
Border	0.49	0.48	-0.46	1.44
Corridor	0.61	0.46	-0.29	1.52
		Razorbill		
	mean	*SD*	*lower*	*upper*
Intercept	0.51	0.27	0.00	1.08
Border	0.53	0.40	-0.25	1.31
Corridor	0.48	0.38	-0.27	1.23
		Lesser black-backed gull		
	mean	*SD*	*lower*	*upper*
Intercept	-0.16	0.33	-0.79	0.50
*Border**	0.95	0.47	0.03	1.89
Corridor	-0.45	0.44	-1.31	0.40
		Black-legged kittiwake		
	mean	*SD*	*lower*	*upper*
Intercept	0.46	0.27	-0.04	1.01
Border	-0.04	0.40	-0.82	0.74
Corridor	0.46	0.37	-0.27	1.19
		Northern gannet		
	mean	*SD*	*lower*	*upper*
Intercept	-1.04	0.28	-1.59	-0.47
*Border**	-2.81	1.07	-5.17	-0.99
Corridor	0.11	0.41	-0.68	0.92
		Common gull		
	mean	*SD*	*lower*	*upper*
Intercept	0.19	0.39	-0.53	1.01
Border	-0.56	0.61	-1.77	0.65
corridor	0.38	0.55	-0.69	1.46

Table 6.5 *Same as Table 6.4, except an outlier in the border zone is left out when running the model. A negative binomial distribution was used.*

	Lesser black-backed gull			
	mean	*SD*	*lower*	*upper*
Intercept	-0.07	0.26	-0.58	0.46
Border	0.35	0.38	-0.40	1.09
corridor	-0.50	0.37	-1.23	0.24

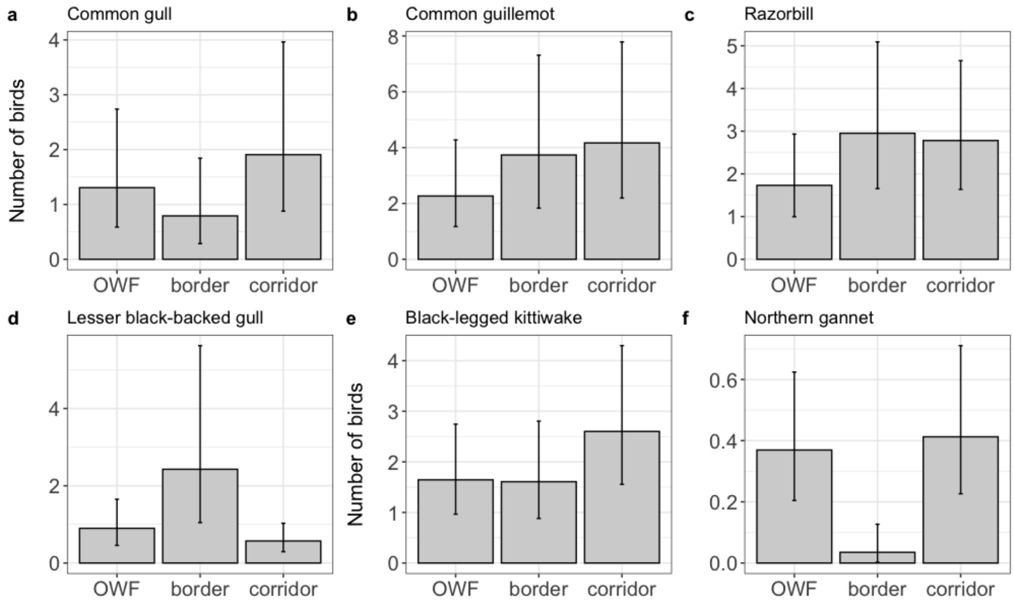

Figure 6.1 *Mean of the predicted number of birds based on the model, error bars represent 95% credible intervals. All densities are corrected using distance analysis except Northern gannet. a) common gull b) common guillemot/razorbill c) lesser black-backed gull d) black-legged kittiwake e) Northern gannet. Note: Scales on the y-axis differ per plot for clarity of the plots.*

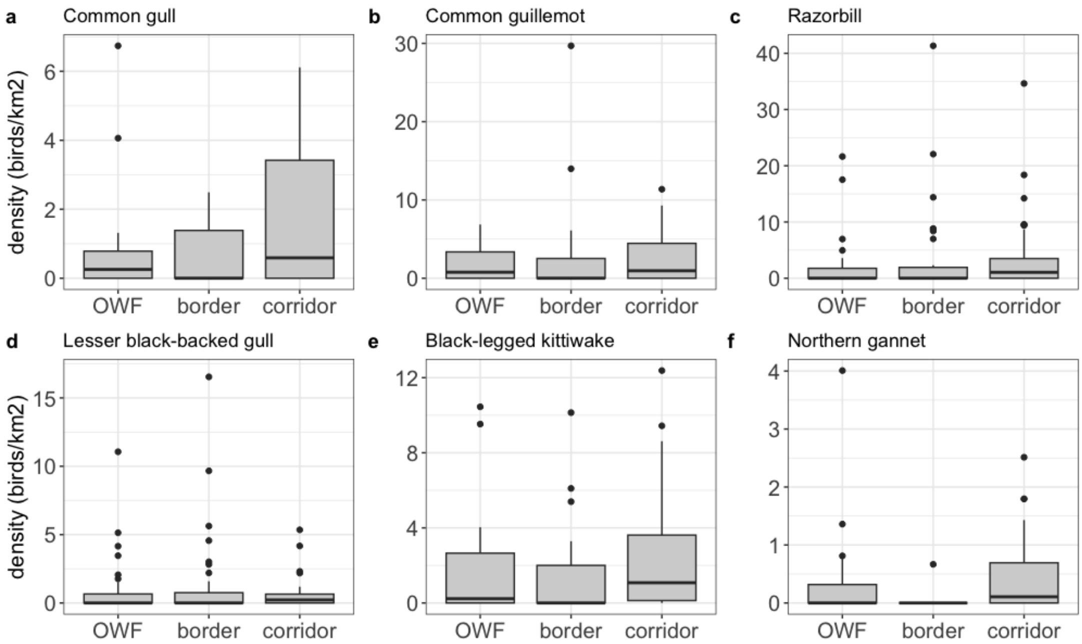

Figure 6.2 Boxplot of the raw bird density per zone, thick line displaying the median of birds per square kilometre, and the boxes the 50% quantile spread around it, divided in quartiles. a) common gull b) common guillemot/razorbill c) lesser black-backed gull d) black-legged kittiwake e) Northern gannet. Note: Scales on the y-axis differ per plot for clarity of the plots. In plot d one outlier in the border, at 107 birds/km^2, was left out for clarity of the plot.

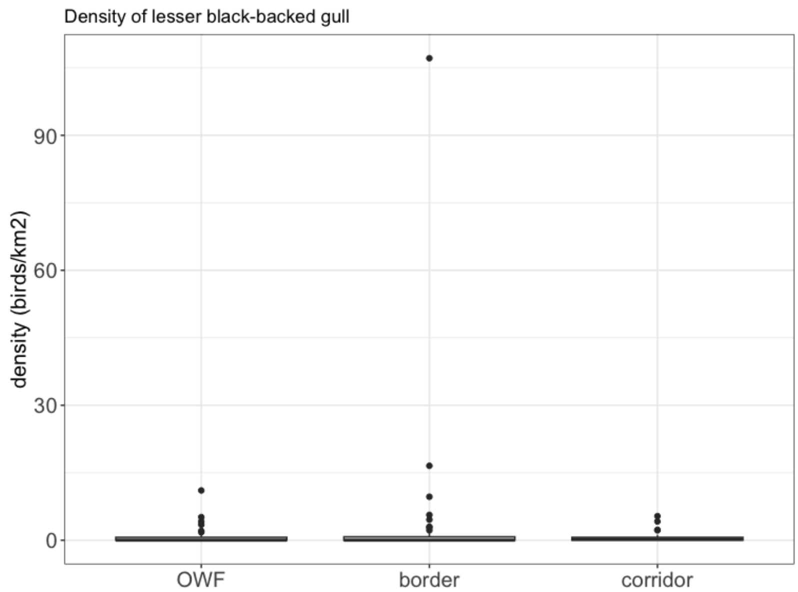

Figure 6.3 Boxplot of the raw bird density of lesser black-backed gull per zone, thick line displaying the median of birds per square kilometre, and the boxes the spread around it, divided in quartiles.

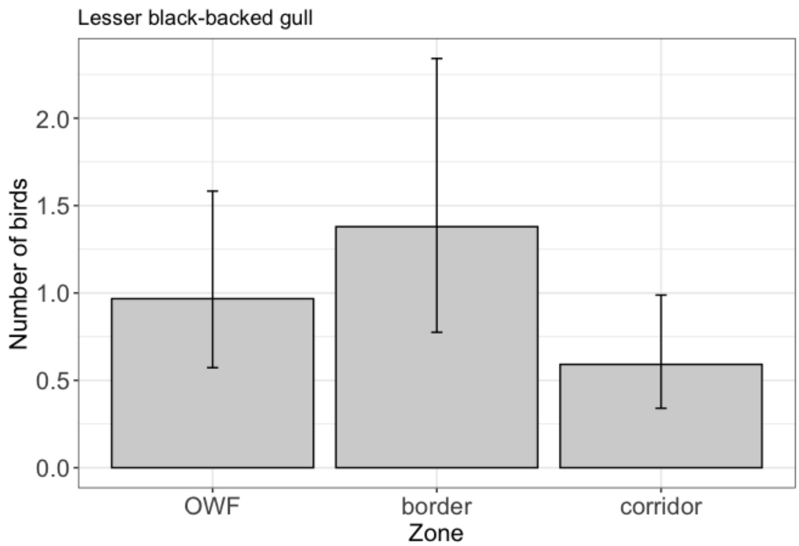

Figure 6.4 *Mean of the predicted number of birds based on the model for lesser black backed gull, error bars represent 95% credible intervals. When running the model, one outlier in the border was left out.*

6.3 Discussion

6.3.1 Bird numbers in different zones of the wind farm

During the first year of this study, preliminary results on corridor use in offshore wind farm Borssele were presented for three selected species. These species were lesser black-backed gull, black-legged kittiwake and common guillemot. In that report, for none of these three species a difference in bird density was found between the corridor or border of the windfarm compared to inside of the windfarm (Heida *et al.* 2022). In the current study, the same species were analysed. Adding the second year of surveying, still no differences were found between the corridor, border or inside the windfarm for these three species. Additional to the species analysed after the first study year, this year also northern gannet, razorbill and common gull were used in the analysis.

For black-legged kittiwake, Cook *et al.* (2018) found a high within-wind farm avoidance (which is equivalent to meso- and micro-avoidance combined) of 0.99 for small gulls including black-legged kittiwake. However, their research defined within-wind farm avoidance as the direct vicinity of the turbine and the turbine itself. Even more, this avoidance rate was calculated from the number of victims recorded on coastal wind farms and not offshore as is the case in our study. A study using long term data before and after presence of an OWF, found that kittiwakes avoid the wind farm in the breeding season, but not in spring, indicating they might be more sensitive for OWFs during the breeding season (Peschko *et al.* 2020b). As our data on kittiwakes is not from the breeding season this might explain the lack of difference between the corridor and the wind farm itself.

For common guillemot and razorbill, the lack of difference in density between corridor and wind farm might be explained by possible presence of ships in the corridor. A study using telemetry found that common guillemots use the wind farm mainly for foraging and resting (Peschko *et al.* 2020a), so presence of ships could result in disturbance of birds on the water (Fliessbach *et al.* 2019). On the other hand, long term research in the Belgian part of this wind farm on displacement of birds was also not conclusive on avoidance of common guillemot and razorbill. Vanermen *et al.* (2021) found a significantly higher number of common guillemots and razorbills inside the windfarm area than outside, but the latest results of this study show a less pronounced difference (Vanermen *et al.* 2023).

Black-legged kittiwake may be associated with razorbill when foraging, something that has been suggested before (Camphuysen & Webb 1999) but never researched. This might be why kittiwakes did not show a difference in the different zones, as this was not the case for razorbill either. In this study we tested for a correlation between kittiwakes and razorbills and found a significant correlation within transects (Pearsons test: $r = 0.49$. $p = 9.71e\text{-}08$). It should be noted this test was performed on presence of kittiwake and razorbill over whole transects. To get better insight in this relationship it would be interesting to look into this in more detail.

For lesser black-backed gull however, a difference was found between the border and inside the wind farm, but this was entirely driven by one far outlier. This outlier occurred during a count with 35 gulls in a small part of the transect (transect I-J) at the border of the wind farm. When including this outlier, it can be concluded there are more lesser black-backed gulls at the border of the windfarm than inside of the windfarm (Table 6.4). This would be in line with findings of Vanermen *et al.* (2019), who found based on GPS data that non-flying lesser black-backed gulls were present more often at the edge of the windfarm than inside of the windfarm. Vanermen *et al.* (2019) hypothesised that this is because the gulls use the turbine foundations as vantage points to detect fishing vessels that operate outside the wind farm. We were, however, unable to test whether lesser black-backed gulls also preferentially used turbines at the perimeter of the wind farms, as turbine foundations were outside the transects in our study and therefore not surveyed. In a multi-year study using buffers of 10 metres around turbines, most lesser black-backed gulls were also observed at the edge of the wind farm (Skov *et al.* 2018). However, the significantly higher densities at the border of the wind farm in the current study disappear when excluding the outlier in transect I-J (Table 6.5). This transect is particularly short (Figure 2.5) which makes the estimated density in that transect very high. Gulls might be more present close to the edge of the wind farm because of turbulence behind turbines creating favourable foraging conditions (Lieber *et al.* 2021).

There were less northern gannets at the border of the wind farm than inside of the wind farm. This might be caused by individual differences in gannets, where there is a distinction within the species that some individuals go into wind farms, but others avoid wind farms at a large distance. Peschko *et al.* (2021) found this kind of individual differences in a GPS study of northern gannets in the breeding season. However, in their study, birds that would avoid the wind farm still came relatively close to the wind farm, possibly corresponding to the border zone in this study. Another study found a large concentration of northern gannets within 1.5 kilometres of the wind farm (Skov *et al.* 2018), which is opposite to what we found in the current study, the transects outside the wind farm were about the same distance from the wind farm, so possibly this was already too far to detect this concentration.

For common gull, no differences in numbers were found between the border or corridor of the wind farm and the wind farm itself. Common gull is a species that is not researched often in relation to wind farms. Dierschke *et al.* (2016) classified common gull as weakly attracted to OWFs. This could indicate that if this species is not reluctant to go into wind farms in the first place, it might not find the corridor extra attractive.

These results do not suggest that a corridor is used more often by species that are generally known to avoid wind farms, such as common guillemot, razorbill and common gannet (Dierschke *et al.* 2016). Flying birds also do not use the corridor more often than the wind farm, as described in 4.2.1.

6.3.2 Comparing calculated bird densities with earlier research

Using the birds observed during the surveys corrected by the distance analysis, true densities could be calculated. These densities were compared with densities of the same area from earlier studies, namely from the KEC 4.0 (Potiek *et al.* 2022) and the Environmental Impact Assessment (cf. Fijn *et al.* 2015b), which was based on boat surveys conducted in the area of the nearby Belgian wind farms (Vanermen *et al.* 2013). For razorbill, our measured densities were higher than those used in the KEC 4.0 and in the EIA study. For black-legged kittiwake and lesser black-backed gull it differed per month whether the measured densities were higher or lower than those from previous studies. For common guillemot, densities were closest to those from KEC, except for August/September. For common gull, densities were higher than in the EIA (Table 6.6), possibly indicating attraction. The KEC 4.0 study relied mainly on large-scale aerial surveys conducted in the pre-construction period, which resulted in interpolated densities in between the flown transects for wind farm Borssele. Therefore, these bird densities could also be considered as representative for a larger area around OWF Borssele before the wind farm arose but seem to deviate largely from the pre-construction densities defined in the area of the nearby Belgian wind farms. As the densities defined in the current study were also based on ship-based counts in an operational wind farm, they should be best comparable with post-construction densities reported by Fijn *et al.* (2015). For common guillemot, razorbill and common gull, densities were higher in the current study (Table 6.6), which could indicate habituation for guillemot and razorbill, as the post construction densities reported by Fijn *et al.* (2015) were determined approximately 10 years earlier. For common gull this could indicate attraction as common gull was identified as weakly attracted earlier (Dierschke *et al.* 2016). For lesser black-backed gull and black-legged kittiwake densities were lower in some months but higher in others, not showing a clear pattern. All in all, our results indicate that the species-specific reaction of birds to offshore wind farms might change in due time or might be different than previously assumed based on expert judgement. Nevertheless, as the sample sizes of our analyses are rather limited, more research (also from other offshore areas) should verify whether habituation and/or attraction of certain bird species to offshore wind farms truly occur.

Table 6.6 *Comparison of densities calculated in this study with densities calculated in earlier studies. KEC 4.0 refers to the latest report of the Dutch Framework for Assessing Ecological and Cumulative Effects (Potiek et al. 2022). EIA pre and EIA post are densities pre- and post-construction of the Belgian part of Borssele wind farm, respectively (cf. Fijn et al. 2015b). All densities are in birds/km². Common gull was not included in the KEC 4.0 (indicated by -).*

Months	Species	Current study	KEC 4.0	EIA pre	EIA post
Dec/Jan	Razorbill	3.39	0.80	0.59	0.98
Feb/Mar	Razorbill	2.07	1.13	0.35	1.37
Aug/Sep	Razorbill	0.64	0.00	0.00	0.00
Dec/Jan	Black-legged kittiwake	2.12	1.43	3.79	5.35
Feb/Mar	Black-legged kittiwake	2.40	1.11	0.55	1.71
Oct/Nov	Black-legged kittiwake	0.34	1.78	4.99	0.99
Apr/May	Lesser black-backed gull	0.60	0.61	14.54	4.58
Jun/Jul	Lesser black-backed gull	2.74	0.38	1.52	2.09
Aug/Sep	Lesser black-backed gull	2.11	0.39	0.10	0.72
Oct/Nov	Lesser black-backed gull	0.30	0.55	0.18	0.09
Feb/Mar	Common gull	1.36	-	0.17	0.50
Aug/Sep	Common gull	0.63	-	0.00	0.01
Dec/Jan	Common guillemot	3.71	3.27	4.47	2.39
Feb/Mar	Common guillemot	2.27	3.64	1.35	0.90
Aug/Sep	Common guillemot	6.00	0.01	0.00	0.02
Oct/Nov	Common guillemot	2.74	2.38	4.22	0.86

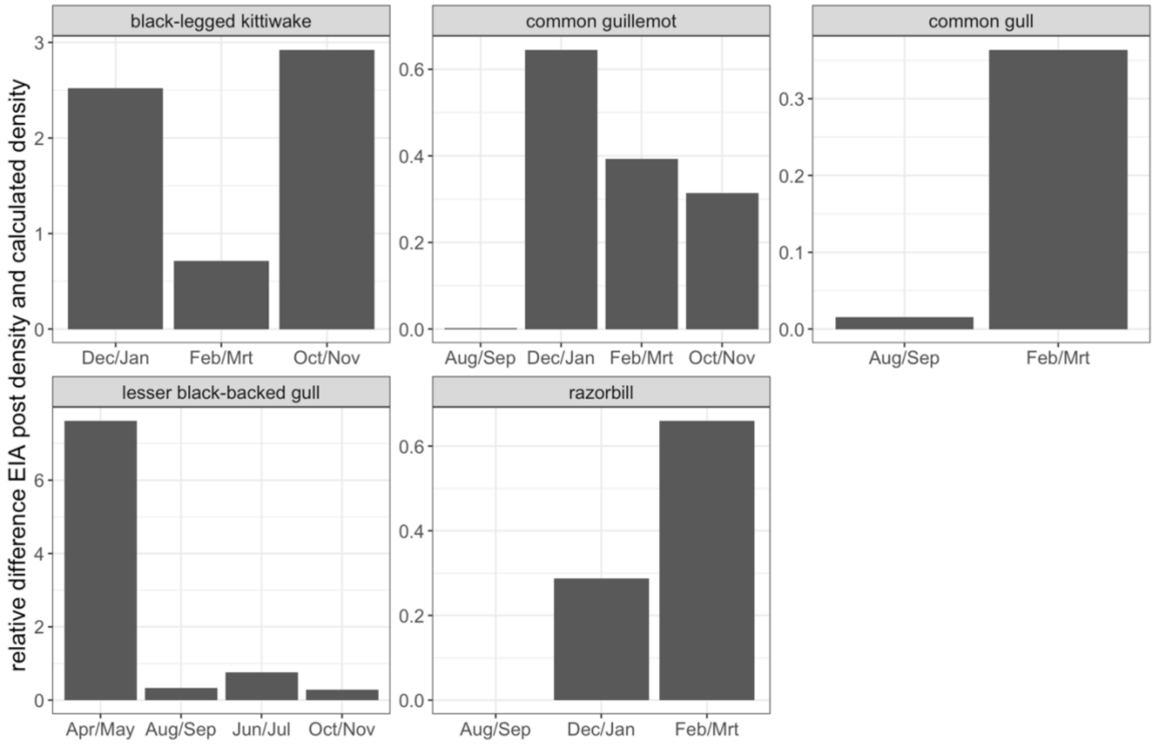

Figure 6.5 *Relative difference between densities measured post construction along the Belgian border by Borssele wind farm (Vanermen et al. 2013) and densities measured in the current study. Belgian densities were divided by calculated densities in the current study.*

7 Relationship between fluxes and daytime densities

As collisions with offshore wind turbines cannot be measured, it is common practice to estimate the number of collision victims using the Band model (Band 2012). One of the input variables for this model is bird density. To test whether the calculations of this density to fluxes reflects actual fluxes, we compared fluxes calculated with densities with fluxes measured in the field. These two fluxes are from the same small area and are expected to be comparable.

7.1 Methods

We used densities calculated from the ship-based surveys (Chapter 6) to calculate total fluxes using the Band model and compared these fluxes with the fluxes that we measured during visual flux observations (§4.2.1). As we were only able to calculate species-specific fluxes for two species, lesser black-backed gull and black-legged kittiwake, we performed this analysis for these two species. Only months with sufficient data during both ship-based surveys and visual flux observations were used. Measured densities were transformed to densities in flight using fractions in flight from literature (Table 7.1). Fractions in flight were also calculated from observed birds during surveys using total number of birds on the water and in flight.

Table 7.1 Densities resulting from the ship-based surveys used as input in the Band model and fluxes measured during visual flux measurements. Sources for fraction in flight; a. Gyimesi et al. (2017a), b. Collins et al. (2016).

species	Month	flux (birds/km)	density (birds/km^2)	fraction in flight	density in flight (birds/km^2)
lesser black-backed gull	June	7.40	0.16	0.43[a]	0.07
	July	12.31	6.62	0.43[a]	2.85
black-legged kittiwake	February	2.07	1.31	0.672[b]	0.88
	December	7.32	1.77	0.672[b]	1.19

The Band model uses a total flux per month flying through the rotor area of the specific wind farm given in the function. Fluxes from the visual flux measurements (in birds/km) were transformed to this same unit as follows:

$$Flux_{month} = (flux_{km} * t_{daylight}) / (2 * r_{rotor}) * A_{total} / 1,000$$

Where $flux_{month}$ is the total flux per month through the rotor swept area, $flux_{km}$ the original flux per kilomter, $t_{daylight}$ the amount of daylight hours in that specific month, r_{rotor} the radius of the rotor swept zone and $A_{totalfrontal}$ the total frontal area for all turbines in the wind farm. Density from the ship-based surveys was calculated to flux per month using the band model, which uses the following formula:

$Flux_{month} = v_{flight} * D / (2 * r_{rotor}) * A_{total} * (t_{daylight}) * 3{,}600/1{,}000{,}000$

With the same parameters as the previous formula. v_{flight} is flight speed of the species in m/s and D calculated density of birds in flight per km^2. Because flight speed is in meters per second, the result should be multiplied by 3,600/1,000,000. Fluxes per month were calculated for the total rotor swept area in Borssele I.

7.2 Results

The relative difference between total fluxes varied between 0.27 – 7.15 times as big, based on the ship-based density compared to the measured fluxes (Table 7.2).

Table 7.2 Total fluxes per month over the total rotor swept area in Borssele I during daytime. Comparison between flux based on density and fluxes measured during visual measurements. N is number of surveys for the visual flux measurements carried out during that month. Ship based surveys underlying the density estimates were always 2 for the included months.

species	month	flux based on density	transformed measured flux	relative difference (density/flux)	N
lesser black-backed gull	June	6,163.10	22,677.17	0.27	5
	July	262,982.72	38,012.41	6.92	1
black-legged kittiwake	February	25,330.13	3,544.21	7.15	3
	December	30,052.03	11,054.53	2.72	1

Fraction in flight for lesser-black backed gull and black-legged kittiwake varied during the year. For black-legged kittiwake fraction in flight was highest in December/January and for lesser black-backed gull fraction of flight was highest in April/May and August/September (Table 7.3).

Table 7.3 *Fraction of birds in flight calculated using ship-based survey data.*

species	months	fraction in flight
black-legged kittiwake	December/January	0.29
	February/March	0.053
	October/November	0.056
lesser black-backed gull	April/May	0.266
	June/July	0.16
	August/September	0.26
	October/November	0.14

7.3 Discussion

There is no consistent over- or underestimation of estimating fluxes using bird densities compared to measured fluxes. For both studied species, lesser black-backed gull and black-legged kittiwake, the differences also differ between the two different months. Part of why the fluxes are often higher when using the density could be because observed fraction in flight during the surveys is lower than fractions used from literature (Table 7.3). Possibly birds spend less time in flight inside a wind farm than outside of it, for example because of increased food availability in the wind farm (more time spent foraging) or avoidance of the turbines. Possibly when using the measured fractions in flight in the calculation of fluxes, fluxes could become closer to measured fluxes. Fraction in flight also varies through the year, whereas normally one value is used for the entire year when calculating collision victims, which could lead to over- or underestimation. We also did a comparison with densities underlying KEC 4.0 (Potiek *et al.* 2022) to estimate flux, as these densities are based on 20 years of observations and are probably more robust. This was done only for lesser black-backed gull.

Table 7.4 *Calculated total fluxes using different inputs and relative differences between different inputs for lesser black-backed gull. Total flux is an average for June/July.*

transformed measured flux	transformed radar flux	based on calculated density	based on calculated density and fraction in flight	based on KEC 4.0 density
25,071.62	70,576.61	97,031.23	36,104.64	13,343.63
	divided by measured flux	divided by measured flux	divided by measured flux	divided by measured flux
	2.18	3.87	1.44	0.53

The flux calculated using KEC 4.0 densities is half as big as the measured flux, whereas the flux based on the measured density is almost 4 times as big (Table 7.4). However, when calculating the flux based on the measured density and measured fraction in flight for June/July (Table 7.3), total flux is 1.5 times as big as measured flux. When comparing with the radar flux approximated for lesser black-backed gull, the flux is closer to the flux based on the calculated density using the standard fraction in flight from literature. It would be interesting to dive into different parameters influencing flux, such as flight speed of birds and fraction of flight. Surveys to estimate density and flux were never done on the same day and sample sizes are quite small. It would be interesting to repeat this kind of research on a bigger scale to get a bigger sample size to account for day-to-day variation and to be able to perform this comparison for more species and months. Still it shows how different input variables can lead to different flux estimations. These flux estimations in turn influence the number of estimated victims, so being able to calculate fluxes accurately is vital for assessing potential new offshore wind farms.

8 Flight height

This chapter presents data on the flight height of birds in wind farm Borssele. First, vertical radar data is used to show general patterns in flight height throughout the year and during the day and then relate these patterns to (weather) circumstances. Then, we present species compositions in different height classes as observed during visual flux measurements and boat surveys. Lastly, we statistically analyse whether species-specific flight heights differ between different areas in the wind farm (*i.e.* corridor, inside wind farm or edge wind farm) or between seasons.

8.1 Methods

8.1.1 Radar flight heights

Flight heights as measured by the vertical radar were analysed based on the filtered dataset of the vertical radar (see §2.2.2), and the weather circumstances as described in §5. The flight height of each track was calculated as the average of height of the track using only vertical radar track points. For each hour, we calculated the median (average) height of all tracks in that hour. To prevent wave clutter from entering the dataset, only tracks with an average height above 3 meters were considered.

The effects of wind, time of the day, season and phase of the wind farm on flight heights were estimated in R using Generalised Linear Models (GLMs), assuming either a Gaussian distribution of the response variable in the case that we modelled median flight height, or a quasibinomial distribution of the response variable with logit link in the case that we modelled the proportion of birds above, at or below rotor height. Models included either wind speed, (the interaction between) time of the day (day or night) and season, or phase of the wind farm as linear fixed effects.

8.1.2 Observed species composition per height class

We identified species composition from two separate data sources using both on-site visual flux measurement surveys (see 2.3.3) and moving boat survey (see 2.3.2) observations. For both surveys we determined the species composition per height class. During visual observations, the flight height of birds was recorded with a Laser Range Finder (LRF) whenever possible. When this was not possible, flight altitude was noted in height classes (0-2m, 3-10m, 11-25m, 25-50m, 50-100m, 100+m).

8.1.3 Species-specific flight height distribution

Using both data sources mentioned under 6.1.2 (visual flux measurements and boat surveys), we identified species-specific height distributions. While for the visual flux measurements we have continuous height values, the boat surveys were analysed using height classes, as the data collection of said data could only warrant height classes. Whenever possible, we analysed each dataset with the appropriate statistical tools. For the flux measurements, descriptive statistics showed further statistical analysis would not be necessary, and for the boat survey data we used the Mood's median test (package RVAideMemoire; version 0.9.83.7 in R) and, when significant, with a pairwise median test (package rcompanion; v 2.4.35 in R) to identify significant patterns in the data. All analyses were executed on observations rather than individual birds. For instance, birds in flocks of 450 were still only counted as a single data point as flocks may influence each other when it comes to flight height. All data was analysed for patterns depending on the season and the position within the wind park (in the park, in the corridor or outside of the wind park). To account for potential low numbers of observation, groupings were made to discern if patterns exist at higher levels of species groupings. Species were grouped by type of species as either large gulls, small gulls, other seabirds, songbirds or other non-seabirds. In Table 8.1 you see what group species are assigned to. It is worth noting that not all species mentioned here are present in the data, this is a more general classification.

8.2 Results

8.2.1 Radar flight heights

Based on the altitudes of the bird targets measured by the vertical radar, we determined general altitude profiles. The highest number of bird tracks was measured at altitudes between 5-10 and 20-30 meters (Figure 8.1). Above 30 meters, the number of detected tracks steadily decreased with altitude. Altitudes above 300 meters are not depicted on Figure 8.1, but the numbers further decreased also at these altitudes.

Table 8.1 Grouping of observed species in the analysis of flux and boat survey data.

group	species assigned to group	
large gulls	- yellow-legged gull	- herring gull
	- black-backed gull spec.	- large gull spec.
	- lesser black-backed gull	- herring/yellow-legged gull
	- great black-backed gull	
small gulls	- black-headed gull	- little gull
	- black-legged kittiwake	- gull spec.
	- common gull	
other seabirds	- great cormorant	- red-throated diver
	- razorbill	- tern spec.
	- razorbill/guillemot	- European storm-petrel
	- Sandwich tern	- common tern
	- northern gannet	- common/arctic tern
	- arctic skua	- common guillemot
	- European shag	- common scoter
songbirds	- barn swallow	- starling
	- meadow pipit	- common chiffchaff
	- grey wagtail	- Eurasian skylark
	- brambling	- white wagtail
	- fieldfare	- song thrush
	- pipit spec.	- songbird spec.
	- European robin	
other non-seabirds	- hen harrier	- great white-fronted goose
	- common ringed plover	- whimbrel
	- great crested grebe	- brent goose
	- carrier pigeon	- Eurasian oystercatcher
	- common swift	- common kestrel
	- greylag goose	- Eurasian teal
	- ruddy turnstone	

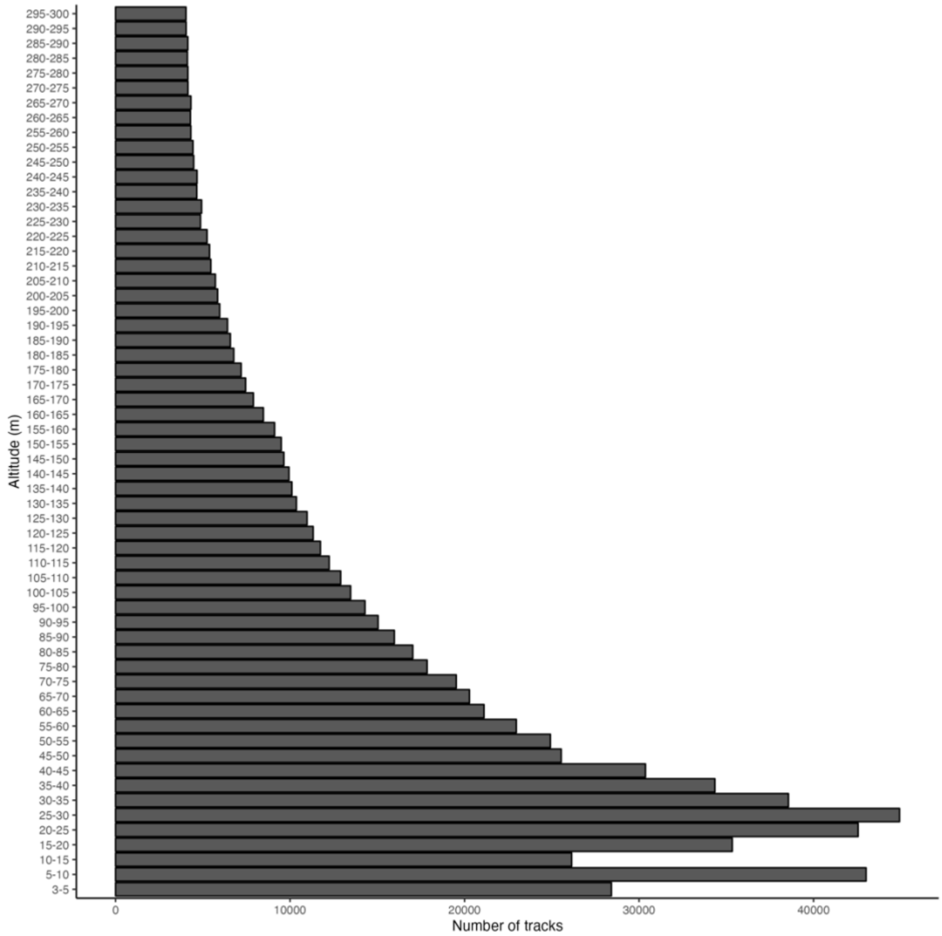

Figure 8.1 *Altitude profile up to 300 m per 5 m altitude classes as measured by the vertical radar at BSA.*

Temporal variation in flight heights

The absolute number of tracks was in all seasons the highest at rotor height between 25 and 192 meters (Figure 8.2). The altitude profiles of summer and winter are nearly identical. In autumn, the number of tracks below rotor height were relatively similar to the number of tracks in the other altitudes classes up to 1,000 meters. Most noticeable are the relatively high numbers of tracks at higher altitudes in spring, which were not recorded in the other seasons. In peak hours with more than 500 tracks/km/hour, the proportion of tracks above rotor height was significantly higher in spring (GLM: $F = 1.69$; $p < 0.0001$) and summer (GLM: $F = 1.22$; $p < 0.05$) (median ≈ 0.8), than in autumn and winter that did not significantly differ from each other (median ≈ 0.4-0.5) (Figure 8.3). On the other hand, the proportion of tracks at rotor height in spring was significantly lower than in winter (GLM: $F = -1.37$; $p < 0.0001$) and autumn (GLM: $F = -1.81$; $p < 0.0001$), while summer only significantly differed from autumn (GLM: $F = -1.38$; $p < 0.01$). The proportion of tracks below rotor height was highest in winter, significantly higher than in spring (GLM: $F = -1.77$; $p < 0.01$) and autumn (GLM: $F = -0.72$; $p < 0.05$), while winter did not significantly differ from summer (GLM: $F = -1.26$; $p = 0.12$).

The median flight height was in each season significantly lower during the day than in the night (GLM: F = -0.485; p < 0.0001) (Figure 8.4). At night, the median flight height was higher in spring than in the other seasons, while in the other seasons the flight height did not significantly differ from each other. During the day, the median flight height was lower in winter compared to the other seasons, while in the other seasons the flight height did not significantly differ from each other (Figure 8.5). The median flight height during peak hours with more than 500 tracks/km/hour in spring is nearly always higher than during peak hours in autumn (Figure 8.6). Furthermore, flight heights in spring were on average somewhat higher between sunset and midnight (Figure 8.7), while in autumn, flight heights were higher at the start and end of the night, especially around sunset, compared to the rest of the night.

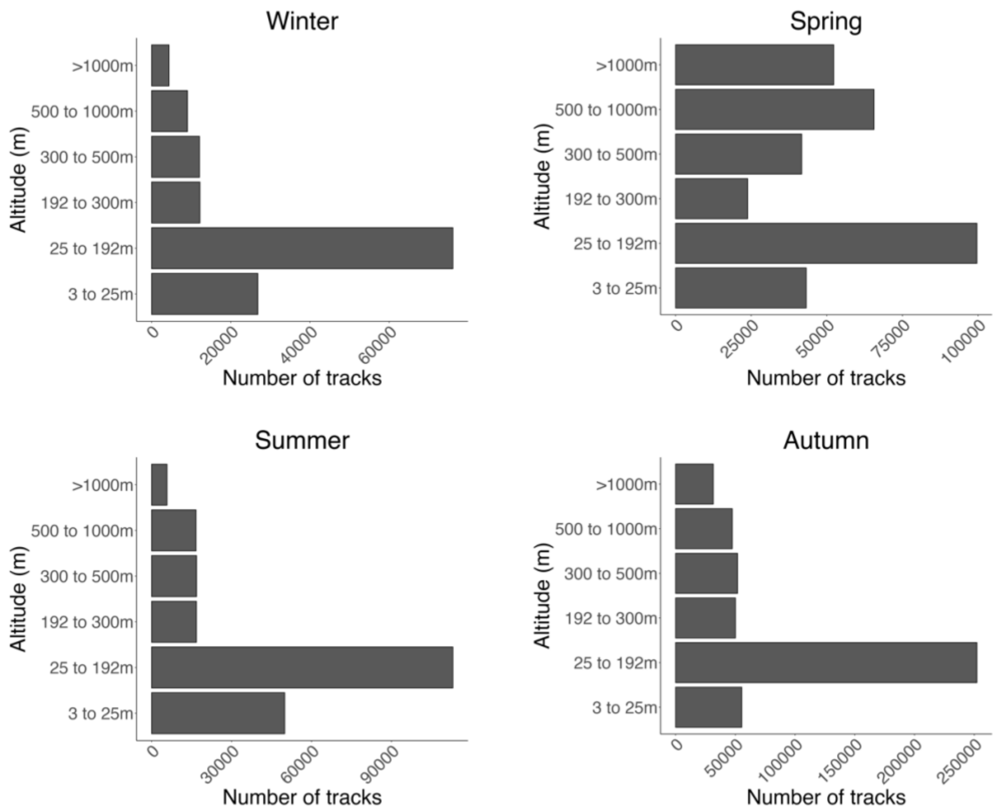

Figure 8.2 *Altitude profile per season based on vertical radar data. The altitude band between 25-192 m represent the zone at rotor height.*

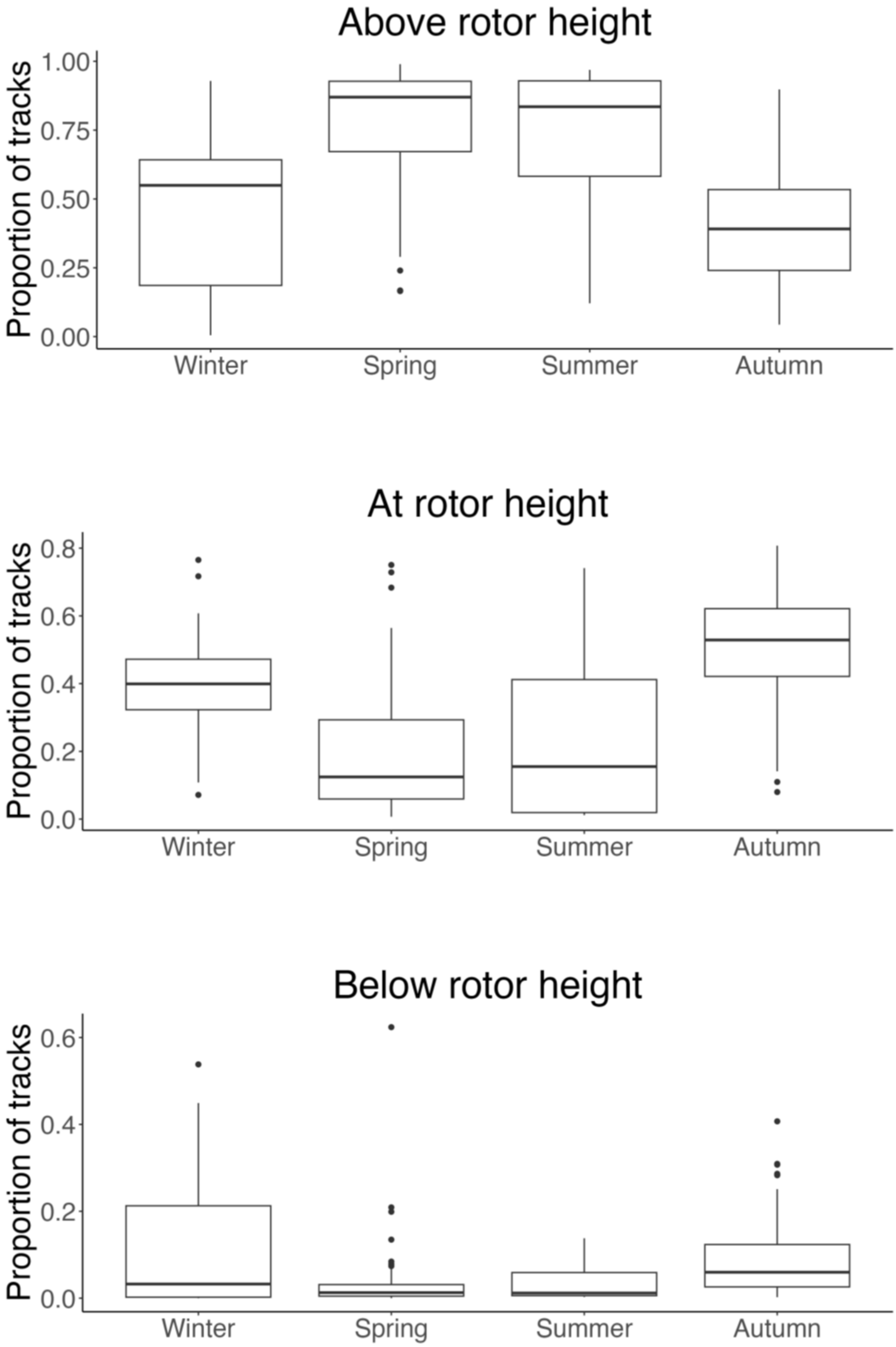

Figure 8.3 *Boxplots showing to proportion of tracks above (top), at (middle) and below (bottom) rotor height in each hour per season, only including hours with an MTR of more than 500 tracks/km/hr, based on vertical radar data.*

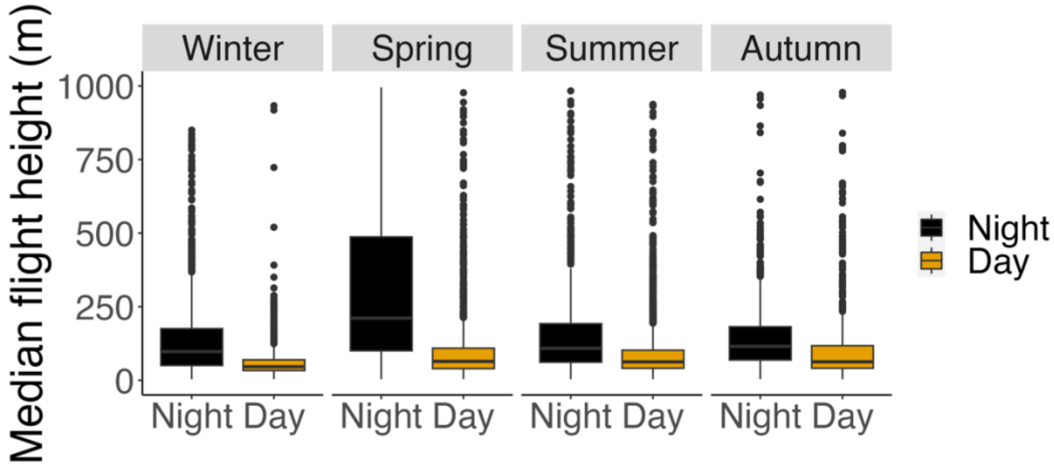

Figure 8.4 *Median flight height (m) at night (black) and day (orange) per season based on vertical radar data. Note that the y-axis is cut-off at 1,000 m for clarity.*

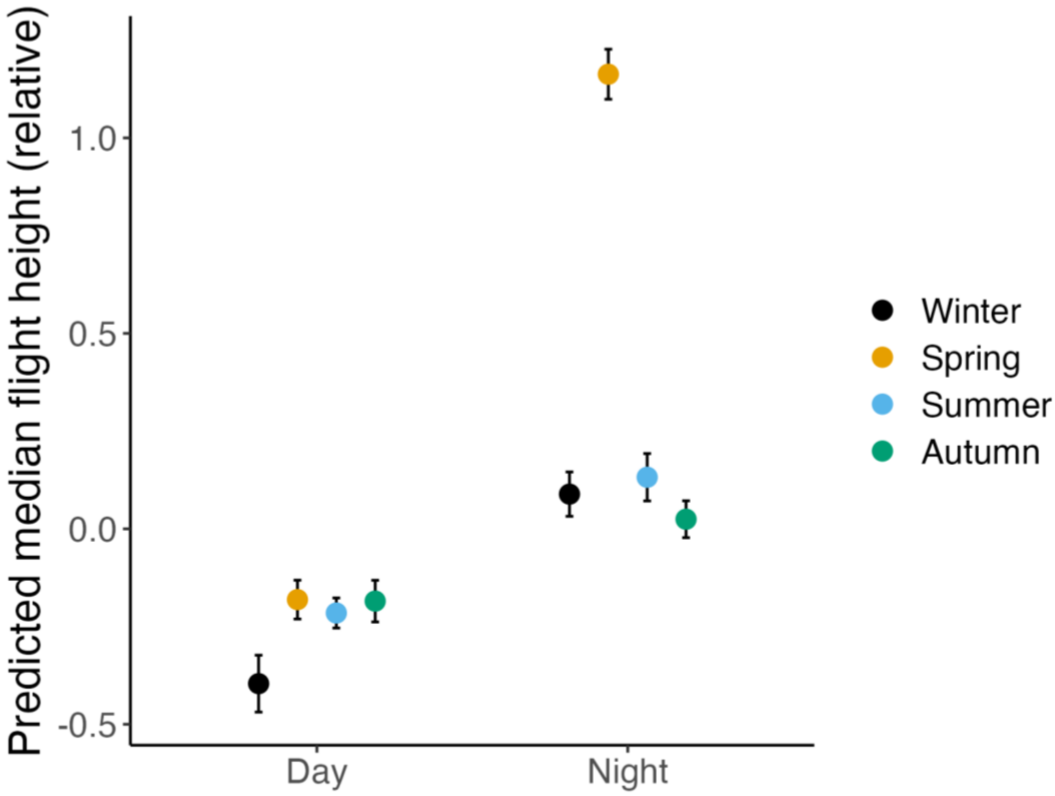

Figure 8.5 *Predicted (GLM) median flight height (relative) in each season at day and night based on vertical radar data.*

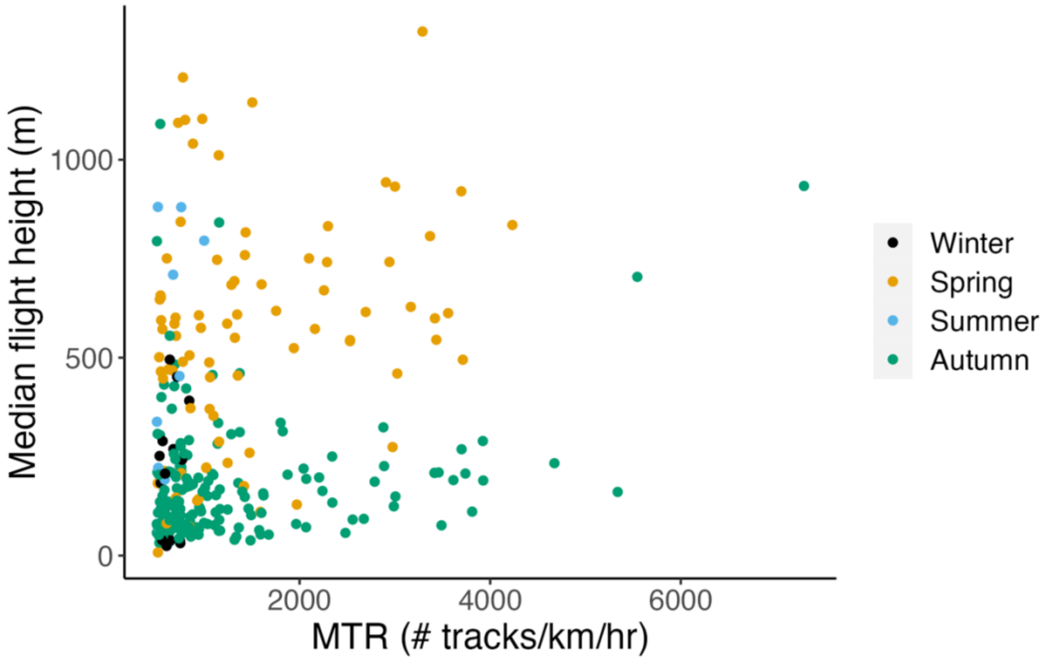

Figure 8.6 *Median flight height (m) based on vertical radar data versus the MTR in that hour, coloured by season.*

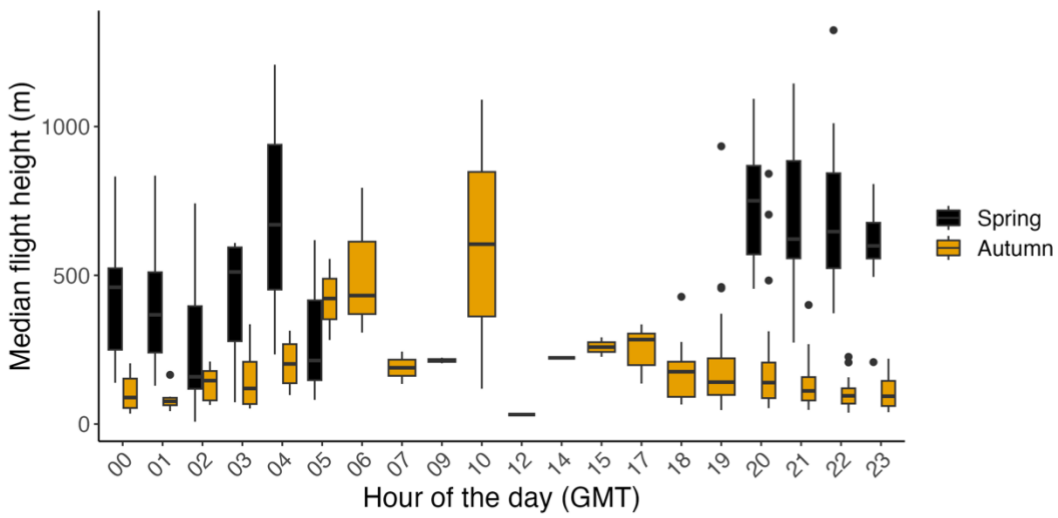

Figure 8.7 *Median flight height (m) based on vertical radar data versus hour of the day (GMT) in spring (black) and autumn (orange), only including hours with an MTR of more than 500 tracks/km/hr.*

Effect of (weather) circumstances on flight heights

The median flight height seems to show a positive correlation with wind speed (Figure 8.8), suggesting that birds tend to increase their flight height with stronger winds. We found no correlation between wind direction and median flight height (Figure 8.9). However, flight heights were generally higher with more tailwind, especially in autumn (Figure 8.10). In spring, flight heights were occasionally also higher with wind from the side.

In peak migration nights in spring and autumn, no effect of wind speed on the proportion of tracks above, at or below rotor height was found (Figure 8.11). The proportion of tracks at rotor height during peak hours in autumn was significantly lower during construction of towers and blades and operation (median of approx. 0.5, F = -0.59/-0.51, $p < 0.0001$), than during the piling of foundations (median just above 0.6) (Figure 8.12).

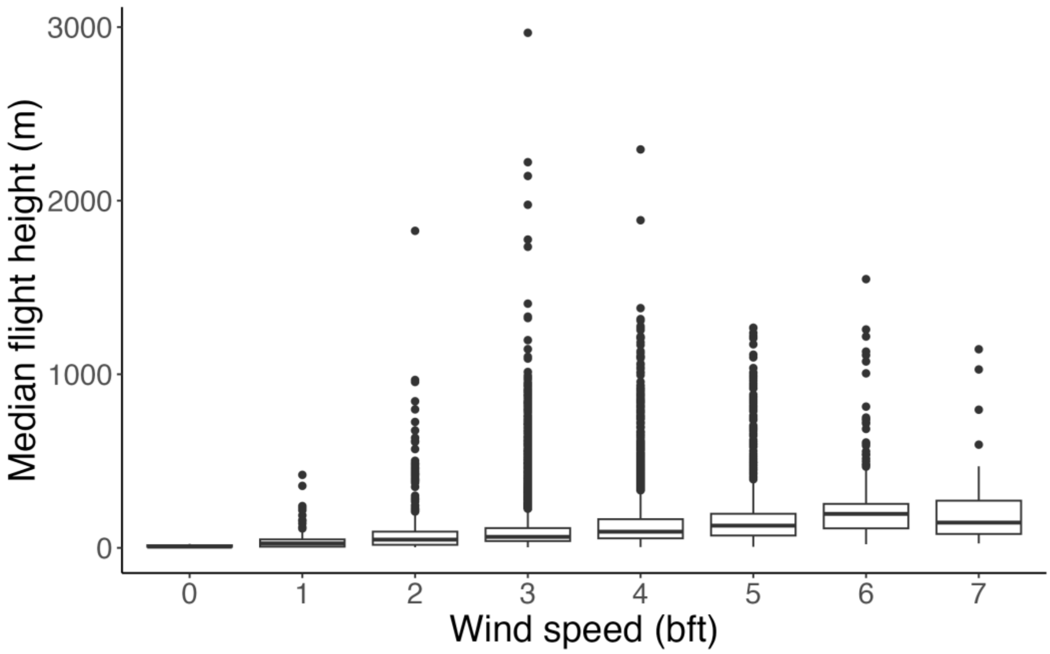

Figure 8.8 Median flight height (m) based on vertical radar data versus wind speed (bft).

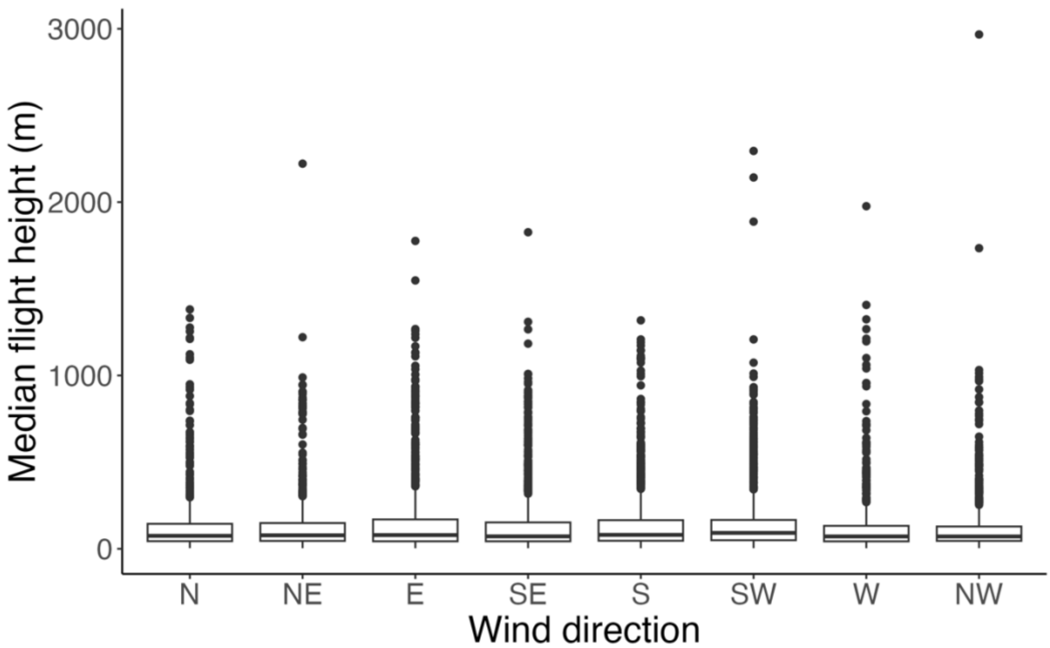

Figure 8.9 Median flight height (m) based on vertical radar data versus wind direction.

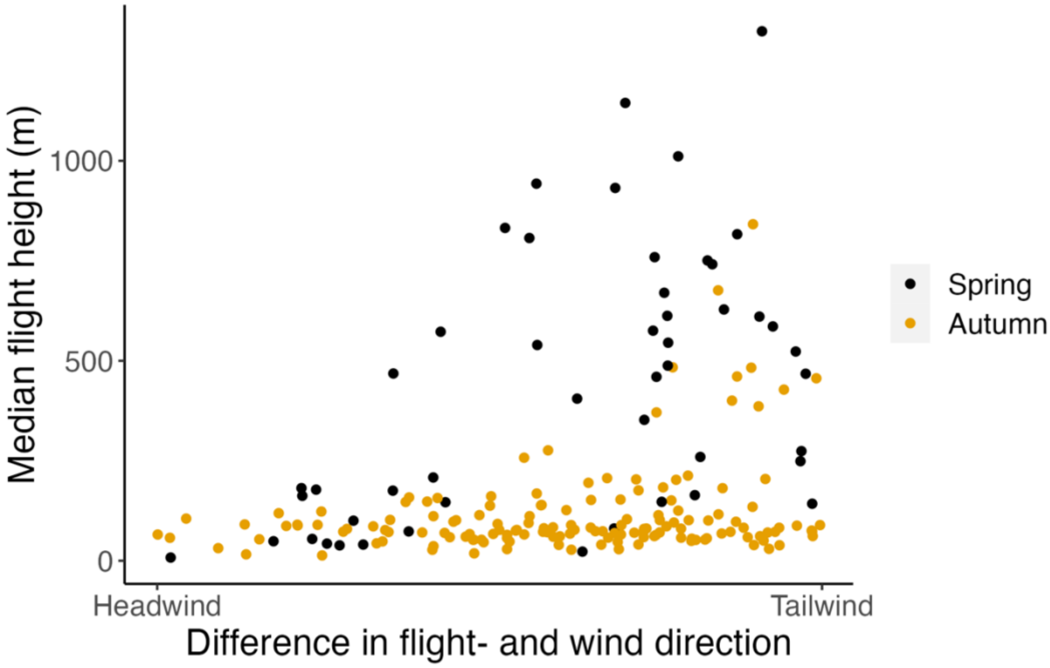

Figure 8.10 *Median flight height (m) based on vertical radar data versus the amount of headwind and tailwind in spring and autumn. Only hours with an MTR of more than 100 tracks/km/hr measured by both the horizontal and the vertical radar were included.*

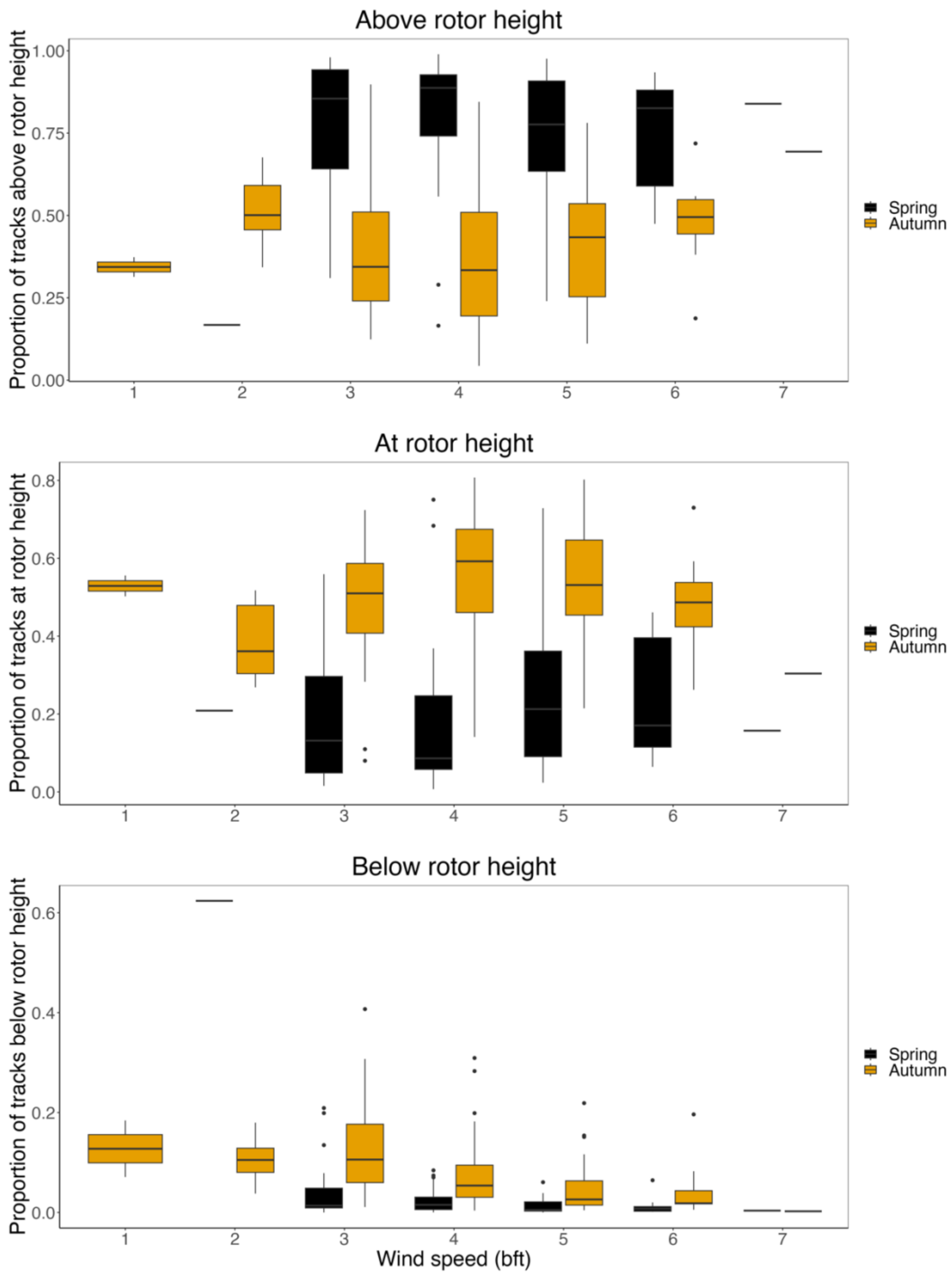

Figure 8.11 *Proportion of tracks above (top), at (middle) and below (bottom) rotor height based on vertical radar data versus wind speed (bft), for spring and autumn and only including hours with an MTR of more than 500 tracks/km/hr.*

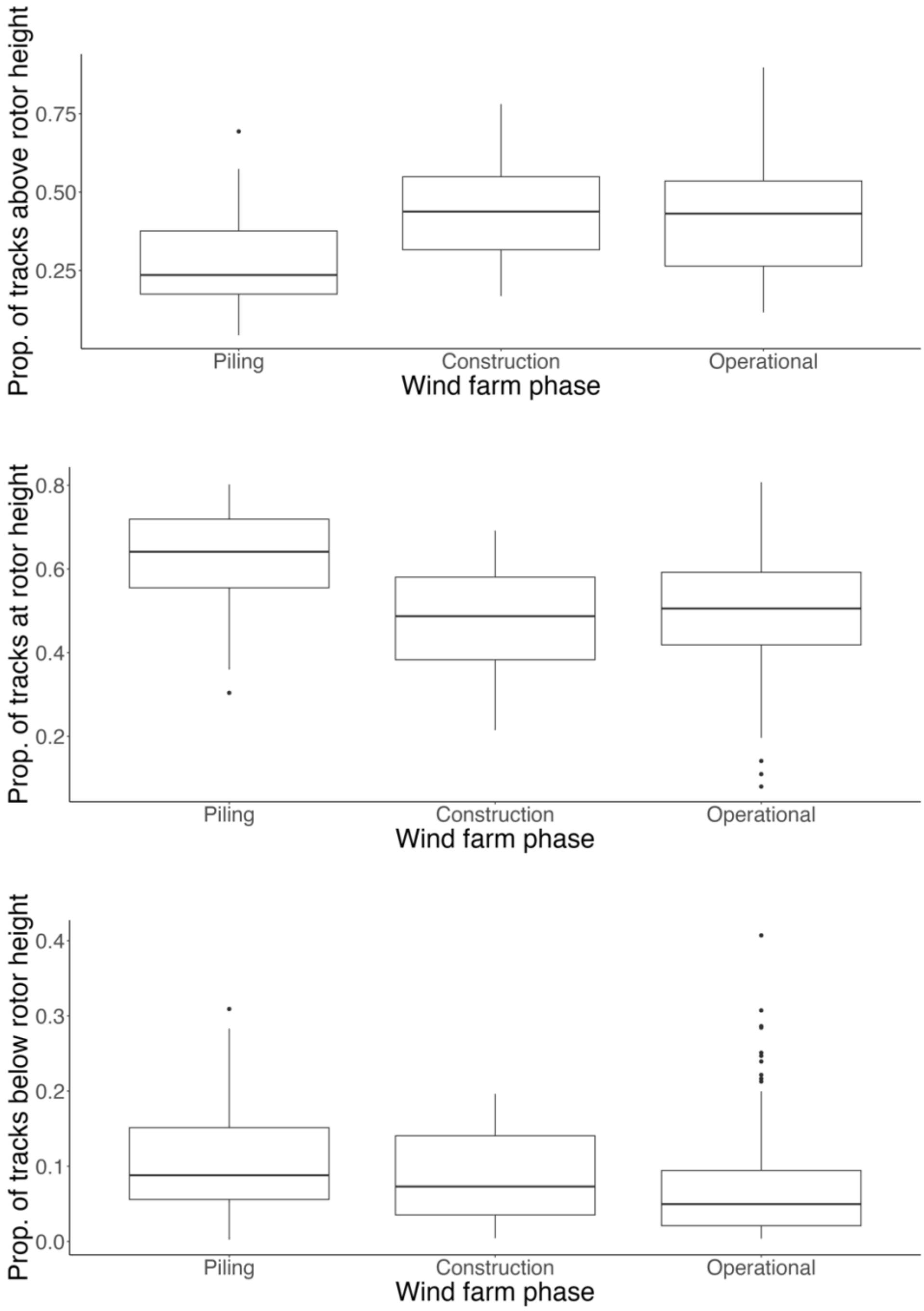

Figure 8.12 *Proportion of tracks above (top), at (middle) and below (bottom) rotor height in different phases of wind farm development in each hour* ***in autumn*** *(the only season in which piling was carried out) and only including hours with an MTR of more than 500 tracks/km/hr. For this, we used the MTR as measured by the vertical radar.*

8.2.2 Observed species composition per height class

In the visual flux data, a total of 399 observations contained valid data on both the species and height class. The data contained 6 height classes and 24 separate species. For a full overview of the species per height class observed in the flux measurements, see Figure 8.13 below. Based on the flux measurement data, the lesser black-backed gull seems to account for the bulk of the observations at rotor height (25-192 m).

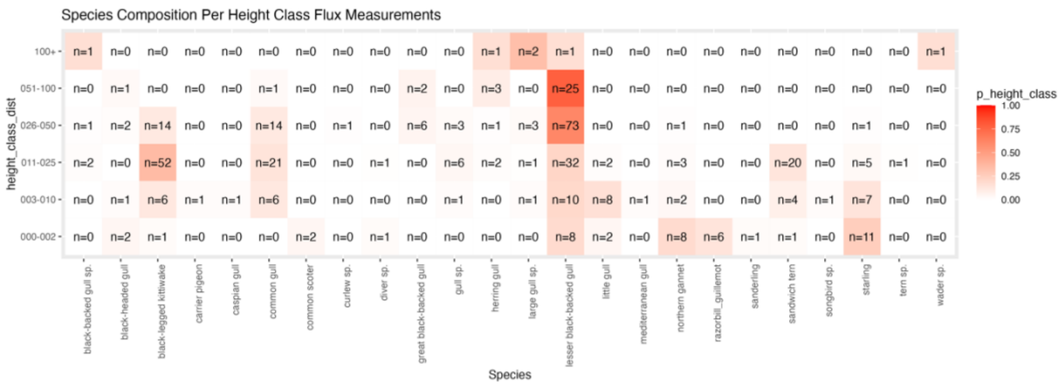

Figure 8.13 *Species composition (x) per observed height class (y) in flux measurement data. The hue of red of each tile indicates the proportion of the species in that specific height class (observations of birds of the considered species in a height class divided by the total number of observations for all birds in that height class). The number in the tile represents the absolute number of observations of that bird in the height class considered. It is good to notice here that roto height within the windfarm corresponds to 25-192 m and therefore covers the top three height classes in the graph.*

In the boat survey data, a total of 1,016 observations contained valid data on both the species and height class. We excluded species with less than 10 observations as this number is too low for robust conclusions. The data contained 6 height classes and 14 separate species. For a full overview of the species per height class observed in the flux measurements, see Figure 8.14 below. Based on the boat survey measurements, the black-legged kittiwake, the common gull and the lesser black-backed gull seem to account for the bulk of the observations around rotor height (25-192 m).

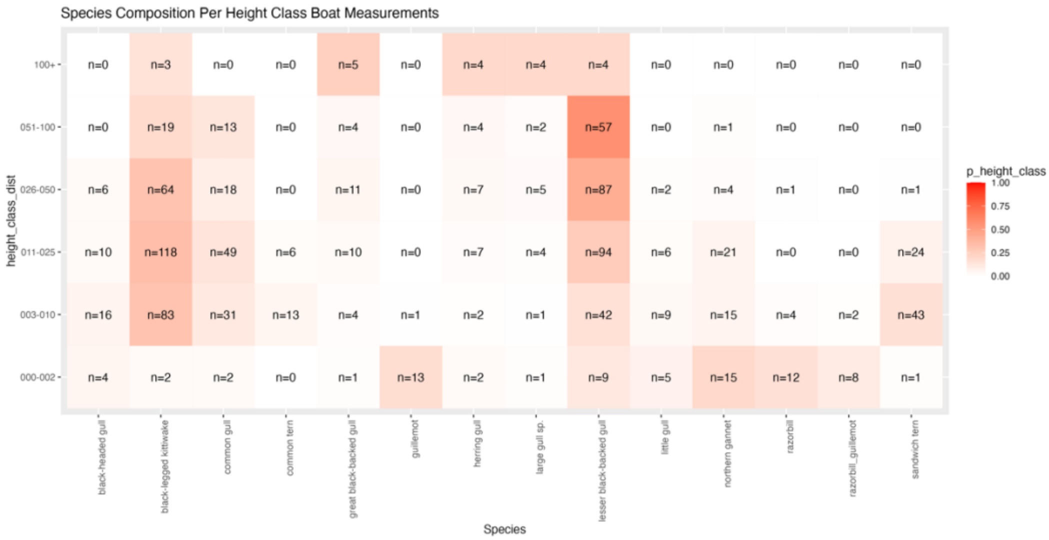

Figure 8.14 *Species composition (x) per observed height class (y) in boat measurement data. The hue of red of each tile indicates the proportion of the species in that specific height class (number of birds of that species observed in the height class divided by the total number of observed birds in that height class). The number in the tile represents the absolute number of observations of that bird in the height class considered.*

For further statistical analysis, the species were grouped. In the next paragraph, we present the height distributions of these groupings. For details on these groupings, see paragraph 8.1.3.

8.2.3 Species-specific flight height distribution

In the flux measurement data, we analysed for 24 species whether flight heights differed per season or per area of the wind farm. After initial exploration of the data, we deemed the number of observations per season and per wind farm area too small to reliably base further conclusions on and hence analyses were only carried out separately for each season and for the different wind farm areas.

In the boat survey data, we found 1,016 valid observations in 6 height classes and 14 separate species, excluding species with less than 10 observations during the study period. The species observed at least 10 times were lesser black-backed gull (n=293), black-legged kittiwake (n=289), common gull (n=113), Sandwich tern (n=69), northern gannet (n=56), black-headed gull (n=36), great black-backed gull (n=35), herring gull (n=26), little gull (n=22), common tern (n=19), unidentified large gulls (n=17), razorbill (n=17), guillemot (n=14) and unidentified razorbill or guillemot (n=10). In this section, we further report on the analysis of the top 2 species (lesser black-backed gull and black-legged kittiwake).

In the boat survey data, we identify that the black-legged kittiwake was rarely observed in autumn (n=7), and summer (n=0), whereas the lesser black-backed gull was less observed in winter (n=7).

Regarding the area in the windfarm of the bird, we observed that black-legged kittiwake shows more concentrated observed numbers in the 11–25m height class, whereas flight heights in the other two areas were more spread out. The lesser black-backed gull showed across all areas a spread of flight height classes, but the highest numbers were always found in the 11-25m and 26-50m height classes. An overview of the distribution of these two most observed species and their flight height classes in the different windfarm areas and seasons is found in

Figure 8.16.

When analysing the data on a species group level (large gulls, small gulls, other seabirds, songbirds and other non-seabirds, we see that the categories songbirds and other non-seabirds have no valid entries for height data at all.

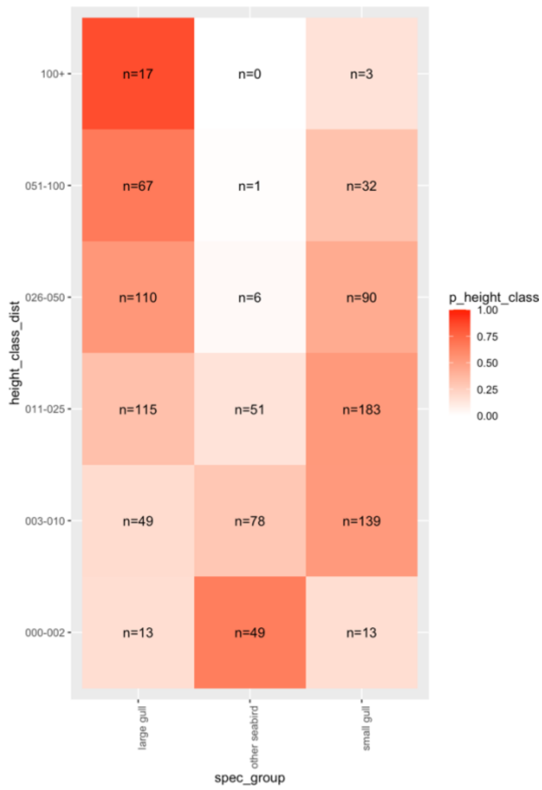

Figure 8.15 Species group composition (x) per observed height class (y) in boat measurement data. The hue of red of each tile indicates the proportion of the species in that specific height class (number of birds in each grouping observed in the height class divided by the total number of observed birds in that height class). The number in the tile represents the absolute number of observations of that bird in the height class considered. Valid height class data were only available for three out of the five species groups defined. The species in the group of other seabirds contribute most to the observations in the lowest height classes.

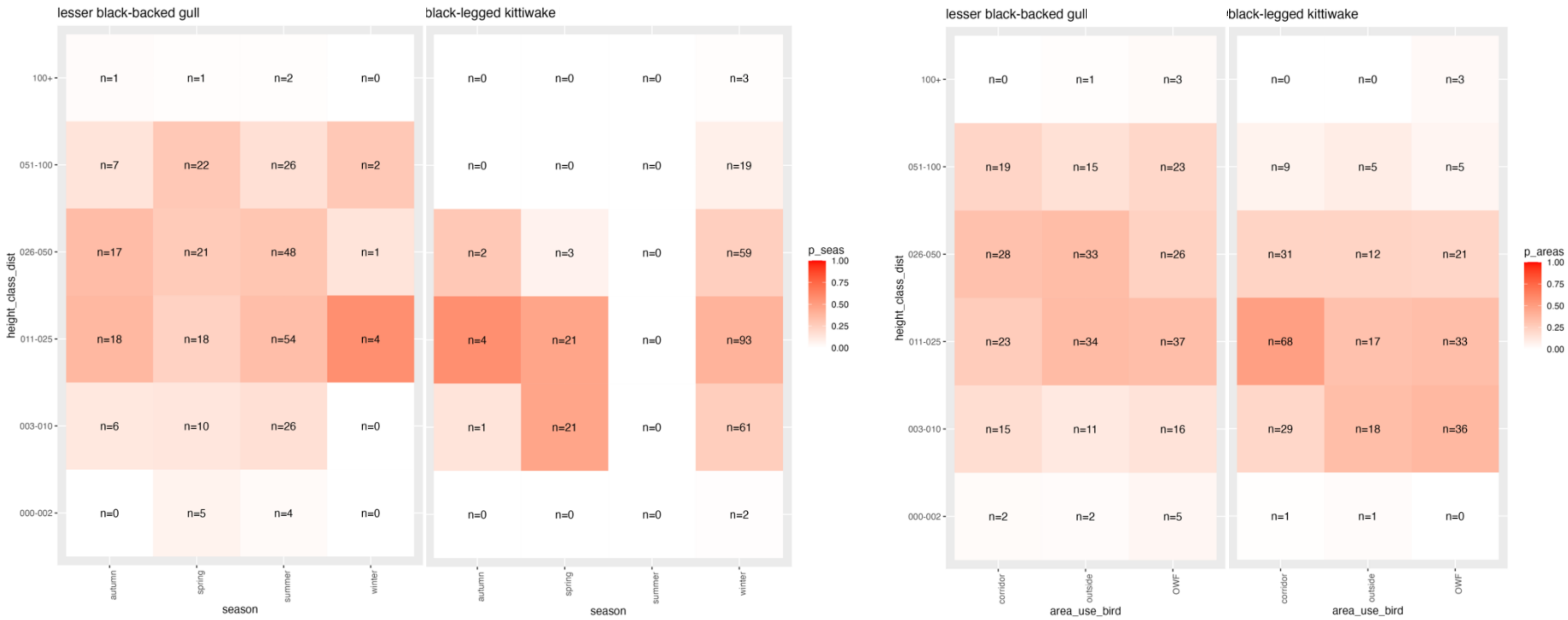

Figure 8.16 *Overview of species-specific distributions over height classes in ascending order (y- axis, in m) in specific seasons (autumn, spring, summer, winter; two left panels; x-axis) or areas within the wind farm (corridor, outside or inside the windfarm; two right panels; x-axis) for the two most observed species (black-legged kittiwake and lesser black-backed gull). The colour scale represents the proportion of observations of the column total observations (area in the windfarm in the left two panels; season in the right two panels), the numbers (n=) represent the absolute numbers of observations of that species.*

Finally, the species and season data were all tested to identify the effects on species-specific and species group specific flight heights. From all analysed species, only the species lesser black-backed gull and black-legged kittiwake have been observed enough to carry out reliable statistics. In all other species, the prerequisites of the Mood's median test were not met due to the low number of observations, and therefore they could not be tested. Within the species groups, we were only able to analyse the large gulls and the small gulls. All other species groups did not meet the requirements of the Mood's median test. Finally, the overall flight height was tested for alle species together, regardless of species or species groups.

Mood's median test only showed an effect of area for black-legged kittiwake ($p \approx 0.023$), where, based on Figure 8.16, we suspect the corridor area causes a narrowing of the flight height distribution to the height class just below the rotor height. Additionally, the effect of season on the flight height of the black-legged kittiwake was found to be significant ($p \approx 0.001$). Based on Figure 8.16, it is likely that this significance is a result of the wider range of flight heights in the winter season. For the lesser black-backed gull, no significant effects were found for either season or area. While significance levels for small gulls (area with $p \approx 0.038$; seasons with $p \approx 0.000$) and large gulls (season with $p \approx 0.008$) were met, it is likely that these are heavily influenced by the black-legged kittiwake (~64%) and lesser black-backed gull (~81%) as their numbers of observations make up well over 50% of each aggregate group (small gulls and large gulls respectively). Therefore, the tests on small gulls and large gulls should be considered carefully. When regarding all species together, we see that season had a significant effect on the flight height of birds near the Borssele wind farm ($p \approx 0.000$). A full overview of the factors tested for and the significance exhibited see Table 8.2.

We further inspected the significant effects found using a pairwise median test on the separate categories in each factor. The results of said post-hoc tests are presented here:

For the black-legged kittiwake, we found a significant effect between the area they were observed in and the flight height class the birds were observed in ($p \approx 0.023$) and between the season and the flight hight class they were observed in ($p \approx 0.001$). Closer inspection between the area and flight height, using the post-hoc test showed a significant difference between the distribution over flight heights in the corridor when compared to the windfarm itself ($adjusted\ p \approx 0.034$). Closer inspection between the season and flight height, showed a significant difference between the distribution over flight heights in the observed birds in winter when compared to the observed birds in spring ($adjusted\ p \approx 0.000$). It is worth noting that the presence of black-legged kittiwakes outside of these significantly different seasons was observed to be minimal (for autumn, n=7, for summer n=0).

For the small gulls, we found a significant effect between the area they were observed in and the flight height class they were observed in ($p \approx 0.038$) and between the season and the flight hight class the birds were observed in ($p \approx 0.000$). Closer inspection between the area and flight height, using the post-hoc test we could not discern any significant difference between the distribution over flight heights in the observed birds in the different areas ($adjusted\ p \approx 0.057, 0.095\ and\ 0.057$). Closer inspection between the season and flight height, showed a significant difference between the distribution over flight heights in the observed birds in winter when compared to the birds observed in spring ($adjusted\ p \approx 0.000$) and summer ($adjusted\ p \approx 0.000$).

For the large gulls, we found a significant effect between the season and the flight hight class the birds were observed in ($p \approx 0.008$). Closer inspection between the season and flight height, showed a significant difference between the distribution over flight heights in the observed birds in winter when compared to the birds observed in summer ($adjusted\ p \approx 0.02$).

Disregarding the specific species or species groupings, we found a significant effect between the season and the flight hight class the birds were observed in ($p \approx 0.008$). Closer inspection between the season and flight height, showed a significant difference between the distribution over flight heights in the observed birds in winter when compared to the birds observed in spring ($adjusted\ p \approx 0.002$), between the birds observed in spring and summer ($adjusted\ p \approx 0.002$) and between the observed birds in spring and autumn ($adjusted\ p \approx 0.002$).

All results of the post-hoc tests executed are presented in Table 8.3.

Table 8.2 *Outcomes of the tests on the effects on the factors season and wind farm area on the flight height of species and species groups that have enough observations to meet the Mood's Median test prerequisites. In the first and third column, the species and factor are given that have been tested to each other. The rest of the columns show the statistical details, with the final three columns indicating if the significance levels for three p-values (0.01, 0.05 and 0.1 respectively) were met. Green rows indicate that a significance levels of at least 0.05 is met. Scale_inverted (column 4) indicates if the height class was tested to regular ordering of the height classes or to a reverse ordered height classes for statistical purposes.*

Species	n_species	Factor_Tested	Scale_Inverted	p_value	Sig.01	Sig.05	Sig.10
black-legged kittiwake	481	area use	no	0.915	no	no	no
black-legged kittiwake	481	area use	yes	0.023	no	Yes	Yes
black-legged kittiwake	481	season	no	0.001	Yes	Yes	Yes
black-legged kittiwake	481	season	yes	0.017	no	Yes	Yes
lesser black-backed gull	449	area use	no	0.452	no	no	no
lesser black-backed gull	449	area use	yes	0.637	no	no	no
lesser black-backed gull	449	season	no	0.124	no	no	no
lesser black-backed gull	449	season	yes	0.551	no	no	no
small gull	757	area use	no	0.627	no	no	no
small gull	757	area use	yes	0.038	no	Yes	Yes
small gull	757	season	no	0.000	Yes	Yes	Yes
small gull	757	season	yes	0.000	Yes	Yes	Yes
large gull	557	area use	no	0.180	no	no	no
large gull	557	area use	yes	0.785	no	no	no
large gull	557	season	no	0.008	Yes	Yes	Yes
large gull	557	season	yes	0.021	no	Yes	Yes
All Species	1980	area use	no	0.688	no	no	no
All Species	1980	area use	yes	0.143	no	no	no
All Species	1980	season	no	0.019	no	Yes	Yes
All Species	1980	season	yes	0.000	Yes	Yes	Yes

Table 8.3 *Outcomes of the pairwise post-hoc tests between the factors season and wind farm area on the flight height of species and species groups that were already found to be significant in the initial Mood's Median test. In the first and second column, the species and factor are given that have been tested to each other. In the third column the pairwise comparison within those factors is indicated. The fourth and fifth column show the p-value and the p-value adjusted for the larger number of statistical tests. The final column gives a summary of the significant pairwise comparisons found. Green rows indicate that a significance levels of at least 0.05 is met with the adjusted p-value.*

Species	Factor	Comparison	P-value	Adjusted P- value	Concusion
black-legged kittiwake	Area	Outside-Corridor	0.04615	0.06	Corridor OWF is significantly different
black-legged kittiwake	Area	Outside-OWF	0.9143	0.91430	
black-legged kittiwake	Area	Corridor-OWF	0.01161	0.03483	
black-legged kittiwake	Season	Winter-Spring	0.0002218	0.0006654	only winter-spring difference
black-legged kittiwake	Season	Winter-Autumn	0.7582	0.7582000	
black-legged kittiwake	Season	Spring-Autumn	0.07012	0.1052000	
small gulls	Area	Outside-Corridor	0.03824	0.05736	No significance
small gulls	Area	Outside-OWF	0.9531	0.95310	
small gulls	Area	Corridor-OWF	0.02407	0.05736	
small gulls	Season	Winter-Spring	0.00001064	0.00006384	Winter is different from spring and summer, summer is different from autumn
small gulls	Season	Winter-Summer	0.0001486	0.00044580	
small gulls	Season	Winter-Autumn	0.1405	0.1405000	
small gulls	Season	Spring-Summer	0.07366	0.08839000	
small gulls	Season	Spring-Autumn	0.05921	0.08839001	
small gulls	Season	Summer-Autumn	0.01033	0.0266000	
large gulls	Season	Winter-Spring	0.2949	0.35390	Summer -Winter only difference
large gulls	Season	Winter-Summer	0.002762	0.01657	
large gulls	Season	Winter-Autumn	0.01277	0.03831	
large gulls	Season	Spring-Summer	0.1988	0.29820	
large gulls	Season	Spring-Autumn	0.09335	0.18670	
large gulls	Season	Summer-Autumn	0.6943	0.69430	
All Observations	Season	Winter-Spring	0.0003588	0.002153	Spring is always different on heights
All Observations	Season	Winter-Summer	0.8393	0.839300	
All Observations	Season	Winter-Autumn	0.3367	0.505000	
All Observations	Season	Spring-Summer	0.001188	0.002376	
All Observations	Season	Spring-Autumn	0.0009282	0.002376	
All Observations	Season	Summer-Autumn	0.4573	0.548800	

8.3 Discussion

8.3.1 Radar flight heights

We found that the flight heights during peak migration hours in spring were significantly higher than during peak hours in autumn and that birds tend to fly mostly above rotor height in spring. Hence, the proportion of tracks at rotor height was higher during peak hours in autumn than in spring. The occurrence of high-altitude migration in spring has been reported before and is believed to be caused by the prevalence of favourable wind conditions at high altitudes in this time of the year (Dokter *et al.* 2013, Bradarić 2022).

The median flight height showed a positive correlation with wind speed, suggesting that birds tend to increase their flight height with stronger winds (Kemp *et al.* 2013). However, we cannot exclude that some clutter related to wave height that may have remained in the dataset also affects this correlation, as prior to filtering we also found a strong positive correlation between flight height and wave height (see Figure 4.13).

The proportion of tracks at rotor height during peak hours in autumn was significantly lower during construction and operation, than during piling. These results suggest that birds have generally increased their flight height after the erection of wind turbines, as the proportion of tracks above rotor height have increased. It must be noted, however, that the data during piling is only based on one season.

8.3.2 Species-specific flight height composition

In both datasets, three main species seem to make up the most of our observations. These species are lesser black-backed gull, common gull and black-legged kittiwake. The three species are predominantly present in the flight height classes just below or just within rotor blade height (25-192m). We found that most observed birds at rotor height were lesser black-backed gulls. Hence, the lesser black-backed gull seems to be the species most at risk for collisions in the Borssele wind farm. Additionally, minor risk to common gulls and black-legged kittiwake is also expected based on our data. All other species were not observed enough to base conclusions on.

Furthermore, we suggest being careful drawing conclusions on the presence of species in highest height classes (above 100m). At high altitudes, birds are more easily missed by observers, likely resulting in an underestimation of their numbers at these altitudes. Nonetheless, the vertical radar data shows that the majority of birds flies within the lowest 30m above the sea surface. At higher altitudes, the number of birds is steadily decreasing.

8.3.3 Species-specific flight height distribution

For species-specific flight height distributions, we tested all observed species and the higher-level grouping that we assigned them to. Only for black-legged kittiwake, we found that flight height was significantly different between the different areas in the wind farm. Further investigation of the relation between area and flight height using post-hoc tests showed a significant difference between flight height in the corridor and flight height in the wind farm. Descriptive figures suggest that the difference is caused by kittiwakes flying slightly lower in the corridor than in the wind farm. Hence, these results may suggest that corridors in wind farms may cause behavioural responses in birds and play a role in (non-)avoidance.

Furthermore, we also found effects of season on flight heights. On a species level, black-legged kittiwake showed significant differences between the seasons in flight height distribution. Based on the post-hoc statistics combined with the descriptive figures, we can infer this significance is the result of a much broader spread in flight height distribution of kittiwakes in winter when compared to spring (in summer and autumn the species was almost not observed in the area). For this phenomenon, we can think of two possible theories. Firstly, we expect the behaviour of kittiwakes to be different in winter as the purpose of their presence may differ between the two seasons. The changes in flight height as a result of season suggest a higher presence of kittiwakes at rotor height (25-192m) in winter. Given the increase in numbers in winter, and their (near) absence in autumn, in winter the birds may be present as residents in the area and may therefore become more familiar and aware of the dangers of the rotors over time. By spring, the birds seem to avoid the risky rotor height, possibly by having learned of its dangers, leading to a higher concentration of flight altitudes (just) below rotor height (<25m), as seen in our results. To expand on this theory, it could be possible that this may be particularly present in naïve young birds, having never been in contact with the dangers of wind farms before and having to learn their dangers over time. Based on this theory on the birds getting more used to the area over the year, starting in winter, we should consider whether the birds that fly at rotor height may not have learned to avoid the rotor blades as part of their habituation. As a result, winter may prove to be a risky season for kittiwake mortality. Hence, we might consider the implications of higher collision risk to kittiwakes in the winter (and hence potentially more victims)and look further into whether or not our theory on habituation of locally wintering (naïve) birds may hold.

Beside species specific effects, we found significant effects on the species group levels of large gulls and small gulls. Large gulls showed significantly different flight height per season, and small gulls showed significantly different flight heights per season and the area of the wind farm. However, these effects should be carefully interpreted, as a majority of observations in both groups are single species. For the small gulls and large gulls specifically, the black-legged kittiwake (~64%) and lesser black-backed gull (~81%) make up for the majority of observations. If we further investigate the effects in small gulls we find similar effects as in kittiwakes: winter is significantly different. Therefore, one might speculate that the effects found in small gulls may merely be inherited from the kittiwake. However, th kittiwakes show near zero presence in the summer and autumn. Hence the significant effect between the winter and the other seasons must be caused by other small gull species. Further research should delve deeper in the effects in this specific group and whether this difference might merely because of the grouping of several species present in different seasons. Additionally, it should be mentioned that further investigation of the effect found on area proved unfruitful due to the statistical power of post-hoc tests being reduced by adjusting the statistical power for the number of tests executed.

Similarly to the effect in small gulls, the effect found in large gulls may at least be very strongly determined by the data of the lesser black-backed gull making up a relatively large portion of the observations, which also has p-values on season not too far off from the significance levels ($p \sim 0.12$).

When considering all species together, we found an effect of season on flight height. For this, multiple explanations may exist. On a methodological level this significance should be considered carefully as the dataset is mostly made up by two species, black-legged kittiwake and lesser black-backed gull, together accounting for ~47% of all observations. With the kittiwake already showing significance to seasonal effects on flight height and the lesser black-backed gull having P-values close to significance, we should be careful the significance is possibly merely inherited by the large proportion of observations of these two species.

9 Flight speed

Flight speed is an important parameter in collision risk models, such as the Band (2012) model. The Band model uses flight speed in the transformation of bird densities to fluxes, as well as in the calculation of the collision risk of each species. Here, we present data on the flight speeds of birds in wind farm Borssele. Horizontal radar data is used to show general patterns in flight speeds throughout the year and during the day and then relate these patterns to weather circumstances. Then, we present species-specific flight speeds based on tagged radar tracks.

9.1 Methods

The horizontal radar can collect data of various parameters, of which one is the airspeed of the detected bird. Airspeed is the speed of an object corrected for the wind speed and direction, as measured by the weather station of the radar. However, that weather station is positioned next to the radar on the turbine and hence measured wind speeds and wind directions are likely influenced by the wind turbine and the radar itself. Moreover, the guidance issued alongside the Band (2012) model, and consequently the Stochastic Collision Risk Model ('sCRM', (Marine Scotland 2018)), clearly states that in collision risk models ground speeds, which is the speed of an object relative to the ground, should be considered. Therefore, in this chapter we present flight speed as ground speed, calculated as the travelled distance of a track divided by the duration of the track.

Ground speeds were analysed using the filtered dataset of horizontal radar data (see §2.2.2), and weather data as described in §5. The effects of time of the day and season on flight speeds were estimated in R using Generalised Linear Models (GLMs), assuming a Gaussian distribution of the response variable. Models included (the interaction between) time of the day (day or night) and season as linear fixed effects. Furthermore, species-specific ground speeds were calculated using the radar tracks that were tagged during visual observations. In this analysis, only species with at least 5 tagged horizontal radar tracks were used.

9.2 Results

The average flight speed of all radar tracks (*i.e.* all birds combined) measured by the horizontal radar in the study period was 13 m/s. Flight speeds did not substantially differ between each season (Figure 9.1), with the exception of summer in which the average flight speed (mean 12.8 m/s) was significantly lower than in the other seasons (mean 13.1-13.2 m/s). Generally, the average flight speed was significantly lower during the day than during night (GLM: $F = -0.40$, $p < 0.0001$). In winter and spring, the difference in the average flight speed between night and day was highest. Only in autumn the average flight speed was not significantly different between night and day. The highest average flight speeds per hour were often recorded in hours with relatively high fluxes (Figure 9.2). As the highest MTRs are found during the bird migration, these results indicate that bird migration occurs at on average higher flight speeds (m/s) than the flight speeds of local birds. Note that hours with the highest MTRs in autumn were only measured by the vertical radar (as horizontal radar data was filtered out), hence we were not able to calculate the flight speeds in these hours.

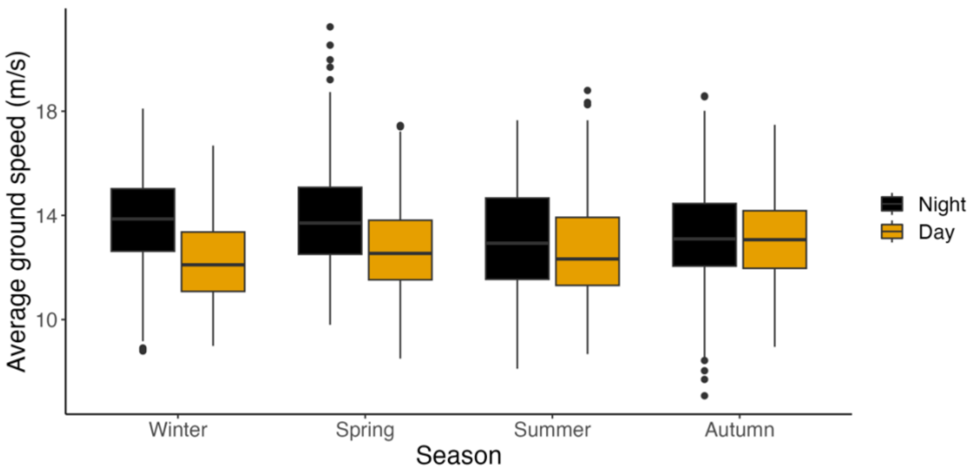

Figure 9.1 *Average ground speed (m/s) of all horizontal radar tracks per season separated for night (black) and day (orange).*

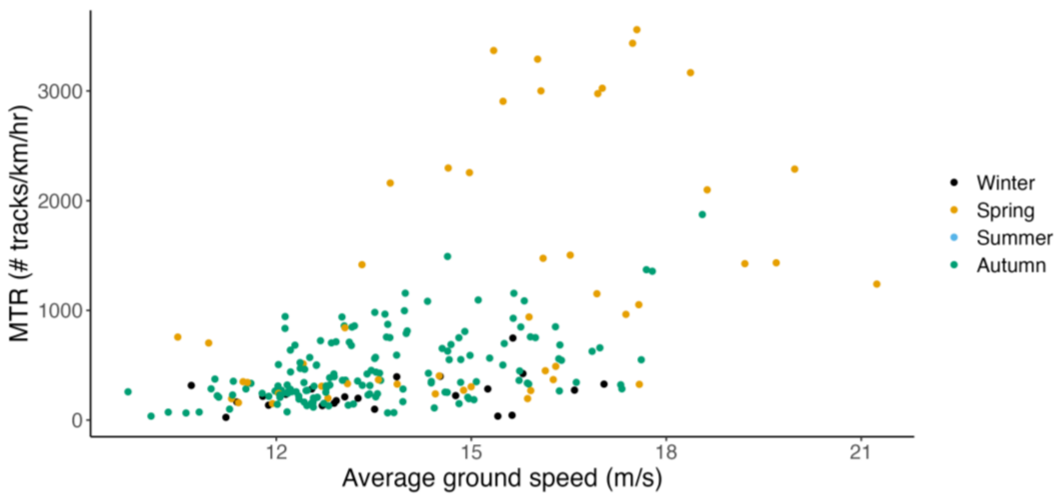

Figure 9.2 *Average ground speed (m/s) of all horizontal radar tracks per season versus the hourly mean traffic rate (# tracks/km/hr). Vertical radar measurements were used as MTR.*

Effect of (weather) circumstances on flight speeds

Flight speeds are directly influenced by wind speeds, although the extent of this influence depends on the difference between flight direction and wind direction. At lower flight speeds (up to roughly 16 m/s), no correlation was found between flight speed and wind speed

(Figure 9.3 left). However, higher average flight speeds were almost only recorded in hours with higher wind speeds (3 bft or higher). When looking at the effect of wind direction, we see that the highest average flight speeds were recorded during the night with winds from the east, northeast, southwest or west (Figure 9.3 right), which matches with the wind directions with which nocturnal bird migration in spring and autumn mainly occurs. Thus, this again indicates that bird migration occurs at on average higher flight speeds (m/s). During the day, no effect of wind direction on flight speed was found, except for higher flight speeds with northern winds.

In spring, the average ground speed showed a clear positive correlation with the amount of tailwind (Figure 9.4). This correlation is less clear in autumn, as in hours with more tailwind the flight speed is often similar to the average flight speeds in hours with less favourable winds. Nonetheless, also in autumn the highest average flight speeds were recorded in hours with more tailwind.

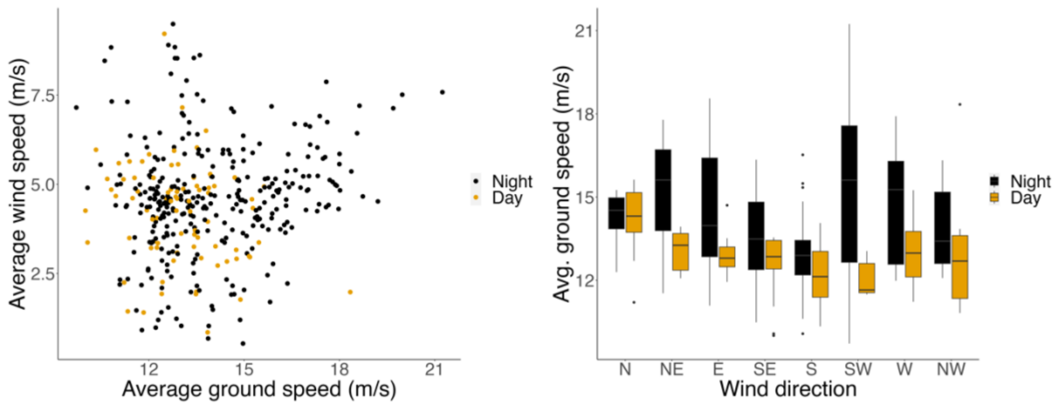

Figure 9.3 *Average ground speed (m/s) of all horizontal radar tracks versus wind speed (left) and wind direction (right) during night (black) and day (orange). Only hours with an MTR of more than 100 tracks/km/hr measured by the horizontal radar were included in this figure.*

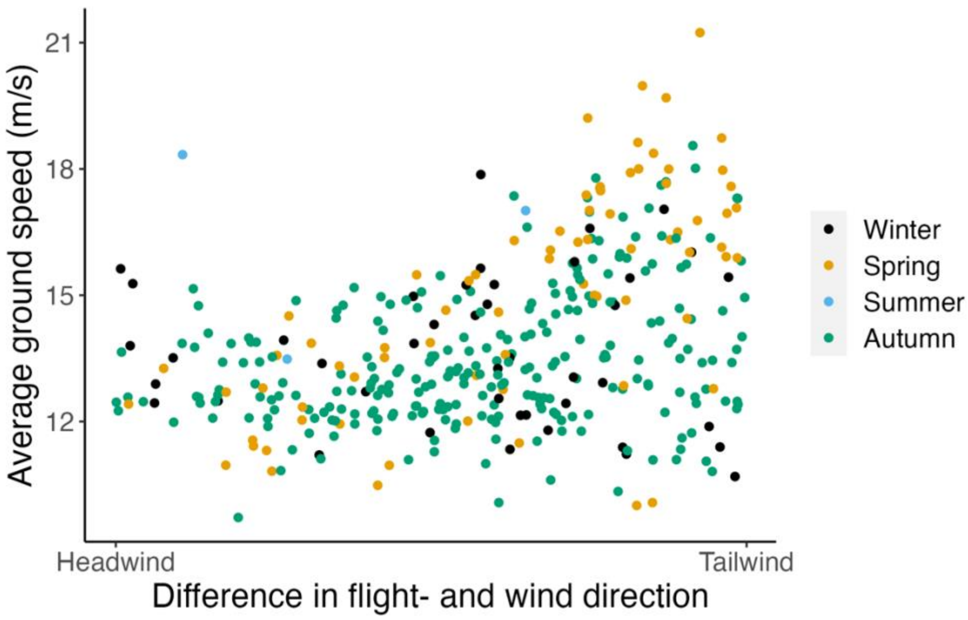

Figure 9.4 *Average ground speed (m/s) of all horizontal radar tracks versus the amount of headwind and tailwind per season. Only hours with an MTR of more than 100 tracks/km/hr measured by the horizontal radar were included in this figure.*

Species-specific flight speeds

The average flight speed was calculated for the eleven most frequently tagged bird species(groups), which consisted of seven gull species(groups) and four other species, namely northern gannet, Sandwich tern, meadow pipit, and common starling. Starlings were tagged most often (n = 48), followed by lesser black-backed gulls (n = 44), and black-legged kittiwakes (n = 32).

The fastest flying species was common starling with an average ground speed of 17 m/s (Figure 9.5 and Table 9.1). Meadow pipits, the other songbird species, had considerably lower average flight speeds (12.3 m/s). Among the gull species(groups), great black-backed gull had to highest average flight speed (12.6 m/s), followed by lesser black-backed gull (11.3 m/s). Little gull had the lowest flight speed of on average 6.5 m/s. The other seabird species, northern gannet and Sandwich tern, had average flight speeds of respectively 14.4 and 11.6 m/s.

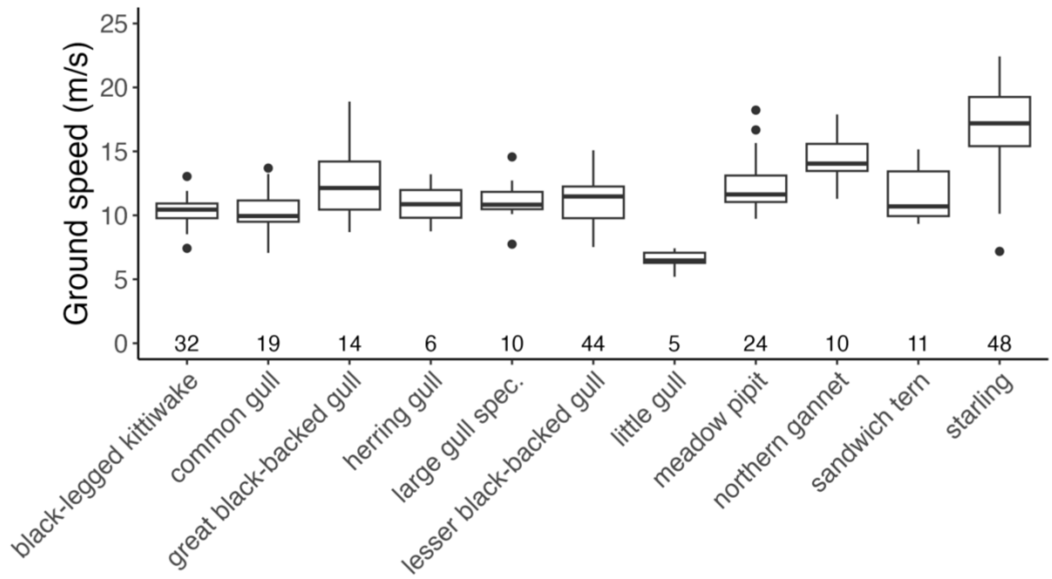

Figure 9.5 *Boxplot of the species(group)-specific ground speeds, as measured by the horizontal radar. Only species with at least 5 measurements are shown. Boxes represent the 25th and 75th percentiles, with the lines within giving the median. Numbers below boxplots show the sample sizes of that species(group).*

9.3 Discussion

In this chapter, general flight (ground) speed patterns based on horizontal radar data were analysed and the average flight (ground) speed of the most abundant species was calculated based on tagged radar tracks. We found that average flight speeds were significantly lower in summer than in the other seasons. Possibly, this may be caused by the relatively low numbers of faster flying species in summer, such as northern gannet, guillemot, razorbill (Pennycuick 1997).

Furthermore, our results indicate that bird migration occurs at on average higher flight speeds (m/s) than the flight speeds of local birds. Firstly, the highest average flight speeds per hour were often recorded in hours with relatively high fluxes while the highest MTRs are found during the bird migration. Also, we found on average higher flight speeds during the night than during day. Lastly, when looking at the effect of wind direction, we found the highest average flight speeds during the night with winds that match the directions with which nocturnal bird migration in spring and autumn mainly occurs.

In winter and spring, the difference in the average flight speed between night and day was highest. Only in autumn the average flight speed was not significantly different between night and day. The average flight speed during the day in autumn may be elevated due to the larger proportion of diurnal migrants (such as starlings) in this season. Additionally, the average flight speed of nocturnal migrants may be lower in autumn due to the on average less favourable wind conditions in this season.

The analysis of tagged radar tracks showed higher flight speeds for common starlings and northern gannets, compared to gull species. All gull species showed similar flight speeds, except little gull which showed a reasonably lower flight speed. The flight speed of little gull is also lower than what is generally used in collision risk modelling (Table 9.1). Variation within species could be the result of varying wind direction and wind speed but also different kind of flights, *e.g.* commuting versus foraging flights (Cleasby *et al.* 2015, Fijn & Gyimesi 2018, Masden *et al.* 2021). As little gulls were often seen in foraging flights at low altitudes above the sea level, we argue that this behaviour was captured within the flight speeds of the five tagged birds. For black-legged kittiwake, ground speeds were on average slightly higher than what was used in the KEC 4.0 study (Potiek *et al.* 2022). Also here, the authors argue that foraging behaviour of black-legged kittiwake might have lowered the average flight speed (Skov *et al.* 2018).

Remarkedly, the flight speeds of all species were lower than the flight speeds measured by radar in wind farm Luchterduinen (Leemans *et al.* 2022b). One hypothesis is that birds in Borssele may show on average more foraging behaviour and thus lower flight speeds than in Luchterduinen. For example, Fijn & Gyimesi (2018) found that Sandwich terns had a higher flight speed when commuting than when foraging. The average flight speed of commuting flights in that study was 12.3 m/s, which is considerably faster than the overall mean of 10.3 m/s (Fijn & Gyimesi 2018). If this also holds for other species, it could give an indication that more commuting birds were recorded by the radar in Luchterduinen compared to Borssele.

Table 9.1 Overview of the mean ground speeds (m/s) and their standard deviations (SD) as measured in this study by the radar, compared the ground speeds measured by the radar in Luchterduinen (Leemans et al. 2022b) and to flight speeds used in CRM calculations in the KEC studies (Leopold et al. 2015, Potiek et al. 2022).

		ground speed Borssele		**ground speed Luchterduinen**		
species	**sample size**	**mean**	**SD**	**mean**	**SD**	**flight speed in CRMs**
black-legged kittiwake	32	10.4	1.1	12.1	4.1	8.7[5]
common gull	19	10.4	1.8	11.4	3.5	13.4[1]
great black-backed gull	14	12.7	3.0	13.2	4.9	13.7[1]
herring gull	6	10.9	1.7	12.8	4.4	11.3[2]
large gull spec.	10	11.2	1.8			
lesser black-backed gull	44	11.3	2.0	12.3	2.8	9.4[2]
little gull	5	6.5	0.9			11.5[1]
meadow pipit	24	12.3	2.2			
northern gannet	10	14.4	2.0	14.9	3.4	14.9[3]
Sandwich tern	11	11.6	2.1	13.9	4.1	10.3[4]
starling	48	17.0	3.1			15.4[6]

Data come from (1) airspeeds in Alerstam *et al.* (2007); (2) ground speeds measured by GPS-loggers in Gyimesi *et al.* (2017b); (3) airspeed in Pennycuick (1990); (4) ground speeds measured by GPS-loggers in Fijn & Gyimesi (2018); (5) ground speed measured by radar in Skov *et al.* 2018; (6) airspeed in Pennycuick *et al.* (2013).

10 Meso-avoidance

The rapid expansion of onshore and offshore wind energy facilities means there will be a growing risk of collisions between birds and wind turbines. The degree to which an approaching bird responds to a wind farm, an individual turbine or the turbine blades largely determine whether it will collide and - if successfully avoiding collision - the energetic costs of avoidance. Estimating avoidance behaviour is therefore important to estimate the effects of wind farms on birds.

Avoidance rates are usually estimated by comparing measurements of bird densities within the wind farm to a reference area outside the wind farm. To control for intrinsic differences in the impact and control areas, a pre-construction period may be included. Bird densities used in such assessments can be obtained from direct observations during daytime (ship-based and aerial surveys), by radar measurements or by tracking individual birds. However, comparing movement intensities or bird densities between two areas does not directly test for avoidance behaviour of individuals, considering that areas may have intrinsic differences in suitability. In addition, studying the effect of covariates on avoidance requires compartmentalization of data. Estimating avoidance behaviour at the level of individual birds may resolve some of these issues, and this has recently been done for several seabird species (Peschko *et al.* 2020a, Peschko *et al.* 2021, Johnston *et al.* 2022, van Bemmelen *et al.* 2023). A next step would be to estimate avoidance behaviour from a more generic source of information on movement intensity such as using radar tracks, but this has not yet been done.

Here, we use integrated Step-selection Functions (iSSFs) to estimate horizontal meso-avoidance rates using radar tracks. In iSSFs, tracks are compared with positions that were available to the animal at the start of each segment between two locations, but not necessarily used. This approach has the advantage of directly quantifying a behavioural response to a turbine or wind farm and can easily be extended with covariates at the level of segments or individual tracks. We estimate horizontal meso-avoidance iSSFs for two data sets. First, using a data set of radar tracks tagged with species identifications during daytime observations, we estimate horizontal meso-avoidance per species. Second, horizontal meso-avoidance were estimated for radar data obtained during six nights with intense nocturnal bird migration.

10.1 Methods

10.1.1 Radar data

Radar data collected by the horizontal radar was used. Two datasets were analysed: 1) radar tracks that were visually identified to species or species-group level and 2) radar tracks recorded during six autumn nights in 2022 with very high bird migration intensity, namely 29-30 September, 11-12 October, 18-19 October, 29-30 October, 12-13 November and 13-14 November. Steps between positions were removed if the log of the speed was lower than -12. Following filter steps defined by the UvA that aim to filter out non-avian tracks, only tracks were included of which the straightness was higher than 0.7, with straightness calculated as the distance between the start- and endpoint divided by the total distance covered by the track. To reduce computational demands, the 25% quantile of the longest tracks per migration night was selected.

The original data has a median temporal resolution of 1.283s. This high temporal resolution leads to high computational demands whereas the response of birds to wind turbines may be apparent from the trajectory shape at lower temporal resolution. In addition, inferences from iSSFs are scale-dependent, and very small step lengths may yield too few (random) positions in the rotor swept zone (see below). For these reasons, we down-sampled the data at a resolution of four times the original median resolution leading to time intervals between subsequent positions of 5.132 s.

10.1.2 Data pre-processing

Tagged radar tracks were grouped into six groups: Northern Gannet *Morus bassanus*, large gulls (Great Black-backed Gull *Larus marinus*, Lesser Black-backed Gull *L fuscus*, Herring Gull *L argentatus*), small gulls (Black-legged Kittiwake *Rissa tridactyla*, Black-headed Gull *Chroicocephalus ridibundus*, Little Gull *Hydrocoloeus minutus*), Sandwich Tern *Thalasseus sandvicensis*, passerines (Starling *Sturnus vulgaris* and unidentified small passerines) and 'other', comprising a variety of seabirds (Red-throated *Gavia stellata* and Black-throated Diver *G arctica*, Razorbill *Alca torda*, Common Guillemot *Uria aalge*).

10.1.3 Statistical analysis

We used integrated Step Selection Functions (iSSF) to estimate avoidance behaviour of the rotor swept zone. The rotor swept zone was defined as a circle around the turbine with a diameter equal to the diameter of the rotor, plus 10 m at each side. In iSSFs, the radar tracks ('used') are compared to positions that were available to the bird, but not used at that time ('available'). The available positions are generated from the perspective of the previous used position, creating 'steps' between used position u_1 and available position $a_{2.1}$, $a_{2.2}$, … $a_{2.n}$. Available positions were generated from the distribution of step lengths (distance between two subsequent positions) and turning angles. Available/used ua is then used as the response variable in conditional logistic regression to estimate the preferential selection of covariate levels.

We defined two types of models:

$ua = \alpha + \beta_{inRSZ}$, where the endpoint of each step was outside (base level) or inside the rotor swept zone, and

$ua = \alpha + \beta_{toRSZ} * \beta_{distance}$, where the direction of the step was not (base level) or was towards a rotor swept zone within a distance of *2* km, conditional on the distance from the first position to the turbine. In other words, the selection of directions towards the rotor swept zone depend on the distance to the turbine.

All models included the step length, the log of the step length and the cosinus of the turning angle as fixed effects, and random intercepts per step-id.

Multiple models were constructed - each to answer a specific question. To estimate the general meso-avoidance rate, a model with `in_RSZ` was fitted. To estimate species-level meso-avoidance rates, a model with random slopes for `in_RSZ` per species, using the tagged data. Likewise, to estimate meso-avoidance rates per species_group, a model with random slopes for `in_RSZ` per species group was fitted, again using the tagged data. To study whether avoidance may differ between migration nights, we also included a model of `in_RSZ` as a function of migration night-id.

Considering birds may start avoiding turbines already at greater distances from the turbine than a single step length, we fitted a model with `to_RSZ` as a fixed effect and an interaction term between `dist_tur`, as a random walk type II smoother, and `to_RSZ`. This, in effect, models the preferential use of flying towards the RSZ as the bird approaches the turbine. Avoidance of selecting the rotor swept zone was calculated from the parameter of `in_RSZ`, β_{inRSZ}, as $1 - exp(\beta_{inRSZ})$. Likewise, avoidance of flying towards the rotor swept zone was calculated from `to_RSZ`, β_{toRSZ}, as $1 - exp(\beta_{toRSZ})$.

10.2 Results

10.2.1 Species- or species-group-level avoidance rates

The tagged data used in the analyses contained 505 tracked tracks, which led to 202,980 steps of 23 species or unidentified groups (Table 10.1). On a species level, most tracks were obtained from Lesser Black-backed Gulls *Larus fuscus*, followed by Black-legged Kittiwake *Rissa tridactlya*. In the grouped data, large gulls were the most abundant (41%), followed by small gulls (22%) and passerines (20%). The tagged data also includes 51 birds not identified to species level (10%).

Table 10.1 Overview of the data set of tagged radar tracks used to estimate horizontal meso-avoidance on species and species-group levels. Track length is expressed as the number of positions.

species group	species	n sightings	n indivi-duals	min track length	median track length	max track length
large gull	great black-backed gull	37	40	11	95	320
large gull	gull sp.	7	19	22	56	148
large gull	herring gull	11	11	14	127	180
large gull	large gull sp.	28	32	11	64	224
large gull	lesser black-backed gull	125	138	17	88	287
large gull	yellow-legged gull	1	1	165	165	165
northern gannet	northern gannet	39	45	11	81	523
other	black-throated diver	1	2	146	146	146
other	goose sp.	1	1	90	90	90
other	great cormorant	4	11	41	90.5	106
other	razorbill	1	1	32	32	32
other	razorbill/guillemot	3	3	11	60	77
other	red-throated diver	2	2	91	107.5	124
other	sandpiper sp.	1	2	57	57	57
passerine	common starling	51	2,464	15	56	261
passerine	meadow pipit	38	165	12	64	207
passerine	small passerine sp.	11	65	15	57	245
sandwich tern	sandwich tern	33	60	11	69	214
small gull	black-headed gull	7	32	18	29	188
small gull	black-legged kittiwake	54	56	13	56.5	203
small gull	common gull	45	49	12	66	289
small gull	little gull	4	4	88	93	129
small gull	small gull sp.	1	2	320	320	320

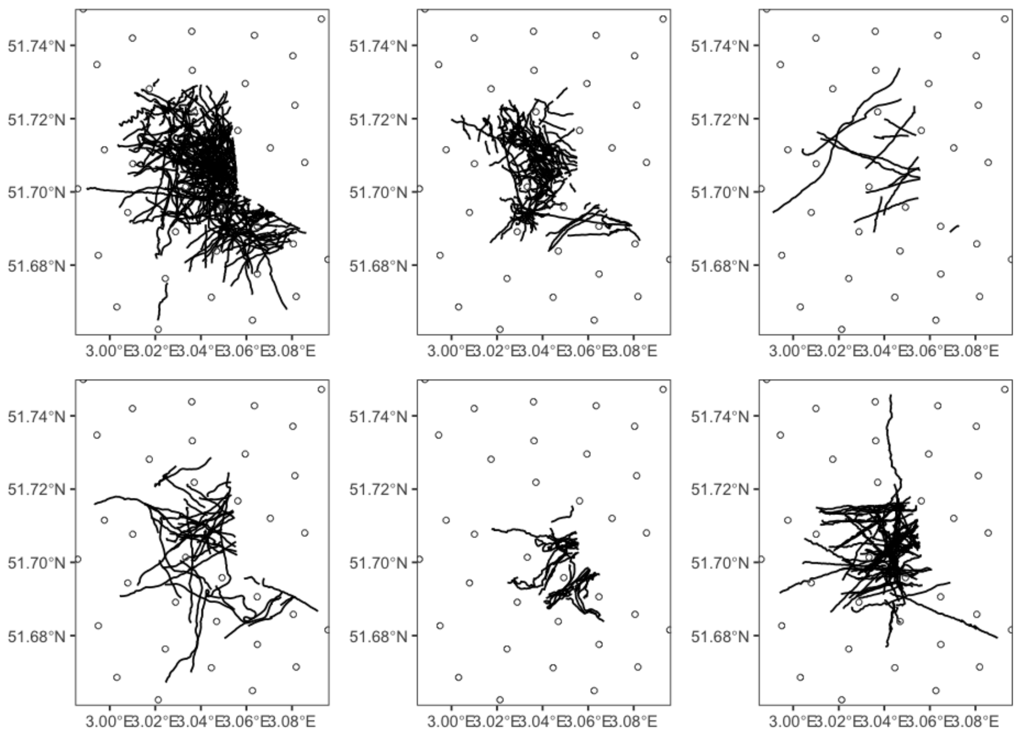

Figure 10.1 *Distribution of tagged radar tracks and turbine rotor swept zones. Open dots show turbine positions.*

Most of the tagged tracks were positioned in the corridor, with only few venturing close to turbines (Figure 10.1). From all used steps, only 12 (0.3%, n = 3980) ended within the rotor swept zone. From the available steps, the percentage was similar: 651, 0.3% (n = 199,000). Only 28 steps had any (used or available) endpoints within the rotor swept zone.

Overall, meso-avoidance of the rotor swept zone was estimated at 27.8%, but with a wide credible interval overlapping with 0, thus not excluding indifference (95% CrI = -116 - 75.9). Estimates of meso-avoidance estimates were very similar across groups, ranging from 24.7 for Sandwich tern to 36.6 for small gulls (Figure 10.2a). Estimates of meso-avoidance at the species level were also associated with wide credible intervals overlapping with 0, centring on the general estimate of 29.9% (95% CrI = -122.2 - 78.3) (Figure 10.2b).

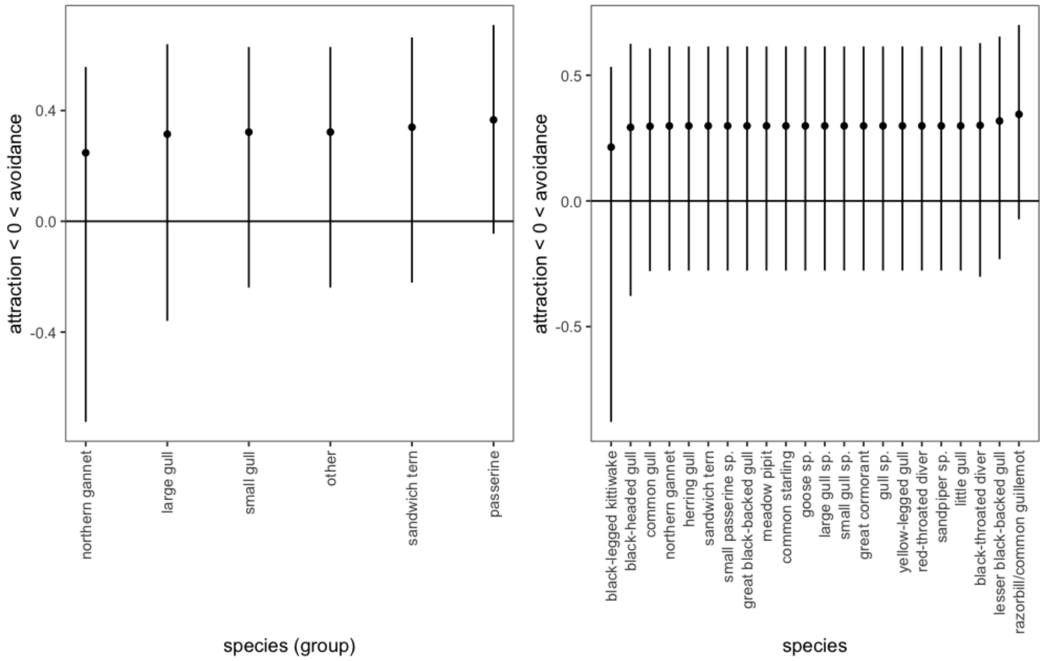

Figure 10.2 *Estimates of horizontal meso-avoidance rates based on tagged radar tracks per species group (left) and species (right). Note that in 10% of the tracks, the bird was not identified to species level.*

10.2.2 **Intense migration nights**

During nights of intense bird migration, birds showed strong avoidance of the rotor swept zone. Overall, the meso-avoidance rate was 62.8% (range = 57.7 - 67.2). Analysed per night, the estimates for meso-avoidance varied between 42.8 and 73.2% (Figure 10.3).

Birds started to avoid flying towards the turbine rotor swept zone already at distances of 530m but seemed to behave indifferently to the presence of the turbine at larger distances (Figure 10.4). However, this relation was less clear when analysed per night: in three nights a similar pattern is observed, but with more uncertainty around the mean estimates. In other nights, whether birds flew towards the rotor swept zone did not seem to depend on distance to the turbine (Figure 10.5).

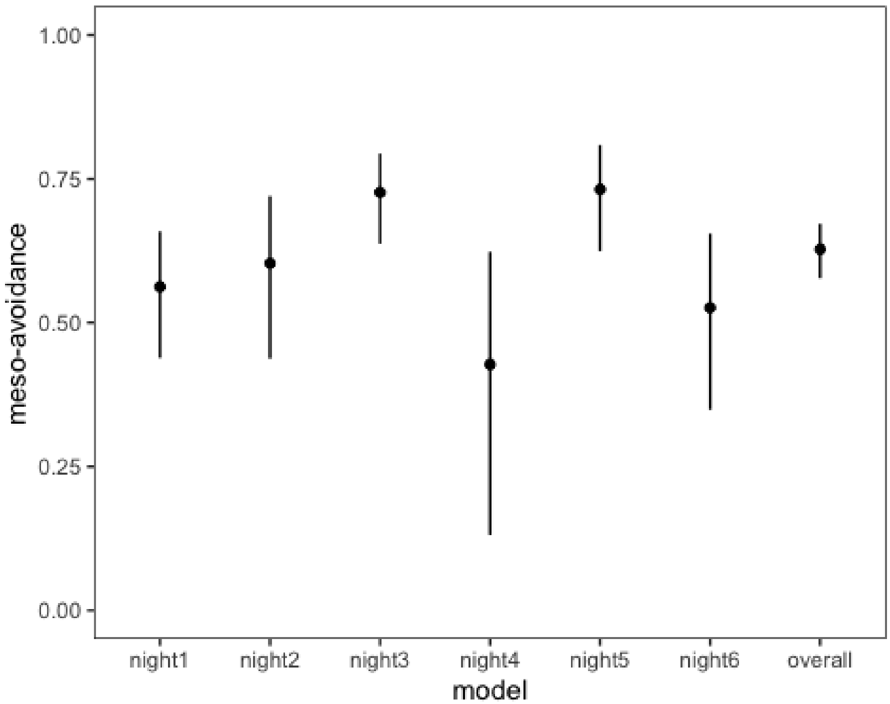

Figure 10.3 *Estimates of horizontal meso-avoidance during six nights of intense migration. The 'overall' estimate is based on a single model using all data.*

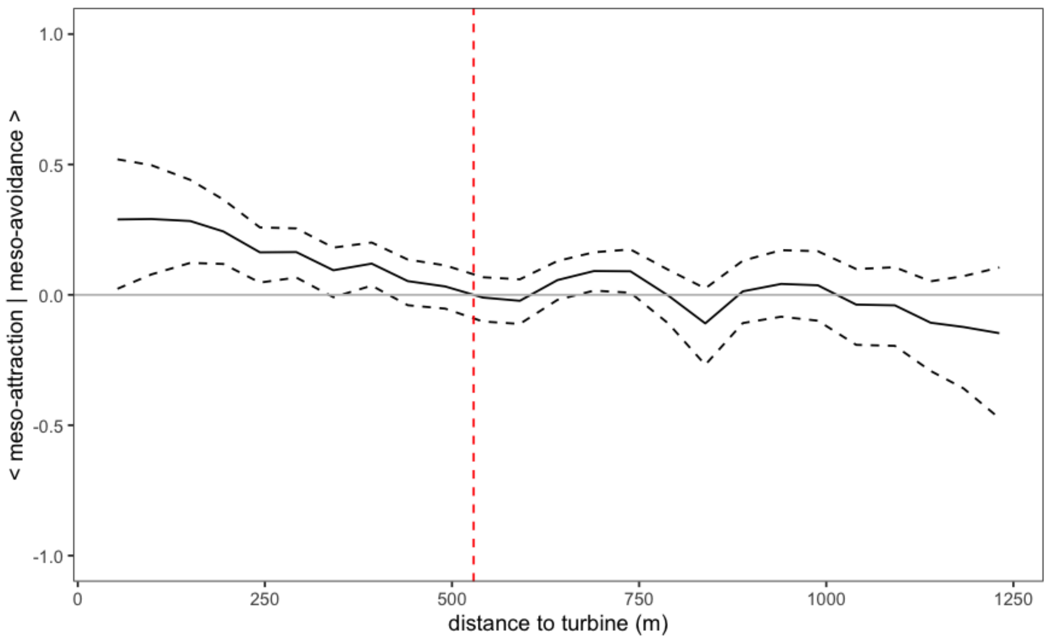

Figure 10.4 *Overall avoidance of flying towards the turbine swept zone as a function of distance to the turbine, estimated from radar tracks during six autumn nights of intense migration.*

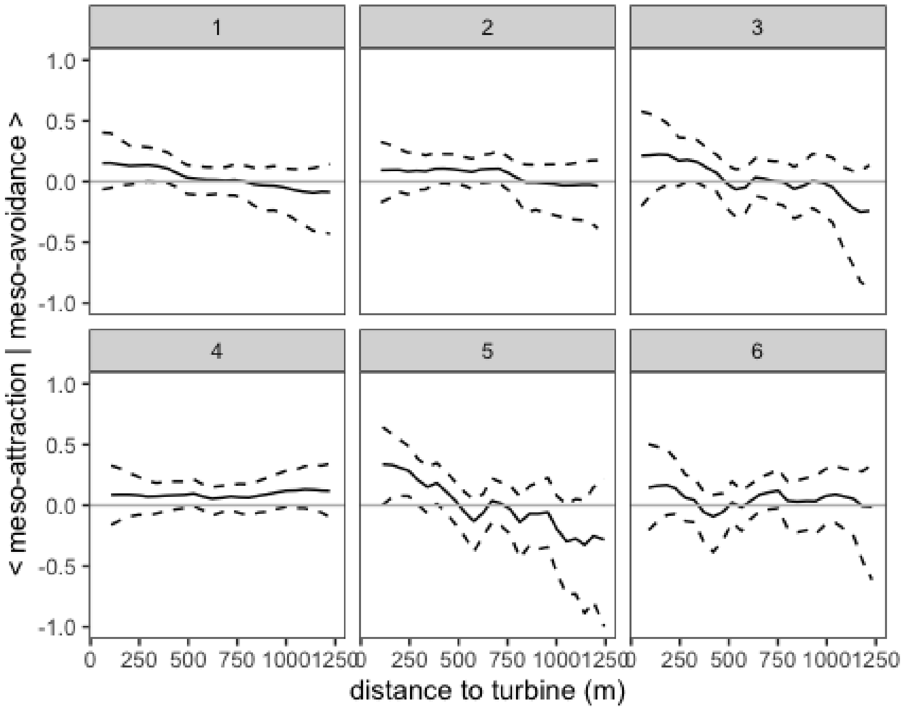

Figure 10.5 *Avoidance of flying towards the turbine swept zone as a function of distance, estimated from radar tracks for each of six autumn nights of intense migration, numbered here 1-6.*

10.3 Discussion

We used integrated Step Selection Functions to estimate horizontal meso-avoidance of the rotor swept zone. Although our results show a first exploration of how iSSFs can be used for estimating meso-avoidance using radar-data, there currently remain some complex potential biases that require adjustment of the methods. The results presented here should therefore be interpreted with caution.

Our study suggests that the horizontal meso-avoidance rates in the Borssele wind farms were *ca.* 27% for tagged tracks, and 63% for tracks during six autumn nights of intense bird migration. However, the species-level and species-group level estimates were surrounded by wide uncertainty intervals, precluding making strong statements on e.g., differences between species responses to turbines. Uncertainty levels can be decreased by collecting more field data.

Considering gulls dominated our sample of tagged radar tracks, comparison with horizontal meso-avoidance reported in other studies of gulls seems most appropriate. Janoska (2012) reported that only 2.5% of gulls traversed the area of 75m from turbines. Skov *et al.* (2012) reported no gulls venturing within 50 m of turbines, thus effectively reporting a meso-avoidance rate of 100%. However, Skov & Tjørnløv (2022) report an avoidance rate of *ca.* 50% of 50m from the turbine. Johnston *et al.* (2022) drew a more complicated picture of avoidance and attraction of Lesser Black-backed Gulls to wind turbines, with total avoidance at or above rotor heights within 60m from the turbine, but strong attraction within that distance to heights below the rotor. Attraction of Lesser Black-backed Gulls to turbine platforms has also been shown by other studies (Vanermen *et al.* 2019).

Horizontal meso-avoidance during migration nights was on average 63%, which varied between the six nights between 43% and 73%. No effort has been spent to find potential reasons for this variation. Interestingly, birds started to avoid flying towards turbines at a distance of 500m. This is a larger distance than the 150m reported for gulls (Skov & Tjørnløv 2022), despite being at night with thus presumably poor visibility of the turbines. The nocturnal migration captured by the radar during the six nights analysed here likely mainly consists of common passerine migrants, in particular thrushes like Redwing *Turdus iliacus* and Song Thrush *T philomelos*.

Our estimate of horizontal meso-scale avoidance of radar tracks during autumn nights with intense migration is substantially higher than the estimate from Krijgsveld *et al.* (2011), who reported a value of 34% reduction of bird numbers (also based on radar data) within 50m of a turbine in the Egmond aan Zee OWF.

However, these were associated with huge uncertainty, which is no surprise given the 1) small overall sample size of tagged tracked and 2) the small number of tracks venturing close enough to the turbine to have endpoints of available steps within the rotor swept zone.

Weaknesses of the current methodology and future directions

An important advantage of the use of iSSFs are that track-level covariates can be included in the model. This advantage has not been exploited fully in this report, except for estimating species-level or species-level group meso-avoidance. Using iSSFs allow the inclusion of further covariates at the level of tracks or steps. This opens many opportunities, such as studying how avoidance rates vary with weather circumstances, the time of day, main direction of flight and flight characteristics.

The main issues with the current approach are caused by imperfect detection of birds by the radar. Detection by the radar is not equal across its range, both horizontally and vertically. This is especially problematic close to turbines, where detection rates of birds appear to be lower, but at the same time the amount of clutter and the chance of incorrect linkage of incomplete tracks are higher. In addition, detectability by the horizontal radar is also affected by flight heights: the altitudinal range of the radar is narrower close to the turbine. In absence of a good way to deal with these issues, we currently assumed equal detection rates within each ‘step’, considering that the bird was observed at a certain distance and that the available positions from the starting position of that step share a similar detection probability. Relaxing this assumption is not straight forward but is important to avoid bias in the generation of available positions. Note that also other approaches to study meso-avoidance, such as track density comparisons or state-space models, are hampered by the imperfect detection in relation to distance from turbines; not only generated available positions, but also the radar tracks of detected birds will be biased by imperfect detection close to turbines.

Inferences of iSSFs are scale-dependent on the length of steps, which is predetermined by at what temporal resolution the data is regularized. Here, we regularized tracks to 5.132 s, or four times the temporal resolution of the original. Down-sampling was required to reach sufficient available positions within the rotor swept zone to be able to estimate some effect of the rotor swept zone. It would be good to further study the effect of the temporal resolution on meso-avoidance.

Our current analysis only considers horizontal meso-avoidance. However, vertical meso-avoidance has also been observed. This can be solved by using 3-d radar data and would require the estimation of turning angles not only in the horizontal but also in the vertical plane. Availability should than be assessed using the distribution of horizontal and vertical turning angles. Until this is implemented, a work-around could be to include mean altitude of a track as a covariate interacting with the factor for rotor swept zone, but mean altitude is only available for tracks that have been detected by both the horizontal and the vertical radar.

Another problem with the current approach is that the rotor swept zone is now taken as the diameter of the rotor swept zone in a horizontal plane around the position of the turbine. However, the rotor swept zone is of course manifested mainly in a vertical plane and horizontally oriented according to the wind direction. In future analyses, orientation of the rotors could be included using the wind direction. However, this will result in a tiny surface area of the rotors in the horizontal plane and therefore a further reduced probability that a used or random step will end within the polygon of the rotor. This may be solved by changing the response to reflect whether a step is directed towards the rotor, as we did here as well.

11 Synthesis

The main aim of this project was to carry out measurements on bird numbers and bird behaviour in relation to an offshore wind farm. More specifically, based on field observations and radar measurements, we collected information on bird fluxes, flight behaviour, meso-avoidance and the use of different areas of the wind farm, in particular a corridor inside the wind farm. The ultimate goal was to gain new insights that help to better understand the effects of offshore wind farms on birds.

Corridor use

Our study is one of the first to examine the use of a corridor inside the wind farm by birds. Based on ship-based survey data, we found no differences in bird densities inside the wind farm compared to inside the corridor in the wind farm. The studied species (lesser black-backed gull, black-legged guillemot, northern gannet, razorbill, common guillemot and common gull) did not seem to prefer the corridor over the rest of the wind farm. An important factor to consider when interpreting these results is that the corridor was not designed for birds, instead it is meant to be a shipping lane. The conclusions of our study about the use of birds of a corridor inside an offshore wind farm hence may only apply to this specific corridor in wind farm Borssele, or at most shipping lanes in offshore wind farms in general. Nonetheless, ships without a link to the wind farm operations were rarely seen inside the corridor by our observers, which means that the actual ship traffic inside the corridor may not have been much more than in the rest of the wind farm. Another important fact to point out is that the width of the corridor is approximately 2 km, while the average distance between turbines in wind farm Borssele is almost 1.3 km. This difference may not have been large enough for most birds that normally avoid offshore wind farms to distinguish the wind farm from the corridor and hence possibly these birds still do not enter the corridor. On the other hand, birds that may avoid individual wind turbines may for example only show an avoidance response close the wind turbines, which would mean that these birds still use other areas in the wind farm as the average distance between turbines is large enough. An analysis of bird densities at different distances to wind turbines could provide valuable insights on the potential effectiveness of wind farm corridors for birds. A similar analysis was already performed on harbour porpoises in wind farm Borssele based on data from digital aerial surveys (Leemans & Fijn 2023).

Reliability of radar measurements

We determined bird fluxes in the area based on radar measurements and visual observations. The temporal and seasonal variability in the mean traffic rates based on radar measurements, as well as the effect of wind on these fluxes, were largely in line with what one would expect ecologically and what was already described in literature before. As such, despite the extensive filtering that was required to remove clutter from radar datasets, the bird radars prove to be a suitable tool to study temporal patterns in bird fluxes. At the moment of writing, a network of in total seven bird radar systems (comprising of a horizontal and a vertical radar) located at different locations in the Dutch North Sea, of which most are located inside offshore wind farms, is already placed by the Dutch governmental body Rijkswaterstaat. An analysis that compares the timing of migration peaks recorded by each radar, would be a next step towards a better understanding of when migration peaks at different locations across the North Sea can be expected and when large numbers of these migrating birds fly at rotor height, risking collision. Even more, such an integral analysis could be extended by involving radar measurements in other North Sea countries, e.g. in Germany and Belgium. Such analyses should preferably consider the effect of weather conditions upstream, at departure locations, during migration peaks, rather than looking at the local conditions. An analysis of the effects of such upstream conditions was out of scope of our current study.

One of the largest drawbacks of bird radars is that they are not able to properly measure bird activity inside offshore wind farms during adverse weather conditions with rain or high waves. Also, we were unable to address this knowledge gap with visual observations, as field days were limited to calm weather conditions due to safety regulations. Although it is widely believed that migration intensity is reduced during rainy periods (e.g. Manola *et al.* 2020), we found that during some hours in the migration periods that were filtered out from the vertical radar dataset due to rain, the horizontal radar did record relatively high MTRs . This may suggest that bird migration could occur in periods with at least some precipitation. It is recommended to explore how data on bird activity inside offshore wind farms during such adverse weather conditions can effectively be collected in future studies.

A potentially promising method to reduce the impact of clutter on radar performance could be using machine learning to identify clutter tracks and ultimately improve the classification of tracks. Waardenburg Ecology has developed an automatic classification of wave clutter by for our own Max 3D radar of Robin Radar of which the first results are very promising. Similar methods may be applied to Robin Radar Flex/Fixed systems in the future. Therefore, besides tagging many true positive bird tracks, we also stress the importance of tagging false positive clutter tracks, including clutter from waves, rain and static objects such as wind turbines. Ultimately, if this results in an improved classification of clutter tracks during the post-processing of radar data, it may allow to lower the strength of the dynamic radar filtering, thus increasing the detection of birds during a broader array of circumstances.

Bird fluxes

The susceptibility of the radar to register clutter as birds and the strong filtering under unfavourable circumstances poses a significant challenge to calculate absolute fluxes based on the radar data. Moreover, as the radars cannot identify bird species, accurate species-specific fluxes that may be used in collision risk models cannot be inferred directly from radar data. Therefore, in this study we used visual observations to determine species-specific fluxes and species-specific densities, as both fluxes and densities can be applied to collision risk models. Most common practice in recent collision risk modelling studies in the Netherlands, such as KEC 4.0 (Potiek *et al.* 2022), is to use bird densities as an input rather than fluxes. The model then transforms these densities into fluxes. To test whether this transformation of density into fluxes reflects the measured fluxes, we compared fluxes calculated with densities with fluxes measured in the field. In three out of four cases, the fluxes derived from densities where higher than the measured fluxes, which could mean that the current common practice of using densities results in an overestimation of collision casualties. However, more research is needed as sample sizes were small and surveys to estimate density and flux were not done on the same day. It would be interesting to set up a study where fluxes and densities are measured simultenously and with a larger sample size to account for day-to-day variation and to perform the comparison for more species and months. Still, our analysis shows how different input variables can lead to largely variant flux estimations. These flux estimations in turn influence the number of estimated victims, so being able to accurately calculate fluxes is vital for assessing potential new offshore wind farms.

Flight altitudes

In line with what has been described in literature before, our study showed that migration during spring occurs at on average higher altitudes than in autumn and hence the proportion of birds at collision risk height (rotor height) is mostly larger in autumn than in spring. Furthermore, several results indicated that birds on migration fly on average higher altitudes than local birds. Visual observations showed that lesser black-backed gull, black-legged kittiwake and common gull were the species of local birds that flew most at rotor height. We found a seasonal effect for black-legged kittiwake showing that kittiwakes in winter generally fly higher and more at rotor height than in spring, which suggests that in our study area these birds are most vulnerable to collide with wind turbines in winter. Such seasonal differences in flight heights are currently not taken into account in collision risk modelling. The methods used in our study, visual observations and radar data, are both not well-suited to collect flight height data that may be used in collision risk models, as radar data is not species-specific and visual observations contain a bias for detection at lower altitudes. Collision risk models require either a proportion at rotor height or (location-specific) flight height distributions with the proportion of birds per 1-meter height band, and hence reliable and unbiased species-specific data on flight height at higher altitudes (at least up to 300m) is required. Therefore, flight height data for collision risk models may best be derived from GPS logger data. These data potentially also allow to differentiate flight height distributions between different seasons, with which collision estimates may be improved.

Flight speed

In this report, we present species-specific flight speeds based on tagged radar tracks. Remarkedly, the flight speeds of all species were lower than the flight speeds measured by radar in wind farm Luchterduinen (Leemans *et al.* 2022b). One hypothesis is that in Borssele birds show on average more foraging behaviour and thus lower flight speeds than in Luchterduinen. These differences in flight speeds between locations show that not one specific value of flight speed can be considered as most suitable for use in collision risk models. Instead, results of different studies (at different locations) may best be averaged, and the resulting mean and standard deviation can then be used in collision risk modelling. However, when modelling collisions in a single wind farm, location-specific flight speeds measured in that specific wind farm are preferably used.

Meso-avoidance

We applied a novel method to estimate meso-avoidance rates based on radar data. Overall, the tagged tracks indicate an meso-avoidance rate of 27%. Meso-avoidance estimate during nights with intense migration suggested a much higher avoidance of 63%, which varied among nights between 43% and 73%. We also showed that migrating birds started to avoid flying towards turbines at a distance of 500 m. Our estimates of meso-avoidance at the species- or species-group-level were associated with considerable uncertainty, which is likely attributable to the low sample sizes. As such, these meso-avoidance rates are not recommended to use in collision risk models. Finally, we highlight potential applications of this model for further study of meso-avoidance and formulate several recommendations for improvements of the model and its estimates.

Conclusions

As described above, our study aimed to extend our understanding of bird behaviour in relation to offshore wind farms. Our measurements on seabird flight intensities and flight patterns highlight the importance of local differences and underline that in collision risk models locally measured values for the different parameters are preferred above general values. This is highlighted by locally measured fluxes, flight speeds and flight heights diverging from earlier results measured elsewhere. However, such location-specific values are often lacking, especially in pre-construction impact assessments, and hence studies like ours supplement to generating a more robust base to work with mean values and a certain variance around it. Further extending the foundations of this knowledge base reduces the uncertainties surrounding the assumptions made in future wind farm impact assessments and therefore also form an important ground for better understanding the long-term cumulative impact of offshore wind farms in the North Sea.

A unique part of our study is formed by investigating the corridor use by birds in wind farm Borssele. As our analyses on this corridor use are one of the first of their kind, they form an important step in setting up effective measures to reduce the effects of offshore wind farms as an ecological barrier. Although our study revealed no positive effect of the corridor on bird numbers, such results are also important to be published to reveal what does not work and further elaborate on what might work.

Our study also provides further understanding of bird migration in the North Sea farther away from the coast. This phenomenon is nearly impossible to study by visual observations, especially during the night, but we demonstrate that radar measurements may give vital insights in the temporal patterns of offshore bird migration. Moreover, based on the radar measurements, we could also explore the effect of wind conditions on migration intensities and the flight height birds use during migration. Finally, we revealed that birds during nocturnal bird migration are well-capable of detecting wind turbines as measured meso-avoidance rates were even higher at these moments than generally during daytime. These results may help to further improve near-term forecasting of intense bird migration moments with high collision risk when offshore wind turbines could be best curtailed to reduce the potential number of collisions.

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Appendix I Corrected ESW values

Date	Side	Razorbill	Common guillemot	Black-legged kittiwake	Lesser black-backed gull	Common gull
14/12/2021		116.27	116.27	216.29	-	-
25/01/2022		299.91	299.91	214.00	-	-
09/03/2022		284.75	284.75	209.38	-	292.38
31/05/2022	larboard	-	-	-	195.26	-
31/05/2022	starboard	-	-	-	210.28	-
21/06/2022	larboard	-	-	-	300.00	-
21/06/2022	starboard	-	-	-	195.26	-
29/07/2022		-	-	-	212.00	-
26/08/2022		-		-	202.49	287.32
30/09/2022		135.35	135.35	-	245.20	-
14/10/2022	larboard	125.59	125.59	211.43	207.32	-
14/10/2022	starboard	116.27	116.27	196.89	189.07	-
06/12/2022		116.27	116.27	271.56	-	-
08/02/2023		118.74	118.74	202.54	-	289.99
14/02/2023		299.91	299.91	200.17	-	287.23
17/03/2023		135.35	135.35	202.24	-	-
27/05/2023		-	-	-	300.00	-
13/06/2023		-	-	-	236.55	-
11/07/2023		-	-	-	179.58	-
15/08/2023		-	-	-	208.94	-
06/09/2023		-	-	-	202.12	-
01/12/2023		118.10	118.10	210.93	-	-