Spatiotemporal variation in bird migration directions and speeds across the Dutch North Sea

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Aims of this report

The primary aim of this report is to investigate **spatiotemporal variation in bird migration directions and airspeeds across the Dutch North Sea**, using a network of offshore tracking radars. The study examines how migration axes and flight behaviour across geographically distinct radar locations across the North Sea, within seasons and nights, with a focus on identifying potential implications for conservation efforts, particularly in the context of offshore wind energy development.

- **In the Introduction**, we outline ecological barriers and their influence on migratory movement strategies, with a focus on the North Sea as a semi-permeable barrier along the East Atlantic Flyway. We review previous findings on migratory movements in the region, introduce the concept of loop migration, and highlight the need for a regionally distributed radar network to characterise migration axes and flight behaviour at finer spatial scales.

- **In Materials and Methods**, we describe the deployment of six offshore radars, their spatial configuration, and the data collection period. We provide details on radar specifications, tracking, and our multistep filtering process to remove clutter and non-bird targets. We also explain how flight headings and airspeeds were calculated and which statistical and circular analyses were used to evaluate spatiotemporal migration patterns.

- **In Results**, we present the predominant seasonal and within-night migration directions and airspeeds across radar sites. We highlight the observed consistency in spring and autumn directional patterns, as well as subtle spatial variation in airspeed distributions. We also detail how within-night directional shifts vary between locations and seasons.

- **In the Discussion**, we interpret the findings in the context of existing literature on barrier-crossing strategies and migratory behaviour. We examine the evidence for loop migration in the region, discuss how local conditions may influence routing decisions, and how radar-based observations reflect broader ecological processes such as differential timing and departure strategies of short- vs. long-distance migrants.

- **In Conservation Implications**, we assess how our findings can inform offshore wind turbine mitigation strategies. We explore how certain predictive model variables can be adjusted to better represent local differences.

- **In the Supplementary Information**, we provide detailed overview of the data filters applied and developed, clutter filtering thresholds, and the results of tests for pairwise comparisons of airspeeds and groundspeeds.

DISCLAIMER: Robin Radar recently reported that the k14 radar requires azimuthal corrections due to misconfigured settings, which have affected recorded track directions. Corrections will be applied once the extent and time frame of the issue are confirmed. Similar checks are underway at other radar sites, and direction data may be updated accordingly based on the findings.

Introduction

Ecological barriers are considered to be topographical features that either physically hinder the movement of animals (e.g. mountain ranges) or do not provide opportunities for rest and refuelling (e.g. large bodies of water). Ecological barriers may therefore result in alternative migratory routes, navigational and orientational alteration or barrier crossings with increased energy expenditure (Alerstam et al. 2003, Newton 2008). Multiple studies show that when faced with such features during migration, birds may choose to either cross or circumnavigate them (Diehl et al. 2012, Bradley et al. 2014, Aschwanden et al. 2019), revealing a multitude of strategies in which they trade off between time, energy and safety (Biebach et al. 2000, Hawkes et al. 2011, Deppe et al. 2015).

The strategies birds employ when encountering ecological barriers can lead to the differentiation of spatiotemporal migration patterns around the barrier itself (Alerstam et al., 2003). Depending on the species, their physiological condition and weather patterns, birds might make varying departure decisions, not only in departure timing but also in the flight course they take (Rüppel et al. 2023). This can cause broad-front migration to split into various, smaller migration routes depending on the size and shape of the barrier and the seasonal environmental conditions, predominantly wind (Åkesson et al., 2016). Birds tend to exploit wind regimes to minimise their energy expenditure when crossing high mountain ranges of the Alps (Aurbach et al. 2018), but also large water bodies of the Gulf of Maine (Woodworth et al. 2015), Gulf of Mexico (Deppe et al. 2015, Ward et al. 2018), the North Sea (Shamoun-Baranes and van Gasteren 2011, Bradarić et al. 2020a) and the Sahara desert (Schmaljohann et al. 2009, Åkesson et al. 2016). Depending on the uniformity of seasonal weather patterns, this often results in birds using different migration axes when navigating ecological barriers in different migration seasons (Åkesson et al. 2016, Léandri-Breton et al. 2019, Bradarić et al. 2020a).

Such a phenomenon seems to occur when birds migrate over the North Sea, one of the ecological barriers for landbirds within the East Atlantic Flyway. Previous studies with shorter deployments of individual radar revealed that, due to the general weather patterns, birds seem to predominantly use different main axes (W-E migration axis in spring, and NE-SW migration axis in autumn) in the two migration seasons (Lack 1959, Buurma 1987, Bradarić et al. 2020a), suggesting that loop migration might occur in the region (Lack 1959, Bradarić et al. 2020a). These observations mainly originated from sporadic radar studies of bird migration, with individual radars being placed at a few locations in coastal areas of the North Sea for a limited amount of time (e.g. a single season). With the recent increase in bird tracking radars deployed in different offshore wind farms at various distances from the Dutch coast (Figure 1), we can now get a more complete picture of bird migration directions in the region and infer the small-scale migration routes.

Besides seasonal differences, the distribution of migration directions and speeds may vary within a migration season, reflecting the passage of migratory populations with different traits (e.g. flight speeds), physiological constraints, origins and destinations, which use varying migration strategies to adapt to changing weather conditions (Packmor et al. 2020). For example, theory and data suggest that early arrival at the breeding grounds is important for outcompeting conspecifics for resources and territory (Kokko 1999, Newton 2008). Therefore, due to shorter journeys they need to perform, short-distance migrants tend to pass earlier in the season in spring, but later in the season in autumn than long-distance migrants (Nilsson et al. 2014), which could result in observations of varying airspeeds and directions throughout the season. In addition, within-night changes in direction and speed may emerge due to immediate responses to local weather conditions or to coastlines. Birds reaching coastal areas may alter their migration directions to avoid being over water during daytime (van Dobben 1953, Bruderer and Liechti 1998, Fortin et al. 1999). This might cause differences in bird behaviour further away from and closer to the coast, thus flight speeds and directions may differ at different distances from the coast.

Spatio-temporal variation in migration speeds and directions can have implications for wind energy over the North Sea. Currently, predictive models used for wind turbine curtailments to reduce collision risk for migratory birds during pulses of intense migration are based on input from a single radar location (Bradarić et al. 2024a). However, it is unclear how representative these observed patterns are of other locations in the North Sea region and whether the predictive model used would benefit from different input variables (e.g. average wind assistance calculated from seasonal directions) at different locations. A regional perspective of migration patterns is essential for the specific tailoring of mitigation measures. We expect that most birds will fly perpendicular to the coast in spring, and along the coast in autumn (Kemp et al. 2012), and that we will observe stronger within-night directional shifts at the radar locations closer to the coast (e.g. birds preparing to land at the end of the night might change directions as a reaction to the nearby coast) (van Dobben 1953, Bruderer and Liechti 1998, Fortin et al. 1999). We expect to see higher migratory speeds in spring than in autumn, and to observe a seasonal shift in the airspeed distribution, reflecting the passage of different species.

Here, we compare seasonal and nightly directions and speeds across a small network of offshore bird tracking radars to reveal small-scale migration axes in the North Sea basin and explore whether they exhibit any differences between seasons and radar locations. We test how airspeeds differ between the radar locations on a seasonal and nightly level, looking for patterns that would suggest a passage of different bird groups (e.g. short- and long-distance migrants). This aims to elucidate the extent to which the North Sea induces variation in migratory pathways across its expanse.

Materials and methods

Study location, period and radar system

The data for this study was collected in the spring (February 15 – May 31) and autumn (August 15 – November 30) migration seasons of 2022 - 2024 by tracking radars (Robin Radar 3D fix, Robin Radar Systems BV, the Hague, Netherlands) located at six different offshore locations positioned at varying distances from the coast: Gemini, k14, Luchterduinen, hkza (HKZ alpha), Ørsted and Borssele (BSA). Even though some of the radars have been operational for a longer period, we have used the indicated years in order to minimize the amount of variation between radar locations that would potentially arise from interannual differences in migration patterns. Details on the radars' positions and data used in this study per radar are available in Table 1.

The radar system consists of two antennae (Furuno Marine) that rotate at 45 rpm in different planes. A vertically-rotating X-band antenna with the power of 25 kW and a beam width of 20° collects information about bird numbers and altitudes, while a horizontally-rotating S-band antenna with a power of 60 kW and a beam width of 12.5° collects information on numbers, directions and speeds of targets. Using proprietary software, the system detects moving targets and, based on echo characteristics (e.g. ground speed, direction, radar-cross section), distinguishes between bird and non-bird targets. All bird targets that were available in at least eight consecutive rotations in the horizontal antenna or five consecutive rotations in the vertical antenna were joined in tracks and stored in a centralised database. Here, we only used the data collected by the horizontal antenna. The primary reason for this choice is that the speed and direction of tracked targets are only available from the horizontal radar. The more information-rich dataset has also facilitated the development and implementation of established post-processing steps (Bradarić et al. 2024a, van

Erp et al 2024). In addition, the horizontal data measures migration of small birds (e.g. passerines) with good detection capacity up to 300 m, an altitude range where most of nocturnal migration occurs in the region (Kemp et al. 2013, Fijn et al. 2015, Bradarić et al. 2024b, Hoekstra et al. 2024). As we are interested in nocturnal migration, we only used data collected by the six radars between civil sunset and sunrise.

Table 1. Overview of radars, their positions and data used in this study, in descending order from north to south.

Radar	Lat (DD)	Long (DD)	Altitude asl (m)	~Straight-line distance from the closest Dutch coast (km)	Spring data used in the study (years)	Autumn data used in the study (years)
Gemini	54.03	6.04	32.0	80.0	2022-2024	2022-2024
K14	53.26	3.62	32.9	85.0	2024	2023-2024
Luchterduinen	52.42	4.18	22.8	25.0	2022-2024	2022-2024
HKZA	52.31	4.04	41.0	28.0	2023-2024	2023-2024
Ørsted	51.78	3.03	17.0	51.0	2023-2024	2023-2024
Borssele	51.69	3.05	48.6	45.0	2022-2024	2022-2024

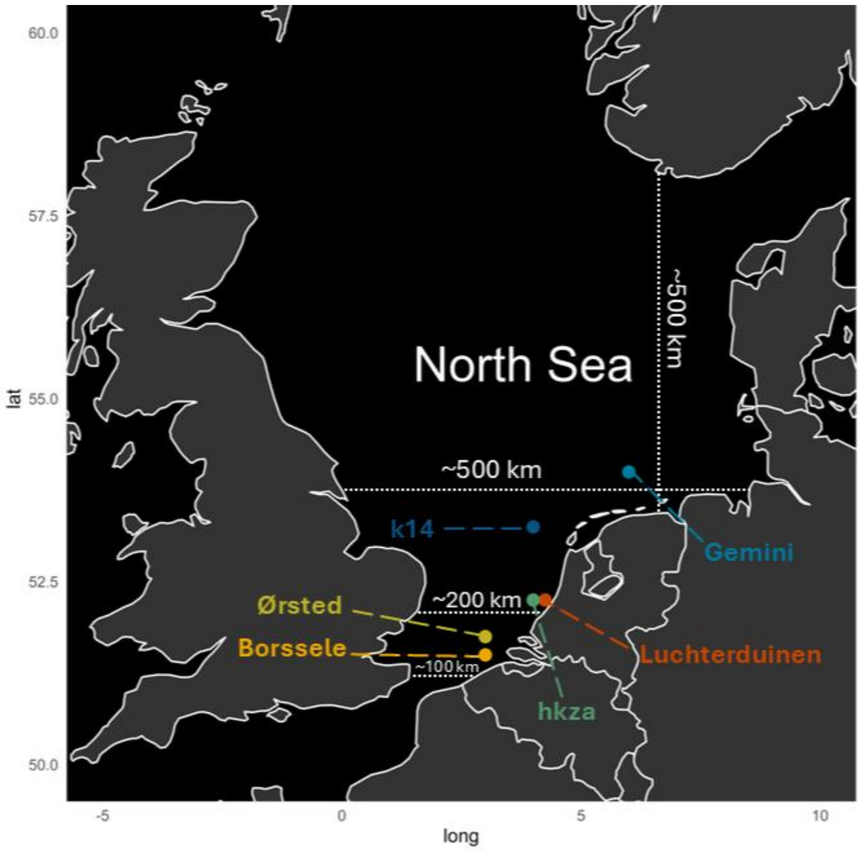

Figure 1. A map of the North Sea and the surrounding countries. Dots represent radar locations in Gemini (blue), k14 (dark blue), Luchterduinen (red), hkza (green), Ørsted (yellow) and Borssele (orange). Dotted white lines indicate approximate distances between different coasts around the North Sea, showing the straight-line crossing distances for migratory birds.

Radar data post-processing

While the proprietary Robin Radar software detected and filtered various types of clutter (e.g., rain, waves) based on echo characteristics before data entry, some clutter with similar echo properties was still mistakenly classified as bird tracks. To discard erroneous tracks and get the most reliable data, we applied post-processing steps with which we further filtered the data based on the tracks' distance from the radar, their straightness, airspeed and moments during which the clutter filter activity was high (expressed as a percentage of radar image in which the clutter is active), as described in Bradarić et al. 2024a and van Erp et al. 2024. Since radars were positioned at different locations and heights within the North Sea (Table 1), resulting in different sensitivities to various types of environmental clutter, some of the thresholds used in the filtering procedure needed to be adjusted per radar (van Erp et al. 2024). Following the methodology of defining the high clutter filter activity threshold described in van Erp et al. 2024, we excluded all minutes of data in which clutter filter activity occurred in more than 21% of the radar image in Gemini, 15% in k14, 30% in Luchterduinen, 19% in hkza, 16% in Ørsted and 20% in Borssele. An additional filtering step with a combination of strict filters for straightness and track length, not described in the previous studies, was introduced to further remove the tracks which most likely originate from static clutter (e.g. turbines). The filtering step was developed by visually inspecting the data and defining two categories of "bird tracks" and "turbine tracks", based on the consistent direction of their movement. A decision tree model was then run on the two categories to explore which track properties explain the two defined categories the best. Finally, based on the results of the model, all tracks that were shorter than 577.5 m and had a straightness lower than 0.95 were removed. More information on the filtering step introduced to further remove the static clutter is provided in S1.

Weather data

We obtained gridded weather data from the European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 reanalysis dataset from a 100 m single-level (Hersbach et al. 2020). These data are available per hour and on a 0.25° (ca 30 km) spatial grid. We extracted wind conditions (m/s), mean sea level pressure (hPa) and precipitation (mm) for grid cells with centroids closest to our respective radar locations: 54.00 N 6.00 E for Gemini, 53.25 N 4.00 E for k14, 52.25 N 4.25 E for Luchterduinen, 52.25 N 4.00 E for hkza, 51.75 N 3.00 E for Ørsted and 51.50 N 3.00 E for Borssele. Wind conditions in this data are expressed by the u-component, which describes the wind in the west-east direction (wind blowing to the east is positive), and the v-component, which describes the wind in the south-north direction (wind blowing to the north is positive). From this data, we calculated hourly wind direction and speed using the rWind package (Fernández-López and Schliep 2018) in R (R Core Team 2020).

Migration directions and speeds

Preferred migration direction (heading) and airspeed were calculated for each track from track direction and ground speed as measured by the radar, and wind direction and speed obtained from the ERA5 single-level dataset from 100 m (Hersbach et al. 2020) using vector summation (Shamoun-Baranes et al. 2007). Multi-year seasonal circular mean and mean resultant vector (r) of the heading and track direction, and seasonal mean ± standard deviation (SD) of airspeed and ground speed were calculated for each radar location. Mean resultant vector length (r) estimates the dispersion of directional data around the mean and ranges between 0 and 1, where 1 represents no dispersion in the data (Jammalamadaka and SenGupta 2001). To determine if directions vary within each season across radar sites, the Rayleigh test (designed for Von Mised, unimodal distribution) was performed to assess circular data uniformity across locations in different seasons, and a t-test was used to compare seasonal means of airspeeds and groundspeeds. Cohen's d (Cohen 1988) was calculated to estimate the effect size, and categories of Cohen's d were defined as: 0 - 0.2 (small), 0.2 – 0.5 (medium), 0.5 – 0.8 (large) and >0.8 (very large). Airspeeds were categorised and visualised per season and radar location in bins of 5 m/s, starting from five to 30.

Seasonal and within-night preferred migration direction and airspeeds

To assess if there are changes in migration directions and speeds throughout season and within night that might originate from different bird species or differences in migration departure and arrival locations, we calculated average directions and speeds per hour and visualized the frequency of hours with respective directions and speeds in heatmaps per day of year and hour after sunset.

Results

Migration directions and speeds

All headings and track directions, except those in spring at the k14 location, are non-uniformly distributed ($p<0.0001$, respective resultant vector lengths in Table 2). At all locations, mean migration headings are towards east and east-south-east in spring and south-west and south-west-south in autumn (Table 2, Figure 2). Track directions at all locations are towards north-east and east in spring, and west-south-west in autumn (Table 2), indicating the influence of southwesterly winds in the region.

The distributions of headings (Figure 2) show that the bulk of migratory movement in spring consists of birds flying towards the east, which likely cross the North Sea from various locations in the UK. At all locations, there is some movement towards the northeast, especially at the two most northern locations. In autumn, southern locations have broader distribution of headings, with quite many birds flying towards west (Figure 2), indicative of the North Sea crossing towards UK, but also birds taking shortcuts to northern France.

In both seasons, airspeeds were significantly different across radar locations, but with generally low (0 – 0.2) and medium (0.2-0.5) effect sizes (Figure S1). Significant differences with large effect sizes were observed between Gemini and Ørsted and Gemini and Luchterduinen (Figure S1). The lowest mean airspeed is observed at Ørsted in autumn, and the highest one in Gemini, also in autumn (Table 2). Groundspeeds in both seasons are also significantly different across all locations, but again with mostly low and medium effect sizes (Figure S2). A very large effect size is observed between Gemini and Ørsted in autumn, and large effect sizes are observed between Gemini and k14, Gemini and Luchterduinen and Gemini and Borssele (Figure S2).

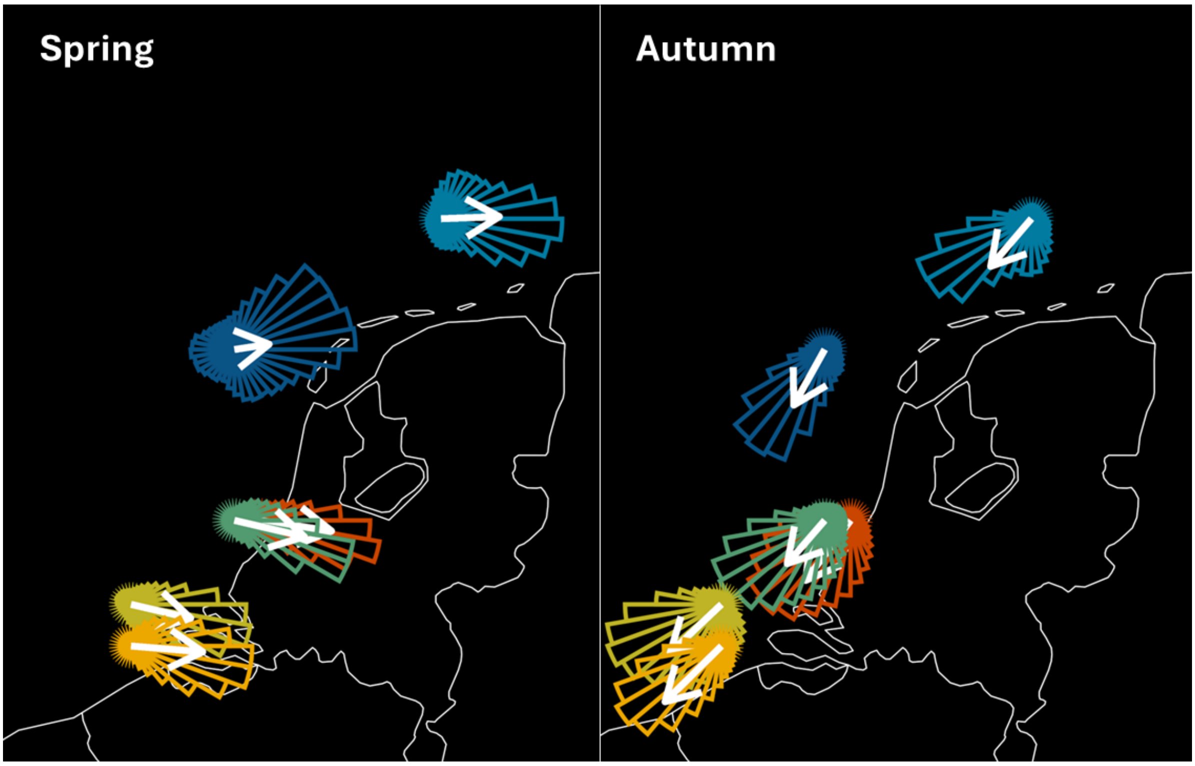

Figure 2. Overview of seasonal preferred migration directions (headings) of the Dutch coast in spring and autumn. White arrows indicate multi-year seasonal mean directions, with the length of the arrow indicating the level of directional dispersion around the mean and corresponding to the mean resultant length (r). Note that the size of the rose plots is scaled per radar and is not indicative of the radar range. All measurements were taken between one and two km from the radar, and all the tracks are observed entirely offshore.

In spring, the most numerous airspeed category was between 10 and 15 m/s in Gemini, k14 and Ørsted, while at Luchterduinen, hkza and Borssele, the most numerous one was the one with airspeeds between 15 and 20 m/s (Figure 3), indicating larger and faster birds that might fly across these locations, generally closer to the coast (Table 1). In autumn, at all locations, the most numerous airspeed category was between 10 and 15 m/s (Figure 3).

Table 2. Overview of means and resultant vector lengths (r) for headings and track directions, as well as means and standard deviations (SD) for airspeeds and groundspeeds across radar locations in spring and autumn.

Radar	Season	# Hours	# Tracks	Heading (degrees)		Airspeed (m/s)		Track direction (degrees)		Groundspeed (m/s)	
				Mean	r	Mean	SD	Mean	r	Mean	SD
Gemini	Spring	1674	267310	87.9	0.5	16.1	4.9	75.6	0.5	17.1	4.9
	Autumn	1531	180338	220.5	0.5	16.3	5.2	228.7	0.5	16.4	5.1
k14	Spring	579	45134	81.3	0.3	14.2	4.1	68.3	0.3	15.3	4.7
	Autumn	1358	171721	209.1	0.5	14.5	3.6	213.2	0.5	13.6	3.4
Luchterduinen	Spring	2004	401246	98.5	0.6	15.0	3.8	81.8	0.6	15.9	4.9
	Autumn	2346	851588	216.8	0.6	14.2	3.3	227.8	0.6	13.8	3.7
hkza	Spring	922	126020	103.07	0.6	15.1	3.8	85.7	0.6	16.9	5.7
	Autumn	1251	540255	220.9	0.5	15.4	4.5	235.1	0.5	15.2	4.6
Ørsted	Spring	871	121450	103.1	0.5	14.1	3.4	78.7	0.6	16.5	5.0
	Autumn	1419	366799	226.6	0.6	13.8	3.0	240.0	0.6	13.2	3.3
Borssele	Spring	1842	298885	94.6	0.6	15.9	3.8	84.9	0.6	15.7	4.4
	Autumn	2312	536209	225.3	0.6	14.7	3.6	236.9	0.6	14.1	3.7

Seasonal and within-night preferred migration direction and airspeeds

Headings are predominantly to the east across the first part of the spring season, with a slight shift to the northeast in the second part of the season at most radar locations (Figure 4a). In autumn, movements towards west and southwest are quite consistent throughout the season, but with the slight predominance of movements towards south-west in the first part of the season and towards west in the second part of the season (Figure 4a). In both seasons, there is also a shift in direction within the night (Figure 4b). At the beginning of the night in spring, there is a broader distribution of directions at all radar locations (Figure 4b). Broad directional distribution is present throughout the rest of the night at Gemini and k14, while other radars show a visible concentration of directions to the east and north-east (Figure 4b). In autumn, directions are more concentrated than in spring, and there is a general shift of directions from west in the beginning of the night to south-west at the end of the night across radar locations (Figure 4b). Seasonal and within-night airspeeds are consistent across locations, with no significant shifts observed (Figure 5).

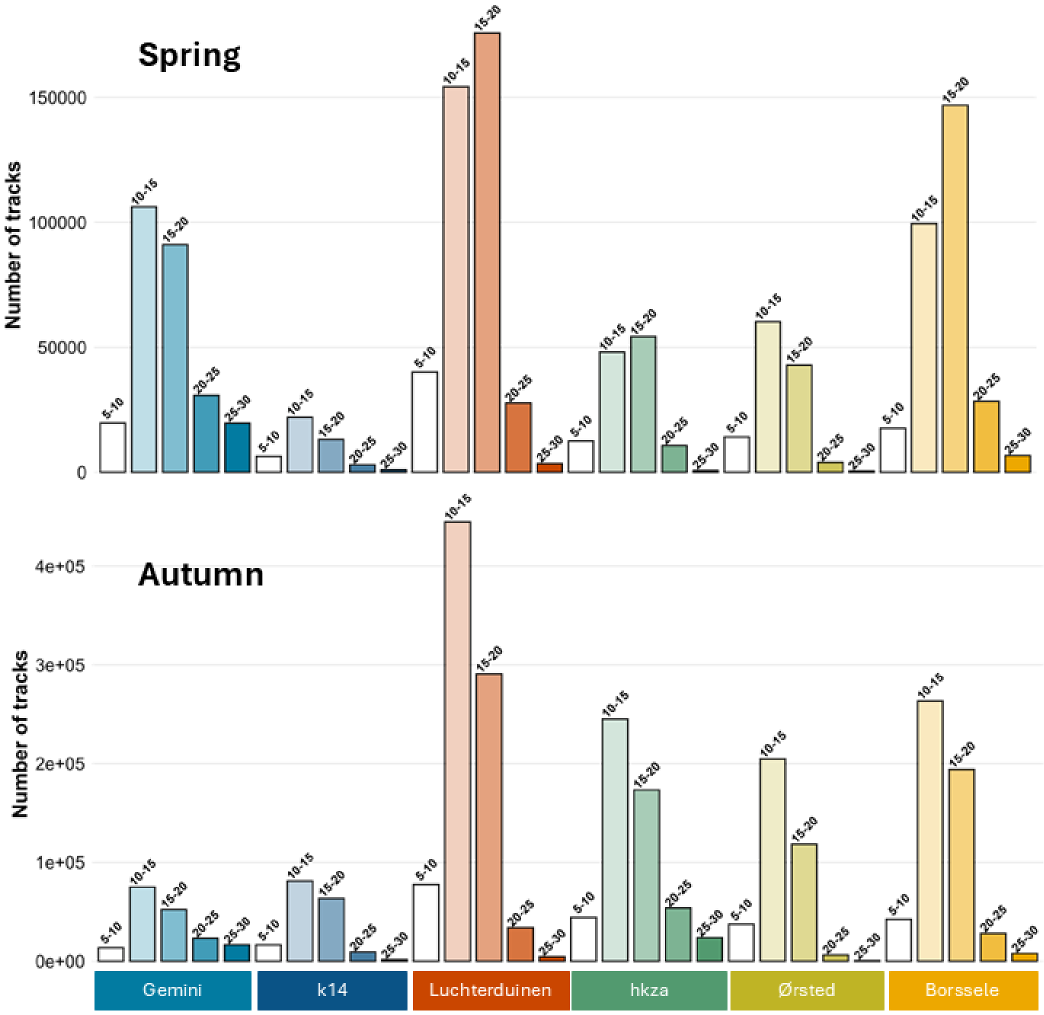

Figure 3. Multi-year overview of the distribution of air speeds per radar location. The x-axis shows airspeeds in 5 m/s bins per radar location. The y-axis provides the number of tracks. Note that the y-axis scale is different in different seasons. Tracks with airspeeds lower than 5 m/s are excluded from the analysis as they are highly unlikely to be birds.

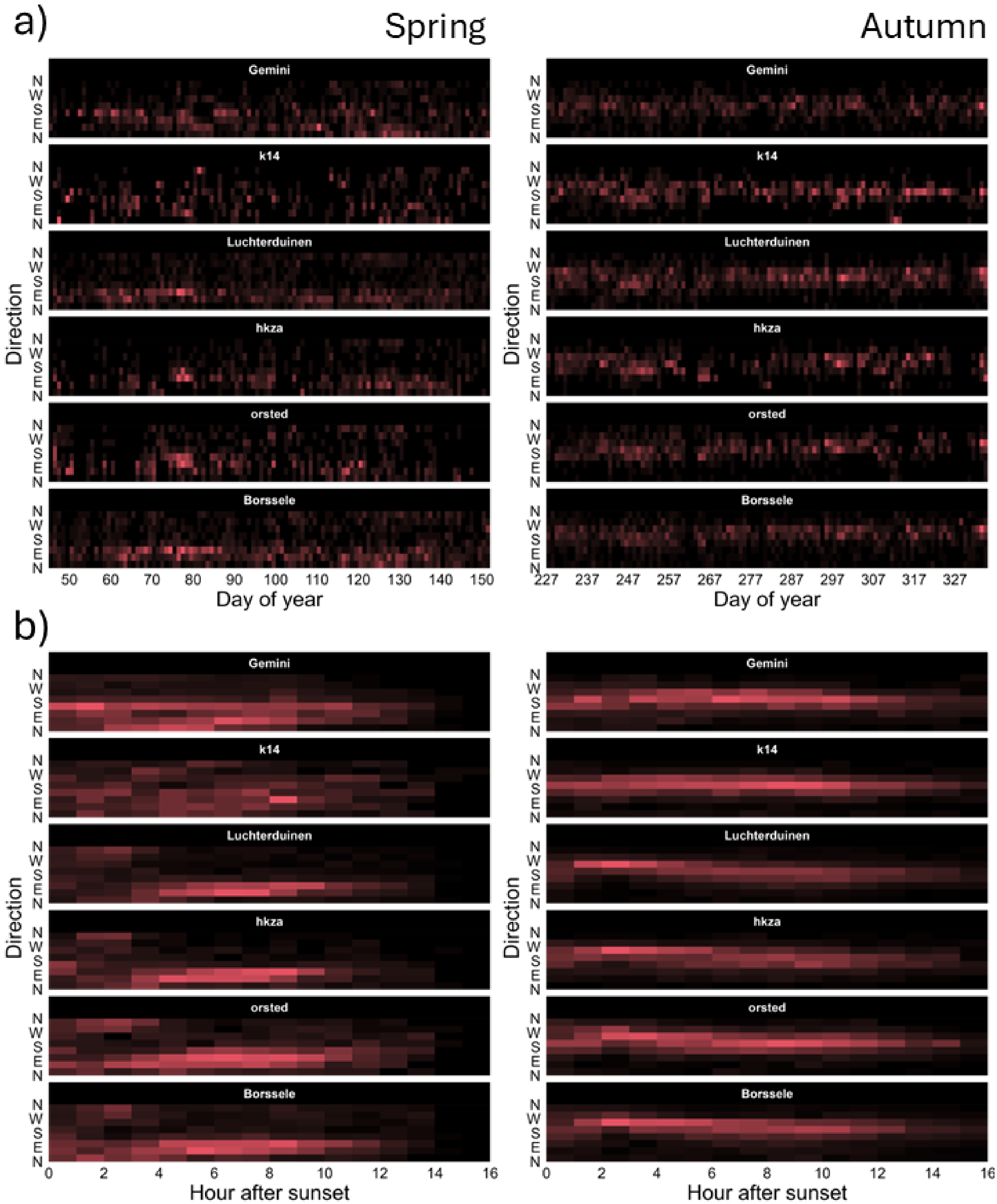

Figure 4. Hourly frequency of seasonal (a) and within-night (b) headings (degrees) scaled per radar location. Note that the horizontal resolution of bins is different in panels a) and b). The vertical resolution is the same in both panels and represents directions in degrees from 0 (indicating north) to 360 degrees, in bins of 45 degrees. Black indicates no measurements, while different hues of red indicate different frequency values (brighter hues indicate higher frequencies) where data is available.

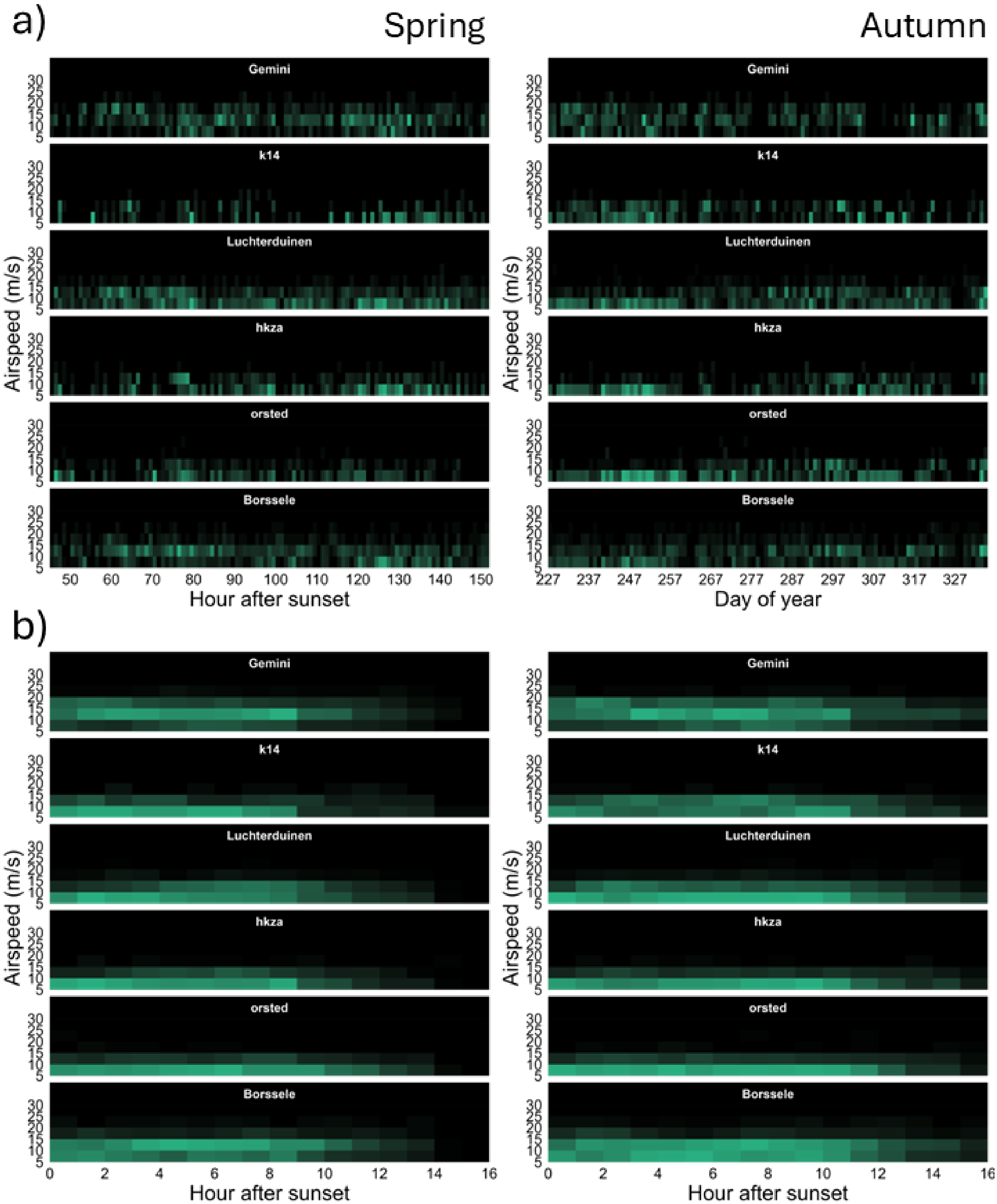

Figure 5. Hourly frequency of seasonal (a) and within-night (b) airspeeds (m/s) scaled per radar location. Note that the bin sizes differ in panels a) and b). Black indicates no measurements, while hues of green indicate different frequency values (brighter hues indicate higher frequencies) where data is available.

Discussion

Migration directions and speeds across the North Sea basin exhibited a high level of homogeneity, with smaller differences at some of the locations (Table 2). As hypothesized, in spring, birds mainly flew perpendicular to the Dutch coast at all radar locations, generally flying in eastern or east-southeastern direction (Figure 2, Table 2). This suggests that the predominant migratory movement in spring across radar locations is indicative of the arrival of migrants from the UK to the Dutch coast, corroborating the results of previous studies (Bradarić et al. 2020b). In autumn, directions were generally towards the southwest, with birds mainly following the shape of the Dutch coast (Figure 2, Table 2). Even though speeds showed a high level of homogeneity across seasons and radar locations, some smaller pairwise differences were observed (Table 2, Figure 3).

While early studies suggested two main migration axes in the region, one oriented northeast–southwest and the other west–east (Lack 1959, Shamoun-Baranes and van Gasteren 2011), numerous smaller-scale routes across the North Sea basin were suggested (Lensink et al. 1999). Our results, by contrast, show a relatively homogeneous distribution of migration directions across radar locations in both spring and autumn, with one of the two main axes dominating in each season. This aligns with the findings in Bradarić et al. (2020), where the occurrence of loop migration in the region was suggested based on observed seasonal differences in migration headings. The concept was originally proposed by Lack (1959), who hypothesized that in autumn, birds aiming to reach the UK may follow the continental coastline until reaching the shortest sea-crossing to avoid adverse winds. In spring, these birds may instead undertake a more direct crossing from the UK, aided by generally more favourable wind conditions. Bradarić et al. 2020 later revisited this theory but emphasized the need for data from multiple sites to validate it more robustly. Our findings provide a broader spatial context, with directional distributions at southern radar locations in autumn showing a stronger westerly component than those further north (Figure 2). This supports the idea that birds heading toward the UK in autumn often take advantage of narrower sea crossings available at these sites. At the same time, other migrants likely follow more southerly trajectories, potentially crossing at the Strait of Dover.

In autumn, predominant directions change slightly throughout the season, being more concentrated around SW directions at the beginning and slightly shifting towards west-southwest movement in the second part of the season (Figure 4a). This could indicate a shift in long- and short-distance migrants' passage, as shown in other studies (Nilsson et al. 2014). On the contrary, spring direction stays relatively homogeneous throughout the season (Figure 4a). While we expected the change in seasonal directions to be followed by the change in the seasonal airspeed, airspeeds remain consistent throughout the season (Figure 5a). However, their distribution differs slightly across radar locations, with Borssele and Gemini observing generally higher airspeeds in both seasons, which could indicate the occurrence of larger birds at these locations (Figure 5a).

Quite a striking difference was observed in within-night directions across locations and in both seasons (Figure 4b). In spring, directions are more dispersed at the beginning of the night, becoming more concentrated around eastward directions between four and ten hours after sunset (Figure 4b). If the majority of birds observed in spring depart from the UK, they need a few hours before reaching the radar locations. The more dispersed directions earlier in the night may indicate a higher proportion of local movements. In autumn, directions visibly shift from those towards the west at the beginning of the night to those towards the southwest as the night progresses (Figure 4b). This is not striking at the two northernmost locations, which suggests that this pattern might be originating from birds that initially fly out towards sea when departing from the Dutch coast nearby, after which they re-route and fly following the coast throughout the rest of the night, as observed in areas where birds experience headwinds (Rüppel et al. 2023). The North Sea has generally adverse wind conditions for the majority of migrants throughout the season (Kemp et al. 2010), and this can be reflected in our observation of within-night directions. Within-night airspeeds did not show any visible change (Figure 5b). While airspeeds did not show that much variation across locations and seasons (Table 2, Figure 3, Figure S3.1), the Gemini location seems to have generally higher airspeeds, indicating slightly different species composition than other radars (Table 2).

Across the North Sea, migration directions and speeds seem to be relatively homogeneous, with small differences exhibited between specific location pairs. The most striking finding is the difference in the predominant axis of migration between spring and autumn, which likely supports the previously suggested notion that loop migration occurs in the region. Techniques such as acoustic monitoring may be helpful in providing additional information on species composition in the future. It is important to note that, while we offer a first insight into bird migration directions and speeds across multiple radar locations and seasons, the portion of migration we are capturing with our radars is limited relative to the size of the North Sea basin. All radars have a limited detection range of several kilometres, and it is possible that different patterns are observed at other locations or at higher altitudes. This emphasizes the need for expanding the offshore radar network in order to have a more detailed overview of what happens in different parts of the North Sea.

Implications for existing conservation efforts

In addition to providing a more comprehensive picture of offshore migration axes and speeds in the region, our results could offer some insight that might benefit conservation efforts aimed at reducing collision risk with offshore wind turbines for nocturnal migrants (Bradarić et al. 2024a). If future efforts are more tailored to protecting specific bird groups, our results could offer some insight into bird group differences across the North Sea locations. Airspeed distributions at the Gemini location might indicate slightly different species composition of nocturnal migrants, but this would need to be further explored, potentially with additional sensors.

Furthermore, although general directions seem to be quite similar across the region, there are slight differences in the overall directional distributions and slight differences observed across seasons and within nights. The current predictive model uses wind assistance as one of the variables to predict mass migration across the North Sea (Bradarić et al. 2024a). This variable is calculated from wind speed and direction, as well as the general airspeed and seasonal migration direction. If local adjustments or models are to be made, wind assistance could be calculated at these locations using the observed values. However, as they are pretty similar to directions and airspeeds already used, this will likely make only a negligible difference in the model output.

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Supplementary information

S1 Filtering steps

After performing the first five filtering steps (Table S1.1) on the data collected at the Gemini radar location, unusual directions towards south and south-east were observed, mainly in spring 2023 (Figure S1.1). As reported in earlier studies, the occurrence of this movement was observed throughout the year at the Gemini location, suggesting its non-biological origin (Van Erp and Shamoun-Baranes 2024). Even though tracks with these directions are prevalent throughout the year, their visibility was more pronounced in spring 2023. Little data was generally collected during this season, with only a few limited moments of intense migration, allowing the dominance of tracks with SE movement.

Table S1.1 Filtering steps in the order in which they were performed according to van Erp et al, 2024, and Bradarić et al, 2024b, with the purpose of each filtering step on the radar data.

Filtering step	Purpose of the filtering step
Remove the tracks that fall into the category of those with the lowest 10% displacement over time	Removes static tracks (appear on the radar screen for a long time, but stay in place)
Remove tracks whose centroids are closer than 1000 m and further than 2000 m away from the radar	Keeps only tracks that fall into the optimal radar detection range, not considering areas close to the radar and far away from the radar that are prone to clutter activity and target loss
Remove tracks with straightness < 0.7	Migration tracks appear long and straight on the radar. This radar step makes sure that everything that is not a migratory bird gets removed
Remove tracks with airspeed < 5 m/s	Removes slow targets and insects
Remove minutes of high-clutter filter activity*	Makes sure to set unreliable moments in which radar collected a lot of clutter from the data to avoid erroneous inclusion of clutter, such as sea waves, into the analysis
Remove tracks with straight-line length < 577.5 & straightness < 0.95	Makes sure to remove relatively short and wiggly tracks that were not removed by the above criteria and are likely static clutter, discovered through visual inspection of the Gemini radar data.

*The filtering thresholds differ per radar location, as indicated in the main text

After the visual inspection, a division was made based on directions between tracks, with directions towards SE (track directions between 100 and 200 degrees) and the rest of the tracks (all the other directions). The visual difference was immediately visible when these tracks were plotted in a horizontal plane. SE tracks were visibly shorter and more wiggly (Figure S1.2) than the rest of the tracks, which were longer and straighter (Figure S1.3), generally fitting more to the appearance of migration tracks on the tracking radars. After looking into SE and other tracks at other radar locations, a similar pattern was observed.

Based on this exploration, two categories of “good tracks” and “bad tracks” were made for multi-year datasets (2022-2023) for spring and autumn migration seasons collected at Gemini, Luchterduinen and Borssele radar locations. After visual inspections of distributions of a number of track properties for both these categories, none clearly delineated the two. Therefore, using a “tree” package in R (Ripley, 2024), a decision tree model was run on the two categories to explore which track properties best explain the two defined categories. Before the model was run, due to class imbalance between good and bad tracks, data sampling was performed using the ROSE package (Lunardon et al., 2014). The sampling method balanced the number of samples in each class ("good" and "bad") within the training set, ensuring that the model would not be biased toward the majority class.

The model was trained on the sampled training dataset using the tree() function, with the response variable type (levels: "good", "bad"). A minimum node size of five (minsize = 5) was specified to prevent overfitting on small sample splits. The decision tree output (Figure S1.4) provided an interpretable set of rules used by the model to classify track quality. The root node and subsequent splits indicate which features best separate “good” from “bad” tracks, based on purity maximization. The first and most significant split in the tree was based on the feature rho_diff, with a threshold of 577.491. Tracks with a rho_diff below this value were routed down the left branch of the tree, while those above were classified as "good" regardless of other variables. Further branching of the left path showed the importance of straightness: if straightness was below 0.9538, the tree continued to consider other variables. Based on these results, all tracks that were shorter than 577.5 m while at the same time having a straightness lower than 0.95 were removed.

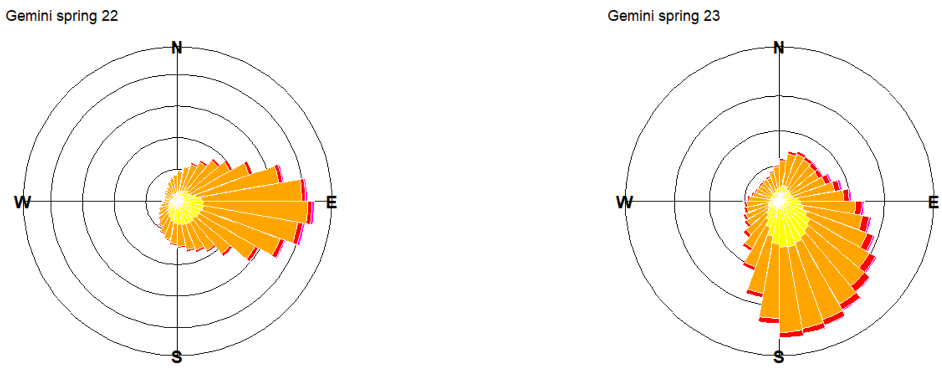

Figure S1.1 Overview of track direction at the Gemini radar locations in spring seasons of 2022 and 2023.

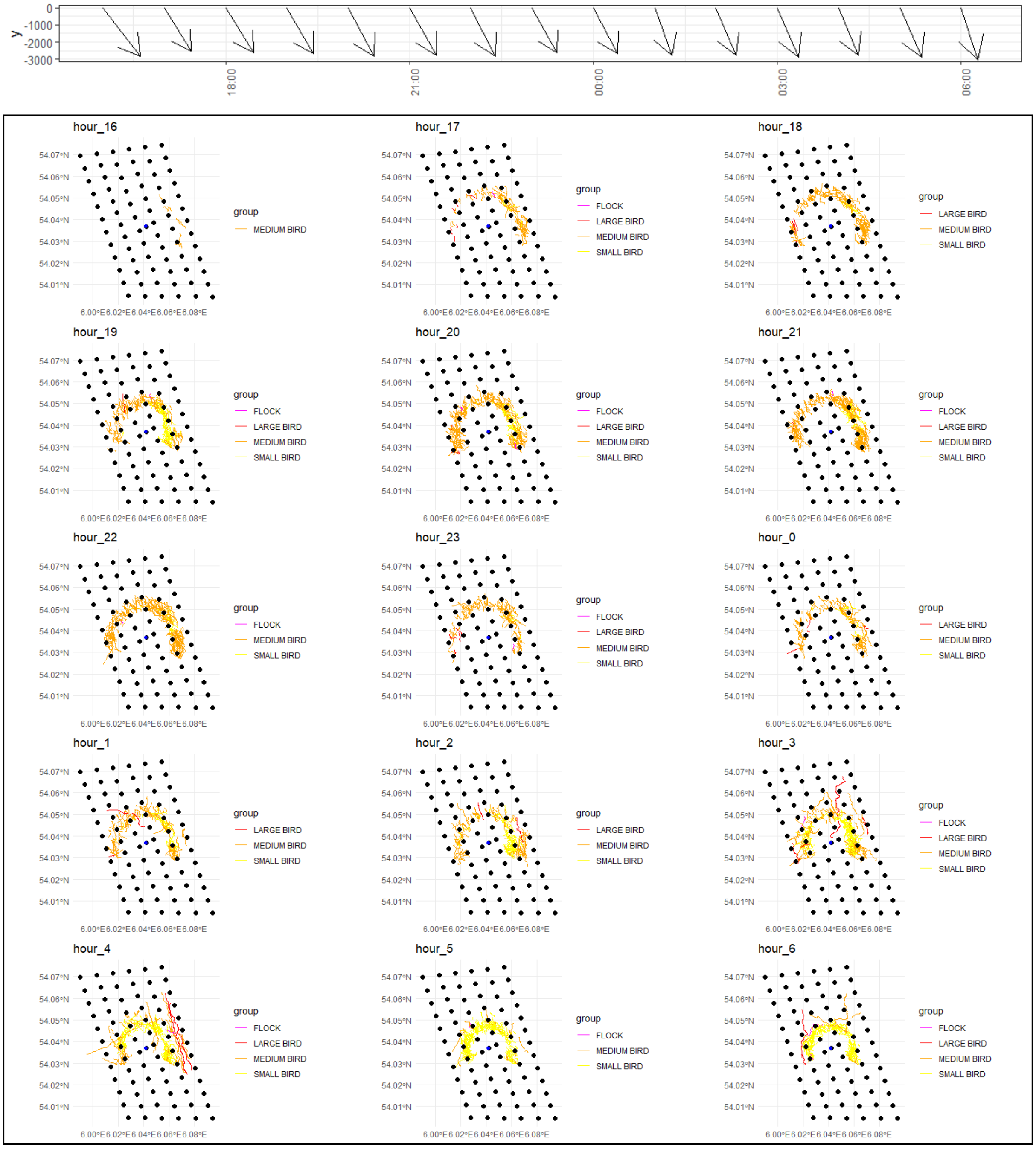

Figure S1.2 An example of what appears to be a migration night with most tracks having the average hourly track direction towards SE (upper panel) and their representation in the horizontal plane amongst wind turbines (lower panel). In the lower panel, tracks in the horizontal plane are visibly shorter and wigglier than those presented in Figure S1.3, which represent the real migration movement.

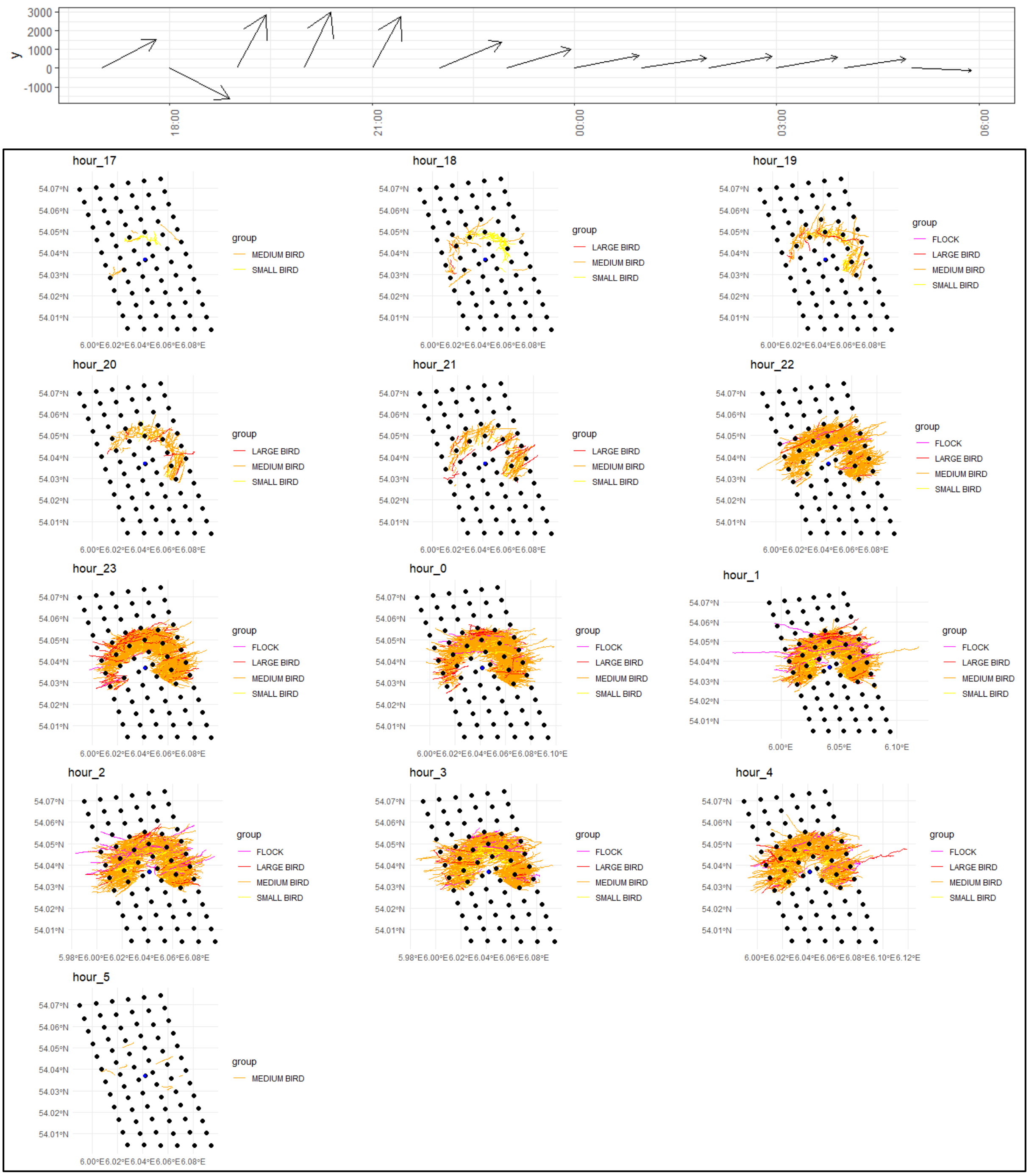

Figure S1.3 An example of a real migration night with most tracks having the average hourly track direction towards NE and E (upper panel) and their representation in the horizontal plane amongst wind turbines (lower panel). In the lower panel, tracks in the horizontal plane are visibly longer and straighter than those presented in Figure S1.2, which mainly represent clutter.

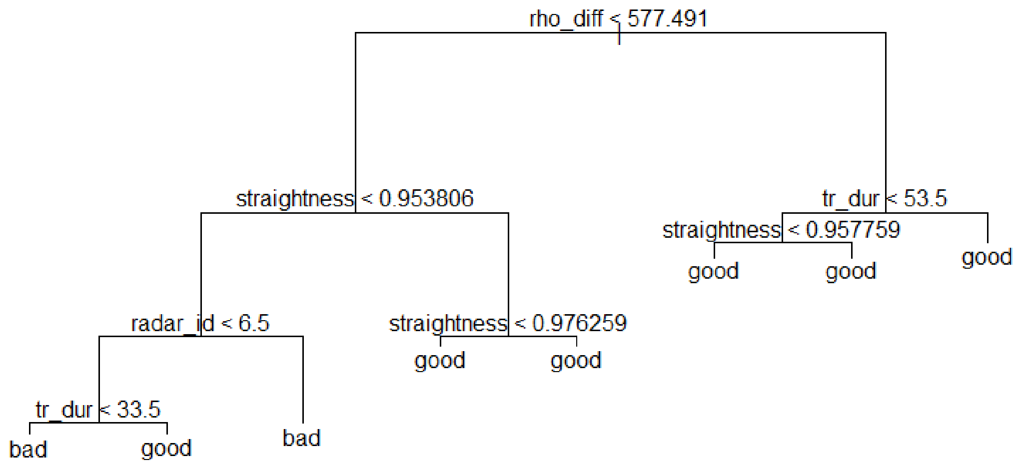

Figure S1.4 Output of the decision tree.

S2 Pairwise distances of radar locations

Table S2.1 Approximate straight-line distance between pairs of radar locations. Distances were approximated using Google Earth Pro (7.3.6.10201).

	Gemini	**k14**	**Luchterduinen**	**hkza**	**Ørsted**	**Borssele**
Gemini	-					
k14	182	-				
Luchterduinen	218	102	-			
hkza	233	110	16	-		
Ørsted	322	170	107	91	-	
Borssele	330	180	112	96	10	-

S3 Pairwise results of t-test and Cohen's d

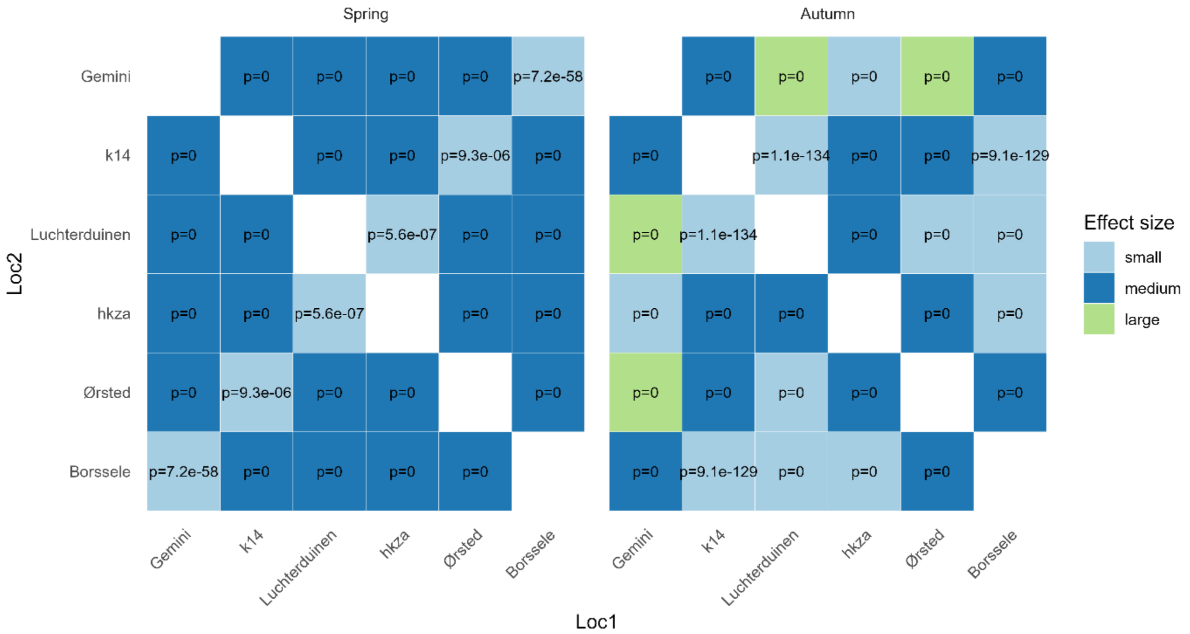

Figure S3.1. Results of the t-test for airspeed comparison between location pairs. P-values can be seen in the heatmaps, and different colours indicate the effect size (Cohen's d).

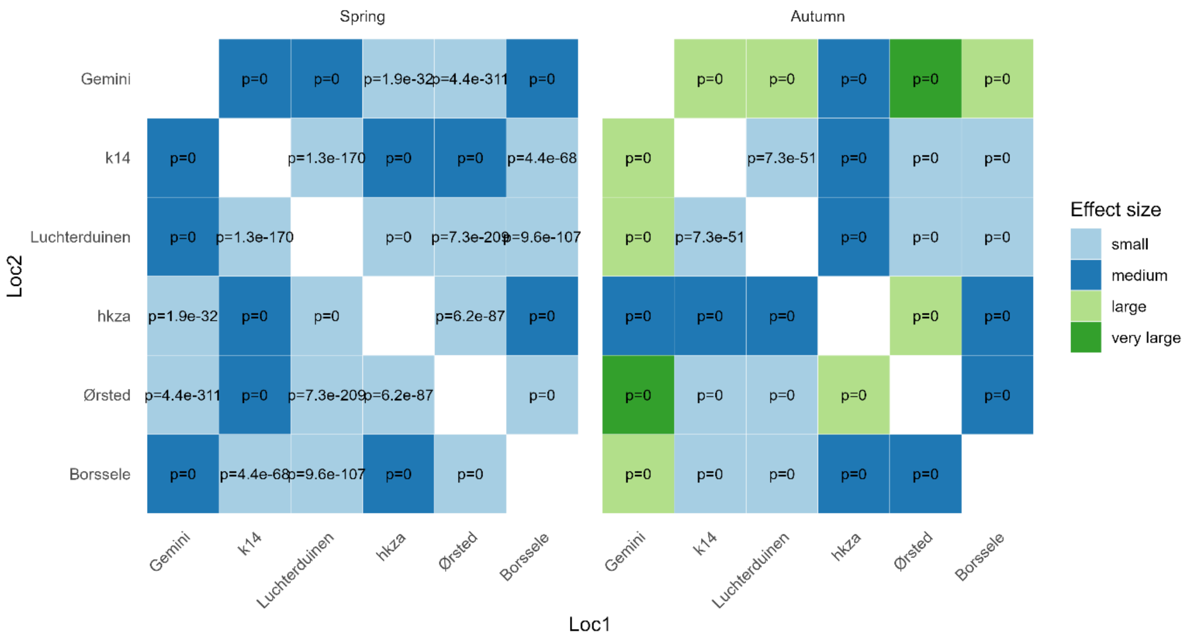

Figure S3.2. Results of the t-test for groundspeed comparison between location pairs. P-values can be seen in the heatmaps, and different colours indicate the effect size (Cohen's d).

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