ProBIRD report

Patterns of nocturnal bird migration in the German North and Baltic Seas

Analysis of radar data from offshore wind farms in the German EEZ

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1 SUMMARY

With the advent of offshore wind facilities in the German Exclusive Economic Zone (EEZ) nocturnal bird migration in these areas has increasingly come into focus. Nocturnally migrating passerines are often considered to be particularly vulnerable to collisions with offshore wind turbines. Detailed information on the spatial and temporal patterns of nocturnal migration is of pivotal importance to assess potential impacts of offshore wind farms (OWFs) on these birds especially since direct data on bird collisions at offshore turbines are still lacking.

Radar devices are widely used to quantify nocturnal bird movements. This method is also an integral part of the migration monitoring programs required for environmental impact assessments and effect studies during construction and operation of German OWFs. Here, we used data from ten offshore locations in the North Sea and two locations in the Baltic Sea collected over a time period of nine years (2008 – 2016) to determine spatial and temporal patterns of nocturnal bird migration in the German EEZ.

Migration intensities (MTRs) showed high day-to-day, inter-annual and between-site variation. There was little evidence that MTRs varied to any extent between the pre- and post-construction periods. However, most radar sites were situated up to 3 km outside the wind farm perimeters and hence might have been too far away to detect potential responses of the birds.

Migration intensities peaked in April and October. The seasonal pattern in fall varied between sites in the North and Baltic Sea. In the Baltic, MTRs were highest in August and September, but reached their maximum in the North Sea in October, presumably indicating differences in the main migratory species involved in the two regions.

With a mean correlation coefficient *rho* of 0.48 the spatial correlation of migration intensities across all study years and locations was relatively high. Correlation strength decreased only slightly with increasing distance between sites in the North Sea but was substantially higher within the North Sea than between the North and Baltic Sea. This suggests that short-term migration patterns were largely independent between the two regions. Similarly, events of mass migration, defined as migration intensities >500 MTR, rarely occurred simultaneously at sites in the North and Baltic Sea.

Overall, migration intensities in the Baltic were about 10% higher than in the North Sea, yet this pattern varied depending on the altitude range and time period considered. Within the North Sea our results supported the notion of a gradient of migration intensities with distance to shore. MTRs were significantly lower at sites further offshore compared to sites closer to shore.

Radars recorded bird migration from sea level to 1000 m altitude. Within this range 35% of all flights were detected below 200 m altitude supporting a number of studies reporting a general prevalence of low flight heights of nocturnal migrants at sea. Flight heights differed between regions and seasons. In spring, mean flight height in the Baltic was significantly lower than in the North Sea while the opposite was true in fall. Additionally, at North Sea sites mean flight height was about 100 m higher in spring compared to fall which might be related to seasonal differences of synoptic wind conditions. Wind conditions may also account for the fact that flight height at North Sea sites decreased with increasing distance to shore, at least in fall.

We found that flight heights were positively related to migration intensities. In nights with high migration intensities flight height tended to be higher than in nights with low migration activity. This might be the consequence of an increase of both migration activity and flight altitude in response to favorable migration conditions. Furthermore, flight heights varied systematically within the course of the night. At the end of the night, birds flew on average 70 m lower than at its beginning. The reasons for this pattern remain speculative but may be related to an increasing proportion of birds preparing to land.

Migration intensities observed by radar and the number of flight call of nocturnal migrants, recorded simultaneously at the same sites, were positively correlated. Correlations were strongest in October and November when most of the migrating species, such as thrushes, are known to be vocally active.

MTRs showed a strong diurnal pattern. Migration intensities increased sharply shortly after sunset and peaked before midnight. MTRs decreased again in the second half of the night. Daytime migration intensity was highest within the first few hours after sunrise. The seasonal variation of this pattern in different parts of the North Sea was in accordance with the expectation that most nocturnal migrants commence migration from coastal areas around sunset.

Finally, we estimated the total number of radar signals (as a proxy for bird movements) passing the footprints of all 23 German OWFs that are currently operational or under construction each spring and fall at rotor height at 24 million. Despite several sources of uncertainty, this result suggests that bird movements at the scale of millions are to be expected at rotor height during the operational phase of offshore wind farms in the North and Baltic Sea.

2 INTRODUCTION

The majority of migratory birds, particularly passerines, migrate during the night (ALERSTAM 1990, 2009; BERTHOLD et al. 2003). In contrast to diurnal migrants which often concentrate along physical features of the landscape such as coastlines and which avoid crossing open water, movements of nocturnally migrating birds are usually spread over wide areas, a pattern called broad-front migration. On these movements nocturnal migrants regularly fly over large expanses of water like the North and Baltic Sea.

With the development of offshore wind farms (OWF) in the German Exclusive Economic Zone (EEZ) of the North and Baltic Sea, nocturnal migration in these areas has increasingly come into focus. The risk of collision of birds with wind turbines is generally regarded as one of the main potential impacts of offshore wind developments on wildlife.

Nocturnally migrating birds are often considered as specifically vulnerable to collision with wind turbines or other anthropogenic structures (LONGCORE et al. 2008, 2012). This risk is thought to be further increased by inclement weather (rain, fog, poor visibility) and the illumination of the structures (AVERY et al. 1977; EVANS OGDEN 1996; GEHRING et al. 2009). However, despite the fact that the first OWFs have been operational for more than 10 years, information on the collision risk of nocturnal migrants at OWFs is still scarce. There is strong evidence that nocturnally migrating passerines constitute a large proportion of collision fatalities at illuminated offshore structures such as platforms where large numbers of birds may collide in single nights (MÜLLER 1981; HÜPPOP et al. 2009, 2016; AUMÜLLER et al. 2011; SCHULZ et al. 2013). On the other hand, there is an increasing number of studies suggesting that nocturnal migrants incur a rather low risk of collision at onshore wind facilities (GRÜNKORN et al. 2009, 2016; KRIJGSVELD et al. 2009; WELCKER et al. 2017; but see ASCHWANDEN et al. 2018). Whether the collision risk of nocturnal migrants at OWFs is similar to that at onshore wind farms or rather resembles that at other offshore structures remains an open question.

This is also due to the fact that nocturnal migration, particularly at sea, is notoriously difficult to observe. One method increasingly applied is the use of radar. Several different radar systems exist that are suitable to record bird migration (EASTWOOD 1967; BRUDERER 1997; VAN BELLE et al. 2007; HÜPPOP et al. 2009; DOKTER et al. 2011; ASSALI et al. 2017; WEISSHAUPT et al. 2018). Most of these systems allow the quantification of nocturnal migration throughout or for large parts of the height zone birds are known to migrate in. The accuracy of these data and the comparability between systems, however, is still debated (WENDELN et al. 2007; SCHMALJOHANN et al. 2008; DOKTER et al. 2013a; MAY et al. 2017; URMY & WARREN 2017; LIECHTI et al. 2018; PHILLIPS et al. 2018; NILSSON et al. 2018). A common property of all radar devices is that they cannot distinguish between species.

For environmental impact assessments as well as subsequent effect monitoring during construction and operation of OWF in the German EEZ, wind farm developers are required to use marine surveillance radars to collect data on nocturnal bird migration. Radars are operated from vessels or platforms close to or within the (planned) footprint of the OWFs. Technical specifications of the devices as well as the main settings are largely standardized by a standard (StUK) issued by the German Federal Maritime and Hydrographic Agency (Standard – Investigation of the impacts of offshore wind turbines on the marine environment; BSH 2013). Data collected within this framework were the basis for this study.

Since the start of OWF developments in Germany several studies have been conducted in order to increase our understanding of patterns of nocturnal migration in the German EEZ. However, these studies were often restricted to one or few study sites and usually spanned only a limited time period (e.g. HÜPPOP et al. 2004, 2006, 2009; OREJAS et al. 2005; BELLEBAUM et al. 2010; SCHULZ et al. 2013, 2014). Therefore, inference about spatial patterns was often difficult and uncertainties remained as to the consistency of observed patterns in time.

In this study we merged the radar data collected within the StUK framework (BSH 2007, 2013) from 12 wind farm sites within the German EEZ from a time period of 9 years. The main aims of the study were to determine temporal and spatial patterns of nocturnal bird migration in the German North and Baltic Sea with respect to migration intensities and flight heights and to compare patterns between the two regions. In addition, results from radar data were compared with those from recordings of bird flight calls. Data of flight calls, collected at similar sites and time periods, were analyzed and reported earlier (WELCKER & VILELA 2018).

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3 MATERIALS & METHODS

3.1 Data collection

Radar data were collected at 10 locations in the German EEZ in the south-eastern North Sea (German Bight) and at two locations in the Baltic Sea during the years 2008 – 2016 (Figure 3.1). The different locations were sampled in different years during that period and for different lengths of time (Table 3.1). Only at one location (FINO1) were data collected during all years of the study period. In total the dataset comprised 51 location-years of data (Table 3.1).

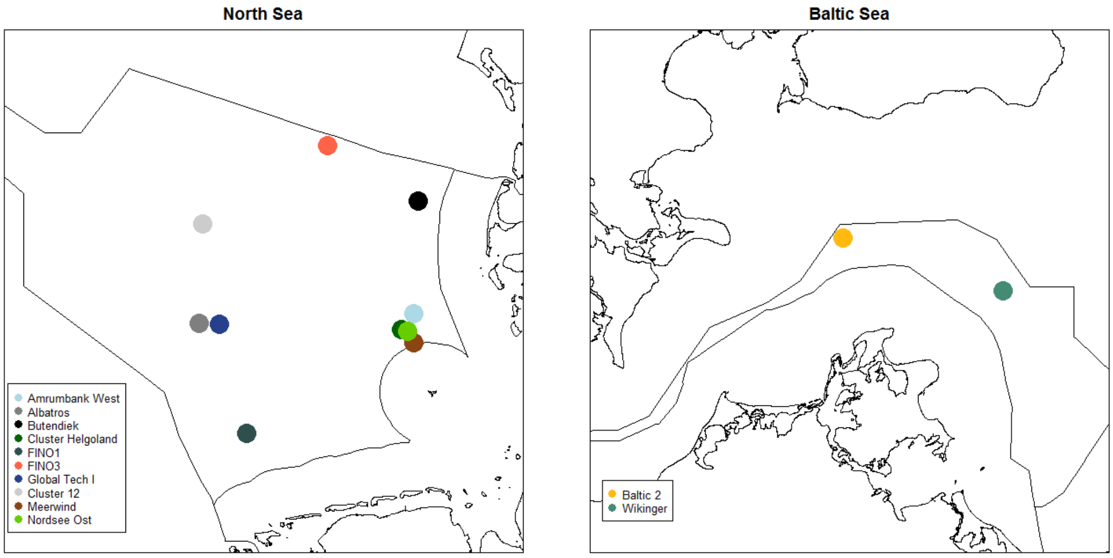

Figure 3.1 Location of the study sites in the EEZ of the German North and Baltic Sea.

The data used in this study were collected within bird migration monitoring programs as part of pre-construction environmental impact assessments as well as effect studies during the construction and operational phases of offshore wind farms (Table 3.1). Four different companies participated in data collection. As methods to collect radar data had to comply with requirements issued by the Federal Maritime and Hydrographic Agency (BSH) as detailed in BSH (2013) data collection was standardized across the different companies involved.

Within each year data acquisition was restricted to the main migration period in spring and fall which were defined as the time between 01/03 – 31/05 (spring) and 15/07 – 30/11 (fall). Data were predominantly collected during ship-based surveys during which the vessels were anchored within or close (approx. 500 m) to the footprint of the projected wind farm (baseline) or outside the safety buffer zone (500 - 3000 m) of wind farms under construction or in operation. At locations and during time periods where suitable platforms were available these were used as radar sites. This was the case at FINO1 (2008-2016), FINO3 (2011-2016), Cluster Helgoland (OSS MSO, 2015-2016) and at Butendiek (2016). FINO1 and FINO3 are located > 1 km outside the nearest wind farm; OSS MSO is situated centrally within the wind farm while the OSS Butendiek is located at the eastern border of the wind farm. Ship-based surveys were carried out for approx. 7 days per month while radars on platforms ran continuously during the migration periods.

Marine surveillance radars from different manufacturers with the antennas tilted vertically were used at all study sites. The technical specifications of the radars were in accordance with requirements of the StUK (BSH 2007, 2013). The main features of the radars were: power output: 25 kW; frequency: X-band, 9.41 GHz; horizontal beam width: 0.95° - 1.3°; vertical beam width: 20° - 24° and pulse length: 0.07 – 0.5 µs. As an exception, a 12 kW X-band radar was used on the FINO1 platform. The main settings were also standardized by StUK. Rain and sea clutter filters were deactivated as these functions may also remove bird signals. The reception gain of the radar was set to the highest possible value which would not lead to interference by static (approx. 70% gain in most cases). The radar range was set to 1,500 m; the target trail function was set to 25 – 60 s afterglow. Thus, each radar signal was displayed with a trail of its positions during the afterglow period leading to characteristic bird tracks. At regular intervals (3-5 min depending on project/year) a screenshot of the radar screen was stored on a hard disk or server. The vertical, horizontal and absolute distance to the radar of all radar signals considered to represent a bird track was recorded using purpose-built software. Screenshots with rain clutter masking bird signals were omitted from the analysis.

Table 3.1 Study sites and sample sizes of the data sets used in this study. In addition, seasons (spring or fall) with available data and the developmental phase of the wind farms during data collection (B – baseline, C – construction, O – operation) is given.

Location	Radar (output power)	N_{spring}, N_{fall}	N_{nights}	Years with data	Phase (years)
Albatros	25 kW	2 , 2	124	2008 - 2009	B (2)
Amrumbank West	25 kW	2 , 2	112	2011 - 2012, 2014	B (2); C (1)
Baltic 2	25 kW	4 , 5	244	2010, 2013 - 2016	B (1); C (3); O (2)
Butendiek	25 kW	3 , 3	276	2011, 2014 - 2016	B (1), C (2), O (1)
Cluster Helgoland	25 kW	2 , 2	424	2015 - 2016	O (2)
FINO1	12 kW	9 , 9	1772	2008 - 2016	B (1), C (1), O (7)
FINO3	25 kW	4 , 5	788	2011, 2013 - 2016	B (1), C (2), O (2)
Global Tech I	25 kW	5 , 6	301	2009, 2012 - 2016	B (1), C (3), O (2)
Cluster 12	25 kW	2 , 2	118	2009 - 2010	B (2)
Meerwind	25 kW	3 , 5	181	2010 - 2014	B (2), C (3)
Nordsee Ost	25 kW	3 , 4	211	2010, 2012 - 2014	B (1), C (3)
Wikinger	25 kW	2 , 3	154	2014 - 2016	B (2), C (1)
TOTAL		41 , 48	4705	2008 - 2016	B (16), C (19), O (16)

3.2 Data analysis

The probability of a bird being detected by radar depends on a variety of factors (BRUDERER 1997). Most importantly, detectability depends strongly on the distance of the object to the radar. To correct for distance-dependent detectability, we applied a distance sampling approach as detailed in HÜPPOP et al.(2006) and WELCKER et al. (2017). This approach is based on the assumption that the horizontal distribution of migrating birds at sea is uniform. The actual distribution of signals in relation to the horizontal distance from the radar is therefore thought to reflect the distance-dependent detectability of birds. We selected all radar signals between 50 m and 150 m altitude for the whole range of 1,500 m (Figure 3.2) and determined the detection function following BUCKLAND et al. (2001). We fitted models with half-normal and hazard-rate key functions with and without cosine series expansions up to the fifth order and selected the best model based on Akaike's information criterion (AIC). Radar signals were then corrected based on this detection function (Figure 3.3). Distance correction was done for all radar devices and time periods separately.

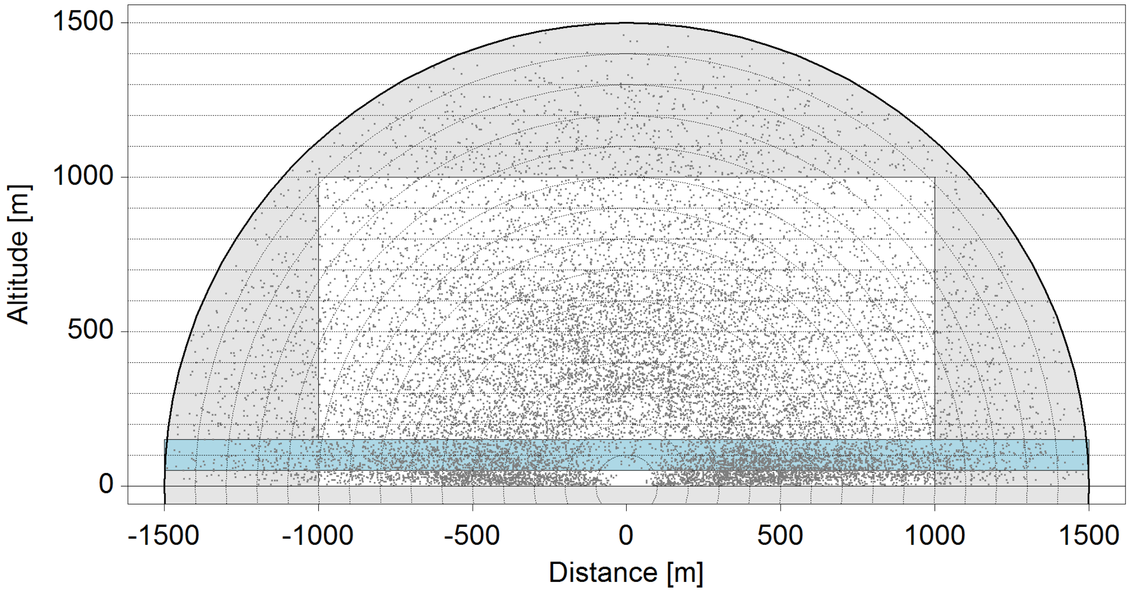

Figure 3.2 *Illustration of the raw radar signals from one year of observations at one radar site. The grey semicircle represents the detection range of 1500 m, the white box is the area from which radar signals were used to calculate MTRs. All signals (black dots) within the altitude range 50 – 150 m (blue rectangle) were used for modelling the distance-dependent detection probability.*

Based on the corrected number of signals, mean migration traffic rates (MTRs – signals*km^{-1}*h^{-1}) were calculated for each hour of data for which at least three valid screenshots were available. All signals within 1,000 m horizontal distance from the radar were included (Figure 3.2). MTRs were calculated for three different altitude ranges: (i) from sea level to 1,000 m a.s.l.; (ii) from sea level to 200 m a.s.l.; and (iii) for the specific rotor diameters of the wind farms adjacent to each radar site (see chapter 3.2.7 and Tab. A 3).

Hourly MTRs were then averaged to derive mean MTRs per night given that hourly values for at least 75% of the duration of the night were available. Night was defined as the time period between civil evening twilight and civil morning twilight.

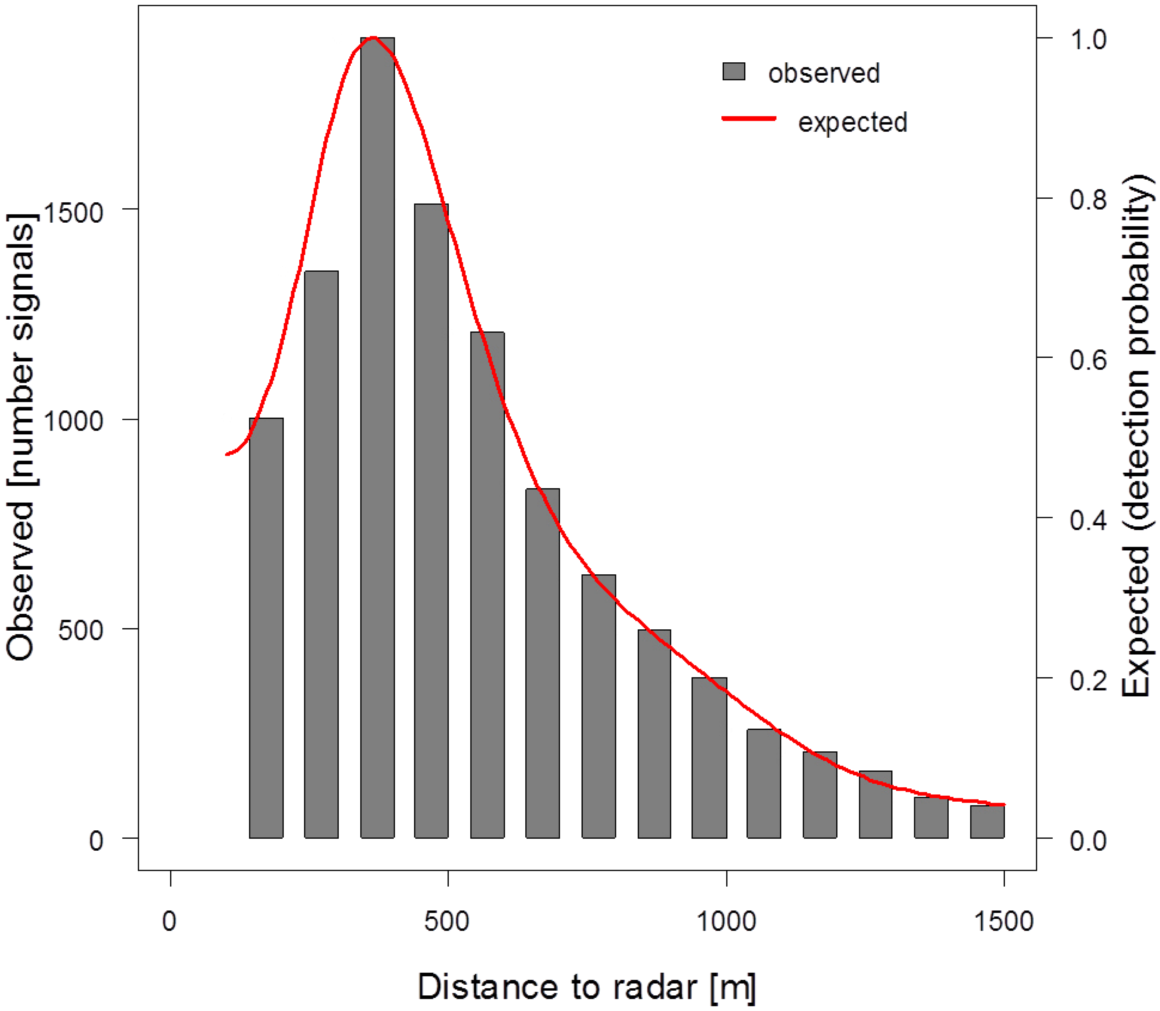

Figure 3.3 Exemplary illustration of a detection function fitted to two years of data from a radar site.

Inspection of the raw radar signals revealed problems in some data sets. The distribution of radar signals from FINO1 differed noticeably from all other sites. This could be attributed to the fact that at this site a radar device with different power output (12 kW instead of 25 kW) was used. The signal distribution led to very high correction factors when correcting for distance-dependent detectability which in turn resulted in considerably higher mean MTRs (see Results, Table 4.1 and Tab. A 1). Raw data from two other sites, FINO3 and Butendiek during the operational phase, showed intermittent interferences, presumably with parts of the platforms the devices were installed on, and with the wind turbines itself (Butendiek), that could not be corrected for. Therefore, data from FINO1, FINO3 and Butendiek (operational phase) were included in analyses comparing relative MTRs only (seasonal pattern (chapter 4.1) and spatial correlation (chapter 4.2)) but were omitted from all other analyses.

3.2.1 Seasonal pattern

To determine the general seasonal pattern of nocturnal migration in the German EEZ of the North and Baltic Sea, we calculated mean standardized migration intensities for each Julian day (night). Migration intensities were log-transformed and standardized across years and sites to avoid uneven leverage of single years or nights with high flux rates. The seasonal pattern was plotted as a three-day moving average and as monthly boxplots.

3.2.2 Spatial correlation of migration intensities

To calculate the correlation of migration intensities between sites we first selected all nights with simultaneous observations in at least two different locations. We then calculated the correlation coefficient *rho* based on Spearman's rank correlation for each pair of sites and years with at least five nights of simultaneous observations. To determine the spatial variation of the correlation strength we regressed the correlation coefficients *rho* against the spatial distance between the locations for which *rho* was calculated. The sample size of the pairwise correlations was included as weights in the regression analysis. This analysis was done for MTRs based on the whole altitude range and repeated for MTRs up to 200 m height.

3.2.3 Mass migration

We evaluated the possibility to derive a data-driven definition of 'mass migration'. To this end we examined histograms and cumulative plots of migration intensities for signs of a bimodal distribution or any other distribution that would allow the definition of a cut-off value to distinguish between 'mass migration events' and 'ordinary' migration intensities.

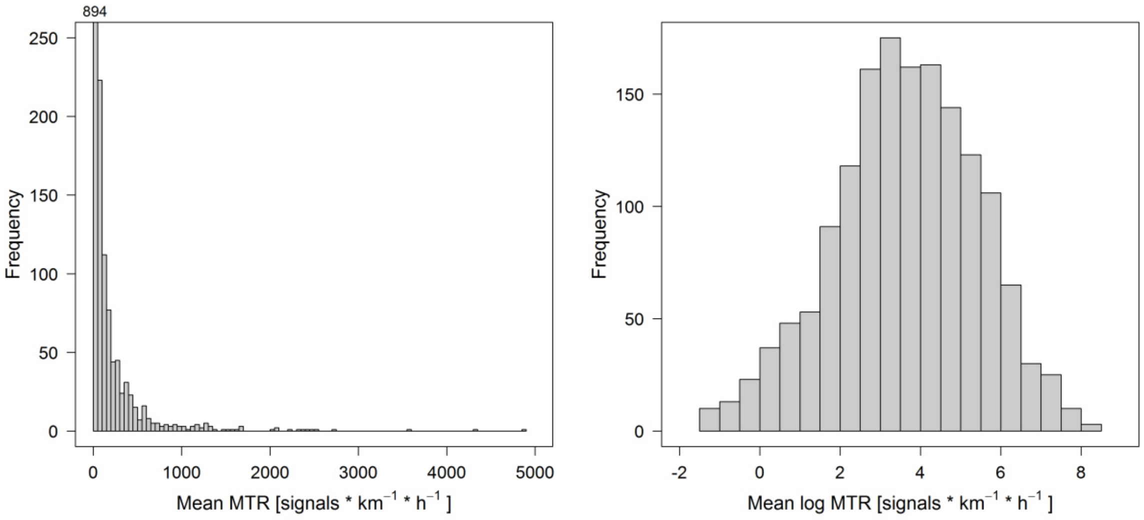

Figure 3.4 Histogram of mean migration intensities [MTR] (left panel) and log-transformed migration intensities (right panel) per night.

The distribution of the raw nocturnal flux rates was highly right-skewed, log-transformation resulted in a roughly normal distribution of the data (Figure 3.4). However, both distributions were continuous and did not show signs of bimodality (Figure 3.3 and Figure 3.4) and hence the definition of 'mass migration' had to be derived independently of the distribution of the data.

We arbitrarily chose the cut-off value for 'mass migration' at 500 MTR. 'High migration intensities' were defined as > 250 MTR (Figure 3.5). These cut-off values were exceeded in 6.3% and 15.0% of the nights, respectively. These values were applied to data from all study sites.

We then tested whether the occurrence of mass migration was correlated across locations. To do so we estimated the effect of distance among sites on the probability of coincidence of mass migration and high migration intensities as defined above by fitting a generalized linear model with binomial error distribution and logit link function.

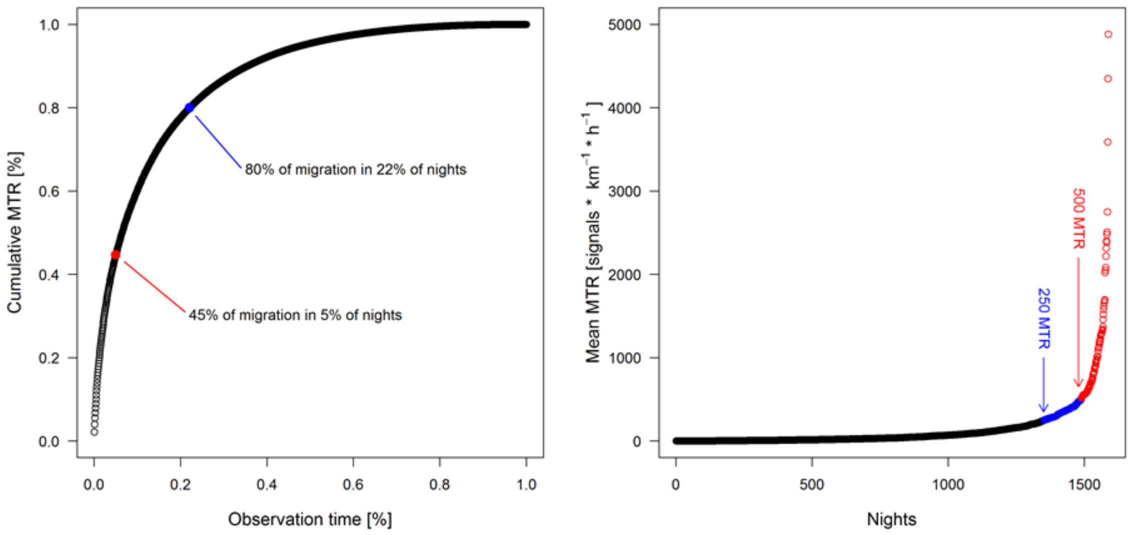

Figure 3.5 Left panel: cumulative MTR [%] per time [%]. Two values are indicated: 45% of radar signals were recorded in 5% of the nights; 80 % of the radar signals were recorded in 22% of the nights. Right panel: Mean migration intensities per night sorted in ascending order to illustrate the definition of 'mass migration' (500 MTR) and 'high migration intensities' (250 MTR).

3.2.4 Spatial gradients

We tested for a systematic difference in migration intensities between the German EEZ of the North Sea and the EEZ of the Baltic Sea, and for a gradient with distance to shore within the North Sea. To determine differences between the North and Baltic Sea we ran paired non-parametric Wilcoxon tests on migration intensities from nights for which simultaneous observations were available from both areas. Tests were run for spring and fall separately, for the combined data and for a subset restricted to simultaneous observations from the same lab. This was done for MTRs of the whole altitude range and for MTRs up to 200 m. Similarly, to determine the gradient with distance to shore within the North Sea paired Wilcoxon tests were used to compare simultaneously observed MTRs at sites closer and further away from shore. Additionally, we ran least-squares linear regressions between the difference in migration intensities between sites and the difference in distance to shore between these sites. Simultaneous observations with migration intensities of zero at both sites were excluded prior to the analysis.

3.2.5 Flight height

For the analysis of flight heights, mean flight height per hour of observation in each project was calculated based on the number of radar signals corrected for distance-dependent detectability. Mean flight height per night was derived from the mean hourly values. Nights with less than five raw radar signals were excluded from further analysis.

We tested for differences in mean flight height between seasons (spring vs. fall) and between regions (North Sea vs. Baltic Sea) with an ANOVA including the sum of (corrected) radar signals per night as weights. To determine whether flight height varied with distance to shore within the North Sea we ran linear regressions between the difference in flight height between sites and the difference in distance to shore between those sites. This was done for spring and fall separately. In addition, a linear regression of flight height on flux rates was fitted with season and region as explanatory variables to test for systematic variation of flight heights with migration intensities. Finally, we examined changes of flight height in the course of the night. To do this, we partitioned each night in four parts of equal length depending on civil dusk and civil dawn at each location. We then compared the mean flight height in each part of the night using ANOVA.

3.2.6 Correlation between migration intensities and call rates

Data of bird flight calls from the same locations and time periods as the radar data were used to determine whether call rates of nocturnal migrants and migration intensities estimated by radar were correlated. Details on the flight call data and the calculation of mean call rates per night can be found in WELCKER & VILELA (2018).

We ran linear regressions of mean MTR per night on mean flight call rate of simultaneous observations at the same sites on a log-log scale. Zeros were removed from the dataset. Season was added as a factor variable to test for differences in correlation strength between spring and fall. Again, models were run for MTRs calculated for the whole altitude range (up to 1000 m) and for MTRs below 200 m. A second set of models was fitted for spring and fall separately with month included as a continuous explanatory variable. In addition, non-parametric Spearman rank correlations were run on the data including zeros to determine whether the exclusion of zeros in the linear models was likely to affect conclusions.

3.2.7 Diurnal pattern

To determine the diurnal pattern of bird migration at the offshore sites migration, intensities were re-calculated based on standardized hours with sunrise set at 06:00 h and sunset at 18:00 h. For each site and season mean MTR was then calculated for each standardized hour of the day. Results were plotted based on relative MTR [%] per hour of the day to allow for a direct comparison of the diurnal pattern between spring and fall.

3.2.8 Estimation of total number of radar signals

We estimated the total number of birds passing through German OWF each spring and fall based on the number of radar signals. For each operational wind farm in the EEZ of the North and Baltic Sea and for each OWF currently under construction the number of radar signals passing through the footprint of the wind farm at altitudes up to 1000 m, up to 200 m and at the specific rotor height of each wind farm was calculated as follows:

The total number of signals per night for each night with observations and each site was calculated by multiplying the mean MTR per night with the length of the night [h] and the maximum extension of the wind farm [km] perpendicular to the assumed main migration axis (45° and 225° in spring and fall, respectively) of the birds. All available nightly totals from all study years for a specific wind farm and season were then taken as the underlying data from which 10,000 bootstrap samples with replacement were drawn, each sample the length of the respective season (92 days in spring [01/03 – 31/05] and 138 days in fall [15/07 – 30/11]). Then the total sum of signals of each bootstrap sample was calculated and the mean of the 10,000 sums taken as the estimated number of signals per season. 95% confidence intervals were derived from the 2.5th and the 97.5th percentile of the bootstrap samples. The same procedure was applied to data collected during daytime in order to derive total estimates for diurnal bird movements.

Not for all focal wind farms data was available. For these wind farms data from the closest radar site(s) was used for bootstrap sampling instead (Tab. A 3).

4 RESULTS

Nocturnal migration intensities showed a high day-to-day variability. In addition, mean migration intensities were highly variable across years and sites (Table 4.1 and Tab. A 1). These two factors explained 18% of the variance of nocturnal MTRs. Overall, there seemed to be a systematic difference between the different labs involved in data collection (LM, $F_{2, 1615} = 25.59$, $p < 0.001$). However, "lab" explained only a small fraction of the variance in MTRs ($R^2 = 0.03$). Similarly, there was a slight but statistically significant effect of the developmental stage of the wind farms (LM, $F_{2, 1615} = 3.40$, $p = 0.034$). During construction, mean MTR was about 8% lower compared to baseline ($t = -2.55$, $p = 0.011$), yet there was no difference between operation and baseline ($t = -0.78$, $p = 0.435$). Also, the explanatory power of the factor "stage" was very low ($R^2 = 0.004$).

Table 4.1 Mean migration intensities (MTR, log-transformed ±SE) at the study sites during the different developmental stages of the wind farms (baseline, construction and operation).

Site	Baseline		Construction		Operation	
	mean log MTR	SE	mean log MTR	SE	mean log MTR	SE
ABW	1.41	±0.12	1.35	±0.11		
Albatros	1.14	±0.06				
Baltic2	1.34	±0.16	1.48	±0.08	1.57	±0.09
Butendiek	1.29	±0.10	1.38	±0.09	0.51	±0.07
Cluster 12	1.59	±0.07				
Cluster Helgoland					1.53	±0.05
FINO1	2.37	±0.04	2.36	±0.05	2.53	±0.02
FINO3	0.77	±0.09	0.49	±0.04	0.45	±0.05
GT1	1.67	±0.11	0.76	±0.09	1.53	±0.08
MSO	2.48	±0.09	1.78	±0.06		
NSO	2.02	±0.09	1.61	±0.06		
Wikinger	1.73	±0.08	2.22	±0.11		
Total*	1.58	±0.03	1.45	±0.04	1.54	±0.04

* Totals for wind farm stages were calculated excluding data from FINO1, FINO3 and Butendiek operation. See text for details.

4.1 Seasonal pattern of bird migration

Within both the spring and fall migration periods a clear temporal pattern of nocturnal bird migration was evident (Figure 4.1 and Figure 4.2). During spring migration intensities increased throughout March, reached a peak in early/mid-April (maximum value: 09/04) and decreased again during May (Figure 4.1). Correspondingly, monthly median MTRs were higher in April compared to March and May (Figure 4.2). This spring pattern was similar in both the North and Baltic Sea (Figure 4.3).

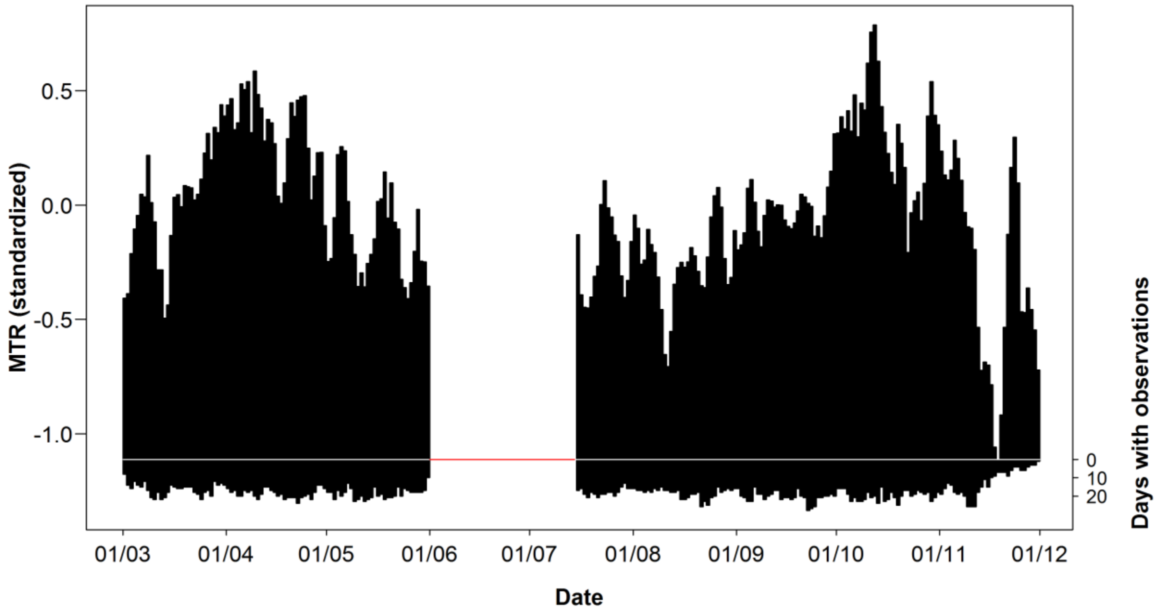

Figure 4.1 *Seasonal pattern of migration intensities (MTR [migration traffic rate]) in the German EEZ of the North and Baltic Sea. Migration intensities were standardized between years and projects and plotted as 3-day moving average.*

During fall, migration intensities increased slightly from mid-July until mid-September. Highest values were reached between end of September and early November (maximum: 12/10). In November migration intensities were highly variable yet the number of days with data was considerably lower than during the other months of the season (Figure 4.1).

The temporal pattern within the fall migration period showed differences between the North and Baltic Sea. At North Sea sites, migration intensities were generally low at the beginning of the season in July and August, peaked in October and remained relatively high in November (Figure 4.3). In contrast, at sites in the Baltic, median MTRs were highest in August and September and decreased in October and November.

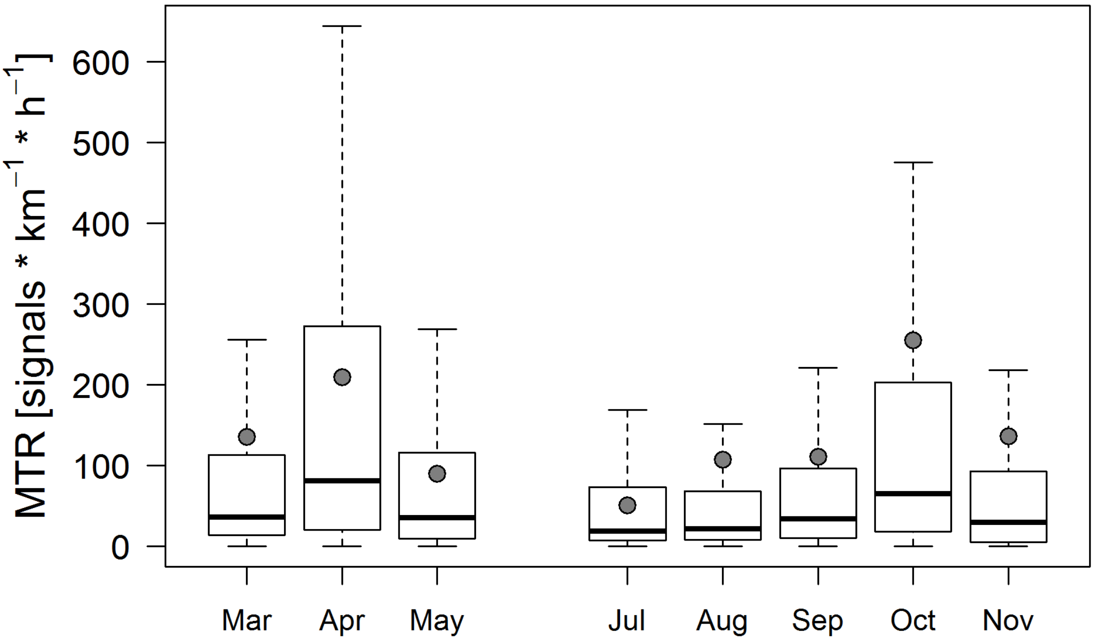

Figure 4.2 *Monthly nocturnal migration intensities [MTR] in the German EEZ of the North and Baltic Sea. Box plots indicate the median (bold black bar) and the interquartile range (box), the whiskers extend to the most extreme data points which are no more than 1.5 times the interquartile range. Grey circles represent the monthly means.*

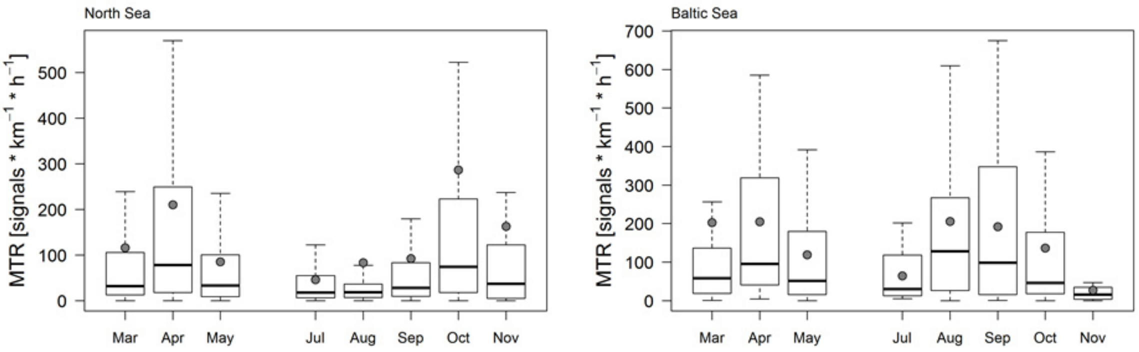

Figure 4.3 *Comparison of the monthly nocturnal migration intensities [MTR] between the North Sea (left panel) and the Baltic Sea (right panel). See Figure 4.2 for details.*

4.2 Spatial correlation of migration intensities

With a mean correlation coefficient *rho* of 0.48 ± 0.02 SE (N = 199 correlations) the spatial correlation of migration intensities across all study years and locations was relatively high. However, the strength of the correlation was significantly higher between sites within the North Sea than between sites across the North and Baltic Sea (Table 4.2). This was the case for both spring and fall. Due to the limited dataset from the Baltic, comparisons within the Baltic Sea were not possible. There was no difference in correlation strength between the seasons (overall: Wilcoxon rank tests, W = 5282, P = 0.265, North Sea only: W = 1900, p = 0.30).

Generally, the correlation strength of MTRs below 200 m altitude was slightly lower than for the whole altitude range (0.40 ±0.02 SE vs. 0.48 ±0.02 SE, W = 22330, p = 0.028). Else, the same patterns with respect to regional and seasonal differences were evident for the data limited to 200 m altitude (Table 4.2)

Table 4.2 Mean correlation coefficients (Spearman's rank correlation coefficient rho*) for correlations of migration intensities between sites within the North Sea and between sites across the North and Baltic Sea. In addition, sample sizes (number of correlations within the North Sea and between the North and Baltic Sea, respectively) and the p-value of Wilcoxon rank tests are given.*

Altitude range	Season	Mean rho North Sea	$N_{\text{North Sea}}$	Mean rho Baltic/North Sea	N_{Baltica}	p
0 – 1000 m	spring	0.61	59	0.21	25	<0.001
	fall	0.54	72	0.31	43	<0.001
	total	0.57	131	0.27	68	<0.001
0 – 200 m	spring	0.48	59	0.21	25	0.007
	fall	0.51	72	0.24	43	<0.001
	total	0.50	131	0.23	68	<0.001

During fall the strength of the spatial correlation of migration intensities between sites in the North Sea depended on the distance between locations (Figure 4.4). Correlation strength decreased significantly with increasing distance. This was also the case when limiting the data to altitudes up to 200 m (Figure 4.5). During spring results were ambiguous. While for MTRs up to 200 m altitude there was a tendency for decreasing correlation strength with increasing distance, there was no such relationship for MTRs of the whole altitude range (Figure 4.4 and Figure 4.5).

When including data from the Baltic Sea the relationships became highly significant during both spring and fall and for both altitude ranges (Figure A. 1). The effect of distance on correlation strength also remained when reducing the data to the same developmental stage of the wind farm (baseline, construction, operation) and when only correlations based on data collected by the same lab where included (Figure A. 2).

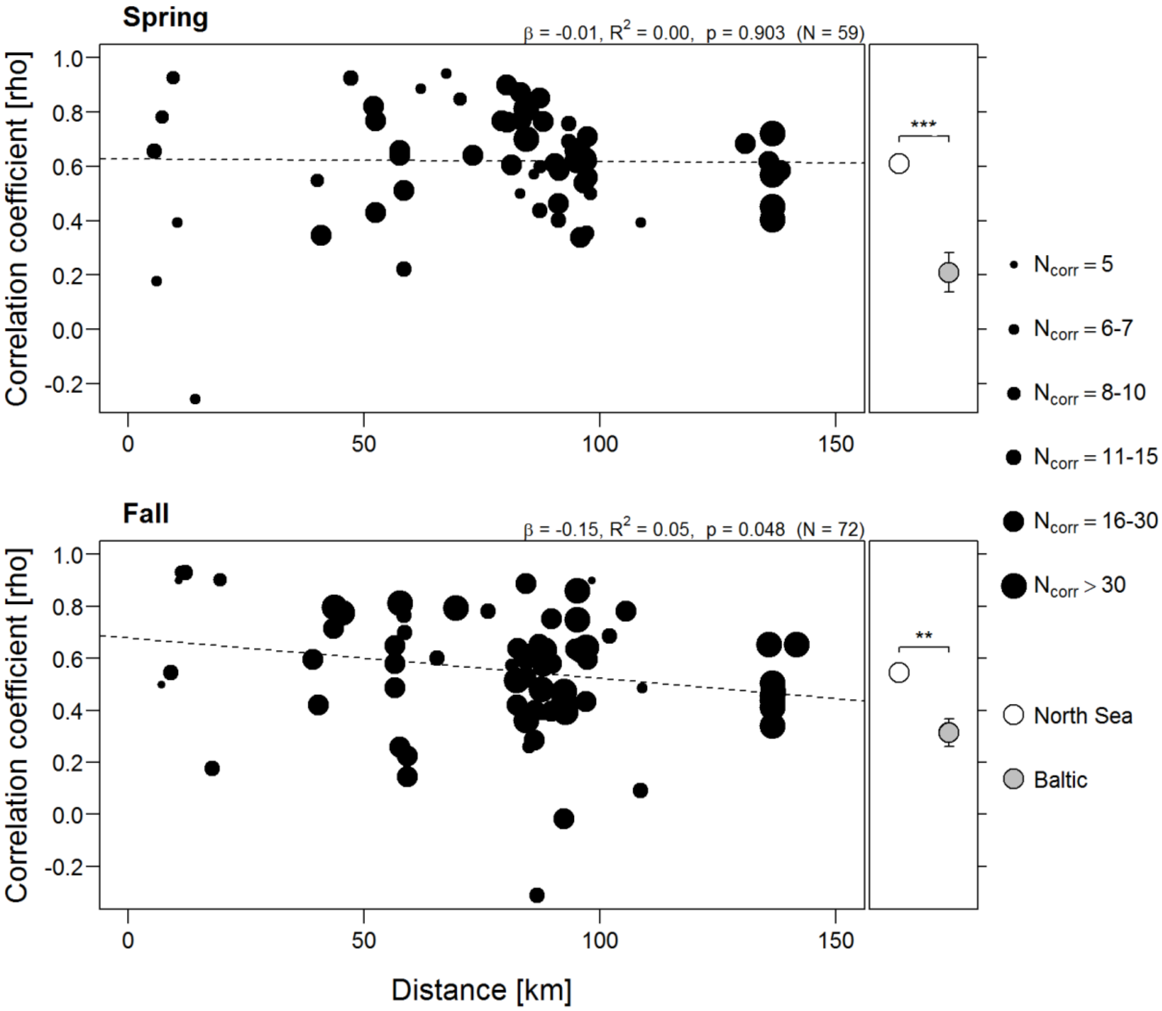

Figure 4.4 *Relationship between distance between sites and the correlation of migration intensities (Spearman's rank correlation coefficient* rho) *for spring (upper panel) and fall (lower panel). Correlation coefficients were calculated based on days with simultaneous observations of each pair of projects and years. The number of days a coefficient is based on is indicated by symbol size (minimum number of days = 5). Left panel: linear regression for data from the North Sea; right panel: mean correlation coefficient [± SE] for North Sea sites (open symbol) and for comparisons between North and Baltic Sea (filled symbols).*

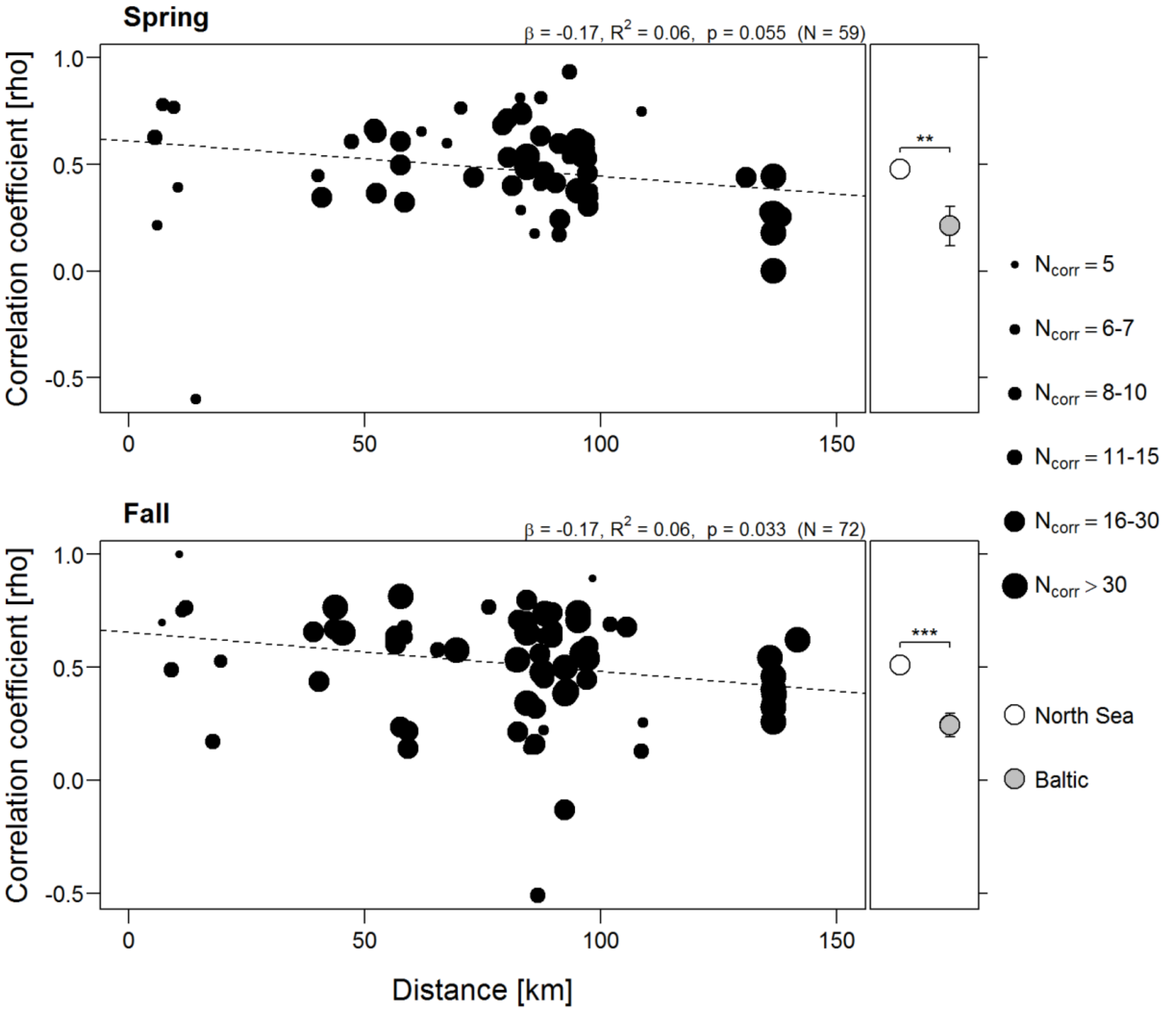

Figure 4.5 Relationship between distance between sites and the correlation of migration intensities up to 200 m altitude (Spearman's rank correlation coefficient rho*) for spring (upper panel) and fall (lower panel). For details see Figure 4.4 and Materials & Methods.*

4.3 Correlation of mass migration

The probability of simultaneous occurrence of high migration intensities decreased significantly with increasing distance between sites in the North Sea in fall (Figure 4.6, GLM: z = -2.25, p = 0.024) but not in spring (Figure 4.6, GLM: z = -1.11, p = 0.269). During fall, the predicted probability of coincidence was about 0.7 – 0.8 for sites in close proximity but declined to about 0.2 at 100 km distance between sites. Including data from the Baltic led to similar results (Figure 4.7) with a significant relationship with distance in fall (GLM: z = -3.19, p = 0.001) but not spring (GLM: z = -0.33, p = 0.744).

The analysis of simultaneous occurrence of events of mass migration corroborated these results (Figure A. 3).

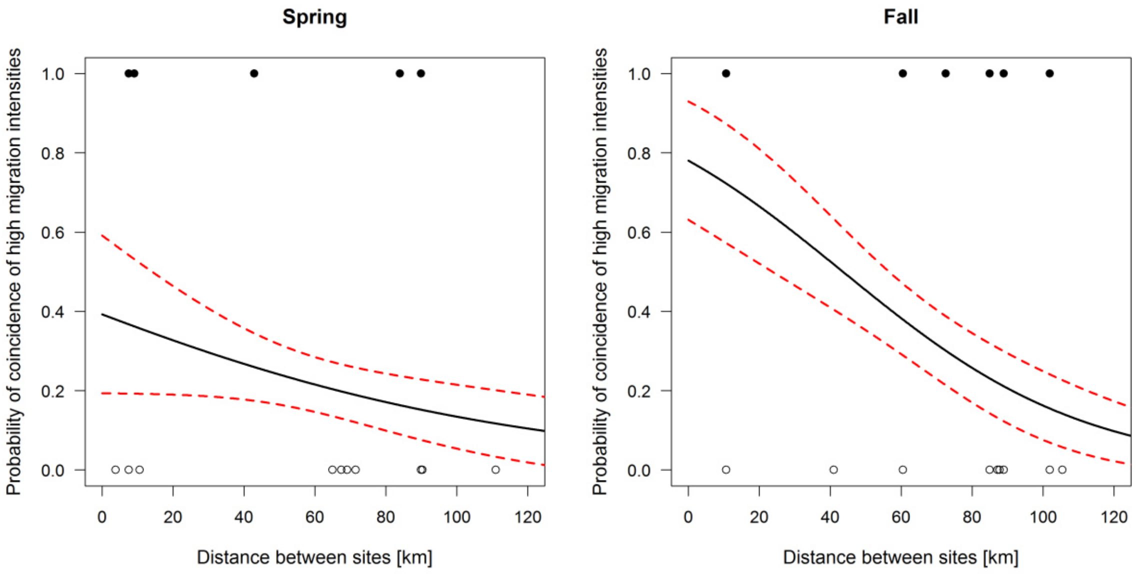

Figure 4.6 *Relationship between the distance between sites and the predicted probability [± SE] of coincidence of high migration intensities at these sites in spring (left panel) and fall (right panel). Data restricted to North Sea only. Predicted probabilities are based on generalized linear models with binomial error structure (see text for further details). Filled symbols represent distances between sites at which high migration intensities coincided, open symbols distances at which high migration intensities did not coincide.*

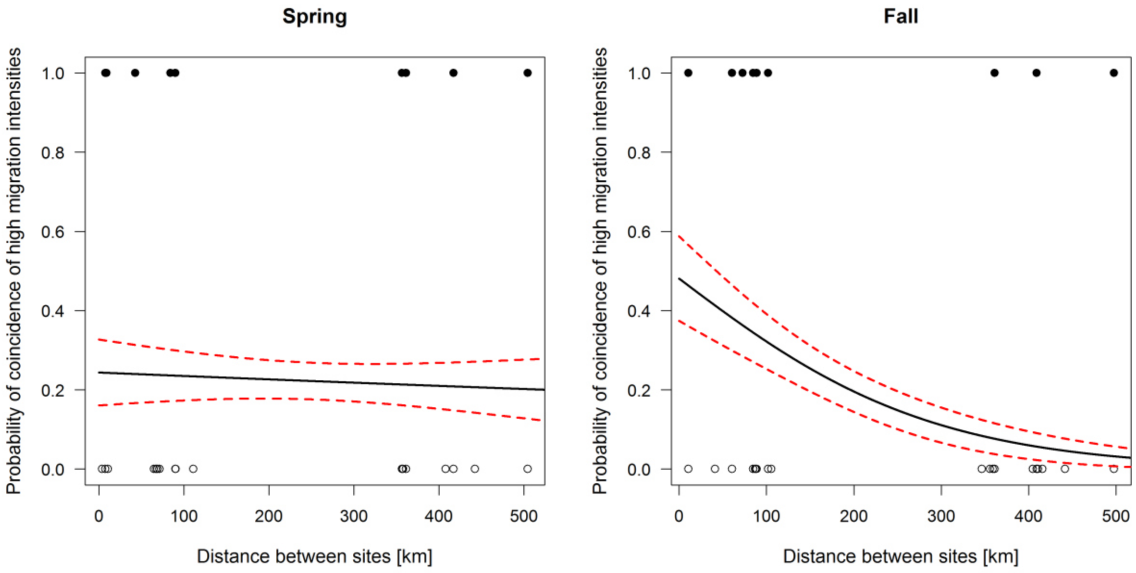

Figure 4.7 *Relationship between the distance between sites and the predicted probability [± SE] of coincidence of high migration intensities at these sites in spring (left panel) and fall (right panel). Data from North and Baltic Sea. Predicted probabilities are based on generalized linear models with binomial error structure (see text for further details). Filled symbols represent distances between sites at which high migration intensities coincided, open symbols distances at which high migration intensities did not coincide.*

4.4 Spatial gradients in the German EEZ

4.4.1 Gradient between North and Baltic Sea

The comparison of simultaneously measured MTRs between sites in the North and Baltic Sea showed mixed results. Overall, there was a significant difference of migration intensities between regions with median MTRs in the Baltic being about 10% higher than in the North Sea (Figure 4.8, paired Wilcoxon rank test: V = 23032, p = 0.013, N = 280). Results for spring (10% difference) and fall (11% difference) and also for the analysis restricted to data collected by the same lab (14% difference) were similar, although statistical significance was only reached in fall (Figure 4.8).

Comparisons of MTRs below 200 m altitude showed different results (Figure 4.9). Here there was a pronounced difference in spring with MTRs in the Baltic being 26% higher than in the North Sea (V = 4277, p = 0.002). In contrast there was no difference in fall (V = 6714, p = 0.829) indicating differences in mean flight heights between seasons and regions (see chapter 4.5).

In addition, the difference in migration intensities between regions varied within seasons (Table 4.3). In spring, migration intensities in the Baltic were higher in April and May while they were higher in the North Sea in March. There was also a strong monthly pattern in fall with higher MTRs in the Baltic in August and September but lower MTRs in October and November compared to the North Sea. There was no difference in July (Table 4.3).

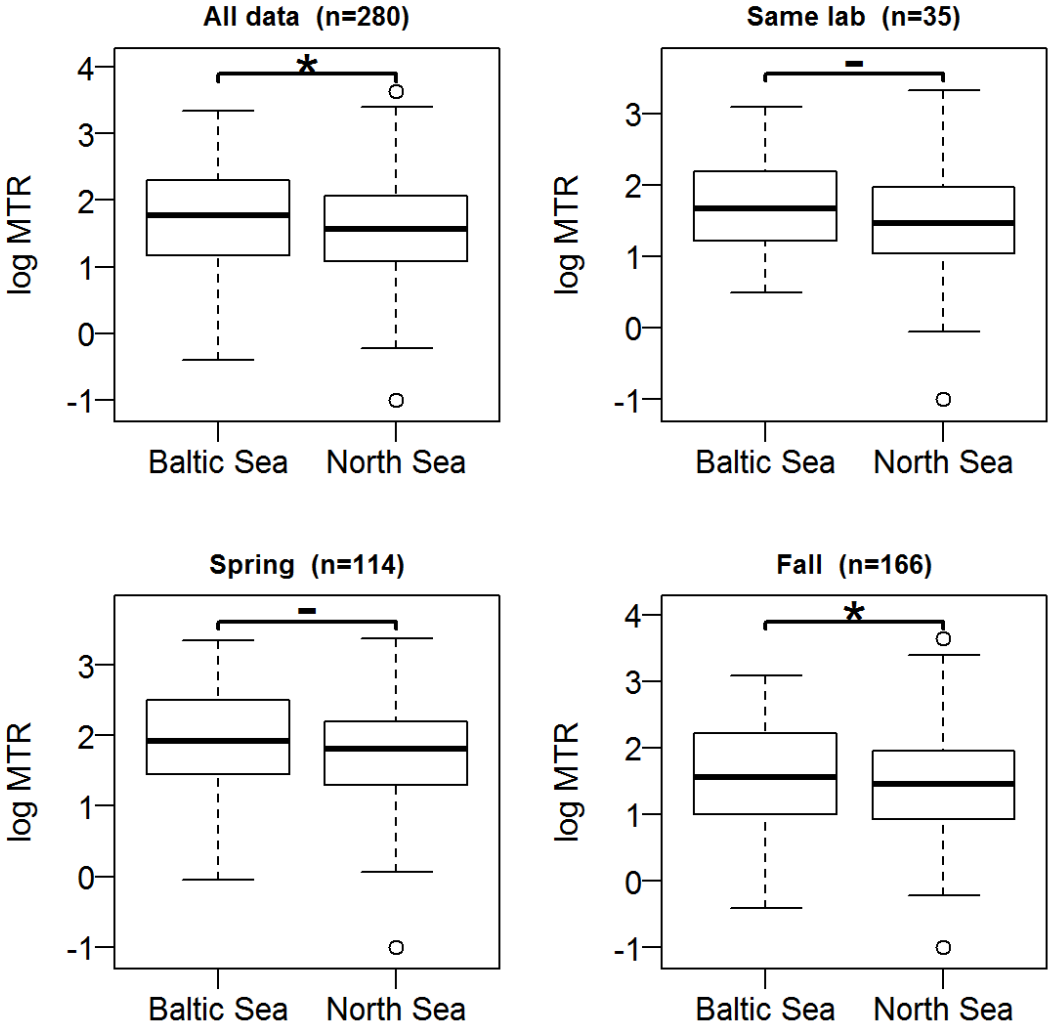

Figure 4.8 *Comparison of migration intensities (MTR, log transformed) simultaneously measured in the Baltic and North Sea. Box plots indicate the median (bold black bar) and the interquartile range (box), the whiskers extend to the most extreme data points which are no more than 1.5 times the interquartile range, open symbols indicate values outside 1.5 times the interquartile range. Additionally, the results of paired Wilcoxon rank-sum tests (*** p < 0,001; ** p < 0,01; * p < 0,05; - p > 0,05) and the sample size of paired observations are given above the box plots. Results are shown separately for spring (lower left panel) and fall (lower right panel), as well as for comparisons restricted to the same lab responsible for data collection (upper right panel) and for all data combined (upper left panel).*

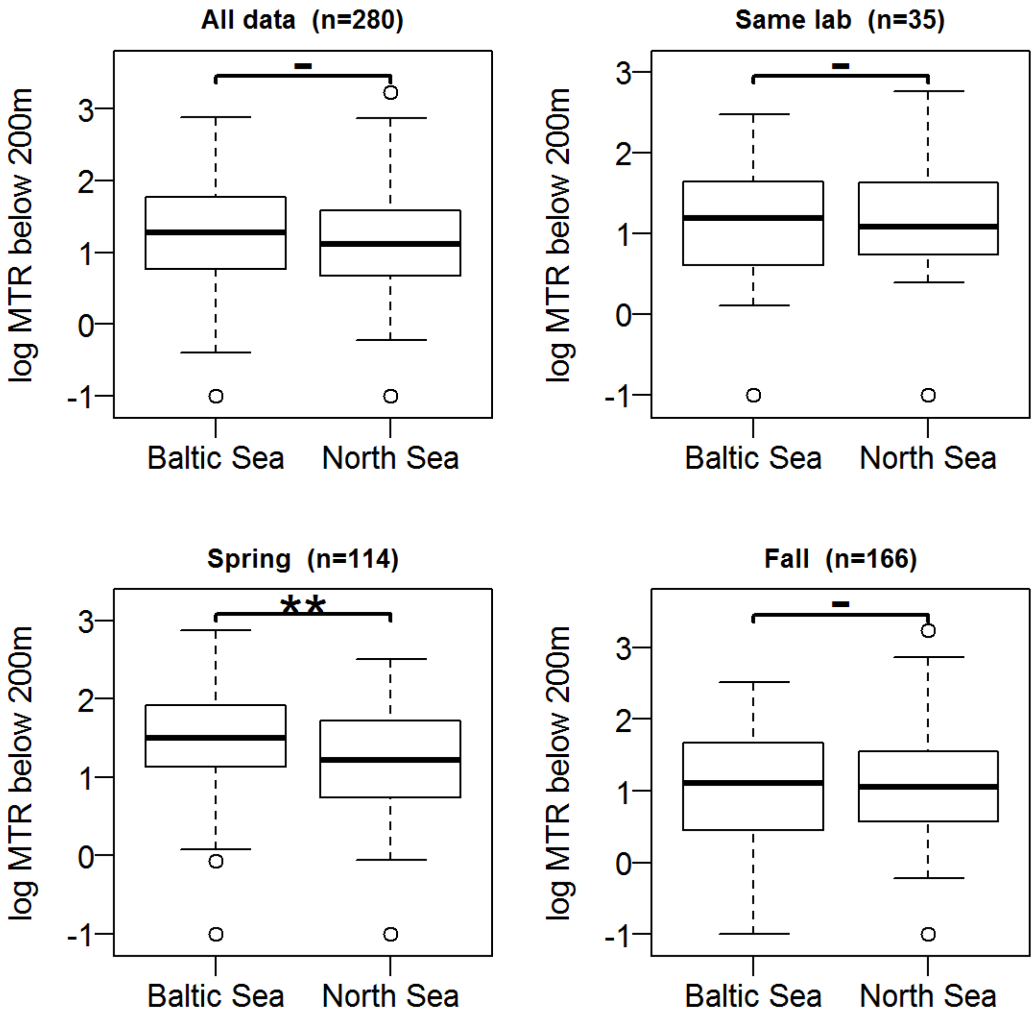

Figure 4.9 *Comparison of migration intensities at altitudes up to 200 m (MTR, log transformed) simultaneously measured in the Baltic and North Sea. Box plots indicate the median (bold black bar) and the interquartile range (box), the whiskers extend to the most extreme data points which are no more than 1.5 times the interquartile range, open symbols indicate values outside 1.5 times the interquartile range. Additionally, the results of paired Wilcoxon rank-sum tests (*** p < 0,001; ** p < 0,01; * p < 0,05; - p > 0,05) and the sample size of paired observations are given above the box plots. Results are shown separately for spring (lower left panel) and fall (lower right panel), as well as for comparisons restricted to the same lab responsible for data collection (upper right panel) and for all data combined (upper left panel).*

Table 4.3 *Difference in mean nocturnal MTR (log-transformed) between sites in the North and Baltic Sea for each month. Negative values indicate higher mean MTR in the North Sea. Only nights with simultaneous observations in both regions were included. Sample size (number of nights) and results of Wilcoxon rank tests comparing monthly MTRs between regions are given.*

Month	**N_{nights}**	**δ log MTR between Baltic and North Sea**	**p Wilcoxon rank test**	**δ log MTR below 200 m between Baltic and North Sea**	**p Wilcoxon rank test**
March	31	-0.35	0.004	-0.20	0.033
April	51	0.43	0.014	0.54	0.001
May	27	0.38	0.016	0.50	0.011
July	17	0.39	0.174	0.28	0.284
August	30	0.49	0.003	0.23	0.171
September	54	0.50	<0.001	0.25	0.061
October	35	-0.35	0.014	-0.32	0.025
November	30	-0.28	0.032	-0.49	0.004

4.4.2 Gradient with distance to shore within the North Sea

There was evidence for a gradient of nocturnal migration intensities with distance to shore within the North Sea. A comparison of MTRs measured simultaneously at two sites showed that migration intensities at the site closer to shore were on average higher than at the site further offshore (Figure 4.10; V = 39496, p < 0.001). This was also the case when seasons were analyzed separately, and for data restricted to the same lab (Figure 4.10). In addition, results did not differ for MTRs below 200 m altitude (Figure A. 4), or when distance to shore was measured perpendicular to the main migration axis (NE – SW) (Figure A. 5).

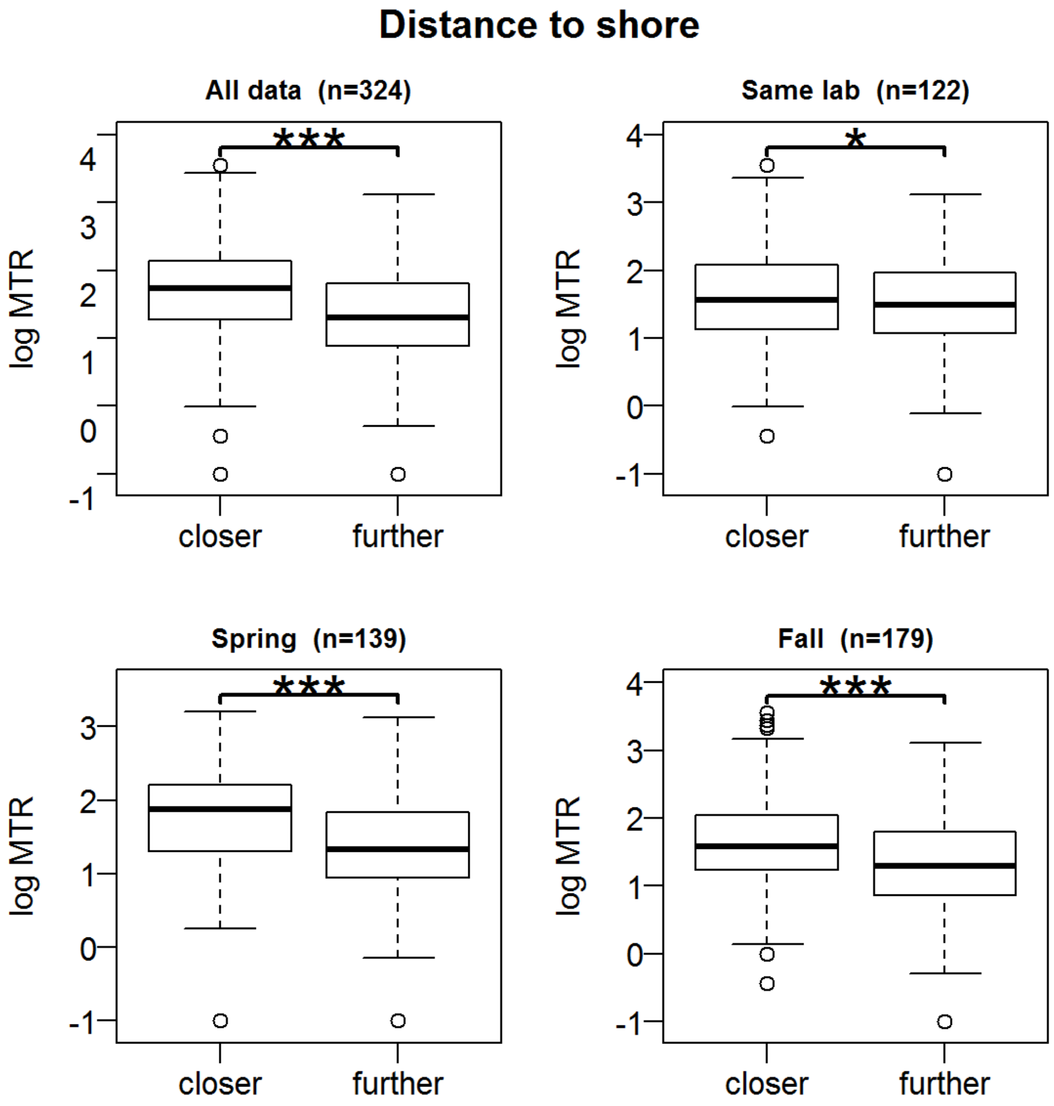

*Figure 4.10 Comparison of migration intensities (MTR, log transformed) simultaneously measured at two different sites in the North Sea with different distances to shore. Box plots indicate the median (bold black bar) and the interquartile range (box), the whiskers extend to the most extreme data points which are no more than 1.5 times the interquartile range, open symbols indicate values outside 1.5 times the interquartile range. Additionally, the results of paired Wilcoxon rank-sum tests (*** p < 0,001; ** p < 0,01; * p < 0,05; - p > 0,05) and the sample size of paired observations are given above the box plots. Results are shown separately for spring (lower left panel) and fall (lower right panel), as well as for comparisons restricted to the same lab responsible for data collection (upper right panel) and for all data combined (upper left panel).*

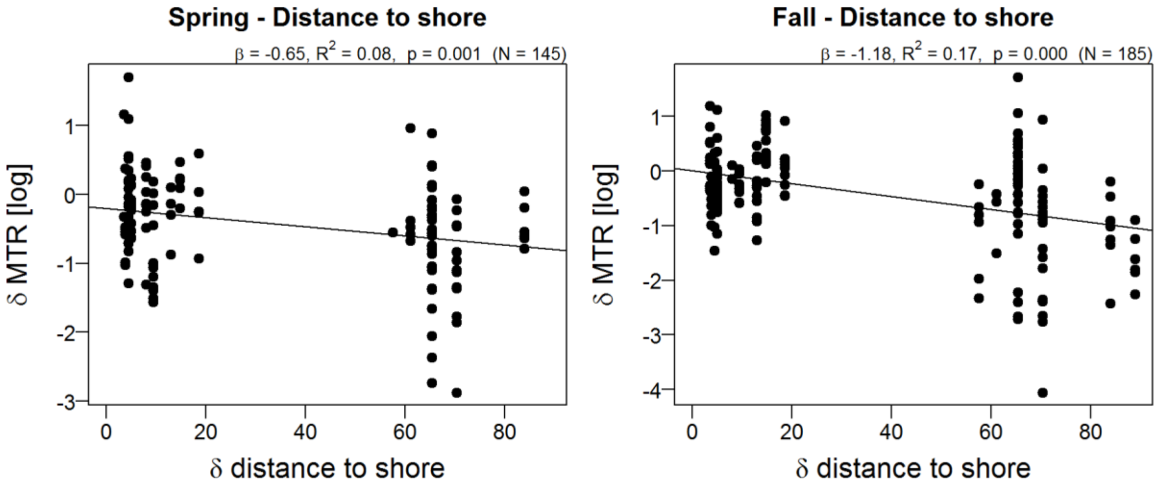

Figure 4.11 Relationship of the difference in migration intensities between two sites and their difference in distance to shore. The results of a linear regression are given above the plot. Left panel: during spring migration; right panel: during fall migration.

Furthermore, there was a significant negative relationship between the difference in migration intensities between sites and the difference in distance to shore for both spring and fall (Figure 4.11). This suggests that MTRs declined with increasing distance to the mainland. Again, these results did not differ for MTRs below 200 m altitude (Figure A. 6) and were independent of the way distance to shore was measured (Figure A. 7). Due to the low number of simultaneous observations and limited distance range models restricted to data from the same lab were not informative.

4.5 Patterns of flight height

Flight heights of nocturnal migrants were unequally distributed within the range of 0 – 1000 m altitude (Figure 4.12). Overall, birds preferred to fly in the altitude band within 200 m above the sea surface (Table 4.4). The proportion of birds flying at low altitudes varied to some extent between seasons and regions. In the North Sea, the proportion of movements below 200 m was substantially higher in fall compared to spring while there was only a trivial difference between seasons in the Baltic Sea (Figure 4.13).

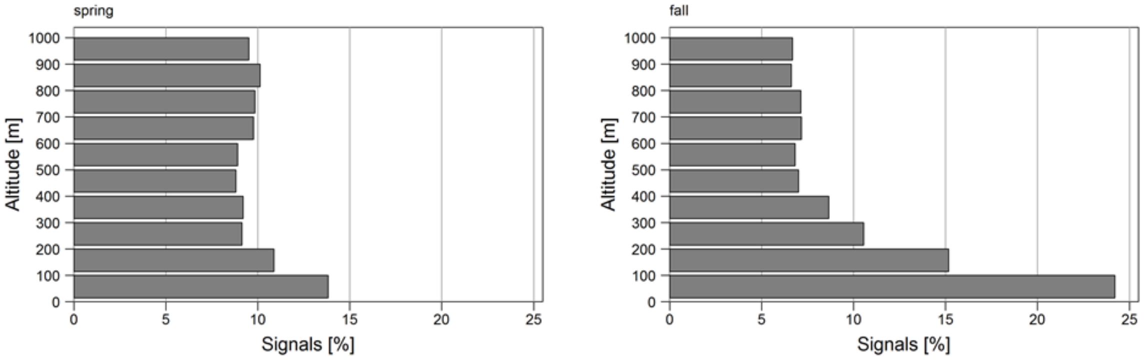

Figure 4.12 Distribution of flight heights [%] of nocturnal migrants in the German EEZ of the North and Baltic Sea in spring (left panel) and fall (right panel).

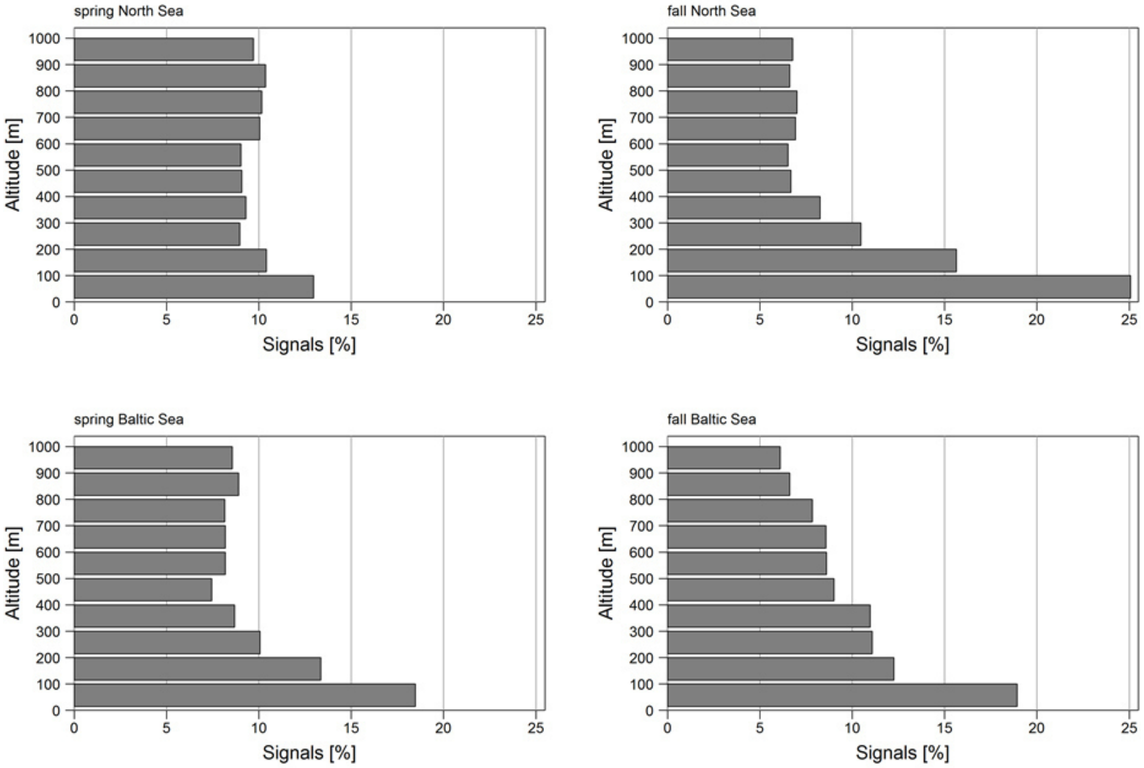

Figure 4.13 Comparison of the distribution of flight heights [%] of nocturnal migrants between the North Sea (upper panels) and the Baltic Sea (lower panels) in spring (left panels) and fall (right panels).

Table 4.4 *Proportion [%] of radar signals at altitudes below 200 m and below 500 m in spring and fall in the German EEZ of the North and Baltic Sea.*

	spring		**fall**		**total**	
	< 200 m	**< 500 m**	**< 200 m**	**< 500 m**	**< 200 m**	**< 500 m**
North Sea	23.4	50.7	40.7	66.1	34.7	60.8
Baltic Sea	31.8	58.0	31.2	62.3	31.4	60.7
Total	24.7	51.9	39.4	65.6	34.2	60.8

Correspondingly, the difference in mean flight height between regions depended on the migration season (LM, $F_{3,\ 2100}$ = 136.5, p < 0.001). In spring, mean flight height was significantly higher in the North Sea than in the Baltic (LM, β = 66.3, t = 6.59, p < 0.001). In contrast, in fall mean flight height was significantly higher in the Baltic compared to the North Sea (β = -51.5, t = -5.38, p < 0.001). Within the Baltic flight altitude did not differ between seasons (t = 0.55, p = 0.585; Figure 4.14).

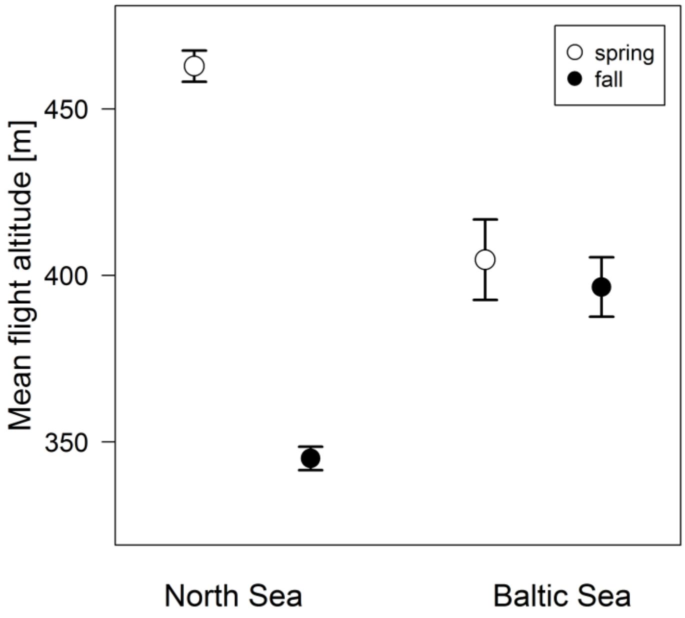

Figure 4.14 *Comparison of the mean flight height per night [m] ±SE between regions (North Sea vs. Baltic Sea) and between seasons (spring vs. fall)*

With respect to a gradient in flight altitude with distance to shore within the North Sea results differed between seasons. In spring, there was no relationship between the difference in mean flight height measured simultaneously at two sites and their difference in distance to shore (Figure 4.15). In contrast, a significant negative relationship between δ flight height and δ distance indicated decreasing flight heights with increasing distance to shore in fall (Figure 4.15).

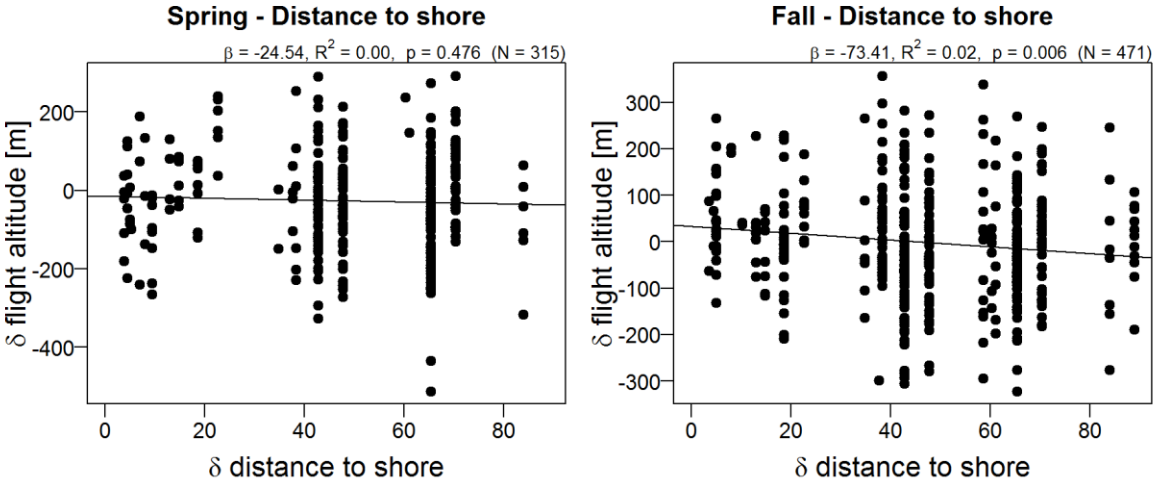

Figure 4.15 Relationship of the difference in mean flight height [m] between two sites and their difference in distance to shore. The results of a linear regression are given above the plot. Left panel: during spring migration; right panel: during fall migration.

Overall, there was a strong positive relationship between migration intensity and mean flight altitude (Figure 4.16, β = 0.71, t = 14.73, p < 0.001). Mean flight height increased with increasing migration intensity. However, the relationship varied with season and region (Figure A. 10). The increase in flight height with increasing MTR was significantly steeper in spring compared to fall in both regions (t = 4.86, p < 0.001). In addition, there was a significant interaction between season and region (t = 3.73, p < 0.001) reflecting differences in mean flight height between regions and seasons (see also Figure 4.14).

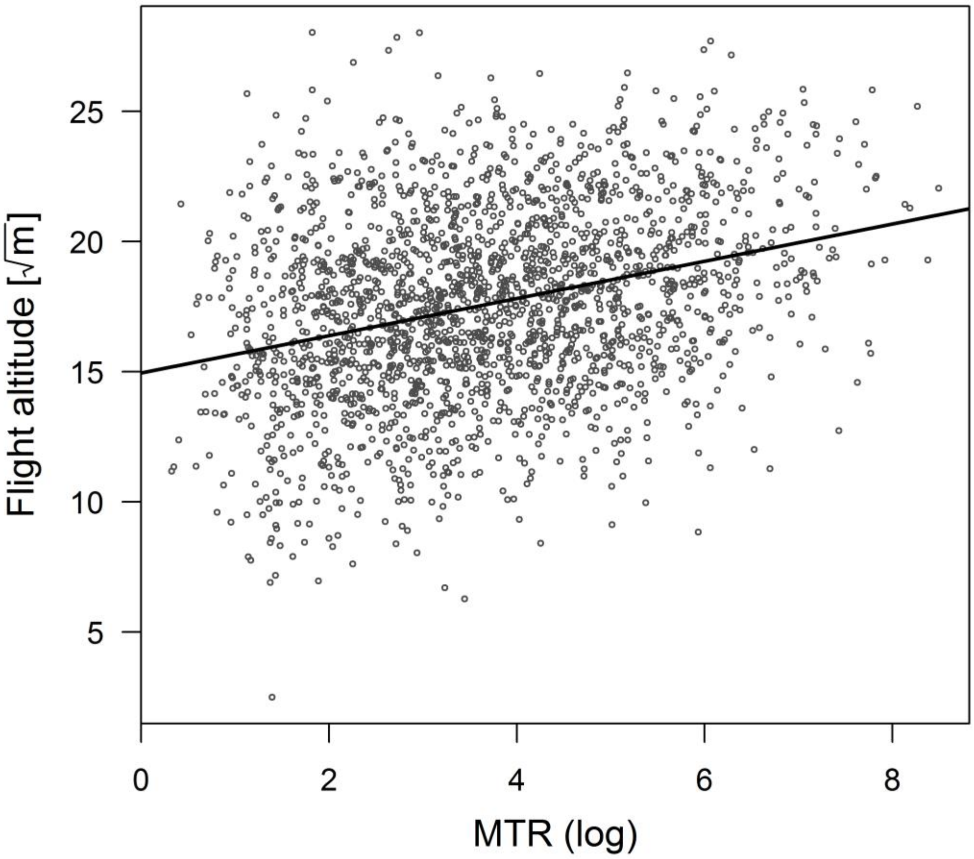

Figure 4.16 Relationship between flight height [m, sqrt-transformed] and migration intensity [MTR, log-transformed].

Moreover, there was a strong pattern of decreasing flight altitudes in the course of the night (LM, $F_{3,\ 9332} = 75.99$, $p < 0.001$). Flight height decreased continuously throughout the night with mean flight height being 75.6 m lower during the final quarter of the night compared to the first (Figure 4.17).

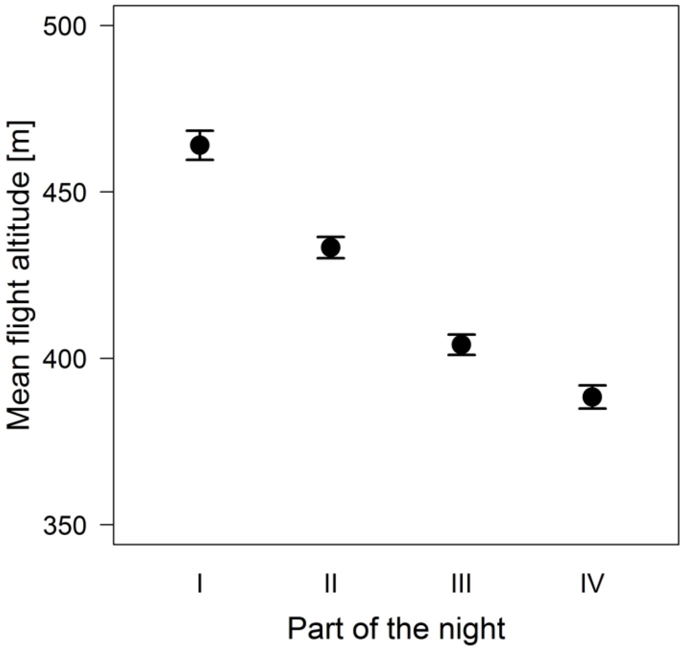

Figure 4.17 Differences in mean flight height [m ±SE] in the course of the night.

4.6 Correlation between migration intensities and call rates

Migration intensities measured by radar and rates of bird flight calls recorded simultaneously at the same sites were positively correlated (Figure 4.18, LM: $t = 9.75$, $p < 0.001$, $R^2 = 0.11$). The relationship differed significantly between seasons with a steeper slope in fall compared to spring (Figure 4.18, $t = 2.73$, $p = 0.007$). Results for MTRs below 200 m altitude were very similar with a moderately better model fit (Figure 4.18, $t = 11.30$, $p < 0.001$, $R^2 = 0.16$).

Non-parametric correlations including zeros confirmed results of the regression analysis ($rho = 0.42$, $p < 0.001$). Also, correlation was higher in fall ($rho = 0.44$) compared to spring ($rho = 0.39$). Fitting linear regressions for the different study months separately showed that coefficients of determination were highest at the end of the fall season (Table 4.5).

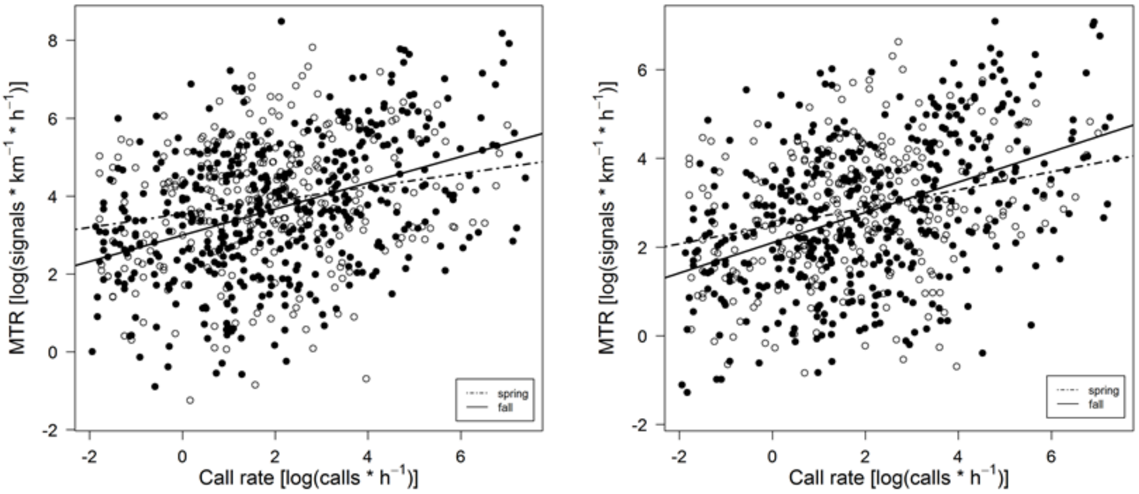

Figure 4.18 *Relationship between migration intensity [MTR, log-transformed] and call rates [calls/h, log-transformed]. Left panel: MTRs calculated for whole altitude range (0 – 1000m), right panel: MTRs up to 200 m altitude.*

Table 4.5 *Parameter estimate (slope, β ± SE) and coefficient of determination (R^2) for linear least-squares regression of MTRs on bird call rates for each month of the spring and fall migration periods. MTRs were calculated for the altitude range up to 1000 m and for altitudes up to 200 m.*

Month	**MTR (altitude up to 1000 m)**		**MTR (altitude up to 200 m)**	
	β ± SE	**R^2**	**β ± SE**	**R^2**
March	0.22 ± 0.06	0.11	0.15 ± 0.06	0.06
April	0.35 ± 0.06	0.17	0.18 ± 0.07	0.05
May	0.31 ± 0.07	0.12	0.32 ± 0.09	0.14
July	0.32 ± 0.12	0.11	0.32 ± 0.16	0.13
August	0.34 ± 0.08	0.12	0.19 ± 0.12	0.03
September	0.36 ± 0.06	0.19	0.26 ± 0.07	0.11
October	0.44 ± 0.05	0.37	0.46 ± 0.05	0.38
November	0.52 ± 0.09	0.25	0.46 ± 0.09	0.25

4.7 Diurnal pattern of bird migration

Migration intensities showed a clear diurnal pattern. Nocturnal MTRs increased steeply after sunset and reached a peak before midnight (Figure 4.19). During the second half of the night MTRs decreased continuously until sunrise. Diurnal migration intensities were generally much lower than MTRs during the night. Diurnal MTRs were highest shortly after sunrise and decreased until noon.

This general pattern was similar in both migration periods and at all study sites (Figure 4.20, Figure A. 12 and Figure A. 13).

However, there were some gradual differences between seasons depending on the geographic location of the sites (Figure 4.20). At sites in the northern German Bight the onset and peak of nocturnal migration was 2-3 h earlier in fall compared to spring. At sites in the central German Bight this seasonal difference was reduced, while the pattern was reversed in the southern part of the German Bight. In this area, the onset and peak of nocturnal migration was earlier in spring compared to fall. In the Baltic, patterns in spring and fall were similar.

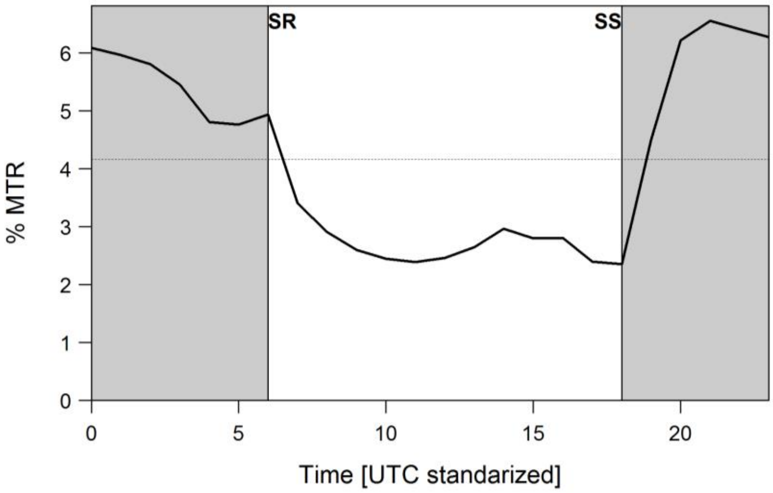

Figure 4.19 Diurnal pattern of migration intensities [%] in the German EEZ of the North and Baltic Sea. The time of day was standardized with sunrise (SR) being set at 06:00 and sunset (SS) at 18:00. The overall mean is indicated by a dotted line. See Chap. 3.2.7 for more details.

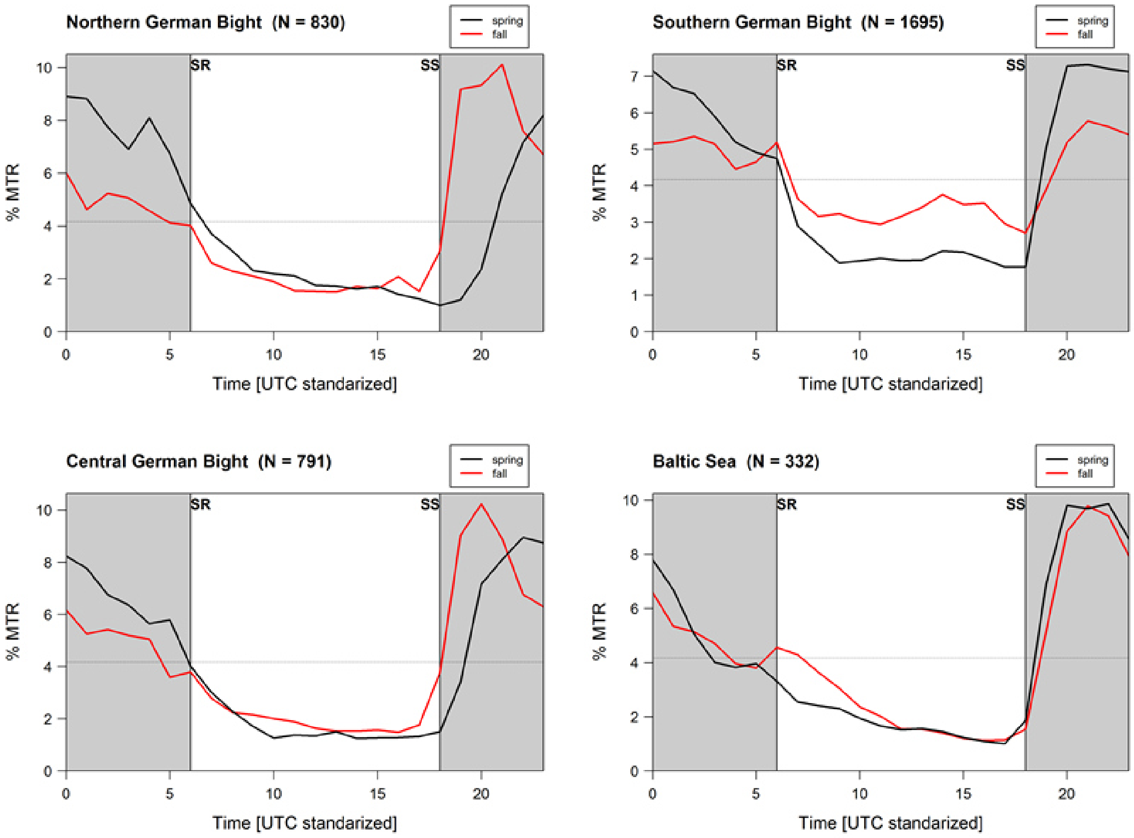

Figure 4.20 *Diurnal pattern of migration intensities [%] in spring (black line) and fall (red line) at different areas in the German EEZ. The time of day was standardized with sunrise (SR) being set at 06:00 and sunset (SS) at 18:00. The overall mean is indicated by a dotted line; N is the number of nights the pattern is based on. See Chap. 3.2.7 for more details.*

4.8 Estimation of total number of radar signals

The total number of bird movements (radar signals) annually passing through the footprints of all operational wind farms and wind farms currently under construction in the German EEZ during the migration periods was estimated at about 98 million for all altitudes up to 1000 m, at about 34 million up to 200 m altitude and at 24 million for the specific rotor heights of the wind farms (Table 4.6). Generally, the estimated number of signals was higher during the night than during the day due to mostly higher nocturnal MTRs. Also, total numbers in fall were higher than in spring, particularly at rotor height (Table 4.6), reflecting higher mean MTRs, lower mean flight heights and the generally longer migration season in fall. Due to the high day-to-day variation as well as high interannual variation of MTRs, 95% confidence intervals were high (Table 4.6).

Table 4.6 Estimated annual total number [±95% CI] of radar signals during spring (01/03 – 31/05) and fall (15/07 – 30/11) and during day and night for offshore wind farms in the German EEZ. See chapter 3.2.8 for more details.

season	day/ night	signal number 0 - 1,000 m [±95%CI]	signal number 0 - 200 m [±95%CI]	signal number rotor height [±95%CI]
spring	day	20,646,347 [9,232,496 – 52,330,990]	5,644,512 [3,967,058 – 7,965,277]	3,821,754 [2,692,345 – 5,539,734]
	night	23,565,445 [14,551,191 – 35,104,276]	5,642,674 [3,875,095 – 7,715,610]	4,167,725 [2,835,123 – 5,761,216]
	total	44,211,792 [23,783,688 – 87,435,266]	11,287,187 [7,842,153 – 15,680,886]	7,989,479 [5,527,468 – 11,300,950]
fall	day	18,153,255 [13,617,692 – 23,637,509]	7,601,567 [5,864,082 – 9,765,790]	5,330,372 [4,103,307 – 6,864,830]
	night	35,431,012 [22,516,695 – 51,668,773]	14,780,264 [9,357,216 – 21,538,625]	10,960,915 [6,893,278 – 16,148,536]
	total	53,584,267 [36,134,387 – 75,306,281]	22,381,830 [15,221,298 – 31,304,415]	16,291,287 [10,996,585 – 23,013,366]
overall total	day and night	97,796,059 [59,918,074 – 162,741,547]	33,669,017 [23,063,451 – 46,985,301]	24,280,766 [16,524,053 – 34,314,316]

5 DISCUSSION

In this study we could comprehensively analyze radar data on nocturnal bird migration from 12 different sites in the German North and Baltic Sea. Together with the fact that our data spanned a time period of nine years this gave us the unprecedented opportunity to determine general patterns of the intensity of nocturnal bird movements in these offshore areas as well as patterns of flight height. A better understanding of these patterns is of pivotal importance to assess and predict potential impacts of offshore wind farms on nocturnal migrants.

Data collection was standardized across the different parties involved by a detailed description of the methods issued by BSH (BSH 2007, 2013). Nonetheless, several sources of variability remained that inevitably led to high heterogeneity of the data. Firstly, a variety of marine surveillance radars from different manufacturers were used at different sites and time periods. The general technical specifications and settings were provided by StUK and were with few exceptions (see chap. 3.2) complied with at all sites. However, data processing of the radars is effectively a black box and differences in detectability of birds are likely to occur between different devices of otherwise similar technical specifications. This is also reflected in the detection function fitted to correct for distance-dependent detectability which varied considerably between different devices. A dedicated calibration of radars from different manufacturers has not been done yet (WENDELN et al. 2007).

Secondly, many different people from four different labs were involved in analyzing the screenshots in the course of the study. Although bird tracks are usually easy to identify, screenshots occasionally leave room for interpretation. Due to limited exchange between the labs involved and the impossibility to validate radar signals this may lead to additional variability in the data.

Furthermore, data were collected during different phases of the wind farm development (baseline, construction, operation). Birds are known to respond to OWFs in various ways (DIERSCHKE et al. 2016; WELCKER & NEHLS 2016). With respect to nocturnal migrants, however, little is known about the sign (attraction vs. avoidance) and the magnitude of the response and several factors such as weather conditions, illumination scheme, distance to turbines and species may all play an important role (MARQUES et al. 2014; SCHULZ et al. 2014).

The generally high day-to-day variation of migration intensities in combination with a high degree of confounding between labs and OWF stages made it difficult to determine systematic differences between the developmental stages of the OWFs and the labs involved in data collection. Pooling all available data suggested that the lab responsible for data collection had a small but significant effect on MTRs. Also, MTRs varied with developmental phase with MTRs being slightly lower during construction compared to baseline but no difference between baseline and operation. However, lab explained only about 3.0%, developmental phase 0.4% of the variance in the data. This suggests that although these factors have added noise to the data a strong effect on results seems unlikely.

Several explanations may account for the negligible overall effect of stage on MTRs. The response of nocturnal migrants may be context-dependent and differ with weather conditions, time of day or species involved. In some situations birds may be attracted, e.g. attraction to illuminated structures during poor visibility or inclement weather, in other situations (e.g. during favorable migration conditions) birds may avoid OWFs. Alternatively, radar sites (anchoring positions or platform locations) were - with few exceptions - located between approx. 0.5 km and 3 km distance from the construction sites or nearest turbines. As many nocturnal migrants, particularly passerines, are likely to respond to turbines at a close range, these distances may have been too large to detect an effect of stage.

The detection probability of a bird by marine surveillance radar is highly distance-dependent. This was corrected for by fitting a detection function following a distance sampling approach (BUCKLAND et al. 2001; HÜPPOP et al. 2004; WELCKER et al. 2017). As the detection function differed considerably between radars from different manufacturers, corrections were done for each device separately. To account for potential differences depending on magnetron characteristics or age, distance correction was also done for each study year or lifetime of a magnetron separately, if the time of magnetron exchange was known.

One general assumption of the distance correction, however, is that the detection probability at its maximum is one, i.e. that at this distance all birds are detected. Whether this is true has to the best of our knowledge never been tested. Comparisons of relative MTRs of different radar types including marine surveillance radars have shown fairly good correspondence of results (FEBI 2013; LIECHTI et al. 2018; NILSSON et al. 2018) but a thorough comparison of absolute migration fluxes as recorded in this study with dedicated bird radars or other calibration methods is still missing (WENDELN et al. 2007; URMY & WARREN 2017). A maximum detection probability smaller than 1 would result in underestimation of MTRs.

On the other hand, the erroneous classification of insects and bats could lead to an overestimation of bird migration intensities. In contrast to systems that are able to measure wing beat frequency, with marine surveillance radars the distinction between different biological signals can only be made by track characteristics. Even though this is usually considered as unproblematic by the radar ornithologists involved in track identification, due to the difficulty of ground truthing the possibility of misidentification cannot be excluded. As the number of bats recorded at offshore sites is usually low (HÜPPOP et al. 2009; SCHULZ et al. 2013) contamination with insect signals has a higher potential impact on calculated MTRs, especially during the summer months.

Hence, MTRs presented in this study have to be regarded as a relative measure of migration intensities.

5.1 Seasonality

The pooled data showed a strong seasonal pattern with peak migration intensities in early April and mid-October. This is in good correspondence with earlier studies in the region (OREJAS et al. 2005; VAN BELLE et al. 2007; FEBI 2013; SCHULZ et al. 2013; FIJN et al. 2015; KRIJGSVELD et al. 2015). While in spring the general pattern was similar in the North and Baltic Sea, in fall migration intensities in the Baltic peaked earlier compared to the North Sea.

The vast majority of nocturnal migrants in the study area are passerines. Radar studies measuring wing beat frequency reported a proportion of songbirds between 75-90% with most of the remaining signals being unidentified (SCHULZ et al. 2013, 2014). The difference in the seasonal pattern in fall may be related to differences in passerine species composition in the two regions. The peak in August/September in the Baltic is probably caused by long-distance migrants such as *sylviid* and *Acrocephalidae* warblers, leaf warblers (*Phylloscopus* spec.) and Old World flycatchers

(*Muscicapidae*), of which the willow warbler (*Phylloscopus trochilus*) may play the most important role as it is the single most common nocturnal migrant breeding in Scandinavia (SCHULZ et al. 2013; BIRDLIFE INTERNATIONAL 2018). The part of the breeding population of these species migrating over the North Sea might be substantially smaller than the proportion crossing the Baltic Sea. This notion is supported by data from collision fatalities at research platforms. Leaf warblers constituted 35% of all carcasses found at FINO2 in the Baltic (SCHULZ et al. 2013) but only 0.9% at FINO1 in the North Sea (HÜPPOP et al. 2009). However, it has to be kept in mind that the seasonal pattern in the Baltic Sea reported in this study is based on data from two sites only. Data from a larger number of sites is necessary to corroborate these results.

5.2 Spatial correlation

Overall, nocturnal migration intensities were strongly correlated within the German EEZ as expected under the assumption of broad-front migration as the predominant migration behavior of migratory passerines in the area. The actual correlation of flux rates might be even higher as noise caused by different radar devices, labs and personnel involved in data collection may have reduced correspondence of MTRs across sites. The correlations of MTRs below 200 m altitude were only slightly lower compared to MTRs of the whole altitude range suggesting that changes in flight height occurred largely simultaneously at the different locations.

In fall correlation strength within the North Sea decreased with increasing distance between sites. However, the decline was small (from a correlation coefficient of about 0.7 at sites in close proximity to about 0.5 between sites 150 km distant) indicating that migration patterns within the North Sea varied relatively little across space. In contrast, correlations between sites across the North and Baltic Sea were much weaker suggesting regional differences in migration activity and indicating the spatial limitations of broad-front migration patterns.

This pattern within the North Sea deviates from results of flight call intensities (WELCKER & VILELA 2018). Call rates of waders and thrushes showed strong declines of correlation strength with increasing distance between sites in both spring and fall. Call rates are to a larger degree dependent on local conditions such as visibility, cloud cover or precipitation (FARNSWORTH 2005; HÜPPOP & HILGERLOH 2012; HORTON et al. 2015; WELCKER & VILELA 2018). In addition to flight height these factors may influence the propensity of birds to utter flight calls and thus cause higher variation among sites. This may also explain why correlations of MTRs derived from radar data were generally higher than those of call intensities (WELCKER & VILELA 2018).

5.3 Mass migration

The term 'mass migration' is often used describing migration events where flux rates seem strikingly high. The term is also used in approval documents of German OWFs where incidental provision 21 regulates potential measures to be taken by the wind farm operators in the event of mass migration. However, a definition of mass migration in terms of a threshold flux rate is still missing. Here we tested whether mass migration can be defined based on the distribution of the data.

The distribution of the raw data of nocturnal migration intensities was highly right-skewed; log-transformation resulted in an approximately normal distribution. As there was no indication of a bi-modal or multi-modal distribution it was not possible to derive a threshold value to separate events of mass migration based on the distribution of the data (see chap. 3.2.3). This was similar to the flight call data which was also continuously distributed and did not allow the determination of a data-driven cut-off value to distinguish mass migration. Hence, the definition of mass migration is essentially arbitrary and needs to be based on considerations other than data distribution.

For the purpose of this study we defined mass migration when a mean migration intensity of 500 MTR was exceeded. This applied to about 6% of the nights. The threshold value for 'high migration intensities' was set at 250 MTR (15% of the nights). These values were solely chosen as to facilitate our analysis of the simultaneous occurrence of high rates of nocturnal migration in the study area. For other purposes these cut-off values are unlikely to be meaningful.

The likelihood of coincidence of high migration intensities decreased with increasing distance between sites in the North Sea, particularly in fall. The estimated probability for simultaneously high MTRs was close to 0.8 for sites less than 20 km apart but declined to <0.2 when distance between sites was >100 km. Hence, the effect of distance on the coincidence of mass migration was stronger than on the general correlation of flux rates. This could be related to a gradient of migration intensities with distance to shore in the North See (see chap. 4.4.2). Migration intensities at sites further offshore tend to be lower and, consequently, the probability of them exceeding an absolute threshold value is also lower compared to sites closer to shore. Hence, our data suggest that mass migration in the German EEZ is often a rather local event, at least when a fixed threshold value is applied to define mass migration.

5.4 Spatial gradient

The number of nocturnally migrating passerines passing over the western Baltic Sea has been estimated to be larger than the number of birds migrating over the North Sea (OREJAS et al. 2005; BELLEBAUM et al. 2010; BSH 2014, 2015). Therefore one would predict higher mean migration intensities in the Baltic than in the North Sea. All data pooled, our results support this hypothesis with median MTRs being about 10% higher in the Baltic compared to the North Sea. However, when analyzing the data in more detail, the situation appears more complex.

With respect to MTRs below 200 m altitude, the difference between the Baltic and the North Sea was considerably larger in spring but absent in fall. This different pattern can be explained by differences in flight height (see chap. 4.5) with birds on average flying higher in the North than the Baltic Sea in spring but vice versa in fall. Furthermore, in correspondence with differences in seasonal patterns, the difference in MTRs between regions varied among months. In the North Sea MTRs were higher in March, October and November while the opposite was true for all other months. Differences in the timing of migration and the species involved are likely to account for this pattern (see chap. 5.1). Together, these results suggest that while overall migration intensities are higher in the Baltic compared to the North Sea, this pattern might be reversed depending on the altitude range and time period considered.

Within the North Sea our results unambiguously suggest a gradient of migration intensities with distance to shore. Comparisons of MTRs measured simultaneously at different locations showed consistently higher migration intensities closer to shore. Additionally, our data suggest a negative relationship between MTR and distance to shore which was independent of the altitude range considered and the way distance to shore was measured. Such a gradient has often been hypothesized. For diurnal migration, previous studies have shown higher migration intensities along the coast than at offshore locations (HÜPPOP et al. 2009). Yet, due to a paucity of data evidence for this hypothesis for nocturnally migrating birds was scarce (JELLMANN 1977; KNUST et al. 2003; BSH 2015). However, the sites included in our analysis covered only the inner part of the German EEZ in the North Sea. The maximum difference in distance to shore between sites was 90 km; the maximum absolute distance to shore was 110 km. Whether the pattern of decreasing nocturnal migration intensities holds also for areas of the EEZ further away from shore remains to be demonstrated.

5.5 Flight height

Flight height is one of the most important factors affecting the collision risk of nocturnal migrants at OWFs. Flight height is influenced by a variety of factors, most notably weather conditions. Cloud cover, precipitation, as well as wind speed and direction have been identified as important parameters (BRUDERER et al. 1995, 2018; DOKTER et al. 2013b; KEMP et al. 2013; SHAMOUN-BARANES et al. 2017). In our data, collected over several years, the influence of weather is presumably levelled out so that flight height distributions reflect the general height preferences of migrating birds in the study area.

In total about 35% of all flights occurred below 200 m altitude. This proportion is presumably a conservative estimate as due to sea clutter close to the sea surface the detection probability of very low flying birds is reduced (BELLEBAUM et al. 2010). On the other hand, radars in this study recorded bird migration only up to 1000 m altitude. Previous studies have shown that bird migration in the study area takes place in heights up to 4000 m with the proportion above 1000 m reaching up to 30% in some nights (JELLMANN 1979; FEBI 2013; SCHULZ et al. 2013, 2014; BRUDERER et al. 2018).

Several earlier studies have reported a similar preference for flight heights below 200 m in coastal and offshore areas of the North and Baltic Sea with its proportion varying between 25-50% (ZEHNDER et al. 2001; OREJAS et al. 2005; HÜPPOP et al. 2006; BELLEBAUM et al. 2010; SCHULZ et al. 2013; BRUDERER et al. 2018). Nocturnal migrants generally seem to favor low altitudes and do not necessarily increase flight height even if optimal conditions prevail at higher altitudes (KEMP et al. 2013). This has been related to the time and energy costs of reaching higher altitudes (LIECHTI et al. 2000), including potentially higher water loss (KLAASSEN 2004), lower oxygen partial pressure and a decrease in lift (PENNYCUICK 2008).

Flight height differed between seasons and regions. In the North Sea, mean flight height was approx. 100 m higher in spring compared to fall. Similar results have been reported previously (EASTWOOD & RIDER 1965; JELLMANN 1989; OREJAS et al. 2005). Seasonal differences in synoptic conditions, particularly with respect to wind support, may account for this pattern (DOKTER et al. 2013b; SHAMOUN-BARANES et al. 2017). With prevailing westerly and south-westerly winds in the study area in spring, birds may encounter favorable wind conditions more often than in fall, and birds tend to fly lower with headwinds. For example, DOKTER et al. (2013b) showed that in temperate Europe wind conditions with high altitude optima for nocturnal migration almost exclusively occurred during spring. Conversely, in fall, westerly winds, usually increasing with altitude, favor low flight altitudes (BRUDERER et al. 2018).

In contrast to the situation in the North Sea, we did not find a difference in mean flight height between seasons in the Baltic. Comparable radar data from other studies is scarce. BELLEBAUM et al. (2010), SCHULZ et al. (2013) and FEBI (2013) present data from both spring and fall showing no apparent difference in flights height distributions between seasons, but none of these studies explicitly compares mean heights. IFAÖ (2010) found a lower proportion of birds flying below 200 m in spring of one but not the other study year. HÜPPOP et al. (2004) reported no difference in flight height between seasons on the island of Rügen but higher flight heights in fall compared to spring on Fehmarn. Despite high interannual variation, these studies seem to confirm the lack of a consistent seasonal difference in flight heights in the Baltic Sea. What drives the difference in seasonal flight heights between the North and Baltic Sea remains unknown.

Within the North Sea we found that flight heights decline with increasing distance to shore, at least in fall. Some earlier evidence suggest that nocturnal migrants fly lower over the sea compared to the coast (EASTWOOD & RIDER 1965; BRUDERER & LIECHTI 1998). Our results indicate that flight heights may further decrease the further offshore birds migrate. Wind conditions may play an important role in this pattern (OREJAS et al. 2005).

There was also a strong positive relationship between flight heights and migration intensities. Hence, when migration intensity is high, the proportion of low flying birds may be smaller than during nights with low migration intensities. This might be related to the fact that migration activity and flight altitude both increase when conditions for migration are favorable (HÜPPOP et al. 2004, 2009; BELLEBAUM et al. 2010; KEMP et al. 2013; SHAMOUN-BARANES et al. 2017).

Flight height also varied systematically within the course of the night. Mean flight height was highest during the first part of the night and decreased continuously as the night progressed. At the end of the night flight height was about 70 m lower than at the beginning. A similar pattern has previously been described (BRUDERER & LIECHTI 1998; FORTIN et al. 1999; ZEHNDER et al. 2001; HÜPPOP et al. 2004). The reasons for this pattern are not quite clear. Nocturnal migrants usually climb relatively quickly to their preferred flight altitude during the first hours after onset of migration (BRUDERER et al. 1995; ZEHNDER et al. 2001). The following decrease in flight height corresponds to a similar decline in migration intensities (FORTIN et al. 1999; ZEHNDER et al. 2001; HÜPPOP et al. 2004, 2009; KEMP 2012; see also chap 4.7). As most migrants commence migration within two hours after sunset this suggests that birds often do not migrate throughout the night but start to land after a few hours aloft (BRUDERER & LIECHTI 1998). Hence, the decrease of flight altitudes in the course of the night might reflect an increasing proportion of birds preparing to land.

5.6 Correlation between migration intensities and call rates

Overall, migration intensities and flight call rates, recorded simultaneously at the same sites (WELCKER & VILELA 2018), were positively correlated although unexplained variance was high (R^2 = 0.11). As can be expected from the fact that flight calls are mostly audible within a distance of 200-300 m, the correlation was higher with MTRs below 200 m altitude(R^2 = 0.16). This corresponds well with results from FARNSWORTH et al. (2004) who reported similar relationships for simultaneous radar observations and recordings of flight calls in the eastern US. Thus, while migration intensity may be an essential driver of flight call rates other factors account for the largest part of the variation (WELCKER & VILELA 2018).

One of these factors is the species composition of migrants at a specific time period. Correlations between migration intensities and call rates were higher in October and November than earlier in the fall migration period. Many of the long-distance migrating passerines that reach their peak migration in August and September do not emit flight calls (e.g. *Sylviid* and *Acrocephalidae* warblers, leaf warblers). Therefore, many of the birds recorded by radar in this time period may not be represented in flight call recordings. In contrast, many of the short-distance migrants such as thrushes that dominate the species composition of nocturnal migrants in October and November are vocally active.

5.7 Diurnal pattern

MTRs showed a strong diurnal pattern which was largely similar at all sites and corresponded well with results from earlier studies (JELLMANN 1977; FORTIN et al. 1999; ZEHNDER et al. 2001; FIJN et al. 2015). The steep increase of MTRs within two hours after sunset as well as the peak before midnight reflects the fact that most nocturnal migrants start migration at or shortly after sunset. It also suggests that the bulk of migrants crossing the North and Baltic Sea start from coastal areas as otherwise peak migration would be expected later during the night. As MTRs decline throughout the second half of the night an increasing proportion of birds seem to avoid crossing a large body of water as the night progresses. This has also been shown for the Mediterranean where FORTIN et al. (1999) reported increasing landward migration in the course of the night at several coastal locations.

The seasonal differences of the pattern in different parts of the German Bight are likely driven by the distance of the offshore sites in relation to the start-off areas of most migrants. In fall, sites in the northeastern German Bight are relatively close to coastal areas of western Denmark from where, assuming a south-westerly migration direction, most nocturnal migrants crossing the North Sea are likely to start from. Correspondingly, MTRs at these sites increase sharply within the first hour after sunset. In contrast, in spring, when most birds are expected to start from coastal areas in north-western Germany and north-eastern Netherlands, the increase and peak of migration occurs 3-4 h later at these northeastern sites. This time difference matches the difference in distance from potential start-off areas to the offshore locations. Accordingly, this pattern was reversed at sites in the southern German Bight. At sites in the Baltic there was no seasonal difference in the onset and peak of nocturnal migration. Both study sites in the Baltic were situated roughly centrally between the coast of southern Sweden and north-eastern Germany. Hence there was no difference in distance to potential start-off sites.

5.8 Estimates of the total number of radar signals

Based on the estimated MTRs, the spatial extent of the wind farms and the duration of the migration periods in spring and fall (according to StUK), we estimated the total number of radar signals (as a proxy for bird movements) annually passing the footprint of all operational wind farms and wind farms currently under construction in the German EEZ. We derived estimates for both daytime and nocturnal migration. As discussed above these estimates are likely to be conservative as it is unlikely that all birds were detected even at the range of the radar with the highest detection probability. In addition, other factors affect detectability (SCHMALJOHANN et al. 2008; see also above). Estimates for daytime migration are subject to further uncertainties. First, in contrast to nocturnal migrants diurnally migrating birds often fly in flocks. Depending on flock size and the size of the birds, and due to the limited spatial resolution of the radar these will often be represented by only a single radar signal. The number of diurnal bird movements will therefore be further underestimated. Additionally, diurnal radar signals are less representative of bird migration as they are likely to contain a larger proportion of movements of resident seabirds.

Our radar data was collected during baseline, construction and the operational phase of OWFs and radar sites were almost exclusively located outside the footprint of the wind farm. Any response of nocturnal migrants to the presence of the wind farms, which is likely to occur at close range to the structures, is therefore not reflected in the data (see also above). As discussed above, whether nocturnal migrants largely avoid or are attracted to OWFs is still debated (SCHULZ et al. 2014), but these responses would affect the number of bird movements within the wind farm perimeter.

Given these sources of uncertainty, we estimated a total of 24.3 million bird movements at rotor height during the migration periods each year in the 23 wind farms considered. One other estimate has been published so far. Using a dedicated bird radar, FIJN et al. (2015) calculated a total of 1.6 million bird echoes at rotor height at a Dutch offshore wind farm throughout a whole year. Due to several reasons, these estimates are not directly comparable. In contrast to our study, FIJN et al. (2015) used a different radar device that applied an internal algorithm to identify bird signals. In addition, there were differences in rotor and turbine dimensions, wind farm size as well as the time period for which the number of bird signals were estimated. Nonetheless both studies confirm that bird movements at the scale of millions are to be expected at rotor height during the operational phase of offshore wind farms in the North and Baltic Sea.

The majority of the estimated number of bird movements at rotor height (c. 62 % or 15.1 million) was recorded during the night. The total number nocturnal passerine migrants has been estimated at about 100 million for the North Sea (40 - 150 million; OREJAS et al. 2005; BSH 2015) and at about 200- 500 million for the western Baltic Sea (BERTHOLD 2000; BELLEBAUM et al. 2010; BSH 2014). These values are not directly comparable as our estimates also contain movements of non-migrating birds and are subject to a number of other uncertainties (see above). Additionally, our estimate is based on the summation of the estimates of single OWFs. Yet, these numbers still suggest that the proportion of birds that pass through an OWF on their nocturnal migration through the German EEZ might be considerable.

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A APPENDIX

Tab. A 1 Mean migration intensities (MTR, log-transformed ±SE) at the study sites during the different study years.

Site	Mean MTR (log-transformed ±SE)								
	2008	2009	2010	2011	2012	2013	2014	2015	2016
ABW				1.26 ±0.15	1.58 ±0.19		1.35 ±0.11		
Albatros	1.07 ±0.09	1.24 ±0.09							
Baltic2			1.34 ±0.16			1.47 ±0.17	1.45 ±0.11	1.61 ±0.14	1.55 ±0.09
Butendiek				1.29 ±0.10			1.30 ±0.11	1.52 ±0.13	0.51 ±0.07
Cluster 12		1.89 ±0.09	1.21 ±0.09						
Cluster Helgoland								1.48 ±0.07	1.59 ±0.06
FINO1	2.37 ±0.04	2.36 ±0.05	2.19 ±0.05	2.76 ±0.03	2.81 ±0.03	2.80 ±0.05	2.55 ±0.04	2.30 ±0.05	2.36 ±0.07
FINO3				0.77 ±0.09		0.49 ±0.06	0.48 ±0.06	0.39 ±0.08	0.52 ±0.07
GT1		1.67 ±0.11			0.23 ±0.20	0.71 ±0.13	1.12 ±0.14	1.45 ±0.14	1.58 ±0.10
MSO			2.67 ±0.14	2.34 ±0.11	1.99 ±0.16	1.89 ±0.09	1.56 ±0.10		
NSO			2.02 ±0.09		1.69 ±0.16	1.62 ±0.09	1.58 ±0.10		
Wikinger							1.84 ±0.14	1.67 ±0.09	2.22 ±0.11

Tab. A 2 Number of nights per site and year. Only nights for which for at least 75% of the hours radar data were available were included in the study

Site	2008	2009	2010	2011	2012	2013	2014	2015	2016
ABW				23	20		48		
Albatros	56	42							
Baltic2			35			24	48	40	40
Butendiek				57			40	22	130
Cluster 12		56	43						
Cluster Helgoland								183	189

Site	2008	2009	2010	2011	2012	2013	2014	2015	2016
FINO1	191	196	198	181	158	192	209	206	174
FINO3				112		162	175	128	119
GT1		44			24	48	41	28	38
MSO			16	24	18	40	39		
NSO			45		13	55	52		
Wikinger							29	54	44

A.1 Spatial correlation of migration intensities

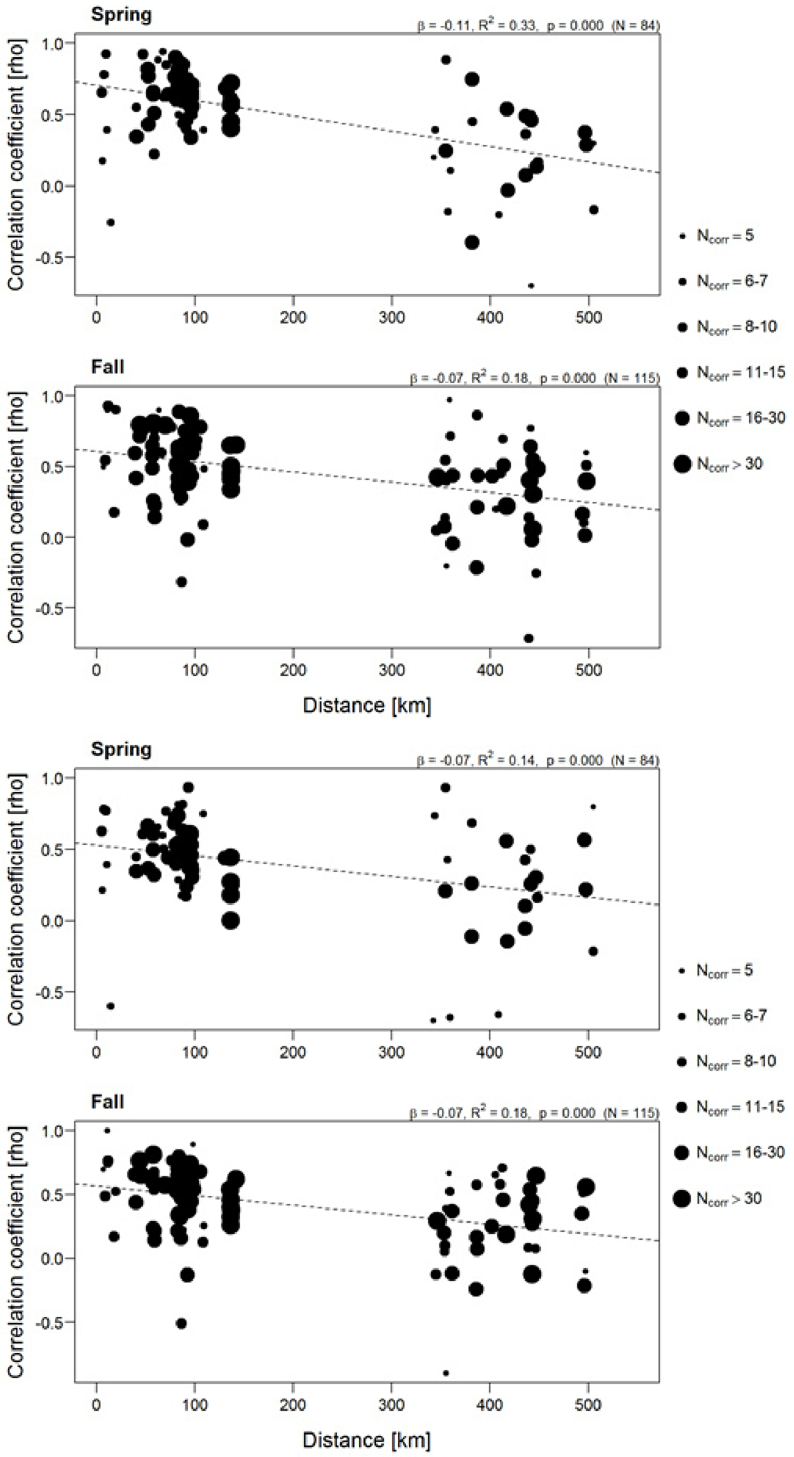

Figure A. 1 Relationship between distance between sites and the correlation of migration intensities (Spearman's rank correlation coefficient rho*) for spring and fall. Upper two panels: altitude range to 1000 m; lower two panels: altitude range to 200 m. At distances >300 km correlation coefficients are based on comparisons between sites in the North and Baltic Sea. For further details see Figure 4.4 and Materials & Methods.*

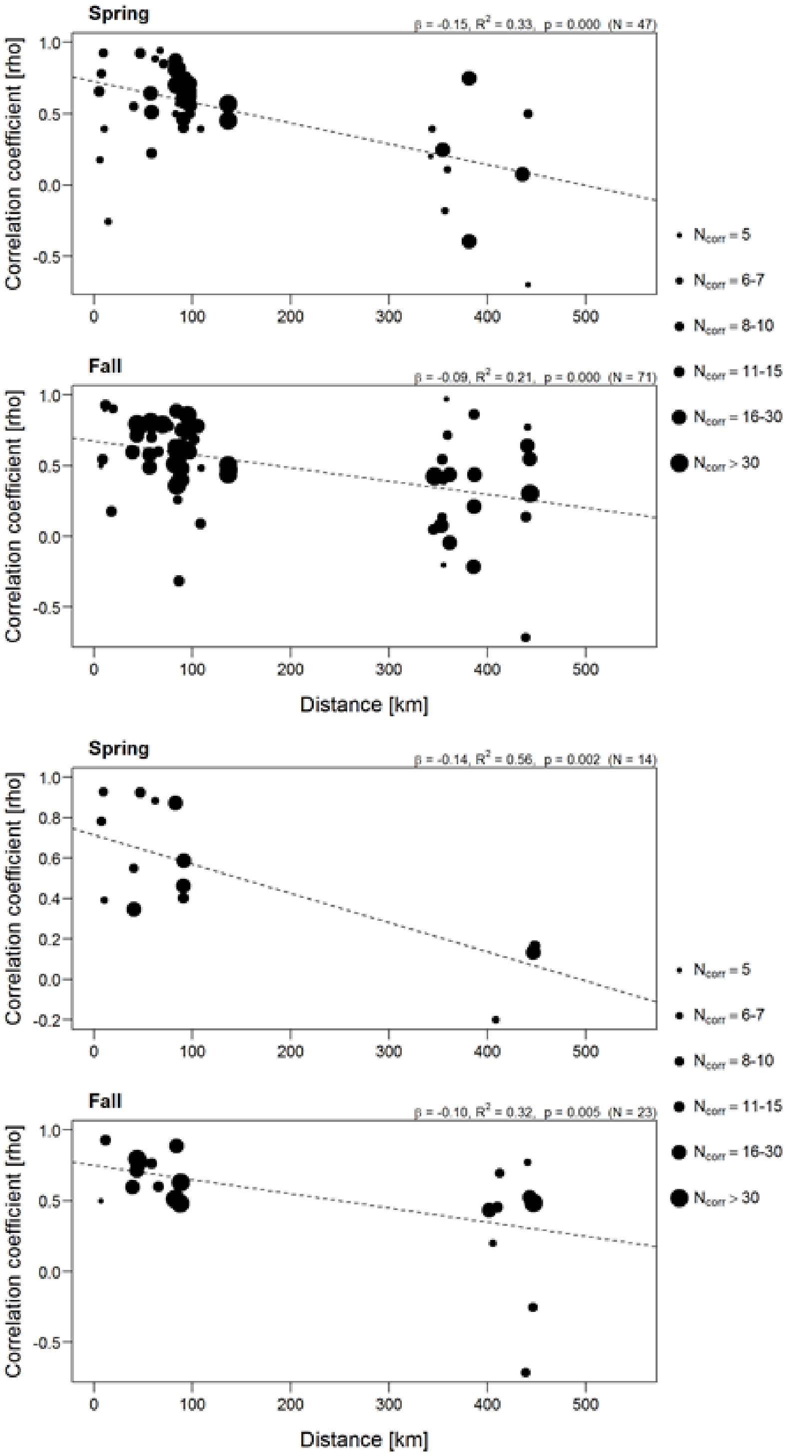

Figure A. 2 *Relationship between distance between sites and the correlation of migration intensities (Spearman's rank correlation coefficient* rho*) for spring and fall). Upper two panels: data collected at the same stage of wind farm development (baseline, construction, operation) only; lower two panels: by the same lab only. At distances >300 km correlation coefficients are based on comparisons between sites in the North and Baltic Sea. For further details see Figure 4.4 and Materials & Methods.*

A.2 Correlation of mass migration

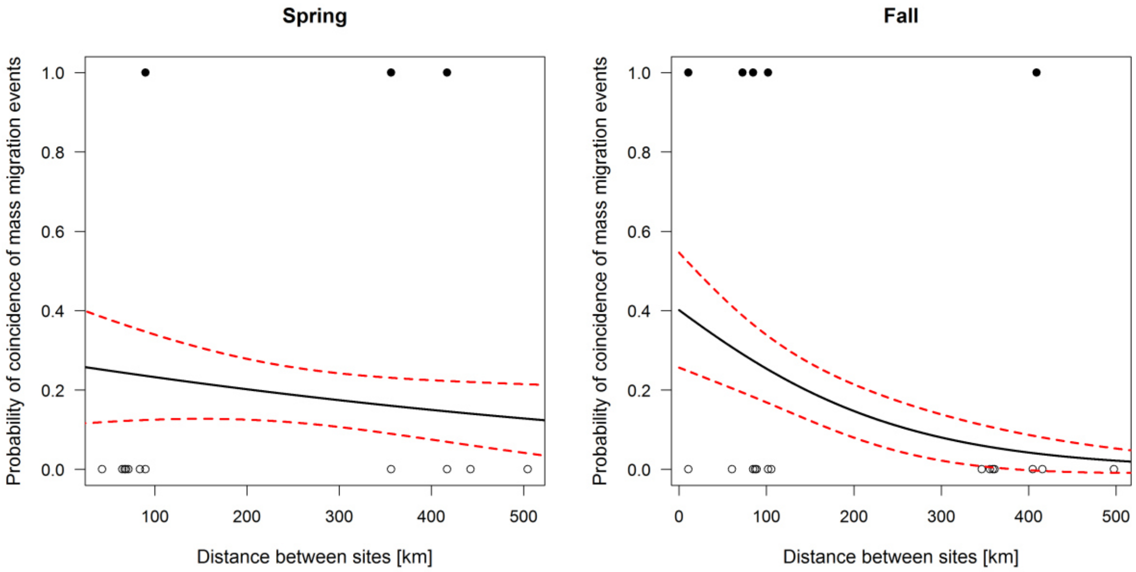

Figure A. 3 *Relationship between the distance between sites and the predicted probability [± SE] of coincidence of mass migration at these sites in spring (left panel) and fall (right panel). Predicted probabilities are based on generalized linear models with binomial error structure (see text for further details). Filled symbols represent distances between sites at which mass migration coincided, open symbols distances at which mass migration did not coincide.*

A.3 Gradient of migration intensities

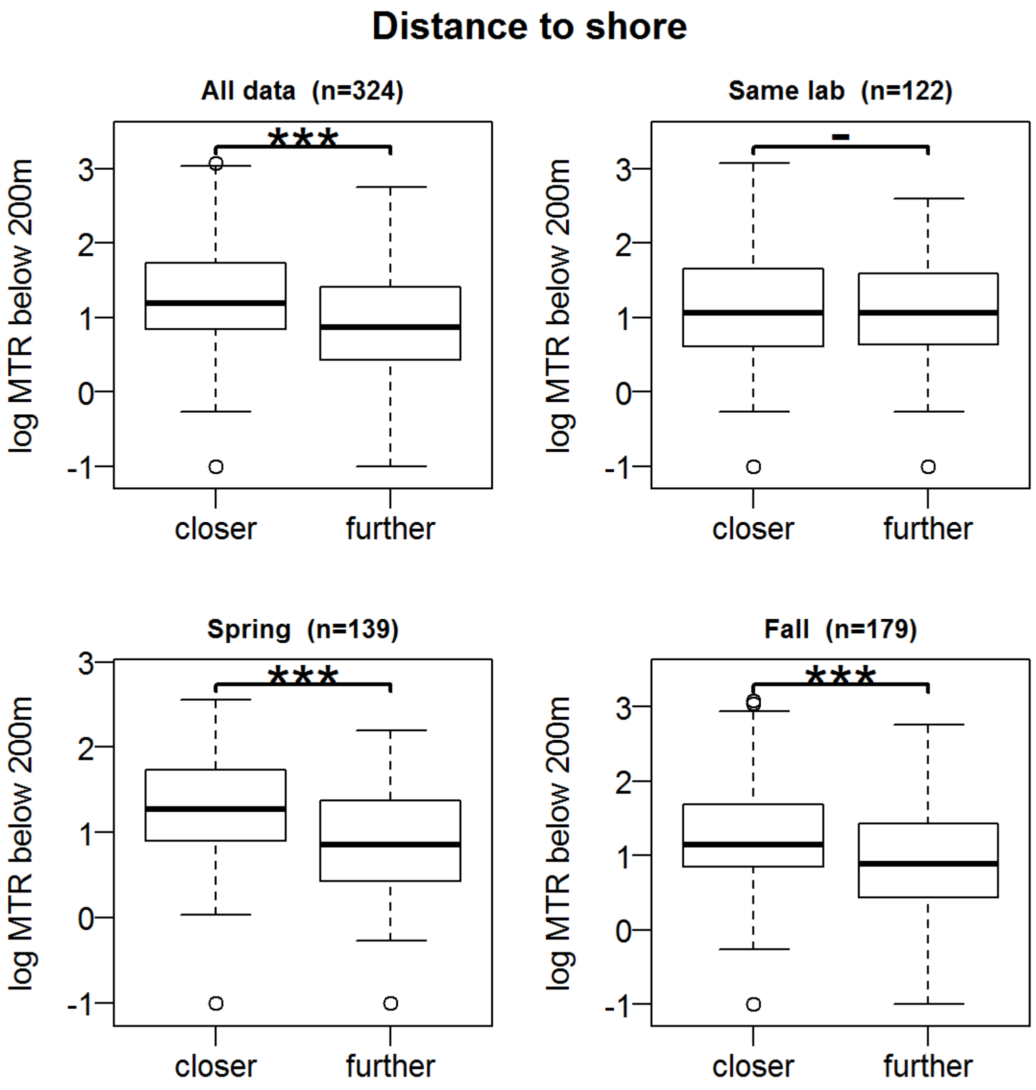

Figure A. 4 Comparison of migration intensities below 200 altitude (MTR, log transformed) simultaneously measured at two different sites in the North Sea with different distances to shore. See Figure 4.10 for details.

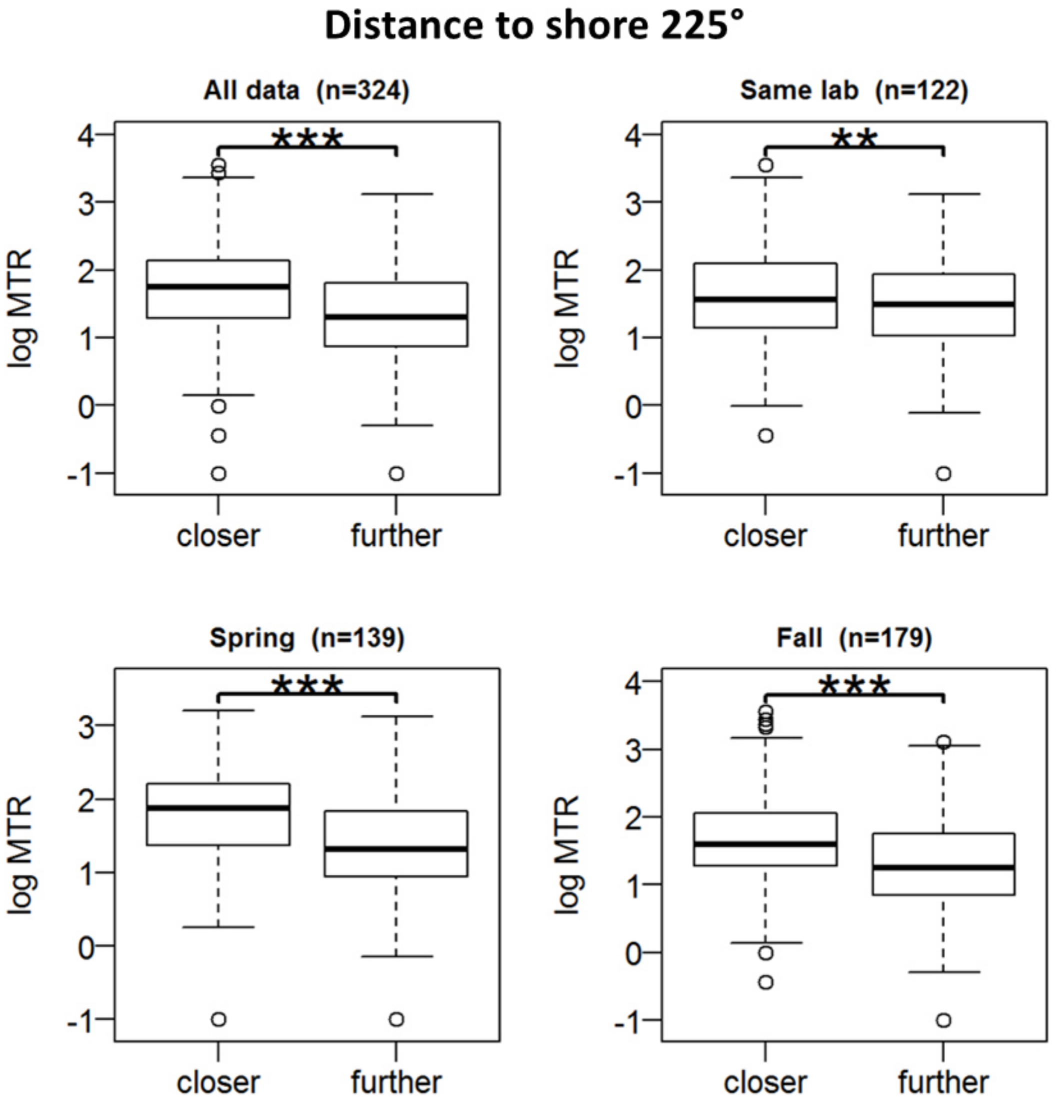

Figure A. 5 Comparison of migration intensities (MTR, log transformed) simultaneously measured at two different sites in the North Sea with different distances to shore as measured perpendicular to the assumed migration direction of 45° and 225° in spring and fall, respectively. See Figure 4.10 for details.

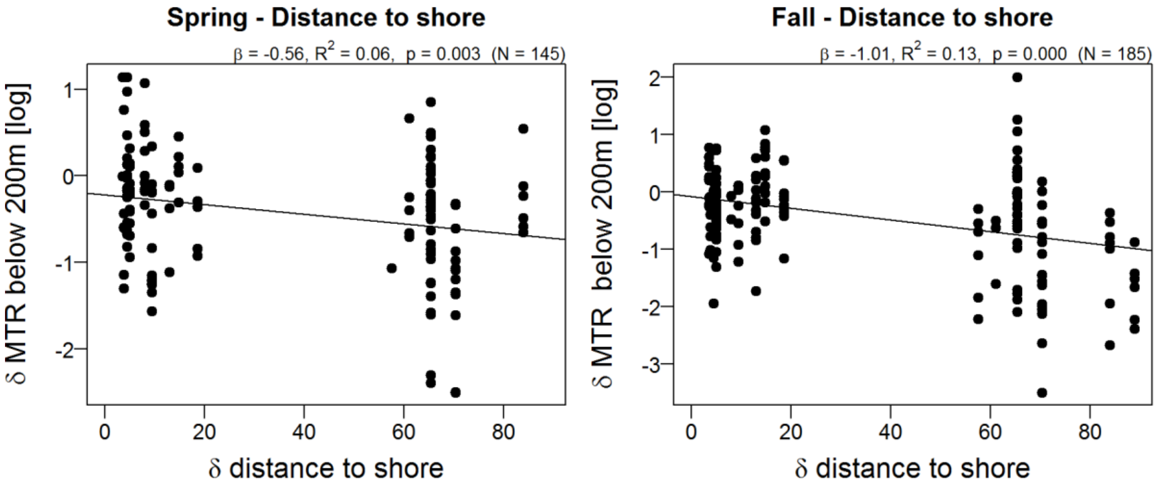

Figure A. 6 *Relationship of the difference in migration intensities below 200 m altitude between two sites and their difference in distance to shore. The results of a linear regression are given above the plot. Left panel: during spring migration; right panel: during fall migration.*

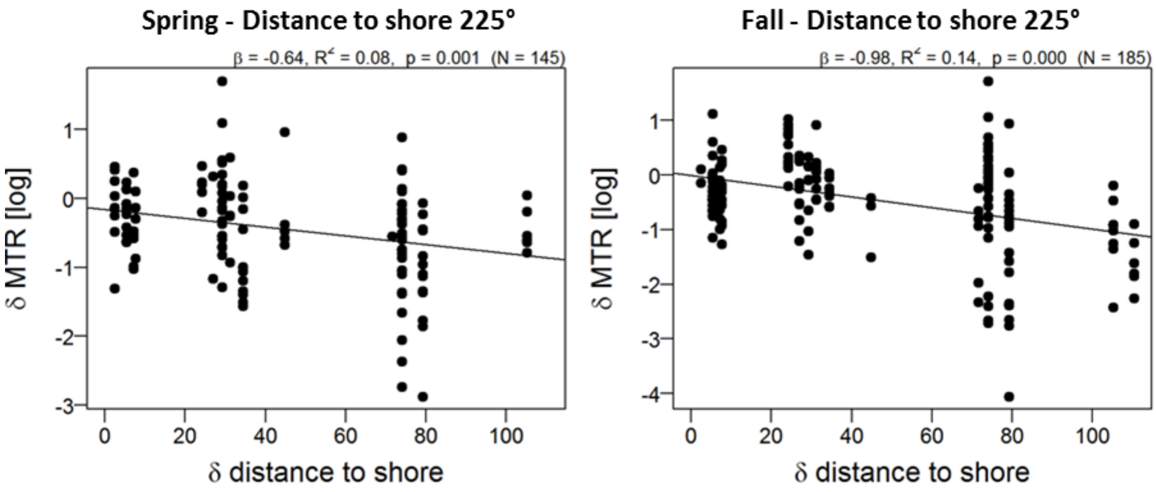

Figure A. 7 *Relationship of the difference in migration intensities between two sites and their difference in distance to shore as measured perpendicular to the assumed migration axis SW-NE (45° and 225° in spring and fall, respectively). The results of a linear regression are given above the plot. Left panel: during spring migration; right panel: during fall migration.*

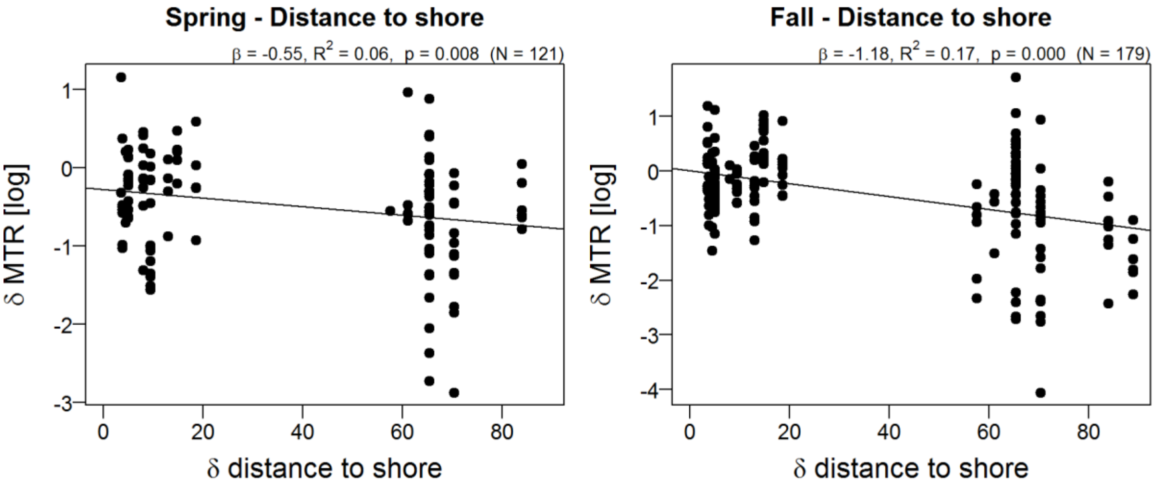

Figure A. 8 Relationship of the difference in migration intensities between two sites and their difference in distance to shore. Data restricted to the same developmental phase of the wind farms. The results of a linear regression are given above the plot. Left panel: during spring migration; right panel: during fall migration.

A.4 Patterns of flight height

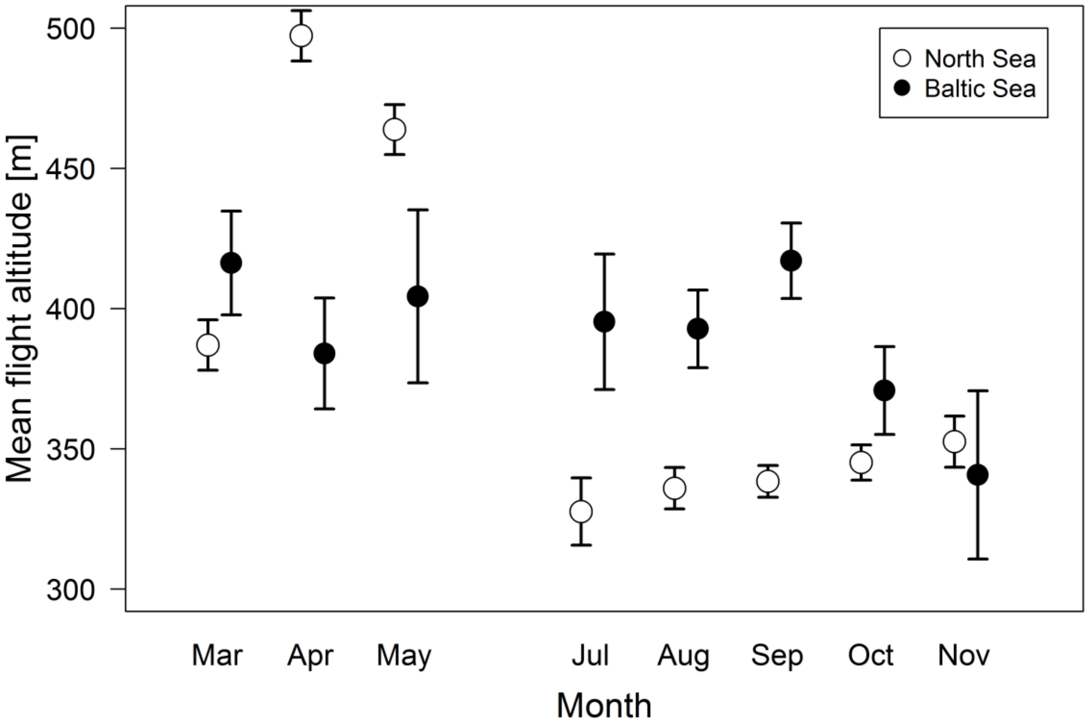

Figure A. 9 Comparison of mean flight height per night [m ±SE] between North Sea and Baltic Sea during the months of spring and fall migration.

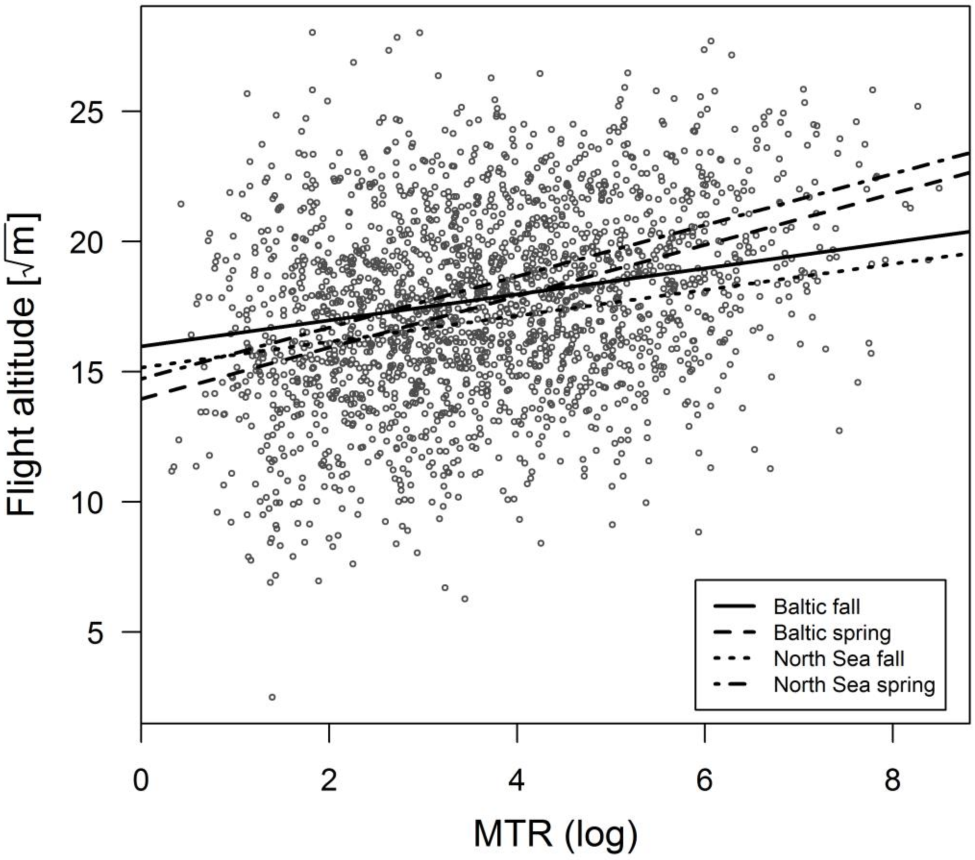

Figure A. 10 Relationship between flight height [m, sqrt-transformed] and migration intensity [MTR, log-transformed] for the North and Baltic Sea, and for spring and fall.

A.5 Estimation of total number of radar signals

Tab. A 3 Offshore wind farms in the German EEZ for which the total number of radar signals per season was estimated. In addition, the data source for each site is given.

Area	Wind farm	Current state (2019)	Data
N-2	**alpha ventus**	operation	Albatros, Cluster Helgoland, Global Tech I, Meerwind Süd/Ost, Nordsee Ost
	Borkum Riffgrund 1	operation	
	Borkum Riffgrund 2	operation	
	Trianel Windpark Borkum I	operation	
	Merkur	construction	
	Trianel Windpark Borkum II	construction	
N-3	**Gode Wind 1 and 2**	operation	Albatros, Cluster Helgoland, Global Tech I, Meerwind Süd/Ost, Nordsee Ost
	Nordsee One	operation	
N-4	**Amrumbank West**	operation	Amrumbank West, Cluster Helgoland
	Nordsee Ost	operation	Cluster Helgoland, Nordsee Ost
	Meerwind Süd/Ost	operation	Cluster Helgoland, Meerwind Süd/Ost
N-5	**Butendiek**	operation	Butendiek
	DanTysk	operation	
	Sandbank	operation	
N-6	**BARD**	operation	Global Tech I
	Deutsche Bucht	construction	
	Veja Mate	operation	
N-8	**Global Tech I**	operation	Global Tech I
	Hohe See	construction	Global Tech I
	Albatros	construction	Albatros
O-1	**Arkona**	operation	Wikinger
	Wikinger	operation	
O-3	**Baltic 2**	operation	Baltic 2

A.6 Diurnal patterns of bird migration

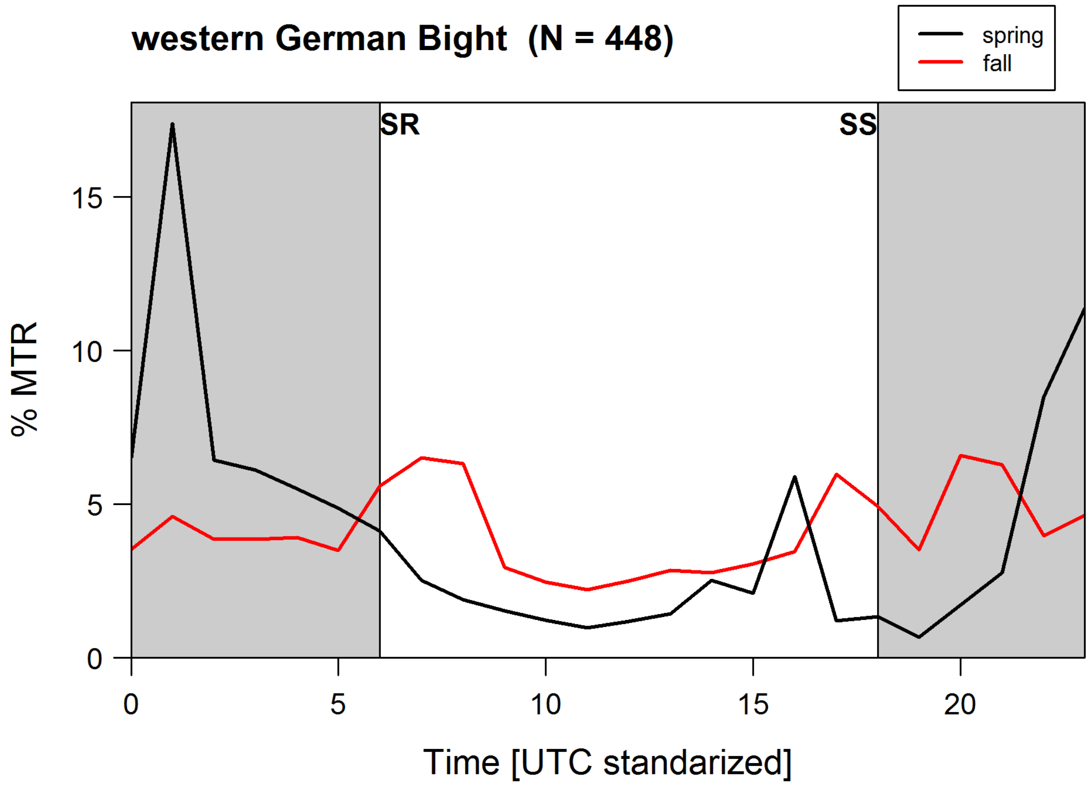

Figure A. 11 Diurnal pattern of migration intensities [%] in spring (black line) and fall (red line) in the western German Bight. The time of day was standardized with sunrise being set at 06:00 and sunset at 18:00. See Chap. 3.2.7 for more details.

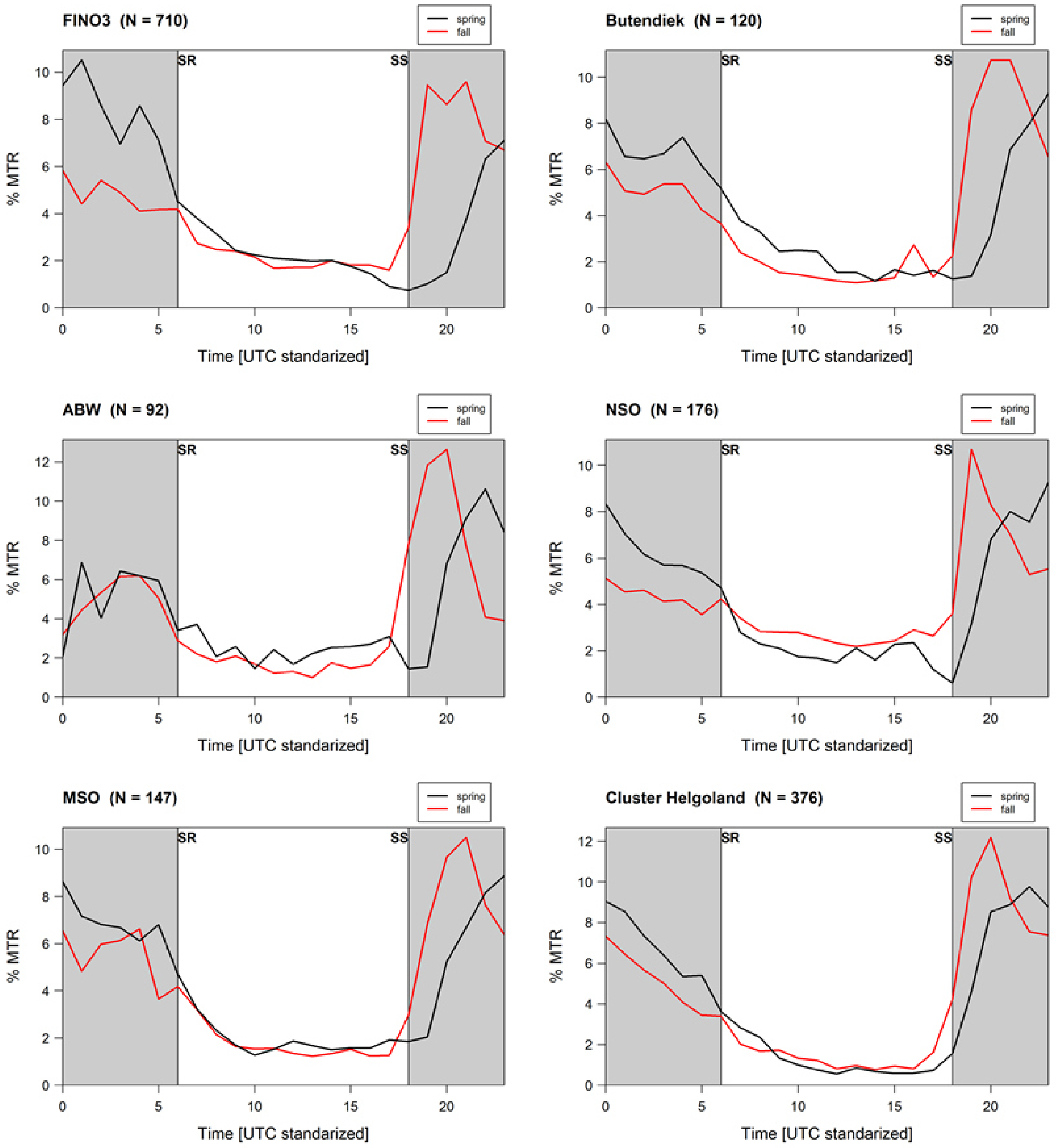

Figure A. 12 Diurnal pattern of migration intensities [%] in spring (black line) and fall (red line) at different OWF locations in the German Bight. The time of day was standardized with sunrise being set at 06:00 and sunset at 18:00. See Chap. 3.2.7 for more details.

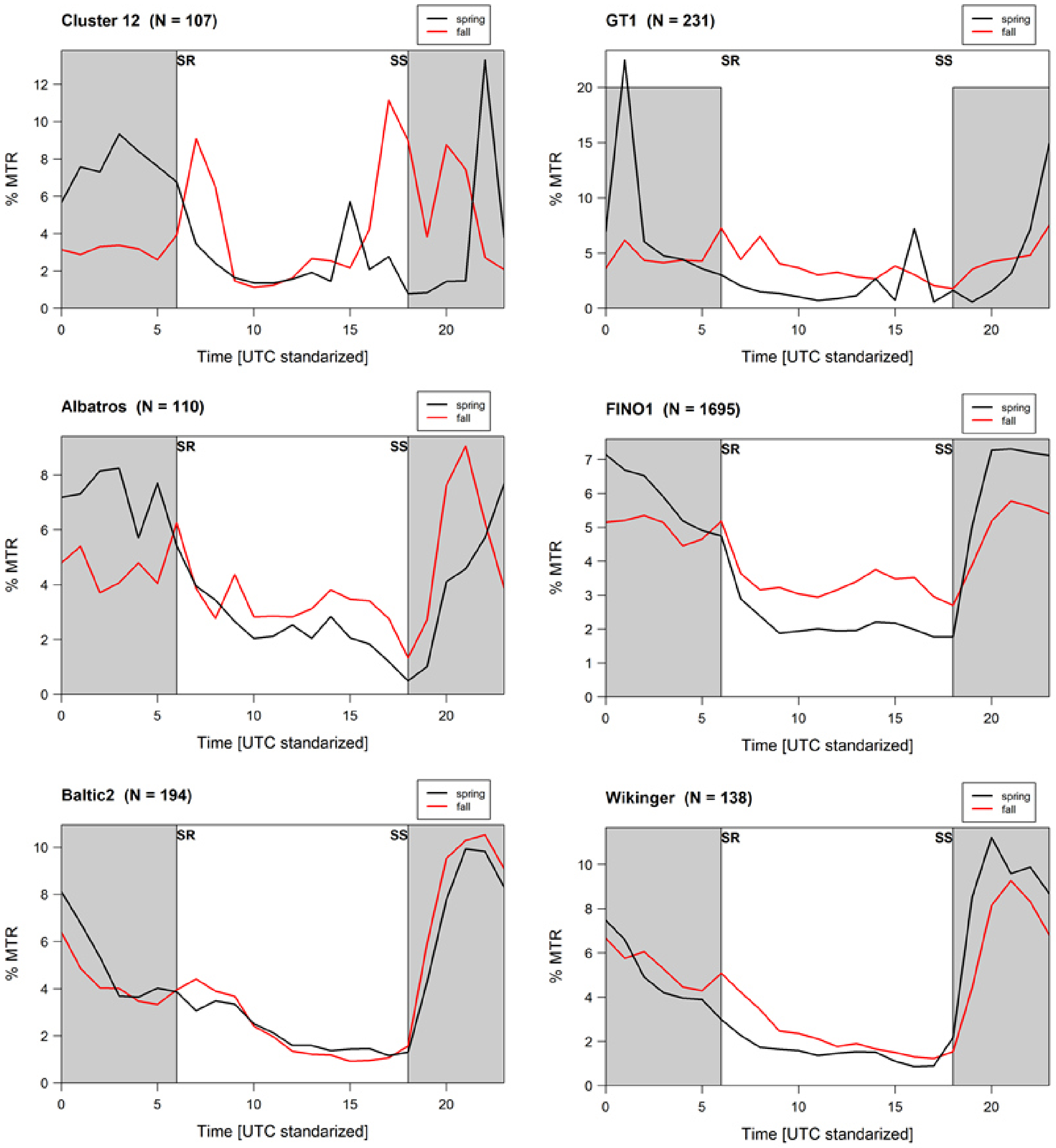

Figure A. 13 Diurnal pattern of migration intensities [%] in spring (black line) and fall (red line) at different OWF locations in the German EEZ of the North Sea and the Baltic Sea. The time of day was standardized with sunrise being set at 06:00 and sunset at 18:00. See Chap. 3.2.7 for more details.