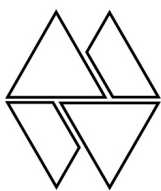


Occurrence of peaks in songbird migration at rotor heights of offshore wind farms in the southern North Sea

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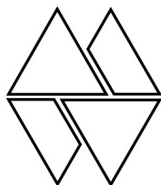


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1 Introduction

Every year songbirds migrate in massive numbers across the North Sea. In the Dutch offshore waters, migration occurs in two major directions. One route is formed by birds migrating between breeding grounds on the mainland of northern Europe / Scandinavia and the UK. The other route is formed by birds migrating between northern Europe / Scandinavia and wintering grounds in southern Europe and Africa (Lack 1958-63, Myres 1964, Lensink *et al.* 2002). Although songbird migration largely takes place at higher altitudes, peaks in activity do also occur at lower altitudes, depending to some extent on weather conditions such as wind speed, wind direction and air temperature (Karlsson *et al.* 2011, Kemp *et al.* 2013). With the on-going development of offshore wind farms, migrating songbirds may collide with offshore wind turbines, potentially resulting in high mortality rates when bird fluxes at rotor height are high. A way to mitigate such mortality is by shutting down wind turbines during periods with high migration activity at rotor altitude. It is, however, largely unknown how often peaks of migration at rotor altitude occur. Here we show the occurrence of peaks in nocturnal migration activity of songbirds at rotor height at sea, as measured at the Dutch Offshore Wind farm Egmond aan Zee (OWEZ) between 2007 and 2011.

2 Methods

Data on bird fluxes were used from the study on flight patterns at Offshore Wind farm Egmond aan Zee (OWEZ; fig. 1), as published in Fijn *et al.* (2015). These data cover the period between 7th of June 2007 and 30th of May 2010 (3 years). Additionally, measurements were continued until March 24 2011, these data were collected to compare the nearshore flight patterns at OWEZ with flight patterns offshore (see below). These additional OWEZ-data are presented briefly, but were not analysed in detail. Briefly, bird fluxes were measured using an automated radar system (Merlin, DeTect Inc., Florida USA) consisting of a 25 kW radar positioned vertically on an offshore metmast at OWEZ (fig. 1). Birds were detected within a range of 1,5 km from the radar. To avoid biases in the data due to detection loss, only data up to 900 m were analysed. Data were collected continuously, except during periods with heavy winds (>7 Bft), rain, or technical failure. Thus, bird fluxes are available over altitudes from sea level up to 900 m altitude. Data analysis was focused on fluxes at altitudes between 25 and 250 m, because these altitudes reflect the rotor heights of current and future offshore wind turbines. For details and further information on study setup and data processing we refer to Fijn *et al.* (2015) and Krijgsveld *et al.* (2011).

The radar system was positioned south of the wind farm, at ca. 1 km from the nearest turbines. This means that migration patterns may be affected by the presence of the wind farm (either attraction or dissuasion). Because our interest is in migration patterns in relation to wind farms, this reflects the desired situation. Depending on for example spacing between turbines and on lighting schemes at the wind farm, migrating songbirds may respond differently to wind farms elsewhere. Turbines at OWEZ emit a continuous red aviation light at night, shining from the hub. Additionally, yellow lights shine intermittently from ca. five buoys and from the metmast, all on the periphery of the wind farm.

A second vertical radar system was positioned at offshore gas platform K14C FA-1 (hereafter K14). This platform is located 60 km west of the Dutch coast, at 53°16'08"N 3°37'44"W (fig. 1). Radar system and settings were the same as in OWEZ. Data were collected between 11th of March 2010 and 21st of March 2011 (1 year), simultaneously with measurements at OWEZ. The radar beam was oriented NW to SE, perpendicular to the expected main flight direction of migrating birds.

The level of migratory activity was determined based on bird flux during hours of darkness. Songbird migration is known to occur mainly at night (Alerstam 2009, Lensink *et al.* 2002). Also Fijn *et al.* (2015) showed for the OWEZ area that during periods of migration the vast majority of birds flew at night. To account for missing data in the database, mean rather than summed fluxes per night were used to assess the (relative) level of migratory activity. Peaks in flight activity were identified by calculating mean flux per night as a percentage of the total annual flux. In 2007 and 2010, flux data were available for only half a year: in 2007 measurements

commenced on 7th of June, while in 2010 measurements ended on 30th of May. Because the data complement each other, and together cover an entire year, 2007 and 2010 were considered to reflect one year, and annual flux for this year was calculated as the summed flux of 2007 and 2010. There were no indications that these years differed in timing and magnitude of migration.

Statistical analyses were carried out using SPSS v19 (SPSS Statistics Software, IBM).

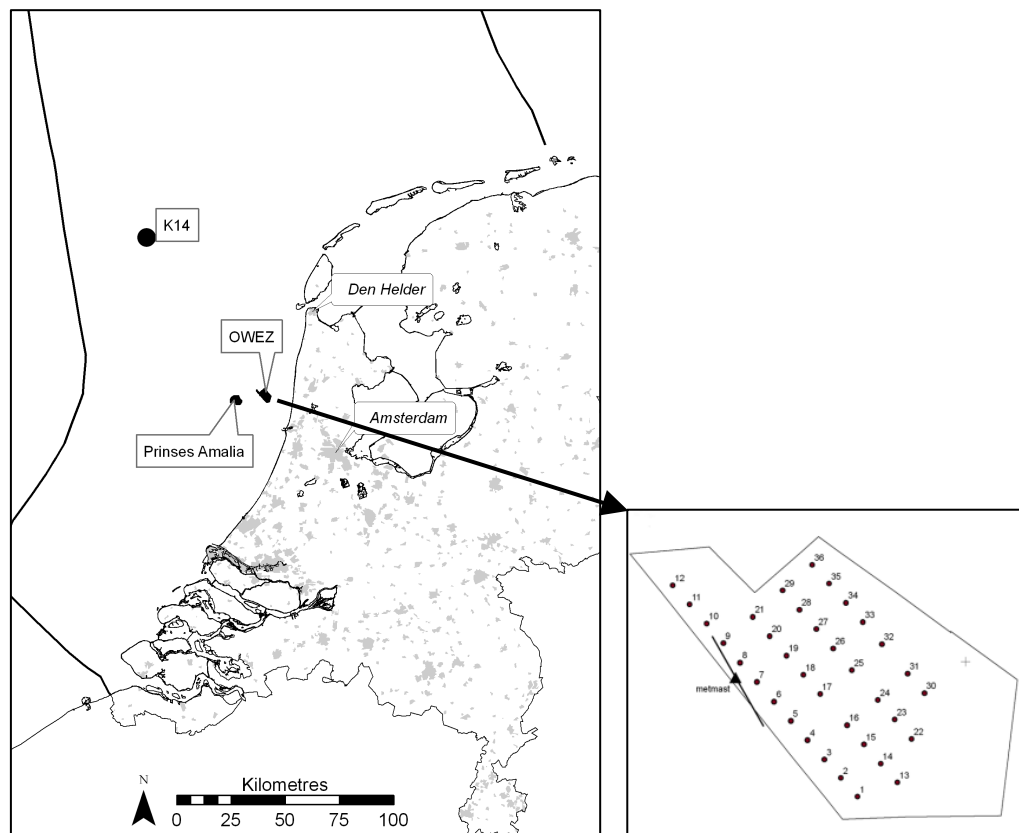


Figure 1 Position of OWEZ wind farm in the North Sea, ca 15 km off the Dutch coast. Turbine positions are shown in the insert, as well as the location of the radar on the metmast (triangle) and the orientation and range of the radar beam (diagonal line through metmast). Position of gas platform K14 in further NW offshore is indicated as well.

3 Results

3.1 Occurrence of migratory peaks at OWEZ

Nocturnal bird activity at rotor heights showed clear peaks in spring and autumn in all years, reflecting migrating songbirds passing through the study area (fig. 2). Patterns are consistent between years, with variation limited to the exact timing and intensity of peaks. In autumn, migratory activity was high for a longer period than in spring. In spring, high fluxes were limited mostly to March. Several smaller peaks were measured in the summer months of July and August. Fluxes reached highest levels in October and March. This was true especially when considering flight activity at all altitudes. At rotor height, highest fluxes also occurred in October and March, but in addition September and November also showed high fluxes at these lower altitudes, in contrast to flight activity at all altitudes combined.

To quantify the occurrence of peaks in migratory activity at rotor height, nocturnal fluxes were calculated as a percentage of the total annual flux at that altitude. Fluxes per night never reached more than 5 % of the annual flux. On two nights flight activity reached levels of 4 % of the annual bird flux through the area, while on 7 additional nights fluxes reached levels of 2.5 % of the annual flux (table 1).

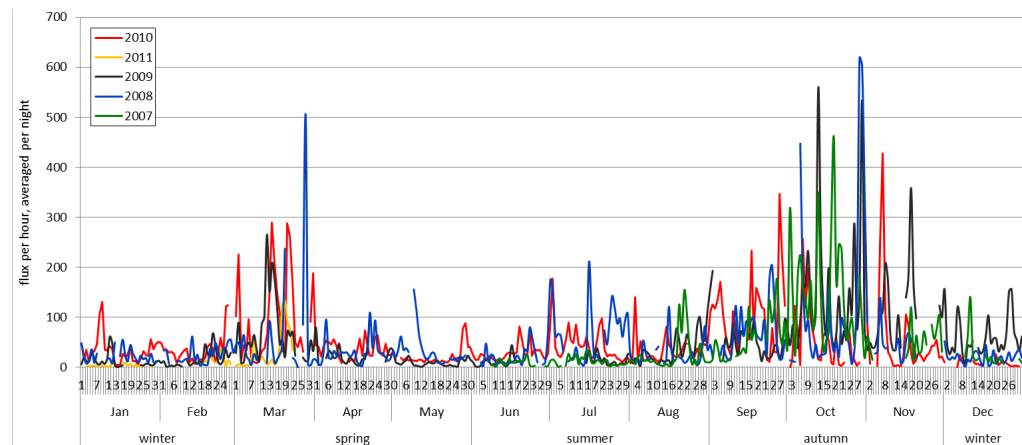


Figure 2 Fluxes at rotor height (25-250 m), presented as flux per hour, averaged per night. Peaks in early spring likely reflect birds migrating NE from the UK. Peaks in autumn reflect birds migrating SW to UK and to a lesser extent SW-Europe. Smaller peaks in 2008 assumedly reflect lapwings and black-headed gulls as well as early starlings. Colours reflect different years.

Table 1 Number of nights on which the nocturnal flux at OWEZ reached a specific percentage of the annual nocturnal flux at rotor height, presented for the entire study period between June 2007 and May 2010 (in 3 yr) as well as for the yearly average (avg/yr); E.g. nocturnal flux was higher than 4% of the annual flux on only two nights. Shown as well is the total percentage of the annual bird flux that is covered on nights that the flux reaches a specific percentage of the annual flux; e.g. on those nights that the flux was higher than $\geq 1\%$ of the annual flux, 33% of all birds that year flew through the area. In the rightmost two columns, the estimated annual number of collision fatalities is given for those nights that the flux reaches a specific percentage of the annual flux. Dates are provided for those nights on which fluxes were highest ($\geq 2.5\%$ of annual flux).

flux level	flux per night as % of annual nocturnal flux	nr of nights		summed flux as % of annual nocturnal flux	nr of fatalities / yr	
		in 3 yr	avg/yr		/turbine	/OWEZ (36 turb)
highest flux ↑	$\geq 4\%$	2*	1	3	1	20
	$\geq 2.5\%$	7**	2	8	2	61
	$\geq 1.5\%$	22	7	18	4	129
	$\geq 1\%$	60	20	33	7	237
	$\geq 0.5\%$	159	53	56	11	404
lowest flux	$\geq 0\%$	948		100	20	720
Total nights		948				

* 29th and 30th October 2008

** 28th of March 2008, 19th of October 2007, 6th of October 2008, 13th and 30th of October 2009

3.2 Fluxes in relation to collision rate

To estimate to what extent collision mortality could be reduced by shutting down turbines during nights of peak migration, we calculated collision rates and related these to nocturnal fluxes. The number of collisions is linearly related to the flux, which means that if we know the % of the total flux passing the study area on a certain night, and we know the annual collision rate, we also know the % of all fatalities that occurs that night. Because the actual fatality rate of birds colliding with turbines at sea is unknown, the Band model is commonly used to estimate this fatality rate (e.g. Brabant *et al.* 2015, Johnston *et al.* 2014). Using the SOSS Band Model (Band 2012), an estimated number of ca. 20 songbirds would collide per wind turbine per year¹. With OWEZ consisting of 36 turbines, this estimate would imply a total of ca. 720 songbirds (range 540-900) colliding with the OWEZ turbines each year (see also Krijgsveld *et al.* 2011).

Shutting down the turbines on nights with heavy migration would result in a decrease in collision fatalities among songbirds that is similar to the percentage of the annual bird flux on those nights. Shutting down the turbines on the two nights with peak migration would result in a reduction of $4.3+4.2=8.5\%$ of collisions, or ca. 60 collision fatalities in the wind farm. Similarly, shutting down the turbines on 20 nights per year

¹ Model option 1; assuming rotor height 25 - 250 m altitude; avoidance = 99%; Estimate of 15 fatalities if 60% of birds are passerine; 25 fatalities if 100% are passerine, i.e. 20 fatalities / turbine / yr on average. Flux as measured at this altitude: 409.000 bird echoes / km / yr, corresponding with 53% of total flux at all altitudes measured [reported in Krijgsveld *et al.* 2011]. Because the actual collision rate is unknown as well as the avoidance rate of passerines offshore, and because estimates depend heavily on avoidance rate used, the numbers of collisions provided are only an indication of the actual collision rate.

on which the nocturnal flux is higher than 1% of the annual flux, would result in a reduction of 33% of fatalities, corresponding to ca. 240 birds in the entire wind farm or ca. 7 birds per turbine on an annual basis (table 1).

3.3 Preventing collisions

To prevent collision fatalities, wind turbines can be shut down in response to the level of the bird flux in the local vicinity (see discussion). We related the flux levels as measured at OWEZ to the number of passerines that will collide with turbines at those flux levels. Based on this, we calculated the number of fatalities that could be prevented if turbines were to be shut down at those flux levels, and we calculated the related number of hours that the turbines would have to be curtailed (table 2).

For example, migration flux reached levels between 250-500 bird tracks/km/h during 109 h per year (table 2, fourth row). This corresponds with 1.3 % of the time. With that flux, the estimated number of collisions would be ca. 0.02 per wind turbine per hour, corresponding with ca. 1.5 collisions in 109 hours. If turbines would be curtailed during hours with fluxes of 250 and more, this would imply that 11% of collisions per year would be prevented at the entire OWEZ wind farm, and that turbines would have to be curtailed during 139 hours per year on average, or 1.6% of the time. Wind speeds during the given fluxes are shown to indicate potential loss of energy production during idling hours.

Table 2 Estimated collision rate for a given hourly flux, and the number of hours per year that such a flux occurs. If turbines would be shut down at a given flux, the number of collisions would be reduced. This reduction is shown as number of collisions prevented (grey area, shown as number per year per turbine, as well as number per year for the entire OWEZ wind farm (36 turbines), and as cumulative % of all victims per year for OWEZ). The 3rd and 2nd column from the right indicate the cumulative time that the turbines would be idle, shown as number of hours per year and as % of time. The rightmost column shows average wind speed.

flux class (nr/km/hr)	nr hours /year	% time	coll.estimate nr/h/WT	nr collisions prevented				cum.time idle		wind speed (Bft)	
				nr/yr/WT	nr/yr/OWEZ (=36 WT)			nr hrs /yr	%time		
					mean	min-	max				cum.%
1000-1250	1,8	0,02	0,0550	0,1	2,6	2,0 -	3,3	0,4	1,8	0,0	4,6
750-1000	9	0,10	0,0428	0,3	9,8	7,3 -	12	1,7	11	0,1	5,0
500-750	19	0,2	0,0306	0,4	15	11 -	19	3,8	29	0,3	4,8
250-500	109	1,3	0,0183	1,5	53	40 -	66	11	139	1,6	4,2
100-250	538	6,1	0,0086	3,4	121	91 -	151	28	676	7,7	4,1
0-100	8084	92	0,0024	14	519	389 -	649	100	8760	100	4,1
Total				20	720	540 -	900				

3.4 Bird concentrations at rotor height versus at higher altitudes

Nights with peak migration activity at rotor height did not coincide with birds all flying at rotor height. On the two nights with highest fluxes, 50 resp. 40% of the bird echoes were measured at rotor height, while the remainder flew above rotor height. Similar

percentages were measured on other nights with high levels of migration, with a maximum of 78% at rotor height on 18th of November 2009. High bird concentrations at rotor height did occur and were observed almost exclusively in the migratory seasons. For example, on 18th of May 2009, 92% of all birds in the air were detected at rotor height. In total, 34 nights were recorded on which more than 75% of all birds flying that night were recorded at rotor height. Such low flight altitudes may occur as a result of head winds or cloud covers, both conditions pushing the birds down to lower altitudes.

3.5 Diurnal patterns

Fluxes were significantly higher at night-time than during daytime or during dusk and dawn (fig. 3) (GLM on square root-transformed data; average flux per hour: effect of date NS, effect of time of day $F_{2, 9539}=324$, $P<0.0001$; where night $t=24.9$, $P<0.0001$; dawn/dusk $t=4.0$, $P<0.0001$). Peaks in nocturnal fluxes did not follow a regular pattern throughout the night. Peaks were often observed shortly after dusk, but also occurred regularly during other hours of the night until shortly before dawn. In autumn, fluxes showed a pronounced increase immediately after dusk, to gradually decrease throughout the night. In spring, fluxes were highest in the hours before dawn (fig. 4, table 3).

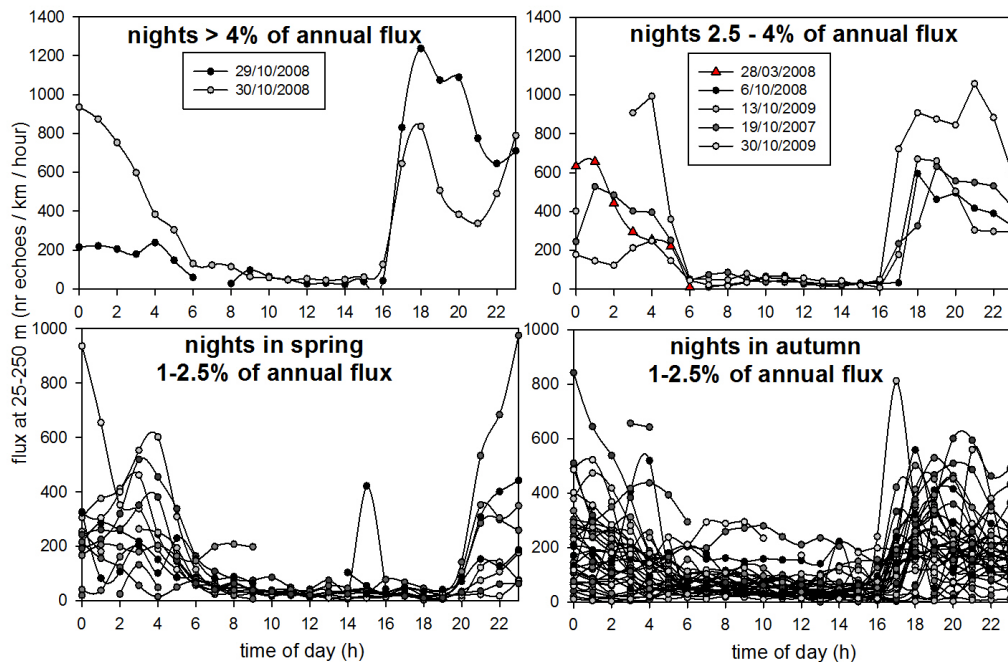


Figure 3 Diurnal pattern of fluxes at OWEZ, shown for those days with high nocturnal fluxes. Upper left panel: nights with more than 4% of the annual nocturnal flux; upper right panel: nights with 2.5-4% of the annual nocturnal flux; Lower left panel: nights in spring and summer with 1-2.5% of the annual nocturnal flux; Lower right panel: same, for nights in autumn.

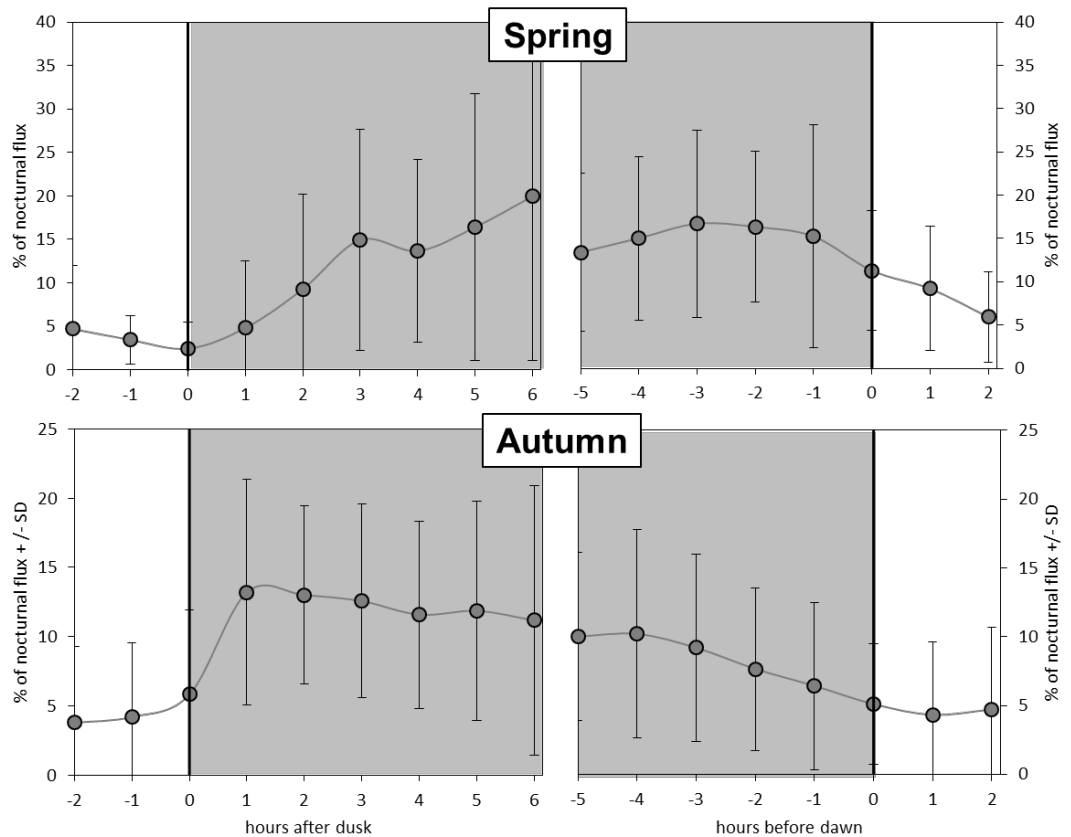


Figure 4 *Diurnal pattern of fluxes at OWEZ, shown for all nights in spring (upper panels) and autumn (lower panels). Values reflect percentages per hour of the total daily flux, where values are averaged per hour over all days with a given flux level. Shaded areas indicate nighttime, vertical lines indicate time of dawn or dusk. Fluxes showed a pronounced increase immediately after dusk in autumn, to gradually decrease throughout the night. In spring, fluxes were highest in the hours before dawn.*

3.6 Occurrence of migration peaks further offshore at K14

Fluxes further offshore at K14 generally were lower than at OWEZ (paired T-test: $t=4.8$, $df=259$, $P<0.005$, average = 46 and 31 tracks/km/h for OWEZ and K14 respectively) (fig. 5). Levels of activity were lower at K14 throughout the summer months, in autumn and in winter. In September 2010 high average flux was measured at OWEZ, while this was not reflected at K14 at all. Only in early spring (March) fluxes were similar or somewhat higher at K14 than at OWEZ. Nocturnal fluxes tended to show stronger peaks in the summer months at OWEZ than at K14 (fig. 6).

Table 3 Variation in flux throughout the night at OWEZ, for both spring and autumn migration. Values given (%) are the percentages per hour of the total flux per night, averaged for the entire season. To illustrate the high level of variation between nights, standard deviations (sd) are given as well.

time of night relative to hour of dusk/dawn	spring		autumn	
	%	sd	%	sd
-2 day	5	7.3	4	5.5
-1	3	2.8	4	5.4
0 dusk	2	3.0	6	6.1
1	5	7.7	13	8.1
2	9	10.9	13	6.4
3	15	12.7	13	7.0
4	14	10.5	12	6.8
5	16	15.3	12	7.9
6	20	18.9	11	9.8
7			10	8.8
↓ night				
-6			9	8.4
-5	13	9.1	10	6.1
-4	15	9.5	10	7.5
-3	17	10.8	9	6.8
-2	16	8.7	8	5.9
-1	15	12.9	6	6.1
0 dawn	11	6.9	5	4.4
1	9	7.2	4	5.3
2 day	6	5.2	5	6.0
-2	16	8.7	8	5.9
-1	15	12.9	6	6.1

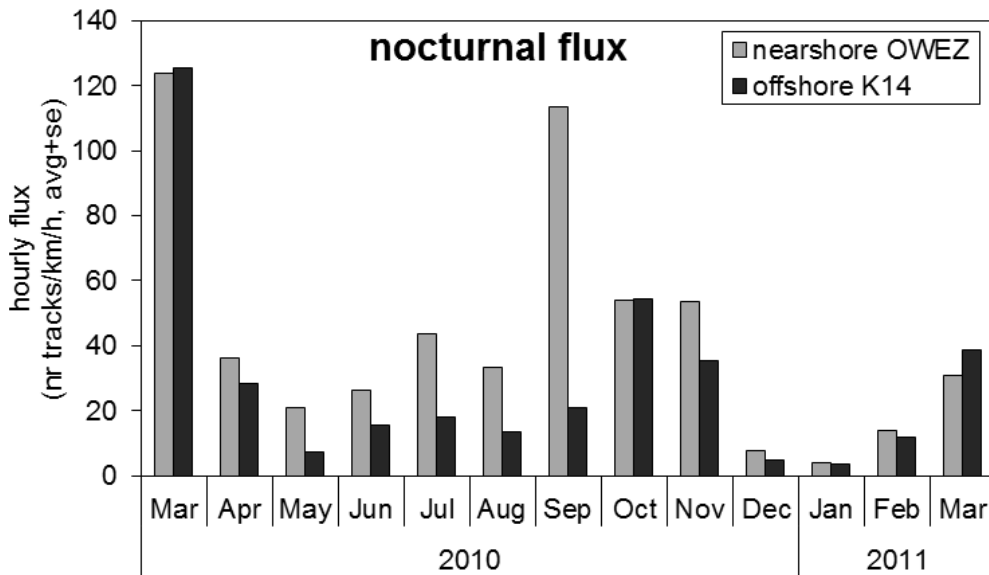


Figure 5 Comparison of flight intensities at wind farm OWEZ (near the Dutch coast) and at gas platform K14 (offshore and further north). Shown are hourly fluxes, averaged per month, for night-time hours only. Fluxes at OWEZ were higher except during early spring, when birds migrating from the UK towards Scandinavia and NW Europe resulted in a slightly higher flux at K14 than at OWEZ.

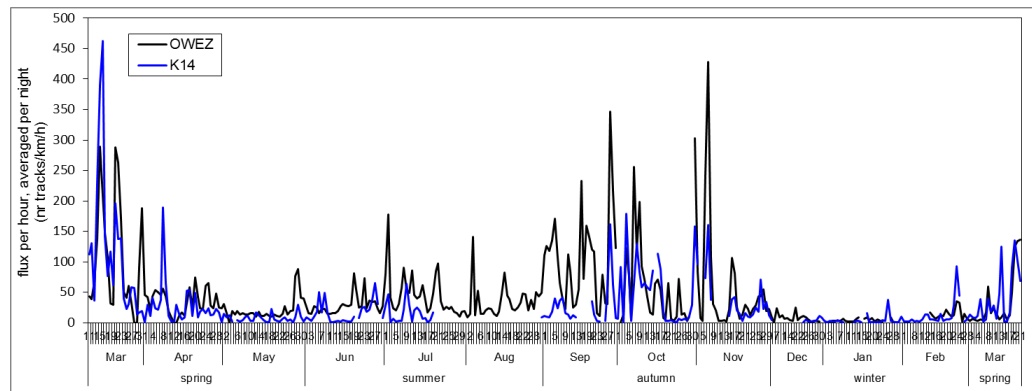


Figure 6 Comparison of nocturnal fluxes at OWEZ and K14. Shown are fluxes during night-time only, averaged per night. Data covering the period between March 2010 and March 2011. Peak fluxes were higher at K14 in March, but other than that peak fluxes were higher at OWEZ.

In spring, fluxes generally increased sooner after dusk at K14 than at OWEZ and decreased earlier at dawn (fig. 7). In autumn, fluxes generally increased later at K14 than at OWEZ, while they remained high for a longer time at dawn. Similar patterns were observed when comparing fluxes for all nights in spring and autumn. Differences probably did not differ significantly, but this was not tested.

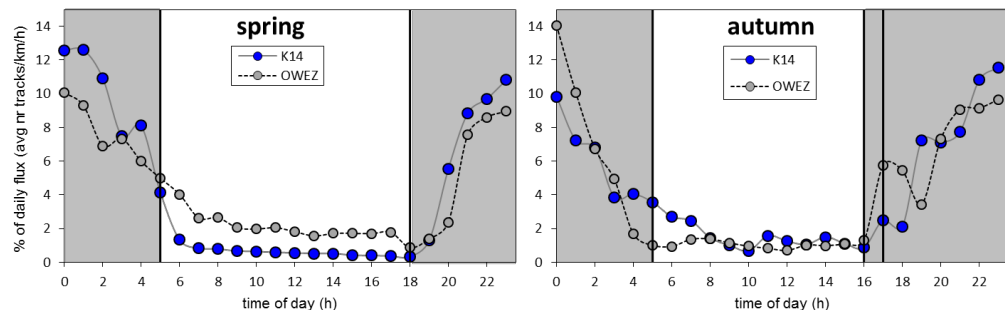


Figure 7 Distribution of fluxes throughout the day, for those nights on which fluxes peaked at K14 (further offshore, mostly March, few in autumn). Fluxes shown for OWEZ cover the same nights. Shown are percentages per hour of the total daily flux. Values are averaged per hour over all days. Shaded areas indicate nighttime, vertical lines reflect time of dawn and dusk. In spring, fluxes generally increased sooner after dusk at K14 than at OWEZ and decreased earlier at dawn. In autumn, fluxes generally increased later at K14 than at OWEZ, while they remained high for a longer time at dawn. This reflects the distance that birds migrating between UK and Netherlands/Scandinavia need to cover before they arrive at the study site.

3.7 Relation with weather conditions

Generally, migration activity peaked with easterly to southeasterly winds in autumn, creating tailwind situations for birds migrating to the UK (fig. 8, see also Fijn *et al.* 2015). Highest migratory activity in autumn was measured at wind speeds between 3 and 5 Bft (fig 9). Weather conditions that are standardly available, such as wind force and - direction and air temperature at the study location, did not show a straightforward relation with the occurrence of migration peaks at OWEZ. Of a total of

948 nights, flux at rotor height exceeded 2,5 % of the annual nocturnal bird flux on seven nights. On these individual nights, weather conditions shifted from more adverse to more favourable conditions. These changes concerned combinations of weather parameters, such as wind direction and speed, precipitation, and also temperature and air pressure.

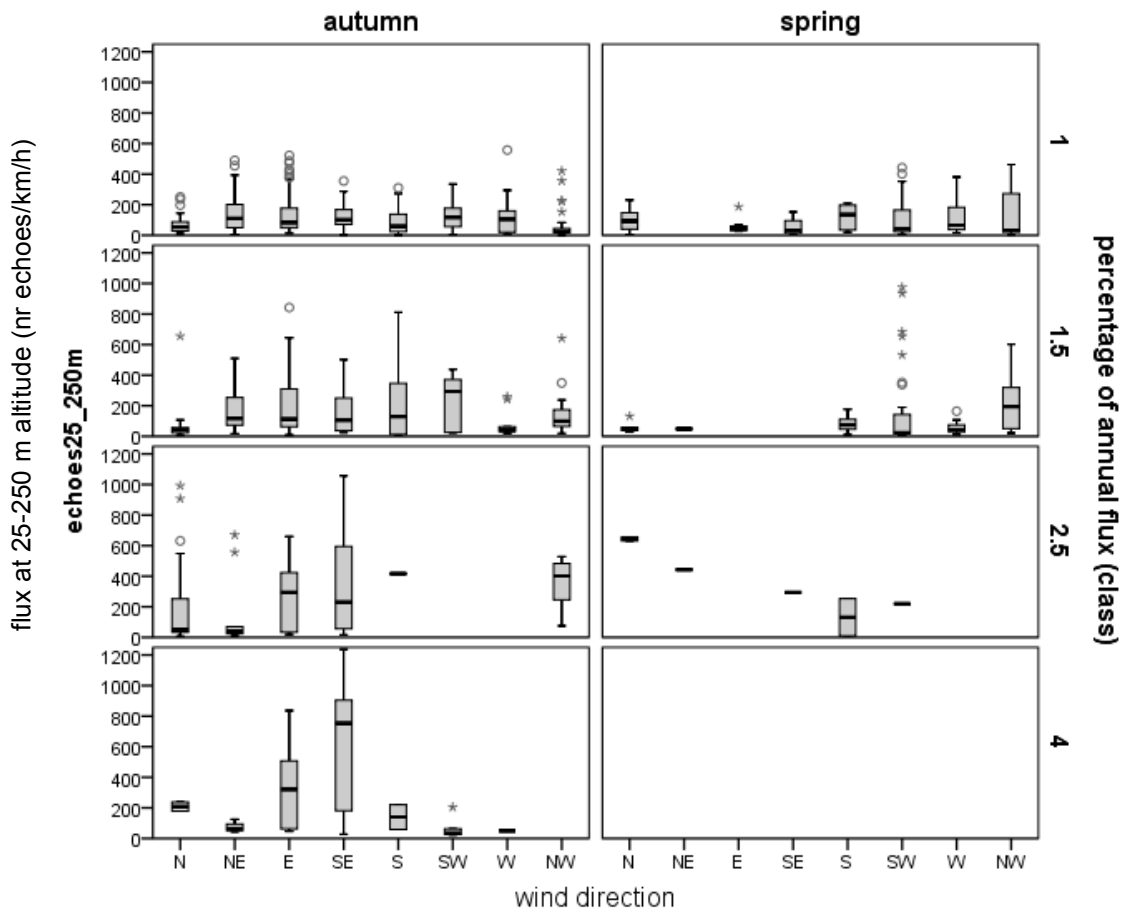


Figure 8 Migratory activity shown in relation to wind direction. Nights with highest migratory activity are shown in the lower panels. Left panels reflect autumn, right panels reflect spring. Data presented as box plots, where: horizontal line = median; box = lower to upper 25% around median or 50% of the data; whiskers = highest and lowest values that are not outliers or extremes.

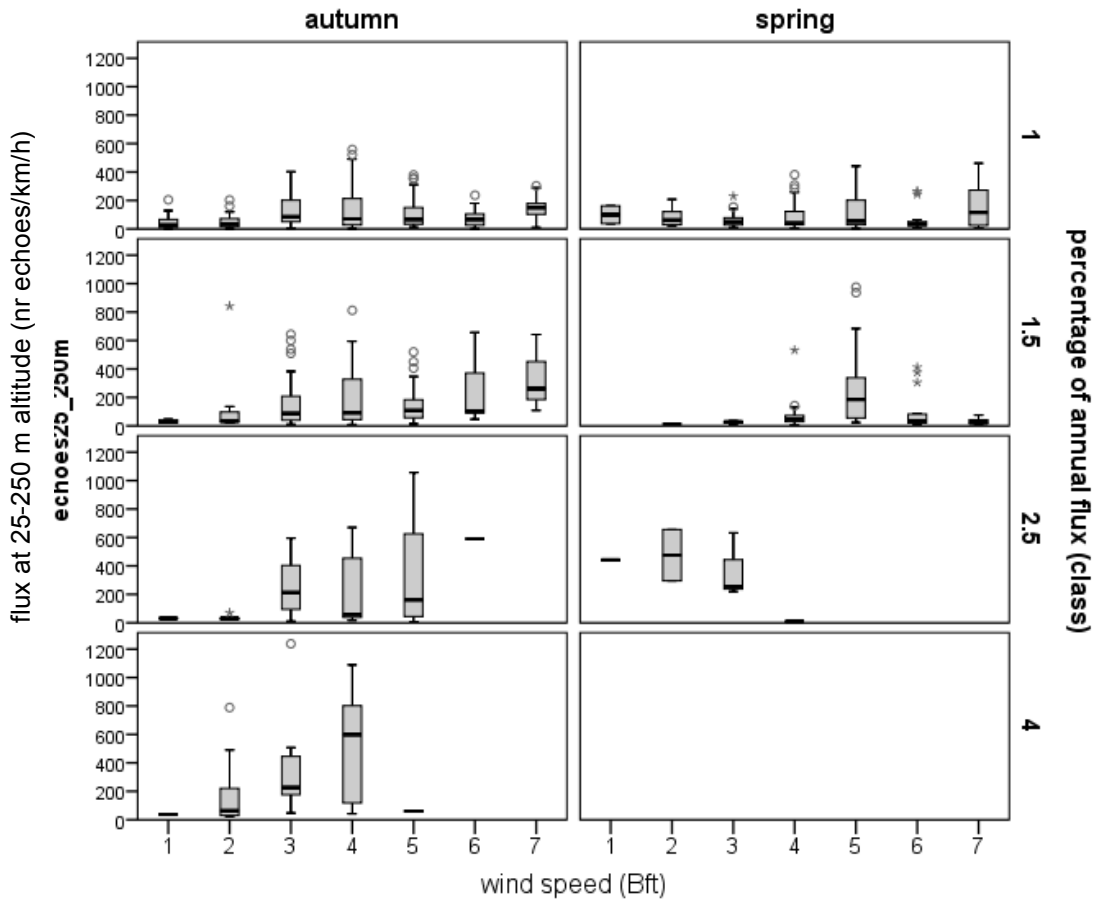


Figure 9 Migratory activity shown in relation to wind speed. Nights with highest migratory activity are shown in the lower panels. Left panels reflect autumn, right panels reflect spring. Data presented as box plots, where: horizontal line = median; box = lower to upper 25% around median or 50% of the data; whiskers = highest and lowest values that are not outliers or extremes.

4 Discussion

High nocturnal fluxes measured at rotor altitude in spring were limited mostly to March. These peaks reflect birds migrating in early spring from the UK, whereas birds migrating from SW Europe arrive in the Netherlands later in the season in April and May (Lensink *et al.* 2002). Passage of these latter birds was, however, hardly reflected in the data, assumedly because birds arriving from the south followed a route closer to shore or more inland, and did not pass the wind farm area. Peaks measured in July and August may reflect lapwings and / or black-headed gulls migrating to the UK (Lack 1962, 1963b, Lensink *et al.* 2002, Krijgsveld *et al.* 2011).

4.1 Occurrence of nights with peak migration

In the three years during which fluxes were measured at OWEZ, a major peak, during which more than 4% was measured of the birds flying through the area annually at night and at rotor height, was observed only on two consecutive nights (29th and 30th of October 2008). The estimated number of bird fatalities on these nights was similarly limited to 4% of all fatalities per year. This means that curtailing the turbines on nights of peak migration would have a limited effect on reducing the total number of bird fatalities. In order to reach a substantial reduction in fatalities, turbines would have to be curtailed on considerably more nights, including those nights with less extreme peaks.

High migratory activity over the southern North Sea may not always be reflected in the flight activity at OWEZ; for instance, on 30th of October 2010, high numbers of thrushes were reported to arrive at the UK shore in the morning (Ian Simms, pers. comm.), but fluxes at OWEZ were very low that entire night (50 tracks/km/h on average at all heights versus a maximum of ca. 1300 tracks on 29th of Oct 2008), indicating birds were arriving at the UK from other locations than the Netherlands (Lack 1958-1963, Myres 1964). Similarly, high levels of thrush migration were reported flying south over land on 2nd of November 2009 (D. Beuker pers. comm.), but these were not measured at OWEZ (67 tracks/km/h on average at all heights).

Falls of birds, characterized by extremely high concentrations of birds at low altitudes (rotor height), occur irregularly and infrequently (Lensink *et al.* 1999). In their review of the occurrence of falls, Lensink *et al.* identified three major falls in the period between 1978 and 1990. These falls were of such a scale that they were detected around the entire southern North Sea area. However, based on the scarcity of offshore data, they conclude that major falls at any location in the southern North Sea are likely to occur on a yearly basis. The size of the area at which such falls occur depends largely on weather conditions and changes therein (leading to larger or smaller numbers of birds departing), on where migrating birds do encounter adverse weather conditions (affecting larger or smaller migratory paths), and on the timing in the season (high migratory activity or not).

The fact that high fluxes at rotor height did not coincide with all birds flying at low altitudes, but rather with high fluxes at higher altitudes as well, suggests that the peak migration nights identified in this study do not reflect falls, where all migrating birds in the air come down to low altitudes. It is highly likely, therefore, that there will be nights when birds will cross wind farms at rotor height at substantially higher concentrations than we measured during the study period at OWEZ.

4.2 Relation with weather

Higher fluxes of migrating birds were observed with moderate easterly to southerly winds in autumn. This pattern is in line with general patterns of bird migration (Lack 1959-1963, Vogelwerkgroep Zuid-Kennemerland 2015). Weather conditions were more or less comparable to other years. We compared weather conditions during the study period with those in surrounding years (2001-2014, data from Airport Den Helder data download www.knmi.nl) (figs. see appendix). Winds were westerly on more days than average and southerly on fewer days. Wind speeds were comparable to those in other years. In March 2008 however, highest average wind speeds for spring in the period between 2001 and 2014 were recorded (6.8 m/s versus average 4.6). Days with strongest winds did not fall in the study period, except for March 2008. Because the radar was turned off at wind speeds over 7 Bft or 17 m/s, no data on fluxes are available for periods with strong winds. March 2008 had the highest number of hours with rain as well (112 h versus an average of 40 for the spring months between 2001 and 2014). Average temperatures were comparable to those in other years, with July 2007 and 2010 having the warmest days in the study (24°C on average) and January 2010 the coldest days (-6°C on average).

The exceptionally wet and windy weather in March 2008 may explain why fluxes were relatively low that month compared to other years, with an exceptionally high peak on 28th of March 2008. After a long period with stronger winds and much rainfall, the wind decreased and shifted to south and east on 26/27th of March with the arrival of a warm front, and the number of hours with rain decreased as well. The adverse weather through most of the month may have led to a build-up of birds that postponed migration, which then all departed northwest simultaneously when the weather turned more favourable on 26/27/28th of March. In addition, birds migrating from SW Europe over the Netherlands may have drifted towards the west coast with the easterly winds, resulting in even more migrating birds being detected at OWEZ.

4.3 Predicting peak nights

Peaks in songbird migration at rotor height are highly irregular and can occur at short notice. The occurrence of peak migration at low altitudes (falls) in relation to weather conditions was reviewed in detail by Lensink *et al.* (1999). From their study they identified the following patterns. Profitable weather conditions during which strong

migration occurs are clear skies, no precipitation and tailwinds. Unprofitable conditions are low visibility, overcast skies, precipitation and head winds. In autumn, highest migration activity occurs after passage of a front and along the east- and south sides of a high-pressure area. In the southern North Sea, falls tend to occur when the weather is profitable in the area of departure (Scandinavia) and unprofitable above the central or southern part of the North Sea. Falls can occur both in areas with bad weather (in the front) and in areas with good weather (behind the front).

Weather aspects thus do play a crucial role in occurrence of migration peaks, but to relate the occurrence of these peaks to specific weather conditions is difficult, and predicting the occurrence of peaks based on these conditions even more so (but see Shamoun-Baranes & van Gasteren 2011). This is due to the fact that weather conditions are concerned that are not easy to measure or model. They are related to large scale weather patterns covering the entire North Sea area, and are dependent for example on locations of fronts and the related changes in wind directions and speeds, changes in barometric pressure, (dense) cloud cover and rain.

Predictions of offshore songbird migratory activity is possible, based on data from aviation and weather radar, as demonstrated for example by the FlySafe-BAM project (www.flysafe-birdtam.eu). These predictions, however, are limited to higher altitudes well above the height of wind turbines. The best way to respond quickly and accurately to high songbird fluxes at rotor height is to install a system that can detect actual fluxes and can instantly shut down the turbines when fluxes exceed a certain threshold level. Such systems are available in the shape of bird radars. Several systems are on the market that operate fully automatically and can detect high songbird fluxes at night as well as send a start-/stop signal to the turbines. Examples of developers are Robin Radars (The Hague, Netherlands) and DeTect Inc. (Florida, USA).

4.4 The attracting effect of turbine lighting on birds

The fluxes described in this paper were measured in a condition with low lighting. When lighting is increased, which tends to be the case in higher turbines, fluxes can increase tremendously due to attraction of nocturnally migrating songbirds to light, especially on overcast nights. As a result, a higher percentage of all birds passing the area that night may concentrate around rotor height, resulting in higher numbers of fatalities.

4.5 Differences between OWEZ and K14 further offshore

Nocturnal fluxes generally were lower at K14 than at OWEZ. This is likely due to the fact that K14 is positioned northwest of the Netherlands. At K14, the majority of migrating passerines that are recorded will be birds flying between the UK and Scandinavia, while birds flying between the European mainland (Netherlands) and the

UK will be recorded to a much lesser extent at K14 than at OWEZ. Also during the summer months, peaks in nocturnal fluxes did occur both at K14 and at OWEZ, but were higher at OWEZ. The position of OWEZ near the Dutch coast may explain this difference. In addition, early migrants such as waders and gulls stopping over in the Wadden Sea, will be flying southward past OWEZ but not K14. In March, nocturnal fluxes were higher at K14 than at OWEZ. This high peak early in the spring season indicates that most passerines from the UK migrated to Scandinavia and to a lesser extent to the Netherlands / NW Europe (Lack 1959-1963).

Patterns in the timing of changes in fluxes around dusk and dawn reflect the distance that birds migrating between UK and Netherlands/Scandinavia need to cover before they arrive at the study site. In spring, birds that leave the UK at dusk to migrate in north-westerly directions, arrive at K14 earlier than they arrive at OWEZ. At dawn, birds will continue to arrive at the coast until a later time than at K14. Similarly, in autumn, birds leaving the Dutch and Scandinavian coasts at dusk to migrate to the UK, will arrive at OWEZ earlier than at K14, while at dawn, birds will have passed through and left the nearshore OWEZ area earlier than the areas further offshore (K14).

4.6 Migration levels at other wind farm locations in the Dutch North Sea

Based on the observed migration patterns at OWEZ and K14, in combination with general migration patterns of songbirds (Lack 1959-1963, Lensink *et al.* 2002), we can to a limited extent predict flux levels at other wind farm locations in the Dutch North Sea. The following differences may be observed in comparison to migration patterns at OWEZ:

- Further northwest of OWEZ higher fluxes are expected in March, and fewer or similar in autumn. Birds migrating between Scandinavia and the UK pass this area.
- Further south of OWEZ: higher fluxes expected in April, May and September, due to the fact that not only birds migrating to and from (the south of) the UK will fly through this area, but also birds migrating to and from SW Europe. Possibly, fluxes will be higher than at OWEZ throughout the migratory seasons, especially at locations close to shore (\leq ca. 15 km).
- North of the Netherlands: higher fluxes than at OWEZ expected in April, May and September, possibly also in other migratory months. This difference is due to fact that part of the birds from SW-Europe and Africa migrate across the Netherlands onwards to Scandinavia and back. The numbers of birds and number of species following this flyway are considerably larger than the numbers flying to and from the UK.
- Further offshore in general: lower fluxes are expected further offshore than closer to land, because fewer of the birds migrating to SW Europe fly through areas further offshore, and these areas are more limited to birds migrating to and from the UK.

5 Literature

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Appendix 1

Overview of weather conditions during the study period (2007-2011) and during surrounding years (2001-2014). Data from Den Helder Airport, NW Netherlands (www.knmi.nl).

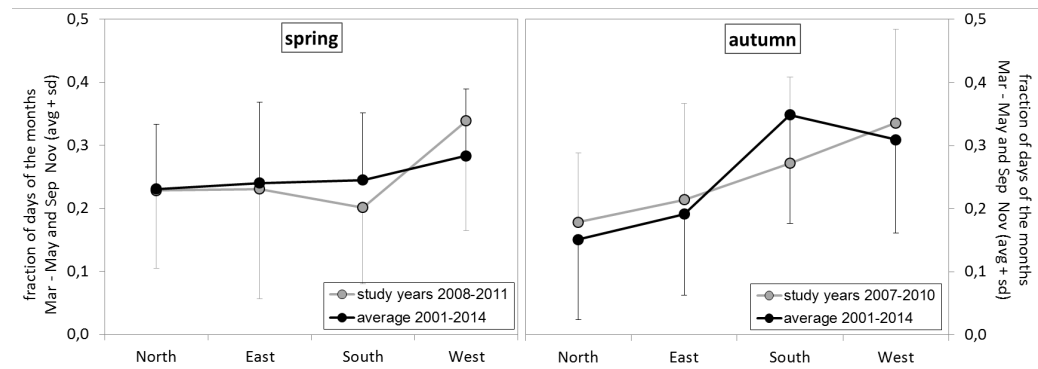


Figure A1 Prevailing wind direction in the study period and in the 13 surrounding years.

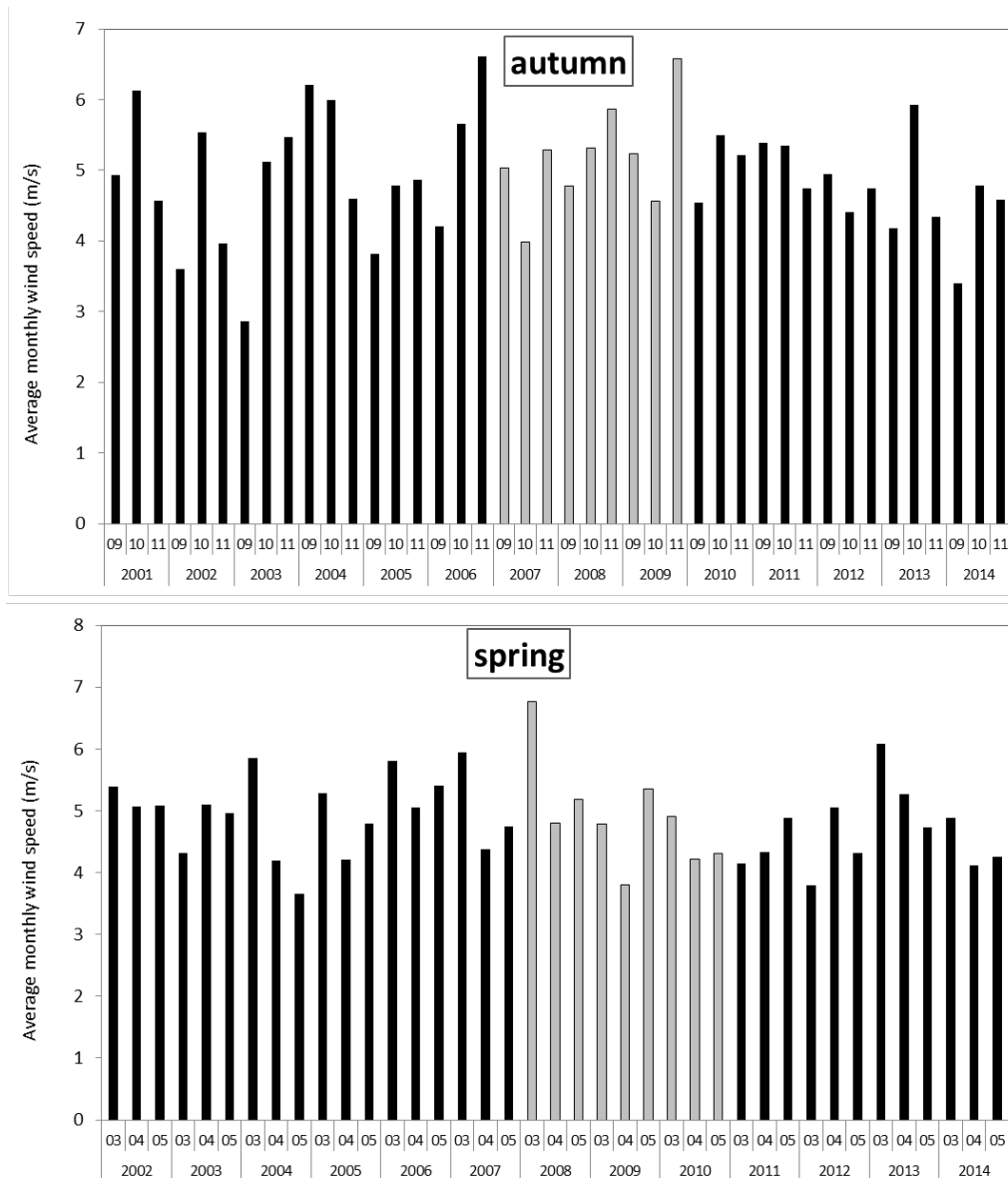


Figure A2 Wind speeds in the study period (grey bars) and in the 13 surrounding years (black bars). Data are presented as monthly averages, and are shown only for the migratory months in autumn (upper panel) and spring (lower panel). Average spring wind speed was exceptionally high in March 2008. In autumn, peaks in average wind speed occurred more regularly.

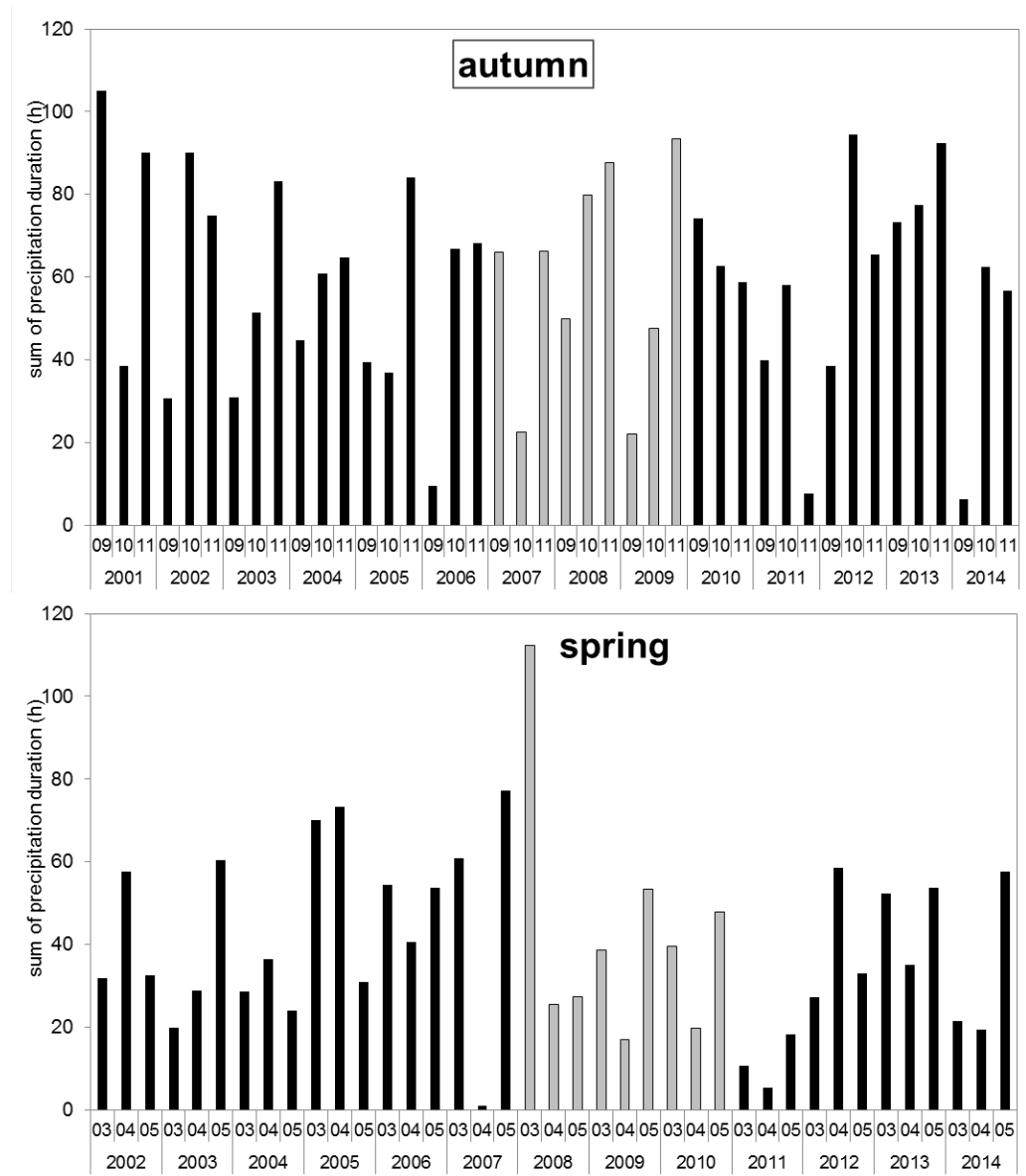


Figure A3 Precipitation in the study period (grey bars) and in the 13 surrounding years (black bars). Data are presented as summed number of hours with precipitation per month, and are shown only for the migratory months in autumn (upper panel) and spring (lower panel). The numbers of hours with rain were maximal in March 2008.

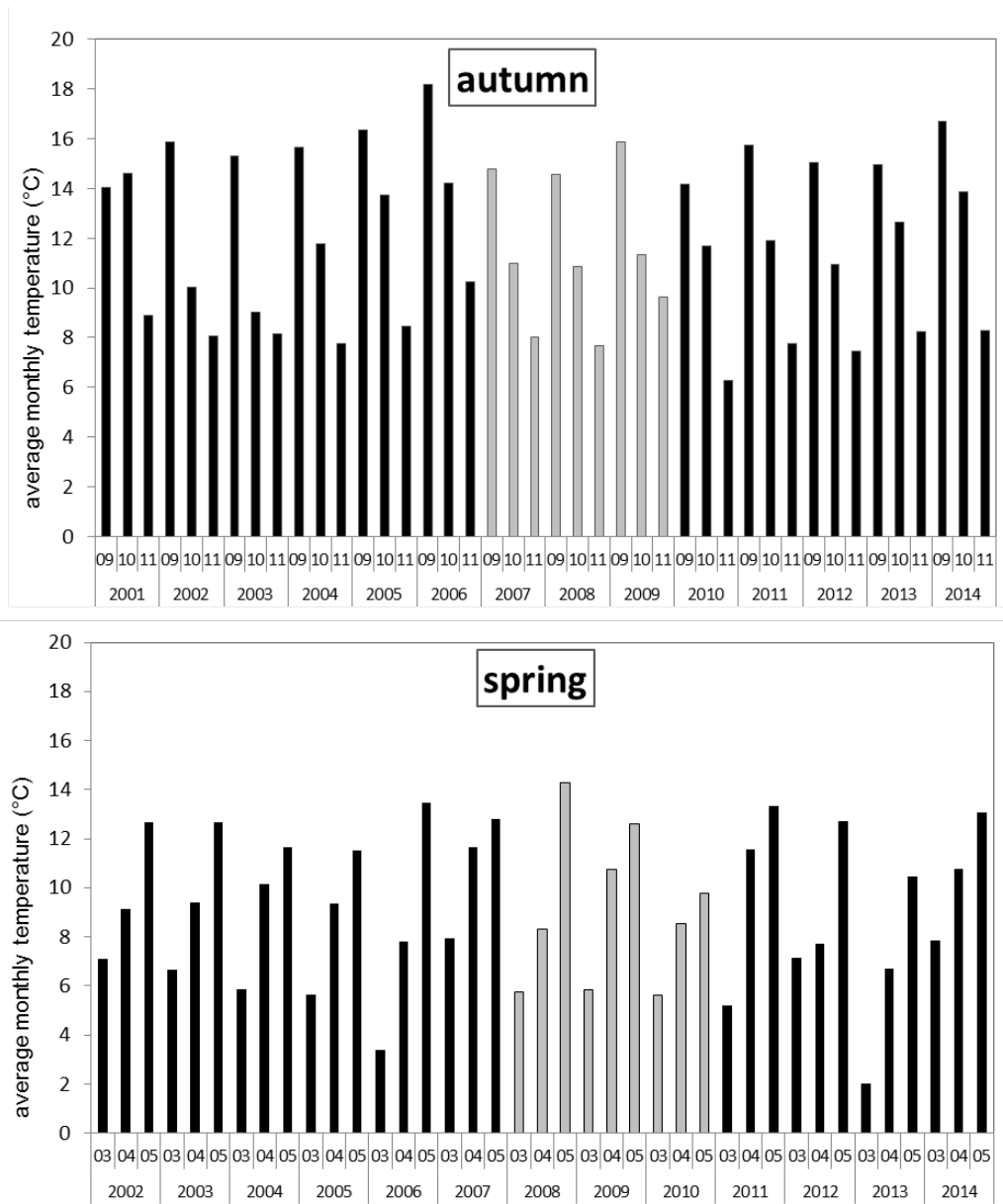


Figure A4 Precipitation in the study period (grey bars) and in the 13 surrounding years (black bars). Data are presented as summed number of hours with precipitation per month, and are shown only for the migratory months in autumn (upper panel) and spring (lower panel). The numbers of hours with rain were maximal in March 2008.