Bird migration studies and potential collision risk with offshore wind turbines

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Worldwide, Germany is the leading country in the use of wind energy. Since sites for the erection of wind turbines became scarce on land, ambitious plans for the offshore regions have arisen. There have been applications for 33 sites within the German Exclusive Economic Zone in the North and Baltic Seas, some of which entail several hundred individual turbines. Eleven pilot projects are approved, and two others rejected. As several hundred million birds cross the North and Baltic Seas at least twice every year, the Offshore Installations Ordinance says that licensing will not be given if the obstacles jeopardize bird migration. Birds are potentially endangered by offshore wind farms through collisions, barrier effects and habitat loss. To judge these potential risks, the occurrence of birds in space and time as well as details on their behaviour in general (migration, influence of weather) and their behaviour when facing wind farms (flight distances, evasive movements, influence of light, collision risk) need to be determined. Furthermore, the influences of construction and maintenance works must be considered. Since 2003, we have investigated year-round bird migration over the North Sea with regard to offshore wind farms. The main objectives were to assess data on the aforementioned aspects of bird migration over sea. These data can contribute to, for example, estimations of collision risks at offshore wind farms, the possible impacts on bird populations and possible mitigation measures. Results from measurements with different techniques, including radar, thermal imaging, and visual and acoustic observations, were compiled. The findings confirm that large numbers of diurnal and nocturnal migrants cross the German Bight. Migration was observed all year round but with considerable variation of intensity, time, altitude and species, depending on season and weather conditions. Almost half of the birds fly at 'dangerous' altitudes with regard to future wind farms. In addition, the number of individuals in reverse migration is considerable, which increases the risk of collision. We demonstrated that, especially under poor visibility, terrestrial birds are attracted by illuminated offshore obstacles and that some species collide in large numbers. Passerines are most frequently involved in collisions. Even if the findings regarding collisions at a research platform cannot be directly applied to offshore wind farms, they do show that on a few nights per year a large number of avian interactions at offshore plants can be expected, especially in view of the number and planned area of projected wind farms. We suggest abandonment of wind farms in zones with dense migration, turning off turbines on nights predicted to have adverse weather and high migration intensity, and actions to make wind turbines more recognizable to birds, including modification of the illumination to intermittent rather than continuous light, as the most appropriate mitigation measures. We further conclude that a combination of methods is necessary to describe the complex patterns of migration over the sea. The recordings are to be continued with the aim of refining the results presented here, and of developing a model for 'forecasting' bird migration over the German Bight. We expect more information on avoidance behaviour and collisions after the construction of a pilot wind park.

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Each year during the migration periods several hundred million birds of roughly 250 species cross the North and Baltic Seas on their journeys between their breeding grounds in northern Asia, North America and especially in Scandinavia and Finland, and their winter quarters, which lie between Central Europe and southern Africa, depending on the species (Dierschke *et al.* 2003). These two seas are situated at the centre of a global network of migration routes. Furthermore, both seas are used as resting, moulting and feeding grounds for internationally important numbers of waterbirds (e.g. Garthe 2003).

It is current policy in many countries, notably in the European Union, to advance the development of renewable energy sources in order to reduce environmental degradation and anthropogenic climate change caused by the use of fossil fuels (Houghton *et al.* 2001, Chow *et al.* 2003). Worldwide, Germany has become the leading country in the use of wind energy. Against the background of limited land resources and especially in view of the greater consistency and force of winds at sea, particular attention is being paid to the production of wind energy in offshore locations. There have been applications for 33 sites within the German Exclusive Economic Zone (EEZ) in the North Sea (27 sites) and in the Baltic Sea (six sites), some of which entail several hundred individual turbines. Eleven pilot projects with 12–80 turbines each are now approved (ten North Sea, one Baltic Sea); two others in the Baltic Sea were rejected because of large concentrations of resting birds in the respective areas. Shoreward of the EEZ, i.e. in coastal waters inside the 12-mile zone, permissions have been granted for further wind farms (for details see, for example, http://www.offshore-wind.de). Even a far more modest development would make the construction of wind farms the greatest human impact in the North and Baltic Seas next to fisheries (Merck & von Nordheim 2000). However, construction works have not yet started at any of the licensed sites in Germany. Potentially, wind farms pose a variety of threats to birds: collision, loss of habitat and barrier effects (e.g. Exo *et al.* 2003, Langston & Pullan 2003, Hüppop *et al.* 2004, Zucco & Merck 2004, Gill 2005, Percival 2005).

In any authorization process issues such as mining rights, shipping routes and safety have to be taken into account. Consideration also needs to be given to the interests of the navy, commercial fishing and nature conservation, as well as those of submarine cable and pipeline operators. One of the reasons for rejection explicitly mentioned in the Offshore Installations Ordinance is 'jeopardising of bird migration' (Dahlke 2002). Approval may not, however, be withheld in the absence of rejection reasons. But what does 'jeopardising of bird migration' mean in terms of, for example, numbers of collision victims or effects and impacts on bird populations?

There exists a comprehensive literature on bird migration over the North Sea from the end of the 19th century onwards (e.g. Gätke 1891), including extensive technical approaches such as surveillance radar studies by Lack and others (reviewed by Eastwood 1967, for the German Bight of the North Sea, e.g. Jellmann & Vauk 1978) or satellite telemetry (Green *et al.* 2002). Nevertheless, with respect to questions regarding environmental effects and impacts connected with the construction of offshore wind turbines, severe gaps in our knowledge became obvious:

(1) How many migrants of which species cross the German Bight at which time?
(2) What is the proportion of birds flying in altitudes up to 200 m (as high as the future wind energy plants)?
(3) How are migration intensity and flight altitude influenced by weather, namely by wind, precipitation and visibility?
(4) How many birds are involved in reverse migration?
(5) How do migrants react to anthropogenic offshore obstacles?
(6) Are birds attracted by the illumination of these structures?
(7) How many birds will collide?
(8) Can days of high collision risk be predicted?
(9) How can collisions be mitigated?
(10) Which impacts on populations can we expect?

Several research projects were initiated by the German environmental authorities. The majority of the data and analyses presented here are derived from the project 'BeoFINO'. The primary objectives were to collect data to address questions (1) to (7), based on measurements of bird migration over the German Bight with a variety of techniques, including radar, thermal imaging, collection of collision victims, and visual and acoustic observations. This is the first project to cover migration year-around continuously with such a variety of complementary methods.

METHODS AND DATA

Within the 'BeoFINO' project, automatic recording of bird migration on three unmanned offshore research platforms in the North and Baltic Seas was initially planned. However, owing to unexpected problems only platform 'FINO 1' (54°01′N, 06°35′E; http://www.fino-offshore.com/) is available. Remote observations including of 'invisible' bird migration became possible with the construction of this platform, where we installed two ship radars, a thermal imaging camera, a video camera and a directional microphone from October 2003 onwards. To allow spatial comparisons, we had to modify the sampling scheme, including the addition of human observers on islands.

Although bird migration over the North Sea takes place throughout the whole year, two periods of intensive migration (spring, autumn) recognizably alternate with two periods of minimal migration activity (summer, winter). Although these seasons have no real precise limits, we have defined them as follows: 'spring' (1 March to 31 May), 'summer' (1 June to 31 July), 'autumn' (1 August to 15 November) and 'winter' (16 November to 29 February). A meaningful subdivision of the day taking into account fluctuating daylength proved more of a problem, exacerbated by the diurnal activities of the gulls resident on the platform. Automatic video recordings (see below) showed gull activity before civil dawn and after civil dusk (when the sun is 6° below the horizon). Yet using nautical dawn and dusk as a reference (sun 12° below the horizon) also seemed impractical as it made the nights too short in summer. We therefore decided to use the median of these two values. This is equivalent to the sun's position at sunrise and sunset minus 9°. In order to take into account the early morning and evening peaks in migration activity we defined two further subdivisions of the day – each delimited by the value of sunset/sunrise ± 9°. This gives us four periods of the day that in the following text are always referred to as 'morning', 'daytime', 'evening' and 'night'. Although there is always a change of date during the night period, because complete nights need to be regarded as a unit, we defined the date of night migration as that valid at the beginning of the night in question.

Sea-watching and passerine passage counts

Standardized systematic recordings of 'visible' bird migration (alternating 'sea-watching' covering recordings of waterbirds over sea, and 'passerine passage counts' covering recordings of passerines, pigeons, owls, swifts and woodpeckers) were carried out by observers on the offshore island of Helgoland (54°11′N, 07°55′E) and simultaneously on the coastal islands of Sylt (54°52′N, 08°17′E) and Wangerooge (53°47′N, 07°55′E) in the years 2003 and 2004 (for locations see Fig. 1, for methods see Hüppop *et al.* 2004, Dierschke *et al.* 2005). On Helgoland, sea-watching was carried out on 233 days throughout all seasons (see Fig. 2), passerine passage counts on 90 days from July 2003 to December 2004 (see Fig. 3). On Sylt, counts were conducted on 156 (sea-watching) and 98 (passerine passage counts) days in autumn 2003, spring 2004 and autumn 2004. On Wangerooge, 90 days were covered by sea-watching and 58 days by passerine passage counts in spring and autumn 2004.

Ship radar

One radar system with a vertically rotating antenna recorded bird migration intensity and altitude at the FINO 1 platform ('vertical radar', Furuno FR-2115-B, X-band 9410 ± 30 MHz, 12-kW peak power, 24 r.p.m., used range scale 0.75 nm, pulse length 0.07 µs, pulse repetition rate 3000 Hz, with 8-ft antenna XN24AF, horizontal beam width 20°, vertical beam width 0.95°, side lobe attenuation within ± 10° 28 dB, side lobe attenuation outside ± 10° 32 dB). The radar had an open view to the west-southwest (248°), but, not to the opposite direction, which was obstructed by the helicopter deck. We assume that this is not important for the results and conclusions presented. A second radar, horizontally rotating, operated on FINO 1 from 30 October 2003 in order to record flight directions ('horizontal radar', Furuno FR-2125-B, X-band 9410 ± 30 MHz, 25-kW peak power, 24 r.p.m., used range scale 1.5 nm, pulse length 0.15 µs, pulse repetition rate 3000 Hz, with 8-ft antenna XN24AF, horizontal beam width 0.95°, vertical beam width 20°, side lobe attenuation within ± 10° 28 dB, side lobe attenuation outside ± 10° 32 dB). This radar scanned the sea north of the platform from 225° to 135°. Another vertical radar was in operation on the premises of the airfield on the island of Sylt (54°55′N, 08°21′E) with a viewing direction west-southwest and north-northeast from 8 June 2004 to 6 November 2004. The aim was to compare migration density and flight altitude at the coast and offshore. We dispensed with a horizontal radar on Sylt as only flight altitude and migration density were to be studied there.

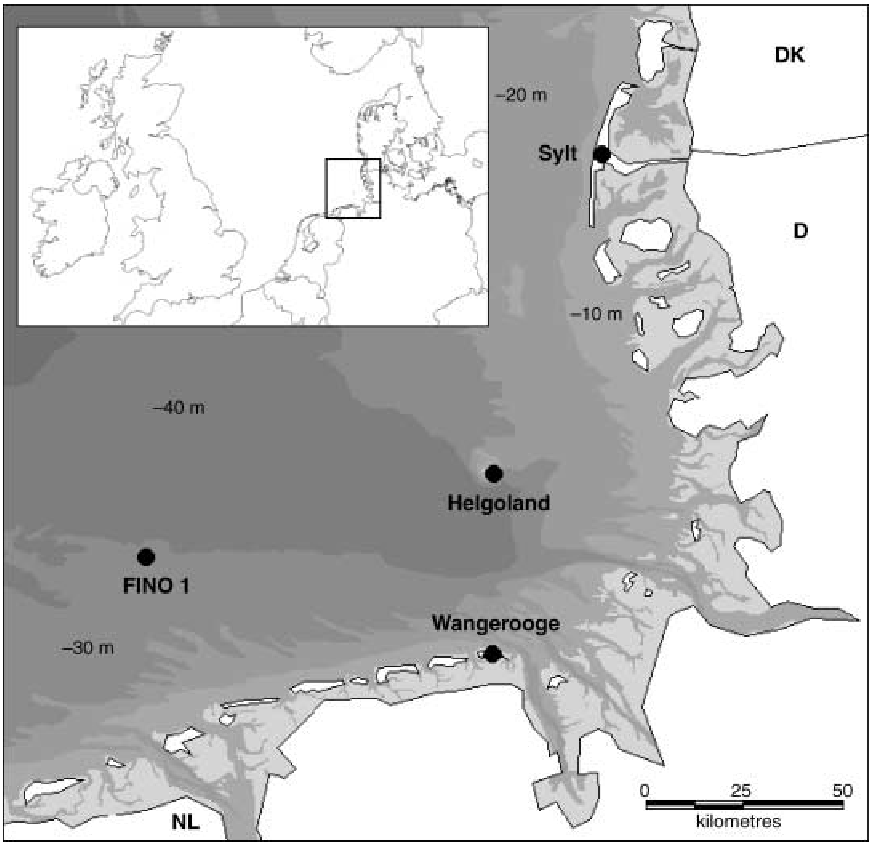

Figure 1. Positions of the research platform FINO 1 and the investigation sites on the offshore island of Helgoland and on the coastal islands of Sylt and Wangerooge.

Although both systems on FINO 1 have continued to operate within the follow-up project 'FINOBIRD' (see Conclusions), this article confines itself to the processing of the data from 1 October 2003 to 15 November 2004 (vertical radar) and those from 1 March 2004 to 31 May 2004 (horizontal radar). Regular inspection by means of a web camera (http://www.fino-offshore.com) occasionally showed large numbers of resting gulls on the helicopter deck of FINO 1. Hence, we assume that bird echoes outside the 'night' are partly attributable to foraging flights of gulls. By contrast, the number of traces recorded at 'night' is in agreement with the phenology described by Hüppop and Hüppop (2004) for 'passerines' on Helgoland, so that the vast majority of signals recorded in this period are undoubtedly attributable to migration. Therefore, some analyses were exclusively based on echoes recorded at 'night' so as to minimize coincidences with other flight activities.

In order to record bird echoes, a screenshot was taken of the current radar image every 5 min by the software IrfanView (http://www.irfanview.com) and subsequently digitized by hand. Thus, each system supplied us with the data from 12 images per hour with date and time to analyse. Despite occasional system crashes with concomitant data losses, the vertical radar was running for 67% of the investigation period on FINO 1 and generated a total of almost 80 000 images (69% on Sylt). All images that were more than 20% obscured by rain reflections were discarded. This applied to 7.8% of the images on FINO 1 and 7.3% on Sylt. Temporary short breaks in the radar recording also occurred within a 24-h period. In these cases only those periods of the day were included in the analysis, which provided at least 50% of the total number of images theoretically possible. Altogether, 62% of the time was covered by images suitable for analysis, both on FINO 1 and on Sylt. Of the 412 'nights' in the 13.5-month recording period, 226 were entered into the analysis. Most of the missing nights belong to lengthy recording gaps caused by radar system breakdowns, which affected some annual segments more than

Table 1. Observation nights with vertical radar on FINO 1.

Month	Nights measured
October 2003	17
November 03	28
December 03	19
January 04	14
February 04	11
March 04	28
April 04	25
May 04	10
June 04	14
July 04	6
August 04	23
September 04	16
October 04	4
November 04	11
Total	226

others (Table 1). None the less, the radar measurements provide a unique almost continuous account of offshore bird migration throughout the annual cycle.

The echoes of each vertical radar sweep were displayed on the screen and remained there with a different colour for the following ten sweeps. Birds flying parallel to the sweep left tracks of dots whereas those flying perpendicular to the sweep produced a single dot. The coordinates of these dots were manually digitized from the screenshots for further calculations. Migration intensities and flight altitudes could be derived from all echoes, while track inclinations and rough flight directions were derived only from tracks with a length of at least 35 m (equivalent to 10 pixels in an image or roughly five times the spatial resolution of the radar).

Whether or not a bird is detected by radar depends on a number of factors (Eastwood 1967, Bruderer 1997a, 1997b). The volume covered by a radar beam increases with distance, while the energy density of emitted and reflected radar beams decreases. This results in a complex relationship between the distance to an object and the probability of the object being detected by radar. In order to compensate for this distance-related 'sensitivity' of radar equipment when undertaking quantitative assessments, the number of echoes recorded had to be corrected for this change in detectability with distance from the radar antenna (Hüppop *et al.* 2002). Therefore, we adjusted the recorded echoes with the help of the program 'Distance 4.1' (http://www.ruwpa.st-and.ac.uk/distance/). This correction was based on the assumption that birds flying over the sea are horizontally equally distributed at such a small scale, and therefore that knowing radar cross-sections of birds, for example, is unnecessary. All values from altitudes between 50 and 150 m and at a distance of over 400 m from the platform were included. This was to eliminate data caused by the inclusion of flight echoes of gulls resident on the platform in order to ensure that data entered into the analysis came predominantly from migrating birds. Only a very few bird echoes were recorded from distances of over 1500 m, and these may have been over-adjusted in the correction. For this reason our calculations involve only values obtained from within a radius of 1500 m (for details see Hüppop *et al.* 2004).

For most of the time, the horizontal radar on FINO 1 produced images with bird traces largely obscured by wave and rain reflections. Consequently, radar images suitable for analysis were obtained only on a few days of light wind and as a result only 4.1% of the total images produced by the horizontal radar were in fact digitized. Presumably, therefore, the horizontal radar did not render representative results. Subsequently, we have attempted to improve the system by modification of the antenna design.

Thermal imaging, video camera and microphone

We developed the new software IRMA ('Infra red Registration of Migrating Aves' using DSPack 2.31: http://www.progdigy.com) that detects flying birds or bats within the real-time images provided by our thermal imaging camera (Zeiss Optronics Opus M: with an uncooled ferroelectric detector, a resolution of 240 lines with 320 pixels each, a spectral range of 7.5–13.5 μm, and automatic adjustment of gain and dynamic range). The field of view of its 75-mm lens was 12 × 9° to the north and with an elevation angle of 60° into the open sky. Therefore, we were able to record movements close to the platform around the clock without any supplementary light necessary, and thus obtain indications of intensity, flock size and flight behaviour under different environmental conditions.

During daylight, a video camera (Panasonic AW-E600E) with motor zoom lens on a pan-and-tilt head was used as our 'sea-watcher' on the unmanned platform. Unfortunately, we were not able to observe birds remotely because of insufficient resolution, combined with a limited field of view and internet bandwidth problems.

Bird calls close to the platform were detected and recorded automatically by a directional microphone (Sennheiser ME67) with the specially developed software AROMA ('Acoustic Recording of Migrating Aves' based on the audio-processing toolkit 'Snack' of Tcl/Tk: http://www.speech.kth.se/snack).

Collision victims

Owing to the lack of offshore wind farms in German waters, investigations on collisions with man-made offshore structures had to be confined to the FINO 1 platform. On each of 44 visits to the facility by helicopter (more or less equally distributed over the period October 2003 to December 2004) all bird carcasses found were documented. The bird remains were generally taken to the laboratory, where measurements were taken and an attempt was made to establish the cause of death. This was done by thoroughly examining each individual for external injuries, contusions and fractures. Additionally, a few birds were X-rayed.

RESULTS

Species composition

At the island of Helgoland, famous for its excellent bird-watching opportunities, more than 425 species have been recorded, emphasizing the enormous number of species crossing the North Sea on their migrations. However, the proportions of any one species can be estimated only very crudely, as many birds are mainly or even exclusively nocturnal migrants being more or less noisy or mute, depending on species, or, for exmaple, visibility conditions (Alerstam 1990), or fly beyond the range of human visibility, as pointed out already by Gätke (1891).

The systematic visual daytime observations in 2003/04 resulted in a total of 217 species (192 on Sylt, 174 on Wangerooge and 167 on Helgoland). At all sites, waterfowl (here including Great Cormorant *Phalacrocorax carbo*), gulls and terns were the dominant groups during sea-watching (Fig. 2), with Great Cormorant, Greylag Goose *Anser anser*, Pink-footed Goose *Anser brachyrhynchus*, Barnacle Goose *Branta leucopsis*, Brent Goose *Branta bernicla*, Common Eider *Somateria mollissima*, Common Scoter *Melanitta nigra*, Common Gull *Larus canus*, Black-headed Gull *Larus ridibundus*, Lesser Black-backed Gull *Larus fuscus*, Sandwich Tern *Sterna sandvicensis* and 'Comic' Tern *Sterna hirundo/paradisaea* being numerically the most important species. Passerine passage counts revealed that the species spectrum was quite similar at all three locations (Fig. 3). Common Wood Pigeon *Columba palumbus*, Meadow Pipit *Anthus pratensis*, Pied Wagtail *Motacilla alba*, Fieldfare *Turdus pilaris*, Redwing *Turdus iliacus*, Song Thrush *Turdus philomelos*, Eurasian Jackdaw *Corvus monedula*, Brambling *Fringilla montifringilla*, Chaffinch *Fringilla coelebs* and Common Linnet *Carduelis cannabina* were the most numerous species.

At the FINO 1 platform, 70 different species were verified by the automatic flight call recording. Over 70% of the registered flight calls (n = 19 776 individual birds) were from thrushes (chiefly Redwings, Blackbirds *Turdus merula*, Fieldfares and Song Thrushes), around 10% came from waders (primarily Common Redshank *Tringa totanus*, Red Knot *Calidris canutus*, Eurasian Golden Plover *Pluvialis apricaria*, Common Sandpiper *Actitis hypoleucos* and Greenshank *Tringa nebularia*). Other frequently encountered species were Sky Lark *Alauda arvensis*, Meadow Pipit, Goldcrest *Regulus regulus*, European Robin *Erithacus rubecula*, Common Starling *Sturnus vulgaris* and Snow Bunting *Plectrophenax nivalis*, although most of the calls made by the last four species came in all likelihood from birds resting on the platform.

Altogether, 13 037 birds were recorded by the thermal imaging camera at night. There were six mass migration events with more than 500 individuals each. The density of birds close to the platform was so high on these nights that it was impossible to distinguish between flocks and single birds. Therefore, 10 340 birds from these nights were not included in flock size calculations. Of the remaining 2697 individual records of night migrants, 763 (28.3%) were capable of rough identification. Of these, 52.2% were passerines and 47.8% non-passerines. Over 94% of these records were of single birds (= 80% of the individuals; Table 2).

Of the 442 carcasses found on FINO 1 only six were non-passerines (one Dunlin *Calidris alpina*, four large gulls, one Feral Pigeon *Columba livia*). Most of the birds involved were thrushes (87.3%) Common Starlings (4.8%) and Sky Larks (1.6%).

Seasonal migration intensities

All methods used confirmed bird migration all year around. With sea-watching at Helgoland most migration peaks were determined in spring and autumn. In addition, during summer and winter there were some

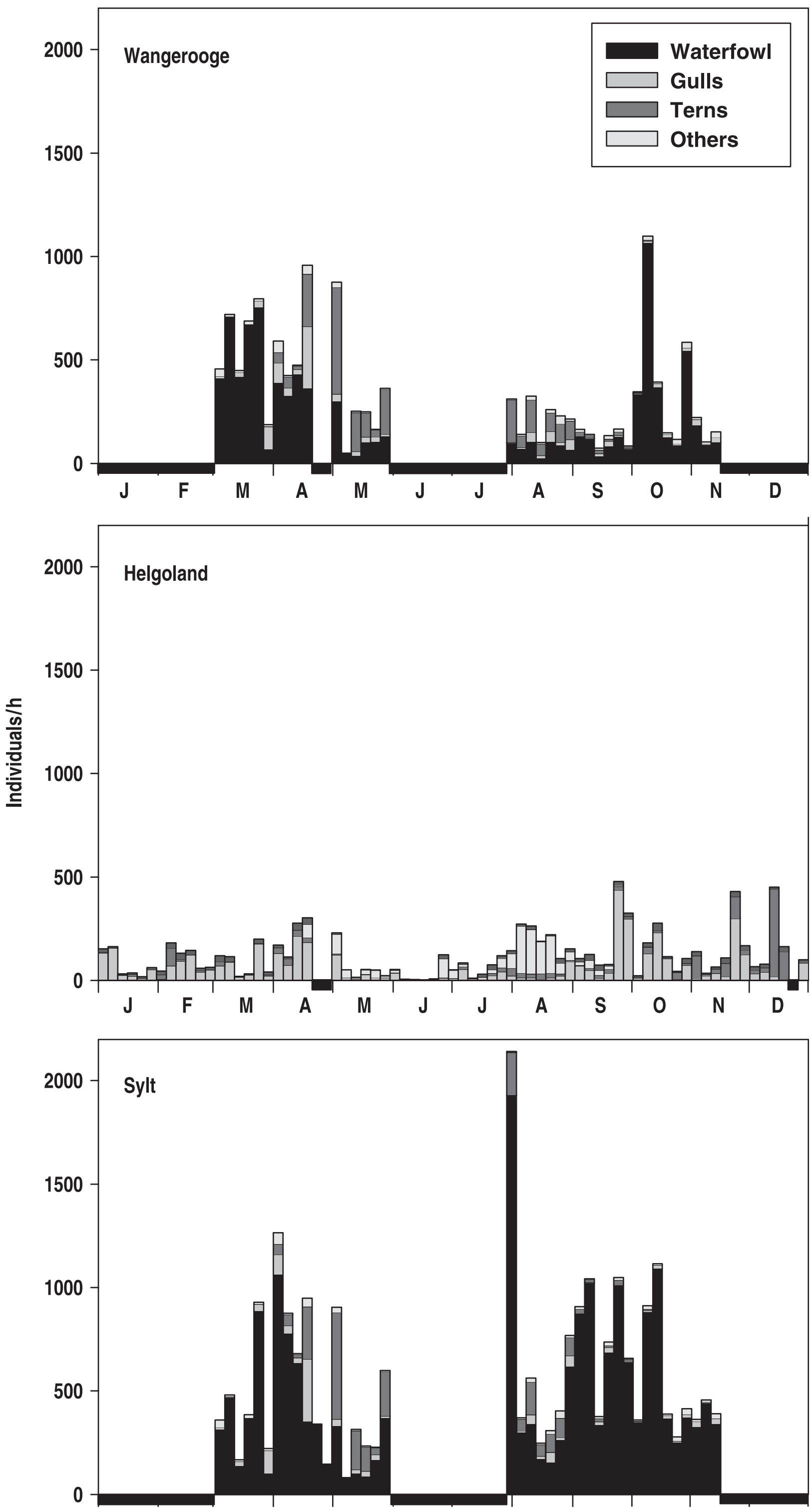

Figure 2. Mean migration intensity per 5-day period (pentade) recorded by sea-watching on the islands of Wangerooge (n = 85 538), Helgoland (n = 87 098) and Sylt (n = 238 765) for main species groups (July 2003 to December 2004). Black bars under histograms indicate periods without sea-watching.

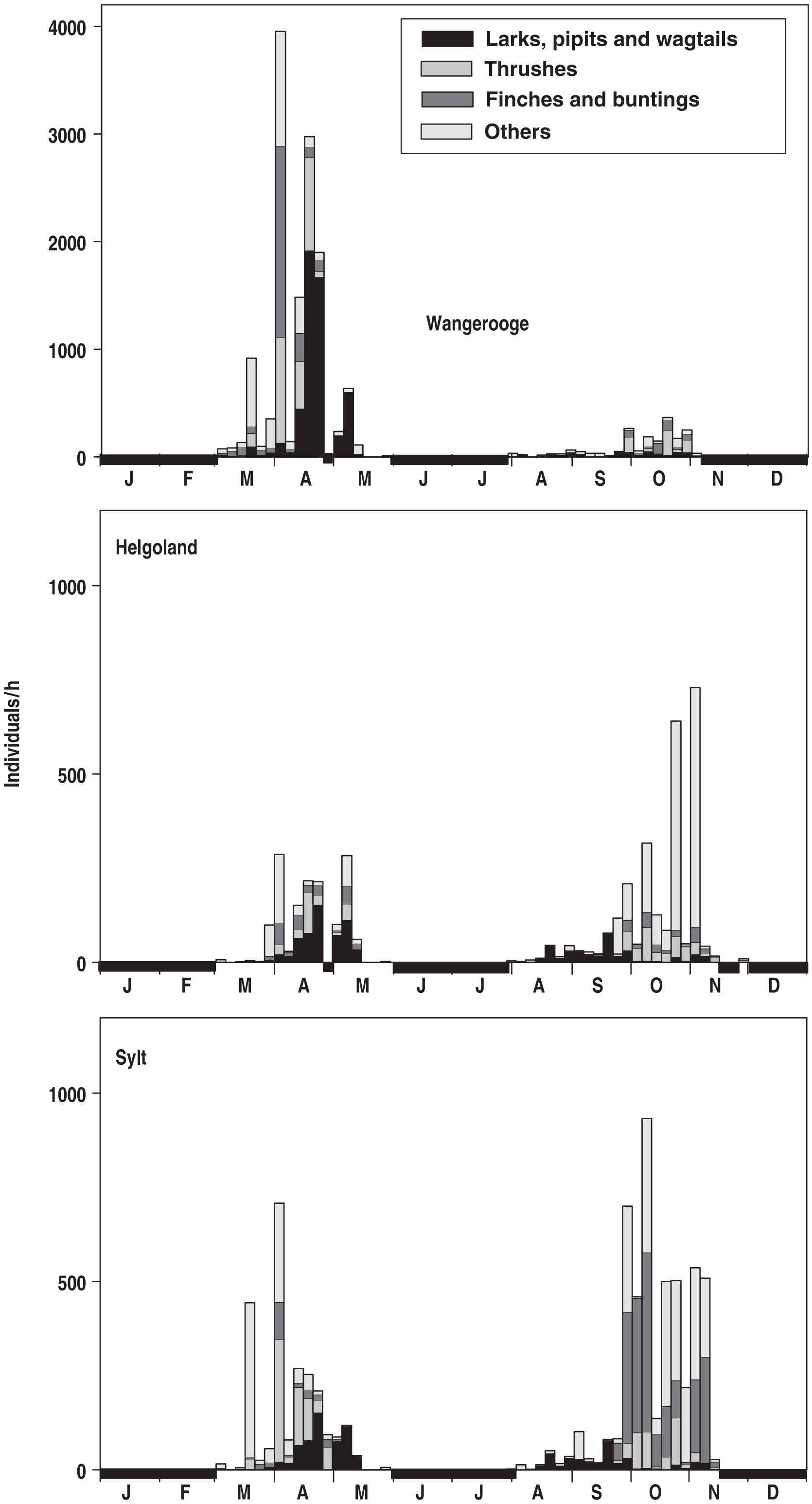

Figure 3. Mean migration intensity per 5-day period (pentade) recorded by passerine passage counts on the islands of Wangerooge (n = 70 302), Helgoland (n = 21 908) and Sylt (n = 67 670) for main species groups (August 2003 to November 2004). Black bars under histograms indicate periods without counts. Note variable scaling of the y-axes.

Table 2. Sizes of nocturnal migrant flocks detected by a thermal imaging camera.

Flock size	No. of cases	% of cases	No. of individuals	% of individuals
1	2153	94.4	2153	79.8
2–5	103	4.5	278	10.3
6–10	18	0.8	142	5.3
> 10	6	0.3	124	4.6
Total	2280	100.0	2697	100.0

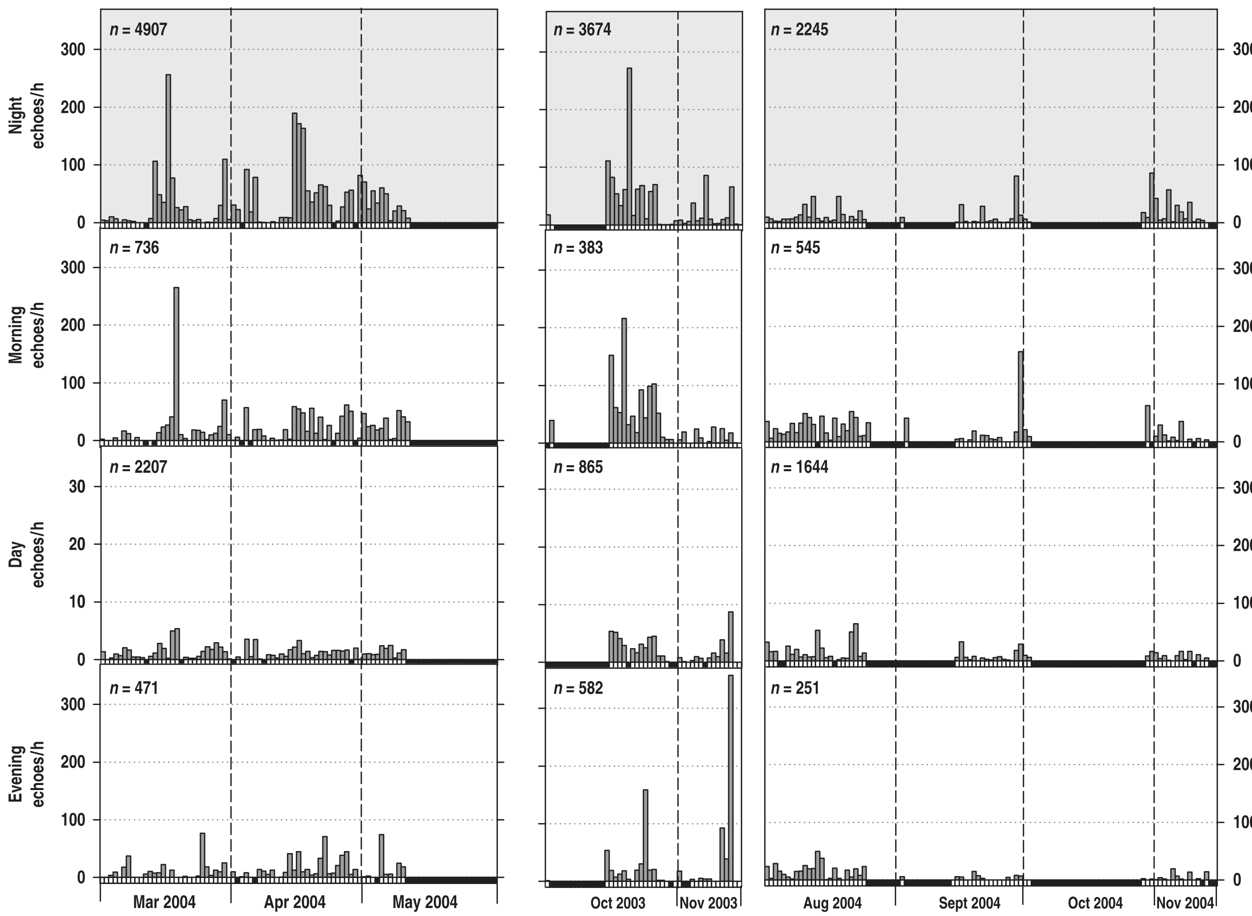

Figure 4. Migration intensity (number of corrected echoes per hour and day, *n* = number of uncorrected echoes) of single observation days in spring (2004, left) and autumn (2003 and 2004, right) in four different periods of the day (for definitions see Methods) at research platform FINO 1. Black bars under histograms indicate periods without radar measurements.

noticeable movements, which were not recorded on Wangerooge and Sylt because of the reduced observation times (Fig. 2). The period with the lowest intensity was in the middle of June. Most ducks were observed in the months September–April, terns dominated in late spring and early autumn, whereas gulls were numerous particularly during the winter months. Passerine migration was strongest in spring on Wangerooge and in autumn on Sylt, while migration intensity on Helgoland was generally relatively low (Fig. 3).

Nocturnal migration observed by vertical radar also showed large seasonal differences of intensity (see Fig. 4 for examples in spring and autumn). Periods of higher migration density were October/November 2003, the middle of March until the beginning of May 2004, and November 2004. Hardly any bird migration was detected between December 2003 and February 2004 and in June and August 2004. Long radar breakdowns in May/June and especially October 2004 need to be taken into account. In autumn 2003, part of the bird migration came unusually late (end of November). At this time, intensive diurnal migration involving mainly Greylag Goose, Eurasian Wigeon *Anas penelope*, Red-breasted Merganser *Mergus serratus*, Black-headed Gull and Blackbird was recorded on Helgoland.

It is noticeable that in spring migration densities are higher with winds from the east, south and southwest, but not with winds from the northwest, north and northeast. In autumn, more intensive migration occurs with winds from the northeast and east, the least migration activity being associated with winds from the southwest and north. In summary, there is a clear increase in migration density with increasing tailwind, both in spring and in autumn, although it is also evident that too much tailwind leads to a reverse effect (O. Hüppop *et al.* unpubl. data).

Daily variation of migration intensities

In all migration periods, bird movements varied substantially from day to day and were concentrated in a few days and nights. In particular, Pink-footed Geese were recorded in such high concentrations by sea-watching that over 75% of the individuals migrated on only 2–5% of the observation days. Considering all species observed by sea-watching, 75% of the individuals were observed on only 39–48% of the days, 50% of the birds on only 17–25% of the days. The visible migration intensity of passerines showed an even higher variability and concentration. Half of the whole passerine passage (total individuals of all species) was recorded on only 6–21% of the observation days, 75% of all individuals on 17–33% of all days, depending on location and season (Fig. 3).

The visual findings were confirmed by radar. In spring, more than half of the echoes were registered in only eight nights (25% of the echoes in three nights, 75% in 18 nights). In autumn 2003 (15 October to 15 November) 50% of the echoes were recorded in five of 31 observation nights, and in autumn 2004 (1 August to 15 November) in six of 61 nights.

There were large differences between the migration density registered at the vertical radar on FINO 1 and that recorded at the Sylt airfield. In autumn 2004, data were collected simultaneously at both sites in 41 nights. The bird migration activity on FINO 1 was greater in only six nights. In one night there was no activity registered at either site, while on the remaining 34 nights the migration activity on Sylt was distinctly greater. In summary, nocturnal migration in autumn 2004 was markedly greater on Sylt than on FINO 1 (Wilcoxon–Wilcox test, $z = -4.342$, $P < 0.001$). The influence of wind direction on migration density was very similar at both sites. Differences occurred in east winds (preference on FINO 1, avoidance on Sylt) as also in north and west winds (avoidance on FINO 1, preference on Sylt).

There was good agreement between call and thermal imaging records (for all 'nights' with at least one bird call/infra-red record: $r_s = 0.385$, $P < 0.02$, $n = 37$ nights) but hardly any with migration intensities recorded by vertical radar. High numbers of birds close to the platform obviously coincide with drizzle or mist. However, the database is still too small for a more detailed analysis.

Daytime variation of migration intensities

Visible migration was strongest at all locations and in all seasons during the first 3 h after sunrise, whereby the third hour often showed clearly lower migration intensities. At noon and in the 3 h before sunset, migration intensity apparently reduced. This daily rhythm was weakest in spring on Helgoland and Sylt as well as on Helgoland in summer and winter.

The adjusted bird echoes derived from the vertical radar revealed that the majority of 'invisible' bird movements were recorded in the 'night', and almost always lower relative migration densities in the 'morning' and 'evening' (see Figs 4 and 7). Whereas Figure 4 indicates high peaks outside the 'night', which are undoubtedly caused by passage migrants, part of the remaining echoes are certainly attributable to foraging gulls (see Methods).

Most birds picked up by the call recording system and thermal imaging camera were recorded at 'night' (75.6 and 77%, respectively, of the total), not including resting gulls and Sandwich Terns. In the 'morning' hours intense migration activity was noted only after that 'night' when the infra-red camera had recorded its third strongest nocturnal passage.

Migration altitude

More than one-third of the registered bird echoes were recorded in the lowest 100 m (Fig. 5). This

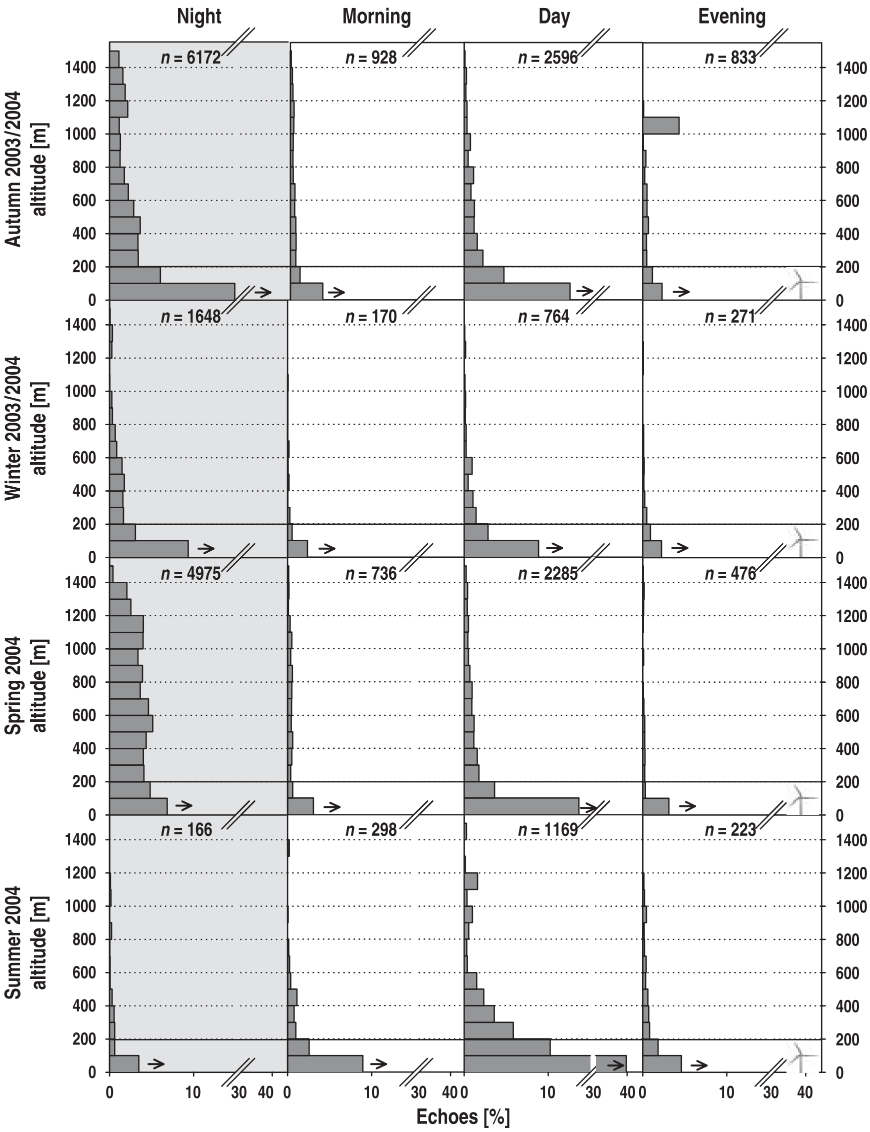

Figure 5. Flight altitudes (percentage of corrected echoes per altitude stratum, *n* = number of uncorrected echoes) in different seasons and times of day (for definitions see Methods) at research platform FINO 1. Seasonal totals = 100%. Echoes of low flying birds cannot be separated from reflections of the sea surface. Thus, the arrows emphasize that the proportion of echoes in the stratum from 0 to 100 m is presumably greater. The line at 200 m represents the approximate maximum height of the future offshore wind energy plants.

result is greatly underestimated by the methods used as it was often not possible to separate echoes of low flying birds from reflections of the sea surface. Almost half of the echoes up to 1500 m came from the lowest 200 m, and thus from birds that flew directly within the activity radius of future offshore wind turbines. Above this level the number of echoes dropped in most cases. Whatever the time of day or season of the year, the highest percentage was almost exclusively registered in the lowest 100 m. This is particularly evident in the daytime and to a lesser extent also in the morning and evening periods (Fig. 5). Because many of the echoes at these times relate presumably to gulls (see above), only birds migrating at night are taken into consideration in the following analysis. At night, most birds also migrate at altitudes below 200 m in a seasonally varying proportion, with a minimum of 20% of all echoes in summer 2004 and at least 64% in winter 2003/04. The greater part of these winter echoes relate to a retarded onset of migration in the second half of November, so that the altitude distribution is closer to that of the autumn. In spring the concentration in the lower strata is less evident. Owing to a shortage of data no interpretation can be made with respect to the summer.

The flight altitudes of the birds recorded on FINO 1 varied according to weather parameters. For instance, in rainy nights the percentage of birds migrating under 200 m was distinctly higher than in nights without rain (33 vs. 25% of all echoes up to 1500 m, G-test, $P < 0.01$).

In both spring and autumn tailwinds and light headwinds were associated with higher flight altitudes. With tailwinds above a certain strength, flight altitudes tended to drop off again. In autumn the five nights of heaviest migration were associated with easterly winds, in spring with southerly winds. The distribution of flight altitudes in the various nights, however, could hardly be more disparate (O. Hüppop *et al.* unpubl. data) and will require additional data and analyses.

Reverse migration

Using horizontal radar to register flight direction proved to be problematic (see Methods). However, rough estimates (i.e. north to east vs. south to west) of flight direction could be made with the vertical radar. Birds migrating roughly from the southwest to the northeast or vice versa ought to generate obvious tracks. For the analysis a track length of at least 35 m was chosen (see above). This permits determination of the proportion of reverse migration (Fig. 6). At night 92.5% of the birds with pronounced tracks migrated in northern to eastern directions, whereas 7.5% migrated in the opposite direction in spring. In autumn 70.1% headed west to south and 29.9% in the reverse direction. According to diurnal and seasonal periods, the 'right' direction predominates only at night and in the morning in spring and autumn (Fig. 7). At all other times of day and year, when migration density was lower anyway, the flight direction distribution pattern was quite clearly dictated by local birds (e.g. gulls residing on or in the vicinity of the platform).

Spatial distribution

The results of the visual observations indicated a clear concentration of waterfowl near the shore (Fig. 2). Only a few species were determined within the offshore range in the same and/or larger individual numbers (e.g. Red-throated Diver *Gavia stellata*, Pink-footed Goose). In addition, passerines concentrated more strongly at the coast than within the offshore range, which confirmed former investigations (Dierschke 2001). Migration concentrated at the 'departure coast', thus in the spring on Wangerooge and in the autumn on Sylt. At the appropriate migration times, there may be impressive concentrations of passerines inshore, while offshore migration is barely noticeable. It seems that birds generally cross the

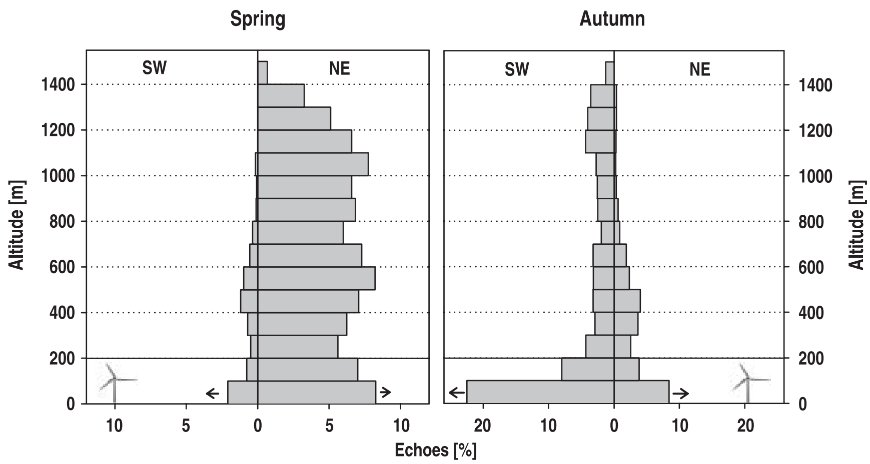

Figure 6. Nocturnal migration directions as recorded by vertical radar at research platform FINO 1 in different altitudes in spring 2004 (left, $n = 2128$ echoes) and in autumn 2003 and 2004 (right, $n = 3159$ echoes). Only tracks with a length of at least 35 m were used. Echoes of low flying birds cannot be separated from reflections of the sea surface. Thus, the arrows emphasize that the proportion of echoes in the stratum from 0 to 100 m is presumably greater. The line at 200 m represents the approximate maximum height of the future offshore wind energy plants. Note different scaling of x-axes.

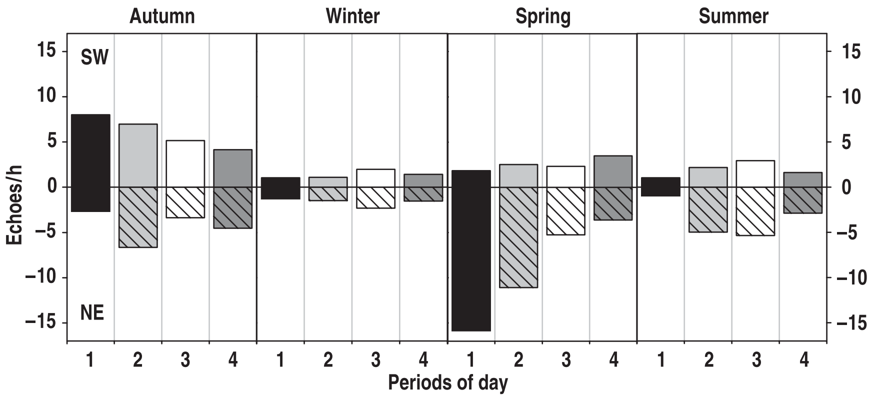

Figure 7. Nocturnal migration directions as recorded by vertical radar at research platform FINO 1 in different seasons and periods of day in autumn 2003 and 2004, in winter 2003/04, in spring 2004 and in summer 2004. Only tracks with a length of at least 35 m were used. 1 = night, 2 = morning, 3 = day, 4 = evening (for definitions see Methods). Positive values = crude direction southwest, negative values = crude direction northeast.

German Bight in offshore winds. As shown above, vertical radar measurements on Sylt and FINO 1 confirmed a higher intensity nearshore for the 'invisible' migration.

Collisions

The platform FINO 1, brightly lit at night, has witnessed numerous collisions. A total of 442 birds of 21 species were found dead at FINO 1 between October 2003 and December 2004. Nearly all were in good physical condition, which excludes starvation as a cause of death. Only six of 322 examined birds had a fat-score of 0 (according to Bairlein 1994) and may thus have died naturally, but three of these were found also to have broken legs. The examination showed that 245 individuals (76.1%) had outwardly apparent injuries, the most common of which were bleeding at the bill (41.3%), contusions on the skull and broken legs (16.8%). We cannot exclude that the remaining quarter died from exhaustion caused by flying around the platform (for such examples see Hope Jones 1980). Over 50% of the strikes occurred in just two nights (1 October 2003 and 29 October 2004) involving 86 and 196 birds in total, respectively. Both nights were characterized by periods of very poor visibility with mist or drizzle and presumably increased attraction of the illuminated research platform. In the second of these nights the thermal imaging camera revealed that many birds flew obviously disorientated around the illuminated platform (in the first night the camera was not yet in operation).

DISCUSSION

Advantages and disadvantages of methods

Visual observation of migrants is the only method that thus far has permitted conclusions to be drawn regarding migration intensity in relation to species composition. It must be stressed, however, that sea-watching covers only the lowest 100 m and passerine passage counts only the lowest 200 m, because at higher altitudes only few birds can be detected (Dierschke *et al.* 2005). Finally, migrants cannot be observed during night and during periods of limited visibility.

Radar systems provide a unique method to acquire large amounts of bird migration data independent of the time of day and across a range of weather conditions, although their performance is affected by rain. The quality of the data obtained only deteriorates with increasing distance and with decreasing bird size (e.g. Sutter 1957, Eastwood 1967, Bruderer 1997a, 1997b). Rotating vertically, an ordinary ship radar serves perfectly to deliver a non-stop record of both flight altitude and migration density (Cooper *et al.* 1991, Hüppop *et al.* 2004). By contrast, it is not yet adequate to permit species identification as with a tracking radar (Bruderer & Jacquat 1972). Low-flying birds can be hidden in surface or sea clutter. Furthermore, owing to the fairly limited range of a ship radar, it is necessary to know how many birds are missed at higher altitudes. Bruderer and Liechti (2004) showed that 50% of all migrants over Switzerland and over southern Germany can be detected at low altitude between 0 m and, depending on season and daytime, 250–750 m (90% from 0 m to 600–2000 m). Hence we believe that the number of missed birds, i.e. those flying above 1500 m, can be neglected in our studies. Although a horizontal ship radar can provide data on flight direction, such as avoidance flights at offshore wind farms, an uninterrupted recording of the migration process at sea is only possible in the absence of waves, which also reflect the radar beams (Hüppop *et al.* 2004). Radar investigations specifically targeting offshore bird migration have been introduced as part of Environmental Impact Assessments (e.g. Gruber & Nehls 2003, Walter & Todeskino 2005), but these are restricted to a few nights per migration season.

The use of civilian or military surveillance radar tremendously improved the understanding of large-scale spatial distribution of bird migration (e.g. Eastwood 1967, Bruderer 1997a, 1997b). However, these instruments, as with weather radars, are not solely used for bird studies owing to their high cost. This means that, in most cases, only data obtained as a by-product of such instruments are available. In Germany data obtained by the large aircraft surveillance radars of the German Airforce are used for bird-strike warnings (Friebe 1998). Unfortunately, as long as the primary as well as the filter and amplifier data fall under military secrecy (in contrast to the Netherlands, Buurma 1995), restrictions apply to the use of the available data to quantify bird migration. Accuracy of altitude and time of migrating birds are limited by the angle precision and spatial resolution and at longer distances by the curvature of the Earth's surface (e.g. Bruderer *et al.* 1995a). Nevertheless, under certain assumptions spatial comparisons of migratory intensity and direction can be made, which could not be determined otherwise.

Although the species that cross the German Bight are well known, it is still a technical challenge to identify altitude distribution and migration intensity with remote techniques on a species level. In contrast to ship radars, thermal imaging and video cameras as well as call recorders cover at most a few hundred metres, but they provide information on species and flock size. Thermal imaging camera and microphone are so far the only techniques to record birds flying disorientated around the platform in nights with poor visibility.

Thermal imaging cameras can also be used to record collisions (Desholm & Kahlert 2005), but the resolution of affordable models is too low, e.g. to detect a colliding passerine at 100 m distance. Although carcass collections can provide reliable estimates on land if typical pitfalls of the method are considered (e.g. Crawford & Engstrom 2001), this is impossible at sea, as a large proportion of corpses can be assumed to fall into the water or are displaced by scavenging gulls. The quantification of collision victims at obstacles at sea therefore remains a technical problem and technical improvements are urgently required.

Seasonal and daily migration intensities

Both migration density and flight altitude are enormously influenced by weather conditions (Bruderer 1971, Alerstam & Ulfstrand 1972, Alerstam 1979, Hilgerloh 1981, Bruderer *et al.* 1995b, Liechti & Bruderer 1998, Erni *et al.* 2002). Whereas migration density is without doubt determined mainly by wide-ranging weather parameters in the departure areas, flight altitude is more influenced by local weather conditions (e.g. Lack 1963, Alerstam *et al.* 1973, Alerstam 1990, Bruderer *et al.* 1995b, Erni *et al.* 2002). Presupposing that the mass of birds migrate along a northeast–southwest axis over the German Bight, in the main it will be the autumn weather conditions in Scandinavia and the spring conditions in the Low Countries and in southern England that apply.

Favourable conditions (especially tailwinds) can often result in very intensive migration, and adverse conditions to the almost complete cessation of migration at sea. We found that tailwinds above certain strength attenuated migration intensity. The bulk of offshore bird migration was reduced to a few nights. The longer weather conditions remained adverse before an abrupt weather amelioration occurred, the higher the density of this movement seemed to be (migration backlog). Similar findings have been reported by Meyer *et al.* (2003) in their studies of trans-Mediterranean raptor migration and Dierschke (2001) in the analysis of raptor occurrence on Helgoland. Other daytime migrants also preferred offshore winds. The FINO 1 findings show that this applied to nocturnal migration as well.

Generally, littoral migration is far more pronounced than offshore migration, as is shown by the comparison between migration densities on Sylt and on FINO 1. Further data on this are likely to be forthcoming from the follow-up project 'FINO-BIRD', as in the meantime radar systems are in operation on the 'Alte Weser' lighthouse (53°52′N, 08°08′E) and on Helgoland. Yet another conclusion that can be reached on the basis of our findings is that sample recordings taken at random, which is the method used in most of the environmental impact studies for offshore wind farms (e.g. Gruber & Nehls 2003, Walter & Todeskino 2005), can result in an area's migration activity being over- or underestimated, depending on prevailing conditions at the time of recording. In relation to our data, however, these results complement insights into local migration processes.

One of the problems involved in interpreting any of these results is the wide variation of bird migration between different years and different seasons. Clearly the number of birds migrating over the German Bight fluctuates enormously from year to year, governed by weather (e.g. Alerstam 1990): by the state of the weather at migration time, by the weather in the breeding areas (and thus by breeding success rates) and by the weather in the winter quarters (and thus by winter mortality). Even within a single migration period the influence of the weather on different species and even individuals can be very diverse. Thus, in March, a set of weather conditions with strong easterly winds can lead to a very cold spell, almost disrupting migration (Hüppop *et al.* 2004). Conversely, in May, easterly winds lead to very warm weather with a high migration density (e.g. Dierschke *et al.* 1998). At the same time, a persistent spell of 'good' weather can, after an initial steep increase in migration density, lead to its collapse within a few days, the mass of migrants having by then passed.

Migration altitude

Birds try mostly to fly in the altitude stratum in which their energy costs are lowest (Bellrose 1967, Bruderer & Liechti 1995). The choice of stratum may also be influenced by a variety of other parameters, such as the length of the intended flight and the experience of the bird (adult birds/young birds; Alerstam 1979). Headwinds and precipitation generally result in a lower flight altitude (Eastwood 1967, Bruderer 1971, Dierschke & Daniels 2003, Gruber & Nehls 2003, Hüppop *et al.* 2004). Time of day, too, has an effect on flight altitude (Lack 1960, Eastwood & Rider 1965, Able 1970, Jellmann 1979, Bruderer & Liechti 2004, Hüppop *et al.* 2004). In general the flight altitude of low migrating birds can be seen to be distinctly lower offshore than on the coast or inland (Berndt & Busche 1993, Dirksen *et al.* 1996, 1998, Krüger & Garthe 2001, Hüppop *et al.* 2004). The greater unevenness of the landscape creates turbulences – more or less depending on the exact topography of the land surface – which are hardly ever encountered at sea. Low stratum winds reach speeds that are greater and more constant over sea than they do over land (Geiger 1961). Accordingly, tailwinds at low altitudes are more favourable at sea than over land, which could be one reason for the lower flight altitudes at sea. Adverse weather conditions, by contrast, lead to even greater reductions of flight altitude, so that many passerines fly low over the water surface (Hüppop *et al.* 2004).

The flight altitude distribution may be influenced also by the range of species involved. Many diurnally migrating species of waterfowl and seabirds migrate mostly at very low altitudes (e.g. Krüger & Garthe 2001, Dierschke & Daniels 2003, Hüppop *et al.* 2004), whereas, for example, arctic waders fly at very high altitudes – at least on their migration to their breeding grounds in May (Green 2003). Altitude distribution differences between nights therefore may be due to a different range of species. Viewed over a longer period of time, however, the effect of this on the whole pattern is likely to be marginal.

Reverse migration

Reverse migration has been observed in many other regions (e.g. Richardson 1982, Åkesson *et al.* 1996, Zehnder *et al.* 2001). It can be explained as an energy-saving strategy (Wikelski *et al.* 2003). However, with respect to the planned offshore wind turbines this means that at least some birds have to pass the 'dangerous areas' more than once per migration season, thus increasing the risk of collision for an individual.

Spatial distribution

Collection of reliable information about the spatial distribution of bird migration over the North Sea is probably the largest issue in the assessment of impacts of offshore wind farms on birds. Visual and radar investigations as well as analyses of ringing recoveries can at least give a crude impression.

The analysis of military surveillance radar data confirmed the findings by our visual and ship radar observations that migratory intensity decreases with increasing distance from the coast. However, the data also clarified that there remains a considerable broad-front migration over the open sea, including birds obviously heading to or coming from southern Norway and eastern England, depending on the weather conditions and season. Additionally, many days with reverse migration were found (Hüppop *et al.* 2004).

Recoveries of ringed birds merely connect the locations of ringing and recovery of a bird. Nevertheless, recoveries within 3 weeks or less can also give an impression of the migration routes. Stolzenbach *et al.* (in press) analysed such recoveries exemplarily for 11 bird species ringed in Norway, Sweden, Denmark and Germany with the aim of reconstructing their flight routes over the southeastern North Sea. The study could partly confirm and extend the existing knowledge of bird migration over the German Bight. In autumn, broad-front migration towards the southwest is the prevailing movement of, for example, Swedish, Danish and northern German Dunnocks *Prunella modularis*, Robins, Garden Warblers *Sylvia borin*, Song Thrushes, Common Redstarts *Phoenicurus phoenicurus* and Pied Flycatchers *Ficedula hypoleuca*. In other species, however, the main direction is probably south-southwest (e.g. Willow Warbler *Phylloscopus trochilus* and Black-headed Gull). The second important movement is a broad-front migration from southern Norway to the south, in which Norwegian and probably parts of the Swedish populations of, for example, Dunnock, Robin, Garden Warbler, Willow Warbler and probably Dunlin are involved, whereas, for example, Pied Flycatchers seem to avoid long sea crossings. A few species, such as Blackbird and Robin, also seem to fly directly from Denmark and Schleswig-Holstein in western directions to Great Britain. In spring, reverse migration routes with obviously stronger coastal orientation can be found. For some species it can be assumed that a crossing of the German Bight is avoided and that migration follows the coastline (e.g. Black-headed Gull, adult Dunlins and Dunnocks in spring).

Collisions

Bird collisions with non-natural structures have long been a well-documented phenomenon. Some of the most obvious manifestations are at lighthouses (Gätke 1891, Hansen 1954, Jones & Francis 2003), but birds also collide with electricity pylons (Haas 1980, Heijnis 1980, Hoerschelmann *et al.* 1988, Richarz 2001), communication masts (Avery *et al.* 1977, Kelm 1978, Lammen & Hartwig 1994, Crawford & Engstrom 2001, Pfeifer 2003), plate glass windows (Dunn 1993, Erickson *et al.* 2001) and wind turbine blades (synopsis in Erickson *et al.* 2001, Langston & Pullan 2003, Percival 2005). Bird strikes at sea are most frequently observed at oil and gas rigs with their flares (Sage 1979, Hope Jones 1980) and offshore marine research facilities (Müller 1981). The extent to which avian migrants are likely to interact with the projected offshore wind farms is currently difficult to estimate (Hüppop *et al.* 2004, Desholm & Kahlert 2005). In weather conditions with poor visibility illuminated objects can attract nocturnal migrants in large numbers. As FINO 1 is brightly lit, one could suppose that the flight altitudes we recorded in the vicinity of the platform were lower than anywhere else in the offshore area. If it were true that the illumination of FINO 1 did result in a distortion of this nature, birds should change flight altitudes close to the platform, i.e. it should be apparent that a greater proportion of birds change height when approaching the platform. The data show that in all altitude strata at least 82% of the birds maintained their flight altitude (n = 4197). Thus, we assume that our data are representative for all higher strata. Owing to the position of the radar at the platform (see Methods) we could only study this phenomenon in birds approaching the platform from westerly directions.

It has been established for over a century on almost all continents that illuminated structures inland, on the coast and at sea attract birds, and that frequent collisions with these structures occur (e.g. Schmiedel 2001). This effect is likely to be even more pronounced at sea than on land as there are no suitable resting places at sea for terrestrial birds. Hence, especially during nights with dense migration traffic and adverse weather conditions the risk of interaction is likely to be considerably greater than on land. Although nights such as this occur every year, there are usually only a few of them in one migration period. Over half the bird cadavers collected on FINO 1 were found in just two nights. Our results clearly show that the mass of birds collected had collided with the structure and in only a few cases could starvation not be ruled out entirely. It is a fair assumption that most of the birds fell into the sea or were taken by gulls. Thus, the actual total of collisions is presumably many times the number quoted here.

Most inland wind farms present few problems for avian migrants. Although it is true that over half the birds passing wind farms by day changed behaviour (Stübing 2004), the effect on migrants of such structures inland can in most cases be regarded as marginal (Bergen 2001, Percival 2005). Frequent collisions were reported from only a few exposed sites with high migration densities (e.g. at passes, straits and peninsulas) or large numbers of, for example, soaring resident raptors (Acha 1997, Langston & Pullan 2003, Thelander *et al.* 2003, Barrios & Rodriguez 2004).

In all likelihood, however, the inland findings will not be applicable to the offshore area, or will be of only limited application. Many birds seem to migrate in much lower altitude strata at sea than they do over land (Bruderer & Liechti 1998, Hüppop *et al.* 2004). Furthermore, nocturnal migrants reduce their flight altitude in particular on dark nights, in headwinds and/or precipitation conditions (Able 1970, Bruderer 1971, Avery *et al.* 1977, Gruber & Nehls 2003, Bruderer & Liechti 2004), thus coming within range of the wind farms.

The consequences of barrier effects, namely those on flight energetics, are largely unknown but are the subject of current research projects. To what extent additional mortality as a result of collisions with offshore wind turbines or higher flight costs will have impacts at the population level is extremely difficult to predict and depends on the life history and population status of the respective species. Dierschke *et al.* (2003) assumed that an increase of the existing adult mortality rate by 0.5–5%, depending on the individual species, seems to be acceptable for the 250 bird species regularly migrating across the German sea areas (including the Baltic Sea). Any further loss of individuals has to be judged to be of considerable impact. Because the area covered by a bird population during migration usually spreads over several countries, an international approach is necessary to assess impacts on populations of migrating birds. Meanwhile, M. Rebke *et al.* (unpubl. data) have developed much more detailed Leslie-matrix models for selected key-species, which will soon be available for predictions for different scenarios.

CONCLUSIONS

Our findings confirm that large numbers of diurnal and nocturnal migrants cross the German Bight, with considerable variation of migration intensity, time, altitude and species, depending on season and weather conditions. The enormous variability makes precise analyses very difficult and requires further investigations. Dierschke (2003) estimated from systematic visual observations that in 18 species significant proportions (> 1%) of the respective biogeographical population pass Helgoland during migration, with more than 10% of the population in Red-throated Diver, Pink-footed Goose, Greylag Goose, Brent Goose and Little Gull *Larus minutus*. From the radar data presented here it can be concluded that also large proportions of nocturnally migrating species fly across the German Bight, although the species composition is partly unknown. With regard to future wind farms it is important to emphasize that almost half of the birds fly at 'dangerous' altitudes. In addition, the number of individuals in reverse migration is considerable, which increases the risk of collision. Normally, migrating birds seem to avoid obstacles, even at night (Isselbächer & Isselbächer 2001, Schmiedel 2001, Desholm & Kahlert 2005), which diminishes collision risk but increases flight costs. However, we were able to demonstrate that under poor visibility, caused by drizzle and mist, terrestrial birds in particular are attracted by illuminated offshore obstacles. We documented with our thermal images that disorientated birds flew around the platform repeatedly, so that both their risk of collision and their energy consumption increased (see also Hope Jones 1980).

Even if the findings regarding collisions at the research platform FINO 1 cannot directly be applied to offshore wind farms, they do show that on a few nights per year a large number of avian interactions at offshore plants can be expected, especially in view of the number and planned area of projected wind farms. Owing to the methods used, previous studies at Swedish or Danish offshore wind farms have been able to investigate diurnal collisions only in good weather conditions, which are expected to be few in number (e.g. Pettersson 2005), or refer only to large species such as geese and ducks (e.g. Desholm & Kahlert 2005), but not to small bird species, which according to our findings are most frequently involved in collisions.

Regardless of the existing knowledge gaps, some mitigation measures can be recommended:

- Abandonment of wind farms in zones with dense migration.
- Alignment of the turbines in rows parallel to the main migratory direction.
- Free migration corridors of several kilometres width between wind farms.
- Avoidance of construction of wind farms between, for example, resting and foraging grounds.
- Turning off turbines in nights predicted to have adverse weather and high migration intensity.

- Refraining from large-scale continuous illumination.
- Taking measures to make wind turbines more recognizable to birds.

In particular, the penultimate of these measures urgently requires appropriate experiments involving the brightness and colour of wind farm illumination in order to minimize collision rates. Perhaps the most effective solution would be to use lighting that is adjusted to the weather conditions, e.g. flash-light with long intervals instead of continuous light in fog and drizzle. During the very few nights in which a high frequency of bird strikes is expected, in predicted adverse weather conditions with high migration intensity, turning off turbines and adjusting the rotor blades to minimize their surface relative to the main direction of migration could be helpful in reducing collision extent.

Our findings lead to the further conclusion that a combination of methods is necessary to describe the complex patterns of migration over the sea. However, even with virtually non-stop recording as on FINO 1, the wide variation in bird migration and in weather (together with its effect on the former) lead to an insufficient number of samples per weather situation. The funding of further research in the follow-up project 'FINOBIRD' (financed by The German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, grant no. 0329983) is a response to this problem. The recordings are to be continued with the aim of refining the results presented here. Furthermore, we plan to develop a model to 'forecast' bird migration over the German Bight with the aid of weather forecasts, for example to establish a basis for mitigation measures. However, as long as no investigations at existing plants are carried out to provide reliable data on collisions and avoidance behaviour, the actual scale of these problems will remain a matter of speculation. We expect more information on avoidance behaviour and collisions with the construction of a pilot wind park close to the FINO 1 platform (not before 2007).

We are especially grateful to all field and 'desktop' workers who helped with this comprehensive project, which was funded by The German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety, grant no. 0327526. We further wish to thank Rowena Langston, Kathrin Hüppop and Sidney A. Gauthreaux, Jr for their useful comments on earlier drafts of the manuscript.

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