On the radar
Weather, bird migration and aeroconservation over the North Sea
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Oh, relax, Kevin!
I'm only pulling your leg!
Of course, I brought sunscreen!
Chapter 6
Synthesis

Migration is a life history strategy which has evolved in many avian species. For many species, their migration routes cross diverse terrains, some of which may be inhospitable. One such example is the migration of terrestrial avian species over the sea. For landbirds, seas can be ecological barriers, as they do not offer opportunities for migratory stopovers, necessary for rest and refuelling. To bypass the hindrance that ecological barriers create, birds evolved different strategies to navigate these inhospitable areas (Alerstam 2001). By using radars to study nocturnal migration over the North Sea, this thesis sheds light on seasonal patterns of migration of birds over an ecological barrier and their environmental drivers. By revealing how local and synoptic weather conditions and seasonal and daily phenologies influence nocturnal bird migration over the sea, we scratch the surface of a complex system which shows seasonal heterogeneity in timing, migration intensity, departure decisions and altitudes. Throughout this thesis, it has been repeatedly shown that environmental variables such as wind assistance, time of year and temperature influence departure decisions, flight altitudes and migration intensity of nocturnal migrants. The results in this thesis give more insight into migration over one of the regions, a crossroad, within the East Atlantic flyway and inform aeroconservation in the region, necessary due to large wind energy expansion. Furthermore, they contribute to understanding migratory behaviour around the ecological barriers – inhospitable environments that birds navigate differently in different parts of the world.

6.1 Navigating the North Sea – an ecological barrier of the East Atlantic Flyway

Even though ecological barriers pose a considerable risk for migratory birds by increasing their mortality through exhaustion, starvation, predation, collision and harsh environmental conditions, birds have evolved physiological and behavioural strategies to successfully navigate them (Alerstam, 2001; Bairlein et al., 2012; Hawkes et al., 2011). The risk of crossing a barrier can be minimised by having enough fuel loads (Schmaljohann & Naef-Daenzer, 2011) and choosing supportive weather conditions (Bulte et al. 2014; Loonstra et al. 2019; Nourani et al. 2021). When these two criteria are fulfilled, barrier crossing, which considerably reduces the time needed for migration compared to circumnavigating them, can be performed quickly and relatively safely. The speed of migration has higher stakes in spring compared to autumn, as birds return to their breeding grounds and need to compete for the best breeding territories, making earlier arrival preferable (Kokko, 1999).
The North Sea can pose a smaller or larger barrier for migratory birds, depending on the migratory axis they use to cross it. For birds that perform direct crossing from Norway and continue alongside the West coast of the Netherlands, the distance they have to cross in one go is around 700 km. Migrants travelling between Denmark and other parts of Scandinavia and southern Europe and Africa must cross around 500 km. In comparison, those travelling between the southwestern coast of the Netherlands and the UK cross approximately 200 km in one go. In Chapter 2, we show that birds embark on journeys across the sea when they experience higher wind assistance at potential departure locations and in Chapter 3, we demonstrate that intense migration nights occur when high-pressure systems, thus stable weather conditions, dominate the region. This was evident even for migrants performing the shortest crossing between the Netherlands and the UK.

In comparison with larger ecological barriers that birds experience on their migratory journeys, such as the Sahara Desert (ca 2500 km), Atlantic (more than 4000 km), and Pacific ocean (ca 11000 km), the North Sea, especially the distance between the Netherlands and the UK could be considered negligible, as birds can cross within a single night of the flight. However, compared to migration over land in the region (Kemp 2012), we observe a lower number of nights with extremely high migration intensity (Chapters 2, 3 and 5), which can indicate that birds are more selective of weather conditions when embarking on journeys across the sea, even with short distances. Such selective behaviour has been observed in birds that cross the Baltic Sea (Sjöberg et al. 2015) or the Gulf of Mexico (Deppe et al. 2015), which are ecological barriers of similar size to the North Sea. In Chapter 2, we show that, throughout most of the spring season, wind conditions at departure in the UK support migration over the North Sea. However, on nights with calmer weather conditions, migration was more intense, showing that birds still select weather conditions to arrive safely on the other side of the barrier. As indicated in Chapter 3, this does not necessarily have to be only due to more favourable wind assistance but better regional synoptic conditions, which bring more dry and stable weather. In autumn, weather conditions that support migration are a rare occurrence. When they occur, birds fly in great numbers, creating much higher migration peaks than in spring (Chapters 3 and 5). This, however, does not mean that birds do not fly during the rest of the migration season. In Chapter 2, we show that birds with slightly higher airspeeds migrated even with suboptimal weather conditions but chose to fly with lower wind speeds to decrease the magnitude of the negative wind assistance (Chapter 2). A similar effect has been observed in Chapter 4, when birds, once aloft, chose altitudes with lower wind speeds if the wind assistance was negative and climbed up to utilise higher wind speeds if the winds were generally supportive of migration. Higher altitude migration was mainly observed in spring, the season with the abundance of supportive wind conditions and more constrained migration timing.

In regions where weather regimes create conditions that are generally supportive
of migration in one season but not in the other, birds can navigate the same ecological barrier differently, for example, crossing the barrier in one season and circumnavigating in other (Bradley et al., 2014; Tøttrup et al., 2012). Alternate routes among seasons are known as loop migration. By modelling migration across the North Sea in Chapter 2, we demonstrate that the two main migratory axes do not show seasonal reversal: the majority of migratory movement in spring is between west and east at our radar location, while the majority in autumn is between northeast and southwest. A question that naturally arose from this observation is: how did the birds flying to the Netherlands from the UK in spring arrive in the UK in autumn? Could it be that they perform loop migration? In autumn, birds seem to fly following the coast of the Netherlands, flying towards the southwest and presumably crossing the North Sea to the UK at the most narrow site, south of our radar location. In spring, birds then cross the North Sea directly from their departure locations due to favourable wind conditions, performing seasonal loop migration. This has been suggested earlier in the pioneering radar studies of bird migration in the North Sea basin by Lack (1959) and Eastwood (1967), and the topic has been re-opened again by Buurma (1987). However, the lack of radar data from the UK and southern parts close to the Dutch coast made this impossible to test in the current research.

Another interesting observation of migration directions in the North Sea is the limited migration along the NE-SW axis in spring, as this is the dominant axis of migratory movement in autumn. Nocturnal migration patterns observed by weather radars at a more inland location (de Bilt) in the Netherlands indicate that the predominant movement in spring is towards NE. However, the coastal weather radars do not mirror this (Kemp, 2012). There are two explanations for this discrepancy. The first is that in spring, the NE-SW migration axis simply occurs more inland, being entirely missed by offshore radars. Second, considering that the weather radars have a longer detection range, thus covering higher altitudes than the bird radars, this movement may occur at higher altitudes in spring, flying above the detection range of offshore bird radars.

When discussing the North Sea as a barrier to the migratory movement of birds, the ecological aspects and the added barrier factor of anthropogenic alterations must be taken into account. We scratched the surface of understanding the migratory behaviour around the southern North Sea and revealed many intricacies on a seasonal level, which are most likely the product of different weather regimes but could also be a result of other factors such as birds’ physiological condition (Sandberg & Moore 1996). As indicated at the beginning of this section, strategies to navigate a barrier have been developed over many years. The added factor of anthropogenic changes, such as wind farm development within an ecological barrier, could trigger the evolution of alternative migration routes (Alerstam, 2001). Alternative migration routes could lead to an indirect increase in mortality through exhaustion or lower reproductive success due to not arriving on time at the
breeding grounds (Baker et al., 2004). On the contrary, using the same migratory routes could lead to increased direct mortality through collisions (Desholm, 2009). Understanding the navigation of ecological barriers in different seasons can be used to inform conservation measures. It can steer the conservation action, for example, by avoiding expensive wind turbine curtailments in certain parts of the North Sea if the barrier crossing occurs in a different place. This is especially important in the later stages of the offshore wind farm development in the North Sea when the turbine density will be high, and a deeper understanding of fine-scale ecological barrier navigation can facilitate cost-effective conservation.

6.2 Radar data quality

While radar is a great tool for studying mass movements of aerial organisms and increasingly serves as an indispensable tool in biological conservation, there are still limitations reflected in its spatial coverage, varying data quality, and inability to identify organisms to the species level (Bauer et al. 2019; Hüppop et al. 2019). So far, only a few studies before this thesis have been using radars located offshore to study patterns of bird migration (e.g. Hüppop et al. 2006; Fijn et al. 2015; Krijgsveld et al. 2015). Collecting radar data offshore has proven to be challenging due to large amounts of reflections from sea waves and other types of noise that clutter the data. Such reflections, however, can be flagged based on their characteristics and excluded from the analysis. Radars used in this study already had automated clutter filters included as part of their software which discarded tracks belonging to sea wave reflections and other types of clutter such as rain, static clutter or reflections from rotating turbines. However, due to similarities between echo characteristics of birds and different clutter types, there was a certain number of tracks that mistakenly entered the database as bird tracks.

Throughout this thesis, constant effort has been made to produce data of the best quality by developing different types of filtering. This was a collaboration between developers of the radars and a team at the University of Amsterdam, and it required numerous hours of explorative analysis and comparisons in order to come up with the best methods for cleaning the data. These methods can be found in the Materials and Methods section of each chapter in this thesis, but also in Fijn et al. (2015) and supporting information therein, Krijgsveld et al. (2015) and van Erp et al. (2021). While these steps have been developed and are currently in use by the University of Amsterdam team, thanks to the collaboration with Robin Radar, they might subsequently be implemented in the radar software.

Improving radar data quality is a continuous process that evolves with technological advancements and new data insights. However, analysing different biological phenomena, such as bird migration during rain events or harsh winds, remains challenging. Under such weather conditions, radar data quality deteriorates, and observed patterns are unreliable. This is because such weather conditions create
noisy environments in which the radar can pick up more echoes, but also due to limitations of the current radar technologies. As the number of radars used in ecological studies increases and new knowledge is gained through exploratory analysis and ground-truthing, more intricate filtering methods will be developed. Furthermore, as there are limits to what current radars can record, the development of new radar technologies will allow researchers to perform studies of good enough quality under different weather conditions.

6.3 Action plan for aeroconservation

Well-established, adequate conservation measures often take years to implement, and their execution generally occurs after the adverse effects have already taken a toll on a specific species or ecosystem. This is why there is general agreement that success in environmental protection on any scale lies with the ability to anticipate what kind of effect a certain environmental alteration will have or when a certain event will occur and act preventively (Clark et al., 2001). Forecast models make such anticipations possible and can help create conservation plans in advance. Most of the existing forecast models, however, are scenario-based projections and are currently not balanced with the conservation needs, which require more near-term projections which would initiate immediate conservation action (Dietze et al., 2018).

Unlike in terrestrial and freshwater habitats, where conservation steps have been relatively well established (Fazey et al. 2005; Orlikowska et al. 2016), aeroconservation is still in its infancy. As explained in Chapter 1, this is mainly due to the aerosphere not having the same habitat status as the other two. However, since airspace is becoming crowded with different types of infrastructure and aircraft, aeroconservation has been quickly catching up in the recent decade. This is especially the case in large urban centres where illuminated high-rise buildings attract birds that collide with them (van Doren et al., 2017). Within the last couple of years, measures to prevent adverse effects of wind turbine infrastructure on aerial wildlife are increasingly in place. However, most efforts have focused on individual wind farms with the aim of protecting specific species (Hayes et al., 2019; McClure et al., 2021).

Combining the increasing need for near-term ecological forecasts and aeroconservation due to the rapid development of wind energy infrastructure, the research conducted in this thesis was a part of a unique framework developed by the Dutch government that combined input from various stakeholders to achieve a common goal – to decrease the number of collisions of nocturnally migrating birds with rotating offshore wind turbines. Studies conducted as part of Chapters 2, 3 and 4 aimed to increase the fundamental knowledge of nocturnal bird migration patterns over the ecological barrier of the southern North Sea, which was relatively scarce. Additionally, these studies aimed to identify moments in time in which the
conservation measures would need to be performed to maximise a safe passage for nocturnally-migrating birds with minimal repercussions on the energy market by looking into which environmental factors drive the occurrence of low-altitude intense bird migration and how often. This was the first necessary step of the conservation framework. The second step of the framework is presented in Chapter 5. It considers using the knowledge about environmental drivers of nocturnal bird migration gathered in previous chapters to develop near-term forecasts that would use weather variables from weather forecasts to predict migration intensity at the radar location 48 hours in advance. This brings us to the next step of the framework, which is the expert committee consisting of avian ecologists. At least in the initial stages, the expert committee will evaluate the model output and make a decision on whether to initiate shutdowns or not. As guidelines, they will use migration traffic rate thresholds developed by an external ecological consultant at the same time during which the model was developed. When the forecasts predict migration traffic rates that exceed the threshold, the expert committee will evaluate other parameters, such as confidence of the model prediction, accuracy of the weather forecast and energy production under forecasted weather conditions, and, together with energy grid operators, make a decision whether to curtail the wind turbines. If the decision to curtail has been made, a blanket curtailment of all operational wind turbines in the Zeeuwse and Hollandse Kust zone of the Dutch North Sea will be performed on a nightly basis. The decision to curtail occurs ca 48 hours in advance of the actual curtailment. During that time, the energy grid operators must make necessary adjustments to keep the grid stable and ensure enough energy to prevent blackouts (calamities). At this point, they can still decide to stop the curtailment if a calamity is possible. The schematic overview of the framework can be found in Figure 6.1.

As demonstrated in Figure 6.1 and the framework description above, blanket wind turbine curtailments of this magnitude can only be performed by coordinated action between various stakeholders. This involves researchers, policy-makers, consultants, governmental and non-governmental organisations and private institutions. A vast majority of conservation literature is focused on describing the states of ecosystems and mechanisms that cause change, but only a handful is used to develop strategies and base policies on (Williams et al. 2020). Besides financial reasons, this is, I believe, often due to a lack of communication between stakeholders and unwillingness to initiate the development of complex procedures, especially within limited time frames, as is necessary in a rapidly changing world. Throughout the development of this thesis, I was actively part of a working group to create conservation action. By working on the common goal together, from various perspectives, we were able to understand the needs and limitations of each side and find the best ways to accommodate them while striving to provide the most robust results. Although working together was challenging at times, we managed to develop a conservation action on which we will continue to work in the coming years. An interdisciplinary approach and knowledge exchange between stakeholders are key to a successful future of environmental management.
Due to extensive offshore wind energy development in the southern North Sea, studies conducted as part of Chapters 2, 3 and 4 aimed to identify the frequency of necessary wind turbine curtailments by looking into which environmental factors drive the occurrence of low-altitude intense bird migration and how often. In Chapter 4, we demonstrate that the majority of nocturnal bird migration over the North Sea occurs at altitudes that overlap with those of wind turbines and that wind turbine curtailments suggested as part of the aeroconservation plans are necessary to allow for a safer passage of nocturnal migrants. Since, unlike in spring, intense nocturnal migration in autumn mainly occurs at low altitudes, it would be easy to suggest that the curtailments are of special importance in autumn. However, care should be taken with such suggestions since intense migration can, at the same time, also occur at low altitudes in high numbers. We need more research to understand fine-scale changes in migration patterns, and until then, we should focus conservation efforts on all nights with intense bird migration.

### 6.4 Future outlook

While data collection by already deployed offshore radars continues into the future, additional radars will be positioned at different offshore locations in the North Sea. The growing radar network and respective time series create opportunities not only for expanding our knowledge about bird migration at the crossroad of migratory axes within the East-Atlantic flyway but also for a comparison of patterns and underlying mechanisms that influence these patterns between different radars.
Longer temporal data coverage will allow for the update of the current migration forecast models and improve predictions of migration intensity. This is in line with the advocated type of conservation, which is action-based and does not wait for years of data collection to pass. Instead, it focuses on developing conservation measures when the minimal data requirements are achieved and improving them as new insights are gained (Dietze et al., 2018).

Combining data collected by different systems is challenging. In the future, it would be of great value to develop methods of combining tracking and weather radar data to gain a complete picture of migration systems in the region. These radars complement each other in what they observe, as tracking radars cover lower altitudes that weather radars miss and weather radars have longer ranges allowing to record migration over larger areas. Combining these systems, which cover areas at sea and on land, with spatially explicit simulation models, will give more opportunities to compare migratory behaviour between different topographies. We could, even on a fine scale, study birds’ response to coastlines, whether migration patterns differ above the sea and land and why, and further explore the theory of loop migration.

Data collected by radars at different locations in the North Sea allows us to look for similarities in migration patterns between different locations but also their differences. Potential differences could exist in local environmental factors that drive diverse migration patterns, even though birds respond similarly to them. Alternatively, environmental factors can be similar, but differences in migration patterns might occur due to behavioural differences caused by different migration strategies in different species. While some of these things are hard or impossible to test with just the radar data, a combination of insights gained through the radar observations and tracking technologies, such as the growing network of MOTUS automated radio-telemetry (Brust et al. 2019; Brust & Hüppop 2021), could open new gates for exploration of fine-scale bird behaviour during mass-migration events. However, we can at least infer the origin of potential differences with the data from a wide range of locations. While important and interesting from a fundamental ecological and barrier crossing perspective, filling this knowledge gap also has important implications for wind farm management. Describing migration patterns at different locations and disentangling their underlying mechanisms will show if there is a need for developing separate migration forecast models for different regions in the North Sea.

### 6.5 Conclusions

The aim of this thesis was to understand how environmental factors influence spatio-temporal migration patterns of nocturnal bird migration in the airspace over an ecological barrier to develop near-term forecasts that would be used to inform offshore wind turbine curtailments during intense nocturnal bird migration. In Chapter 2, we developed trajectory models to explore how birds navigate the
ecological barrier of the North Sea and what influences their departure in high numbers. We reveal that seasonal wind regimes drive intense bird migration across the North Sea and that birds navigate the barrier differently in different seasons, following different migratory axes, which indicates that they might be performing loop migration. In Chapter 3, we learnt that it is not only wind regimes but rather high-pressure systems in the region which bring more stable weather conditions (thus also more supportive winds) that influence the occurrence of migration peaks. Chapter 4 shows that the majority of migratory movement across the North Sea occurs at low altitudes (below 300 m), except for intense bird migration that occurs in spring when generally positive wind assistance prompts birds to make use of higher wind speeds at higher altitudes to speed up their migration and arrive on breeding grounds on time. Finally, in Chapter 5, we show that migration intensity across the sea can successfully be predicted even with datasets of limited temporal coverage. We also show that near-term forecast outputs, in combination with relevant policies, can be used to inform offshore turbine curtailments necessary to reduce collision risk between migratory birds and rotating turbine blades. We demonstrate a detailed curtailment plan based on the results of this thesis and hope to encourage action-based (aero)conservation which is necessary in a rapidly changing world.