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RADAR REGISTRATIONS OF BIRD MIGRATION VALIDATION THROUGH AN INTERDISCIPLINARY APPROACH

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SUMMARY

Context

Weather radars are used primarily to detect precipitation, but they are also particularly sensitive to the presence of birds in the atmosphere. They thus offer a great tool to study bird migration because of the ability to register birds continuously at a large spatial scale and at high altitudes, day and night. There is, however, a need to validate the detections of migrating birds made by weather radars. Therefore, we cross-validated the movement intensity and general flight patterns of migrating birds as detected by three different radar systems, a weather radar in Jabbeke near the Belgian coast (Belgium; 51°11'N 3° 30'E), a Merlin bird radar on the Thorntonbank in the Belgian part of the North Sea (51°31'N, 2°57'E) and a BirdScan-MR1 (Swiss birdradar©) installed in Herzeele (France; 50°53'N, 2°32'E).

Objectives

The objectives of the project were to cross-validate bird registrations of weather and bird radars to assess their accuracy in the detection of migrating birds. Based on these findings we refined bird detections made by the weather radar in Jabbeke which offers the possibility to detect bird migration at sea. These efforts were focused on (1) splitting the measurement volume of the Jabbeke weather radar in bird detections at sea and detections on land, (2) adjusting the settings of the bird detection algorithm to improve bird detections with the Jabbeke weather radar and (3) exploring the possibilities of dual polarization data to improve bird detections with the weather radar.

Splitting the measurement volume of the weather radar is a novelty of this study. The measurement volume of the weather radar, which is located near the coastline, has been separated in two areas of interest: the area above land and the part at sea. This allowed to get a better understanding of bird migration ecology in the study area, e.g. phenology and intensity of bird migration, with a special focus on differences between bird migration at sea and on land.

Conclusions

In general, good correspondence was found for the relative day-to-day pattern in migration intensities among the radar systems that were compared. Correlations of the absolute intensities measured by the radars deployed in this case study were significant, but rather low during the study period (r^2 ranging from 0.29 to 0.64). The specific habitats where these radars were set up may partially explain this observed weak correlation. The findings of this cross-validation study can be used to derive absolute bird migration intensities measured by different radar systems and consequently help resolving methodological issues regarding the estimation of numbers of migrating birds.

The exploration of the dual polarisation data provided some additional insights to improve bird detections by the weather radar. The main conclusion of this exercise was that the difference between birds and insects was most clear in the radar quantities ZDR (differential reflectivity Z_H-Z_V) and uPhiDP (uncorrected differential phase).

Although the bird detection algorithm implemented on the weather radar data is not designed to monitor very local migration features within the field of view of the radar, we demonstrated that the radar volume can be successfully divided in multiple areas of interest. This is especially useful for radars at the coast the separate migration on land and at sea. Which can then be of use for the impact assessment of offshore wind farms.

The (preliminary) results show a parallel temporal pattern of the movements offshore and onshore. However, migration intensity on land was higher than migration at sea at night-time as well as at day-time (2.17 and 1.75 times higher respectively). Nocturnal migration intensity was always higher than diurnal migration intensity (ranging from 1.4 to 5.4 times higher) for the different systems and throughout the different months in the study period. Diurnal variation in migration intensity shows clear peaks of migration within the few hours after sunset as detected by all systems and in all months. The altitude pattern of birds at sea is comparable with birds flying above land, but the median flying altitude is higher at sea compared to on land. The median flying altitude as registered by the on-land part of the weather radar was 600 m, both during the night and during daytime. For the offshore part of the weather radar this was 800 m and 1000 m for respectively daytime and night-time.

This study promotes the use of combined ornithological and weather surveillance radars for monitoring the spatial and temporal patterns of bird migration as this provides crucial information for impact assessment studies and adaptive management plans. A better understanding of peaks in bird migration can lead to a better mitigation of human impacts.

Keywords

Bird migration, weather radar, Merlin bird radar, BirdScan-MR1, cross-validation, Belgium, North Sea

SAMENVATTING

Context

Weerradars worden in de eerste plaats gebruikt om neerslag te detecteren, maar ze kunnen ook de aanwezigheid van vogels in de atmosfeer waarnemen. Ze zijn dus een nuttig hulpmiddel om vogeltrek continue en op een grote ruimtelijke schaal en op grote hoogte te registreren, dag en nacht. Er is echter wel een nood om deze detecties te valideren. Daarom hebben we tijdens dit project de intensiteit en patronen van vogeltrek gecrossvalideert met drie verschillende radarsystemen, een weerradar in Jabbeke dicht bij de Belgische kust (België; 51°11'N 3° 30'E), een Merlin vogelradar op de Thorntonbank in het Belgisch deel van de Noordzee (51°31'N, 2°57'E) en een BirdScan-MR1 (Swiss birdradar©) geïnstalleerd in Herzeele (Frankrijk; 50°53'N, 2°32'E).

Doelstellingen

De doelstellingen van het project waren het cross-valideren van vogeldetecties door weer- en vogelradars om zo hun nauwkeurigheid bij het registreren van vogeltrek te bepalen. Aan de hand van deze bevindingen hebben we gepoogd de vogeldetecties door de weerradar in Jabbeke, die het mogelijk maakt vogeltrek op zee te detecteren, verder te verfijnen. We hebben hierbij gefocused op (1) het opdelen van het meetvolume van de Jabbeke weerradar in detecties van vogels op land en op zee, (2) het optimaliseren van de settings van het vogeldetectie-algoritme van de Jabbeke weerradar en (3) het onderzoeken van de mogelijkheden van dual polarisatie gegevens om vogeldetecties met weerradars te verbeteren.

Het opdelen van het meetvolume van een weerradar is een nieuwigheid van deze studie. Het meetvolume van de radar, die dicht bij de kust staat, werd opgedeeld in het gedeelte boven land en het deel boven zee. Dit liet toe om de verschillen in de ecologie van vogeltrek boven zee en boven land te onderzoeken.

Besluiten

In het algemeen was er een goede overeenstemming tussen het relatieve dagelijkse patroon van de intensiteit van de vogelmigratie tussen de verschillende radarsystemen die onderzocht werden. De correlatie van de absolute intensiteit, zoals gemeten door de verschillende radars, was significant maar eerder laag tijdens de studie periode (r^2 tussen 0.29 en 0.64). De verschillende habitats waar de radars werden opgesteld kan mogelijks deels verklaren waarom de correlatie zo laag is. De bevindingen van het cross-validatie experiment kunnen worden gebruikt om absolute aantallen van gedetecteerde vogels door verschillende radarsystemen beter in te schatten en om methodologische problemen met betrekking tot het bepalen van het aantal migrerende vogels op te lossen.

De exploratie van de dual polarisatie data hebben geleid tot een aantal nieuwe inzichten voor wat betreft het verbeteren van vogeldetecties met weerradars. De voornaamste conclusie is dat het verschil in de detecties van vogels en insecten het duidelijkst is in de radar variabelen ZDR (differentiale reflectiviteit Z_H-Z_V) en uPhiDP (niet-gecorrigeerde differentiaal fase).

Hoewel het vogeldetectie-algoritme geïmplementeerd in de weerradar processing niet werd ontworpen om erg lokale trekbewegingen waar te nemen, hebben we aangetoond dat het

meetvolume succesvol kan opgedeeld worden in verschillende interessegebieden. Dit is in het bijzonder nuttig voor weerradars aan de kust om een onderscheid te maken tussen migratie over land en op zee. Dit kan dan bijdragen tot het bepalen van de impact van windmolenparken op zee op de trekbewegingen van vogels.

De (voorlopige) resultaten tonen een parallel temporeel patroon van trekbewegingen op land en op zee. De intensiteit is op land wel hoger dan op zee, zowel ‘s nachts als overdag (respectievelijk 2.17 en 1.75 keer hoger). De intensiteit van nachtelijke trek was altijd hoger dan overdag (tussen 1.4 en 5.4 keer hoger) voor alle radarsystemen en voor de verschillende maanden in de studieperiode. Het diurnale patroon vertoont een duidelijke piek in de uren na zonsondergang bij alle systemen en tijdens de verschillende maanden. Het patroon van de vlieghoogte van vogels op zee is vergelijkbaar met de vogels op land, maar de mediane vlieghoogte op zee is hoger dan op land. De mediane vlieghoogte geregistreerd door het op-land gedeelte van de weerradar, was 600 m, zowel ‘s nachts als overdag. Voor het gedeelte op zee van de weerradar was dit 800 m overdag en 1000 m ‘s nachts.

Deze studie toont aan dat het gecombineerd gebruik van weerradar en ornithologische radarsystemen zinvol is om de temporele en spatiale patronen van vogeltrek te bestuderen. Het leidt tot een beter begrip van patronen in vogeltrek en kan bijdragen aan betere impactstudies van menselijke activiteiten en beheersplannen. Een betere begrip van pieken in vogeltrek kan leiden tot een betere mitigatie van menselijke impacts.

Trefwoorden

Vogeltrek, weerradar, Merlin vogelradar, BirdScan-MR1, cross-validatie, België, Noordzee

RÉSUMÉ

Contexte

Les radars météorologiques sont principalement utilisés pour détecter les précipitations, mais ils sont également particulièrement sensibles à la présence d'oiseaux dans l'atmosphère. Ils offrent donc un excellent outil pour étudier la migration des oiseaux en raison de leur capacité à enregistrer les oiseaux en permanence à grande échelle et à haute altitude. Il est toutefois nécessaire de valider les détections d'oiseaux migrateurs effectuées par les radars météorologiques. Par conséquent, nous avons validé de manière croisée l'intensité des mouvements et les schémas de vol des oiseaux migrateurs tels que détectés par les trois différents systèmes de radar, un radar météorologique à Jabbeke situé près de la côte belge (Belgique; 51°11'N 3° 30'E), un radar ornithologique Merlin sur le Thorntonbank dans la partie Belge de la Mer du Nord (51°31'N, 2°57'E) et un BirdScan-MR1 (Swiss birdradar©) installé à Herzeele (France; 50°53'N, 2°32'E).

Objectifs

Les objectifs du projet étaient de valider de manière croisée les enregistrements d'oiseaux par le radar météo et le radar ornithologique afin d'évaluer la précision des détections pour chacun des deux radars. Sur la base de ces résultats, nous avons affiné les détections d'oiseaux effectuées par le radar météorologique de Jabbeke, ce qui offre la possibilité de détecter la migration des oiseaux en mer. Ces efforts ont été concentrés sur (1) la division du volume de mesure du radar météorologique situé à Jabbeke pour les détections d'oiseaux en mer et les détections à terre, (2) le réglage des paramètres de l'algorithme de détection des oiseaux pour améliorer la détection des oiseaux avec le radar météorologique situé à Jabbeke et (3) l'exploration des possibilités des données à double polarisation pour améliorer la détection des oiseaux avec le radar météorologique.

La division du volume de mesure du radar météorologique est une nouveauté de cette étude. Le volume de mesure du radar météorologique, situé près de la côte, a été séparé en deux zones d'intérêt: la zone au-dessus de la terre et la partie en mer. Cela a permis de mieux comprendre l'écologie de la migration aviaire dans la zone d'étude, par exemple la phénologie et l'intensité de la migration, avec une attention particulière à la différence entre la migration en mer et à terre.

Conclusions

En ce qui concerne les intensités relatives du schéma journalier de migration une bonne correspondance a été trouvée entre les systèmes radar qui ont été comparés. Les corrélations des intensités absolues mesurées par les radars déployés dans cette étude étaient significatives, mais plutôt faibles au cours de la période d'étude (r^2 compris entre 0,29 et 0,64). Les habitats spécifiques dans lesquels ces radars ont été mis en place pourraient expliquer en partie cette faible corrélation observée. Les résultats de cette étude de validation croisée peuvent être utilisés pour dériver les intensités absolues de migration des oiseaux mesurées par différents systèmes radar et ainsi aider à résoudre les problèmes méthodologiques concernant l'estimation du nombre d'oiseaux migrateurs.

L'exploration des données à double polarisation a fourni quelques informations supplémentaires pour améliorer la détection des oiseaux par le radar météorologique. La principale conclusion de cet

exercice était que la différence entre les oiseaux et les insectes était plus nette dans les quantités radar ZDR (réflectivité différentielle ZH-ZV) et uPhiDP (phase différentielle non corrigée).

Bien que l'algorithme de détection des oiseaux mis en œuvre sur les données radar météorologique ne soit pas conçu pour surveiller les caractéristiques très locales de migration aviaire dans le champ de vision du radar, nous avons démontré que le volume radar peut être divisé avec succès en plusieurs zones d'intérêt. Ceci est particulièrement utile pour les radars situés le long de la côte pour séparer la migration à terre et en mer. Ceci peut ensuite être utilisé pour l'évaluation d'impact des parcs éoliens offshore.

Les résultats (préliminaires) montrent un schéma temporel parallèle des mouvements au large et au-dessus de la terre. Cependant, les intensités de la migration terrestre nocturne et diurne étaient supérieures à celle de la mer (2,17 et 1,75 fois plus élevées respectivement). L'intensité de la migration nocturne était toujours supérieure à l'intensité de la migration diurne (de 1,4 à 5,4 fois plus élevée) selon les différents systèmes et au cours des différents mois de la période d'étude. La variation diurne de l'intensité de la migration montre des pics clairs de migration dans les quelques heures qui suivent le coucher du soleil, tels que détectés par tous les systèmes et pendant tous les mois observés. Le schéma d'altitude des oiseaux en mer est comparable à celui des oiseaux volant au-dessus de la terre, mais l'altitude médiane de vol est plus élevée en mer que sur terre. L'altitude médiane de vol enregistrée au-dessus de la partie terrestre du radar météorologique était de 600 m, de nuit comme de jour. Pour la partie au large du radar météorologique, elle était de 800 m et 1000 m respectivement pour le jour et la nuit.

Cette étude encourage l'utilisation combinée de radars de surveillance ornithologique et météorologique pour surveiller les tendances spatiales et temporelles de la migration des oiseaux, car elle fournit des informations cruciales pour les études d'évaluation d'impact et les plans de gestion adaptative. Une meilleure compréhension des pics de migration des oiseaux peut conduire à une meilleure atténuation des impacts humains.

Mots-clés

Migration d'oiseaux, radar ornithologique Merlin, BirdScan-MR1, radar météorologique, cross-validation, Belgique, Mer du Nord

1. INTRODUCTION

1.1. Background and subject

Bird migration is one of the world's most conspicuous ecological phenomena. Twice a year, during autumn and spring, hundreds of millions of birds fly over Europe during their migration towards and from their wintering grounds. Migration is known to be impacted by climate change (e.g. altered phenology, meteorological triggers; Jenni & Kéry, 2003) and migrating birds suffer from ever increasing human pressures (e.g. increased mortality due to desertification, loss of suited stop-over places or collision with man-made structures; Erickson et al. 2005; Strandberg et al. 2009). From a conservational point of view, it is crucial to understand and monitor this unique phenomenon. Data on bird migration help elucidating spatially and temporally altered bird migration patterns. Nowadays, these data however suffer from a lack of spatial and temporal comprehensiveness. Radar observations greatly contribute to the understanding of bird migration because of the ability to register birds continuously at a large spatial scale and at high altitudes (Eastwood, 1967; Bruderer, 1997a, b; Gauthreaux et al., 2003). Radars offer several advantages compared to visual observations as they are not limited to lower altitudes, daylight and good visibility.

Belgium is part of one of the main European migration flyways, which makes it an ideal area to study bird migration. The Belgian part of the North Sea (BPNS) is part of a very important seabird migration route through the Southern North Sea. Because of its shape, this part of the North Sea acts as a migration bottleneck, concentrating birds during migration. An estimated number of no less than 1.0 to 1.3 million seabirds migrate through this area on an annual basis (Stienen et al., 2007). Also, large numbers of non-seabirds are known to migrate at sea (Bourne, 1980; Buurma, 1987; Alerstam, 1990; Lensink, 2002). Estimates of the number of birds seasonally travelling through the Southern North Sea vary from 85 million (Lensink et al., 2002) up to several hundreds of millions (estimates of Helgoland mentioned in Hüppop et al., 2006).

Additional to its location, Belgium also has a network of weather radars and a specialized bird-radar system installed. The Royal Meteorological Institute of Belgium (RMI) uses three weather radars for meteorological observations. These are in Zaventem (property of Belgocontrol), Wideumont and Jabbeke. The three weather radars completely cover the Belgian territory, including a large part of the BPNS. Weather radars are used primarily to detect precipitation (e.g. rain fall). Also, non-meteorological targets are detected by the radar, such as airplanes, large ships, wind turbines, etc... The radar is particularly sensitive to the presence of birds in the atmosphere, at least when the number of birds per volume is high enough to produce a significantly strong echo. Strong bird signals are seen in periods of heavy bird migration. Several of these registrations of birds were already extensively reported in the press (e.g. migrating cranes, massive thrush migration, frightened birds during New Year's fireworks, dawn-ascent flight of common swifts). As a result, weather radars have become more and more a standard tool to monitor nocturnal broad front migration of birds (e.g. Able 1970, Diehl et al. 2003, Gauthreaux and Belser 1998, Dokter et al. 2011, Nilsson et al., 2018a). It is however still unknown how many of these systems perform with regard to detection and quantification of bird migration intensities (Liehti et al., 2018).

A bird radar, owned and operated by the Royal Belgian Institute of Natural Sciences (RBINS), and located at approximately 40 km of the weather radar in Jabbeke, therefore offers an ideal situation to cross-validate the data of both types of radar and to gain insight into the comparability of the measured bird migration intensities.

This combination of equipment, plus several other data sources (e.g. existing telemetry data of tagged lesser black-backed gulls *Larus fuscus*, feeding e.g. in the wind farm area and known to be sensitive to wind turbine collision, Brabant & Vanermen et al. 2015) facilitate the validation of the radar registrations.

1.2. Study objectives:

The objectives of this study are:

1. to cross-validate bird registrations of weather and bird radars to assess their accuracy in the detection of migrating birds (i.e. to what extent do migration intensities measured by different radar systems match on the relative and absolute scale?).
2. to refine the bird detections made by the weather radar in Jabbeke.
3. to get a better understanding of bird migration ecology, e.g. phenology and intensity of bird migration, with a special focus on differences between bird migration at sea and on land.
4. to estimate the total flux of birds during a migration season in the detection volume of the weather radar and compare this with the currently accepted flux estimates as taken from literature.

2. METHODOLOGY

The flow of the project was in certain cases not exactly as was proposed in the research proposal. Figure 1 shows the original project flow as presented in the project proposal. The actual flow of the project as it was executed is shown in figure 2. The reasons why the proposed approach was changed are explained per work package.

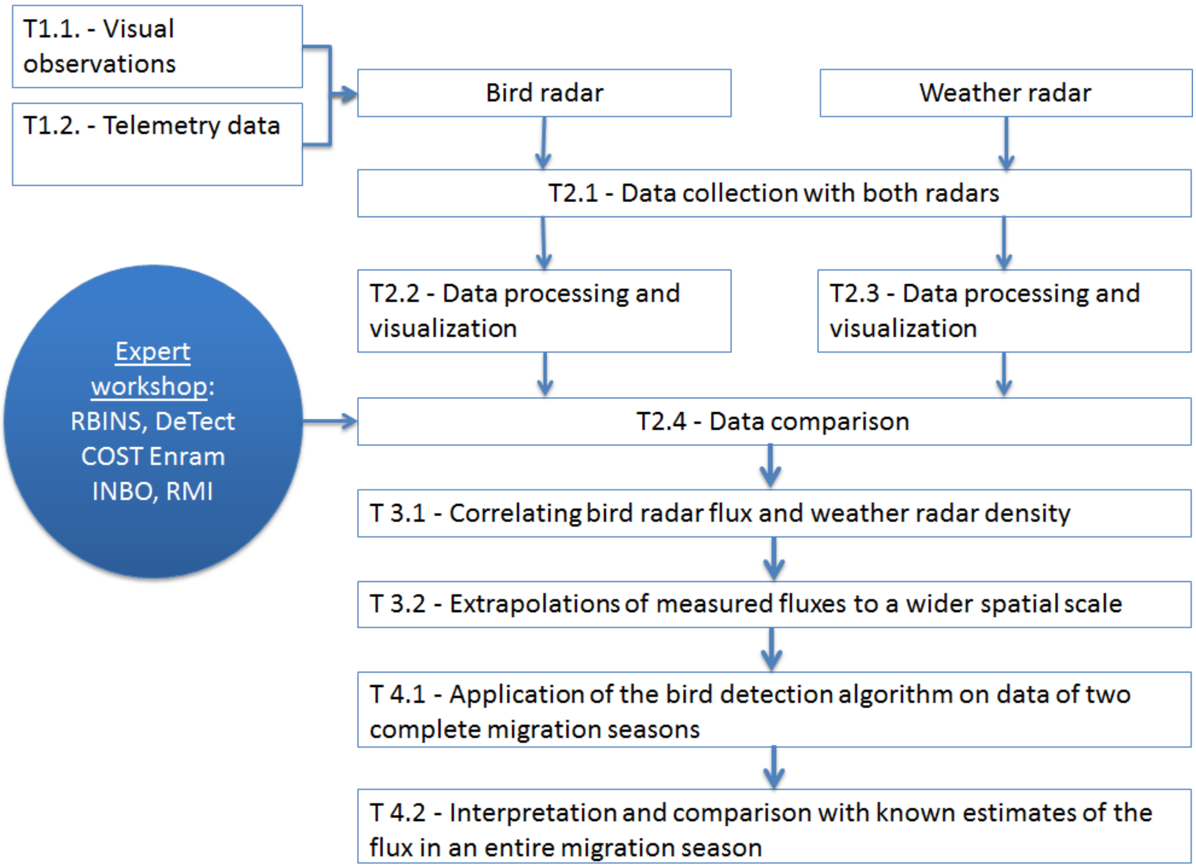

Figure 1. Anticipated approach and research strategy of the RAVen project as presented in the research proposal.

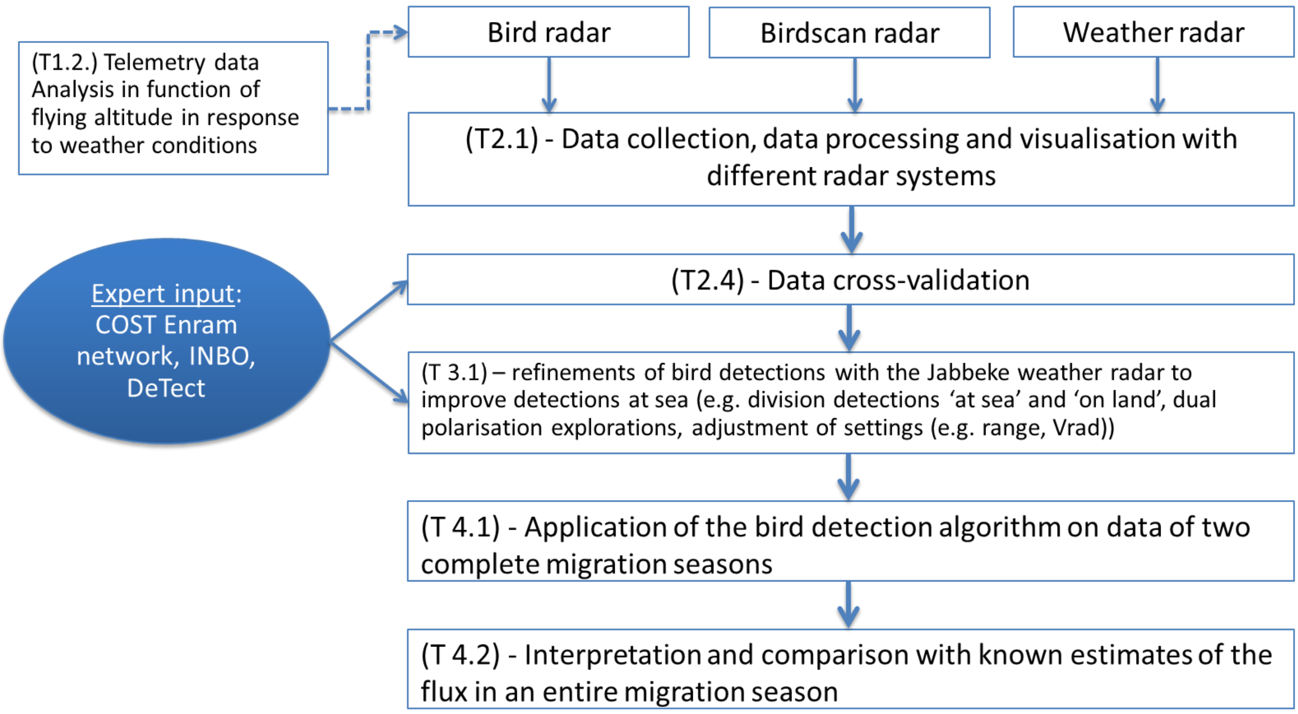

Figure 2. Realised approach and research strategy of the RAVen project as executed.

2.1. Validation of bird radar registrations with visual observations and telemetry data of tagged gulls breeding along the Belgian coastline (WP1)

To validate the detections made by the bird radar at sea we planned a twofold approach. Visual observations in the detection volume of the radar would allow comparing the bird radar detections with the actual bird flux, as counted (task 1.1). In a second step, we planned to compare the bird radar detections with data of tagged gulls flying in the detection volume of the bird radar (task 1.2).

2.1.1. Visual counts at bird radar location (Task 1.1)

Logistic reasons have made the fulfilment of this task impossible. The research vessel Belgica, which we planned to use for the visual counts, was out of business due to technical problems during the majority of 2016. On top of that, before the start of the project we identified major detection problems of the bird radar, especially in the lower part of the detection range (0-150 m above sea level). Together with the developer we agreed to replace the radar antenna by a conventional X-band magnetron radar, which has proved to perform better in offshore conditions (see Krijgsveld et al. 2011). Logistical obstacles did not allow to replace the radar antenna to date, making visual observations meaningless at this point.

2.1.2. Telemetry data of tagged seabirds to validate bird radar data (Task 1.2)

Between 2013 to 2016, 112 lesser black-backed gulls breeding at Zeebrugge (Belgium) and Vlissingen (the Netherlands) have been equipped with a UvA-BiTS tracker. We selected all available GPS tracking data of birds logged within 4 nautical miles from the bird radar located at the Thorntonbank offshore wind farm, coinciding with the operational range of the horizontal radar. Analysis of the telemetry data aimed at revealing patterns between birds' flight characteristics and weather conditions to facilitate explaining variation in detectability of seabird migration by the bird radar.

The horizontal bird radar, providing information on the flight paths of birds, is suffering from seaclutter and shadow effects of the wind turbines. This results in enormous amounts of noise in the dataset. As there is no datafilter in place yet, a comparison of telemetry data with the horizontal radar data is useless at this point. As it became clear that a horizontal bird radar filter would not be developed on time, we decided to halt the execution of task 1.2 after the preliminary analyses of the telemetry data.

Selecting all available GPS tracking data of the lesser black-backed gulls logged within 4 nautical miles from the bird radar from June 5th 2013 until August 15th 2016, resulted in a dataset of 13,330 records of 71 individual lesser black-backed gulls, with information on location, speed and altitude (fig. 3). Preliminary assessment of offshore telemetry data indicate that wind speed and relative wind direction strongly influenced the flying altitude of lesser black-backed gulls (fig. 4).

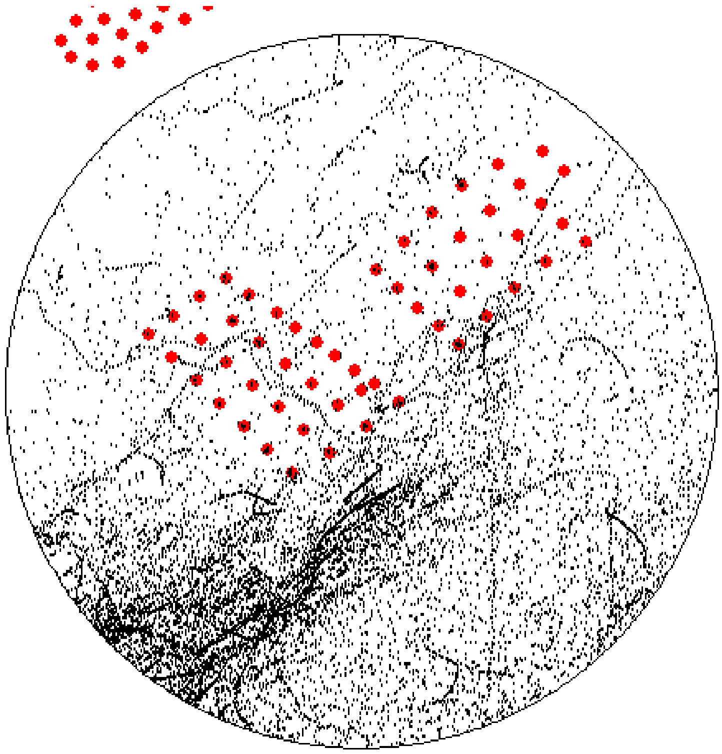

Figure 3. GPS tracking data of 71 lesser black-backed gulls that were logged within the range of the horizontal Merlin bird radar between June 5th 2013 until August 15th 2016. The range of the bird radar is indicated by the black circle. Black dots indicate the logs of lesser black-backed gulls. The red dots are wind turbines.

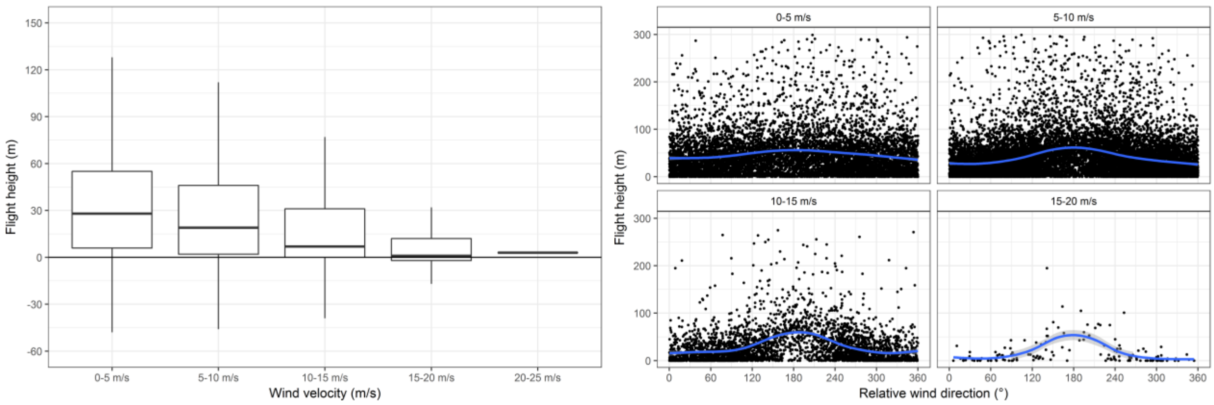

Figure 4. Boxplots of offshore flight heights of tagged lesser black-backed gulls for five wind velocity categories (left panel) and interaction between flight height, wind velocity and relative wind direction (180° representing back wind) (right panel) (Vanermen et al. 2018).

2.2. Validation of weather radar registrations of birds with bird radar data (WP 2)

We cross-validated the bird detections of the weather radar in Jabbeke (Belgium; 51°11'N 3° 30'E), a Merlin bird radar on the Thorntonbank in the BPNS (51°31'N, 2°57'E) and a BirdScan-MR1 (Swiss birdradar©) installed in Herzeele (France; 50°53'N, 2°32'E, fig. 5), near the Belgian-French border. The latter type of bird radar (originally not foreseen to be deployed in this project) already proved its usefulness to validate weather radar bird registrations (Nilsson et al., 2018b). The distance of the BirdScan and the Merlin avian radars to the weather radar was 53 and 38 km, respectively. The

BirdScan radar and the Merlin radar were 70 km apart. The weather radar and the Merlin bird radar were continuously collecting data (from date to date). The Birdscan was operated between August 18th 2016 and October 14th 2016.

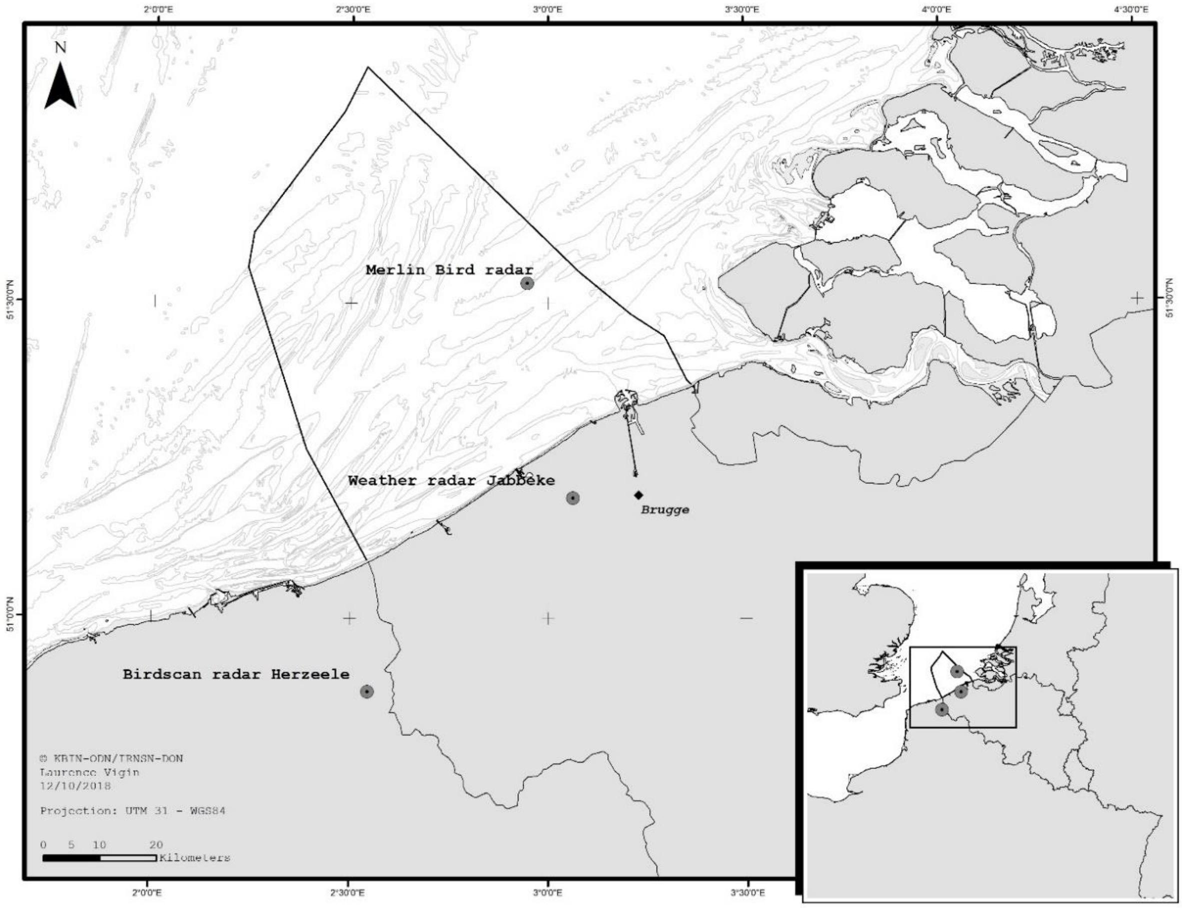

Figure 5. Map of the study area with indication of the location of the three radars: the weather radar in Jabbeke (Belgium), the Merlin bird radar in the Belgian part of the North Sea and the BirdScan radar in Herzeele (France).

This cross-validation study was organised within the framework of the COST Enram project (European Network for the Radar Surveillance of Animal Movement), with which the RAVen project ran in parallel. The COST Enram networking project started on October 21, 2013 and ran for four years. Enram aimed at creating a European network to join forces in the field of aeroecology and to foster a continent-wide remote sensing network to monitor bird migration by means of weather radars. Both RBINS and INBO were partners in the Enram project.

The last few years, similar validation experiments were executed throughout Europe. This fits in the framework of working group 2 of the COST Enram project (WG2: Improvement of Weather Radar Data Quality and Validation of Biological-classification Algorithms).

2.2.1. *Weather radar*

The C-band Doppler dual-polarisation weather radar (WR) in Jabbeke, at 9 km from the Belgian coast, performs a volume scan consisting of 15 elevations every five minutes, with reflectivity and velocity elevations interleaved. The nine elevations executed in dual-PRF mode (800 and 1000 Hz) have a range of 150 km and provide both reflectivity and velocity information. The bird detection is performed on the raw weather data, using the bird detection algorithm developed by Dokter et al. (2011), Vol2Bird hereafter, as available in the R-package bioRad (Dokter et al. 2018). The algorithm removes precipitation cells and ground clutter and estimates bird densities and flight information (direction and speed) based on the remaining reflectivity and the radial velocity data, at 5 to 25 km from the weather radar location. The volume data of the different elevations are aggregated into 20 altitude layers of 200 m, ranging from 0 m to 4000 m above mean sea level. The algorithm calculates an average reflectivity for each layer and converts reflectivity into bird density, assuming an 11 cm^2 bird cross-section (Dokter et al., 2011). The speed and flight direction for each altitude layer are estimated by fitting the clean velocity data to a constant velocity model (see equation A1 in Dokter et al., 2011).

Values from all altitude bands within a range of 25 km were recalculated into an integrated value of migration traffic rate (MTR; birds*$km^{-1*}h^{-1}$), which is the number of birds crossing a virtual line of 1 km perpendicular to the main migratory direction within 1 hour (Schmaljohan et al. 2008, Dokter et al 2018). We calculated hourly MTR for the entire height range of the weather radar, by multiplying the bird densities (birds*km^{-3}) by the bird ground speed (km*h^{-1}) and the altitude layer (i.e. 0.2 km).

2.2.2. *Birdscan radar*

The Birdscan-MR1 is a vertically looking radar system based on a commercial marine radar (25 kW pulsed X-band radar (9.4 GHz)), further referred to as vertical beam radar (VBR). The detection range and range resolution depend on the pulse duration. We sequentially used 65 ns pulse duration (short-pulse, PRF 1800 Hz, range resolution 7.5 m, 300 m STC, -93 dB detection threshold) to register bird movements below 800 m, and 750 ns pulse duration (long-pulse, PRF 785 Hz, range resolution 110 m, 500 m STC, -102 dB detection threshold) to register bird movements above 800 m, up to 1400 m above ground level (agl). Targets crossing the beam are illuminated constantly and thus the echo signature, which includes the temporal pattern of echo intensity, can be derived and used to distinguish birds from other targets (mainly insects). MTR is calculated based on target size-specific surveyed volume. For details see Nilsson et al. (2018b).

2.2.3. *Merlin radar*

The Merlin radar system consists of two identical solid-state S-band radar antennas, one scanning in the horizontal pane (HSR) and one in the vertical pane (VSR). By rotating in the vertical pane, the vertical radar creates a 'radar screen' that registers all targets moving through that screen. Every registration by the VSR is one (or a group of) target(s) passing through that area. This way of data collection allows quantifying the flux of birds through the area (birds*km^{-1}*h^{-1}), and it also provides information on flight altitudes. The horizontal radar is rotating 360° in the horizontal pane and provides information on the direction of flight and the flight paths of individual birds and small groups of birds. The Merlin software is specifically designed to track individual birds (DeTect Inc., 2010), linking consecutive registrations of a target, and thus registers the flight path of a moving target. Unwanted echoes (i.e. noise) from different sources (e.g. rain, waves, ships, wind turbines, side lobes) are filtered from the data set using a decision tree model that was developed based on reference data. As we used the radar data to determine the flux of birds in the area, it is very important to remove clutter as accurate as possible. Unfortunately, we were able to develop a data filter only for the vertical radar data, hampering a correct interpretation of the horizontal radar data at present.

The Merlin radar is a solid-state marine radar antenna (Kelvin-Hughes Sharpeye solid state S-band, operating frequency of 2.92 to 3.08 GHz, output power of 170 W). The solid-state antenna simultaneously transmits a sequence of pulses of differing length, short (12 µs), medium (64 µs) and long (365 µs) pulse, with each pulse covering a specified range scale. The beam of the vertically rotating radar (horizontal beam width: 2°; vertical beam width: 26.5°) creates a vertical 'radar screen' that registers all the targets moving through that screen. The rotation speed of the antenna is 20 rounds per minute and the detection range was set at one nautical mile (1852 m). The orientation of the radar is east to west, which approaches being perpendicular to the expected main bird migration direction (i.e. mainly northeast – southwest).

The MTR is calculated as the sum of the number of bird tracks per hour, registered in two columns of 500 m wide selected from the entire measurement volume (250 to 750 m distance from the radar, both to the east and west. Doing so, we avoid using the data close to the radar location, which are saturated with reflections of the radar platform, and further than 750 m from the radar to avoid detection loss at long range (fig. 6, details in Fijn et al. 2015). The number of bird tracks observed within those two columns in one hour, equals the MTR. As the radar is not able to differentiate single birds from a small group of birds, the Merlin-MTR is a minimum estimate of the number of birds.

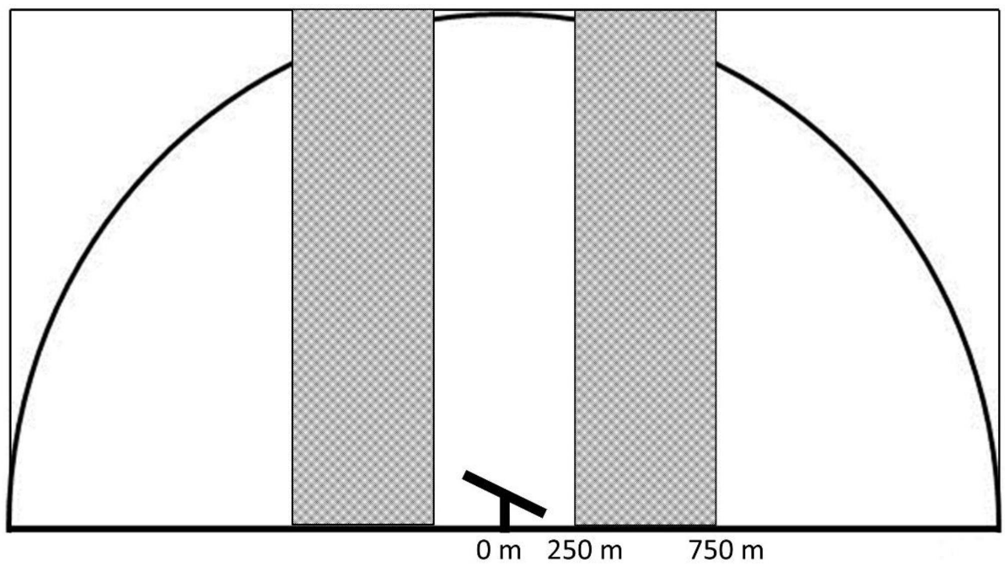

Figure 6. Schematic representation of the two columns within the measurement volume of the vertical bird radar, used to determine the migration traffic rate.

We limited the validation case study to night time, where night was defined as the period between evening and morning civil twilights, which represents the time when the sun position is at least 6 degrees below the horizon.

2.3. Coupling small scale bird radar registrations and large-scale weather radar observations to investigate migration events at a wider spatial scale (WP 3)

Spatial representation of the output of the weather radar (cf. bird density per grid cell), instead of an, was intended to compare bird detections in the spatial overlap of the weather radar and the horizontal Merlin bird radar; this to be able to correct the weather radar detections based on the bird radar data. Spatial representation of the bird density measured by the weather radar (e.g. in a spatial grid) was, however, not possible ad the bird detection algorithm can only be applied on the full volume of the weather radar, resulting in an integrated density profile of the entire weather radar range.

Moreover, the Merlin bird radar is performing suboptimal (e.g. very few detections in comparison with detections made in similar circumstances with a magnetron radar), which was also shown in the cross-validation study of WP2, making an extrapolation of the flux data from the Merlin radar to the spatial extent of the radar unreliable.

Therefore, we decided to emphasize on refining the bird detections with the weather radar in Jabbeke which offers the possibility to detect bird migration at sea. The efforts were focused on (1) splitting the measurement volume of the Jabbeke weather radar in bird detections at sea and detections on land, (2) adjusting the settings of the Vol2Bird algorithm to improve bird detections with the Jabbeke weather radar and (3) exploring the possibilities of the dual polarization data to improve bird detections with the weather radar.

2.3.1. Splitting the measurement volume of the Jabbeke weather radar in detections at sea and detections on land

To be able to focus on migration at sea and migration on land, we have split the detection volume of the Jabbeke radar. The Vol2Bird bird detection algorithm was then applied on those two sub volumes. To cover a larger area at sea, we used weather radar data ranging from 5 to 35 km radius from the radar. The standard range to which Vol2Bird is applied is from 5 to 25 km, but Dokter et al. (2018) state that a range of up to 35 km still is reliable. For the radar volume, 115.157 (72%) of the radar bins were located on land while 43.963 (28%) were at sea.

To make this division ‘on land’ and ‘at sea’, we have extended the original algorithm to separately analyse samples registered in distinct areas covered by the radar. To discriminate between bird migration on land and at sea, we used the coast line to separate areas covered by the radar on land (hereafter referred as to WR-land) from areas covered by the radar at sea (hereafter referred as to WR-sea). Strictly confining the part of the radar range on land to the area with land cover is artificial since bird migration at sea and over land obviously overlaps, but in this way our study is reproducible, and the developed extension of the algorithm can be exported to other radar sites.

The MTR for the WR-sea and the WR-land were calculated from the densities and the speed estimates. As the speed estimated from the WR-sea and the WR-land may become zero due to insufficient amount of data at each elevation layer, the speed estimated from the full domain was used instead.

The algorithm extension checks the MTR value of WR-sea and WR-land for every elevation layer of every scan of the Jabbeke radar. The data in which their weighted sum of the MTR of the partial volumes (values proportional to the relative number of used radar bins) differs from the MTR value calculated on the full radar volume by more than 3 percentage points were removed. These cases are related to remaining high reflectivity values influencing the calculation of the mean reflectivity per radar bin performed by the algorithm.

2.3.2. Refinement of the settings of the Vol2Bird algorithm for the Jabbeke weather radar

The default settings of the bird detection algorithm (based on Dokter et al., 2011) were scrutinized and modified where necessary to optimise bird detections with the weather radar in Jabbeke. Indeed, an essential part of the bird detection algorithm is the pre-processing of the radar data prior to the bird quantification. This pre-processing mainly consists of the clutter detection and the bird/precipitation differentiation. The fine-tuning of the algorithm settings is especially important for the weather radar in Jabbeke, since also sea clutter is present within the bird detection range (5 km-35 km) of this radar.

2.3.3. Exploration of the dual polarisation data to improve bird detections by the weather radar

Dual-polarization radar data provide a lot of additional information on the scatterers present in the atmosphere. These extra data allow for a better clutter mitigation, for more precise precipitation estimates, and for hydrometeor classification. Also, in the field of bird detection there is much potential, but up to now the use of dual-pol quantities for this purpose is still limited. Only some explorative studies have been published so far, and from these studies dual polarisation quantities often reveal a lot of additional information regarding the distinction between birds and insects (e.g. Stepanian et al., 2016), bird orientation and even species (e.g. Koistinen et al., 2014).

To explore the potential benefits of including the dual-pol radar quantities in bird detection studies some episodes with intense bird migration during the RAVen study period were visualized in full detail, and animations were made showing several radar quantities simultaneously.

The radar quantities that were examined in these cases studies were:

- dBZ: (horizontal) reflectivity
- V: radial velocity (from the horizontal channel)
- ZDR: differential reflectivity Z_H-Z_V
- ρHV: co-polar correlation function
- uPhiDP: uncorrected differential phase

2.4. Estimating and comparing seasonal bird fluxes (WP 4)

In the proposal we aimed to estimate the total number of birds flying through the detection volume of the weather radar during a complete migration season in both spring and fall.

The division 'above land' and 'at sea', as described above (section 2.3), allowed focussing on the differences between migration intensity in the two sub-areas of the detection volume of the Jabbeke weather radar.

We analysed the seasonal, diurnal and height variation in MTR, using civil twilight to distinguish between day and night, as implemented in the bioRad R-package (Dokter et al., 2018). An hourly bin was allocated to daytime if more than 30 minutes of the bin were within daytime. To investigate the seasonal phenology in migration intensity, we first summed the hourly MTR across the altitude layers and then calculated the mean MTR values per day and per night. To investigate the diurnal phenology for every month, we calculated the mean MTR for every hour of the day (HoD) for the different months (e.g. the mean of all MTR values from 0:00 to 1:00 am for all days in October). We divided the hourly MTR by the sum of the hourly values per day to obtain the relative migration intensity. To investigate the height distributions, we calculated the mean MTR per 200 m altitude layer for day and night, separately.

The same analyses were done for the Merlin bird radar data and the Birdscan data. For the BirdScan, we calculated the MTR including all bird echoes, and for each echo-type separately (“passerine-type”, “wader-type”, “unidentified-bird-type”; Nilsson et al. 2018b).

Calculations and graphs were made in R version 3.4.3 (R Core Team, 2017).

In this project, this approach was first tested on a dataset from 14 August 2016 until 30 November 2016.

3. RESULTS

3.1. Cross-validation

Part of this analysis has been published in Liechti F., Aschwanden J., Blew J., Boos M., Brabant B., Dokter A., Kosarev V., Lukach M., Maruri M., Reyniers M., Sapir N., Schekler I., Schmaljohann H., Schmid S. & Weisshaupt N., 2018. Cross-calibration of different radar systems for monitoring nocturnal bird migration across Europe and the Near East. Ecography 42: 1 - 12. DOI: 10.1111/ecog.04041

The mean nighttime MTR, as registered by the three different radar systems, was calculated for the entire study period. This value shows substantial temporal variation and varies between 23 and 5032 for the Birdscan radar, between 1 and 816 for the Merlin birdradar and between 12 and 2443 for the weather radar. Absolute values differ largely, especially for the Merlin radar compared to the weather and Birdscan radar. The relative pattern of the three datasets is similar throughout the study period (fig. 7).

Correlations of the MTR between the three radars were significant, but rather low during the study period (max. 0.64), with no improvement when only considering the overlapping height intervals (max. 0.62; table 1).

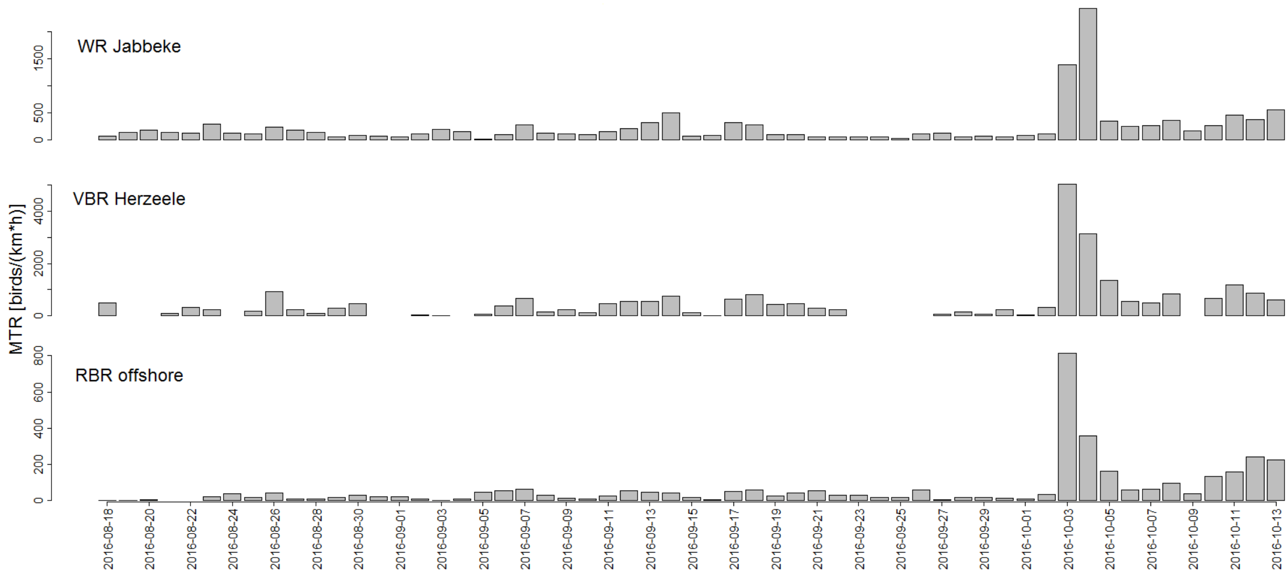

Figure 7. Seasonal pattern of the mean nighttime MTR (birds/(km*h) as registered by the three radar systems. WR is the weather radar; VBR is the Birdscan radar; RBR is the Merlin bird radar. Note that the scale of the Y-axis is different in the three graphs. Graph also published in Liechti et al. 2018.

Table 1. Overview of the results of pairwise comparisons among radar systems. Variables with the subscript “tot” give values including all height ranges covered by a system, the subscript “overlap” gives values for the overlapping height range between systems compared. N is the number of nights included. MTR is given in birds*km^{-1}*hour^{-1}. MTR1 refers to the first site given under “pairs compared”, MTR2 to the second site.

pairs compared	r^2_{tot}	n_{tot}	$r^2_{overlap}$	$n_{overlap}$	$MTR1_{tot}$	$MTR2_{tot}$	$MTR1_{overlap}$	$MTR2_{overlap}$
Weather radar – Birdscan radar	0.47	46	0.44	46	259	567	237	339
Weather radar – Merlin radar	0.29	55	0.36	53	228	63	215	41
Merlin radar – Birdscan radar	0.64	44	0.62	44	75	585	46	349

3.2. Refinements to bird detection with the Jabbeke weather radar

Part of these data have been published as:

Reyniers M., R. Brabant, M. Lukach, B. Schmid & M. Boos, 2018. Comparison of onshore and offshore bird migration by different radar systems near the Belgian coast. Poster presentation at the 10th European Conference on Radar in Meteorology and Hydrology (ERAD 2018), 1-6 July 2018, Ede-Wageningen, The Netherlands.

3.2.1. Split onshore and offshore data bins

Figure 8 visually presents the division into two sub-areas, one detecting on-land, the other one at-sea, of the Jabbeke weather radar. The Vol2Bird algorithm was then applied on the sub-areas separately.

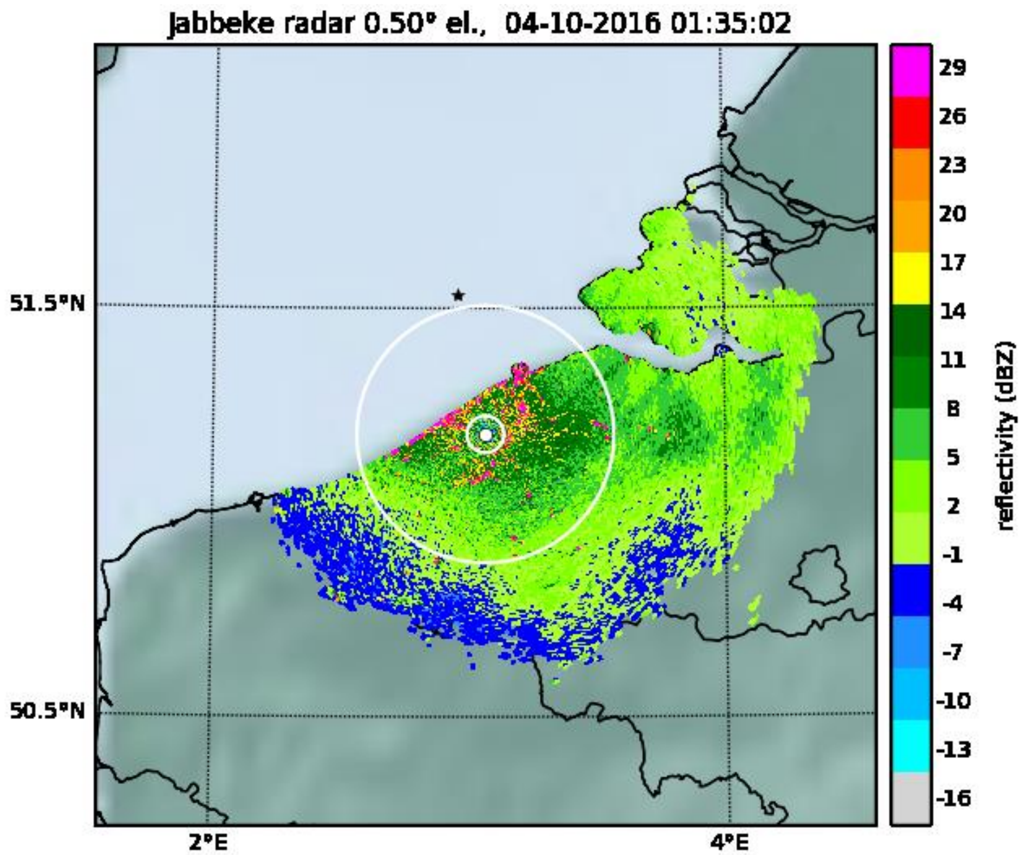

Figure 8. Visualisation of the bird detection range on land by the Jabbeke weather radar (white dot). The Vol2Bird algorithm is applied from 5 to 35 km from the radar (white circles). The coastline was used to divide the detection volumes ‘on land’ and ‘at sea’.

3.2.2. Adjustments of settings

The fine-tuning of the Vol2Bird algorithm settings is crucial to adequately discriminate birds from precipitation and clutter. For example, the azimuthal dependence of the radial velocity measurements is much noisier for birds than for precipitation. This feature is used to discriminate birds from precipitation and a threshold is set on the standard deviation of the radial velocity to eliminate the precipitation. The 2.0 m*s^{-1} threshold, used in van Gasteren et al. (2008) was set to 3.0 m*s^{-1}, resulting in a more conservative removal of the precipitation.

The Vol2Bird parameter REQUIRE_VRAD requires to have a valid radial velocity from a range bin to contribute to the calculation. With these settings, the total number of points (on- + off- shore), used for calculation of the bird reflectivity for each altitude level, equals the number of points used for the calculation on the whole domain. The full list of adjusted parameters used by the algorithm is given in Annex 1 (List of adjusted parameters of the bird detection algorithm).

3.2.3. Dual polarization tests

The dual polarisation quantities of the case studies provided some additional insights in the migration events. The animations of the four case studies can be accessed through the links that are added in annex of this report, together with some additional information per case. The main conclusion of this exercise was that the difference between birds and insects was most clear in ZDR and uPhiDP. For ZDR (fig. 9) we could conclude that both insects and birds can induce very large ZDR values, but for the insect cases, there is much less variability/texture in the ZDR field (it is constantly very high). The conclusion for uPhiDP (fig. 10) was that insects seem to be unable to induce large differential phase shifts while birds can induce large differential phase shifts and sometimes the field gives an indication of a common orientation (probably also related to the species). These findings were presented at the 10th European Conference on Radar in Meteorology and Hydrology (ERAD 2018) in The Netherlands (Reyniers et al., 2018).

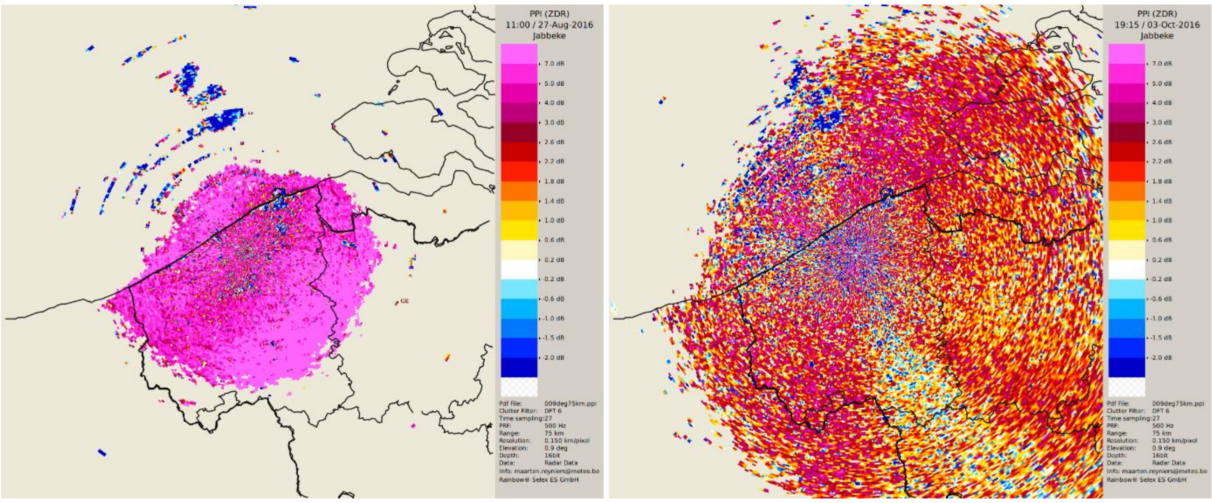

Figure 9. Differential reflectivity (ZDR) for 27-Aug-2016 11:00 UTC (left) and 03-Oct-2016 19:15 UTC (right). In the left image, the signal is induced by insects, while the signal on the right image is due to birds. The smooth and very high ZDR values of insects are striking in this case. The ZDR induced by birds is much more scattered and on average lower. There is also an indication of common orientation: the ZDR values perpendicular to the birds' displacement (from NE to SW) are significantly lower than parallel to their movement.

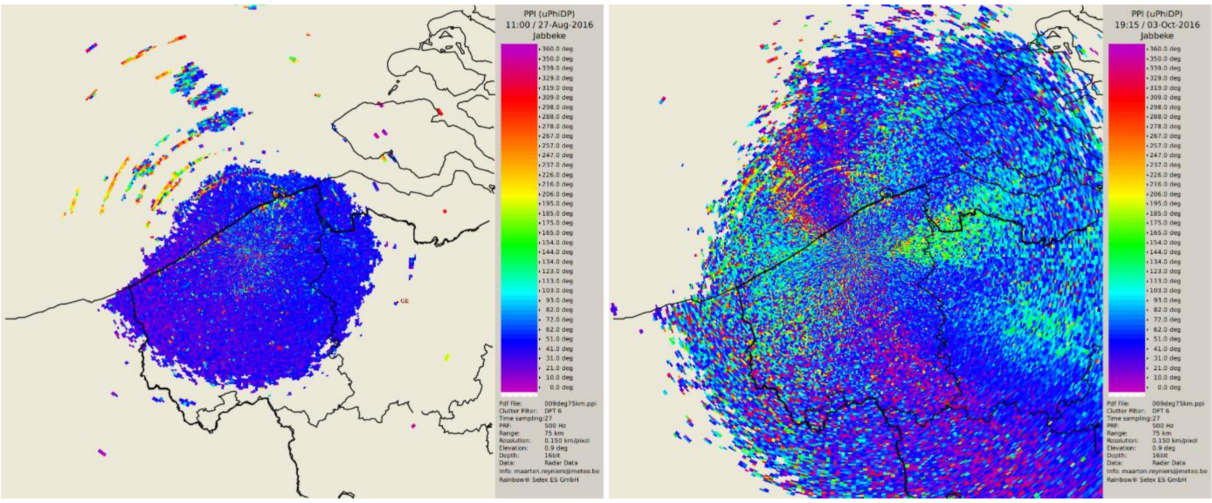

Figure 10. Uncorrected differential phase (uPhiDP) for the same timestamps as fig. 9. Contrary to ZDR, the insects (left) are not able to generate large uPhiDP values. For the bird signal (right), higher values are attained, and the azimuthal dependence, probably caused by a common orientation of the birds, is striking.

3.2.4. Seasonal, diurnal and altitude patterns of bird migration on land versus at sea

The results in this section are still preliminary and might still change in the future as we continue to optimise the data processing chain of the weather radar data. They should be interpreted as preliminary results and are a showcase of the processing possibilities. The final results will be presented in Brabant et al. (in prep.).

Seasonal phenology

Nocturnal migration intensity was always higher than diurnal migration intensity (ranging from 1.4 to 5.4 times higher) for the different systems and throughout the different months in the study period (Table 2). The differences between nocturnal and diurnal migration are particularly pronounced in October due to peak nocturnal migration events on October 2nd and 3rd (fig. 11, see also the right panels of figs. 9 and 10). This peak coincided with strong NE winds, pushing migrating birds to the West, explaining the high numbers registered at the Belgian coastline. These high peaks in migration intensity are less pronounced in the weather radar data compared to the dedicated bird radars (Merlin and BirdScan). The proportion of wader-type echoes detected by the BirdScan tends to decrease between mid-August and mid-October.

Migration intensity, as detected with the weather radar, on land was higher than migration at sea at night-time as well as at day-time (2.17 and 1.75 times higher respectively, table 2). Spearman's ranking correlation coefficients ρ were higher for night-time than day-time (table 3). The MTR from WR-sea and WR-land showed the highest Spearman's ρ (0.83 for daytime and 0.92 for night-time values). Diurnal Spearman's ρ were particularly low between the BirdScan and the WR-land and WR-sea MTR (<0.01). The correlation between MTR values of radars covering the same habitat (land *vs.* sea), were similar to those correlations between radars covering a different habitat (e.g. Merlin radar and WR-land).

Table 2. Averaged diurnal and nocturnal MTR (birds*km-1*hr-1) ± standard deviation registered by the different radar systems in the Autumn of 2016. The value between brackets is the number of days/nights. In August we only collected data from 18 until 31 of August. Data collection with the BirdScan stopped on October 13, 2016. Data collection with the Merlin bird radar stopped on November 16, 2016.

Migration traffic rate – DAYTIME				
	WR - land	WR - sea	Merlin	BirdScan
August	111 ± 59 (14)	67 ± 29 (14)	3 ± 3 (16)	124 ± 72 (13)
September	88 ± 58 (30)	57 ± 31 (30)	8 ± 8 (30)	147 ± 127 (25)
October	159 ± 121 (31)	75 ± 53 (31)	43 ± 33 (31)	238 ± 176 (13)
November	93 ± 58 (30)	56 ± 35 (30)	18 ± 17 (15)	-

Migration traffic rate – NIGHTTIME				
	WR - land	WR – sea	Merlin	BirdScan
August	152 ± 49 (15)	92 ± 40 (15)	12 ± 14 (17)	341 ± 251 (10)
September	170 ± 107 (30)	92 ± 48 (30)	28 ± 20 (30)	308 ± 243 (24)
October	379 ± 293 (31)	118 ± 80 (31)	138 ± 168 (31)	1283 ± 1519 (13)
November	132 ± 154 (30)	68 ± 50 (30)	35 ± 59 (15)	-

Table 3. Spearman's rank order correlation of the mean MTR per day (upper triangle, yellow) and per night (lower triangle, blue) as registered by the different radar systems [Merlin, weather radar on land (WR-land) and weather radar at sea (WR-sea), BirdScan].

	0.30	0.50	0.32	DAY
0.55		0.83	<0.01	
0.65	0.92		<0.01	
0.80	0.53	0.54		
NIGHT				

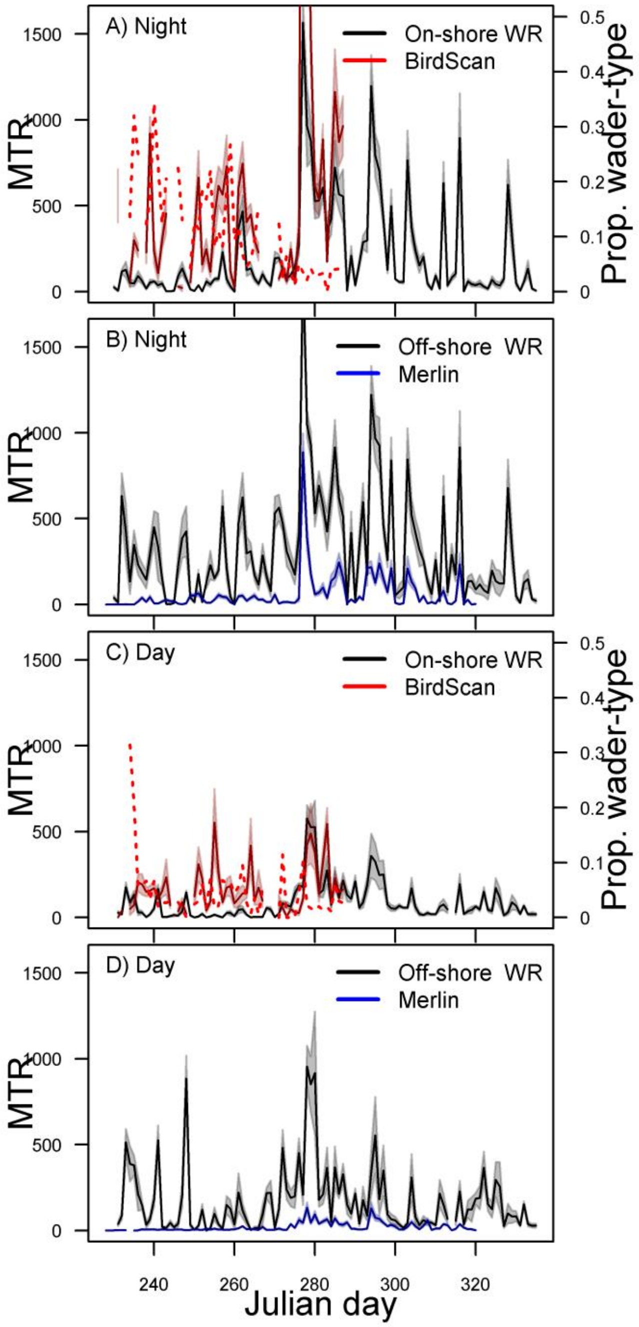

Figure 11. Mean migration traffic rates (MTR ± SE: lines ± shading) per night (A-B) and day (C-D) as registered by the different radars during the study period. Detections on land (A-C) and at sea (B-D) are presented separately. The proportion of waders-type birds as registered by the BirdScan (orange dotted line) are shown on the secondary Y-axis on the right.

Diurnal pattern

Diurnal variation in migration intensity shows clear peaks of migration within the few hours after sunset as detected by all systems and in all months. In October especially, we also observe a small peak in migration intensity after sunrise. The proportion of wader-type echoes detected by the BirdScan is lowest around sunrise and sunset events.

Pearson's correlation coefficients between radar systems are high, in particularly in September and October (minimum 0.61 and maximum 0.99), to a lesser extent in August (minimum <0.01 and maximum 0.66, table 4). This is caused by movements of local birds, at the Birdscan location. The similarity of the diurnal patterns of birds as registered on land and at sea increases throughout the autumn migration season (fig. 12), which is being confirmed by the Pearson correlation coefficients (table 4).

Table 4. Pearson correlation of the relative MTR per hour for each month as registered by the different radar systems [Merlin, weather radar on land (WR-land) and weather radar at sea (WR-sea), BirdScan].

	Merlin	WR-sea	WR-land		Merlin	WR-sea	WR-land
				Merlin			
	0.29			WR-sea	0.83		
	0.16	0.66		WR-land	0.92	0.95	
	0.38	0.46	<0.01	BirdScan	0.61	0.76	0.77

				November			
	Merlin	WR-sea	WR-land		Merlin	WR-sea	WR-land
				Merlin			
	0.89			WR-sea	0.72		
	0.90	0.99		WR-land	0.83	0.96	
	0.95	0.88	0.89	BirdScan	-	-	-

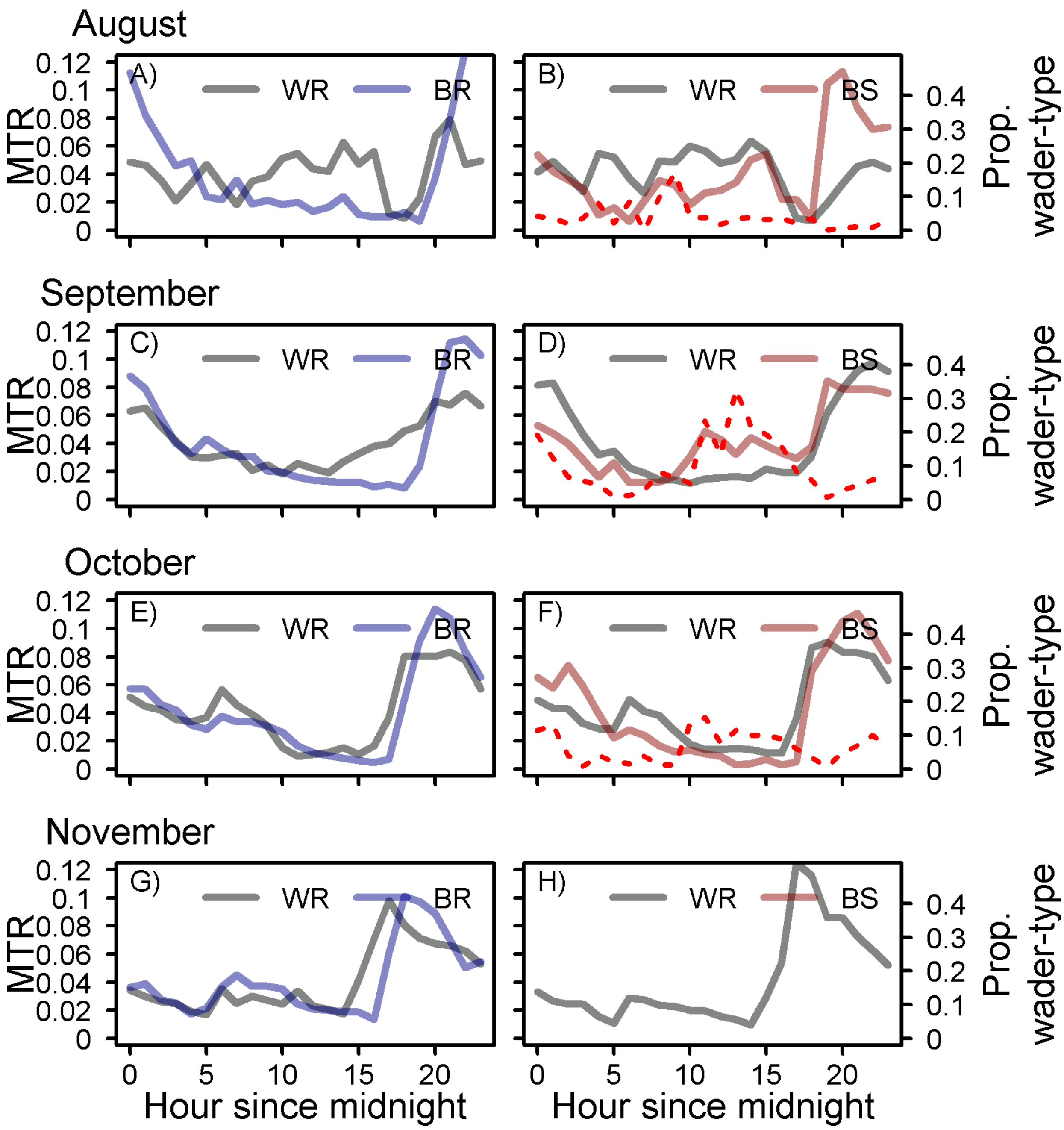

Figure 12. Diurnal pattern of bird migration presented as mean relative MTR per hour, for the different months in the study period. In the figures on the left are the detections made at sea by the Merlin bird radar and the weather radar (WR-sea). On the right are the diurnal patterns of birds registered by the weather radar (WR-land) and the Birdscan on land. The proportion of waders-type birds as registered by the Birdscan radar (orange dotted line) are shown on the secondary Y-axis on the right.

Altitude profile

The altitude pattern of birds at sea is comparable with birds flying above land, however, the median flying altitude is higher at sea compared to on land (fig. 13). The median flying altitude as registered by the WR-onshore was 600 m, both during the night and during daytime. For the WR-offshore this was 800 m and 1000 m for the daytime and night-time respectively. The altitude pattern does not change throughout the study period. When plotting these data for every single month separately, the pattern is identical. Omitting the data of the intense migration peak between 3 and 5 October 2016 also does not change the altitudinal pattern.

The weather radar detected the highest mean MTR values in the second altitude layer (200-400m), both on land and at sea. The Birdscan radar detected the highest mean MTR values in the lowest altitude bin (0-200m), this was also the case for the Merlin bird radar during daytime. At night, the Merlin radar registered the highest mean MTR from 200 to 400m (fig. 13).

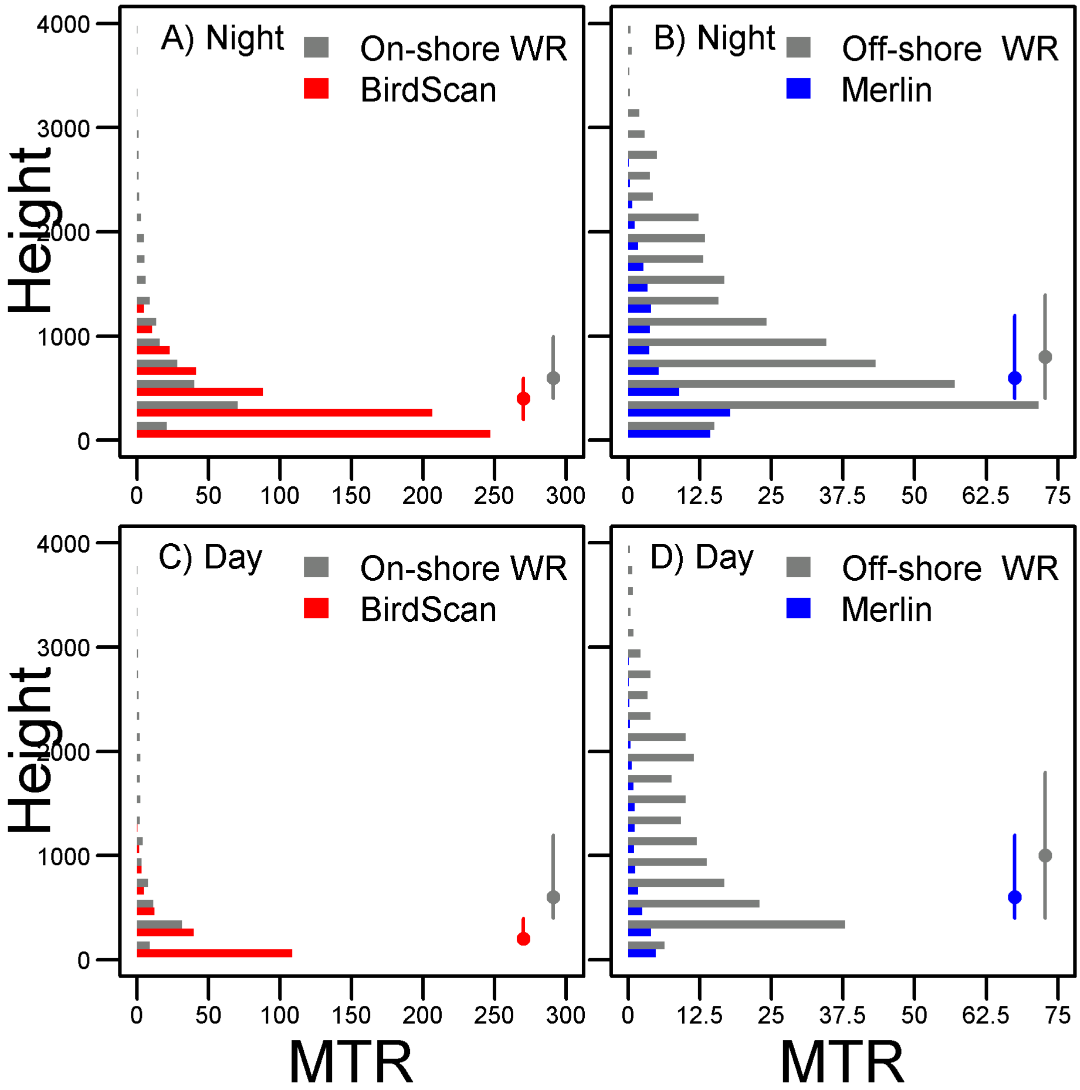

Figure 13. Mean MTR per altitude layer of 200m during the study period, birds registered by the radars on land (i.e. Birdscan and weather radar land) and the radars at sea (i.e. Merlin and weather radar sea) nighttime and daytime. Note that the scale on the X-axis of the figures on the left is different from the figures on the right. Median flying height is shown on the right of each panel. The upper and lower line represent the 25 and 75 percentile of registered flying height.

There is no clear difference between Spearman's rank correlation coefficients for the detections at night compared to daytime (table 5). Correlation of the Birdscan altitude profile with the Merlin bird radar is higher than the correlation between the Birdscan radar and the respective part of the weather radar. This might be caused by the lower detection capability in the lowest altitude band by the weather radar.

Table 5. Spearman's rank order correlation of the mean MTR per altitude layer during *daytime* and **nighttime**.

		0.73	*0.93*	*0.96*
	0.89		*0.92*	*0.25*
	0.98	**0.97**		*0.86*
	0.82	**0.25**	**0.79**	

4. DISCUSSION

4.1. Telemetry data

Although logistic drawbacks led to the decision not to further analyse the telemetry data (§2.1), further analysis of the telemetry data can reveal patterns between birds' flight characteristics and weather conditions. In the future, this might help explain any variation in detectability of seabird migration with radar technologies.

4.2. Cross-validation

In the cross-validation study, bird migration intensity was monitored with weather radar and two dedicated bird radars. The aim of this study was to gain insight into the comparability of bird migration intensities measured by weather radar and small-scaled radars, specifically developed to monitor birds.

The broad overview of validation studies presented by Liechti et al. (2018) confirms that in most cases bird MTR extracted from weather radar, when following the protocol implemented by Dokter et al. (2011), provide reliable results with respect to the relative pattern of day-to-day variation. In general, good correspondence was found for the relative day-to-day pattern in migration intensities among the radar systems that were compared. Absolute intensities varied between different systems and regions. The findings of cross-validation studies can be used to derive absolute bird migration intensities measured by different radar systems and consequently help resolving methodological issues regarding the estimation of numbers of migrating birds (Liechti et al. 2018).

Correlations of the measured MTR between the radars deployed in this case study were significant, but rather low during the study period, with no improvement when only considering the overlapping height intervals. The specific habitats where these radars were set up may partially explain this observed weak correlation. . The BirdScan-MR1 radar was installed in a rural area at approximately 20 km from the coast. The Merlin radar is installed on an offshore platform, and as such it only detects migrating birds at sea. The measurement volume of the WR in Jabbeke is partly inland and partly offshore. Although large numbers of birds are known to cross the North Sea (Buurma 1987, Alerstam 1990, Lensink et al. 2002, van Gasteren et al. 2002), these numbers are presumably lower than at the coast and inland. Nevertheless, the seasonal pattern as detected by the three radars matches well, with a clear peak in MTR early October. A storm front covering Germany and Poland at that time, resulting in (north-)easterly winds, pushed large numbers of birds to our study area (see also Nilsson et al. 2018).

We note that the difference between the weather radar and the Birdscan radar in absolute numbers was mainly due to intense movements at lower altitudes (<200 m agl), which was not included in the weather radar data. There are several reasons why the absolute numbers detected by the Merlin radar are lower compared to the WR and VBR. (1) The Merlin radar antenna has a wavelength in the S-band spectrum (7.5 - 15 cm), which is less suited to register smaller birds and thus, presumably, the number of small songbirds detected by this radar is underestimated. (2) The Merlin tracking software (DeTect, 2010) of the Merlin radar is not always able to differentiate between single birds and small groups of birds. As shown by Fijn et al. (2015), this might result in an underestimation of the MTR by up to 10%. Liechti et al. (2018) also showed that small scale bird radars may underestimate the number of individuals, because tight flocks are generally detected as a single target. (3) The orientation of the vertically rotating antenna is along the E – W axis, which was logistically the only possibility. A radar positioning perpendicular to the main migratory routes would have ensured the highest detection probability for birds flying through the area (Fijn et al. 2015). Therefore, in this case MTR may have been slightly underestimated. Because no confirmed flight direction data is available in this study region, no corrections could be made for this potential bias in MTR calculations. (4) We considered Merlin radar data up to the full altitudinal range of 3600 m asl and did not correct for a potential loss in detection probability with distance. There is no information available on target specific detection range for this type of solid-state radar antenna. Thus, some small high-flying migrants might have been missed by the system. It is unclear to what extent this contributed to the low number of birds recorded by the Merlin radar. Looking at the results of Krijgsveld et al. (2015) and Fijn et al. (2015), in similar circumstances, it was shown that 50% of the total flux occurred below 115 m. In our study, only 13.1% of the echoes are detected in the lowest 150 m. Fijn et al. (2015) also used a Merlin bird radar, but with an X-band magnetron radar. Compared to the total flux measured in an entire autumn season (September – November) by Fijn et al. (2015), the total flux measured with our Merlin vertical radar is about a factor 10 smaller. Not taking the lowest 150 m into account, this is still a factor 5. This has led to the decision to replace the currently deployed antenna with a conventional magnetron X-band antenna, like the one successfully being used in the Dutch part of the North Sea (Krijgsveld et al., 2011; Fijn et al., 2015).

4.3. Refinements of the bird detection algorithm to improve detections at sea

The location of the weather radar in Jabbeke offers the possibility to detect migrating birds at sea. Several modifications of the processing of the weather radar data were done during the project to improve the detections of birds at sea: (1) we finetuned the settings in the algorithm to reduce sea clutter and (2) we split the measurement volume of the Jabbeke radar in a part overviewing land and the part overviewing the sea. The standardly used R-package bioRad (Dokter et al. 2018) offers a function to set a minimum and maximum azimuth to select an area of interest within the measurement volume of a weather radar. This does not allow to split the volume of the weather radar in Jabbeke in an onshore and offshore part. Setting the minimum and maximum azimuth at 60° and 240°, then the volume would be split along a line parallel to the coast line. The resulting part of the volume overlooking the sea would also include the coastal zone. As we want to differentiate between migration at sea and on land, this would not be a good solution in this case. Weather radar detections on land versus at sea

A novelty of this study is that the measurement volume of the weather radar, which is located near the coastline, was separated in two areas of interest: the area above land and the part at sea. This allowed comparing the migration intensity and flight behaviour along the coast and at sea, with a focus on (1) the seasonal phenology; (2) the diurnal pattern and (3) the vertical distribution (altitude). The two bird radars provided high resolution data at a small spatial scale, the Birdscan radar can even make a distinction of species groups (e.g. passerines, waders), as a validation of the weather radar observations.

The results presented in section 3.3.4. are still preliminary and might change in the future as we continue to optimise the data processing chain of the weather radar data on land and at sea. They should be interpreted as preliminary results and are a showcase of the processing possibilities. We could reliably extract the seasonal, diurnal and altitude patterns of migrating birds for Autumn 2016. The final results will be presented in Brabant et al. (in prep.).

The current results already show a parallel temporal pattern of the movements offshore and onshore. The mean MTR detected by the weather radar, both on land and at sea, are of the same order of magnitude as the MTR values measured in Autumn 2007 by weather radars in Den Helder (243 birds/km.h) and De Bilt (504 birds.km^{-1}.h^{-1}) by Dokter et al. (2011). The MTR values show that migration was most intense during the nights of October and early November, both on land and at sea.

We did not find a better correlation for the migration intensity (i.e. MTR) registered by the Merlin radar and WR_sea compared to the correlation between WR_sea and the Birdscan radar, although this is what we expected. This might be explained by the large number of migrating birds that are close to the coastline, both at the sea side and the land side. As we split the weather radar volume at the coastline, this coastal migration flow is split into two and is partially included in the WR_sea data and partially in the WR_land data. If the WR_sea data would only include birds from 5 km from the coastline and further offshore, then the correlation of the MTR between the WR_sea and the birdradar at sea would presumably be higher than is the case now.

During the study period (Autumn 2016) the diurnal pattern changes considerably. At the start of study period, mid-August, we also registered local birds in the surroundings of the different radars. This is clearly visualized by the afternoon peak in the diurnal pattern in the measurement volume of the Birdscan in August, reflecting local foraging birds in the area. This explains the dissimilarity in the diurnal pattern of the bird radars on land and at sea in August. Later on, detections are dominated by nocturnal migrants.

The flight intensity was highest after dusk when nocturnal migrants take off. The flight activity peak at dusk is also clearly registered by the offshore Merlin bird radar, but somewhat later compared to the pattern detected on land. This time lag corresponds to the time needed for birds departing at the coast to reach the offshore location of the bird radar.

The provisional results suggest that the median flying altitude registered by the weather radar at sea is higher compared to the detections of the weather radar on land. This was also reported by Alerstam (1990). Detections of the weather radar in the lowest altitude bin are low. This confirms that this lowest altitude bin of the weather radar is less suited for bird detections.

Although the bird detection algorithm implemented on the weather radar data is not designed to monitor very local migration features within the field of view of the radar (Dokter et al. 2011), in the second part of this project we demonstrated that the radar volume can be successfully divided in multiple areas of interest. This is especially useful for radars at the coast the separate migration on land and at sea. Which can then be of used for the impact assessment of offshore wind farms.

This study promotes the use of combined ornithological and weather surveillance radars for monitoring the spatial and temporal patterns of bird migration as this provides crucial information for impact assessment studies and adaptive management plans. A better understanding of peaks in bird migration can lead to a better mitigation of human impacts. This can then lead to mitigation measures for (offshore) wind farms. For instance, a requirement for the neighbouring Dutch Borssele wind farms is to shut down the turbines when the bird flux at rotor height exceeds 500 birds.km^{-1}.hr^{-1}. To practically apply such a measure will require a lot of cooperation of all involved parties and model results can assist in this process.

5. CONCLUSIONS

In general, good correspondence was found for the relative day-to-day pattern in migration intensities among the radar systems that were compared. Correlations of the absolute intensities measured by the radars deployed in this case study were significant, but rather low during the study period. The specific habitats where these radars were set up may partially explain this observed weak correlation. The findings of this cross-validation study can be used to derive absolute bird migration intensities measured by different radar systems and consequently help resolving methodological issues regarding the estimation of numbers of migrating birds (Liechti et al. 2018).

Although the bird detection algorithm implemented on the weather radar data is not designed to monitor very local migration features within the field of view of the radar (Dokter et al. 2011), in the second part of this project we demonstrated that the radar volume can be successfully divided in multiple areas of interest. This is especially useful for radars at the coast the separate migration on land and at sea. Which can then be of used for the impact assessment of offshore wind farms.

This study promotes the use of combined ornithological and weather surveillance radars for monitoring the spatial and temporal patterns of bird migration as this provides crucial information for impact assessment studies and adaptive management plans. A better understanding of peaks in bird migration can lead to a better mitigation of human impacts.

6. DISSEMINATION AND VALORISATION

6.1. Presentations

- Brabant Robin, Maarten Reyniers, Maryna Lukach, Vanermen Nicolas & Steven Degraer. 2017. RAVen-project: Validating radar technologies to study near- and offshore bird migration. Pitch and poster presentation at the Radar Aeroecology Conference, 23-24 February 2017, Rome, Italy.

- Boos, M., Brabant R., Reyniers, M., Lukach M., Schmid, B. & Liechti, F. (2017). Monitoring of migrating birds along the French-Belgian border: an approach combining meteorological and ornithological radars. Pitch and poster presentation at the Radar Aeroecology Conference, 23-24 February 2017, Rome, Italy.

- Maarten Reyniers, Brabant Robin, Maryna Lukach, Schmid, B. & Boos, M. 2018. Comparison of onshore and offshore bird migration by different radar systems near the Belgian coast. Poster presentation at the 10th European Conference on Radar in Meteorology and Hydrology (ERAD 2018): 1-6 July 2018, Ede-Wageningen, The Netherlands.

- Brabant Robin, 2016. RAVen-project: Validating radar technologies to study near- and offshore bird migration. Presentation at COST Enram meeting Malta (18-21 April 2016)

6.2. Capacity building:

- 3-day training school (20-22 February 2018, Rome): the international training school (30 participants) aimed to provide the knowledge and tools to allow you to use weather radar data for ecological research independently. The program combined lectures in the mornings, explaining the basics of (weather) radar and its applications in ecology, and afternoon practical exercises for people to gain hands-on expertise in processing, visualising and analysing weather radar data. Maarten Reyniers and Maryna Lukach of the RMI attended the training school.

6.3. Link with COST Enram:

- the RAVen project ran in parallel with the COST Enram project (European Network for the Radar Surveillance of Animal Movement). The COST Enram networking project started on October 21, 2013 and ran for four years. Enram aimed at creating a European network to join forces in the field of aeroecology and to foster a continent-wide remote sensing network to monitor bird migration by means of weather radars. Both RBINS and INBO were partners in the Enram project.
- On the one hand, RAVen benefited from collaboration with Enram (e.g. international network of experts). On the other hand, the outcome of RAVen contributed to the objectives of the COST Enram project. It is important to stress that a COST action is only providing

means for networking events (i.e. meetings and workshops) and not for the actual scientific research. The BRAIN-be budget of RAVen allowed for an in-depth analysis of the Belgian dataset at hand.

- During the RAVen project, we hosted (in collaboration with INBO) the final COST Enram meeting in Gent (11 and 12 September 2017). This meeting replaced the RAVen workshop, as was foreseen in the project proposal.

6.4. Scripts:

- The script to apply the Vol2Bird algorithm on partial volumes of a weather radar data is available on github: https://github.com/MLukach/RAVen.git

6.5. Other achievements:

- Apart from the Belgian radars, the RMI is now also processing the data from the weather radars in Herwijnen (KNMI, the Netherlands), Avesnois (Météo-France) and Abbeville (Météo-France). The bird detection output of all six radars is sent to the Wildlife Hazard Management section of the Belgian Airforce for issuing BIRDTAMs (bird notice to airmen) and flight planning. Previously, the flight safety assessment was only based on the bird profiles of the Belgian radars, which was not very convenient for several air bases like the one in Kleine Brogel.
- The COST Enram project has set up a data repository where the weather radar data are available of all the participating countries. The format of the Belgian data was not suited for that repository. During RAVen, the format of the Belgian data has been adapted according to the COST Enram data standards and is now available in the COST Enram data repository.

7. PERSPECTIVES

- Logistic drawbacks led to the decision not to further analyse the telemetry data (§2.1). However, further analysis of the telemetry data can reveal patterns between birds' flight characteristics in relation to weather conditions. In the future, this might help explaining any variation in the detectability of seabird migration with radar.
- Density calculation of the WR bird algorithm is based on the assumption that the weather radar is detecting migrating passerines. Therefore, a bird is estimated to have a radar cross section (RCS) of 11 cm^2 (Dokter et al. 2011). The estimates of the weather radar detections in specific areas (e.g. at sea) could be improved if the RCS could be adjusted to a measured RCS of birds in the area. To this extent, a specific campaign with fixed beam radar on an offshore platform would be needed.
- Estimates of total flux of migrating birds at sea, during one migration season, as was planned in the research proposal, was not possible yet. Once the processing of the weather data is completely finetuned, this will be done and the outcome will be compared with the flux

estimates known from literature (e.g. Lensink et al., 2002; Stienen et al, 2007; Krijgsveld et al., 2011).

- The project partners were granted funding from BELSPO for a valorisation action to exploit the full potential of the outcome of the BELSPO pioneer project RAVen (15/03/2019 – 15/03/2021). The objective of the proposed project CROW (Communicating RAVen to the Outside World) is to transfer the research to operations by (1) adding a modern, interactive data visualisation appealing to a large community of potential users, and by (2) offering the data visualisation package as open source and the bird detection data as open data, which can serve as building blocks for future research projects or flourish new collaborations.

8. PUBLICATIONS

Liechti F., Aschwanden J., Blew J., Boos M., Brabant B., Dokter A., Kosarev V., Lukach M., Maruri M., Reyniers M., Sapir N., Schekler I., Schmaljohann H., Schmid S. & Weisshaupt N., 2018. Cross-calibration of different radar systems for monitoring nocturnal bird migration across Europe and the Near East. Ecography 42: 1 - 12. DOI: 10.1111/ecog.04041

Brabant B., Schmid S., Lukach M., Reyniers M., Boos M., Vidao J. & Liechti F. Comparison of movement patterns of migratory birds on land and at sea, studied by different radar systems near the Belgian coast. In preparation

Nilsson, C., Dokter, A., Verlinden, L., Shamoun-Baranes, J., Schmid, B., Desmet, P., Bauer, S., Alves, J., Stepanian, P., Sapir, N., Wainwright, C., Boos, M., Górska, A., Menz, M., Rodrigues, P., Leijnse, H., Zehtindjiev, P., Brabant, R., Haase, G., Weisshaupt, N., Ciach, M. & Liechti, F., 2018. Revealing patterns of nocturnal migration using the European weather radar network. Ecography 42, 1 - 11. DOI: 10.1111/ecog.04003

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ANNEX 1. ADJUSTED PARAMETERS OF THE BIRD DETECTION ALGORITHM

This is being discussed in section 3.3.2.

# the number of layers in an altitude profile
NLAYER = 20

# the maximum range [m] used for constructing the bird density profile
RANGEMAX = 35000.0

# VVP Radial velocity standard deviation threshold 2.0
STDEV_BIRD = 3.0

# for a range gate to contribute it should have a valid radial velocity
REQUIRE_VRAD = TRUE

# correlation coefficients higher than this threshold will be classified as precipitation
RHOHVMIN = 0.95

ANNEX 2. LINKS TO THE DUAL-POL CASE STUDIES

The case studies are briefly discussed in Sect 3.3.3. Additional comments are found through the respective links.

Date + QR-code	Link to movie + description
2016-08-27	https://bit.ly/2K9ot2q During daytime: strong signal of insects drifting from land to the seaside (and disappear there). Note the very high ZDR values (>7) and the uniform texture for both ZDR and uPhiDP. Apparently insects do not have the capability to introduce any significant differential phase shift. Some organization is seen in the insect pattern (a line in dBZ parallel to the coast between 09:30 and 11:15 UTC). During nighttime: insect signal gets mixed with birds. The radial velocity direction indicates that these birds are not migrators, but that they are merely chasing insects so these are probably swifts and/or bats.
2016-09-14	https://bit.ly/2Pya5GU Probably there is a mixture of insects, birds chasing these insects but also migrating birds. It was a very warm night so probably mainly insects and (non-migrating) birds are seen here.
2016-10-03	https://bit.ly/2ON8rMu Massive passerine migration. Both ZDR and uPhiDP give strong indication for a common orientation of the birds. Bird migration at sea was more intense compare to on land.
2016-10-29	https://bit.ly/2K915Cn Massive passerine migration, but now the ZDR and uPhiDP do not give such a clear indication of orientation. Is this due to a different species than in 2016-03-10? It seems that a large group of birds lifts off in Zeeland/South-Holland and then crosses the channel towards England in the beginning of the night.