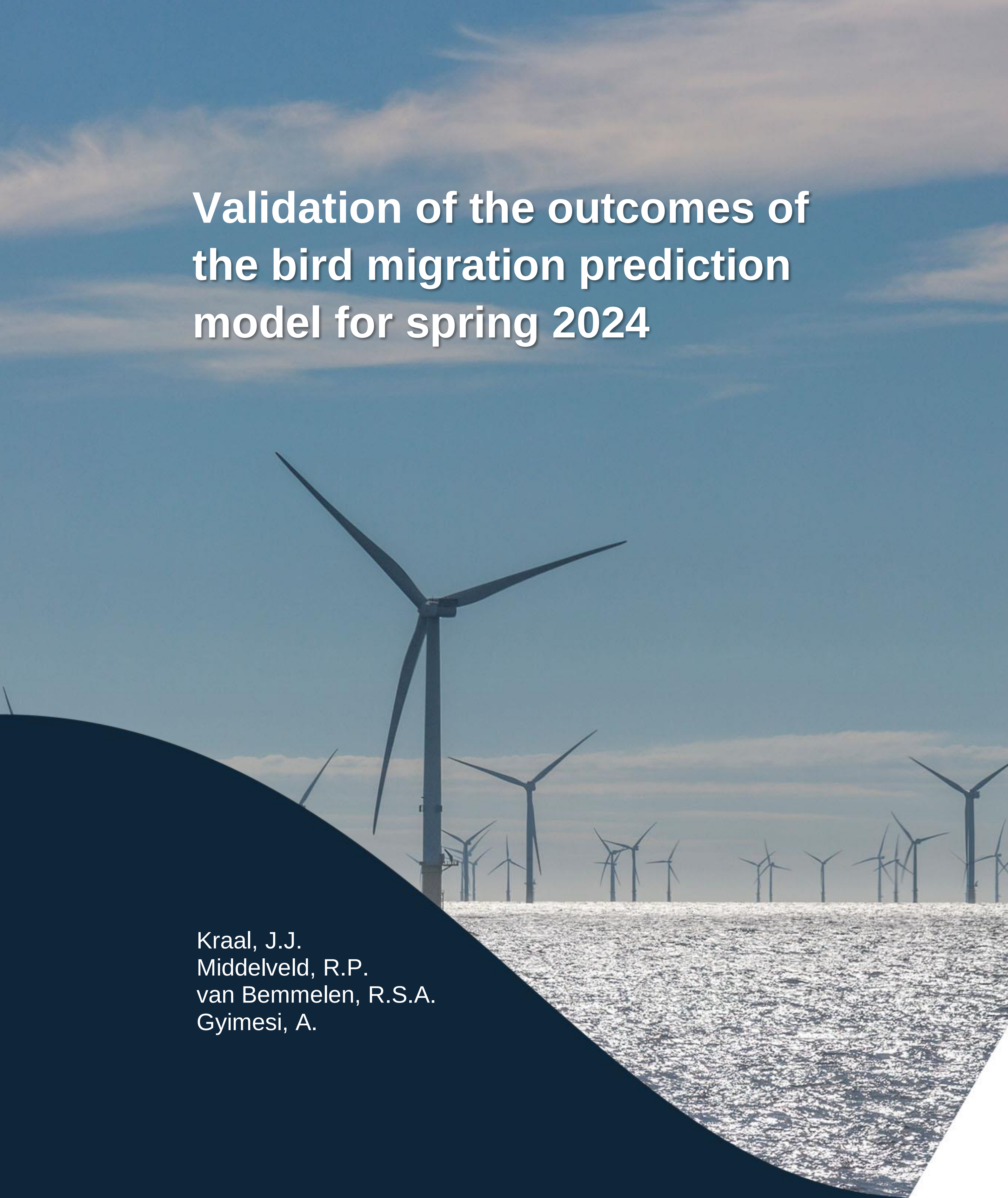

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Status: final report

Report nr:	24-303
Project nr:	23-0712
Date of publication:	5 November 2024
Photo credits cover page:	Daniel Beuker / Waardenburg Ecology
Project manager:	dr. Abel Gyimesi
Quality control:	dr. Astrid Potiek
Name & address client:	RWS, Water, Verkeer en Leefomgeving (Lelystad) Postbus 2232 3500 GE Utrecht Nederland
Reference client:	Zaak 31192818
Signed for publication:	Team Manager Waardenburg Ecology R.C. Fijn *MSc*.

Please cite as: Kraal, J.J., R.P. Middelveld, R.S.A. van Bemmelen, A. Gyimesi 2024. Validation of the outcomes of the bird migration prediction model for spring 2024. Report 24-303. Waardenburg Ecology, Culemborg.

Keywords: bird migration, offshore wind energy, machine learning, radar, expert team, clutter, weather forecast

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Preface

Shutting down wind turbines during major bird migration events is expected to be an effective mitigation measure to reduce the number of bird casualties. The Dutch government is implementing such a measure at a large scale in Dutch offshore wind farms. The energy market demands that such a drop in energy is known well in advance. Therefore, the University of Amsterdam developed a model to predict bird migration at the North Sea 48 hours in advance. This forecast model has an autumn and a spring module, both delivered in 2022. Waardenburg Ecology was asked to validate the model outcomes. In a previous report the migration seasons of 2023 were validated (Middelveld *et al.* 2024). The current report summarizes the results of the validation of the spring of 2024, and provides insights in possible reasons for the mismatches, which can be helpful in the further development of the model.

Next to the authors of this report, Jacco Leemans from Waardenburg Ecology gave advice on the analyses of this project. Sander van der Horst and Martijn Zondervan from Eneco provided weather data measured in wind farm Luchterduinen and Borssele, while Gerben Bergman from TNO provided rain measurements at the LEG platform. We thank Maja Bradarić from the University of Amsterdam for a fruitful discussion on the working of the forecast model. The project was coordinated by Aylin Erkman and Jos de Visser from Rijkswaterstaat.

Contents

1 Introduction

Twice a year, large numbers of birds migrate over the North Sea from their breeding grounds to their wintering areas and vice versa. Most of these birds are passerines and other terrestrial birds, which migrate mostly at night (Shamoun-Baranes & van Gasteren 2011, Fijn *et al.* 2015, Welcker 2019). These birds may encounter several risks during their migratory journey. Due to the development of offshore wind farms, one of those risks is the possibility of colliding with a wind turbine. The number of wind turbines is increasing rapidly, leading to increased danger of collisions for migrating birds (Brabant *et al.* 2015).

A promising way to prevent collisions is curtailing wind turbines during the migration season. As this reduces the amount of energy generated by the turbines, it is key to find a good balance between wind energy generation and safe passage of migrating birds through the wind farms. Bird migration peaks at certain moments and the most optimal balance would therefore be to only curtail during these high peaks (van Bemmelen *et al.* 2022).

For reliable energy supply, it is essential to know the energy yield of offshore wind farms up front. Therefore, these peaks in migration intensity need to be predicted 48 hours in advance. To do this, a bird migration prediction model was developed by the University of Amsterdam (UvA) (Bradarić 2022). This machine learning model aims to predict bird migration over the North Sea based on earlier measurements on bird migration by a dedicated bird radar in offshore wind farm Luchterduinen and the corresponding weather circumstances there and at departure locations of the birds. The model has a separate module for the spring migration, trained on data from the period 15 February - 1 May and for the autumn migration, trained on radar data from October and November. Note that in the present validation also data from May was involved, on special request by Rijkswaterstaat, due to the fact that the curtailment procedure is also applied to this month.

The bird migration prediction model was trained on weather data from the ERA5 reanalysis model. This is a weather model that aims to estimate a large variety of weather variables in the past (Hersbach *et al.* 2023). Although this is a solid way to train a machine learning model for migration patterns in relation to weather conditions, for the curtailment of offshore turbines a weather forecast of two days in advance is needed. Therefore, instead of the reanalysis data of the ERA5 model, weather forecast data need to be used as input for the bird migration prediction model. These weather forecasts come from the European Centre for Medium-Range Weather Forecasts (ECMWF-model, www.ecmwf.int).

The outcome of the UvA bird migration model is a prediction of bird migration intensity in the form of the *migration traffic rate* (MTR). MTR is defined as the number of birds per kilometre per hour and is used to illustrate the migration intensity. The curtailment procedure of Dutch offshore wind farms is also based on predictions in this unit. Hence, it is essential to validate how accurately the model predicts bird migration. In this current report, we therefore compare the model predictions for the spring of 2024 with radar measurements from the same bird radar in offshore wind farm Luchterduinen that was also used to train the bird migration prediction model. We furthermore give insights in how these model predictions and radar measurements at Luchterduinen relate to measurements of another offshore bird radar, located in wind farm Borssele. The wind farms involved in the curtailment procedure are located near one of these two radar locations.

The Robin 3D fixed systems operating in the wind farms Luchterduinen and Borssele provide horizontal measurements, yielding information on the spatial distribution of flight paths and their intensities, supplemented by a vertical radar component (a radar tilted 90 degrees), providing information on flight heights and the altitudinal distribution of flight intensities. The UvA bird migration model was trained on the horizontal radar data of Luchterduinen, and hence we also validated the model predictions based on these radar data. Bird radars store the detected flight paths (tracks) of birds which can be subsequently analysed to compute MTRs. In this report, we validated model predictions by MTRs calculated following the method used by Bradarić (2022), namely by taking the density of bird tracks and the ground speed within an hour in consideration to quantify the number of birds that fly through a specified area.

It is worth mentioning that the horizontal and vertical radars also differ in technical aspects. The vertical radar operates in the X-band and has a shorter wavelength, resulting in an increased sensitivity to smaller objects than the horizontal radar. Consequently, the vertical radar has a higher detection probability for small birds but also for potential contamination (shading) of bird detections by rain and waves (Krijgsveld *et al.* 2011). The longer wavelength of the S-band means that the horizontal radar has reduced sensitivity to smaller objects, which then reduces the detection probability of small birds. However, this longer wavelength also reduces the potential contamination of bird detections by rain and waves (Krijgsveld *et al.* 2011). Despite the larger influence of waves on the vertical bird detections, this phenomenon is limited to the scanned area near the sea surface. In contrast, although the horizontal radar is in general less sensitive to wave clutter, during moments when clutter does play a role, the measurements are also more impacted, as the whole beam of the radar is affected. For these reasons, we also analysed measurements of the vertical radars, to see whether the horizontal radars potentially missed bird migration peaks. For these analyses of the vertical radar data, we used the method of Leemans *et al.* (2022b) to calculate the number of birds crossing a virtual line of one kilometre within an hour.

The procedure of curtailing offshore wind farms starts with producing predictions by the bird migration model for 48 hours in advance. These model outcomes are compared with certain prequalified trigger values. For the spring, this trigger value is currently defined by the Dutch government at an MTR of 151 birds/km/h. Be aware that these predicted MTR values are lower than the legal definition of peak migration set at a MTR of 500 birds/km/h (cf. Bradarić 2022), which was defined based on earlier measurements by a vertical bird radar in OWEZ (Krijgsveld *et al.* 2015). However, the model predicts far lower MTR values during migration peaks than what the radars measure. Therefore, a lower value predicted by the model can be interpreted to correspond with higher values of the radar. Synchronically to generating model predictions, an expert team of seven ornithologists from a variety of institutions independently predict based on expert judgement whether an increased migration intensity reaching the curtailment threshold is likely to occur. A combination of the model outcome and the expert team predictions is used to implement curtailment. Being an important element in the curtailment procedure, the expert team predictions made for the spring of 2024 are also presented in this report. This curtailment procedure resulted in one actual curtailment moment in 2024, which is also discussed in this report.

Reading guide

- The methods of the analyses are presented in Chapter 2.
- In Chapter 3, we present the basic validation of the model for the spring 2024 migration season as measured by the horizontal radar in Luchterduinen and predicted by the model and the expert team.
- The possible causes for the mismatches between the peaks in bird migration as predicted by the model and measured by the radar are discussed in Chapter 0.
- In Chapter 5, an additional analysis on threshold levels for the radar and trigger values for the model is presented. In addition, the sizes of detected birds are studied in more detail and compared between the vertical and horizontal radar in Luchterduinen.

2 Methods

2.1 Method of validation

The main validation was carried out by comparing detected MTRs of the horizontal radar in Luchterduinen with the MTR predictions by the model. Measurements of the vertical radar in Luchterduinen were used to fill in gaps of missing data (filtered hours, see §2.2.1 and 2.2.2) in the dataset of this radar and to check for possible migration peaks at higher altitudes than the range of the horizontal radar. To be able to check for spatial differences on the North Sea, the bird activity measured around Borssele was also used, both based on the horizontal and the vertical radars at Borssele wind farm.

To investigate mismatches between the radars and the model predictions, weather conditions were examined. For this, the ECMWF weather forecasts used by the predictive model were provided by Technolution B.V., which they automatically retrieved from the ECMWF database (published under a Creative Commons Attribution 4.0 International (CC BY 4.0); Copyright: © 2024. ECMWF does not accept any liability whatsoever for any error or omission in the data, their availability, or for any loss or damage arising from their use). To investigate actual weather patterns during peak migration nights, two sources of weather information were used. First, local weather sensors at Luchterduinen provided wind conditions (data courtesy of Eneco). Second, the global reanalysis of the ERA5 model was used for areas where no local meters were present (Hersbach *et al.* 2023).

All analyses were performed in R version 4.3.1 (R Core Team 2023).

2.2 Radar measurements

In this report, we calculated bird migration intensities in the form of MTRs both for the horizontal and the vertical radar of the Robin 3D Fixed System in Luchterduinen (LUD). MTR is defined as the measured number of tracks per kilometre per hour. The MTR calculations differ between the horizontal and vertical radar. To calculate the MTR for the horizontal bird radar, the same method was used as described by Bradarić (2022). Since the horizontal radar resembles a helicopter view of the study area, a density-based approach needs to be used (§2.2.1). In contrast, the vertical radar images look like a side view from the study area and therefore can be utilized to calculate MTRs with flux lines (§2.2.2). The method to calculate the MTRs from the vertical radar followed the methods of Leemans *et al.* (2022). Together, both types of radars provide detailed information about the flight behaviour of individual birds and flight intensity in the study area. The horizontal radar measurements were used to calculate the MTRs the same way as was done for training the model. Measurements of the vertical radar were not used in the development of the forecast model by Bradarić (2022). Nevertheless, we used the vertical radar measurements in this report to investigate whether the horizontal radars missed migration peaks. For instance, a peak in migration might also happen at higher altitudes than the range of the horizontal radar, but which can be detected by the vertical radar.

Radar specification

Two bird radars are located on the railing of one of the turbines (WTG 42) in offshore wind farm Luchterduinen at approximately 23 m above mean sea level. The two radars together form the so-called Robin 3D Fixed System, consisting of a horizontal Furuno magnetron-based S-band radar and fixed vertical Furuno magnetron-based pulse X-band radar. The aim of the horizontal radar is to detect and measure spatial flight patterns and flight speeds of birds. The horizontal radar radiates in theory 360 degrees round, but to protect the wind turbine and personnel from radiation damage, and prevent excessive clutter formation due to the wind turbine affecting the radar measurements, a blank sector is created towards the turbine where no radar measurements took place. This blank sector consists of 19.4% of the complete study circle around the radar.

The vertical radar works similar to the horizontal radar but is tilted 90 degrees. The radar is blinded towards the sea level to prevent substantial reflections from the water. The beam forms a bow-tie shape widening with distance to the radar, but it stays relatively narrow. Radar tracks detected by both radars are combined into a so-called combined track. These are 3D tracks, containing information on both horizontal position and altitude. The combined tracks were used in the analyses of both locations.

2.2.1 Horizontal radar measurements

Data filtering

A few filtering steps were taken to prevent non-bird tracks from entering the analysis. For data filtering and calculating the MTR, we followed the method of the UvA as this was used during the training of the bird migration prediction model (Bradarić 2022). First of all, our analyses need to focus on migrating birds. The flight of migrating birds tends to be directed and therefore relatively straight. Hence, tracks that seemed to be originating from local movements were removed using the track characteristics ‘displacement over time’ (DOT) and ‘straightness of the track’. DOT was calculated by dividing the shortest distance between the start point and end point by the duration of the track. The tracks that belong to the lowest 10 percent based on their DOT were removed, leaving out the most undirected tracks. The straightness of a track was calculated by dividing the shortest distance between the start and end point by the total distance that was travelled. All tracks with a straightness of lower than 0.7 were deleted. This leaves out tortuous tracks, which are unlikely to belong to migratory birds.

Tracks with an airspeed below 5 m/s were also filtered out of the database, as those are most likely either not birds or not flying birds (Shamoun-Baranes *et al.* 2011). The airspeed was calculated by measuring the ground speed and direction of the track relative to the wind speed and direction. The wind speed and direction from the ERA5 weather model were used from the Copernicus website (Hersbach *et al.* 2023).

Finally, all minutes with high filtering activity by the radar were labelled as high-clutter minutes. A high filtering minute was determined based on the radar metric called ‘variant mask filtering’, providing the percentage of the area the radar was filtering. Filtering by the radar is an automatic feature to reduce the number of non-bird tracks (clutter caused by waves and rain) ending up in the database as birds. However, such filtering usually also leads to a lower detection probability of birds, and hence the number of birds measured by the radar during heavy filtering is likely an underestimation of reality. As this results in a less reliable MTR value, the minutes with high filtering activity (more than 30 percent of the area is filtered out by the radar) are removed from the analysis. If an hour only contained 10 or less minutes of reliable data, it was also removed from the analysis. This arbitrary threshold of at least 10 minutes ensures that hourly MTRs are not based on a small number of minutely observations.

MTR calculation

The MTR was calculated as a measure of the number of birds flying through the wind farm. This was done by first calculating the density of birds within a certain area. The area that was used is donut-like shaped, drawn around the radar, with the inner border of the donut at 1,000 meters and the outer border at 2,000 meters from the radar. Figure 2.1 provides a schematic view of the study area in LUD, with an area left out due to the blanking sector of the radar towards the wind turbine it is installed on, leaving a 7.57 km^2 surface area of the donut in LUD. Every radar track with its centroid inside the donut area was used for the analysis. As the horizontal radar radiates at 20^o, the horizontal radar can detect birds up to approximately 300 metres above mean sea level.

The radar rotates every second, and during each rotation an individual bird can be detected. When a bird is detected during a certain rotation, a ‘plot’ is added to the track. The number of plots hence indicates the number of times the bird is recorded by the radar.

As a first step in the calculation of the MTR, the number of plots of all tracks within a certain hour are summed and divided by the number of radar rotations within that hour, which gives the average number of birds recorded by the radar during each rotation. As only the tracks within the donut area are involved, the number of birds at a certain moment are divided by the surface of the donut area, leading to the average number of birds per km^2 for a certain hour. This number of birds within a certain area is called the *density* at a certain moment in time. Subsequently, the MTR is calculated by multiplying the density of birds with the average ground speed (in km/h) of all bird tracks that are used in the analysis in that hour. Note that the horizontal radar does not provide altitude measurements. Therefore, these MTRs visualise the migration intensity in the lower approximately 300 metres. The rotor swept zone of offshore wind turbines is within this band.

Figure 2.1 *Donut-shaped area which was used to calculate the MTR from the horizontal radar data in Luchterduinen wind farm. The blue marker shows the radar position. The missing part of the donut the represents the blanking area of the radar to avoid excessive reflection from the turbine on which the radar is installed.*

2.2.2 Vertical radar measurements

Data filtering

To prevent any non-bird tracks from entering the dataset of the vertical radar, several filtering steps were taken. These steps were based on Leemans *et al.* (2022). Because the vertical radars have other characteristics than the horizontal radars, other filtering steps need to be used than during the calculation of MTRs of the horizontal radars.

Especially rain showers are known to contaminate the dataset of the vertical radars. As the filters of the radar are so-called dynamic filters, it usually takes some time until the radar rightly classifies rain showers as clutter. In the period that the filters are not yet activated, to a lot of tracks falsely classified as birds may enter the dataset. Therefore, all seconds in which the rain filter was active in at least 5 percent of the total image of the radar, were marked as *rain seconds*. Next, all minutes with 30 or more rain seconds were counted as *rain minutes*. Finally, all hours with 10 or more rain minutes were filtered out. This filtering excludes most hours with rain but may not prevent all rain showers entering the dataset, falsely classified as bird tracks. To ensure exclusion of hours with rain with a higher certainty, rain measurements of the TNO rain meter on Lichteiland Goeree and the KNMI weather station in Wijk aan Zee were also investigated. If rain was measured at both locations, that hour was also filtered out.

In a subsequent step, the total number of radar tracks were calculated per five minutes. A sudden increase in the number of birds between two succeeding five-minute periods is an ecologically unlikely phenomenon and was used as an indication for a rain shower falsely entering the database as bird tracks. If this increase between two succeeding five-minute periods was above a threshold of 300 percent, and the second five-minute period contained at least 100 bird tracks, this increase was assumed to be caused by a rain shower. This way, only the extreme and very sudden increases in number of radar tracks were marked as rain shower. If such a sudden increase in number of radar tracks occurred, the whole hour was filtered out, as we could not ensure with confidence that the rest of the hour was not contaminated by rain clutter.

For the final rain filtering step, a label that is assigned by the radar was used. Based on the behaviour and characteristics of each track, the property 'In Blob Formation' is assigned to every track that has multiple reflection centres. A large proportion of the bird tracks generated by rain showers were found to have this label. Therefore, all hours with at least 100 tracks and of which more than 15% had the property 'In Blob Formation' at either of the two sides of the radar (Figure 2.2) were filtered out.

MTR calculation

Vertical radar measurements were done based on *flux lines* that were placed from 500 – 1000 meters from the radar, on both sides of the radar beam. Figure 2.2 shows the flux lines in LUD. This is slightly closer to the radar than where the horizontal radar measurements were done, which was done to prevent false tracks entering the data because of turbines. Note that this is also one of the reasons that MTRs calculated from both vertical and horizontal radars should not directly be compared.

In order to show vertical layering of the flux, we present results using height bands. 0-3 meters were filtered out to remove any tracks caused by sea waves. 3-25 meters were shown to depict the air layer just below rotor height. 25-137 meters is the rotor height in LUD. 137-300 meters is the air layer just above rotor height in LUD that might still be visible by the horizontal radar. The rest of the vertical column, up to 1000 meters was divided in two layers, up to 500 meters and up to 1000 meters.

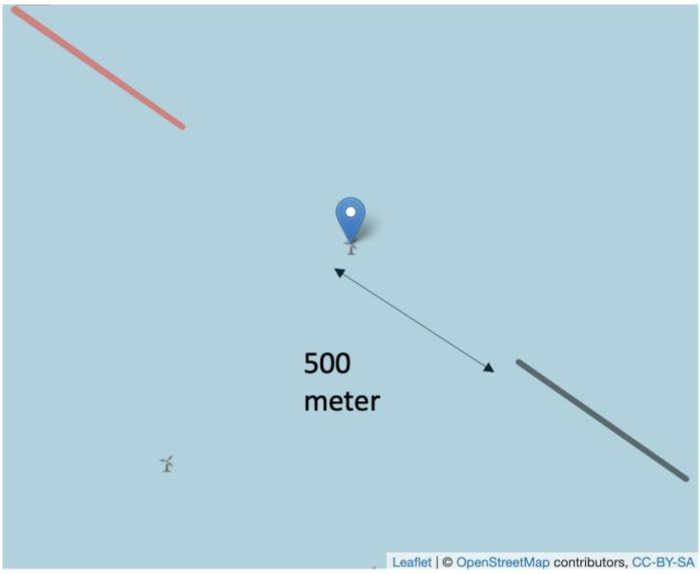

Figure 2.2 Flux line placement around the vertical radar to the northwest (red line) and southeast (black line) in Luchterduinen wind farm. The marker depicts the radar location. Both flux lines are 500 meters long.

2.2.3 MTR calculation for the Borssele radars

For both radars in Borssele, the MTR calculations were kept as similar as possible to the calculations of the radars in Luchterduinen. However, as these radars function in a different environment and are placed at different heights, some steps during the MTR calculations had to be adjusted.

For the horizontal radar in Borssele, a different threshold had to be determined as the filtering activity by the radar differed a lot. To determine a new threshold for the filtering value to exclude hours from the analysis, a method was used using a Generalized Additive Model (van Erp *et al.* 2023) specifically for the offshore radars of Rijkswaterstaat. This method uses a modelled relationship between the number of tracks within an hour and the average land mask filter value. By taking the minimum value of the first derivative of this model, one receives the masking value where the decrease in bird numbers is the largest (landmask = 0.21).

Subsequently, it was noticed based on expert judgement that a lot of tracks entered the database of the vertical radar that were supposedly not bird tracks. Although it is not yet clear what phenomenon exactly causes these false positive tracks, there was a relationship between wave height and the number of these tracks (Leemans *et al.* 2024). Therefore, additional filtering steps were needed to erase hours containing too much of false positive tracks. The filtering steps followed the methods of Leemans *et al.* (2024). Finally, as there is no rain station nearby Borssele, the filtering step based on actual rain measurements could not be carried out for the Borssele vertical radar.

2.3 Model predictions

The bird migration model was developed by Bradarić (2022). The spring module was trained on radar data from the period 15 February – 30 April of 2019, 2020 and 2021. Note that the current validation report also covers the month May, as this month is included in the curtailment period. The model was not trained on using data from this month. Consequences of using the model on months it was not trained on are discussed in Box 1.

The model predicts bird migration at Luchterduinen based on weather information from the ECMWF database. The required weather variables are the u-component of wind at 100 m single level (west to east) (m/s), v-component of wind at 100 m single level (south to north) (m/s), total precipitation (mm), mean sea level pressure (hPa), temperature in degrees Celsius that is averaged over altitudes of 100 to 300 m. The model takes different departure locations into account when calculating a prediction. These departure locations are the southwest part of the United Kingdom and North-France for the spring (Figure 2.3). For weather data for Luchterduinen, the coordinates 52.25 N 4.00 E were used.

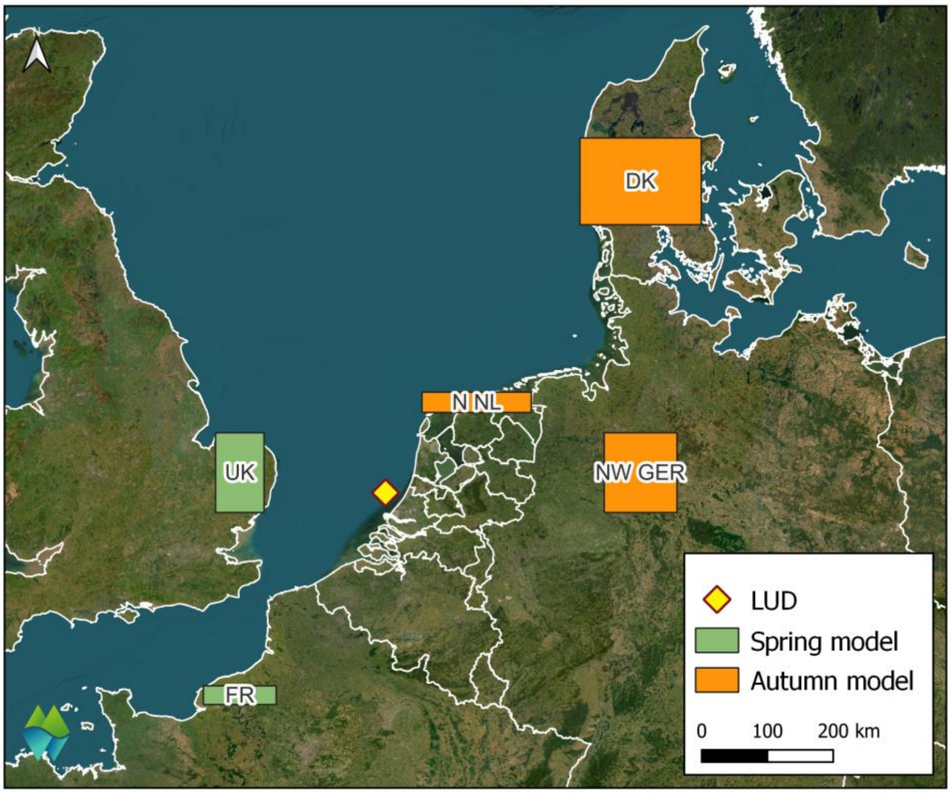

Figure 2.3 Departure locations for bird migration at Luchterduinen for both spring and autumn.

2.4 Expert team predictions

A team of seven bird migration specialists predicted occurrence of migration peaks in the spring of 2024, in order to offer an additional prediction next to the model predictions. These expert predictions were made from 15 February 2024 to 31 May 2024, for the periods midnight to sunrise and sunset to midnight of two days ahead. Thus, for instance, on Monday afternoon before 14:00 one prediction was made from sunset to midnight and one from midnight to sunrise (Central European Time zone) for the night from Wednesday to Thursday. Predictions for a migration peak in the lower 300 meters were made with a distinction of two regions: the Southern North Sea west of Holland (the area south of IJmuiden) and the area above the Wadden Islands. In this analysis, we used the predictions for the Southern North Sea west of Holland. Note that results are presented in time zone UTC. Therefore, midnight translates to 22:00 UTC for daylight saving time, and to 23:00 for the period in wintertime.

Expert predictions were based on predicted weather conditions (wind speed and direction at various altitudes, temperature, pressure systems, precipitation), both locally and in the areas of expected bird departure. The progress of the migration season was considered as well, based, amongst others, on information of the European network of visual migration counts, nocturnal migration recordings and ringing sites. The expert team made their predictions without information on predictions of the bird migration prediction model.

2.5 Weather circumstances during the study period

Based on information from the Royal Netherlands Meteorological Institute (www.knmi.nl) we provide here below a short summary of the weather circumstances of the study period.

In general, the temperature of the spring season was clearly higher than the long-term average, with 11.8°C against the average of 9.8°C, providing the highest spring temperature since the beginning of the KNMI weather measurements. The warmth of the spring already started in February, which was the warmest February ever measured with an average temperature of 8.2°C while the long-term average is 3.9°C. March and May were also very warm, while April had only slightly higher temperatures than the long-term average.

The spring of 2024 was moreover exceptional in the large amount of rain that mostly fell in April and May. May 2024 was, of all months of May measured, the one with the highest amount of rainfall since the beginning of the measurements. April was the third wettest ever. In addition, April experienced also three different periods with exceptionally hard wind (9-10 April, 15 April, 28 April). In the spring of 2024, the only other notable days with strong wind occurred on 22 February and 24 March.

3 Basic validation of the spring migration model

3.1 General patterns measured by the horizontal radar

The spring migration prediction model was developed for the period of 15 February – 30 April (Bradarić 2022), but the validation was requested to be carried out for the period of 15 February – 31 May (see Box 1). Following the filtering steps described in Chapter 2.2.1, Table 3.1 describes the availability of horizontal radar data at Luchterduinen for the spring of 2024 that was used for validation purposes.

Table 3.1 *Overview of hours in the radar dataset with suitable horizontal radar data for the spring of 2024. Data is included from the 15th of February until 31st of May. The column 'Night-time available hours' refers to the number of hours that were used in the analyses. The column 'Cause of missing data' provides a specification of the night-time hours that were not considered in the analyses.*

	Total		Total daytime	Nighttime		Cause of missing data	
Month	hours	days	hours	total hours	available hours	hours filtered	hours radar off
2	360	15	150	210	129	49	32
3	744	31	347	397	361	36	0
4	720	30	397	323	190	93	40
5	744	31	468	276	257	19	0

The percentage of hours with suitable data was ~90% for March and May but was lower for February and April with ~60%. The lack of data for February and April was mainly due to too strong filtering, mainly caused by rain and high waves (see also Chapter 2.5). The radar was turned off for some period during these 2 months causing 72 of the total 269 missing nightly hours (27%).

The radar measurements over time are presented in Figure 3.1. Considering MTR > 500 birds/km/h as peak bird migration, the available horizontal radar data showed **no peaks** of bird migration in the spring of 2024. The maximum MTR of 386 birds/km/h was measured on the night of 17/18 March. Elevated MTRs started at midnight in local time (MTR of 195), but the peak was at 4:00, so at the second half of the night.

March is in general the month where the highest bird activity is expected, and this expectation was confirmed in the spring season of 2023 (Middelveld *et al.* 2024) as well as for this season. However, apart from the night of 17/18 March, all maximum MTRs per night were below 250 birds/km/h for all months.

Box 1: Predictions in months the model was not trained on
The model is trained to find patterns from the real world, in this case to find correlations between migration patterns and weather conditions. The model, however, was only trained on the months of February to April for spring. However, during the curtailment procedures, as well as in this current validation, the model was forced to make predictions also for May. Theoretically, this could mean that the model would not perform well on these months if migration dynamics were dissimilar between the months the model was trained on and the months it was used for.

For birds, these distinctions of months do not exist. However, some bird species tend to migrate earlier or later in the season than others and might therefore react differently to certain weather conditions. In other words, the start sign for a mass migration event in May might be different than in March. Thereby, phenology, an important feature of the model, is specific for the time within the migration season and the model is therefore not trained to use this data for May. Hence, it is generally expected that the model performs worse in these months.

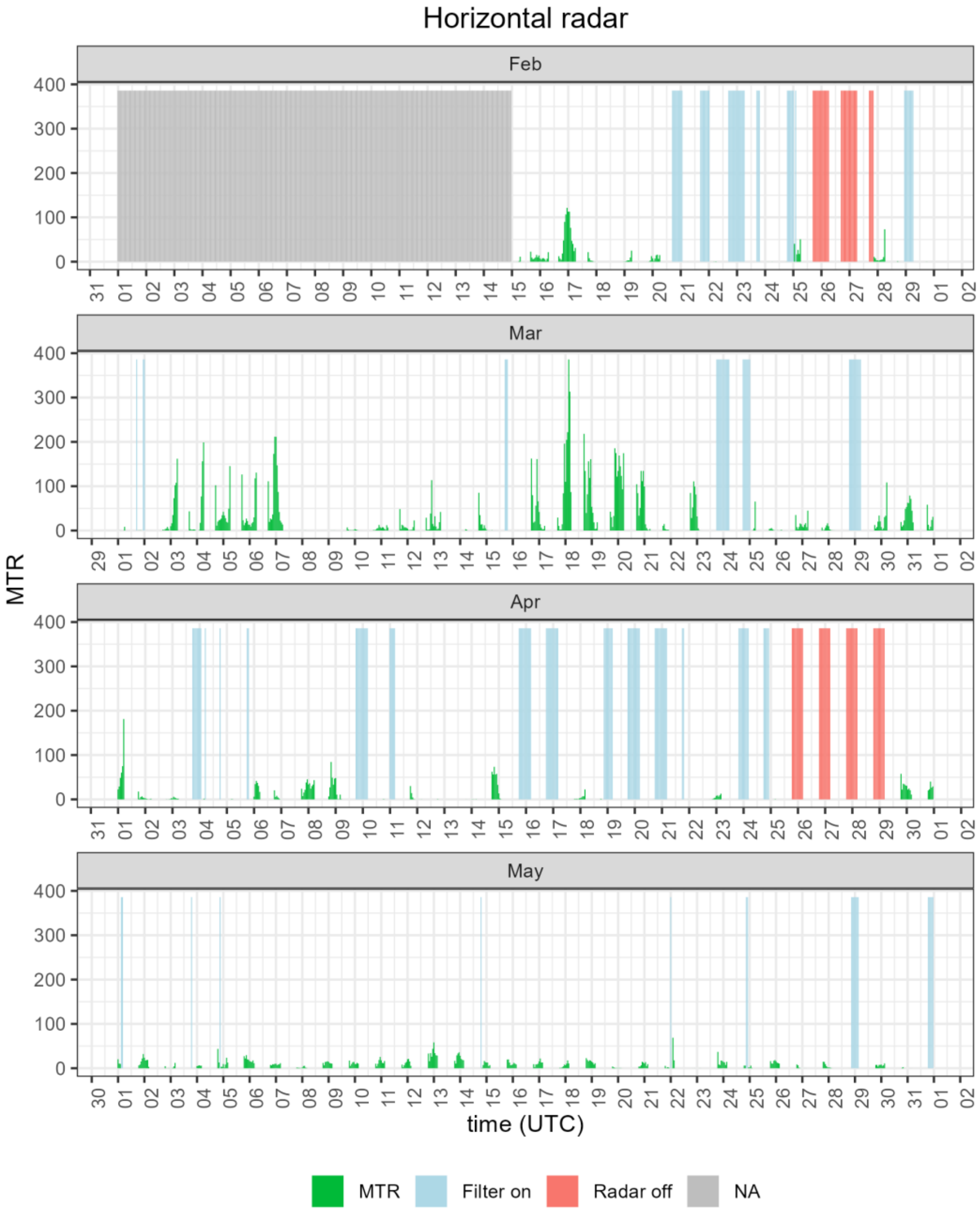

Figure 3.1 *Mean traffic rate (birds/km/h) measured by the horizontal radar in Luchterduinen in the spring of 2024 (teal bars). The four graphs show per month the nocturnal hours, between sunset and sunrise based on UTC time. In February only data from the 15th are included. Periods with unavailable radar data are classified into periods of high filtering activity (blue bars) or periods where the radar was turned off (red bars).*

Table 3.2 *Summary statistics of the horizontal radar. Only nocturnal hours were included, where the radar was on and not filtering too strong.*

month	MTR per hour						max MTR per night			
	n hour	max	mean	sd	median	sumSum	n night	mean	sd	median
2	133	121	11	24	1	1,464	13	27	36	16
3	371	386	31	54	7	11,423	30	94	93	82
4	197	181	12	21	1	2,308	21	22	26	13
5	267	69	10	10	9	2,723	30	20	16	17

3.2 Model predictions

The model predictions for the spring of 2024 started at 2024-02-17 23:00 UTC and ran until the end of May. For 7 March no predictions were made due to lack of weather data availability. The predicted MTRs showed on average a higher bird activity for the nights in February and March, compared to the months of April and May, which is in line with the results of the spring migration season of 2023 (Middelveld *et al.* 2024). Considering the currently applied trigger value of MTR > 151 birds/km/h, *the bird migration forecast model predicted four peak migration nights*. Modelled peaks occurred at the nights of 24/25 and 25/26 February, 16/17 March and 14/15 April (Figure 3.2). Maximum modelled MTR for a peak migration night amounted to 316 birds/km/h (Table 3.3). Several other nights showed relatively high MTRs (blue line in Figure 3.2) but did not exceed the peak trigger value. In general, the model predictions showed a similar temporal pattern for all spring nights: a higher MTR at the end of the night. This pattern is expectedly caused by the hourly phenology used for the model combined with the geographic locations of departure.

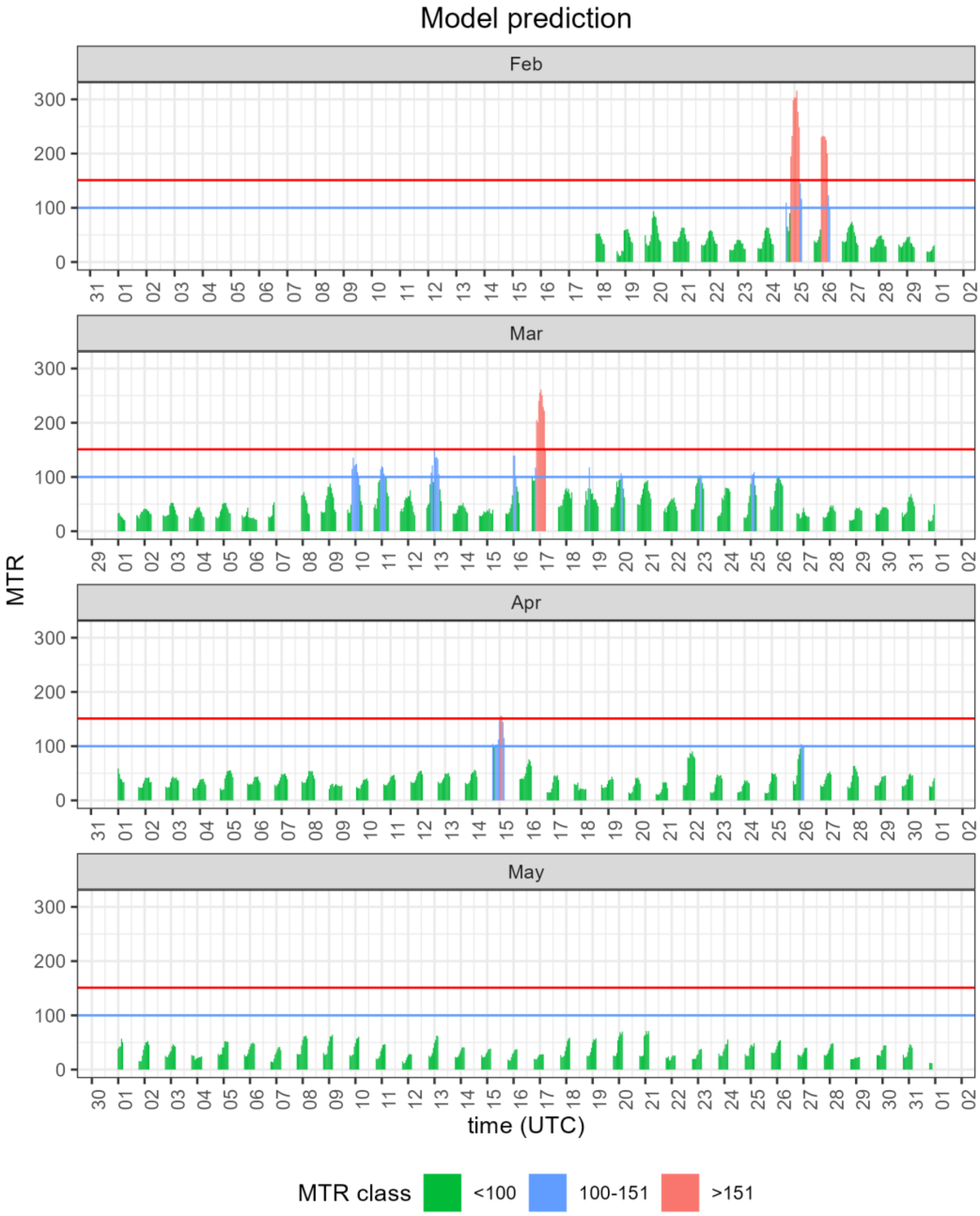

Figure 3.2 *Mean traffic rates (MTR; birds/km/h) predicted by the model for nocturnal hours (between sunset and sunrise) for Luchterduinen in the spring of 2024. Traffic rates are classified by MTR value: low rates <100 (green), medium rates 100-151 (blue) and high rates exceeding the trigger value of 151 (red).*

Table 3.3 *Peak migration nights predicted by the model, sorted by maximum mean traffic rate (MTR). All columns are based on the hours where the model is exceeding the trigger value of 151 birds/km/h.*

Night	start	end	duration (hour)	max MTR	sum MTR	mean MTR
24/25 Feb	21:00	05:00	8	316	2,173	272
16/17 Mar	21:00	06:00	9	261	2,017	224
25/26 Feb	23:00	05:00	6	233	1,351	225
14/15 Apr	01:00	03:00	2	156	311	155

3.3 Expert team predictions

During the spring of 2024, the expert team predicted each day whether a migration peak would occur, for the period 17 February – 31 May, specified for the morning and evening of a night. Their prediction was a simple yes or no, indicating if they would expect a peak migration event. *Six nights with peak migration were predicted by the expert team*, most of them in March. On one night (17/18 March) two migration peaks were predicted for the same night: one in the evening and one in the morning (Table 3.4).

Table 3.4 *Expert team predictions of peak moments for spring. The expert team made predictions for two parts of the night: evening is the period from sunset to 00:00, and morning is the part from 00:00 to sunrise.*

Night	nightpart
10/11 Mar	evening
15/16 Mar	evening
16/17 Mar	evening
17/18 Mar	evening
17/18 Mar	morning
18/19 Mar	evening
19/20 Mar	evening

3.4 Comparing predictions and radar measurements

3.4.1 Predictions and measurements over time

In this chapter we compare the radar measurements, the model predictions and the expert predictions for the spring season of 2024. Figure 3.3 depicts both radar measurements and the model predictions, next to the expert team predictions. In contrast to the two previous validations (Kraal *et al.* 2023, Middelveld *et al.* 2024), the difference in maximum MTR between radar and model in the spring of 2024 is small. This is partly due to the absence of migration peaks (i.e. >500 birds/km/h) detected by the horizontal radar in contrast to earlier migration seasons. T￼maximum peak of the radar measurements reaches up to 386 birds/km/h, where the maximum peak of the model predictions amounted to 316 birds/km/h. The overall lower MTR predictions by the model were already known and have been reported before (Kraal *et al.* 2023, Middelveld *et al.* 2024) and are confirmed here again.

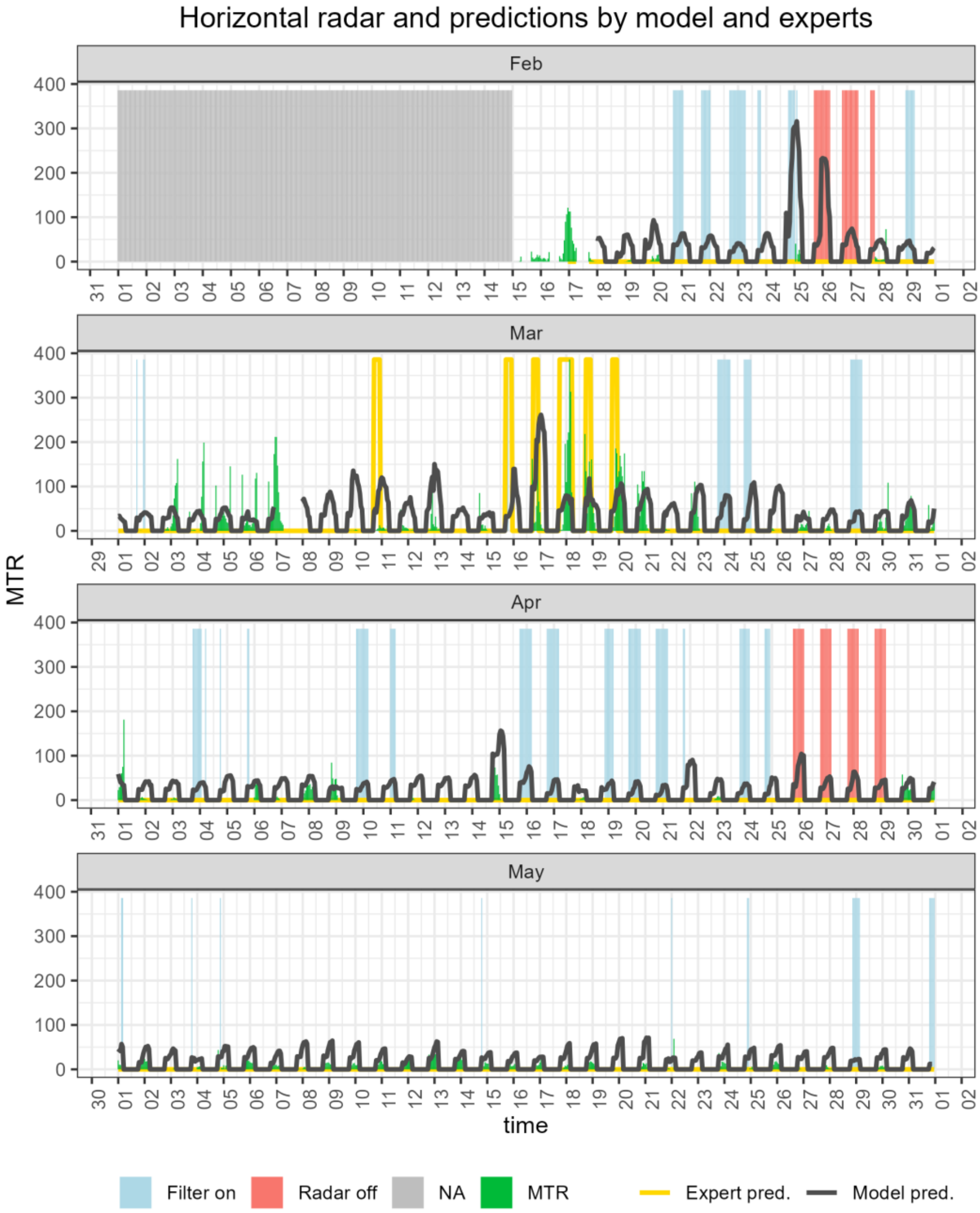

Figure 3.3 *Results of horizontal radar measurements in Luchterduinen (green), predictions by the model (black) and by the expert team (yellow) for the period of 15 February – 31 May 2024. Blue bars indicate hours excluded from the analysis due to high radar filtering activities, while red bars indicate hours during which the radar was tuned off. The study period starts at 15 February, i.e. the first half of that month is not included in the analyses.*

Table 3.5 summarizes the outcome of the comparison of the radar measurements and the predictions by the model and the expert team. Only nights are included when either of the sources highlighted a peak migration moment. The nights in the table are ordered according to the measurements of the horizontal radar.

All in all, ten nights occurred in the spring of 2024 when either the bird migration forecast model, or the expert team highlighted peak bird migration. Of these nights, seven occurred in March, two in February and one in April. However, none of the measurements by the **horizontal radar** qualified as peak migration nights according to the threshold value of MTR >500 bidsbirds/km/h. For the night with the highest MTR recorded by the radar (MTR 386 bidsbirds/km/h at 17/18 March), also the expert team predicted peak migration, but the model did not.

The **expert team** predicted migration peaks for six nights. One of these was the night with the highest MTR measured by the radar (17/18 March). Another one matched the model predictions (16/17 March), while one matched a model prediction that was within 25% of the trigger value of 151 MTR (15/16 March). The remaining three predictions by the expert team did not match either the radar measurements or the model predictions.

For the four peak migration nights predicted by the **bird migration forecast model**, the horizontal radar measurements could not reveal intense migration, but three of these nights were also predicted by the expert team. On the nights that were predicted by the model, the horizontal radar produced MTRs that were either low or practically zero (Table 3.5). The possible reasons for the mismatches between the radar measurements and the model predictions are discussed in Chapter 0.

Table 3.5 *Nights of spring 2024 when either the horizontal radar, the bird migration forecast model, or the expert team highlighted peak bird migration. For the radar, none of the MTRs exceeded the threshold value of 500 birds/km/h. Peaks predicted by the model (MTR >151 birds/km/h) or by the expert team are coloured red. Traffic rates that were close (within 25%) to the threshold- or trigger value are marked orange. Yellow indicates that horizontal radar data was at least partly not available.*

		Maximum MTR		Expert prediction		Rank	
Night	Peak based on	Hor. radar	Model	Evening	Morning	Hor. radar	Model
17/18 Mar	(radar) + experts	386	80	1	1	1	20
18/19 Mar	experts	218	118	1	0	2	9
19/20 Mar	experts	186	107	1	0	5	11
16/17 Mar	model + experts	162	261	1	0	7	2
12/13 Mar	(model)	114	150	0	0	13	5
14/15 Apr	model	73	156	0	0	19	4
24/25 Feb	model	51	316	0	0	25	1
10/11 Mar	experts	13	120	1	0	59	8
15/16 Mar	(model) + experts	0	139	1	0	93	6
25/26 Feb	model	NA	233	0	0	98	3

3.4.2 Comparison of cumulative MTRs

By comparing the cumulative MTRs (MTRs sequentially added up in the course of the season), we can get an impression of how many birds have passed the windfarm at a certain moment in time. Figure 3.4 shows the cumulative MTRs over the spring of 2024. For this figure only night hours were used where the radar was functional and where the model produced predictions (i.e. 7 March lacked a prediction due to the lack of weather data). This means that the figure should be interpreted with caution as we have no information on the level of nocturnal bird migration during the moments that the radar was either turned off or was filtering heavily. Therefore, the total number of approximately 16,000 birds depicted on Figure 3.4 as measured by the horizontal radar at a 1 km segment should be treated as a minimum for the lower 300 metres. For the same period and height, the total number of birds predicted by the model to pass by amounted to approximately 43,000 individuals. The difference can be partially explained by the radar's filtering activity, which was at times too strong to detect birds, resulting in very low MTRs. Contrastingly however, the model is known to produce lower MTR predictions than the radar measurements for discrete hours (Kraal *et al.* 2023, Middelveld *et al.* 2024). Therefore, it cannot be excluded that the difference is also caused by bird migration occurring with distinct peaks and hardly any movements in between, just as measured by the radar, while the model nearly always predicts some movements, but with much less distinctive peaks, leading to overall more birds predicted to pass by than measured by the radar. Despite these differences, the midpoint, the point where 50% of the birds have passed, lies for both methods in the 3rd week of March.

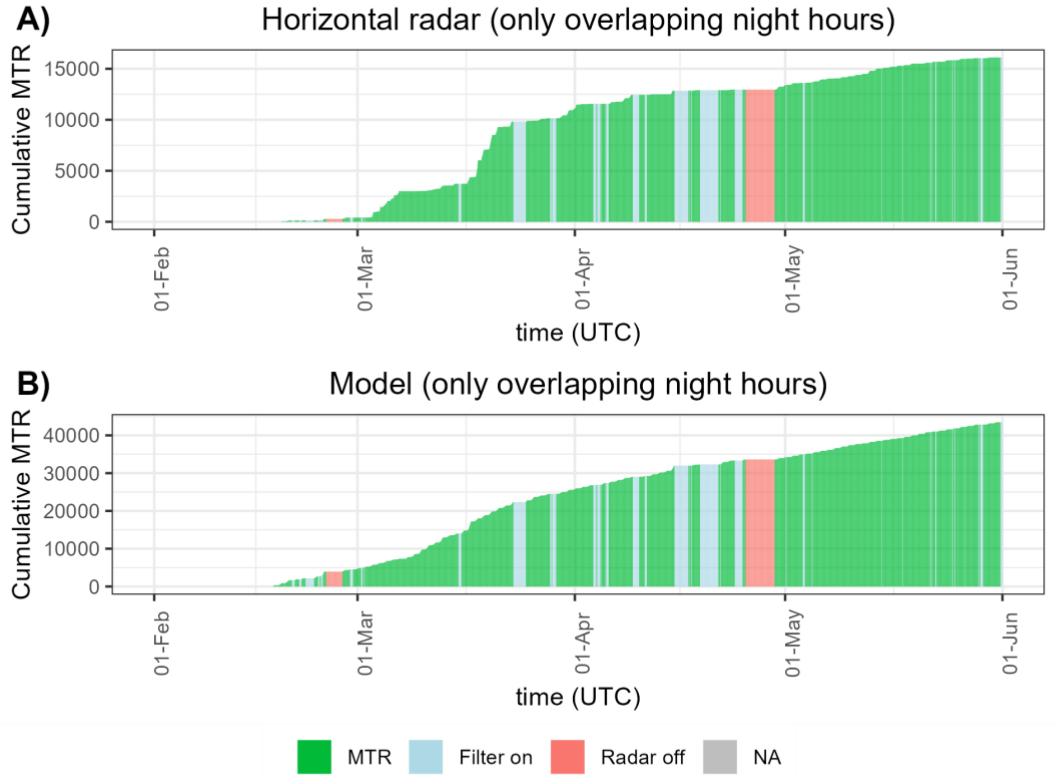

Figure 3.4 *Cumulative MTRs (birds/km/h) over the spring for 2024 for A) the horizontal radar and B) the model. Only night hours were included where both radar and model were producing valid results.*

3.4.3 Curtailment moments of spring 2024

There has been one curtailment moment in spring 2024, based on model and expert team predictions. Table 3.6 provides details of the curtailment moment. The horizontal radar did not detect peak traffic rates for this specific night, although the following night the radar did measure the highest MTR of the season. The highest MTR measured by the horizontal radar during the three hours of curtailment was 161 birds/km/h. The filtering activity by the horizontal radar was well below the threshold level, and hence there are no indications that the radar missed a migration peak due to high waves or rain causing intense clutter formation. This curtailment could not be confirmed by the vertical radar either, as it was turned off in this period (see 4.1.2). Possible reasons for the mismatch between this predicted migration peak and the radar measurements are discussed in Chapter 0.

Table 3.6 *Curtailment moment of spring 2024.*

time start (local time)	time end (local time)	duration (hr)	Summed MTR by hor. radar	Summed MTR by model
2024-03-16 21:00	2023-03-17 00:00:00	3	238	523

4 Exploring causes of mismatches

There are two types of errors the predictive model could make. Firstly, a false positive prediction indicates an event where the model predicts peak migration, while there was in reality no peak. The second type of error is when there was a real peak migration but was not predicted by the model, which is called a false negative prediction.

In this study, the measurements of the horizontal radar were used to validate the predictions of the model. Although the radar measurements are the best available objective data on migration peaks, note that there are some points of consideration regarding the classification of **false positives**:

- the absence of a peak on the horizontal radar on nights with a peak by the model could be caused by malfunctioning of the radar;
- high filtering activities can lead to a reduced number of detected tracks and thus erroneously low MTR values. If this happens on a night where the model predicted a high number of birds passing through the wind farm, this model peak may erroneously be classified as a false positive.

Other reasons why a model peak is not detected by the horizontal radar could be that the migrating birds avoided the area of the Luchterduinen wind farm, either in the horizontal plane (taking another route) or the vertical plane (flying high over the wind farm). In order to explore this latter possibility, we use next to the horizontal radar data also the data of the vertical radar in Luchterduinen. Moreover, we also investigated measurements of the horizontal and vertical radar in another wind farm, namely Borssele.

In case of a **false negative** prediction, it seems more straightforward that based on radar measurements a migration peak did actually take place but was not predicted by the model. During the season of spring 2024, no peak migration was measured by the horizontal radar in Luchterduinen according to the threshold value of 500 birds/km/h, and hence no official false negative prediction could take place either. Nevertheless, we carried out an in-depth analysis of the vertical radars in Borssele and Luchterduinen and the horizontal radar in Borssele to ensure that there were indeed no false negative predictions.

4.1 Apparent mismatches between the bird migration prediction model and the radar measurements

4.1.1 Mismatches due to malfunctioning or filtering of the horizontal radar in Luchterduinen

During the spring of 2024, the model predicted an MTR above the trigger value of 151 birds/km/h for four nights. On all four nights, there was no peak measured by the horizontal radar in Luchterduinen, which suggests that all four peak predictions were false positives.

However, as mentioned before, the lack of a peak in the horizontal radar measurements does not necessarily mean that the model falsely predicted a migration peak. Considering the four moments of peak migration predicted by the model in the spring season of 2024, the dataset of the horizontal radar was on two nights not complete:

- On the night of the 24/25 February, a part of the data was filtered out as being unreliable (see Figure 3.3);
- the horizontal radar was for almost the whole night of 25/26 February not operational (see Figure 3.3).

Therefore, these two migration peak nights predicted by the model could not be validated by the horizontal radar simply due to the lack of radar data. During the other two peak migration nights predicted by the model, the horizontal radar was operational, and the filtering activities did not seem to be significant, and hence based on this radar the possibility of false positive predictions cannot be ruled out.

4.1.2 Examining mismatches with the vertical radar in Luchterduinen

As discussed in the previous paragraphs, the horizontal radar cannot provide a complete representation of the spring migration season of 2024, due to (essential) filtering activities. Although this is also the case for the vertical radar, the filtering is different between the horizontal and vertical radar. The horizontal and vertical radar differ in their way of scanning the environment (see Chapter 2). Because of this, both radars vary in their filtering activities to prevent clutter from entering the data as a bird track. For instance, as the beam of the horizontal radar suffers in its full range from waves, this radar generally needs more seaclutter filtering than the vertical radar, of which the beam only encounters waves at the lowest altitudes. Therefore, periods with high waves in the data of the vertical radar can be simply dealt with by removing the lowest few meters from the analyses. Due to the different filtering activities, the periods of missing data do not necessarily overlap between the two radars, and the vertical radar might aid in verifying the potential false positive model predictions. Moreover, migration peaks taking place at higher altitudes may be missed by the horizontal radar due to its limited height coverage (~300 m at the distance that tracks are used for the MTR calculation) but may be picked up by the vertically looking radar. On top of this, the methods used to calculate migration traffic rates differ between the two radars (see again Chapter 2). This leads to completely different MTR values, which should only be compared with care (Middelveld *et al*., 2024).

Nonetheless, the vertical radar only gathered data during a small period of the spring season of 2024. Due to safety reasons, all offshore vertical radars of Rijkswaterstaat were shut down in March and were not operational any more for the rest of season. Consequently, *on all nights during spring that were potentially predicted as peak migration night by the bird migration prediction model*, *the vertical radar was turned off* (Figure 4.1).

In the four weeks at the beginning of the season during which the vertical radar did collect data, it measured one peak including rotor height (between 3 and 300 meter above sea level), namely at the night of **12/13 March,** just before the radar was switched off (Figure 4.1). This peak lasted at least two hours with a peak MTR of 3,055 birds/km/h. Interestingly, the two peak hours during this night were separated by one hour that was excluded from analyses during filtering steps because there were signs of rain. Those signs of rain were confirmed after rewatching the radar images of that hour, which showed a rain shower of around five minutes long. This shows that slight rains on their route do not necessarily stop migrating birds to continue their journey (Erni *et al.* 2002).

The prediction of the bird migration model of 150 MTR for this night just missed the trigger value of 151 MTR. On the other hand, the horizontal radar in Luchterduinen did clearly not detect a peak, its maximum MTR was 113 birds/km/h. Filtering activity of the horizontal radar was not significant. This may indicate that the horizontal radar completely missed a migration peak, which was detected by the vertical radar.

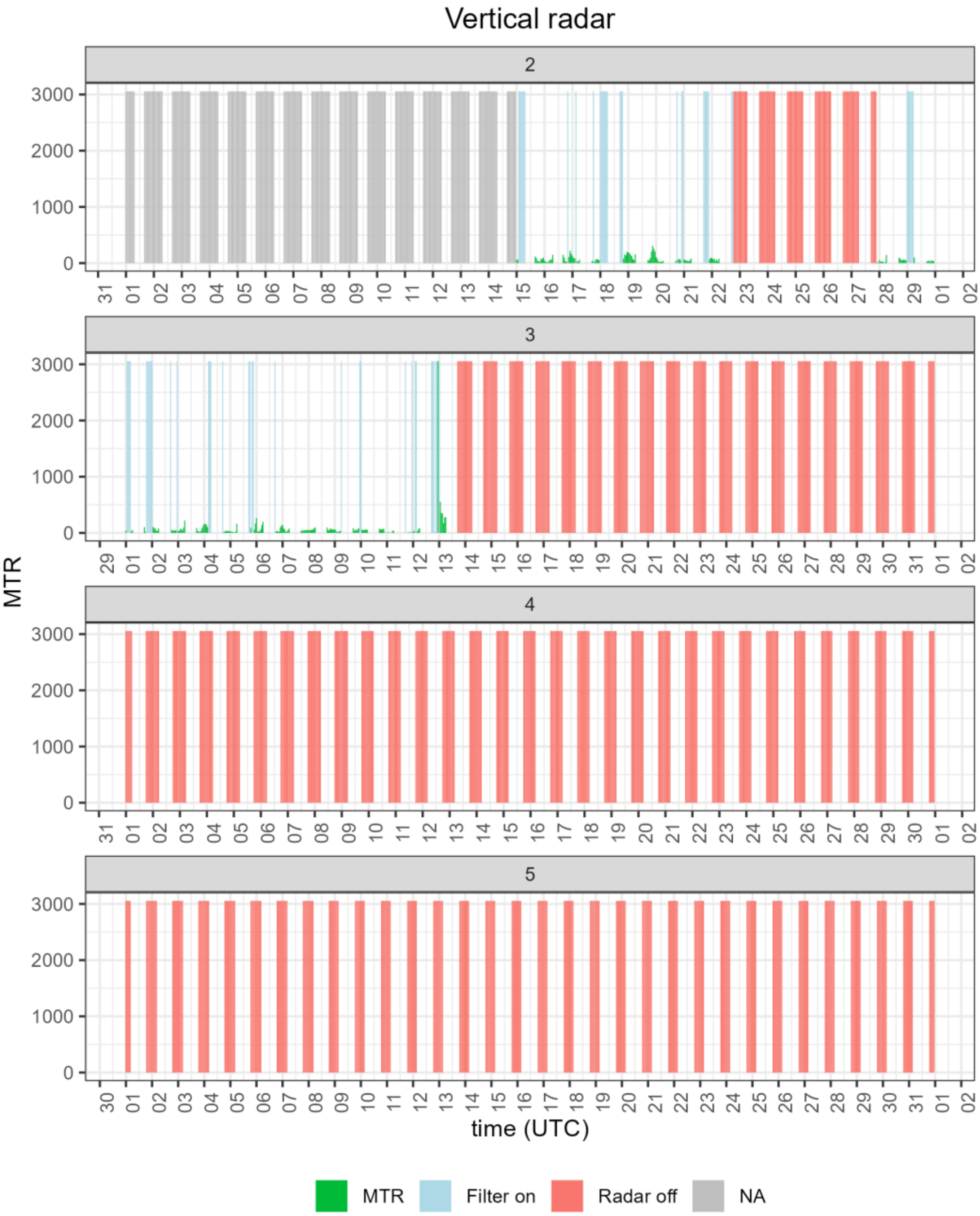

Figure 4.1 *Temporal pattern of migration intensity (MTR) as measured by the Luchterduinen vertical radar for the spring season of 2024. Measurements are considered from the 15th of February.*

4.1.3 Examining mismatches with the horizontal radar in Borssele

The same conclusion as for the horizontal radar in Luchterduinen also applies for the horizontal radar in Borssele: there was no hour with an MTR above the official threshold of 500 birds/km/h. The hour that was the closest to this threshold was during the night of 2/3 March just after midnight (UTC), which had an MTR of 459 birds/km/h. This means that the four modelled peak migration nights can also not be confirmed by the horizontal radar in the Borssele wind farm. Moreover, during none of these four nights did the horizontal radar in Borssele detect MTRs above 100 birds/km/h. However, for this radar no data were available for the two peak migration nights of 24/25 and 25/26 February. In addition, the data of the night of 16/17 March were almost completely excluded due to extensive filtering.

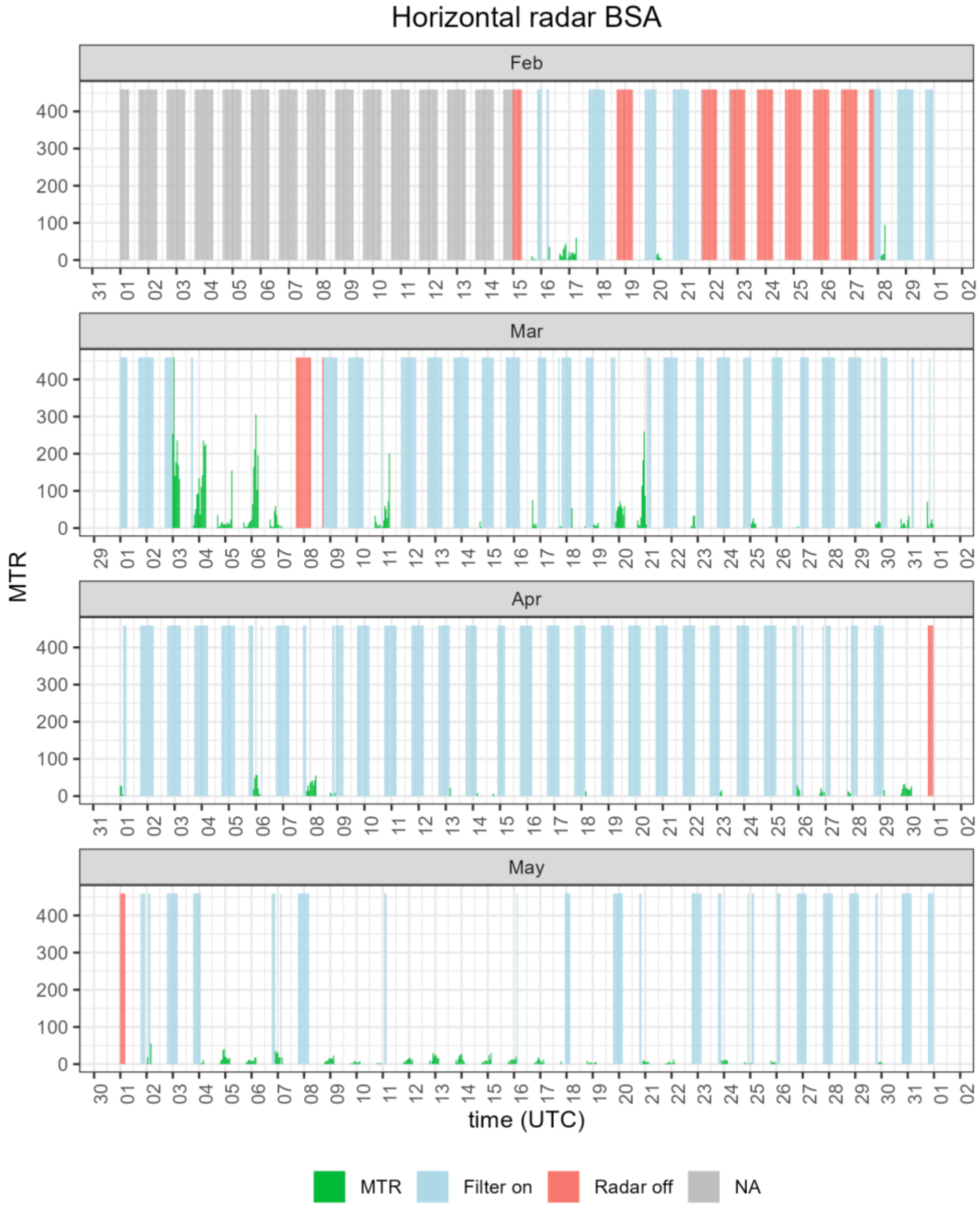

Figure 4.2 *Temporal pattern of mean traffic rate (birds/km/h) as measured by the horizontal radar of offshore windpark Borssele (BSA) for spring 2024. Measurements are considered from the 15th of February.*

4.1.4 Examining mismatches with the vertical radar in Borssele

Just as the vertical radar in Luchterduinen, the vertical radar in Borssele was shut down after 13 March, although it has been turned on for a few days at the end of March.

Therefore, the two migration peak moments of 16/17 March and 14/15 April predicted by the model could not be validated using this radar. Unfortunately, this radar was also not operational on 24/25 and 25/26 February. This means that none of the four peak moments predicted by the model could be validated with the vertical radar in Borssele.

Interestingly, this radar showed three peak hours that were above 500 birds/km/h, distributed over two nights. First, the large numbers of migrating birds that were detected by the vertical radar in Luchterduinen on *12/13 March*, also seemed to cross the Borssele wind farm. The migration peak in Borssele seemed to occur slightly earlier than in Luchterduinen. In the former location, the highest number of birds (775 birds/km/h) was detected at 22:00 (UTC), while in Luchterduinen this was one hour later. However, due to heavy wave filtering the rest of the hours of the night were filtered out from the analysis for the Borssele radar. In conclusion, data from both radars seem to confirm that there was a peak of migrating birds on 12/13 March over the North Sea between 3 and 300 meter above sea level that was not detected by either of the horizontal radars. The model predicted an MTR value of 150 MTR that nearly matched the trigger value of 151 MTR.

The other peak migration hour indicated by the vertical radar in Borssele occurred on 1 March. Neither the model nor the expert team predicted peak migration for this night and none of the other radars detected a peak.

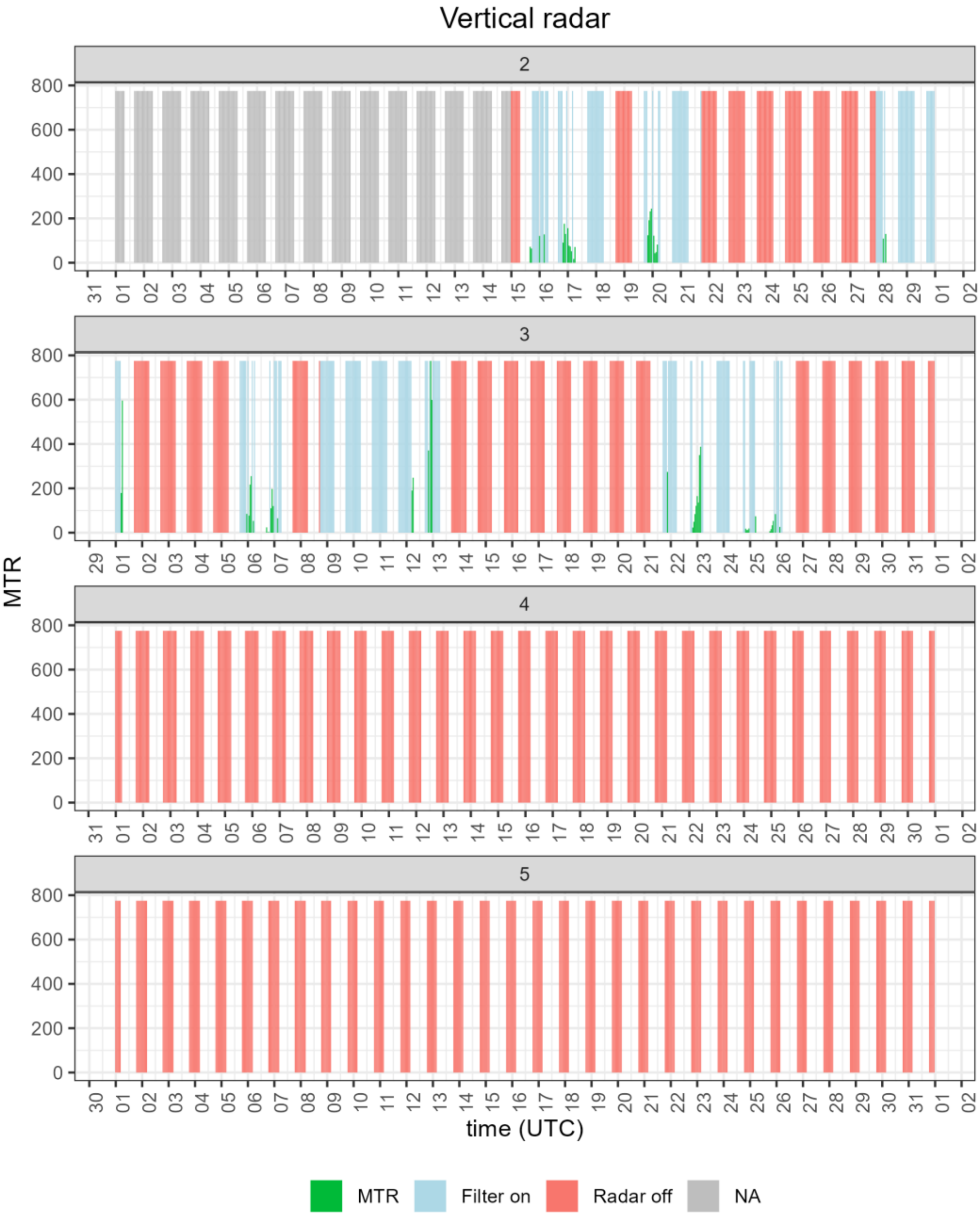

Figure 4.3 *Temporal pattern of mean traffic rate (birds/km/h) as measured by the vertical radar in offshore wind farm Borssele (BSA) in spring 2024. Measurements are considered from the 15th of February.*

4.1.5 Summary of mismatches after examining other radars

The vertical radar in Luchterduinen and both radars in Borssele could not be used to validate the modelled peak migration nights of 24/25 February and 25/26 February because all radars were at least partly turned off during these nights. Both vertical radars were shut down after 13 March and were therefore also not useful for validating the other two peak moments of 16/17 March and 14/15 April predicted by the model. The horizontal radar in

Borssele was functional however, and did not detect peaks during these nights either. Therefore, even after consulting the other three radars, we still cannot exclude that all four modelled peak migration nights were false positive predictions. More specifically, also during the only curtailment in the spring season of 2024, namely in the evening 16 March, the vertical radars were shut down and the horizontal radar of Borssele was filtering too actively to have realistic MTR calculations. Therefore, the curtailment moment cannot be supported by any of the radar measurements.

Two extra peak migration nights were shown in the measurements of the vertical radars of Borssele and Luchterduinen, of which 12/13 March was the most obvious with a peak migration indicated by both radars. The Borssele radar showed an additional peak migration hour on 1 March. Interestingly, the model did predict elevated MTRs on 12/13 March that were nearly matching the trigger value. The expert team did not predict peak migration for this night.

Table 4.1 Overview of potential false positive and false negative predictions by the bird migration prediction model in spring 2024 based on radar measurements.

Night	False positive or negative	Based on
24/25 Feb	Not applicable	Heavy filtering of horizontal radar Luchterduinen
25/26 Feb	Not applicable	All radars off
16/17 Mar	False positive	Horizontal radar Luchterduinen
14/15 Apr	False positive	Horizontal radars Luchterduinen and Borssele
29 Feb/1 Mar	False negative	Vertical radar Borssele
12/13 Mar	False negative	Vertical radars Luchterduinen and Borssele
17/18 Mar	False negative	Horizontal radar Luchterduinen

4.1.6 Comparing filtering of horizontal radars between Borssele and Luchterduinen

For the horizontal radar of Borssele, a different method of excluding hours with too high radar filtering activities had to be used. In contrast to the method of the horizontal radar in Luchterduinen, the selection procedure of the horizontal radar in Borssele was not based on the so-called variant mask filter, but on the land mask filter. This was done because both radars operate in a different environment (e.g. different distances to nearby turbines, different height). Hence, the threshold for the allowable filtering activities of the horizontal radar in Borssele needed to be reconsidered. Following the method presented in van Erp *et al.* (2023), the landmask filter was used. This method resulted in many hours where the data were considered unreliable due to high filtering activity by the radar (61% of nightly hours).

Many of these hours did overlap with hours that were filtered out of the horizontal radar data of Luchterduinen (Figure 4.4). In total 165 hours occurred where both radars were filtering too strong, 365 hours occurred where both radars where functioning well. However, there were also 520 hours where the Borssele was filtering too strong, while the Luchterduinen radar was producing valid results (according to the classification), and only 4 hours occurred where the Luchterduinen radar was not producing valid results, while the Borssele radar did. Even though most filtering hours of the Luchterduinen radar overlapped with the Borssele radar, it is striking that so many hours were excluded from the Borssele dataset. The high number of excluded hours might be related to the new method of filtering, but more likely it is caused by the position of the radar higher on a TenneT platform surrounded by wind turbines, due to which this radar has to deal with more false reflections.

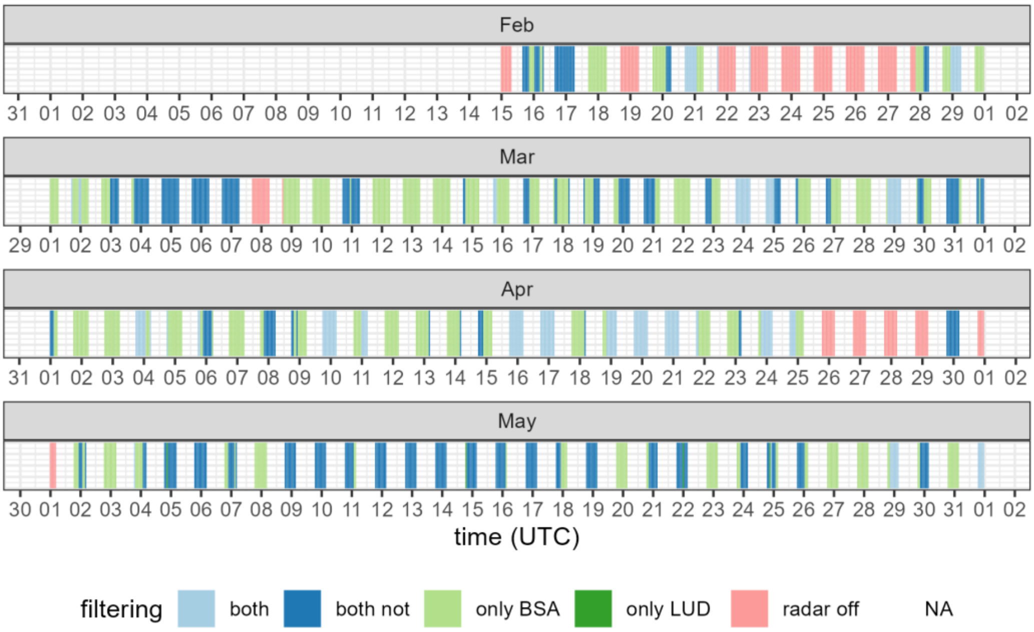

Figure 4.4 *Filtering activity of the horizontal radars of Borssele (BSA) and Luchterduinen (LUD). Dark blue indicates that both radars are filtering too strong (also in previous figures designated as 'Filter on'). Light blue indicates that both radars were operating well. Light green indicates that only BSA was filtering too strong, while LUD was functioning properly. The moments where LUD was filtering too strong while BSA was operating well is indicated in dark green.*

Comparing the variant mask (v mask) filtering of both radars shows a fairly linear relationship (Figure 4.5). The variant mask values of the Borssele radar range between 0 and 0.25, while the variant mask values of the Luchterduinen radar range between 0 and 0.6. Apparently, the radars differ in determining the variant mask values. If the filtering method that was used for Luchterduinen (variant mask>0.3), had been applied to the Borssele data no hours would have been excluded. By colouring the variant mask values with the current filtering method used for Borssele (using the so-called land mask filter), we see that a variant mask value of 0.07 would give about the same results. This underlines the importance of redefining the filtering threshold for each radar.

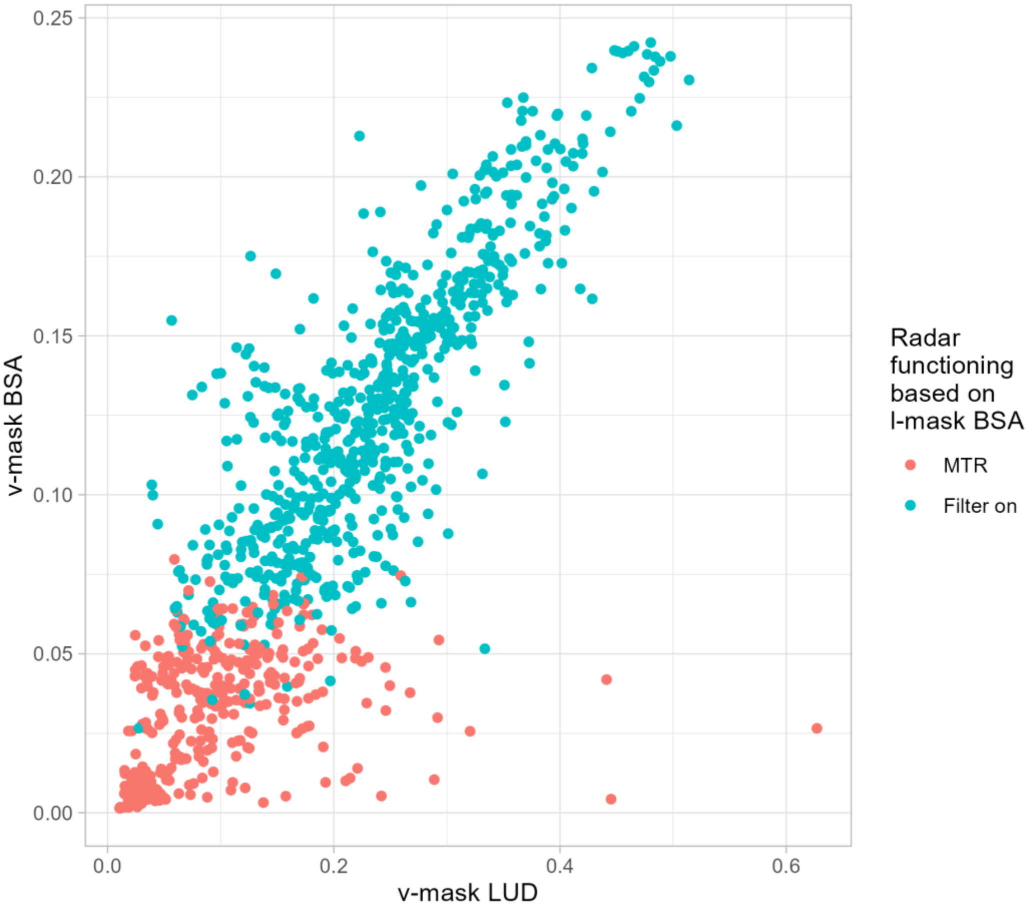

Figure 4.5 Comparing the variant mask filtering activity for Luchterduinen (LUD) and Borssele (BSA).

4.2 Effect of weather circumstances

An important data source fuelling the predictive model are weather conditions in wind farm Luchterduinen. The wind direction and speed in the wind farm influence the model predictions through the parameter of wind assistance. This parameter indicates how supporting the wind is for migrating birds. Precipitation and temperature also influence the model prediction as these parameters indicate suitable circumstances for migration. Finally, all these weather conditions are considered in multiple accumulation parameters that describes the number of birds that do not depart during unfavourable weather conditions and wait until conditions improve.

The weather conditions that are considered by the model are from the ECMWF predictions of 48 hours to 71 hours in advance. This means that the accuracy of the weather predictions themselves could also play a role in the accuracy of the bird migration prediction model. Therefore, investigating those weather conditions and predictions during false positive or false negative prediction events could give more insight in the causes of erroneous predictions, and may help to further develop the predictive model. In this paragraph, the weather conditions and predictions are presented for the night with the highest migration intensities measured by the bird radars in Luchterduinen, as well as for the four migration peaks predicted by the model.

4.2.1 Weather conditions before and during peak migration nights as measured in Luchterduinen

Just before the only peak migration night classified by the vertical radar, which was the night of **12/13 March**, there was a shift from days of eastern and northern winds towards southern to western winds, both in Luchterduinen and in the departure locations in the UK (Figure 4.6, for departure locations see Figure 2.3). The wind was quite calm and stayed below 10 m/s in both areas. In the UK, there was a sudden rise in temperature on the day just before that night (Figure 4.7). Moreover, just before this night, a large amount of rain fell in both departure locations, as well as in Luchterduinen (Figure 4.8). The increase in temperature, change in wind direction to south/west and passage of a rain front may have induced the take-off of large numbers of birds to migrate over the North Sea. Conceivably, this pattern was recognized by the model, which predicted a maximum MTR of 150 birds/km/h, just below the trigger value.

For the night of **17/18 March** (the highest migration intensity measured by the horizontal radar in Luchterduinen), winds were again southwestern in the UK and in Luchterduinen, and northwestern in departure locations of France. In contrast to the night of 12/13 March, there was no increase in temperature before this night. Also, in contrast to that earlier peak migration night, there were no unfavourable weather conditions in the days preceding this night. One explanation for an accumulation of birds at their departure locations before 17/18 March (leading to elevated migration intensity), could be the rain measured on the night of 16/17 March, especially in the UK.

In conclusion, on the peak migration night of 12/13, the change in wind direction from headwind to tailwind conditions and a sudden rise in temperature preceding this night could have functioned as a go-sign for the migration of a large number of birds. For the night of 17/18 March, the only potential indication of conditions causing accumulation of migrating birds (and a subsequent elevated level of migration intensity), was rain at the departure locations on the night before. Both moments occurred at the peak of the migration season, with seemingly a lot of birds on the way of their migration being held back at departure locations, waiting for more suitable weather conditions.

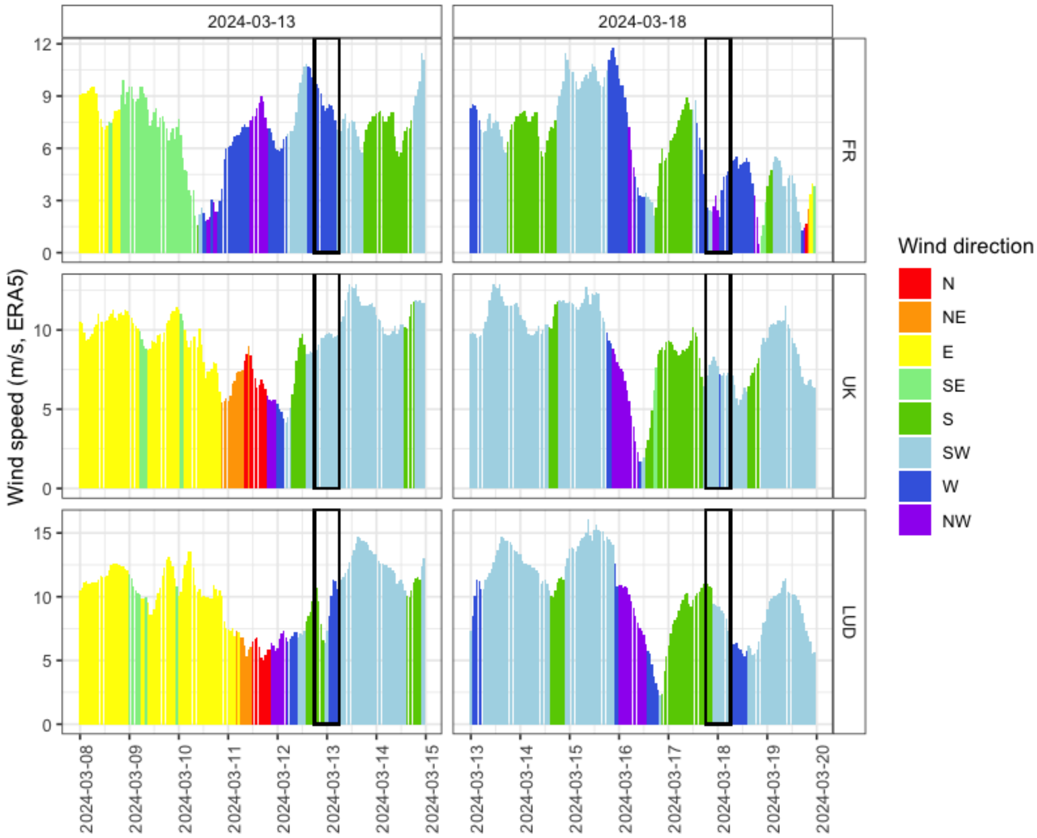

Figure 4.6 *Temporal pattern of wind speed and direction at 100 meters above sea level in departure locations and in wind farm Luchterduinen according to the ERA5 model before and during nights of intense migration measured by the bird radars in Luchterduinen. Nights with intense migration are marked with black rectangles.*

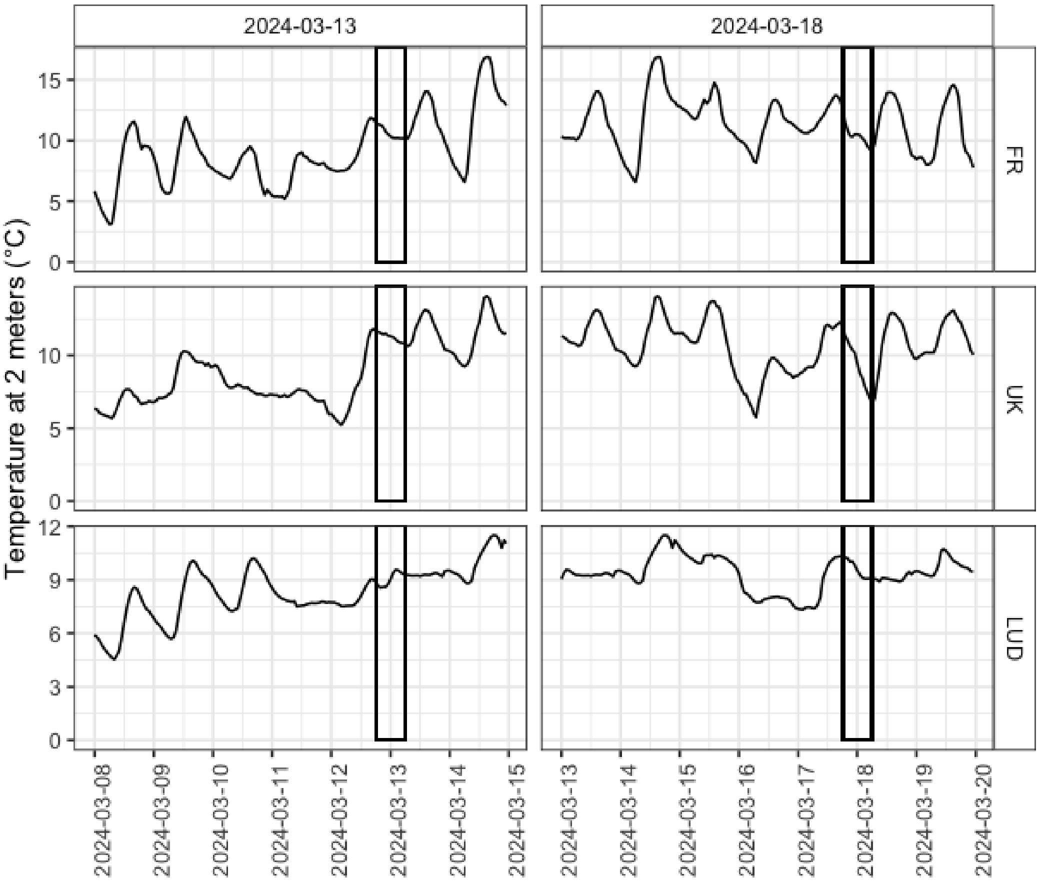

Figure 4.7 *Temporal pattern of temperature in departure locations and in wind farm Luchterduinen before and during nights of intense migration measured by the bird radars in Luchterduinen. Nights with intense migration are marked with black rectangles. Temperature is taken from the ERA5 model at 2 meters above sea level (NB this is different than the 100 meters above sea level used for the model).*

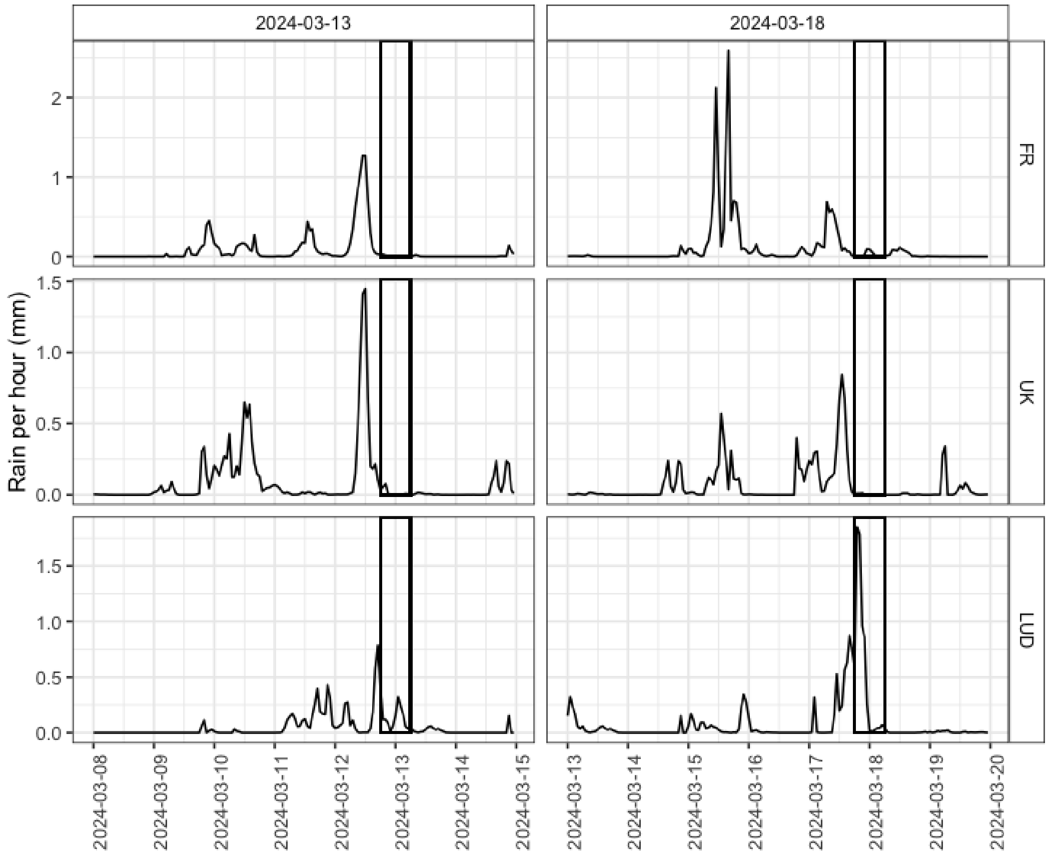

Figure 4.8 Temporal pattern of the rainfall in departure locations and in Luchterduinen before and during peak migration nights. Total precipitation is taken from the ERA5 model. Peak migration nights are marked with a black rectangle.

4.2.2 Weather conditions during modelled peak migration nights in Luchterduinen

There was a large diversity in wind conditions in Luchterduinen and at departure locations during peak migration moments predicted by the model (Figure 4.9). The most remarkable difference was between two successive predicted peak migration nights at the end of February, namely 24/25 and 25/26 February. During the first night (**24/25 February**), the wind came from the south with a low speed. These wind conditions could be favourable for a migration peak, although the predicted temperature was quite low (Figure 4.10). Moreover, there was a lot of rainfall in Luchterduinen during this night, as well as the nights before (Figure 4.11). However, it was dry in the UK, which could have been interpreted by the model as a favourable departure condition. *The model prediction was therefore likely triggered by a drop in wind speed and the absence of rain on the preceding the night*.

In contrast, on the following night (**25/26 February**), the wind conditions did not seem to be favourable for migration. Mainly the hours after midnight were forecasted by the ECMWF to have high wind speeds from the northeast and east in the UK and in Luchterduinen. Strong northeastern and eastern winds do not favour bird migration over the North Sea during spring. As mentioned before, the model predicted also for the night before a peak in migration intensity, which means that the accumulation factor was probably also not the reason for the migration peak predicted for 25/26 February. Based on Figure 4.9 and Figure

4.10, the only change in weather conditions that could have triggered a prediction of peak migration was a drop in wind speed and change in wind direction in France and a sudden rise of the average temperature at 100 to 300 meters above sea level in Luchterduinen after days of cold weather. According to the ERA5 recalculation model of actual weather conditions, this rise in temperature did not occur at 2 meters height (Figure 4.10) and the temperature in Luchterduinen stayed between 5 to 7 degrees for days. Therefore, the model could have reacted on a wrongfully predicted temperature increase, but it is also important to note that the two modelled temperature values are from a different air layer.

Based on weather parameters, we can conclude that the weather circumstances on the night of 24/25 February, in combination with conditions on the day/night before, were favourable for the occurrence of a peak in migration intensity. Interestingly, the model also predicted peak migration intensities for the night of 25/26 February, with seemingly unfavourable wind conditions. The only change in weather conditions forecasted by the ECMWF model that could have triggered this migration prediction was a slight temperature increase at Luchterduinen and a drop in wind speed and change in wind direction in France. Unfortunately, no conclusions on the validity of this predicted peak migration could be drawn based on the bird radar measurements because none of the radars was operational.

On **16/17 March**, the model predicted a migration peak, while the horizontal radar detected increased migration traffic only a night later. The wind conditions during the night of 16/17 March seemed to be favourable for migration. Thereby, the predicted wind conditions corresponded the actual measurements, so a difference between predictions and actual wind conditions was likely not the reason for a mismatch between model predictions and radar measurements. However, slight rainfall in the UK on the night of 16/17 March, which was not predicted by the ECMWF forecast model (Figure 4.11), could have prevented birds from departing, causing a false positive model prediction. The day after (i.e. 17/18 March), the wind conditions still seemed favourable for migration, with relatively calm wind from the southwest / west and dry weather around wind farm Luchterduinen, leading to high migration intensities measured by the horizontal radar. Therefore, the birds seemed to have waited for a dry night to cross the North Sea. Nevertheless, the model could not predict this migration peak, as due to its prediction for the night of 16/17 March, the accumulation factor (*i.e.* factor to describe the potential number of migrants ready to depart for migration, depending on preceding weather conditions) was expectedly low, leading to a false negative prediction by the model.

On **14/15 April**, there were westerly winds in France and in Luchterduinen. In UK the wind direction was southwest. However, mainly the wind in UK was quite hard, with speeds between 10 and 15 m/s. In Luchterduinen the wind was quite hard for days already before this night, and then decreased during the day of 14/15 April. These wind conditions according to ERA5 also correspond to the wind conditions predicted by the ECMWF model. Based on these high expected wind speeds in Luchterduinen and in the UK, the model could have built up a high accumulation factor. Subsequently, the model seems to have predicted a migration peak for the night of 14/15 April after a drop in wind speeds in Luchterduinen. However, last year, as well as this year, none of the actually measured migration peaks in Luchterduinen have taken place in April. Therefore, based on these two years of model validations, migration phenology over the North Sea seems not to reach peak intensities in April, despite favourable weather conditions.

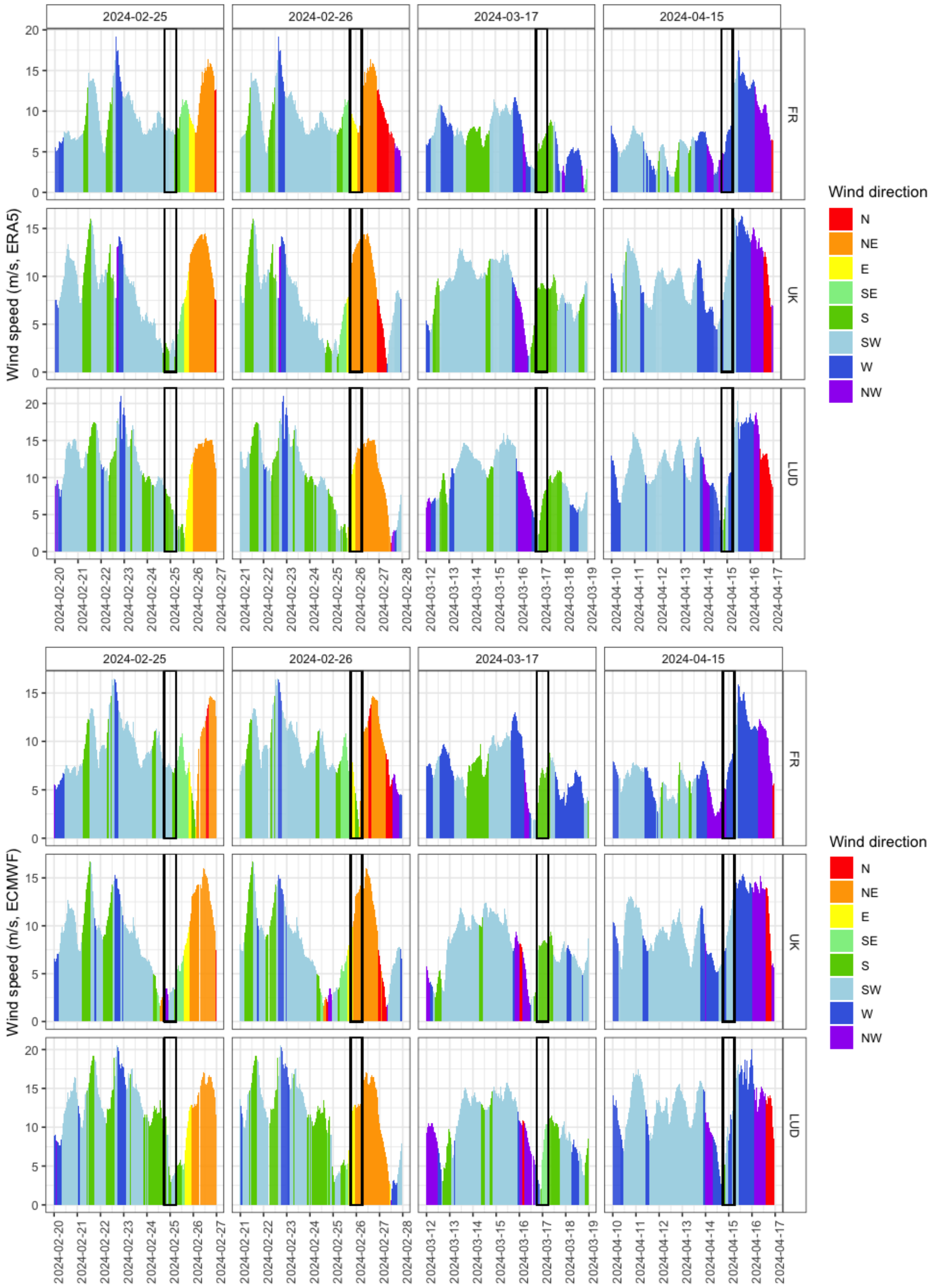

Figure 4.9 *Temporal pattern of the wind speed and direction at 100 meters above sea level at departure locations and in wind farm Luchterduinen according to the ERA5 model (top) and the predictions of the ECMWF for 48 hours in advance (bottom) before and during peak migration nights predicted by the model. Peak migration nights are marked with a black rectangle.*

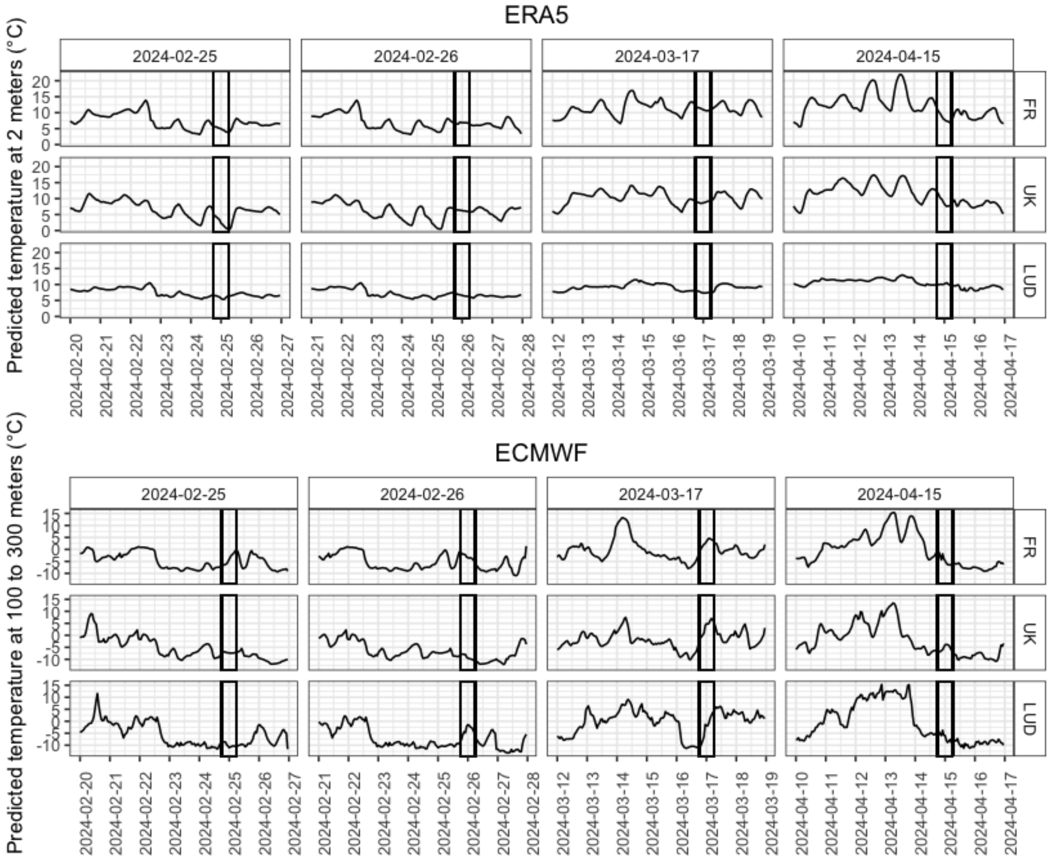

Figure 4.10 *Average air temperature (°C) at 2 meters above sea level according to* ***ERA5 (top)*** *and from 100 and 300 meters above sea level according to* ***ECMWF predictions of 48-71 in advance (bottom)*** *over time in the spring season of 2024. (N.B. both temperature data represent another air layer and should therefore not be compared, ERA5 is used as a measure of what the actual weather conditions during possible migration peaks were and ECMWF was used to see which weather predictions were used by the model).*

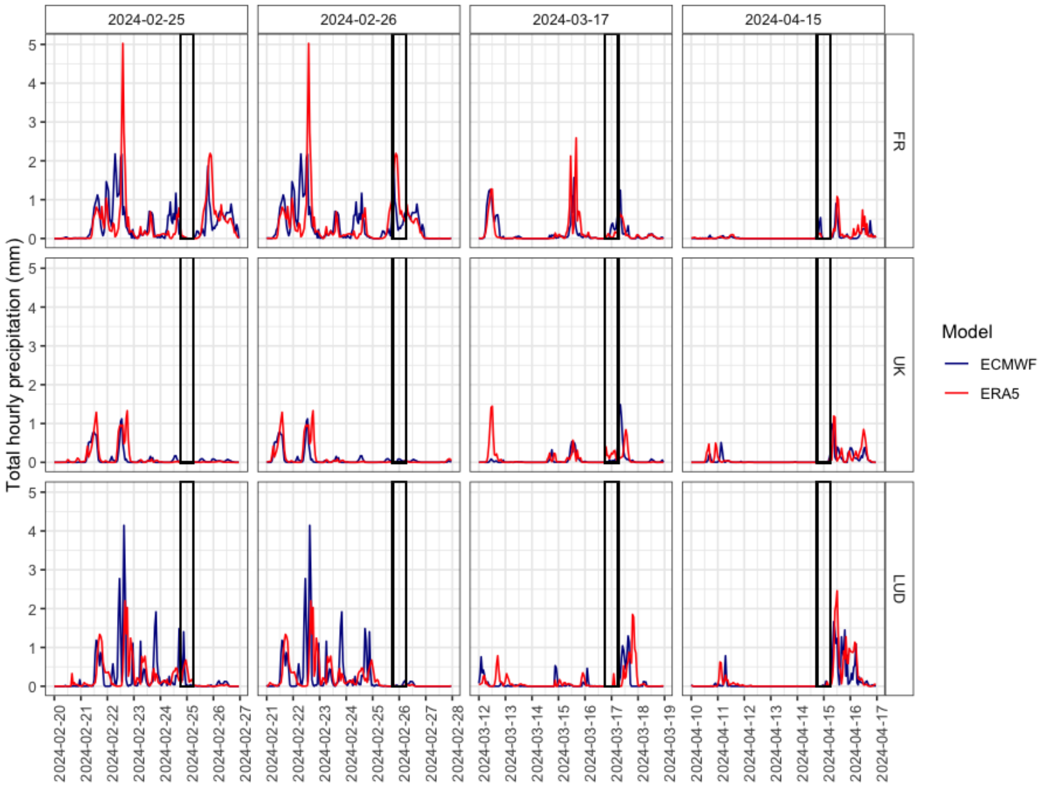

Figure 4.11 *Temporal pattern of rain fall at departure locations and in Luchterduinen according to the ECMWF forecast model (blue) and the ERA5 reanalysis model (red) before and during model peak migration nights. Peak migration nights are marked with a black rectangle.*

4.2.3 Comparison between predictions and measurements

As discussed above, a potential cause of wrong predictions by the model could be a difference between weather forecasts that are used by the model and actual weather conditions during the night. Figure 4.12 shows the comparison between predictions of the wind speed by the ECMWF 48 to 71 hours in advance and the actual wind speed measured in Luchterduinen. Generally, the predicted wind speeds are slightly higher than the measured wind speeds, but both wind speeds are very similar. On some occasions, there is a larger difference between both, but those events are rare. Figure 4.12 shows that measured wind speeds during modelled peak hours do not deviate more from forecasted wind speeds than during non-peak hours according to the model.

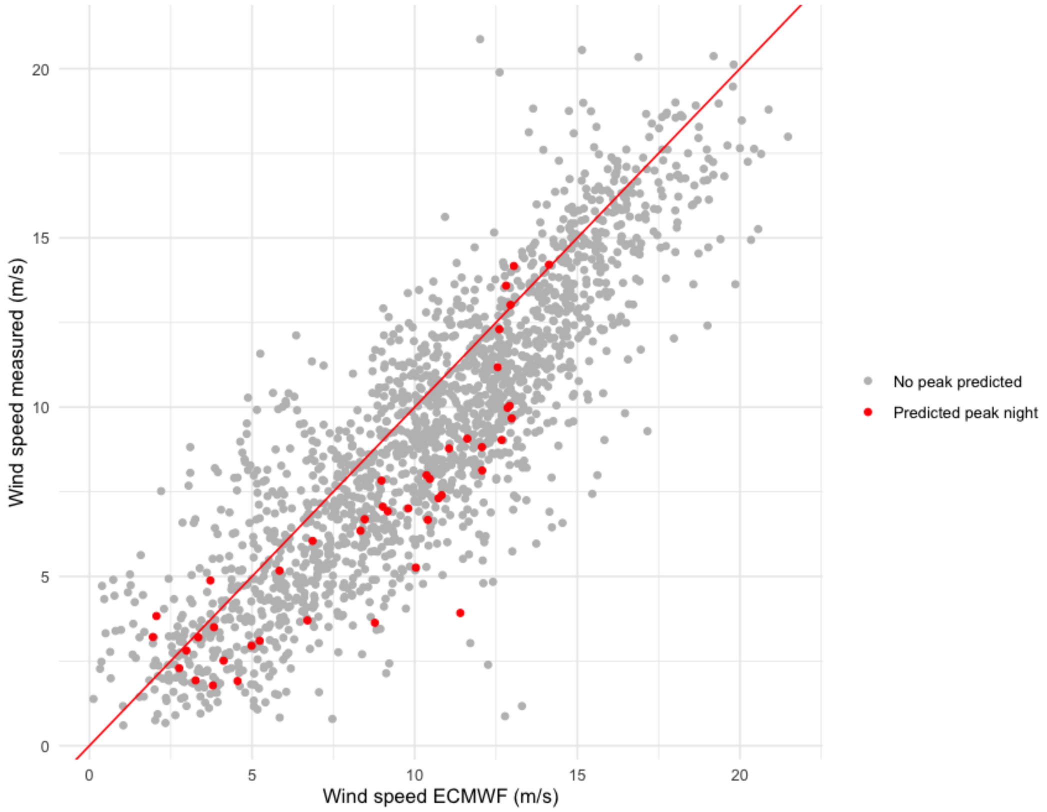

Figure 4.12 *Comparison between wind speed as predicted by the ECMWF 48 to 71 hours in advance and wind speed as measured in Luchterduinen. Red points indicate hours that belong to the nights that were predicted to be a peak by the model. Note that the wind speed as predicted by the ECMWF is at 100 meters above sea level and the wind speed in Luchterduinen is measured by wind sensors at the top of the wind turbine nacelle at approximately 80-90 meters above sea level. The red line shows the x = y line, where the two values are equal.*

Figure 4.13 shows the difference in degrees between predicted and measured wind directions in Luchterduinen. Interestingly, while the wind direction was nearly the same for most of the hours, there were some hours in which the prediction was up to 180° different from the measured wind direction. Those occasions seem extra susceptible for erroneous model predictions, as the model was then working with wrong wind predictions. The highest number of large deviations were in March, with up to seven isolated periods of time with more than 90 degrees difference. Although the differences in wind direction are sometimes quite large, the wind speed at those moments was often not high. This indicates that unjust wind predictions mostly occur with lower wind speed conditions and therefore might not substantially influence the model's predictions. However, during two of the four predicted peak nights (24/25 February and 16/17 March), the predicted wind direction diverged considerably from measured wind directions (Figure 4.13). Although the wind speeds were rather low, the *erroneous wind direction forecasts on these two nights could have led to wrong predictions by the model*.

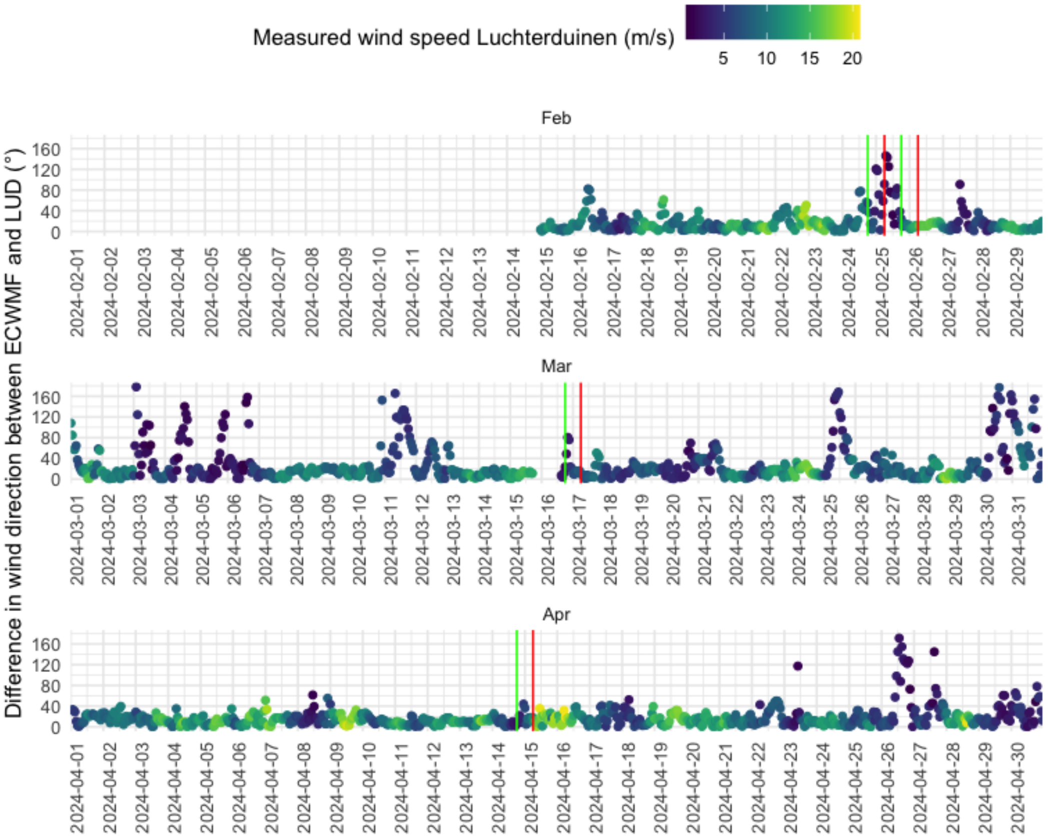

Figure 4.13 *Difference in wind direction in degrees as predicted by the ECMWF 48 to 71 hours in advance and wind speed as measured by wind sensors of the wind turbines in Luchterduinen. Peak nights predicted by the model are marked with green lines (start of the night) and red lines (end of the night). Note that the wind direction as predicted by the ECMWF is at 100 meters above sea level and the wind direction in Luchterduinen is measured by wind sensors at approximately 80-90 meters above sea level.*

5 Additional analyses

In this chapter, we present some additional analyses that are not directly relevant for the validation of the migration prediction model during spring 2024, but which do give insight in the effectivity of the shutdown. First of all, we aimed to find out whether the current threshold and trigger values are sufficient. For this, we show the MTR distributions that are measured by the radar and predicted by the model during the spring season of 2024. In addition, we aimed to gain insight in the bird size classes during peak migration nights, as measured by radar.

5.1 Exploration of threshold/trigger values in relation to MTR distributions

In this chapter we discuss how the current threshold and trigger values relate to the distribution of MTRs during the spring of 2024. Figure 5.1 and Figure 5.2 show distributions that are based on the measured MTR per hour and maximum MTR per night respectively. The vertical lines indicate the percentage of hours that fall below a certain value. Only hours were used that were available for both methods the horizontal radar in Luchterduinen as well as the model. The distribution of MTR per night includes nights where at least one valid hour was available.

From the previous chapters, it has already become clear that the current threshold for classifying peak migration (MTR > 500 birds/km/h) based on the horizontal radar measurements is higher than any MTR recorded during the spring of 2024. Nonetheless, although this (arbitrary) threshold of a migration peak is not met, the measured MTR does vary over time (Figure 3.1). Moreover, the threshold of 500 birds/km/h was determined based on a vertical radar, and not a horizontal radar as in the current assessment. Therefore, one could delineate alternative definitions of a migration peak based on measured migration intensities. For instance, if we take the 99th percentile MTR value based on all available measurement hours, meaning that 99% of the radar measurements fall below this value (or alternatively, 1% of the measurements is higher), results in a threshold of 175 birds/km/h (Table 5.1). Such a calculation can also be conducted based on maximum MTRs per night, leading to a 99th percentile of 218 birds/km/h (Table 5.2). Both values are much smaller than the current threshold of 500 birds/km/h.

A similar exercise can be conducted for the trigger values of the model predictions. Here, the current trigger value (MTR > 151 birds/km/h) lies between the 95th and 99th percentile for both the distribution based on MTR predictions per hours as well as on nights (Figure 5.1, Figure 5.2).

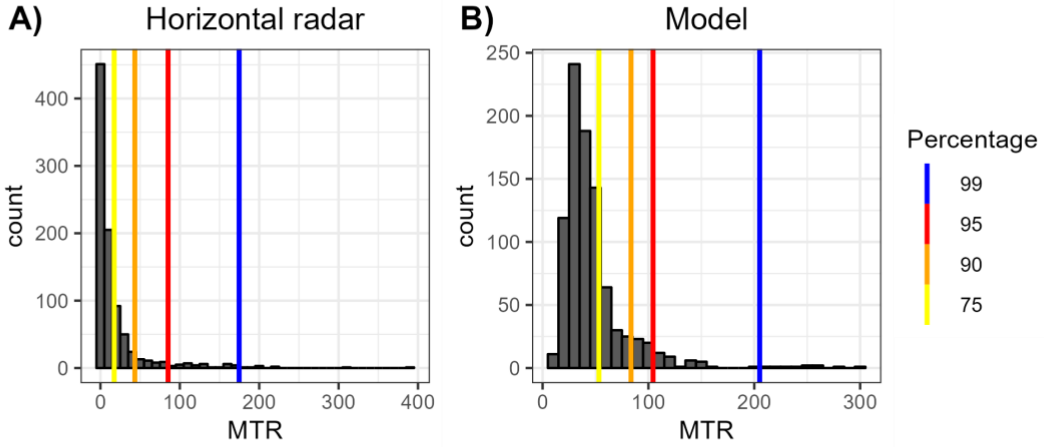

Figure 5.1 *Distribution of* ***hours*** *by MTR during nighttime for A) the horizonal radar, and for B) the model. Only overlapping hours with suitable data were used. Vertical lines indicate the approximate percentage of hours that fall below a certain percentile, represented by different colours.*

Table 5.1 *MTR values per percentile based on ranking of hours. Only hours were used where both the horizontal radar in Luchterduinen and model produced valid results. Rank indicates the (rounded) rank of the e.g. 99% of the total number of hours (909). From this rounded rank number, the number of hours above this threshold was calculated.*

percentile	rank	hours above threshold	MTR hor. radar	 model
99	900	9	175	205
95	864	45	85	104
90	818	91	43	84
75	682	227	17	53

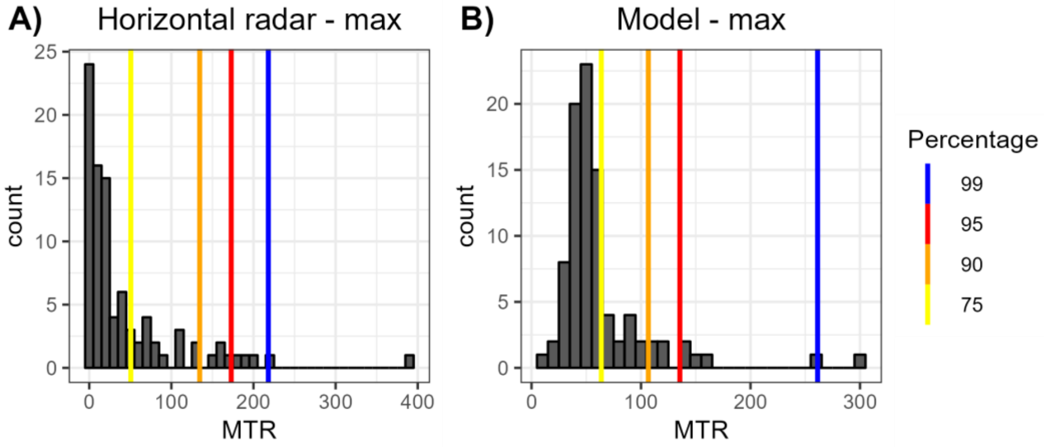

Figure 5.2 *Distribution of maximum MTR* ***per night*** *for A) the horizonal radar, and B) the model (for comparison only overlapping hours were used). Vertical lines indicate the percentage of hours that fall below a certain value.*

Table 5.2 *MTR values per percentile based on ranking of the maximum MTR per night. Only hours were used where both the horizontal radar in Luchterduinen and model produced valid results. Rank indicates the (rounded) rank of the e.g. 99% of the total number of hours (91). From this rounded rank number, the number of nights above this threshold is calculated.*

percent	rank	nights above threshold	max. MTR	
			hor. radar	model
99	90	1	218	261
95	86	5	173	135
90	82	9	134	107
75	68	13	51	64

The histograms of MTR by hour and by night also provide some insight in the pattern of the model predictions relative to the radar measurements (Figure 5.1, Figure 5.2 and also visible in Figure 3.3). The histograms differ a lot in their shape. The radar data (left panel) shows a lot of low values suggesting that there were relatively many hours where no or a limited number of birds were detected. There were only a few hours with large numbers of birds (peak migration moments). In contrast, the model data shows in general a more constant and lower MTR (around 30 birds/km/h). Consequently, there were a limited number of hours with very low activity but also a limited number of higher values (>151 birds/km/h). In other words: the model predicted a more evenly distributed migration, while the radar commonly indicated low migration intensities with few moments of increased migration intensity.

Although the top 20 nights for spring 2024 sorted by MTR values for both radar and model look surprisingly similar in shape (Figure 5.3), the actual dates were quite different. The radar showed only one night with intense migration: the night of 17/18 March. This night is not considered as a ‘peak’ according to the current threshold, but it can be seen as a ‘peak’ relative to the other nights.

The model results show two outstanding nights; 24/25 February and 16/17 March. These nights are considered peaks, together with two other nights, by having a maximum modelled MTR > 151 birds/km/h. These two nights have, in contrast to the other two peaks, much higher maximum MTRs than all other nights.

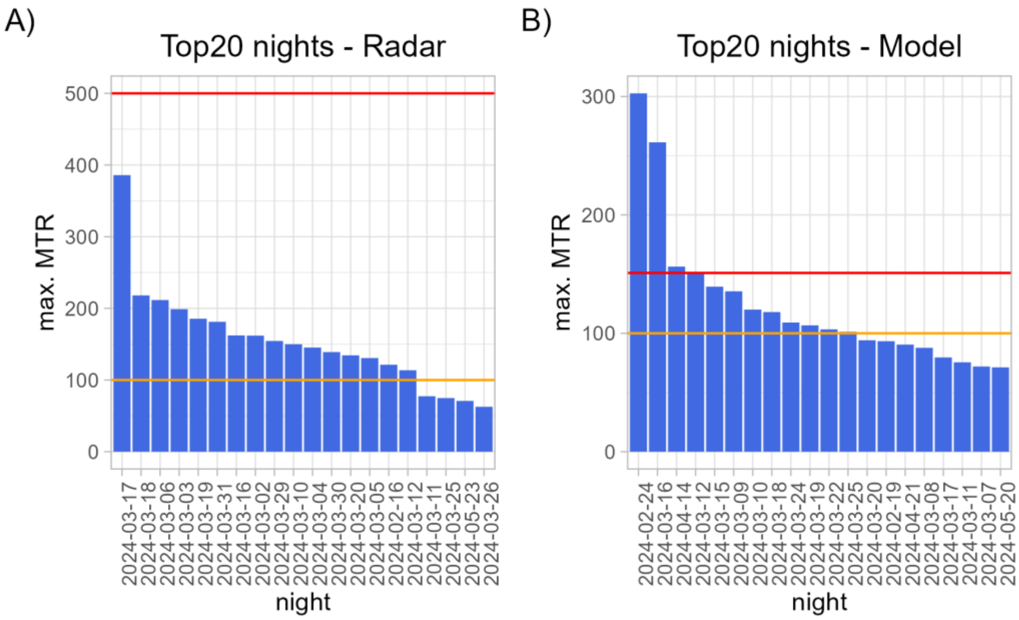

Figure 5.3 *Top 20 nights based on maximum MTR per night according to A) the horizontal radar, and B) the bird migration prediction model. Red lines indicate the migration peak threshold for the radar (500 birds/km/h) and the trigger value for model predictions (151 birds/km/h). Orange lines indicate 100 birds/km/h. Nights are indicated with the date on which the night started.*

The validation of the model is highly dependent on the choice of threshold and trigger value. According to the radar data, no peak events occurred during this season. Intuitively, the threshold needs to be lowered, as even the highest MTR value of the migration season does not surpass this value. The question then remains what a good threshold value would be. The only night with obviously outstandingly high MTRs is the night of 17/18 March, which suggests taking a value somewhere between 250 and 350 birds/km/h (Figure 5.4). Below that value, there are many nights with similar maximum MTRs. Choosing a threshold somewhere between these values would increase the number of peak nights but would still be rather arbitrary.

In order to investigate alternative thresholds that are in a certain way standardized, we present here the consequences of several options. First of all, Figure 5.4 provides the effect of lowering the threshold value for the radar data to 95% of all measurements, i.e. 173 birds/km/h (see Table 5.2). This would lead to several nights in the radar data that classify as peak migration. However, still none of these peak moments would match the predictions of the model. Therefore, the additional hours that according to the alternative threshold at 95% of all radar measurements would classify as a migration peak would increase the number of false negative predictions by the model, while the number of hours where the model predicted a peak, but the radar did not measure intense migration, the so-called false positives, would remain the same.

Further lowering the threshold would further increase the number of moments that would qualify as peaks measured by the radar, thus increasing the number of false negative predictions (Figure 5.5). Note that the first new true positive prediction would only occur when the threshold of the radar measurements was lowered to an MTR of 161 birds/km/h. Some of the peaks according to the model match with very low detected MTRs by the horizontal radar. Hence, these hours would only be classified as a peak by the model with an unrealistically low threshold value for the radar. The potential maximum number of hours for true positive predictions would be 14. This number of true positive predictions could only be achieved if the threshold is below the lowest measured MTR. To correctly predict all 14 true positive hours, the threshold value would need to be lowered to 0.295 birds/km/h.

In conclusion, in the spring migration season of 2024 the threshold value of 500 birds/km/h would not result in any nights that would qualify as a peak migration. However, it needs to be emphasized that the threshold of 500 birds/km/h was defined based on a vertical radar and not a horizontal radar as in the current assessment, and hence an alternative definition of a threshold would be reasonable. During the spring season of 2024, only one night had a distinctively high MTR, while all the nights with lower migration intensities showed similar maximum MTRs. Therefore, based on the data for this season, a suitable alternative threshold value would lie somewhere between the maximum MTR of the night with the highest migration intensities and the maximum MTR of the night ranked as second highest migration intensity. However, note that the MTR distributions as presented in this chapter vary per season and the perfect threshold might therefore vary per year. Hence, a thorough analysis, using more years of data might help in determining the threshold for defining peak events in migration.

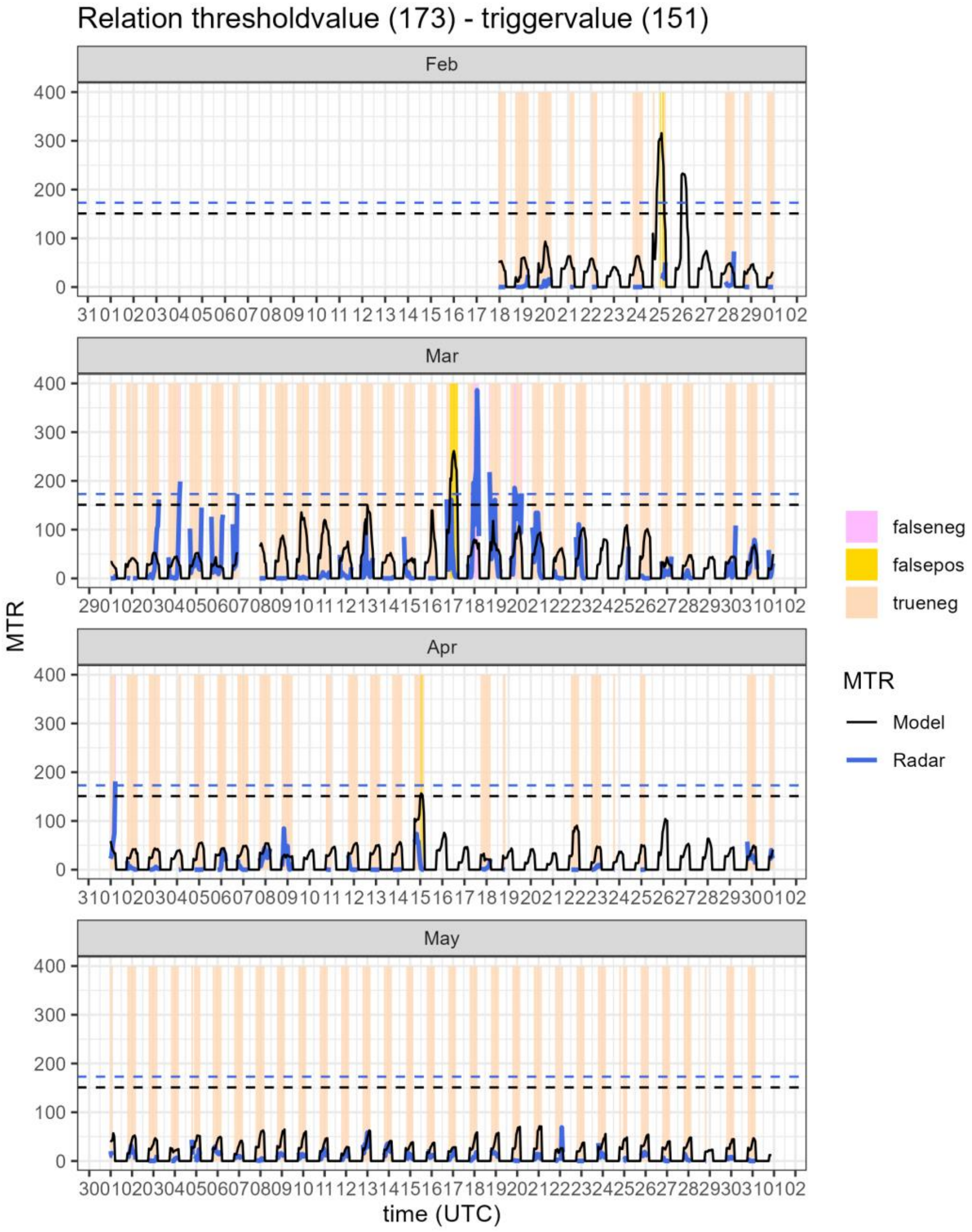

Figure 5.4 *Threshold value for radar data and trigger value for the predictive model (blue and black dashed lines) in relation to radar and model results for spring 2024 (solid lines). Only hours where both radar and model have suitable data were used. The classifications of each hour are: falsneg = the hour is considered as a peak based on the radar, but not by the model (purple), falsepos = the hour is classified as a peak by the model, but not by the radar (orange), trueneg = the hour is not defined as a peak either by the radar or the model (pink), truepos = both radar and model consider the hour as a peak (not occurring on the figure).*

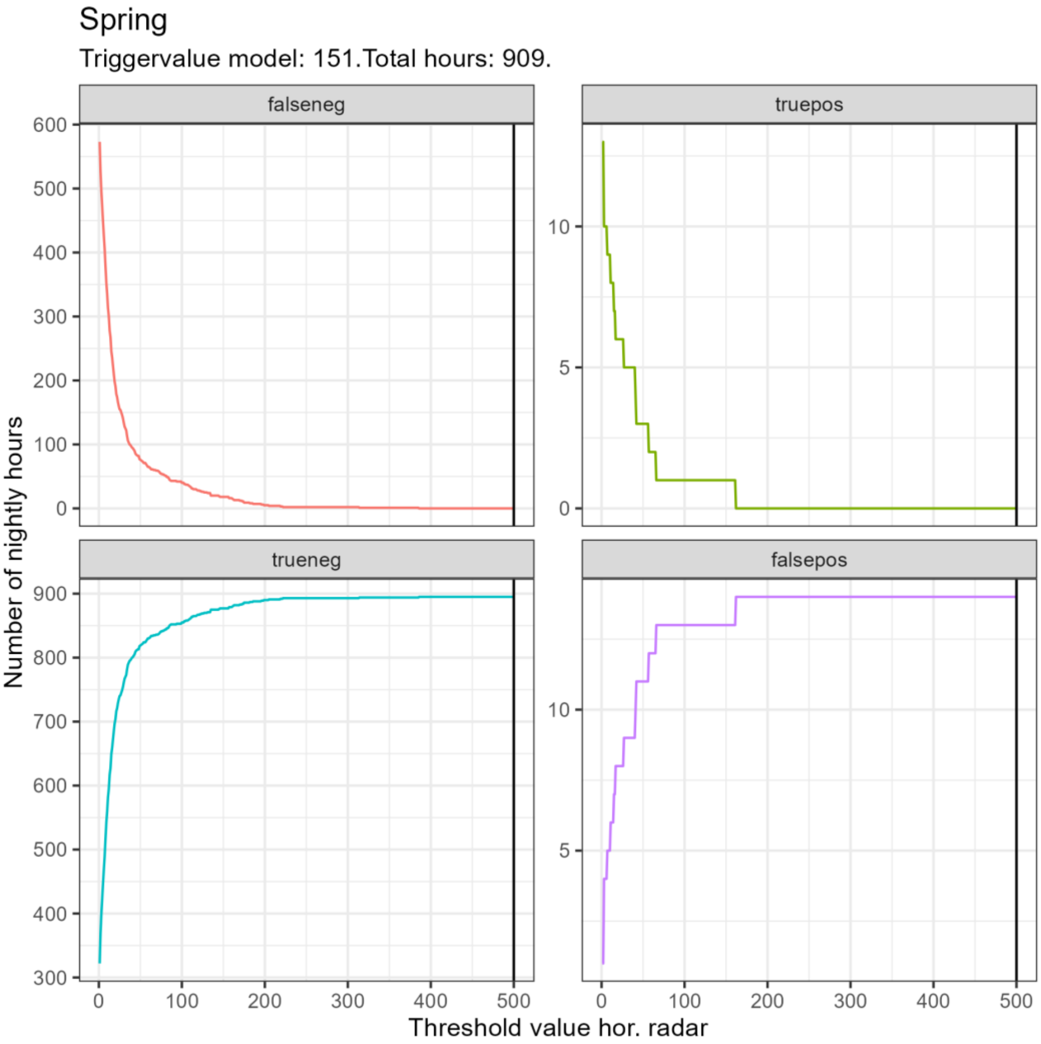

Figure 5.5 *The effect of changing the threshold value on the number of false negatives, true positives, true negatives and false positives by a constant trigger value for the model (151 birds/km/h). The current threshold for the horizontal radar is indicated with a black line (at 500 birds/km/h).*

5.2 Classification of bird sizes during peak migration nights according to the radars

During these moments of intense migration, it is obvious that high numbers of birds are detected. However, species compositions during these nights remain unclear. An extra set of information that is gathered by the radars, is the size of the detected birds. This information could be used to determine what kind of birds migrate during the intense migration moments. The radars can assign four types of classifications to every bird track, which are small bird, medium bird, large bird and flock. The first three indicate, logically, the size of the bird, while the latter indicates multiple birds flying near to each other.

Figure 5.6 shows that during the most intense migration night (17/18 March), the horizontal radar measured a strong increase in numbers of mainly the so-called medium birds. In contrast, the numbers of small birds, large birds and flocks were only slightly elevated during the moments of the highest migration intensity. The figure also shows that medium birds provide the highest peak in the horizontal radar.

In comparison, the vertical radar measured an increase in smaller birds during a peak night (Figure 5.7). However, in contrast to the horizontal radar during peak migration nights, the shift in the vertical radar measurements is from medium birds to small birds, instead of from large birds to medium birds. During the rest of the night, the numbers of small and medium birds return to almost equal.

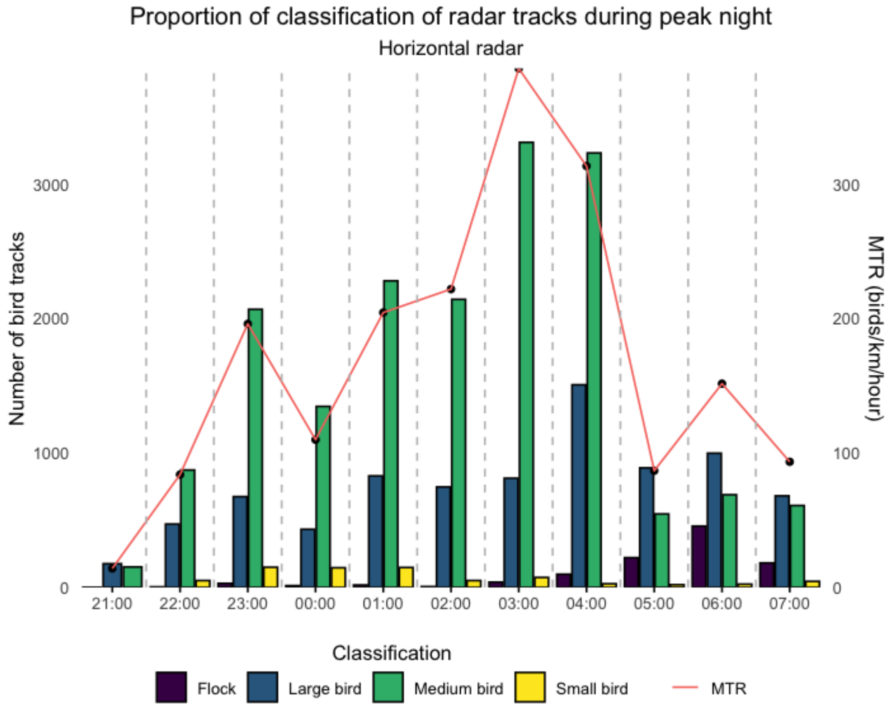

Figure 5.6 *Number of tracks per classification (large-, medium-, small bird and flocks) during the night with the most intense migration (17/18 March) according to the* ***horizontal radar****. Coloured bars indicate the number of bird tracks with a certain classification. The red line and black dots show the calculated MTR during the same hours. The second axis on the right correspond to this red line.*

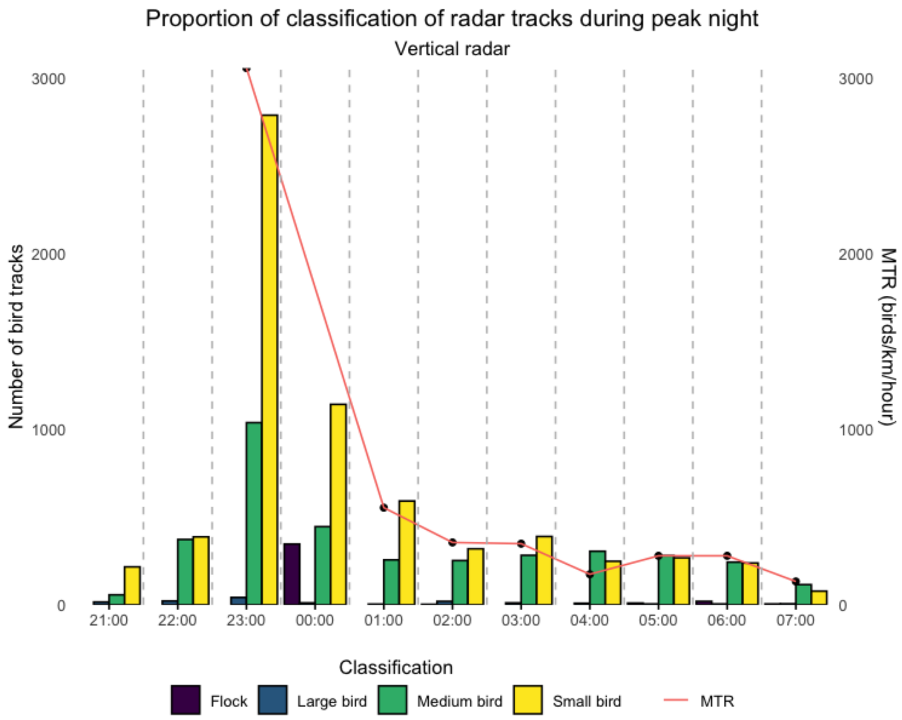

Figure 5.7 *Number of tracks per classification (large-, medium-, small bird and flocks) during the night with the most intense migration (17/18 March) according to the* ***vertical radar****. Coloured bars indicate the number of bird tracks with a certain classification. The red line and black dots show the calculated MTR during the same hours. The second axis on the right correspond to this red line.*

These results from both radars indicate that during the night with the highest migration intensity, there was an increase in relatively smaller-sized birds. Figure 5.8 shows the percentage per radar track classification during hours with intense and lower-level bird migration during nighttime for both radars, which confirms this general pattern. Normally (i.e. lower flight intensities), the horizontal radar detects a lot of large and medium birds during the night. During intense migration hours however, the ratio between these categories shifts more towards the medium birds. For the vertical radar, this shift is also seen, but then from medium to small birds. This indicates that possibly the vertical radar is better capable of detecting smaller birds, in contrast to the horizontal radar, which is better at detecting larger birds. However, this could also be caused by a difference in classifying birds based on size between both radars.

That there is a difference in detection capabilities of smaller birds between both radars is partly already known information, as the vertical radar is an X-band radar, with a smaller wavelength and thus equipped to detect smaller objects. The horizontal radar on the other hand is an S-band radar, with a longer wavelength. However, there are also indications that the horizontal radar classifies small songbirds in a large number of cases as medium birds (as found by Leemans *et al.* 2022a in wind farm Borssele), and hence it could be that the horizontal radar detects the small birds similarly to the vertical radar, only classifies them in another way.

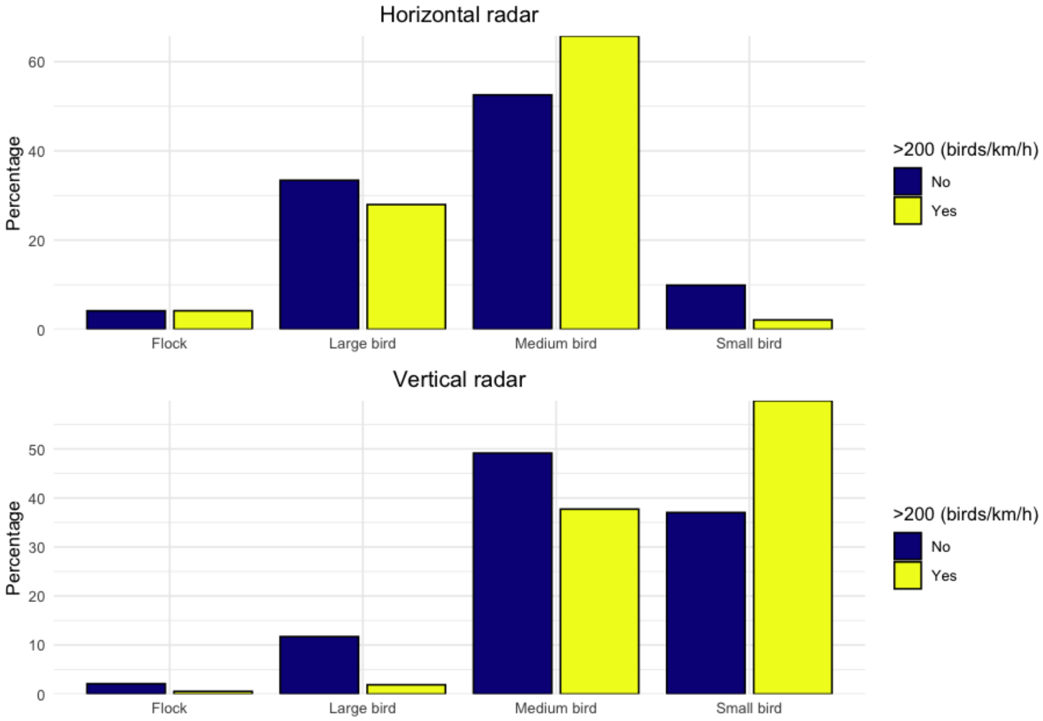

Figure 5.8 *Percentage of tracks per classification category for both radars in Luchterduinen during hours with MTRs above 200 (yellow) and MTRs below 200 (blue).*

6 Synthesis

The aim of this report was to validate the predictions by the bird migration prediction model (developed by the UvA (Bradarić 2022)) for the spring migration season of 2024, in order to provide curtailment advise for Dutch offshore wind farms. Validation was done by analysing potential bird migration peak events detected by the horizontal radar in wind farm Luchterduinen and by combining these results with predictions of an expert team. Moreover, mismatches between the model and the radar were investigated in more detail, also using the vertical radar in Luchterduinen and the horizontal and vertical radar in wind farm Borssele. Next, weather conditions during predicted and detected intense migration nights were analysed. Finally, we presented additional analyses of the performances of the radar and an exploration of potential methods to find new threshold values for the radar data.

Basic validation

A comparison between the detected migration peaks by the horizontal radar in Luchterduinen and the predicted migration peaks by the bird migration prediction model did not show any matches. This was partly caused by the lack of detected peaks by the radar based on the threshold of 500 birds/km/h. However, one night, 17/18 March, stood out amongst the others with a maximum measured MTR of 386 birds/km/h and could be considered a peak in migration. The model predicted four peak migration nights, one of which was 16/17 March, i.e. one day earlier than the peak measured by radar. That night (16/17 March), offshore wind turbines were curtailed because of a combined peak prediction by the model and the expert team. The horizontal radar in Luchterduinen measured a maximum MTR of 161 during this night, which is substantially lower than the night after (i.e. 386 birds/km/h).

Examining mismatches

We also studied the bird activity on other offshore bird radars, to examine whether mismatches could be explained by either detection loss of the horizontal radar or by vertical- or spatial differentiation. Results from this analysis showed that neither the vertical radar in Luchterduinen nor the horizontal and vertical radars in Borssele could support the prediction of peak migration moments by the model. In contrast, both vertical radars detected migration peaks at rotor height at the night of 12/13 March. Moreover, the Borssele vertical radar detected a migration peak on 29 February/1 March. During the former night (12/13 March), the model predicted maximum MTRs of 150 birds/km/h, just below the trigger value.

During both detected peak nights in Luchterduinen, 12/13 and 17/18 March, there were southwestern winds in the UK. In Luchterduinen itself there were southern to western winds. This indicates the importance of wind assistance for migrating birds to decide to go or not. Interestingly, the model predicted peaks during nights with seemingly less wind assistance. Especially the wind conditions that were predicted for the night of 25/26 February seem adverse for bird migration, with strong winds from the north. Insights in why the model predicted a peak for this night would be very interesting, as this would indicate which weather patterns triggered the model and might help to explain other mismatches.

Limitations of validation

It is important to note that this analysis is limited by the performance of the bird radars. First of all, none of the radars were operational during 25/26 February, for which the model predicted a peak. This night could therefore not be validated by any of the radars and can therefore not be marked as false positive nights. Moreover, the vertical radars were shut down from 13 March onwards and could not be used to validate the rest of the season. Besides these technical issues, one of the largest limitations of bird radars is the inability to detect birds during adverse weather conditions. For instance, periods with high waves tend to lead to higher filtering activities by the horizontal radar, leading to detection loss. Moreover, vertical radar data is sensitive to be polluted by tracks caused by rain. Filtering out these periods with signs of rain also leads to information loss of many hours. That was shown during the night of 12/13 March in the vertical radar data of Luchterduinen, where one hour in the middle of a migration peak was filtered out because of a rain shower. These considerations show that the results of these bird radars should be treated with caution.

An example of these limitations is the night of 12/13 March, where a peak is detected by both vertical radars but by none of the horizontal radars. The filtering activity by the Luchterduinen horizontal radar during that night was far from the threshold that is used for filtering out hours with ‘negative observation bias’ (too low number of detected tracks due to high masking activities, van Erp *et al.* (2023)). In earlier validation reports, lowering this threshold was mentioned as a possible adjustment to the MTR calculation in order to produce more reliable results. A method as was used for the horizontal radar in Borssele could provide a potential solution. However, using this method for this particular season would also not have filtered out this specific night.

This indicates that the horizontal radar missed a migration peak in the night of 12/13 March, without having high filtering activities. Another explanation could be that the peak consisted of smaller birds, for which the horizontal radar is less sensitive. We present in this report that the horizontal radar tends to detect mostly larger birds. It is known that the majority of the birds during migration peaks are smaller passerines (Hahn *et al.* 2009), and hence the horizontal radar missing a migration peak could therefore be caused by a lower sensitivity for smaller birds.

Threshold value

The validation is largely affected by the choice for an MTR threshold value that needs to be exceeded in order to call an hour or night a peak in the radar measurements. Currently, a threshold (500 birds/km/h) is used that was determined based on a different radar system and an MTR calculation that differs from the MTR calculation used for the horizontal radar (Krijgsveld *et al.* 2011). Note that this threshold value may suggest that the calculated MTR represents the exact number of birds flying through the area. However, due to detection loss and filtering occurring in these radar systems, a threshold value should mostly function as a separation of peak migration nights from the vast majority of low activity nights. The lack of a migration peak on the horizontal radar in this spring season can therefore be also interpreted as the threshold being too high.

A threshold value should in fact mostly differentiate average nights from peaks in migration. When looking for an alternative threshold, one could argue that this could be based on hourly values, but aggregated values per night might also be useful. Especially in the case of the validation of the bird migration forecast model, a match between radar measurements and model predictions at an exact hour is rather scarce (Middelveld *et al.* 2024), and hence hourly thresholds might be too detailed and result in a lot of mismatches. Moreover, in case of an hourly threshold, a peak night with many peak hours with high MTRs would alter the threshold value in such a way that shorter and slightly lower peaks would be disregarded. Such an aggregated threshold for peak nights could be expressed as the maximum MTR within a night.

Finding the perfect value should rely on an analysis of multiple years of radar data. This season, seemingly only one night stood out from the rest and could be considered as a night with elevated migration intensity. Therefore, multiple years of data could help in determining an alternative threshold, as there would be more peaks to base the value on. Moreover, whether autumn and spring should have the same threshold value should be reconsidered, as this contrasts with the trigger values for the model, where different values are used for autumn and spring. A potential method of finding such a value could be to select the top few nights per season.

Potential species involved in migration peaks

Besides estimating the general size of birds, the radars are unable to identify bird tracks to species level. Therefore, the question remains which species are involved in migration peaks. Here, we discuss likely involved, with special attention to species potentially vulnerable to offshore windfarm development, following Potiek *et al.* (2022) and Brinkman & Schekkerman (2024).

In general, the bulk of large migration peaks consist of common species that migrate in flocks. Strong migration peaks in mid-March typically mainly involve European Starlings *Sturnus vulgaris* and thrushes crossing from the United Kingdom to the European mainland – in particular Belgium and the Netherlands. This is supported by land-based observations in the Netherlands, where spring numbers of Blackbirds *Turdus merula*, Redwing *T iliacus* and Mistle Thrush *T viscivorus* peaked mid-March. The latter species, however, usually occurs in only low numbers along the Dutch coast and is therefore unlikely to play a major role in oversea peak migration in mid-March. Substantial numbers of Blackbirds, Redwings and European Starlings winter in the United Kingdom. The migration peak in mid-March 2024 likely also involved these species. This is supported by numbers observed at land-based migration watchpoints along the Dutch coast in the morning of 18 March (www.trektellen.nl). For example, 231 European Starlings and 281 Redwings passed De Vulkaan (Den Haag), between 7:00 and 10:30. It should be noted that mass migration from the UK to the mainland is probably less visible along the Dutch coast, because the spring migration from the UK is directed from west to east, with numbers consequently spreading out across the coast instead of accumulating, as is the case when migration is oriented perpendicular to the coast. In contrast, autumn migration of passerines along the Dutch coast usually involves much larger numbers, as population sizes are larger in autumn due to many first-year birds (i.e. juveniles born that year), but also because the migration axis in autumn is to the southwest and, with the suitable winds, birds often accumulate in the coastal zone.

Nocturnal migration is recorded at a few sites using continuous sound recording. In the night of 17-18 March, Redwings made up the bulk of individual flight calls at Zoetermeer, an inland site in Zuid-Holland. Likewise, Redwing was the dominant species among vocally active birds during that night over Amsterdam, with a few Blackbird and Song Thrush calls also recorded (www.trektellen.nl).

Both Redwing and European Starling were mentioned by Brinkman & Schekkerman (2024) as species that are potentially most vulnerable to increased mortality due to offshore wind farms in the North Sea, based on the percentage of the population that migrates across the North Sea and the current conservation status (‘Staat van Instandhouding’). In addition, European Starling has been considered in the KEC 4.0 project (Potiek *et al.* 2022).

Although the radar data collected at LUD recorded the highest intensity during the night of 17-18 March, migration count data on trektellen.nl from sites across the Netherlands indicate a broader peak in March 2024 for Redwings. Hourly averages of this species slowly increased between 10-13 March, peaking on 15 March and staying at high levels until 21 March. The absolute numbers, however, peaked on 16 March and 18 March. For European Starling, absolute numbers across all sites peaked on 16-17 March, and hourly averages on 16-19 March.

Although the bulk of individual passerine migrants likely consists of Redwings and European Starlings, other species will have likely seized the opportunity of good migration conditions to cross the North Sea as well. Focusing on the species listed by Brinkman & Schekkerman (2024), migration intensity of Black-headed Gull *Chroicocephalus ridibundus*, Eurasian Teal *Anas crecca* and Eurasian Wigeon *Mareca penelope* can peak in mid-March as well. Indeed, hourly averages of Black-headed Gull peaked in 2024 between 16-18 March, Eurasian Teal between 15-19 March and Eurasian Wigeon on 16 and 19 March. Hence, these species may also have been involved in the recorded migration peak at LUD in the night of 17-18 March.

The data from migration counts (www.trektellen.nl) indicate a much broader migration peak of several days, across the Netherlands than only the night of 17-18 March. This is based on data from sites that are not necessarily across the North Sea; these sites are situated across the Netherlands. Therefore, migrants recorded at these sites have not necessarily crossed the North Sea or may have crossed the North Sea in a previous day or night. Interestingly though, a broader peak between 15 and 19 or 20 March has been suggested by the expert team predictions, as well as – for some nights – the model. That the radar at

LUD has picked up peak numbers only on 17-18 March indicates that migration over the North Sea may have been concentrated elsewhere, or that the radar has failed to detect birds, for example if they travelled at very high elevations.

Besides the species considered above, other species mentioned by Brinkman & Schekkerman (2024) and/or considered by Potiek *et al.* (2022) generally migrate later in spring (e.g. Bar-tailed godwit *Limosa lapponica*), or less peaked and over a longer period (e.g. Eurasian Curlew *Numenius arquata*).

Curtailment in May

During this spring migration season, as well as during the spring migration season of 2023, there were no peaks detected in the month of May. This year, the bird migration prediction model did not predict a peak in this month and neither did the expert team. Besides that, the model was not trained and tested on this month, meaning it is unclear how reliable the model's predictions are during May. Therefore, it may be a point of discussion whether this month should be included in the curtailment procedure as it is now.

General conclusions

As described above, the aim of this study was to validate the bird migration prediction model for the spring migration season of 2024. We showed that none of the four peaks that were predicted by the bird migration prediction model could be confirmed by the bird radars, and could have been interpreted as false positive predictions. However, we found several reasons for the apparent mismatches between the model predictions and the radar measurements:

- Heavy filtering of the horizontal radar can lead to incomplete datasets, due to which the validation of the model predictions cannot be conclusive either. This was the case on the first night with peak migration predicted by the model (24/25 February);
- Frequent inactive periods of the radars also limit the possibilities of our validation exercise. For instance, both the vertical radar in wind farm Luchterduinen as in Borssele were not operational during the four moments for which the bird migration forecast model predicted a migration peak. Moreover, also the horizontal radar was turned off for the largest part of the night during the second peak migration predicted by the model (25/26 February);
- The actual weather circumstances may diverge from the weather forecasts used by the model. For instance, both the model and the expert team forecasted a migration peak for 16/17 March, leading to the only curtailment moment of the spring of 2024. However, this migration peak could not be verified by any of the radars. Our analysis on weather data showed that there was rain detected at the departure locations on this night, which was not forecasted by the ECMWF model. This erroneous weather forecast could have led to the false positive prediction of peak migration by the model and the expert team. Moreover, it could be that due to this false positive prediction the accumulation factor of the factor was not high enough to predict peak migration for the following night, which did occur according to the radar measurements, leading to a false negative prediction.

The fourth night with peak migration predicted by the model occurred on 14/15 April. Based on our current analyses, we could not exclude that this night was indeed a false positive prediction by the model. As none of the validations up till have found peak migration occurring in April, it may be that the accumulation of birds in this period of the migration phenology is not extensive enough to create a migration peak according to the current definitions of peak migration threshold.

Based on analyses of weather characteristics, our study also showed that detected peaks by the radars in Luchterduinen occur mostly with relatively calm southwestern winds. We also found that migration peaks could happen right before and after rain fronts.

Furthermore, we investigated whether the current threshold value for the horizontal radar to select peak nights is adequate for the spring migration season. Paragraph 5.1 could function as a starting point for finding an alternative threshold based on either hourly measurements or nightly aggregates such as the maximum value per night.

Finally, we discussed that the vertical radar is more prone to detect smaller objects and can therefore complement the data from the horizontal radar during peaks of small passerines. For instance, we found one night during which the vertical radars in Luchterduinen and Borssele measured peak migration, but the horizontal radars did not, while also the model predicted MTRs (i.e. 150 MTR) that were just below the trigger value.

These results may help to further understand the nocturnal bird migration patterns better and improve the bird migration prediction model.

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