Validation of the outcomes of the bird migration prediction model for 2023

Middelveld, R.P.,
Kraal, J.J.,
Gyimesi, A.

WAARDEN
BURG
Ecology

we
consult
nature.

Validation of the outcomes of the bird migration prediction model for 2023

Middelveld, R.P., Kraal, J.J., Gyimesi, A.

Status: final report

Report nr:	24-114
Project nr:	23-0712
Date of publication:	4 July 2024
Photo credits cover page:	Daniel Beuker / Waardenburg Ecology
Project manager:	dr. Abel Gyimesi
Quality control:	dr. Astrid Potiek, drs. Sytske van den Akker
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: Middelveld, R.P., J.J. Kraal, A. Gyimesi 2024. Validation of the outcomes of the bird migration prediction model for 2023. Report 24-114. Waardenburg Ecology, Culemborg.

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

Waardenburg Ecology Varkensmarkt 9, 4101 CK Culemborg, 0345 512710
info@waardenburg.eco, www.waardenburg.eco

WAARDEN
BURG
Ecology

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 intends to implement such a measure at a large scale in Dutch offshore wind farms and is currently carrying out a pilot study. The energy market demands that such a drop in energy needs to be known well in advance. Therefore, the University of Amsterdam developed a bird migration forecast 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 for both migration seasons in 2023. This report summarizes the results of this validation and provides insights in the possible reasons for the mismatches, which could be helpful in the further development of the model.

Next to the authors of this report, Jacco Leemans and Rob van Bemmelen from Waardenburg Ecology were involved in or gave advice on the analyses of this project. Marin van Regteren from Eneco provided weather data measured in wind farm Luchterduinen. We thank Maja Bradaric from the University of Amsterdam for providing data and for fruitful discussions on the working of the forecast model. The project was coordinated by Aylin Erkman and Jos de Visser from Rijkswaterstaat. Karin Bilo, Marin van Regteren, Pim Somers, Jurre Honkoop and Tim van Ooijen van de ecology advisory board and Martin Poot, Karen Krijgsveld and Adri Clemens from the migration expert team provided comments on a previous version of this report, we thank them all for their contribution.

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, the possibility of colliding with a wind turbine may be one of those risks. 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 by curtailing wind turbines during the migration season. However, this reduces the amount of energy generated by the turbines. Therefore, 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 (ML) model aims to predict bird migration over the North Sea based on weather conditions along the migration route of these birds, 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 had 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 the months of May in spring and August and September in the autumn were involved, on special request by Rijkswaterstaat.

The bird migration prediction model was trained on weather data from the ERA5 reanalysis model (Hersbach *et al.* 2023). This is a weather model that tries to estimate a large variety of weather variables in the past. Although this is a solid way to train an ML 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 needs be used as input for the bird migration prediction model. The weather forecasts that are used come from the European Centre for Medium-Range Weather Forecasts (ECMWF-model).

The outcome of the model is a prediction of bird migration intensity in the form of the *mean traffic rate* (MTR) per hour. The curtailment procedure of Dutch offshore wind farms is also based on predictions in this unit of predictions. MTR is defined as the number of birds per kilometre per hour and is used to illustrate the migration intensity. It is essential to validate how precise the model predicts bird migration. In this current report, we therefore compare the model predictions for the migration seasons of 2023 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.

Bird radars are commonly used to compute MTRs, as the flight path (tracks) of birds that are detected by these radars are stored and can be analysed afterwards. In this report, we validated the model predictions by MTRs measured by the horizontal radar in wind farm Luchterduinen 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. The Robin 3D fixed system operating in Luchterduinen has also a vertical radar component, to supplement the horizontal radar measurements. Besides the main difference that the antenna of the vertical radar is tilted 90 degrees and hence it looks more upwards than the horizontal radar and is therefore capable of measuring the altitude of the tracks (what the horizontal radar tracks are lacking), the two radars differ also in technical aspects. The vertical radar operates in the X-band and has a shorter wavelength, due to which it has 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. 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 but also of the potential contamination of bird detections by rain and waves. However, the influence of waves on the vertical bird detections is limited to the scanned area near the sea surface. In contrast, although the horizontal radar is in general less sensitive to wave clutter, if it occurs, it affects the whole beam of the radar, which can lead to a substantial impact on the measurements. For these reasons, we additionally analysed measurements of the vertical radar in Luchterduinen, to see whether the horizontal radar potentially missed bird migration peaks. For these analyses of the vertical radar data, we used the method of Leemans *et al.* (2022b) that calculates the number of birds crossing a virtual line of one kilometre within an hour. The former method uses data from the horizontal radar and the latter uses the vertical radar.

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. These are currently an MTR of 173 for the autumn and 151 for the spring defined by the Dutch government based on the top 30 hours of the model predictions in the first year of the curtailment procedure in 2022. Be aware that these predicted MTR values are lower than the legal definition of peak migration set at 500 MTR (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 expert ornithologists from a variety of institutions produces their own prediction (based on expert judgement) on bird migration events independently (whether or not a migration intensity would occur that reaches a threshold when curtailment should be applied). 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 migration seasons of 2023 are also presented in this report. This curtailment procedure resulted in several actual curtailments in 2023, which moments are 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 spring 2023 migration season as measured by the horizontal radar in Luchterduinen and predicted by the model and the expert team.
- In Chapter 4, we show the basic validation of the autumn 2023 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 5.
- In Chapter 6, an additional analysis on bird migration patterns during the whole day cycle are presented. In addition, also some insights in radar measurements in wind farm Borssele, in order to see how those match predictions of the bird migration forecast model and the radar measurements in Luchterduinen wind farm.

2 Methods

2.1 Radar measurements

In this report, we calculated bird migration intensities in the form of a Migration Traffic Rate (MTR) 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. The same method to calculate the MTR for the horizontal bird radar was used as described by Bradarić (2022). Since the horizontal radar resembles a helicopter view of the study area, a density-based approach had to be used (§2.1.1). 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 (§2.1.2). 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 was 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 predictive model by Bradariç (2022). In this report, we used these measurements to investigate whether the horizontal radars missed migration peaks. For instance, a peak in migration might also happen at higher altitudes than the horizontal radar can measure, but which can be detected by the vertical radar. Moreover, we assess flight height distributions during peaks predicted by the model.

<u>*Radar specification*</u>
Two bird radars were installed 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, a blank sector is created towards the turbine. The blank sector consists of 19.4% of the complete circle around the radar.

The vertical radar works comparably to the horizontal radar but is tilted 90 degrees. The radar is blinded towards the sea level to prevent heavy 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 horizontal position and altitude. For both radars, the combined tracks were used in the analyses as well.

2.1.1 **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 it was used during the training of the bird migration prediction model (Bradarić 2022). First of all, tracks that seemed to be locally oriented were removed using the metric of 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, this leaves 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. In contrast, migrating birds tend to fly really efficient and therefore relatively straight.

Tracks with an airspeed below 5 m/s were also filtered out of the database. The airspeed was calculated by measuring the ground speed and direction of an object relative to the wind speed and direction. Tracks with an airspeed below 5 m/s are almost certainly not birds. 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 completely labelled as high-clutter minutes. A high filtering minute was determined based on a metric called 'variant mask filtering', which is a measure in what percentage of the area the radar is filtering. Filtering by the radar is used to reduce the number of non-bird tracks ending up in the database; however, as this usually leads to a lower detection probability of a real bird, the number of birds during that minute will likely be an underestimation. 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 removed from the analysis. This threshold of at least 10 minutes is an arbitrary one but 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 in approximately the lower 300 metres altitudes above mean sea level. 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.

Figure 2.1 *Donut-shaped area which was used to calculate the MTR from the horizontal radar data in the Luchterduinen Wind Farm. The blue marker shows the radar position. The white triangle represents the blanking area of the radar to avoid radiation from the turbine on which the radar is installed.*

The radar rotates every second, and during each rotation an individual track may or may not be detected. All radar tracks in the database have a feature which is called '*the number of plots'*. This metric indicates the number of times the bird is recorded by the radar. Therefore, if the number of plots of all tracks within a certain hour are summed and divided by the number of radar rotations within that hour, one gets the average number of birds recorded by the radar on each rotation. As only the tracks within the donut area are involved, the number of birds on a certain moment divided by the surface of the donut area leads 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*. The density of birds can be converted to the *MTR* by multiplying it 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 only visualise the migration intensity in the lower few hundred (approximately 300) metres of the vertical column.

2.1.2 Vertical radar measurements

Data filtering

To prevent any non-bird tracks from entering the dataset of vertical radar measurements, several filtering steps were taken for the vertical data as well. These steps were based on Leemans *et al.* (2022). Because the vertical radars have other characteristics than the horizontal radars, other filtering steps had to be used than during the calculation of MTRs with the horizontal radars. Especially rain showers are known to contaminate the data of the vertical radars. These rain showers are classified as bird tracks until the filter is activated, leading to a lot of false bird tracks entering the data.

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 will filter out many of the hours with rain but may not prevent all rain showers to enter the dataset falsely as bird tracks due to the delay of the dynamic radar filtering. For the LUD measurements, the data of a rain meter in a nearby wind farm, the Prinses Amalia Windpark, was used to erase all hours from the dataset that had some indication of rain.

Next, the total number of radar tracks were calculated per five minutes. A sudden increase between two succeeding five-minute periods was used as an indication for a rain shower. If this increase between two succeeding five-minute periods was above a threshold of 300 percent, and the second five-minute period contains at least 100 bird tracks, this increase is assumed to be due to a rain shower. This way, only the extreme and very sudden increases in number of radar tracks were marked as rain shower. If this sudden increase in number of radar tracks occurred, the whole hour was filtered out.

For the final rain filtering step, a label that is assigned to some tracks 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 one 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 – 1,000 meters from the radar, towards both sides of the beam. Figure 2.2 show the flux line in LUD. This is slightly closer to the radar than where the horizontal radar measurements were done, this 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 wave tracks. 3-25 meters were shown to depict the air layer just below rotor height. 25-137 meters is 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 1,000 meters was divided in two layers, up to 500 meters and up to 1,000 meters.

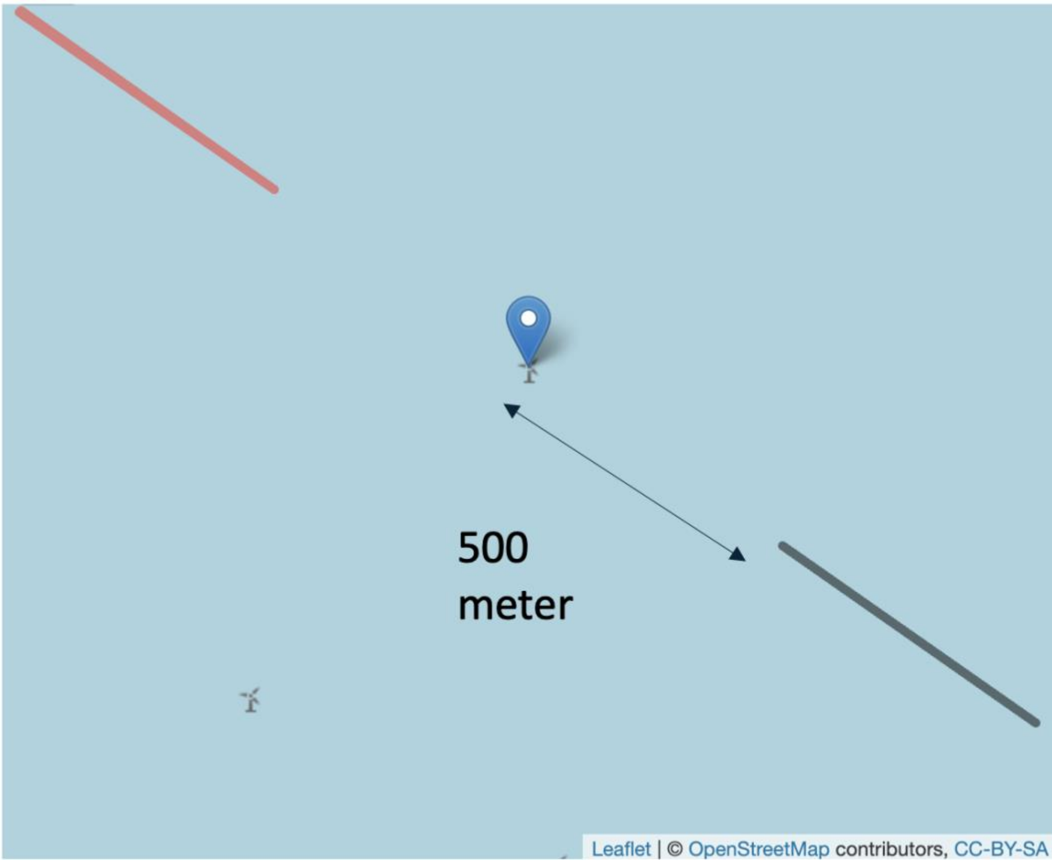

Figure 2.2 Flux line placement around the radar to the northwest (red line) and southeast (black line) in the Luchterduinen Wind Farm. The marker depicts the radar location. Both flux lines are 500 meters long.

2.2 Model predictions

The bird migration model was developed by Bradarić (2022). The autumn module was trained on radar data from October and November of 2019 and 2021 and the spring module on data from the period 15 February - 1 May of 2019, 2020 and 2021. Note that the current validation report also considers August and September in autumn and May in spring, months for which the model was not trained. The consequences of this will be further discussed in Box 1 on page 16.

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 Denmark, North of the Netherlands and Northwest-Germany for the autumn and the Southwest of the United Kingdom and North-France for the spring (Figure 2.3).

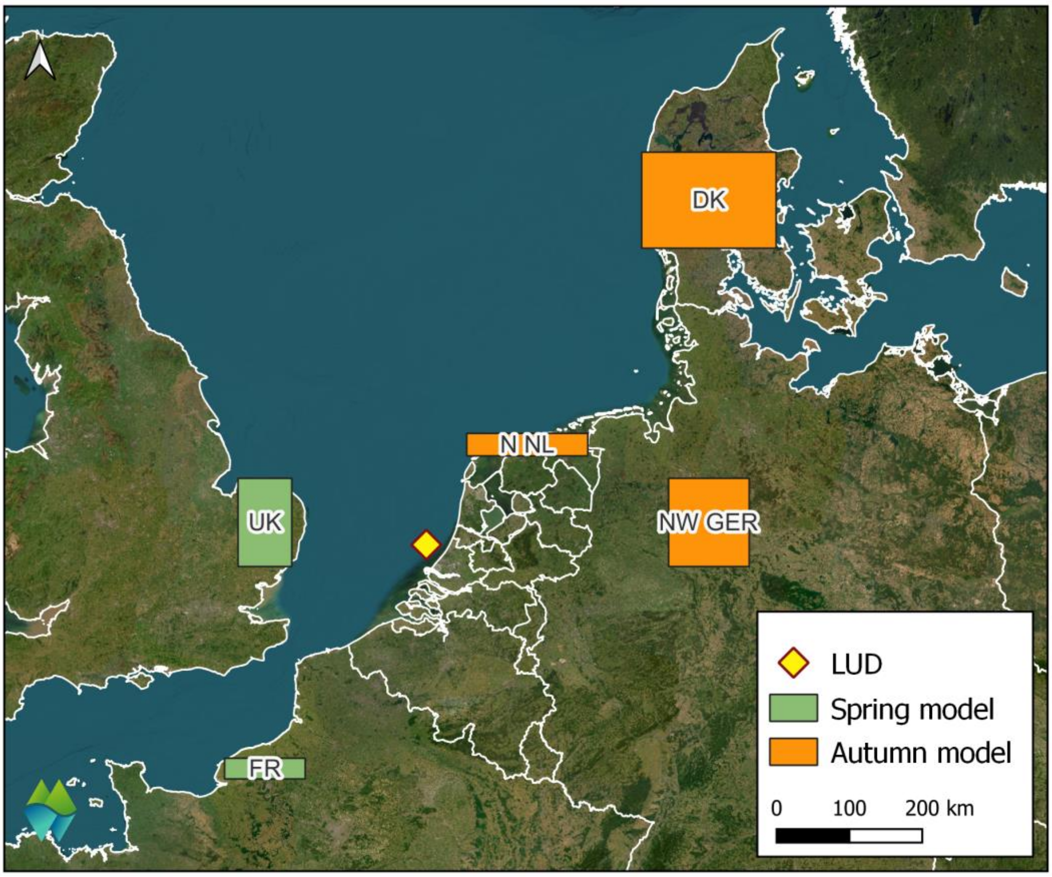

Figure 2.3 Departure locations for bird migration at Luchterduinen for both spring and autumn.

2.3 Expert team predictions

A team of seven bird migration specialists predicted occurrence of migration peaks in the spring and autumn of 2023, in order to offer an additional prediction next to the model predictions and to act as a check of the model predictions preventing curtailment during most false positive peak predictions. These expert predictions were made for 90 nights in spring, from 3 March 2023 to 31 May 2023 and for 91 nights in autumn, from 1 September to 30 November. From 3 to 9 March 2023, the expert predictions were made for the full night of two days ahead. After that, the predictions were made for midnight to sunrise and sunset to midnight of two days ahead. Thus, for instance, on Monday afternoon a prediction was made for the night from midnight to sunrise and from sunset to midnight on Wednesday. A warning for a migration peak was given when the team predicted a migration peak at altitudes up to ca 250 m, over the Dutch North Sea in the area south from IJmuiden. Furthermore, the migration expert team indicated whether they expected a peak to happen before or after midnight or during the entire night. Predictions were made at CET for 0h-sunrise and sunset-24, with a distinction of two regions: the Southern North Sea west of Holland and 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 UTC. Therefore, for daylight saving time, midnight translates to 22:00 UTC and to 23:00 for the other period.

Expert predictions were based on predicted weather conditions (wind force 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. The expert team will also produce a report on their predictions independently.

2.4 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.

Spring 2023

The spring started in February with a relatively mild period. In general, the temperature of the spring season was not considerably different from the long-term average, only April was somewhat cooler with 8.7°C against the average of 9.8°C. The spring of 2023 was mainly exceptional in the large amount of rain that mostly fell in March and April. May also began wet with heavy showers, but in the second half of the month it became dry.

Autumn 2023

The autumn of 2023 was exceptionally mild in temperature. The first 10 days of September were exceptionally warm, sunny and mostly dry. However, thanks to a very wet October and November, this autumn was on average particularly wet (the autumn with the second most precipitation ever). Especially in November, the weather was dominated by high wind speeds.

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. Following the filtering steps described in Chapter 2.1.1, Table 3.1 describes the availability of radar data for the spring of 2023 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 2023. Data is included from the 15th of February until 31st of May. 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	Night-time		Cause of missing data	
Month	hours	days	hours	total hours	available hours	hours filtered	hours radar off
2	336	14	140	196	161	34	1
3	744	31	346	398	293	93	12
4	720	30	395	325	271	54	0
5	744	31	467	277	263	14	0

Considering the months for which the model was developed, the fraction of hours with suitable data was relatively high, varying between 74% in March (mainly due to missing data caused by heavy filtering from the middle of the month onwards) to 83% in April. The radar measurements over time are presented in Figure 3.1. The available horizontal radar data shows altogether three peaks (mean traffic rate; MTR > 500) of bird migration, on three consecutive nights in March: 17/18, 18/19 and 19/20. These three peaks captured about 4.5% of the total traffic measured by the radar (Table 3.2). For the rest of the spring, the horizontal radar measured low or very low migration intensities, all below 250 MTR (maximum MTR of 211 in April). This also holds for the month May (with a maximum MTR of 96) that did not form part of the spring period for which the migration prediction model was trained (see Box 1). In May the fraction of available data was high (95%), and hence the chance is small that elevated migration intensities were missed by the horizontal radar. This will be further discussed in Chapter 5. Next to the number of peaks, it is interesting to note that based on the horizontal radar measurements the nocturnal peaks during the spring migration refer to a single peak each night, occurring around midnight. The exact moments and the duration of these migration peaks with >500 MTRs measured by the horizontal radar in Luchterduinen are provided in Table 3.2. The measured migration peaks are discussed in more detail in 3.5.

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 and October and November for autumn. However, during the curtailment procedures, as well as in this current validation, the model was forced to make predictions also for May in spring and August and September in autumn. 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 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 September might be different than in October. 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, August and September. Hence, it is generally expected that the model performs worse in these months.

May, August and September do not show any peaks on the horizontal radar in Luchterduinen in 2023. In autumn 2022 the first peak was at the very end of September (Kraal et al. 2023). This arises the question if it is important that the months of May and August and the first part of September should be included in the curtailment procedure.

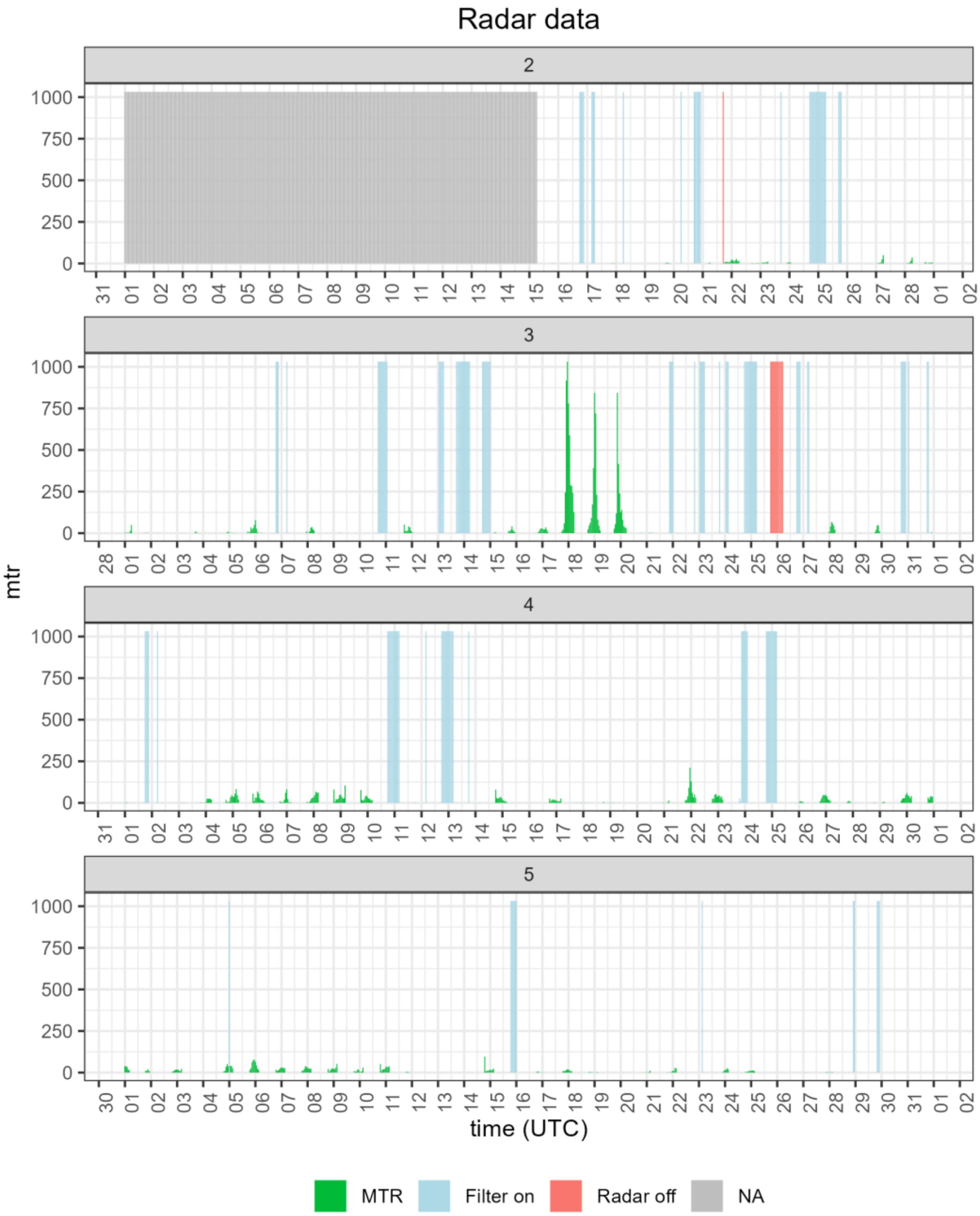

Figure 3.1 *Mean traffic rate (number of tracks/km/h) measured by the horizontal radar in Luchterduinen in the spring of 2023 (teal bars). The four graphs show per month the nocturnal (between sunset and sunrise) hours (based on UTC time) per day. In February (month 2) only the period starting from 15th is included. Periods with unavailable radar data are classified into periods of high filtering activity (blue bars), or periods where the radar was turned radar off (red bars).*

Table 3.2 Moments of peak migration (>500 MTR) and their duration measured by the horizontal radar in Luchterduinen in spring 2023.

night	start	end	duration peak (hours)	max MTR	sum MTR during peak	percentage of total MTR of the season*
17/18 March 2023	23:00	03:00	4	1032	3,317	17.74
19/20 March 2023	22:00	23:00	1	844	844	4.51
18/19 March 2023	01:00	03:00	2	843	1,563	8.36

** note that the total MTR of 18,701 was determined on a subset of hours where the horizontal the radar was turned on and not filtering too strong.*

3.2 Model predictions

The model predictions for the spring of 2023 show only a few peaks if we consider the current trigger value chosen (MTR>151). In general, the modelled MTR was higher for the months February and March. During this period, the model predicted two peak nights, namely 23/24 February and 11/12 March (Figure 3.2). Maximum modelled peak night amounted to 228 birds/km/hour (Table 3.3). Several other nights show relative high MTRs but not higher than the peak-trigger value (blue line in Figure 3.2). In general, the model predictions show 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, the two departure locations and averaging over 500 simulations (pers. comm. M. Bradariç). The migration peaks are discussed in more detail in Chapter 3.5.

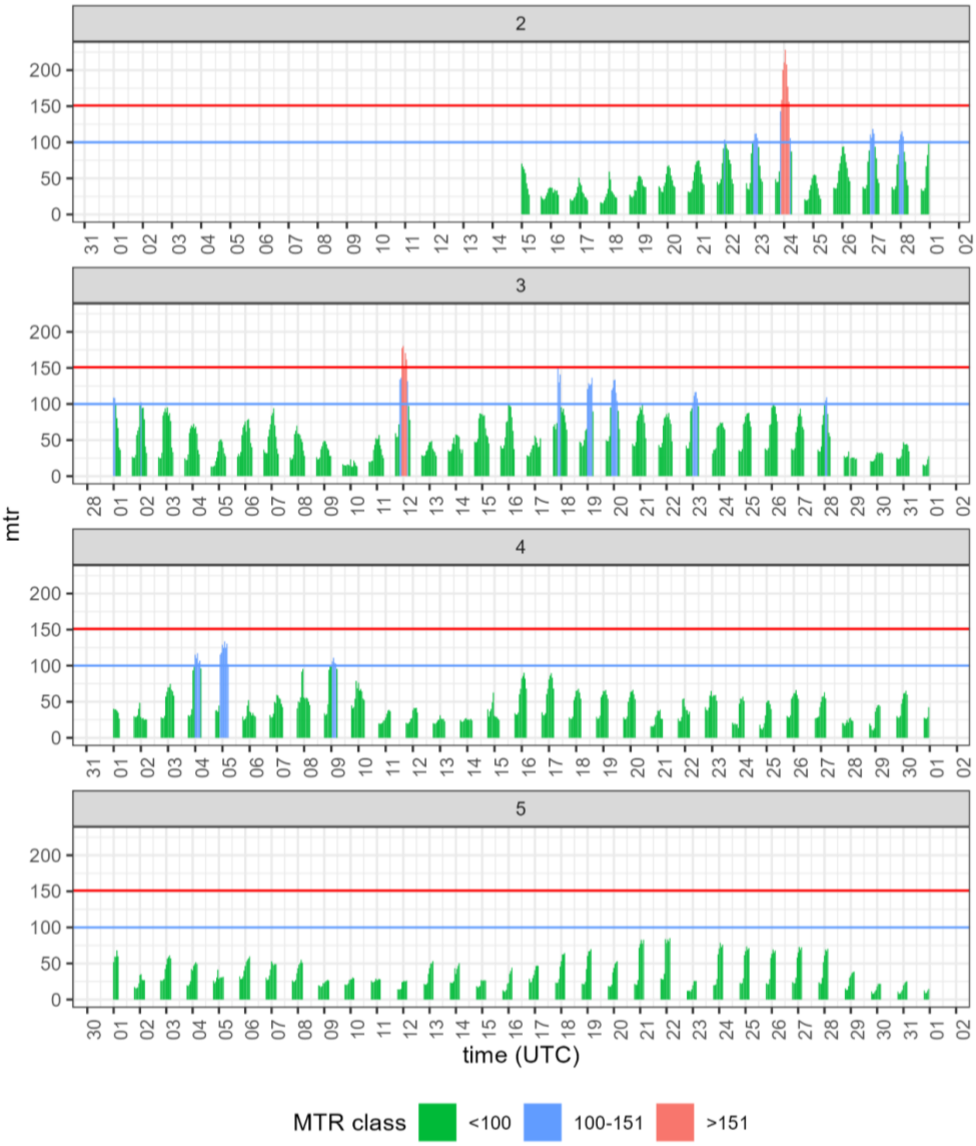

Figure 3.2 *Model predictions over time for spring (birds/km/hour) for night-time (between sunset and sunrise) hours for Luchterduinen. Traffic rates are classified by the MTR value (low rates <100 green, medium rates 100-151 and high rates >151).*

Table 3.3 *Peak nights predicted by the model, sorted by maximum mean traffic rate. Only the first two nights qualify as peak migration according to the current trigger value for spring (>151 MTR).*

Night	max MTR	start	end	duration (hours)	sum MTR during peak
02/03 February 2023	228	23:00	06:00	7	1339
11/12 March 2023	180	00:00	05:00	5	842

3.3 Expert team predictions

During the spring of 2023, the expert team made predictions each day in the period 3 March – 31 May whether a migration peak would occur, specified for the morning and evening period. Their prediction was a simple yes or no, indicating if they would expect a peak migration event. **Nineteen nights with peaks were predicted** by the expert team, most of them in March. On three nights (25/26 and 27/28 March and 12/13 May) 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 autumn. 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.

Date	Night part
03/05/2023	evening
03/11/2023	evening
03/15/2023	morning
03/15/2023	evening
03/17/2023	evening
03/25/2023	evening
03/26/2023	morning
03/27/2023	evening
03/28/2023	morning
03/28/2023	evening
04/04/2023	evening
04/06/2023	evening
04/08/2023	morning
05/04/2023	morning
05/04/2023	evening
05/12/2023	morning
05/12/2023	evening
05/13/2023	morning
05/13/2023	evening

3.4 Comparing predictions and radar measurements

3.4.1 Predictions and measurements over time

In this chapter we compare the radar measurements with the model predictions for the spring season. Figure 3.3 depicts both radar measurements and the model predictions, next to the expert team predictions. Note the two vertical axes in this figure, which already indicates a major difference in the radar measurements and the model predictions: the maximum peak of the radar measurements reaches up to 1,032 tracks/km/hr, where the maximum peak of the model predictions was an MTR of 228 birds/km/hr. These overall lower MTR predictions by the model were already known and have been reported before (Kraal *et al.* 2023) and are here confirmed again.

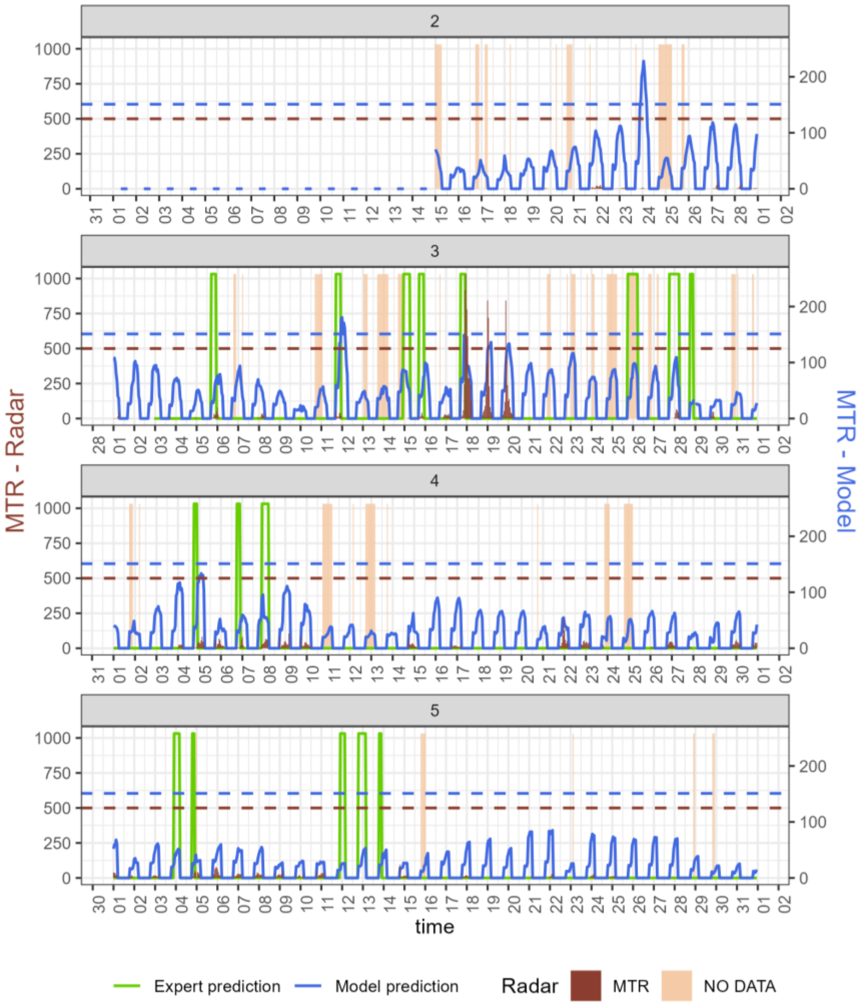

Figure 3.3 *Merged results of horizontal radar measurements in Luchterduinen (brown), predictions by the model (blue) and the expert team (green) for the period of 15 February – 31 May. Note the two vertical axes: left axis refers to the radar measurements (brown) and the right axis to the model prediction (blue). Green lines indicate the moment of peak migration (>500 MTR) predicted by the expert team, without an exact value. Brown dashed line shows the threshold of 500 MTR for the radar measurements, blue dashed line the trigger value of 151 MTR for the model predictions.*

Table 3.5 summarizes the outcome of the comparison of the radar measurements and the predictions by the model and the expert team. The nights in the table are ordered according to the measurements of the horizontal radar. None of the top five measurements of the horizontal radar (of which three qualified as peak migration nights with >500 MTR) were also predicted by the model as peaks. However, the predictions for 17/18, 18/19 and 19/20 March almost reached the trigger value of >151 MTR for the model. Of the top five radar measurements one was predicted by the expert team to be a migration peak.

Table 3.5 All peak nights of spring 2023 measured by horizontal radar (>500MTR) and predicted by the model (>151 MTR) and expert team (>500 MTR per period of the night). Peaks are coloured in red. High traffic rates are the nights that rank top five of peak nights, but do not reach the trigger value. These are marked orange. Yellow indicates that the horizontal radar did not produce a full night of data.

		Maximum MTR		Expert Prediction		Rank	
Night	Peak based on	Hor. Radar	Model	Evening	Morning	Hor. Radar	Model
17/18 March	radar (model) expert	1,032	149	1	0	1	3
19/20 March	radar (model)	844	134	0	0	2	6
18/19 March	radar (model)	843	136	0	0	3	4
21/22 April	(radar)	211	55	0	0	4	67
08/09 April	(radar)	105	111	0	0	5	12
04/05 April	model expert	83	134	1	0	7	5
06/07 April	expert	81	59	1	0	8	59
05/06 March	expert	79	79	1	0	10	32
07/08 April	expert	67	95	0	1	14	20
27/28 March	expert	67	109	1	1	15	13
11/12 March	model expert	52	180	1	0	18	2
04/05 May	expert	51	41	1	0	20	86
15/16 March	expert	41	99	1	0	26	17
23/24 February	model	8	228			51	1
11/12 May	expert	6	26	0	1	54	102
14/15 March	expert	4	87	0	1	59	29
28/29 March	expert	1	34	1	0	75	93
12/13 May	expert	0	53	1	1	78	69
13/14 May	expert	0	50	1	0	79	77
03/04 May	expert	0	52	0	1	82	73
25/26 March	expert	0	98	1	1	98	19

On the other hand, at the moments of the highest model predictions (2 exceeding the trigger value of 151 MTR), the horizontal radar produced MTR measurements 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 5. The expert team predictions matched in one case the model predictions (11/12 March).

3.4.2 Comparison of MTR distributions

The summary of Table 3.5 is based on a classification of migration peaks for the horizontal radar and for the model. However, there is in fact no absolute value to define what a migration peak is. Figure 3.4 shows which percentage of the radar measurements classifies as peak migration as a certain proportion of all the measurements. Based on this graph, the current thresholds for classifying peak migration of >500 MTR for the radar leaves less than 1% of all measurements (cut-off value of 289 MTR for 99% of all measurements) in the spring of 2023. The current trigger value for the model predictions of >151 MTR does match approximately the 99% cut-off point (158 MTR). In other words, the current trigger value refers approximately to the top 1% of the model predictions of spring 2023.

Figure 3.4 also provides a further insight in the pattern of the model predictions relative to the radar measurements (also visible in Figure 3.3). The histograms show the distribution of all MTR values that were measured in spring 2023. Red lines within the histograms indicate a certain percentage of the data that is above and below that line. The histograms differ a lot in their shape. The radar data (left panel) showed a lot of low values suggesting that there were relatively many hours where no or a limited number of birds were passing by. There were only a few hours with large numbers of birds (peak migration moments). In contrast, the model data showed in general a more constant and lower MTR (around 30). There were a limited number of hours with zero activity and a limited number of higher values (>151). In other words: the model predicted more evenly distributed migration, while the radar commonly indicated low migration intensities with a few peaks, more resembling autumn migration. However, this may be due to specific weather circumstances during the spring of 2023 and not a general pattern of the spring migration phenology.

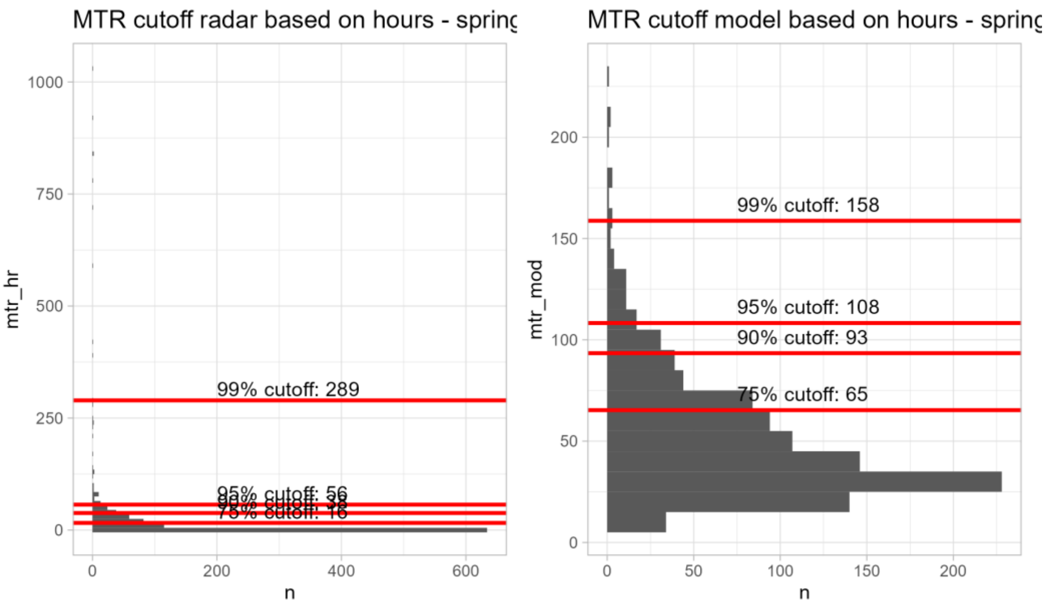

Figure 3.4 *Histograms of hourly MTRs predicted by the model (left) and measured by the horizontal radar (right) for the nights of spring 2023. The horizontal red lines indicate different percentiles. For instance, the 99% cut-off line means that 1% of the hours is above this line and 99% is beneath it.*

This is supported by Figure 3.5 which depicts the maximum MTR for the top 20 nights within the study period of spring 2023. Again, the panel showing the maximum MTRs of the radar has a few high bars, followed by a lot of relatively low bars. This, again, indicates that there are only a few nights with high measured MTRs and that the flight intensity is rather low on the other nights. The same figure shows that there are a lot of nights with very similar maximum MTR predictions according to the model. The nights with the highest predicted MTRs do not differ a lot from the other nights. In conclusion, the radar peaks are far more accentuated than the model peaks.

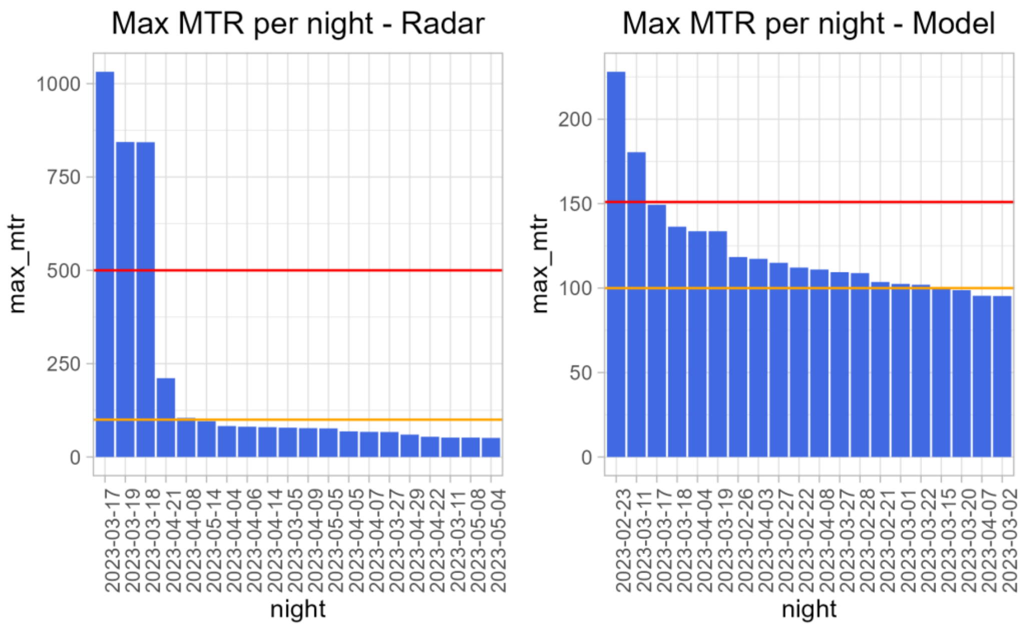

Figure 3.5 *Maximum MTR per night according to the radar (left panel) and the bird migration prediction model (right panel). Red lines in both panels indicate the migration peak threshold for radar and the trigger value for model predictions. Orange lines indicate the threshold used in this report for hours to be marked as 'increased traffic'. Max_mtr stands for the maximum MTR within a night. Nights are indicated with the date on which the night started.*

3.4.3 Curtailment moments of spring 2023

Curtailment in spring 2023 of the offshore wind farms was carried out to test the curtailment procedure. These curtailment moments were not chosen based on model predictions. The first of the two curtailments took place during a night on which the expert team predicted a peak. Table 3.6 provides the exact curtailment moments. During none of the two moments did the horizontal radar predict a peak.

Table 3.6 *Curtailment moments of spring 2023.*

time start (local time)	time end (local time)	duration (hr)
2023-05-13 00:00:00	2023-05-13 04:00:00	4
2023-05-25 02:00:00	2023-05-25 03:00:00	1

3.5 Migration peaks in detail

In this chapter, we examine the relevant migration moments of spring 2023 in more detail. As described in the previous chapter, during none of the moments when according to the horizontal radar migration intensities were >500 MTR did the model predict flight intensities that exceeded the trigger value of 151 MTR. Basically, all of these moments could therefore qualify as ***false negative*** predictions: the model did not predict intense migration, while in reality it did take place. On the contrary, the model predicted migration peaks that were not detected by the horizontal radar two moments. Both moments qualify as ***false positive*** predictions: the model predicted a migration peak exceeding the trigger value of 151 MTR, but no peak was measured by the horizontal radar. In this chapter, we analyse in more detail whether these harsh definitions of false negative and false positive predictions hold for the migration moments of spring 2023.

3.5.1 Migration peaks measured by the horizontal radar

In the spring of 2023, the horizontal radar detected three nights with migration peaks (MTR > 500). For each of these nights, we present the hourly trend in MTR, and compare this with the model- and expert team predictions.

Nights of 17/18 until 19/20 March

The peak nights according to the horizontal radar are three successive nights, namely 17/18, 18/19 and 19/20 March. Figure 3.6 shows the radar measurements for those nights along with the model predictions and expert predictions. The night of 17/18 March had the highest measured maximum bird activity, followed by 19/20 March and then 18/19 March. On none of the three nights had the model predicted MTRs above the trigger value of 151 birds/km/h. However, it predicted MTR values very close to the trigger value on 17/18 March, with a maximum MTR value of 149 birds/km/h. The exact timing of the model's peak prediction was almost right, with a small peak (just below the trigger value) two hours before midnight and a small peak one hour after midnight (UTC). According to the horizontal radar, the peak actually happened from one hour before midnight until one hour after midnight (UTC). That night, the expert prediction also predicted a migration peak. The expert team predicted the peak, however, before midnight and therefore only entailed one of the two hours that exceeded the threshold.

On 18/19 and 19/20 March, the model predicted relatively high MTRs as well, but were a little further off from the trigger value. Also, the timing of the peak during the night according to the model was a bit more inaccurate. On 18/19 March, the horizontal radar measured a peak one hour after midnight, while the model predicted its highest MTR a few hours later. On 19/20 March, the model did predict its highest MTR around midnight, but that night the peak actually occurred a few hours earlier. None of these nights were predicted to be a peak by the expert team.

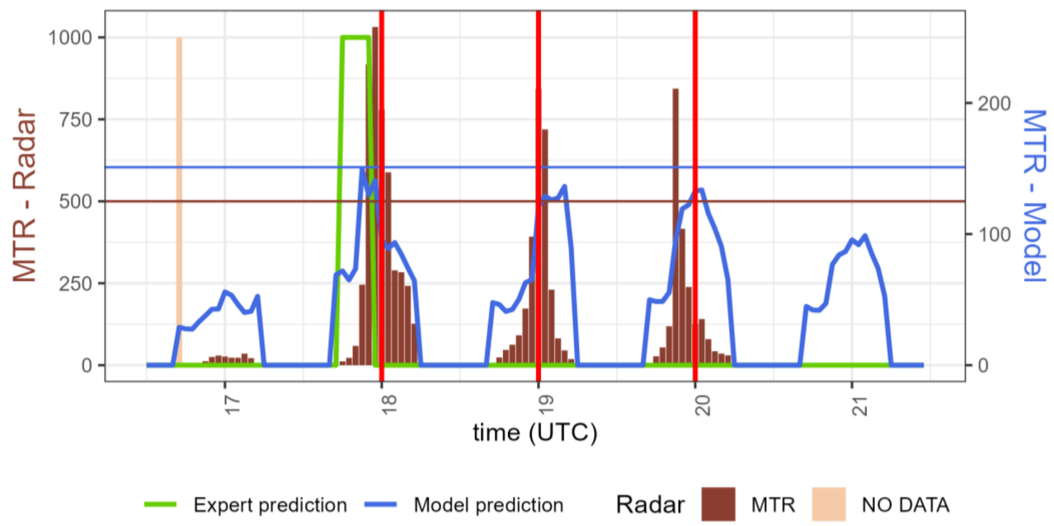

Figure 3.6 *Comparison of hourly radar measurements, hourly model prediction and expert prediction (per 4 hours), for the nights starting at March 17 until March 19 2023 and the surrounding nights. Horizontal lines present the threshold for peak classification for radar (left y-axis) and the trigger value for the model (right y-axis). The expert prediction is a yes/no-decision, with green blocks for each four-hour period for which the experts predicted a peak.*

3.5.2 Peaks in model predictions

The model has predicted a high peak for the night of 23/24 February and for 11/12 March. However, the horizontal radar showed hardly any bird flight activity (Figure 3.7). Unfortunately, the expert team did not make predictions for the month of February but did predict a peak on 11 March just before midnight (Figure 3.7). The predicted peaks by the model were both around midnight (UTC). The peak predicted on 23/24 February was the longest, from 22:00 until 5:00 (UTC). The peak on 11/12 March was predicted from 23:00 until 4:00 (UTC). The latter moment had two separate peaks but the hour between it also exceeded the trigger value of 151 birds/km/hour (Figure 3.7).

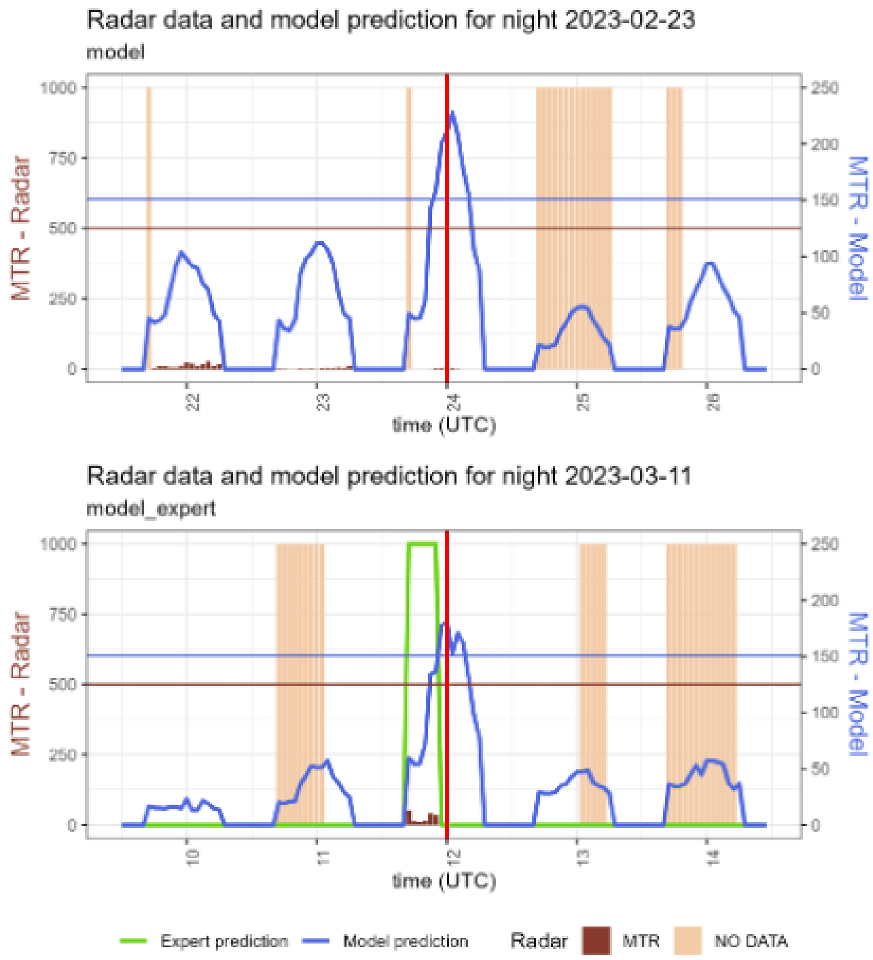

Figure 3.7 *Comparison of hourly radar measurements, hourly model prediction and expert prediction (per 4 hours), for the nights starting at 23 February and 11 March 2023 and the surrounding nights. Horizontal lines represent the threshold for peak classification for radar (left y-axis) and the trigger value for the model (right y-axis). The expert prediction is a yes/no-decision, with green blocks for each four-hour period for which the experts predicted a peak.*

4 Basic validation of the autumn migration model

4.1 General patterns measured by the horizontal radar

The autumn migration prediction model was developed for the period of 1 October – 30 November (Bradarić 2022), but the validation was requested to be carried out for the period 15 August – 30 November. Following the filtering steps described in Chapter 2.1.1, Table 4.1 describes the availability of radar data for the autumn of 2023 that was used for validation purposes.

Table 4.1 *Overview of hours in the radar dataset with suitable horizontal radar data. Data is included from the 15th of August until 30th of November. 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	Night-time		Cause of missing data	
Month	days	hours	hours	total hours	available hours	hours filtered	hours radar off
8	17	408	232	176	158	8	10
9	30	720	360	360	206	42	112
10	31	744	309	435	237	153	45
11	30	720	244	476	150	280	46

Considering the months of October and November for which the model was developed, 237 nightly hours with suitable data were available for October (54%) and 150 hours for November (32%). In these two months, the low availability of suitable data was mainly due to hours when data were discarded during the filtering steps (Table 4.1). In August 84% and in September 57% of the night-time radar data was available. The radar measurements over time are presented in Figure 4.1. The large number of nightly hours unavailable for validation purposes (red bars), is also clear from this graph. The available horizontal radar data shows altogether **three peaks** (during which MTR > 500) of bird migration: one peak in October (night of 25/26 October), and two peaks in November (nights of 11/12 November and 16/17 November). These three peaks captured together 17.9% of the total measured MTR (Table 4.2). The total measured MTR of 29142 was determined for hours where the radar was functioning properly and was not having difficulties with high filtering due to e.g. rain. In November the horizontal radar indicated two additional moments with increased migration traffic rates (MTR between 200 and 500; evening of 17 November and night of 21/22 November), while the horizontal radar measured for the rest of the autumn migration

intensities below 200 MTR. Note that for the months August and September, not any elevated migration intensities were measured by the horizontal radar.
Furthermore, it is interesting to note that based on the horizontal radar measurements the three nocturnal peaks during the autumn migration of 2023 referred to a single peak each night, occurring either shortly after sunset or around midnight. The exact moments and the duration of these peaks with >500 MTRs are provided in **Error! Reference source not found.**. The measured migration peaks are discussed in more detail in Chapter 4.5.

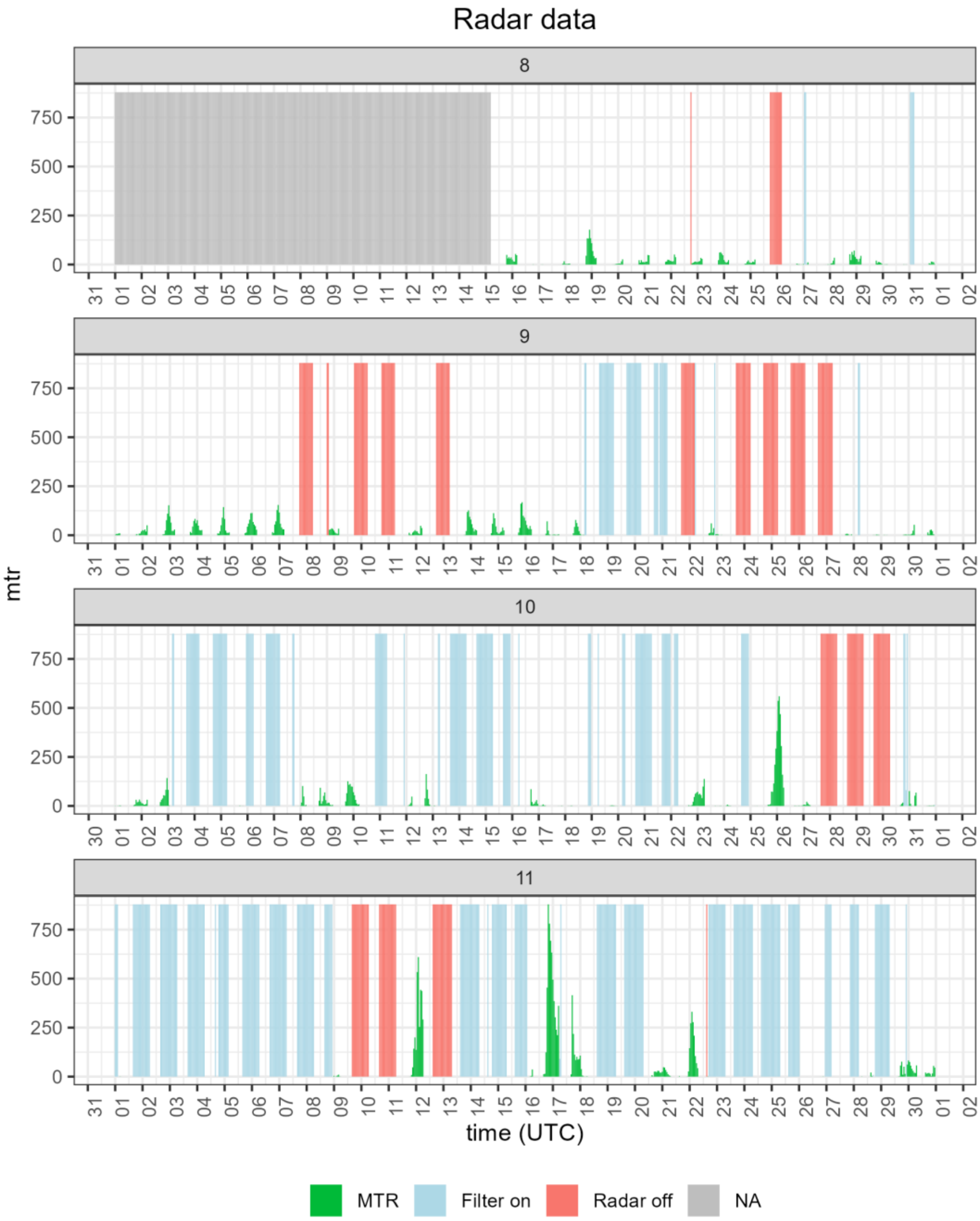

Figure 4.1 *Hourly mean traffic rate (number of tracks/km/h) measured by the horizontal radar in Luchterduinen (green bars). The four graphs show per month the nocturnal (between sunset and sunrise) hours (based on UTC time) per day. Periods with unavailable radar data are classified into periods of high filtering activity (blue bars), or periods where the radar was turned radar off (red bars)). red bars.*

Table 4.2 Moments of peak migration (>500 MTR) and their duration measured by the horizontal radar in Luchterduinen in autumn 2023.

date	start	End	duration of peak (hours)	max MTR	sum MTR during peak	percentage of total MTR of the season*
16/17 November	21:00	01:00	4	879	2,986	10.2
11/12 November	02:00	04:00	2	610	1,144	3.93
25/26 October	03:00	05:00	2	559	1,096	3.76

** note that the total mtr of 29142 was determined on a subset of hours where the horizontal the radar was turned on and not filtering too strong.*

4.2 Model predictions

Although the model was developed for the months October and November, we were requested to run the model also for the period 15 August – 30 September (since the curtailment requirements are also for this period). Therefore, Figure 4.2 presents the model predictions over time for the autumn of 2023 for the period 15 August – 30 November. Note that for the predictive model, any hour with an estimated MTR of 173 or higher is classified as a peak hour. Based on this criterium, the model predicted migration peaks in October and November, but also in August and September. Besides these peaks, the model predicted for all days some bird movements and for the whole period of 15 August – 30 November regular medium levels of migration intensity (Figure 4.2). In general, the model predictions show a similar temporal pattern for all autumn nights: a higher number of birds at the start of the night and a smaller second increase in numbers at the end of the night (see in contrast the radar measurements with one peak in the spring (Chapter 3.1)). This pattern is expectedly caused by hourly phenology used for the model, the departure locations and averaging over 500 simulations (pers. comm. M Bradaric). The predicted migration peaks are discussed in more detail in Chapter 4.5.

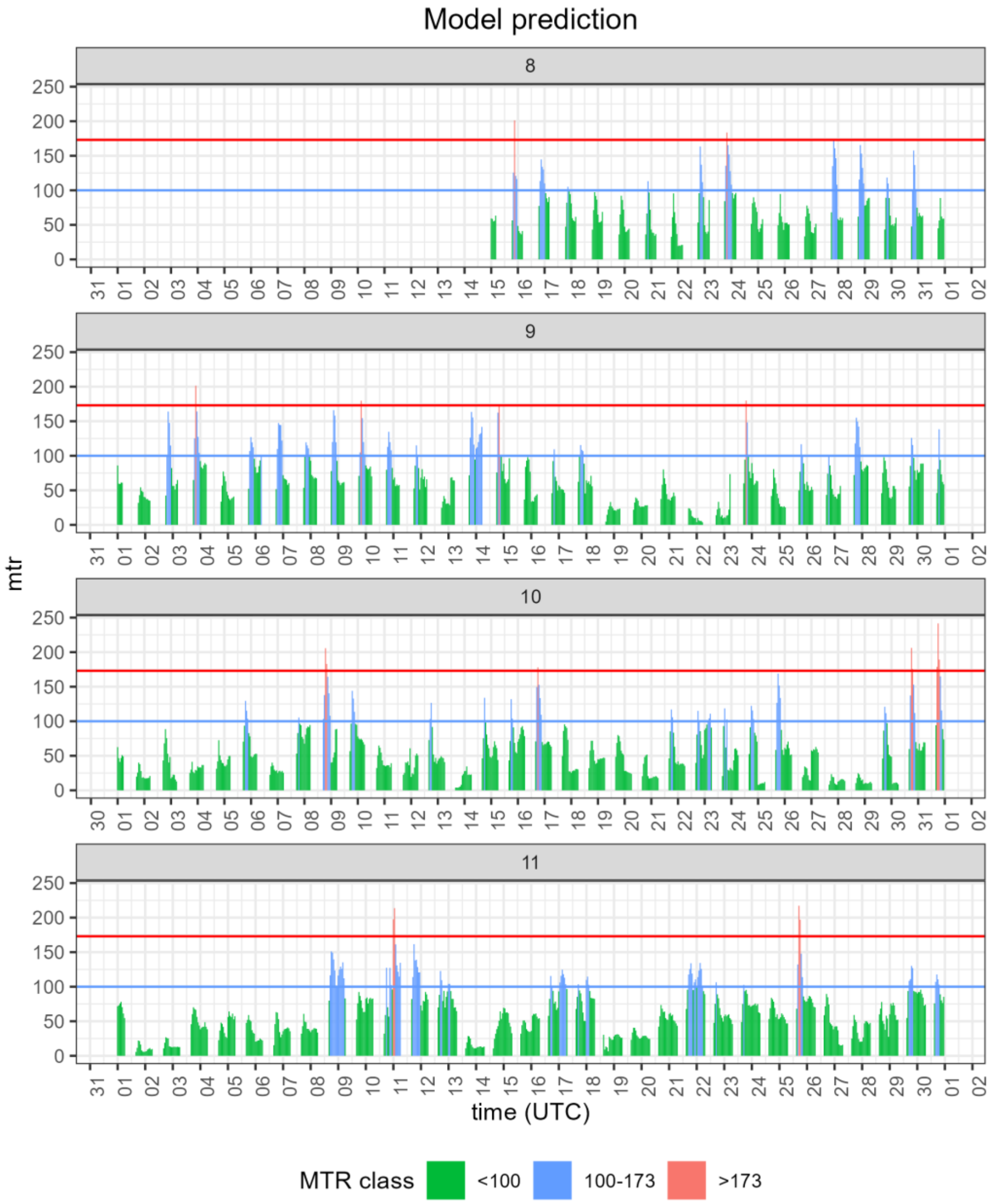

Figure 4.2 *Modelled mean traffic rates (birds/km/hour) for night-time hours for Luchterduinen in the period of 15 August – 30 November. Note that the model was trained exclusively for October and November. Traffic rates are classified by MTR value (low rates <100 green, medium rates 100-173 and high rates >173).*

All in all, from the modelled bird migration we can distinguish **12 nights with predicted peak migration** (MTR>=173) shown in Table 4.3.

Table 4.3 Overview of the moments predicted by the model (ranked by maximum mean traffic rate) as peak migration nights (>173 MTR) for the period of 15 August – 30 November. Note that the model was trained exclusively for October and November.

night	start	end	max MTR during peak	sum MTR during peak	duration peak (hours)	mean MTR during night
31 October/ 01 November	18:00	21:00	242	610	3	109
25/26 November	18:00	20:00	217	414	2	103
10/11 November	01:00	03:00	214	411	2	116
30/31 October	21:00	23:00	206	389	2	94
08/09 October	19:00	21:00	206	382	2	108
03/04 September	23:00	00:00	201	201	1	111
15/16 August	22:00	23:00	201	201	1	83
23/24 August	22:00	23:00	184	184	1	121
23/24 September	22:00	23:00	180	180	1	87
09/10 September	21:00	23:00	180	180	1	101
16/17 October	20:00	21:00	178	178	1	93
14/15 September	22:00	23:00	173	173	1	94

4.3 Expert team predictions

During the autumn of 2023, in the period September to November, the expert team daily predicted whether a migration peak (defined as an >500 MTR) would occur, specified for the morning and evening period. **Ten nights with peaks were predicted** by the expert team, most of them in October. On two nights (16/17 October and 16/17 November) two migration peaks were predicted for the same night: one in the evening and one in the morning (Table 4.4).

Table 4.4 Expert team predictions of peak migration moments in the autumn of 2023. The expert team made predictions for two parts of the night: evening refers to the period from sunset to 00:00, and morning from 00:00 to sunrise.

Night	period
07/08 October	morning
08/09 October	evening
12/13 October	evening
15/16 October	morning
16/17 October	evening
16/17 October	morning
17/18 October	evening
25/26 October	evening
31 October/ 01 November	evening
16/17 November	evening
16/17 November	morning
17/18 November	evening

4.4 Comparing predictions and radar measurements

In this chapter we compare the radar measurements with the model predictions and the expert predictions for the autumn season.

4.4.1 Predictions and radar measurements over time

Figure 4.3 depicts both radar measurements and the model predictions, next to the expert team predictions. Note the two vertical axes in this figure, which already indicates a major difference in the radar measurements and the model predictions: the maximum peak of the radar measurements reaches up to 880 tracks/km/hr, whereas the maximum peak of the model predictions was an MTR of 242 birds/km/hr. These overall lower MTR predictions by the model were already known and have been reported before (Kraal *et al.* 2023) and are here confirmed again.

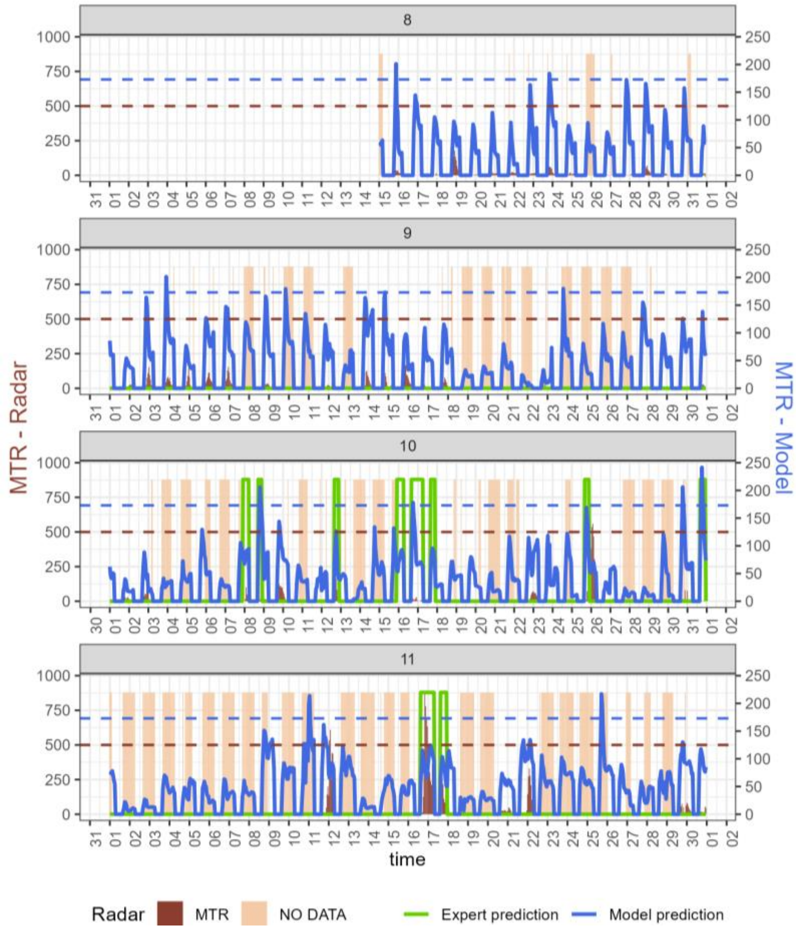

Figure 4.3 *Merged results of horizontal radar measurements in Luchterduinen (brown), predictions by the model (blue) and the expert team (green) for the period of 15 August – 30 November. Note the two vertical axes: left axis refers to the radar measurements (brown) and the right axis to the model prediction (blue). Green lines indicate the moment of peak migration predicted by the expert team, without an exact value. Brown dashed line shows the threshold of 500 MTR for the radar measurements, blue dashed line the trigger value of 173 MTR for the model predictions.*

Table 4.5 summarizes the outcome of the comparison of the radar measurements and the predictions by the model and the expert team. The nights in the table are ordered according to the horizontal radar measurements, which makes it directly clear that none of the top five measurements of the horizontal radar (of which three qualified as peak migration nights with >500 MTR) were also predicted by the model as peaks, although the predictions for 11/12 November and 25/26 October almost reached the trigger value of >173 MTR for the model. Of the top five radar measurements, the expert group predicted three to be a migration peak. On the other hand, whenever the model predicted a peak (12 predictions exceeding the trigger value of 173 MTR), the horizontal radar measured low MTRs (note that for three moments no radar data were available). The expert team predictions matched in three cases the model predictions.

Table 4.5 Dates (i.e. indicating the beginning of the night) of autumn 2023 (ordered by the horizontal radar measurements) when peak migration intensities were measured by the horizontal radar (>500 MTR) or predicted either by the model (>173 MTR) or the expert team (per period) for the period of 15 August – 30 November. Note that the model was trained exclusively for October and November. Grey shading of dates indicates nights with curtailment. Measured or predicted intensities that qualify as peaks are indicated by a red colour. Traffic rates that were high but did not qualify as a peak are indicated by an orange colour. NA indicates no radar data available for these nights. Yellow colours indicate that horizontal radar data were not available for the whole night. The last two columns provide the rank of the measurements for the horizontal radar and the model predictions based on all available data.

		Maximum MTR		Expert prediction		Rank	
Night	Peak based on	Hor. Radar	Model	Evening	Morning	Hor. Radar	Model
16/17 November	radar + expert	879	125	1	1	1	37
11/12 November	radar + (model)	610	162	0	0	2	20
25/26 October	radar + expert + (model)	559	169	1	0	3	14
17/18 November	(radar) + expert	415	115	1	0	4	50
21/22 November	(radar) + expert	331	134	0	0	5	29
12/13 October	expert	162	127	1	0	8	35
14/15 September	model	112	173	0	0	17	12
07/08 October	expert	101	105	0	1	18	54
08/09 October	model + expert	93	206	1	0	19	5
16/17 October	model + expert	85	178	1	1	20	11
03/04 September	model	83	201	0	0	21	6
30/31 October	model	80	206	0	0	23	4
23/24 August	model	63	184	0	0	27	8
15/16 August	model	54	201	0	0	30	7
31 October / 01 November	model + expert	5	242	1	0	55	1
17/18 October	expert	1	96	1	0	59	61
15/16 October	expert	0	132	0	1	66	31
25/26 November	model	0	217	0	0	71	2
10/11 November	model	NA	214	0	0	73	3
23/24 September	model	NA	180	0	0	74	9
09/10 September	model	NA	180	0	0	75	10

4.4.2 Curtailment moments autumn 2023

Dates of curtailments are indicated in Table 4.55 by a grey colour, which makes it clear that during curtailments in the autumn 2023 the horizontal radar did not measure high MTRs. Table 4.6 provides the exact curtailment moments.

Table 4.6 Curtailment moments of autumn 2c 023.

time start (local time)	time end (local time)	duration (hr)
2023-10-08 21:00:00	2023-10-09 00:00:00	3
2023-10-16 19:00:00	2023-10-16 22:00:00	3
2023-10-31 18:00:00	2023-10-31 21:00:00	3

Table 4.7 shows the cumulative MTRs measured by the horizontal radar in Luchterduinen during the autumn of 2023, with specifications of the cumulative MTRs during the peak migration moments as indicated by the radar, but also the MTRs during the actual curtailment hours. The reported total MTRs are based on the available hours and are not corrected for the missing hours. However, the figures clearly show that a large fraction of the total bird migration passed by during the peak moments: 15% in October and 32% in November, the two months for which also the predictive model was developed. Considering these months, altogether 26% of all bird migration passed by during the peak moments. Curtailment took place based on the model- and the expert team predictions. As indicated earlier, during these moments horizontal radar data were either not available or showed low MTRs. **In contrast, the vertical radar did show a peak during two of the three nights on which curtailment has taken place, which is discussed in Chapter 5.**

Table 4.7 Overview of cumulative MTRs measured by the horizontal radar in the autumn months of 2023 and during peak migration- and curtailment hours. <u>Hours where horizontal radar was not operational or filtering was too strong were not included</u>.

	total MTR	Peaks		MTR during	%MTR	curtailment	total MTR
month	per month	N	hours	peak migration hours	of total per month	hours	during curtailment
8	3,093	0	0	0		0	0
9	6,225	0	0	0		0	0
10	7,151	1	2	1,096	15%	9	202
11	12,873	2	6	4,129	32%	0	0

4.4.3 Definition of peak threshold

The summary of Table 4.5 is based on a pre-defined thresholds (radar) and trigger values (model) for migration peaks, being MTR > 500 for the horizontal radar and a predicted MTR > 173 for the model. However, the definition of a migration peak is disputable, as what exactly qualifies as a migration peak? The radar measurements clearly show a number of moments when significantly more birds pass by than during the rest of the season. Figure 4.4 shows that the current threshold of >500 MTR for the radar data matches 1% of all radar measurements (99% cut-off) in the autumn of 2023. For the model predictions, the classification of migration peaks is more difficult, but it may also be defined as a certain proportion of all predictions. As Figure 4.4 shows, the current trigger value of >173 MTR for the model is close to the 99% cut-off point (183 MTR) and hence match the cut-off value (536 MTR) of the radar measurements for the autumn of 2023 that comes closest to the threshold of 500 MTR. In other words, the current threshold and trigger value refer to the top 1% of all radar measurements and model predictions of autumn 2023.

Figure 4.4 provides also a further insight in the pattern of the model predictions relative to the radar measurements (also visible in Figure 4.3): the model seems to predict a relatively stable MTR with small fluctuations, while the radar measurements indicate large fluctuations, with many hours of low to very low MTRs and a relatively much lower number of hours with medium to high MTRs. Hence, the peaks in the model predictions do not largely deviate from the remainder of the predictions, while these differences can be rather extreme in the radar data.

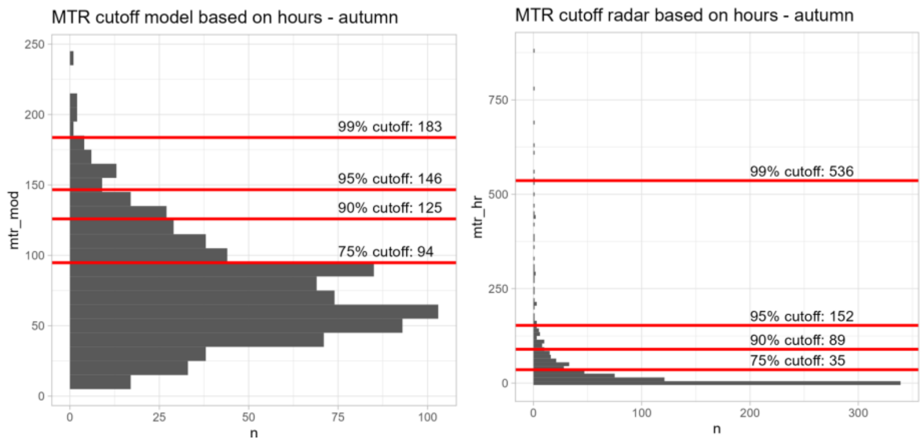

Figure 4.4 *Histograms of hourly MTRs predicted by the model (left) and measured by the horizontal radar based on the filtered dataset (right) for the nights of autumn 2023. The horizontal red lines indicate different cut-off percentiles.*

4.5 Migration peaks in detail

In this chapter, we examine the relevant migration moments of autumn 2023 in more detail. As described in the previous chapter, during none of the moments when according to the horizontal radar migration intensities were >500 MTR did the model predict flight intensities that exceeded the trigger value of 173 MTR. Basically, all three of these moments could therefore qualify as ***false negative*** predictions: the model did not predict intense migration, while in reality it did take place. On the contrary, the model predicted migration peaks that were not detected by the horizontal radar at 12 moments. Nine of these qualify as ***false positive*** predictions: the model predicted a migration peak exceeding the trigger value of 173 MTR, but no peak was measured by the horizontal radar. In three cases where the model predicted a peak, the horizontal radar was either not operational or data were filtered out. In this chapter, we analyse in more detail whether these harsh definitions of false negative and false positive predictions hold for the migration moments of autumn 2023.

4.5.1 Migration peaks measured by the horizontal radar

In the autumn of 2023, the horizontal radar detected three nights with migration peaks (MTR > 500). For each of these nights, we present the hourly trend in MTR, and compare this with the model- and expert team predictions. Nights are ordered based on radar measurements, starting with the night with the highest peak according to the radar.

Night of 16/17 November 2023

During the autumn season 2023, the highest peak in MTRs measured by the horizontal radar was during the night of 16/17 November. The peak was reached shortly after sunset and the migration intensity gradually decreased afterwards (Figure 4.5). The model predicted high MTRs relative to the surrounding days of about 130 MTR with two comparable peaks during the night, but the predictions did not reach the trigger value of >173 MTR. The expert team predicted a peak migration intensity for this night as well, both for the first as for the second half of the night (Figure 4.5).

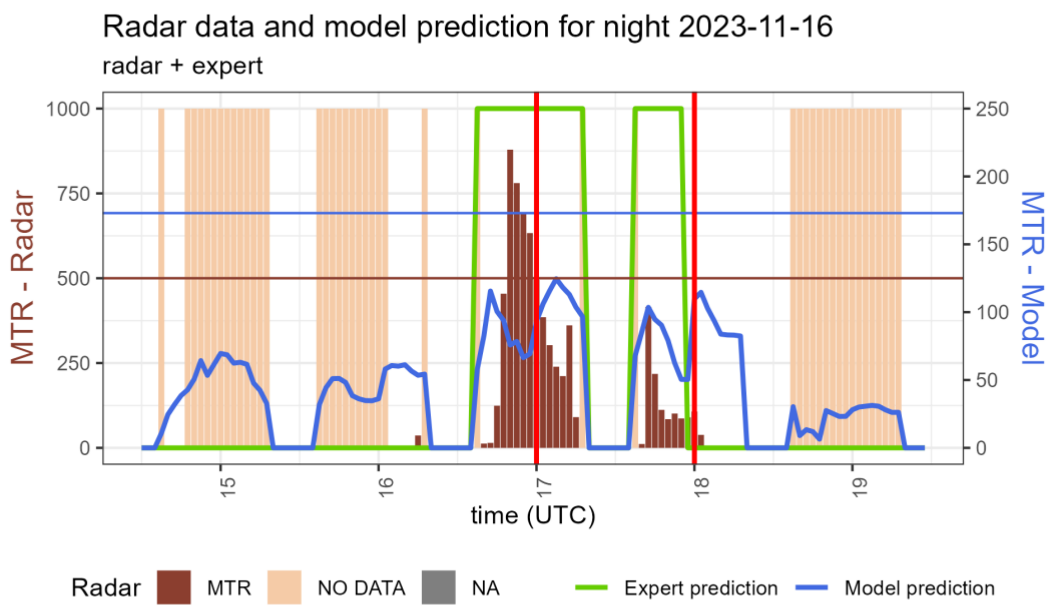

Figure 4.5 *Comparison of hourly radar measurements, hourly model prediction and expert prediction for the peak night at November 16/17 2023 and the surrounding days. Horizontal lines present the threshold for peak classification for radar (left y-axis) and the trigger value for the model (right y-axis). The expert prediction is a yes/no-decision, with green blocks for the evening and/or morning. Red lines represent midnight of the nights discussed.*

Nights of 11/12 and 10/11 November

The radar measurements indicated the second highest peak in bird migration for the night of 11/12 November, namely in the second half of the night (Figure 4.6). Although the model also predicted an increased traffic rate, the peak was just below the trigger value of 173 MTR. Moreover, the highest MTRs in the model predictions occurred in the first half of the night, with only a smaller second peak in the second half of the night. Interestingly, the model predicted migration traffic rates exceeding the trigger value for the night before, 10/11 November. Unfortunately, the radar was not operational that night, and hence no radar data were available for validation purposes (Figure 4.6).

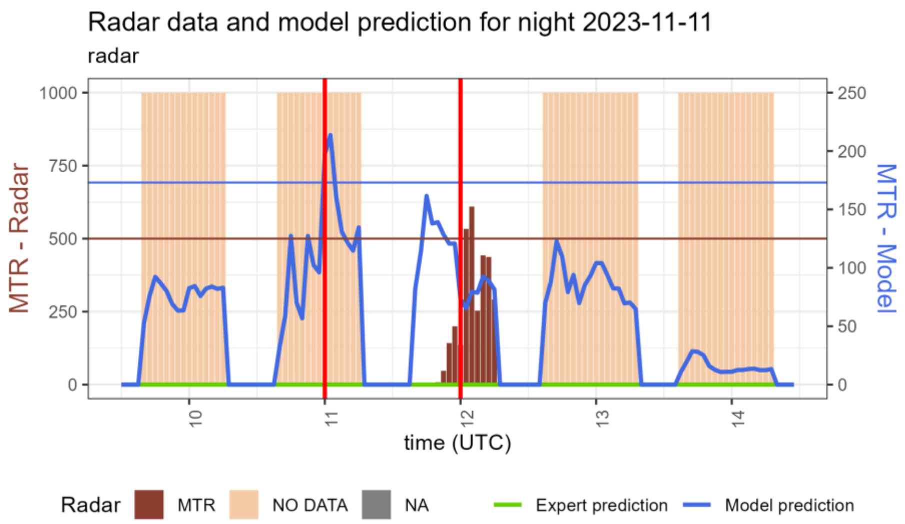

Figure 4.6 *Comparison of hourly radar measurements, hourly model prediction and expert prediction , for the peak night at November 11/12 2023 and the surrounding days. Horizontal lines present the threshold for peak classification for radar (left y-axis) and the trigger value for the model (right y-axis). The expert prediction is a yes/no-decision, with green blocks for the evening and/or morning. Red lines represent midnight of the nights discussed.*

Night of 25/26 October 2023

The horizontal radar measured high migration intensities during the second half of the night of 25/26 October, exceeding the threshold of 500 MTR in 2 consecutive hours (Figure 4.7). Although the model also indicated higher bird traffic (maximum 169 MTR, being 38% higher than the maximum value the night before), it just did not reach the trigger value of 173 MTR. Moreover, the highest predicted MTRs of the model only occurred in the first half of the night, matching the predictions of the expert team, but not of the MTRs measured by the horizontal radar (Figure 4.7).

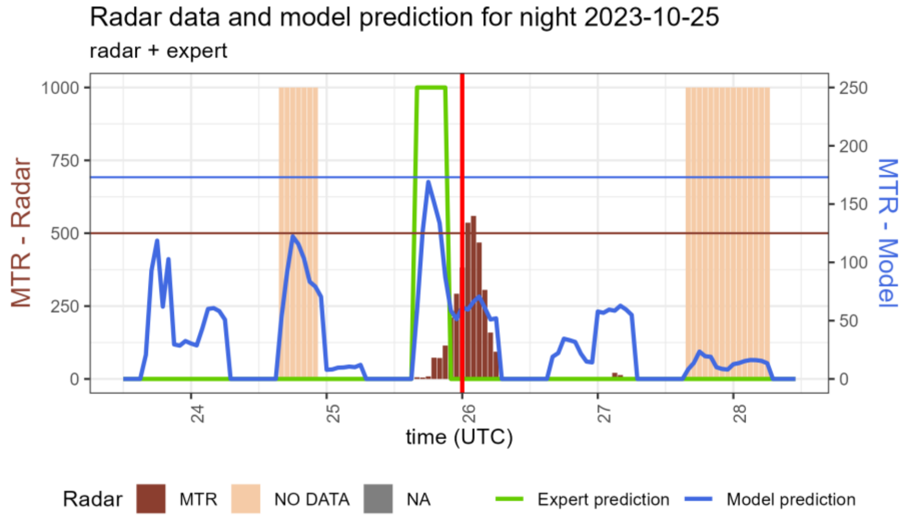

Figure 4.7 *Comparison of hourly radar measurements, hourly model prediction and expert prediction , for the peak night at October 25/26 2023 and the surrounding days. Horizontal lines present the threshold for peak classification for radar (left y-axis) and the trigger value for the model (right y-axis). The expert prediction is a yes/no-decision, with green blocks for the evening and/or morning. Red lines represent midnight of the nights discussed.*

Summary

In summary, the model predicted elevated migration intensities for all the three migration peaks measured by the horizontal radar, but none of these predictions reached the trigger value of 173 MTR. Furthermore, the model predictions of the temporal pattern of migration during these nights deviated from the horizontal radar measurements. For all three nights, the migration peak measured by the radar occurred later than the first peak of the night predicted by the model. In Chapter 5, we further discuss the possible mismatches between radar measurements and model predictions.

4.5.2 Peaks in model predictions

In total, the model predicted 12 peak nights in the autumn of 2023. The temporal pattern of the model predictions and horizontal radar measurements for these nights are presented in Figure 4.8 and Figure 4.9. As mentioned in the previous paragraphs, during none of these nights did the horizontal radar detect a peak in bird migration. However, the expert team concurred with the model on three occasions.

For most nights, the model predicted a peak just before midnight (UTC) after which the peak quickly declined. Only on the night of 10/11 November did the model predict a peak just after midnight. On nights where the expert team concurred with the model, they also predicted a peak during the same part of the night.

The model often predicted a second smaller peak later in the night, but every night there was always only one peak that exceeded the trigger value. The longest duration of a peak was on the night starting on 31 October, with three consecutive hours that were predicted to exceed the trigger value. This was from 18:00 until 21:00 (UTC). Other nights with multiple consecutive hours that exceeded the trigger value according to the model were 8/9 October (19:00 to 21:00, UTC), 30/31 October (18:00 to 20:00, UTC), 10/11 November (00:00 to 02:00) and 25/26 November (17:00 to 19:00, UTC).

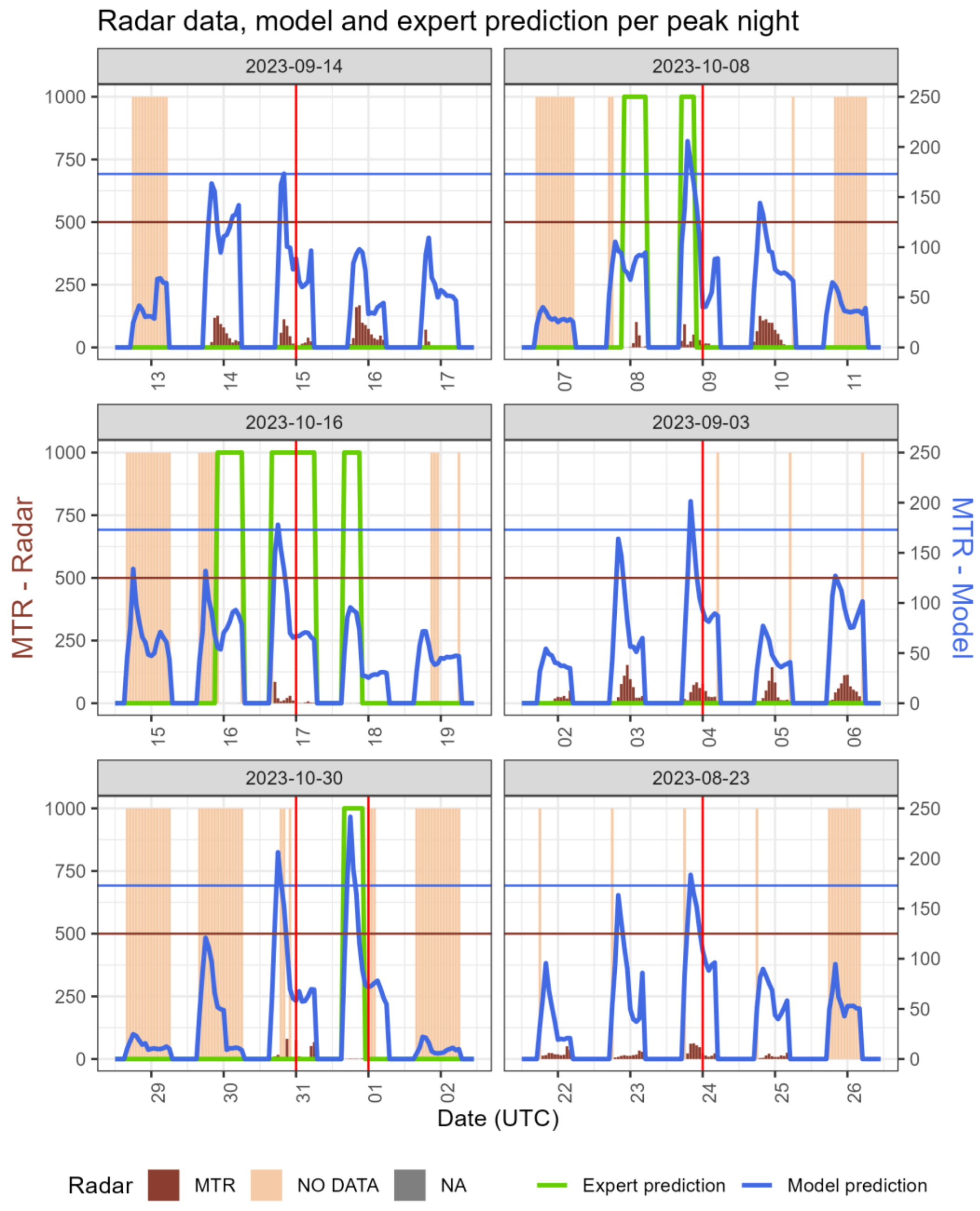

Figure 4.8 *Comparison of hourly radar measurements, hourly model prediction and expert prediction, for the peak nights according to the model and the surrounding days. Horizontal lines present the threshold for peak classification for radar (left y-axis) and the trigger value for the model (right y-axis). The expert prediction is a yes/no-decision, with green blocks for the evening and/or morning. Red lines represent midnight of the nights discussed.*

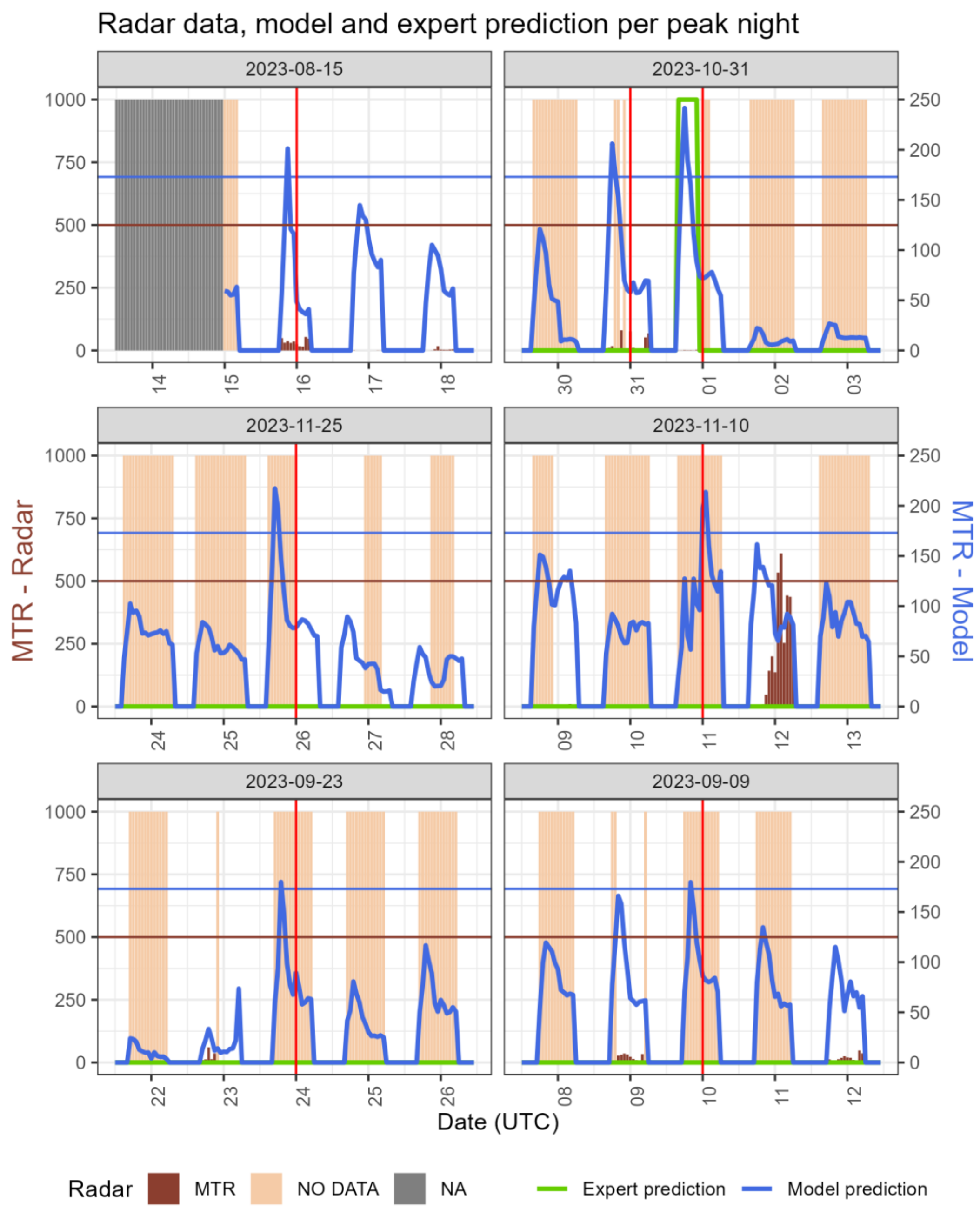

Figure 4.9 *Succession of Figure 4.8: comparison of hourly radar measurements, hourly model prediction and expert prediction, for the peak nights according to the model and the surrounding days. Horizontal lines present the threshold for peak classification for radar (left y-axis) and the trigger value for the model (right y-axis). The expert prediction is a yes/no-decision, with green blocks for the evening and/or morning. Red lines represent midnight of the nights discussed.*

5 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, which was not predicted by the model, called a false negative.

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 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 radar on nights with a peak by the model could be caused by malfunctioning of the horizontal radar.
- high filtering activities can lead to a reduced number of detected tracks and thus erroneous 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 explored vertical radar data next to the horizontal data.

In case of a **false negative** prediction, it seems more straightforward that an actual peak based on radar measurements did actually take place but was missed by the model predictions. For these cases, we here explore the vertical radar results and the expert team predictions in order to gain more insight in general patterns on nights with prediction errors.

5.1 Apparent false positive predictions by the bird migration model

5.1.1 Mismatches due to malfunctioning or filtering of the horizontal radar

As mentioned before, lack of a peak on the horizontal radar does not necessarily mean that the model falsely predicted a migration peak. In Figure 3.3, the results of the horizontal radar MTR calculations are depicted for the spring season, along with the predictions by the bird migration prediction model. In that figure, hours without data due to malfunctioning or high filtering activities of the horizontal radar can clearly be identified. In the spring season, there is no peak of the bird migration prediction model during hours in which there is no data for the horizontal radar. However, there are multiple bird migration prediction model peaks in the autumn season during hours with no data for the horizontal radar. Those peaks could logically not be validated by the horizontal radar. Later in this chapter, those nights will be studied based on the vertical radar.

Hours with high filtering on the horizontal radar are left out of this validation. The radar gives a value for variant mask filtering activity every second, which indicates the amount of filtering during that second. This value depends on, amongst others, weather conditions, such as wind speed and related sea wave height. This variant mask filtering activity can be used to identify those time periods with high filtering activity. Following the method that is used during the training of the bird migration prediction model, we selected only minutes with an average filtering mask activity below 0.3 (marked as TRUE in Figure 5.1). As is shown in Figure 5.1, the horizontal radar already detects fewer birds in hours with lower filtering activities than that threshold. This is a replication of an analysis in the validation report of the autumn season of 2022 (Kraal *et al.* 2023). It is important to note that this does not necessarily mean that a wrong threshold is used. For instance, higher filtering activities could result from weather conditions that are also unfavourable for high bird activity. However, both Figure 5.1 and the previous validation report, indicate that MTRs are never high in hours with a variant mask filtering activity level of above 0.2. This suggests that radar measurements during hours with filtering activities between 0.2 and 0.3 should be treated carefully.

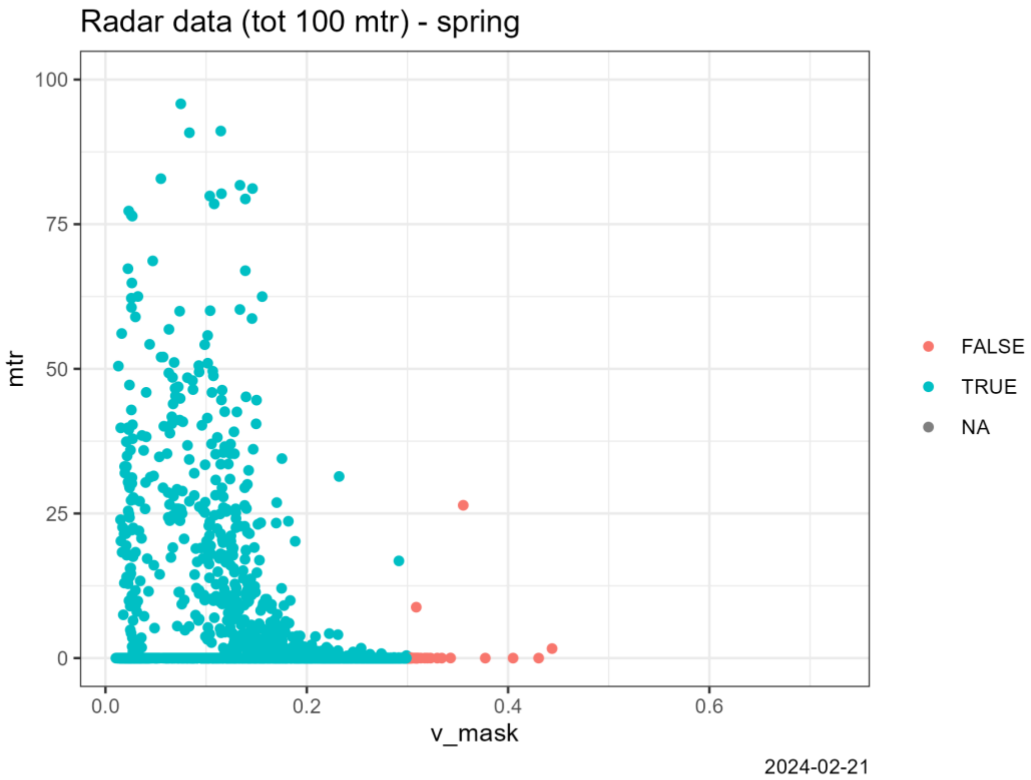

Figure 5.1 *Variant mask filtering (v_mask) versus the measured MTR for the horizontal radar during hours within the spring season. Only hours with a lower MTR than 100 are depicted. TRUE indicates filtering activity below 0,3; FALSE above.*

During spring, the potential false positive model predictions are on 23/24 February and 11/12 March, both just after midnight. The horizontal radar measurements do not show any high bird activity in the wind farm of Luchterduinen during those nights. The absence of a peak during those nights on the horizontal radar could be caused by high filtering activities. As can be seen in Figure 5.2, the filtering activities of the radar increase suddenly during the night of 11/12 March and reach a value of above 0.2 just after midnight. These higher filtering activities could be an explanation of the mismatch between the horizontal radar and the bird migration prediction model during that night. However, during the night of 23/24 February, it seems like there is no elevated filtering activity causing a possible reduction in bird detection by the horizontal radar.

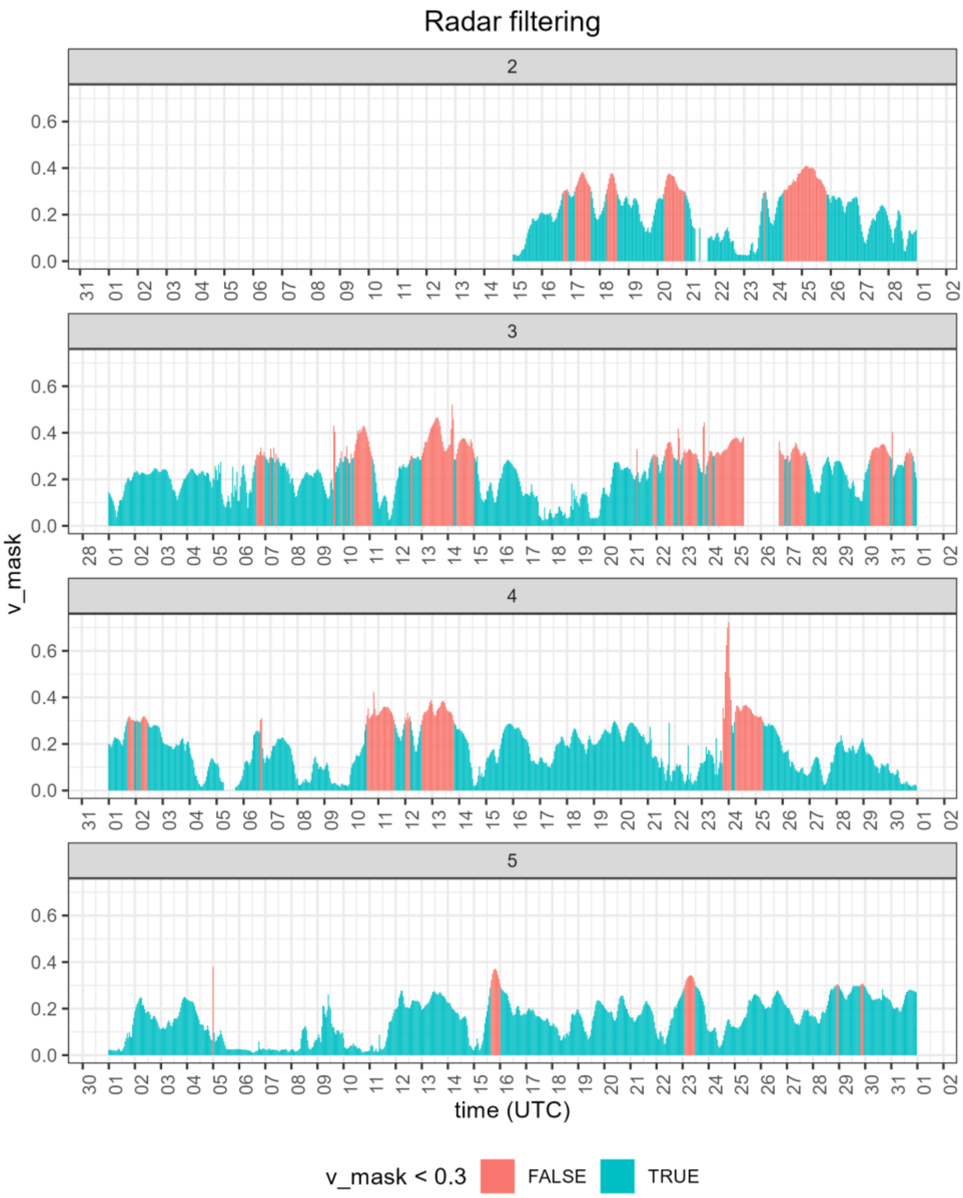

Figure 5.2 *Temporal pattern of variant mask filtering activities (v_mask) of the horizontal radar in spring. For this figure, the v_mask was averaged for an hour. This is slightly different than during the MTR calculations where the v_mask values are averaged per minute and if more than 50 minutes are above this threshold, an hour is filtered out of the analysis. However, this gives a good overview of filtering activities during the season.*

There are 12 possible false positive predictions by the model in the autumn migration season. Six of them happen in August and September. The model's predictions during these months are not reliable as the model was only trained on data from October and November. In other words, it was only taught how to recognize peaks in those months and is not trained to recognize weather patterns that correlate with migration peaks in the earlier two months. Therefore, the six mismatches in August and September will not be further examined.

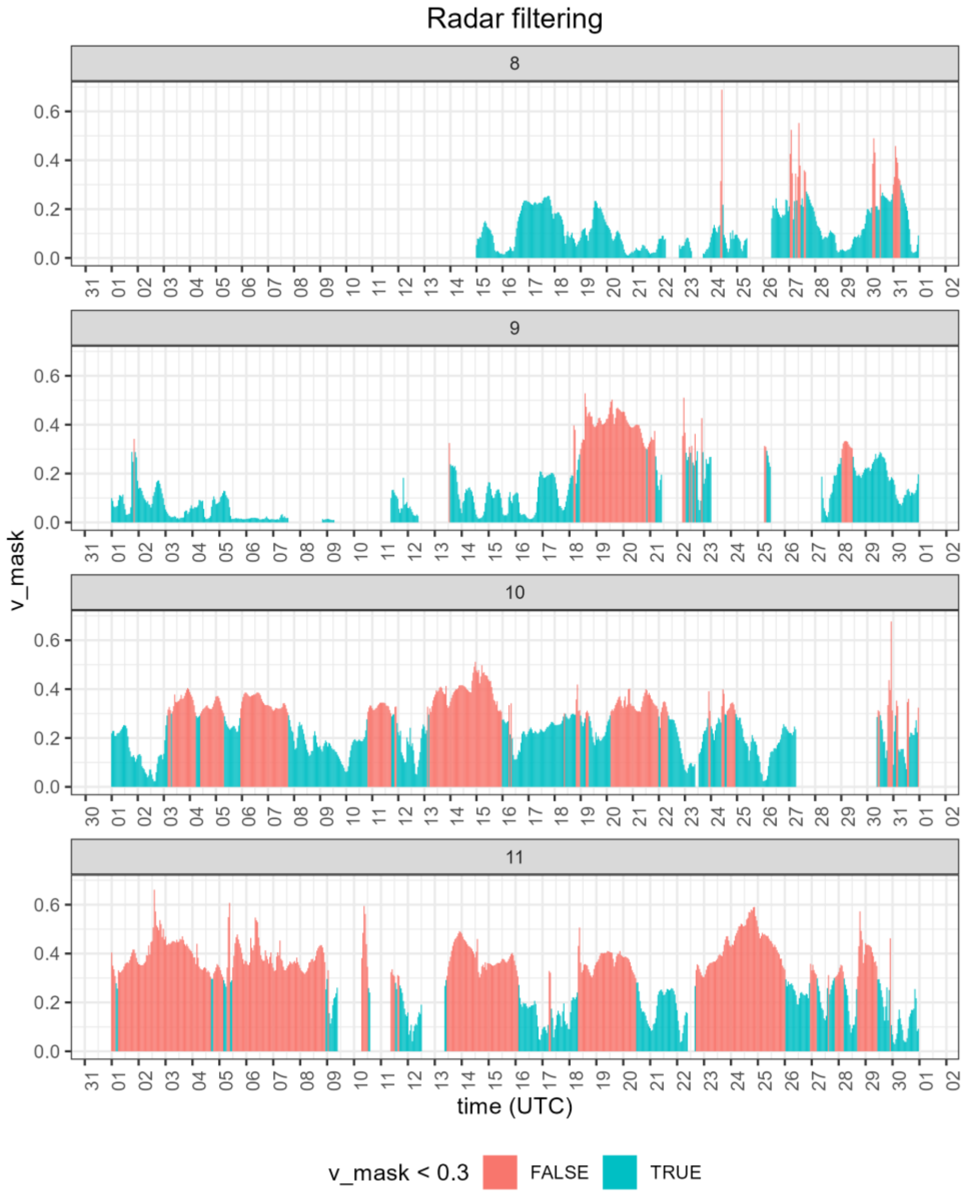

Figure 5.3 *Temporal pattern of variant mask filtering activities (v_mask) of the horizontal radar in spring. For this figure, the v_mask was averaged per hour. This is slightly different than during the MTR calculations where the v_mask values are averaged per minute and if more than 50 minutes are above this threshold, an hour is filtered out of the analysis. However, this gives a good overview of filtering activities during the season.*

The other six possible false positives in the autumn migration season happen on the nights beginning on 8, 16, 30 and 31 October and 10 and 25 November. There is no horizontal radar data at all on the 10/11 November (Figure 5.3). On all other nights but 8/9 October, high filtering activities could have caused an underestimation of the MTR by the horizontal radar. On 8/9 October, the filtering was not above 0.2.

5.1.2 Examining possible false positive peak predictions with the vertical radar

As is discussed in the previous paragraphs, the horizontal radar cannot provide a complete picture of the migration seasons of 2023, due to (essential) filtering. 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, periods with higher waves tend to lead to higher filtering activities in the horizontal radar. In the vertical radar data, periods with high waves can be dealt with by removing the lower few meters from the analysis. Therefore, 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 due to its limited height coverage may be missed by the horizontal radar but may be picked up by the vertical radar.

On top of this, the methods used to calculate migration traffic rates differ between the two radars (again see Chapter 2). This leads to completely different MTR values, which should only be compared with care. Therefore, in the first part of the paragraph, a cautious comparison will be made between the horizontal and vertical radar measurements. Next, the possible false positive peak predictions will be checked on the vertical radar in the lower 300 metres.

Comparison between horizontal and vertical radar measurements

Figure 5.4 shows that there are a lot of hours with extremely low horizontal radar MTRs in contrast with the high vertical radar MTRs. If a peak occurs in the horizontal radar data, one expects a peak in the lower range of the vertical radar (0-300m). The relationship, however, is not strong. The highest MTRs for the vertical radar occur when the horizontal radar reports low MTRs. Possibly the horizontal radar reports too low MTRs due to strong filtering. To avoid these possible filtering issues, we shall look only at relatively high horizontal MTR's (>250, see lower panel of Figure 5.4). There does seem to be a weak correlation between higher horizontal MTRs and vertical MTRs. This suggests that during hours with good conditions (i.e. low radar filtering activity on the horizontal radar), the measurements of bird activity match rather nicely between the horizontal and vertical radar.

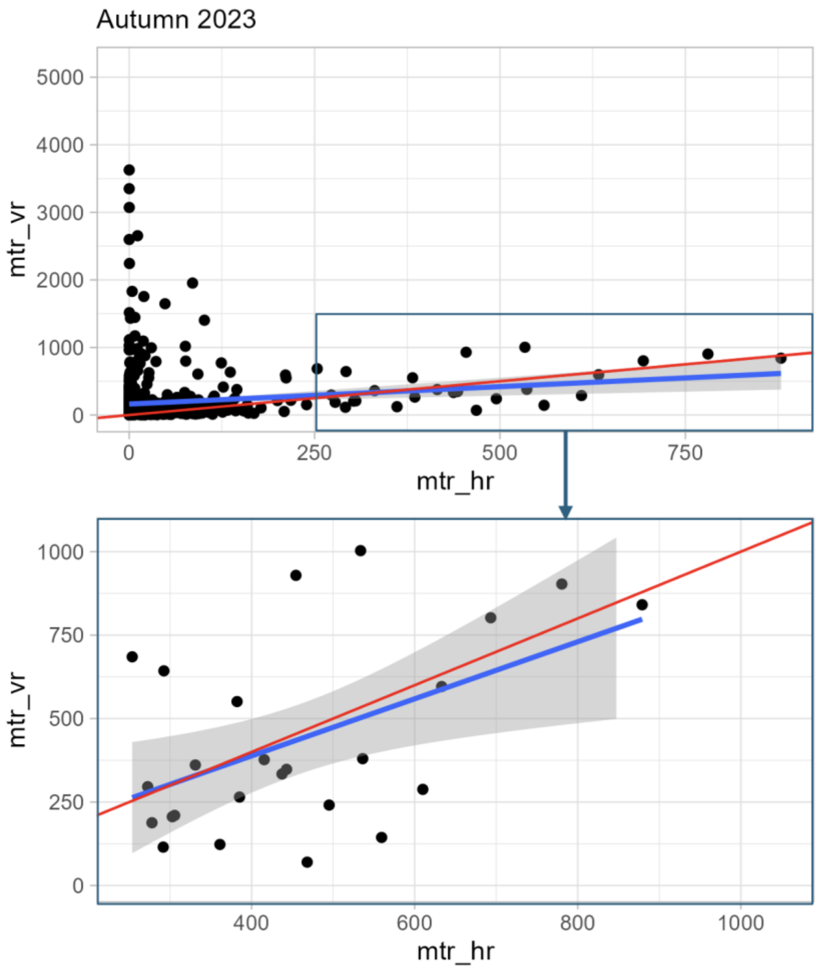

Figure 5.4 *Correlation between the hourly MTRs produced by the horizontal radar (mtr_hr on x-axis) and the vertical radar (mtr_vr on y-axis). The top panel shows results for the whole season of autumn 2023. The lower panel shows results for hours in which the horizontal radar MTRs are above 250 birds/km/hour. The red lines are the x = y lines. The blue lines show the linear model correlation line, with its 95% confidence interval in grey around the blue line.*

Vertical radar measurements on potential false positive prediction nights

On both **nights during spring** that were potentially falsely predicted as peak night by the bird migration prediction model (23/24 February and 11/12 March), the vertical radar did not show any increased bird activity in the lower 300 metres (the altitude range of the horizontal radar and also relevant for bird migration at rotor height) either (Figure 5.5). It is important to note that the vertical radar did not have data for the peak hours within those nights due to filtering steps in the analysis. The expert team did not predict a peak during these two nights either. The lack of peaks in these two extra information sources further suggests that the predicted peaks were incorrect.

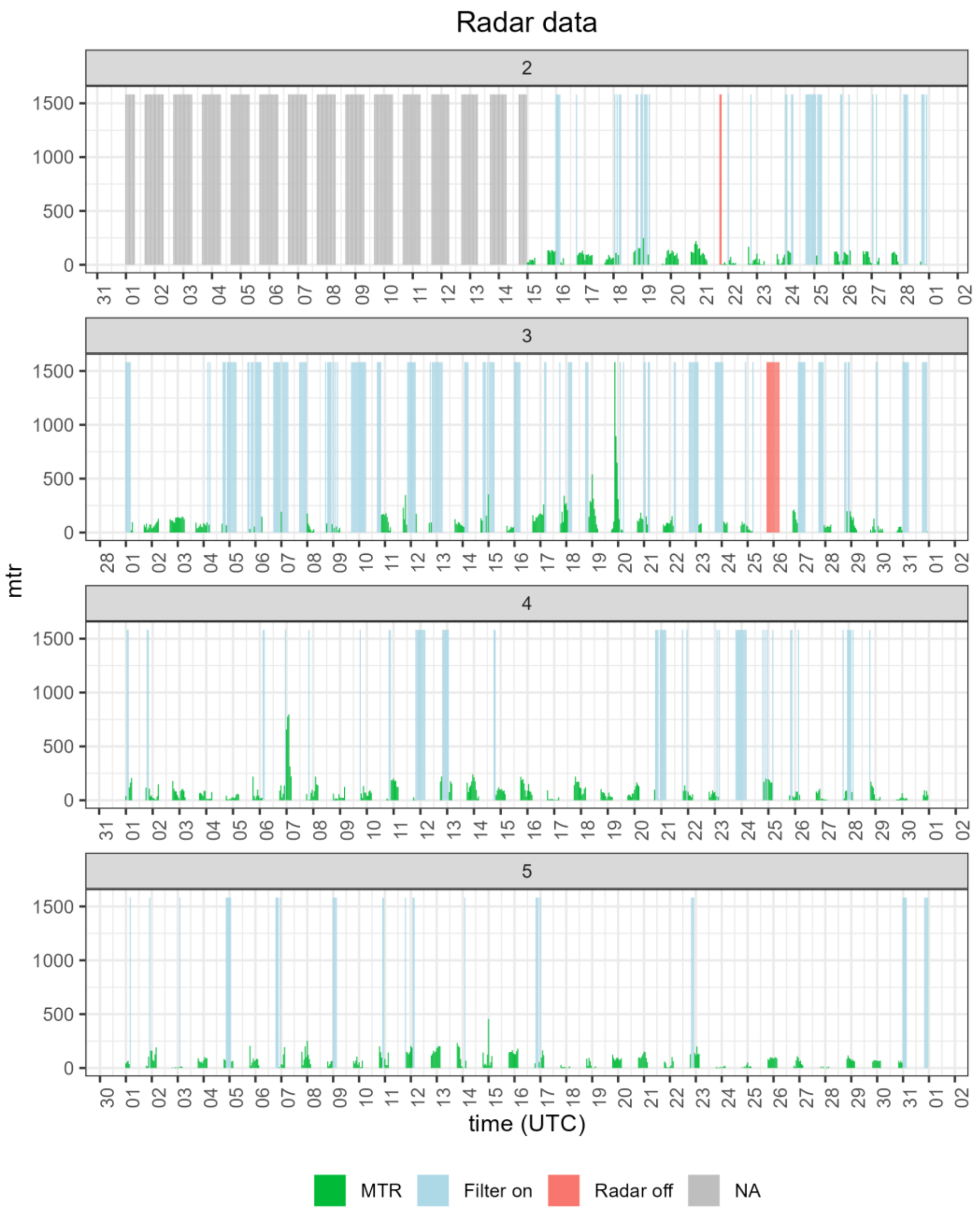

Figure 5.5 *Temporal pattern of migration intensity as measured by the (vertical radar) MTR value for the spring season of 2023. Measurements are considered from the 15th of February.*

For two of the potentially false positives in the **autumn season**, 08/09 and 16/17 October, the vertical radar did measure a peak in the lower 300 metres (Figure 5.6). This indicates that the bird migration prediction model did not falsely predict a migration peak on those nights, but that the horizontal radar did not detect it. Moreover, the expert team did predict a peak for both of those nights, which is why a curtailment signal was issued. That was also the case for 31 October / 01 November, but there was no peak measured on either of the radars. Therefore, the nights starting on 30 and 31 October and 10 and 25 November are the four nights with peak predictions by the bird migration prediction model without empirical evidence from the radars suggesting a migration peak. However, for the peak hours during these nights according to the model, the vertical radar did not have any data due to filtering steps in the analysis.

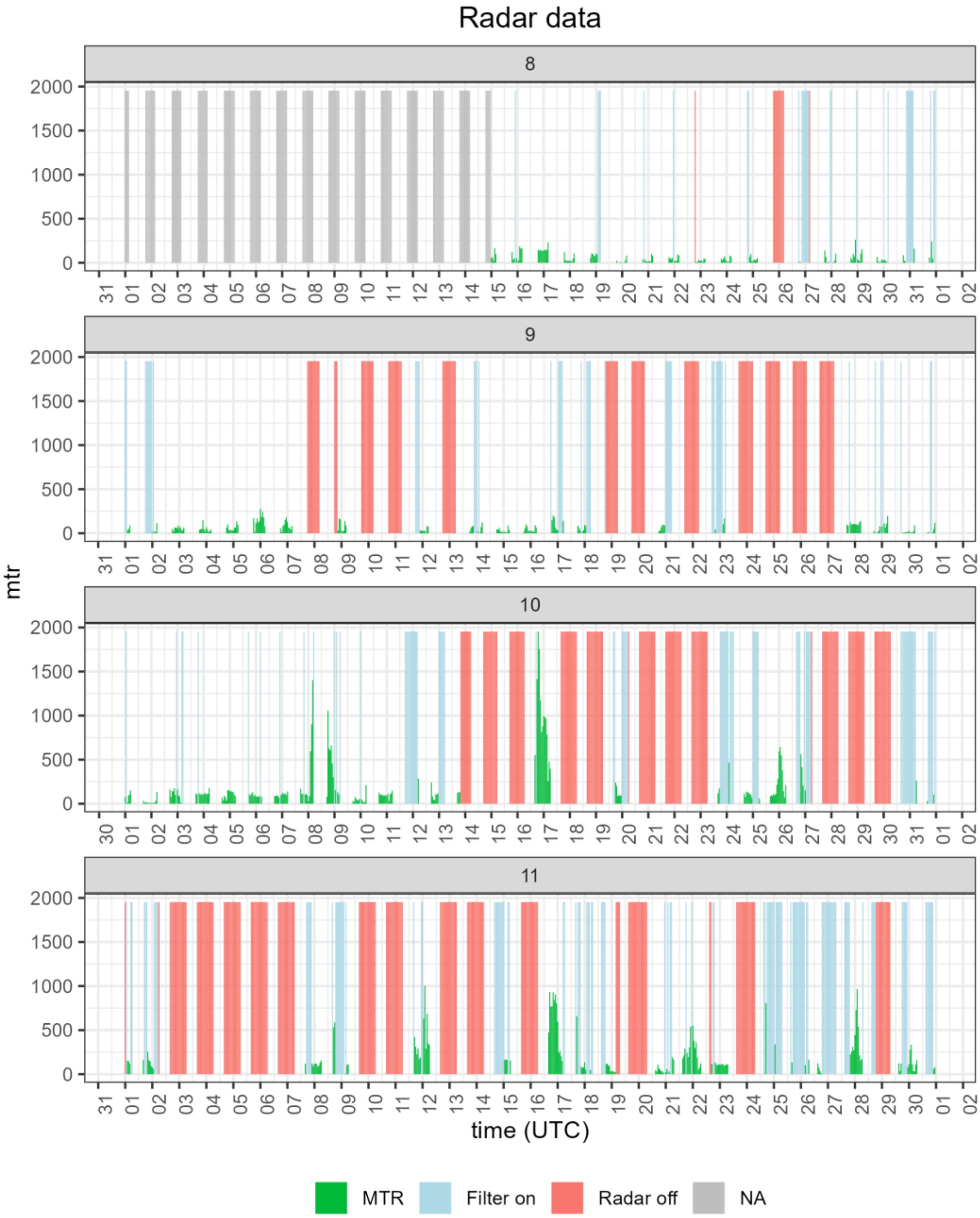

Figure 5.6 *Temporal pattern of migration intensity as measured by the (vertical radar) MTR value for the autumn season of 2023. Measurements are considered from the 15th of August.*

Table 5.1 Overview of functioning of the vertical radar per month in autumn 2023 and total mtr measured between 3-300m for the period where radardata was available.

	Nighttime	Missing hours		Total mtr
mnd	available hours	hours filtered	hours radar off	during available hours
8	134	30	12	7,829
9	172	51	137	11,554
10	187	89	159	39,456
11	145	126	205	33,029

Vertical layering of bird activity on false positive nights
On 30/31 October,31 October / 01 November and 10/11 and 25/26 November, the model seems to have falsely predicted a peak in the lower 300 metres in Luchterduinen. No peak has been observed on the horizontal as well as on the vertical radar data. This is partly because there was no vertical radar data for the peak hours that were predicted by the model. This also means that it is not possible to check whether a migration peak did pass the Luchterduinen wind farm but at higher altitudes.

5.1.3 Curtailment moments in autumn 2023 verified by the vertical radar

Three times in autumn 2023 a signal to curtailment has been issued to offshore wind farms. This happened on 08/09, 16/17 October and 31 October / 01 November (Table 4.6). These decisions for curtailment were based on a combination of the predictive model and expert team predictions. The horizontal radar, however, did not detect a migration peak during any of those nights. In contrast, as mentioned in paragraph 5.1.2, the vertical radar did measure a peak migration event in the lower 300 metres on 08/09 and 16/17 October (Figure 5.7). This indicates that the curtailment of offshore wind farms during those nights likely indeed coincided with peaks of bird migration. Unfortunately, there was no vertical radar data for the curtailment hours on the night of 31 October / 01 November because it was filtered out (Table 5.2).

Table 5.2 Total summed MTR during curtailment measured by the vertical radar for available hours. The summed MTR is also expressed as percentage of the total measured MTR for autumn (91868). Note that the total MTR could only be calculated for hours where data was available.

time start (local time)	time end (local time)	duration (hr)	available hours	summed mtr for available hours	percentage of total mtr for the season
08/10/2023 21:00	09/10/2023 00:00	3	3	1,891	2.06
16/10/2023 19:00	16/10/2023 22:00	3	2	3,366	3.66
31/10/2023 18:00	31/10/2023 21:00	3	0		

The curtailment period on 8 October was from 19:00 to 22:00 (UTC). The highest peak that night on the vertical radar was at 18:00 followed by four hours with high MTRs (Figure 5.7). The curtailment therefore slightly missed the extreme peak but was executed during hours with a lot of bird passages. On 16 October the most extreme peak was captured by the curtailment period, which was from 17:00 to 20:00 (UTC). The hour following was included in the curtailment period and had high numbers of bird tracks on the vertical radar as well (Figure 5.7). During the peaks on 8 and 16 October 2 resp. 3,6 % of the total measured MTR for autumn passed the offshore wind farm.

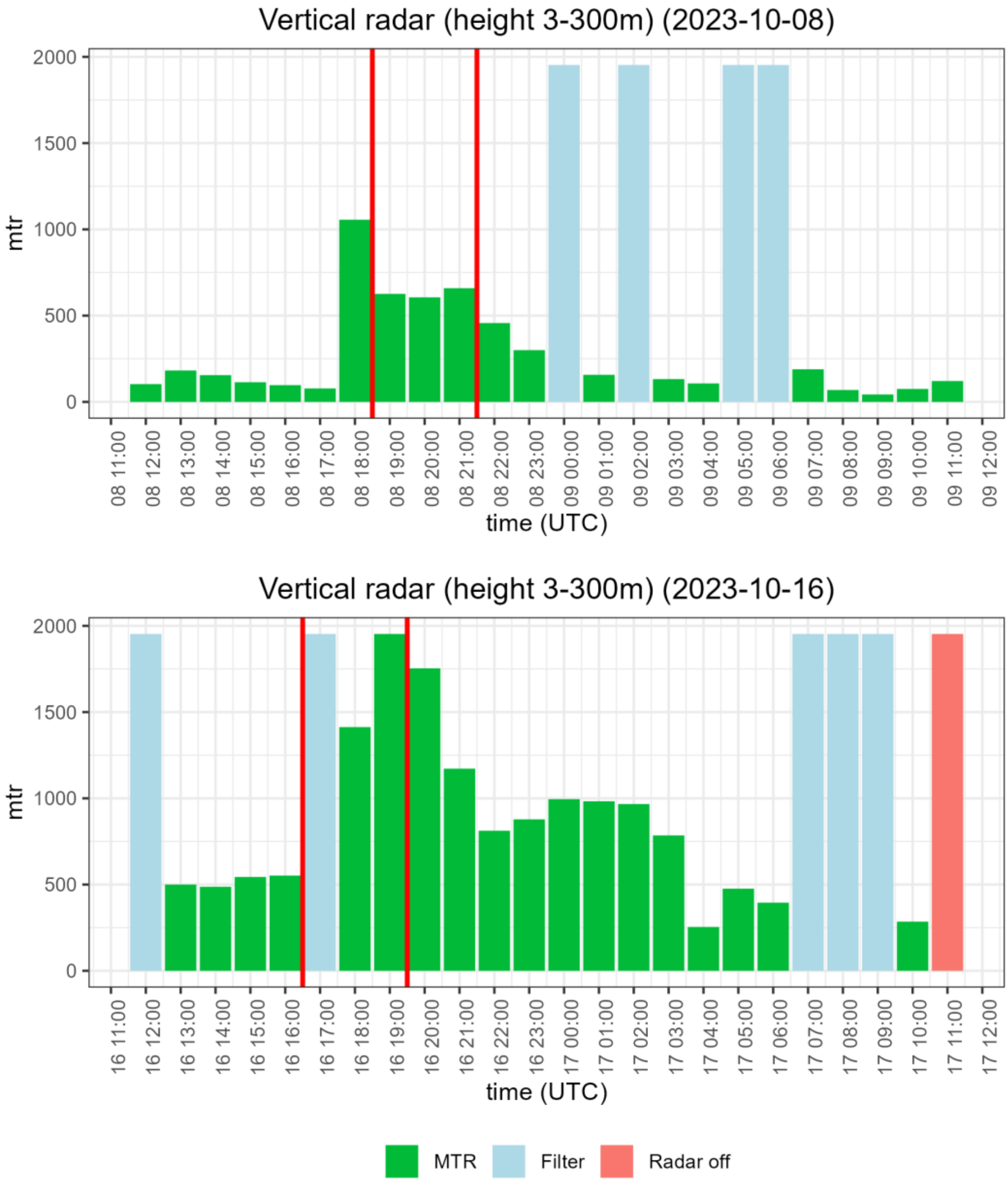

Figure 5.7 *Temporal pattern of measured MTRs (birds/km/h) by the vertical radar during two curtailment moments with data for the vertical radar. Red bars indicate start and end time of curtailment. Dates on x-axis indicate the day number of the month and the hour in the UTC time zone.*

5.2 Apparent false negative predictions by the bird migration model

According to the horizontal radar, the bird migration prediction model missed peaks on the nights starting on 17, 18 and 19 March. However, the predicted MTR values by the model for those nights were quite high. In fact, all three nights belonged to the top five of nights according to the model, although the trigger value was not exceeded (see Figure 3.6). This suggests that the trigger value for the predictive model might be too high.

The vertical radar measured a high bird activity peak on the nights starting on 13 March and 7 April. For the latter, the migration expert team also predicted a peak. The horizontal radar did not detect high bird activity, nor did the bird migration prediction model predict a peak.

There were three nights in the autumn season with high measured bird activity on the horizontal radar without a predicted peak by the bird migration prediction model. Those nights were starting on 25 October and 11 and 16 November (see also §4.5.1). None of these nights belonged to the top ten of nights as predicted by the model. In contrast, two of those nights (25/26 October and 16/17 November) were predicted to be a peak night by the expert team. Moreover, all three nights were measured as a peak night also by the vertical radar. This seems to indicate that the model missed peaks on those three nights. Note that the model predictions were not particularly low, as the maximum predicted MTR was above 100 for each of those nights. However, the trigger value was not exceeded, and these nights all did not belong to the top 10 of nights according to the maximum MTR value as predicted by the model. .

The vertical radar measurements indicated two additional nights with peak migration, namely 21/22 and 28/29 November. The first of those nights belonged to the top five of nights according to the horizontal radar, while the horizontal radar did not show elevated bird activity for the second night. The model predicted mass migration on neither of these nights.

5.3 Effect of weather circumstances

An important data source fuelling the model predictions are weather conditions in the Luchterduinen wind farm. The wind direction and speed in the Luchterduinen wind farm influence the model's predictions through the parameter of wind assistance. This parameter indicates how supporting the wind is for migrating birds. Therefore, investigating those weather conditions during false positive or false negative events could give more insight in the causes of erroneous predictions, and may help to further develop the predictive model. Figure 5.8 shows the wind direction and speed during a set of eight nights with either false positive model peak predictions or false negative nights. During the three false negative nights, 17/18, 18/19 and 19/20 March, there was mostly a southwestern wind. South was the dominant wind direction on the other two top five nights according to the horizontal radar, 8/9 and 21/22 April. This is also visible in Figure 5.9, which presents the hourly wind conditions along with the MTRs according to the horizontal radar and the model for spring 2023. Here, the points with a high horizontal radar MTR (right part of the figure) are all coloured blue or purple, indicating a western or southwestern wind. The points that do not have high MTRs according to the radar but do according to the model (upper left part of Figure 5.9), have a purple or green colour, indicating wind from the south, southeast or northwest.

Thus, the south-eastern to southwestern winds were also apparent on one of the false positive nights (11/12 March) and a night with model predictions just below the trigger value, but no sign of a peak on the horizontal radar (4 April). The weather conditions during those nights therefore follow the patterns of the earlier peak nights, but the radars show no peak. Figure 5.10, however, shows a sudden drop in the average forecasted temperature in Luchterduinen between 100 and 300 metres just before 11/12 March and 04/05 April. Possibly, that could have prohibited birds from migrating through the wind farm of Luchterduinen. This is supported by the relatively high temperatures during the two of the three peak nights on the horizontal radar. These findings may point towards the importance of temperature patterns in shaping bird migration that might be worth further investigation in the future.

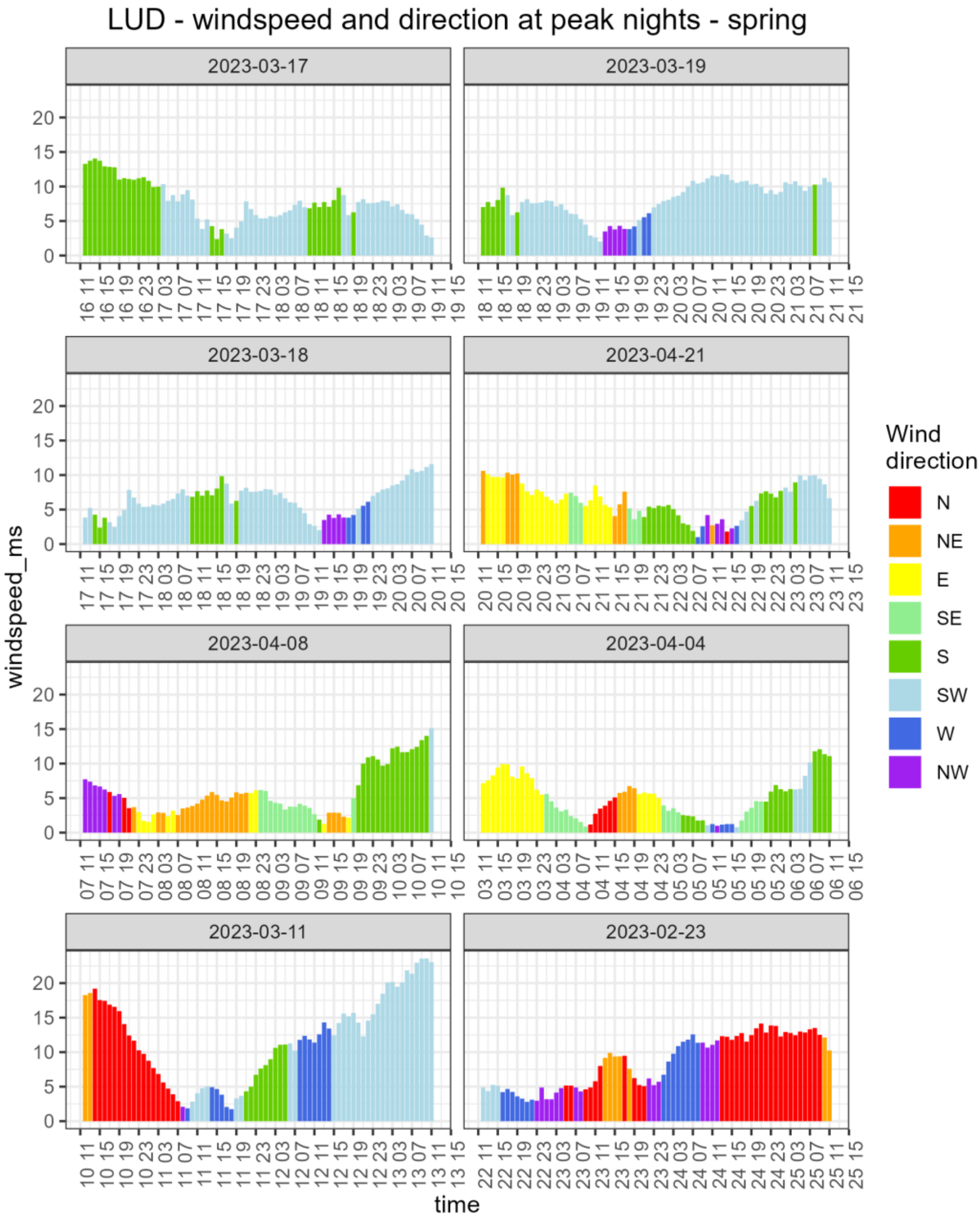

Figure 5.8 *Wind conditions during spring peak migration nights according to the horizontal radar (17/18, 18/19 and 19/20 March), two nights with increased migration activity on the horizontal radar but not peak nights (08/09 and 21/22 April), an almost peak night according to the model (04/05 April) and two nights that were peak nights according to the model (23/24 February and 11/12 March). The panels of the nights are sorted by MTR value on horizontal radar. Wind speed (m/s) is measured in Luchterduinen. The x-axis presents the day of the month (lower number) and the hour of the day (upper number).*

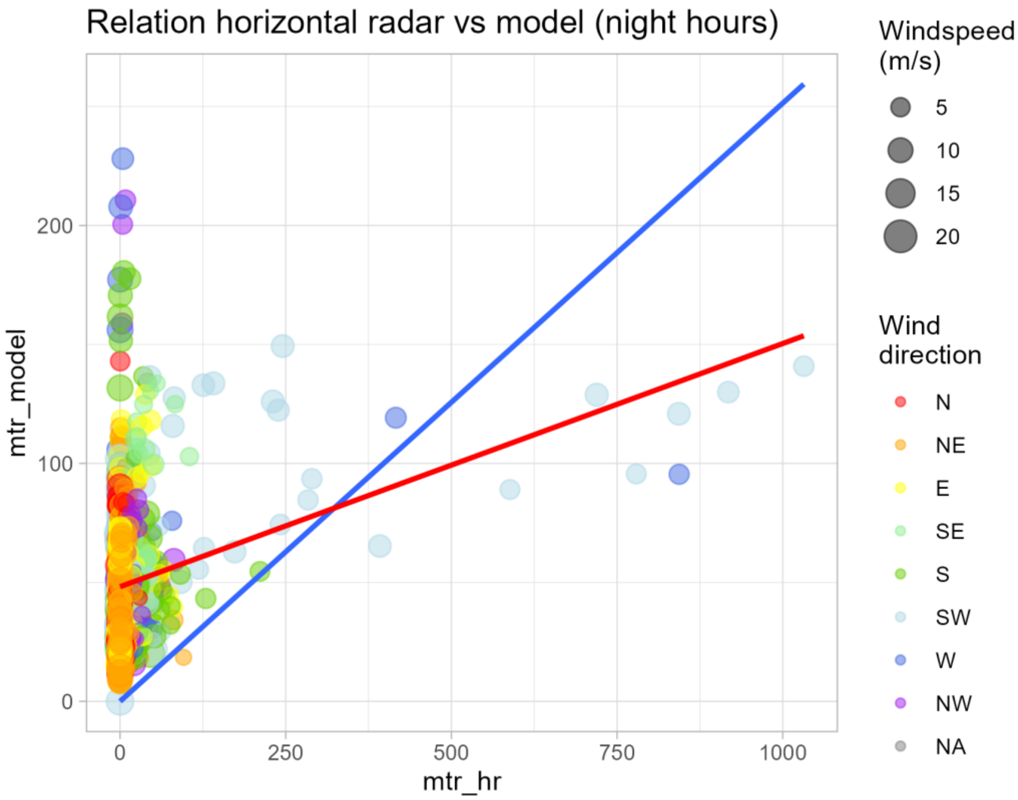

Figure 5.9 *Relationship between the MTRs according to the horizontal radar (mtr_hr on x-axis) and MTRs according to the model (mtr_model on y-axis) for spring 2023. Points are colored in based on the dominant wind direction and are sized based on the wind speed within the hour of that MTR value. The blue line shows the expected linear relationship (through zero, y ~ 0 + ax). The red line shows the linear relationship with an intercept not a zero (y ~ ax + b). NB wind direction N indicates that the wind is coming from the North. (wind origin). NB2 only points plotted where the radar was functioning, and wind data was present.*

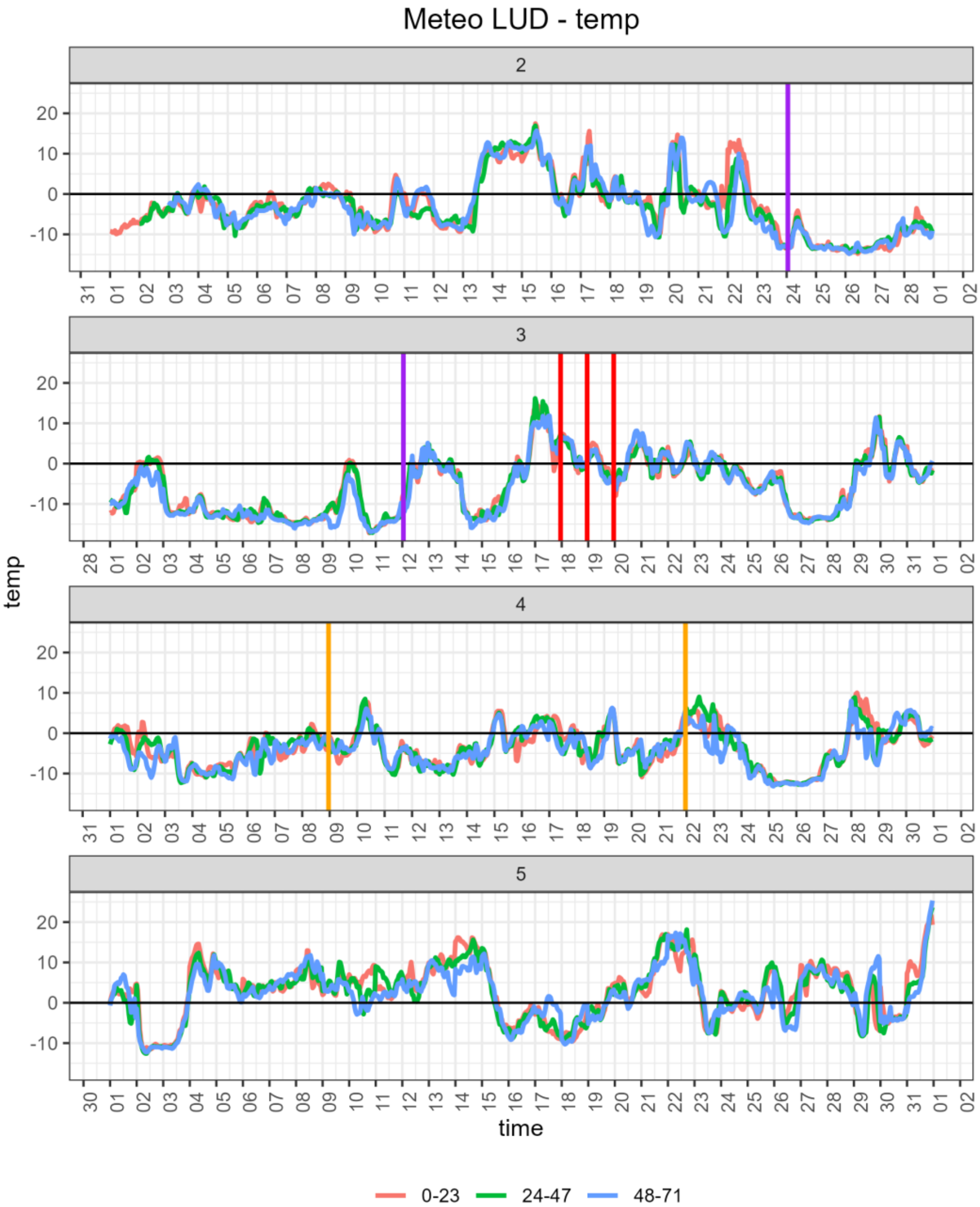

Figure 5.10 *Temporal pattern of the temperature (℃) forecasts between 100 and 300 meters altitude in Luchterduinen throughout the spring migration season. Different colors of the lines stand for how far ahead the forecast is (0-23 means 0 to 23 hours ahead). Vertical bars in the graph indicate key moments, either a peak on the horizontal radar (17/18, 18/19, 19/20 March, in red), according to the model (23/24 February, 11/12 March, in purple), or almost a peak according to the radar (8/9 and 21/22 April, in orange) and almost a peak according to the model (4/5 April).*

Interestingly, during the peaks of 11/12 and 16/17 November on the horizontal radar, there was a mild southwestern wind (Figure 5.11 and Figure 5.12). This is counterintuitive because birds migrate between southern and western directions in the autumn season and southwestern winds therefore actually form headwind. On both of these nights, however, the sudden change of wind direction and speed lead to less unfavourable wind conditions than the days before, possibly a start sign for accumulated birds to start their migration. The southeastern to eastern winds on 25 October seem to be in line with results from the validation report of autumn 2022, where it was shown that migration peaks during that season almost always contained an eastern component (Kraal *et al.* 2023).

The nights of 08/09 and 16/17 October were marked as peak nights by the vertical radar results and were also predicted as such by the bird migration prediction model. However, the wind direction between these two nights is completely opposite. There is also no pattern in the wind direction during the other peak nights according to the bird migration prediction model.

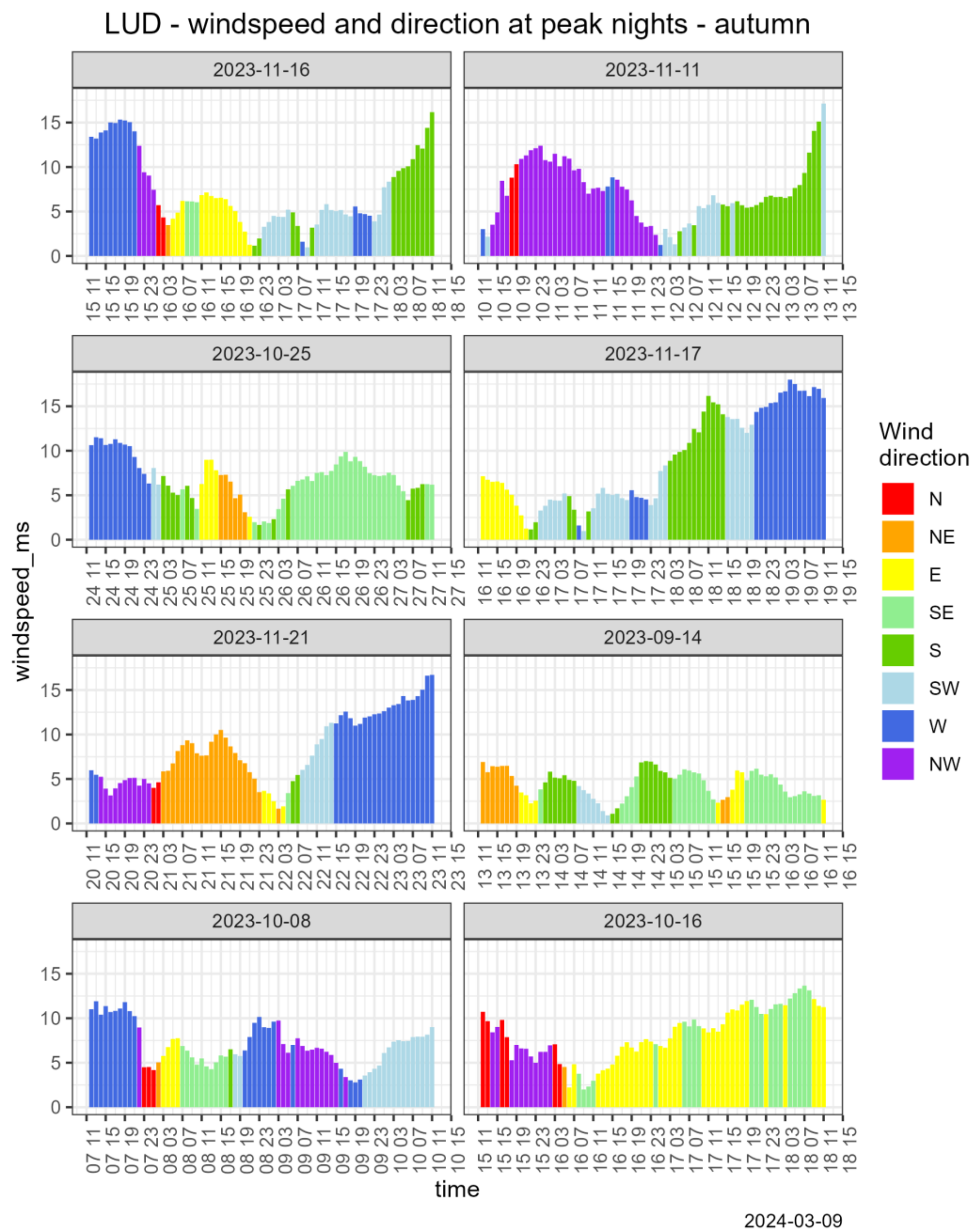

Figure 5.11 *Wind conditions during autumn peak migration nights according to the horizontal radar (25/26 October and 11/12 and 16/17 November), two nights with increased migration activity on the horizontal radar but not peak nights (17/18 and 21/22 November), and three nights that were peak nights according to the model (14/15 September and 08/09 and 16/17 October). The panels of the nights are sorted by MTR value on horizontal radar. Wind speed is in m/s and is measured in Luchterduinen. The x-axis holds the day of the month (lower number) and the hour of the day (upper number).*

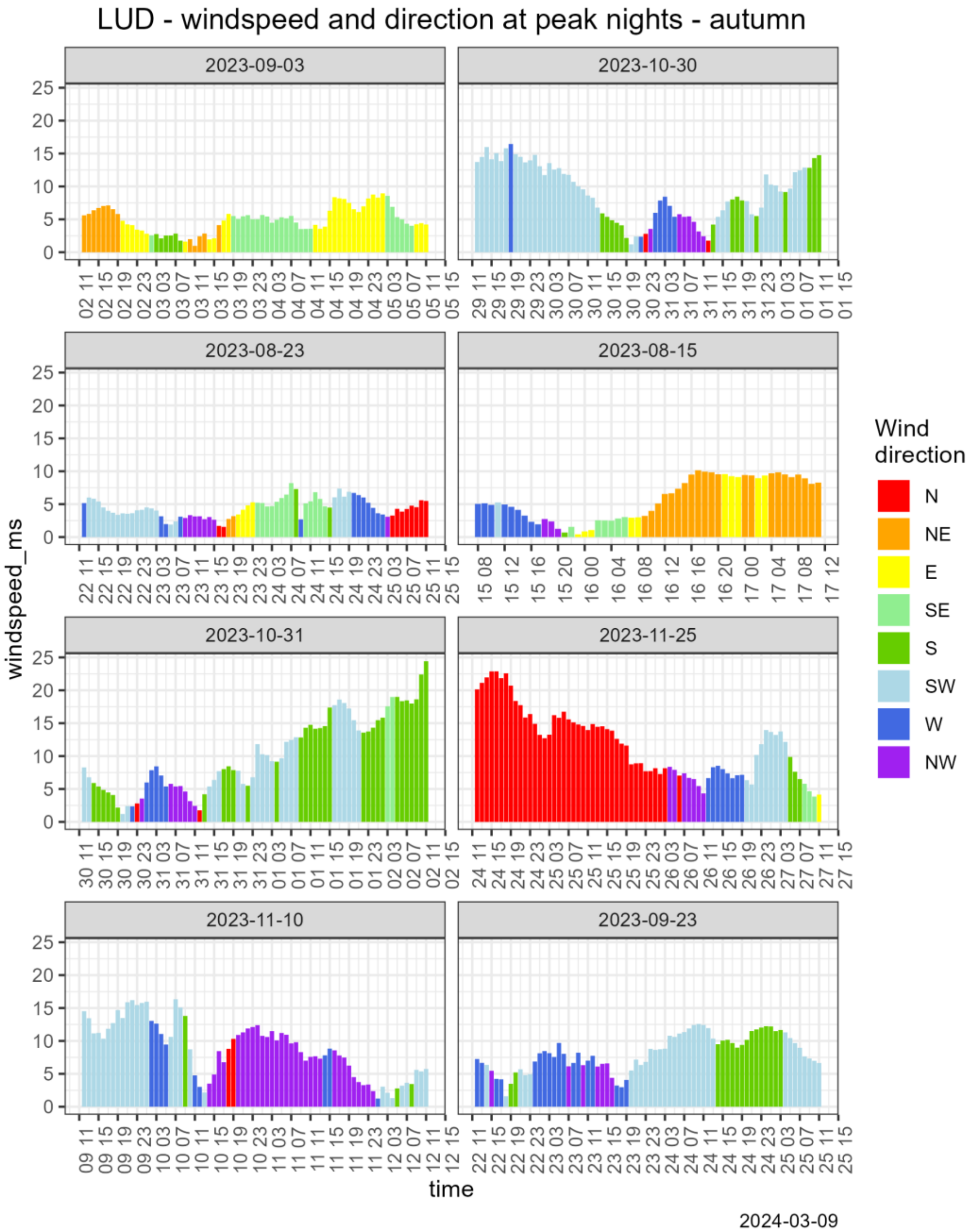

Figure 5.12 *Succession of Figure 5.11Figure 5.11 for the rest of the nights that were predicted as peak night by the bird migration prediction model. The panels of the nights are sorted by MTR value on horizontal radar. Wind speed (m/s) is measured in Luchterduinen. The x-axis holds the day of the month (lower number) and the hour of the day (upper number).*

6 Additional analyses

In this chapter, we present some additional analyses that are not directly relevant for the validation of the migration prediction model, but that provide further details of the measurements of the offshore bird radars. First of all, we discuss an often-raised question, why the prediction model is only developed for nocturnal migration. Secondly, we touch upon the functioning of another offshore bird radar, placed in offshore wind farm Borssele, and how those measurements relate to those of the radar in Luchterduinen.

6.1 Migration intensity ratio day vs night.

We carried out an additional analysis on the number of bird tracks measured by the horizontal radar in wind farm Luchterduinen in the spring of 2023 to investigate whether migration peaks also occur during daytime. This could give an answer on the general temporal patterns of offshore bird migration, but also whether peak migration moments (>500 MTR) are missed if the curtailment procedure only concentrates on nocturnal migration. As Figure 6.1 clearly shows, besides the migration peaks measured during the nights in March (reported in Chapter 3), the radar measurements indicated no peaks during the day. All MTRs during the daytime remained below 250 MTR, comparable to the measurements during the nights of February, April and May. For the whole migration season of spring 2023, only three of the top 20 hours of flight intensities measured in Luchterduinen occurred during daytime.

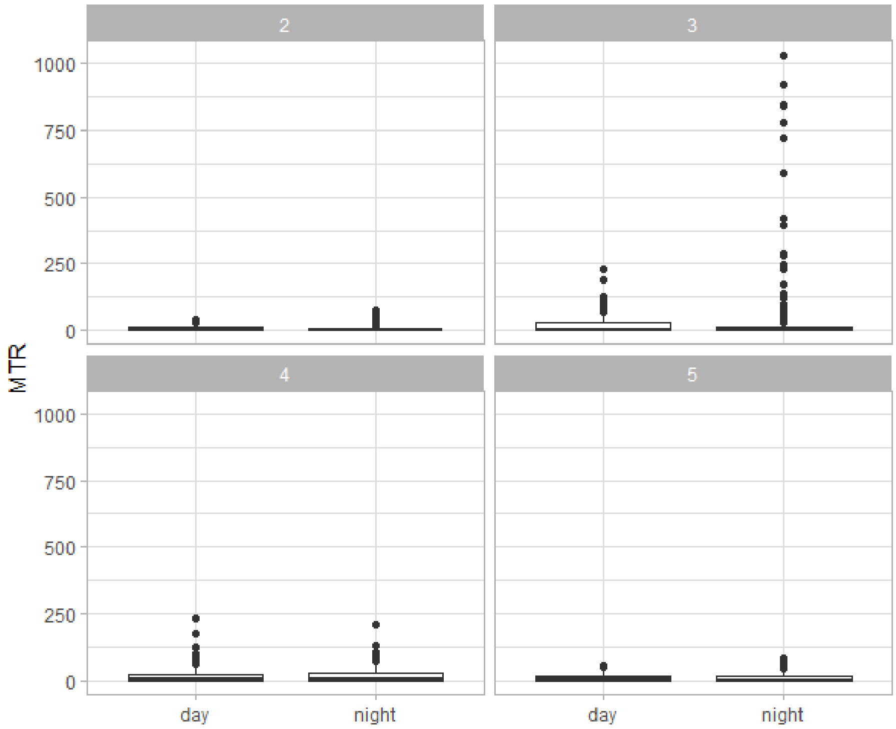

Figure 6.1 *Boxplot of MTRs per hour measured by the horizontal radar during the spring of 2023 in Luchterduinen. Only complete days were taken into account; that is where the radar was functioning for the whole day (no NA's).*

Looking not only at the peak migration moments but at all the tracks that the horizontal radar measued in spring 2023 also revealed that especially in March most of the bird movements occurred during the night (Figure 6.2). Although in this graph no correction was carried out for the length of the night, it is obvious that the relative proportion of nocturnal bird traffic in March is outstandigly high.

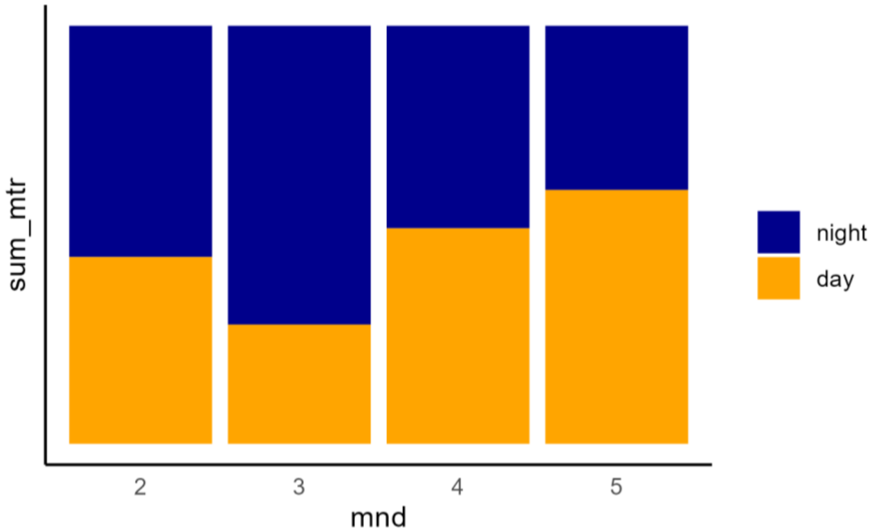

Figure 6.2 *Ratio of all the tracks measured by the horizontal radar in Luchterduinen during night and day. Only complete days were taken into account; that is where the radar was functioning for the whole day (no NA's).*

6.2 Radar measurements offshore wind farm Borssele

The current bird migration prediction model is developed based on horizontal radar data collected in offshore wind farm Luchterduinen (LUD). However, the outcomes of the model predictions apply to all newly developed offshore wind farms along the west coast of the Netherlands. Therefore, it is relevant to know how the model performs relative to local measurements on bird traffic in other wind farms. In offshore wind farm Borssele, located on the Tennet platform Alpha (BSA), a bird radar has been operational since 2019. The radar system is technically identical to the one in wind farm Luchterduinen. However, the horizontal radar in Borssele is located at approximately 40 meters above sea level (the Utility Deck of the platform), instead of approximately 23 meters above sea level in Luchterduinen (the railing on the turbine). Calculation of the bird migration activity around the Borssele radar slightly differed from the Luchterduinen radar, as local wind meters were used to calculate the airspeed and the *landmask* filter activity was used to filter out hours with a too high filtering activity instead of the *variantmask* filter. The latter was based on a study carried out by the UvA (van Erp *et al.* 2023) and uses the first derivative of a general additive model between the filtering activity and the birdcount within an hour (Leemans *et al.* 2024). In this chapter, we provide an overview of the data collected by the horizontal radar in Borssele during the migration seasons of 2023.

6.2.1 Data availability

As Table 6.1 shows, both in spring and autumn of 2023, the BSA radar had suffered a lot from intensive clutter development, and hence most of the hours were excluded during the filtering process (cf. the same steps as described in Chapter 2.1). All in all, only 15% of the data were left in the database for analyses of the spring and 12% of the autumn. Even more, if we consider in the autumn only October and November, the months for which the model was developed and when most of the migration takes place, only 4% of the data were found to be suitable. As the radar system is identical to the one operating in Luchterduinen that had during the same period less problems with data availability, we suspect that the higher location of the radar in Borssele leads to more clutter generation and a consequent higher filtering activity. The difference in data availability between the Luchterduinen and Borssele radars can also result from a different method of erasing hours with high filtering activity from the database. This different method is needed as the environment is unique for each radar and hence the filtering activities.

Table 6.1 *Overview of hours in the radar dataset with suitable horizontal radar data. 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		Daytime	Nighttime		Cause of missing data	
Month	days	hours	total hours	total hours	available hours	hours filtered	hours radar off
2	28	672	259	413	112	271	30
3	31	744	346	398	16	368	14
4	30	720	395	325	37	288	0
5	31	744	467	277	54	223	0
8	31	744	432	312	46	266	0
9	30	720	360	360	105	253	2
10	31	744	309	435	32	403	0
11	30	720	244	476	7	469	0

Figure 6.3 and Figure 6.4 show more in detail the large amount of unavailable hours for analyses of the Borssele horizontal radar, mostly due to filtering activities of the radar. None of the hours in the spring of 2023 that were left in the database for analyses exceeded the threshold of 500 birds/km/hour. Although this was the case for the autumn migration season of 2023 (see Chapter 6.2.2), for this season was even more data filtered out of the horizontal radar measurements. The lack of radar data for the vast majority of hours in the migration seasons makes it practically impossible to carry out a meaningful validation of the model predictions based on the Borssele radar measurements.

Although the Luchterduinen radar also had large fractions of the data unavailable for analyses, the radar system in the Borssele had seemingly much greater issues with clutter filtering. This occurred recently also during a detailed analysis on bird radar data of the Borssele radar wind farm (Leemans *et al.* 2024) and was also reported during the validation of the radar measurements (Leemans *et al.* 2021; Leemans *et al.* 2022a). Despite the radars located in Borssele and Luchterduinen consisting of the same type of Robin 3D Fixed radars, the one in Borssele is situated on a TenneT platform (Alpha) while that in Luchterduinen at the railing of a wind turbine. Consequently, the radars at the two locations operate at diverging altitudes: the horizontal radar at BSA is installed 39.5 meters above sea level, while that in Luchterduinen at approximately 23 m above mean sea level. Moreover, the platform in Borssele where the radar is installed is in the middle of the wind farm, in contrast with the Luchterduinen radar at the edge of the wind farm. Except for a different blanking sector of the horizontal radar at BSA (34.4% of the full circle) that should not influence data availability, the installation altitude and location of the radars are the only difference between the two locations, as the systems themselves are identical. Seemingly, the location and altitude of the Borssele radar leads to a lot of generated clutter, due to which data availability of this radar is currently extremely low. By understanding the nature of this clutter better, hopefully future filtering steps devoted to the Borssele radar may leave more data available.

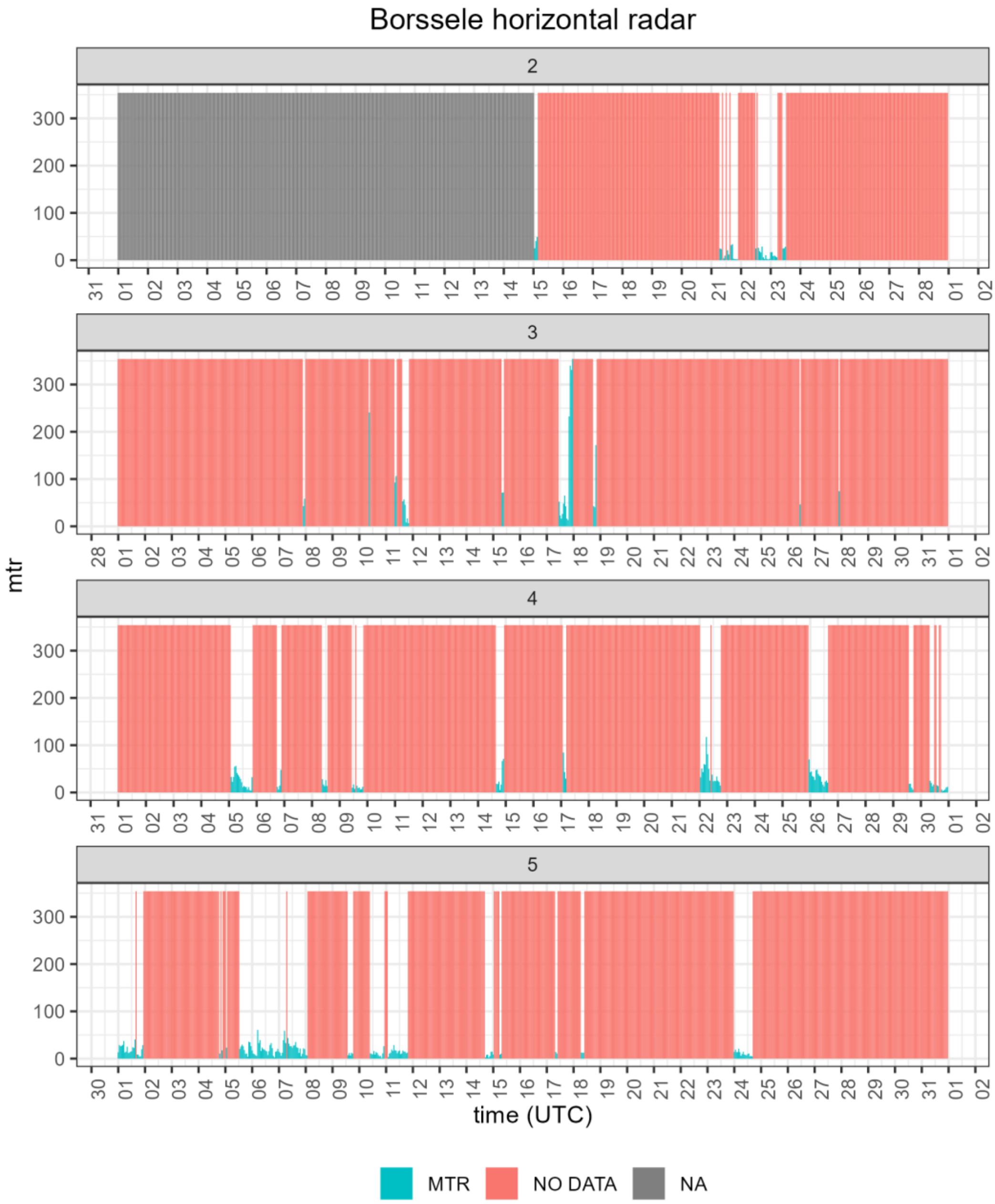

Figure 6.3 *Hourly mean traffic rate (number of tracks/km/h) measured by the horizontal radar in Borssele (teal bars) in spring 2023. Periods with unavailable radar data are indicated with the red bars.*

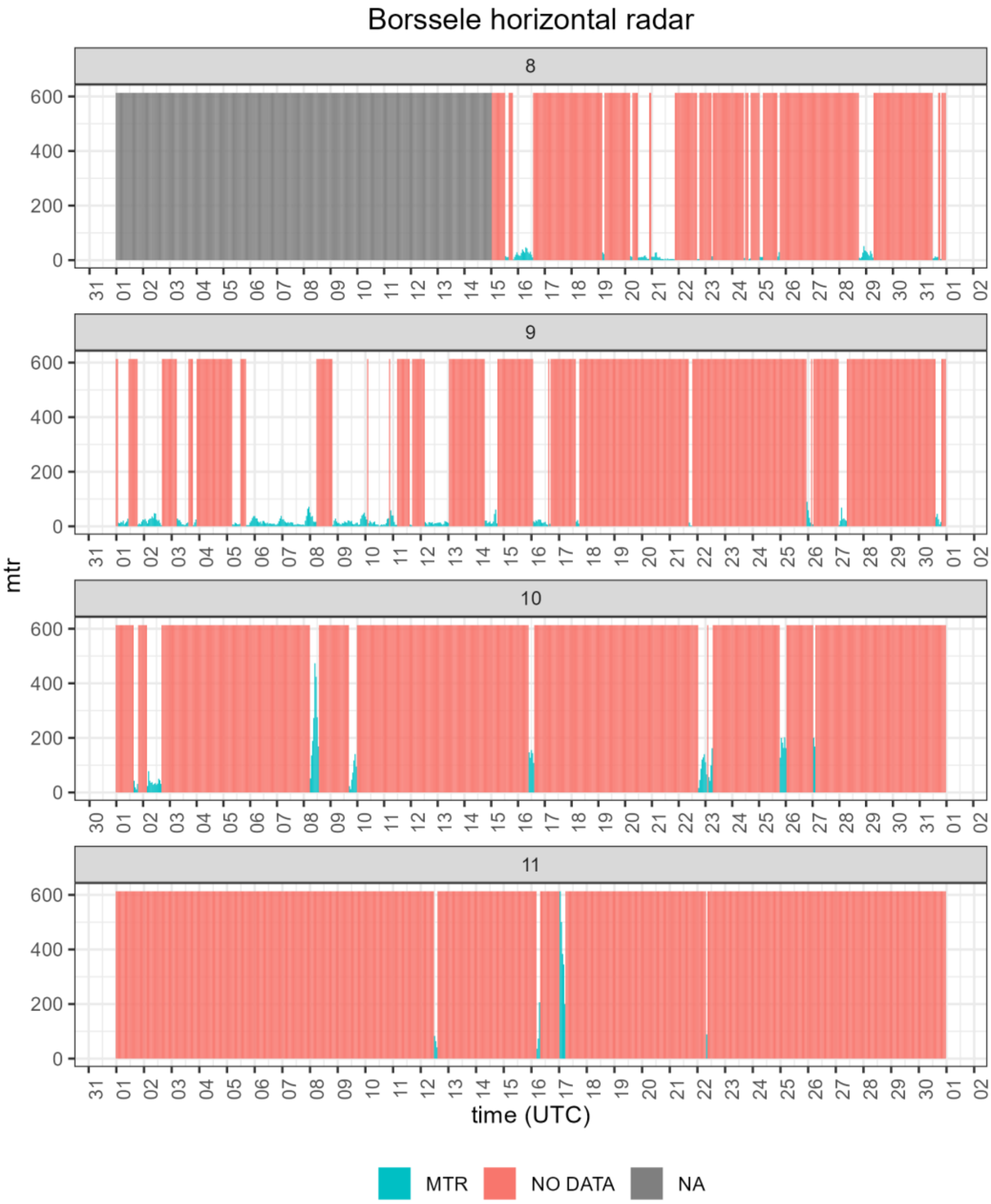

Figure 6.4 *Hourly mean traffic rate (number of tracks/km/h) measured by the horizontal radar in Borssele (teal bars). Periods with unavailable radar data are indicated with the red bars.*

6.2.2 Relation between radar measurements and model results of Luchterduinen with radar measurements in Borssele

As the model predictions are intended to be used also for curtailment for wind farms farther from Luchterduinen, it is interesting to see how horizontal radar results of Borssele compare to those of the horizontal Luchterduinen radar or the model. Therefore, for the moments the available data overlapped, we compared the measured and predicted peak moments (Table 6.2).

For **spring 2023**, neither the model nor the BSA horizontal radar showed peaks during the available hours. From the peaks the Luchterduinen radar measured, the BSA radar had data for two hours. Although the threshold of 500 MTR was not exceeded, the BSA MTRs were also elevated at these moments and belonged to the top 3 of hours (Figure *6.5*). However, these MTRs were only approximately one third of the peaks measured in Luchterduinen (Table 6.2).

For **autumn 2023**, the model predicted three peak hours that were not considered peaks according to the BSA and LUD results (Table 6.2). Note, that these peaks occurred in August and September, thus in the period that the model was not trained on. And the other way around, the BSA radar measured two peak hours on the night of 16/17 November that did not match predicted peaks by the model or measured peaks by the Luchterduinen radar (Table 6.2). For this latter, however, holds that the LUD horizontal radar measurements did show elevated MTRs during the peak moments of the BSA radar (Figure *6.5*). Moreover, the night of 16/17 November was also the night with the highest measured flight intensities on the horizontal radar in Luchterduinen and was predicted to be a peak night by the expert team. That the exact timing of the peaks did not match at the two locations may not be surprising: the predictive model is developed based on the radar data of the Luchterduinen radar. As shown in Chapter 4.5.1 the peak of bird migration was reached in Luchterduinen shortly after sunset, in the first half of the night (Figure 4.5), indicating birds departing after sunset from the relative vicinity of Luchterduinen (likely the coast of the Netherlands). In contrast, the peak of bird migration on the same night was reached in Borssele a few hours later, after midnight (Table 6.2). If these consider the same birds passing by Luchterduinen, it is not surprising that the peak occurs a few hours later, as Borssele lays approximately 100 km further southwards on the migration from Luchterduinen.

Table 6.2 Overlapping hours with mean traffic rates measured by radars at Borssele and Luchterduinen and model results, where at least one of these detected a peak.

Date	Hour (UTC)	Borssele	Luchterduinen	Model
17/18 March	23:00	331	**918**	130
17/18 March	00:00	354	**1,032**	141
15/16 August	23:00	12	38	**201**
03/04 September	22:00	14	44	**201**
09/10 September	22:00	28		**180**
17/18 November	02:00	**613**	385	106
17/18 November	03:00	**500**	303	116

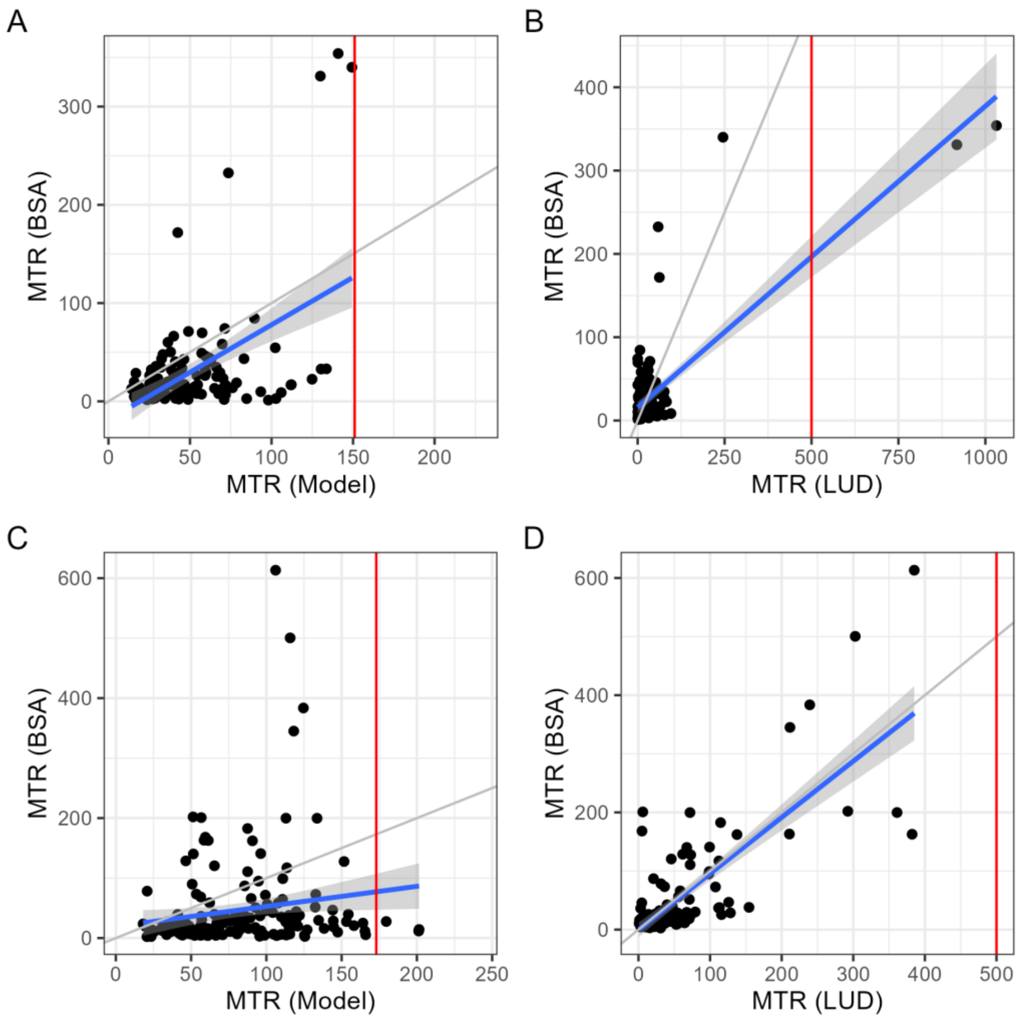

Figure 6.5 *Relation between the MTR predicted for nightly hours by, respectively the model or the radar, versus the MTR measured by the horizontal radar at Borssele (BSA) for spring (A+B) and autumn(C+D). The vertical red line indicates the threshold to define a peak. A linear relation was fitted in blue. The grey line indicates the relation x=y.*

7 Synthesis

7.1 Aim of the report

The aim of this report was to validate the bird migration prediction model that was created by the UvA (Bradarić 2022) for the migration seasons of 2023 in order to provide curtailment advise for Dutch offshore wind farms. This was done by analysing potential bird migration peak events detected by the horizontal radar in the Luchterduinen wind farm 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. Finally, weather conditions during potential peak nights were analysed, as well as bird activity in the Borssele wind farm based on the horizontal radar. Due to heavy filtering activities by the latter radar, the data was unsuitable to perform thorough analyses on.

7.2 Most important findings

7.2.1 Spring

During spring, there were three migration peaks indicated by the horizontal radar (corresponding to an MTR above 500 birds/km/hour). These three peaks happened during three consecutive nights, namely the night of the 17th to the 18th of March until the night of the 19th to the 20th of March. The trigger value of the model, 151 birds/km/hour in spring, was not exceeded during these nights, although the model predictions were close to that level and all occurred in the top 5 of nights of the model predictions. The model did predict MTRs above the trigger value in two occasions, namely the nights of 23/24 February and 11/12 March, during both of which no peak migration events were detected by the horizontal radar. Filtering activities by the radar to prevent clutter from entering the dataset might have played a role in reducing the number of detected birds, although filtering values were not high on the night of 23/24 February. Moreover, the vertical radar did not detect a peak during both nights either.

Weather conditions differed slightly between the detected peak nights by the radar and the predicted peaks by the model. During the three peak nights detected by the radar, there was a slight southwestern wind. In contrast, the nights of 23/24 February and 11/12 March predicted by the model as peak migration nights experienced a southern and western wind, respectively.

7.2.2 Autumn

In autumn, the horizontal radar detected three peak nights again, which were the nights of 25/26 October, 11/12 November and 16/17 November. The trigger value in autumn was 173 birds/km/hour based on the model predictions and was not exceeded during these nights indicated by the radar as peak nights. In contrast, during 12 other nights, the model predicted peak migration events. Six of those nights were in the months of August and September. The model was not trained to recognize migration patterns during these months which could explain these apparent false positive predictions. The other six predicted peak migration nights were not detected by the horizontal radar.

A combination of the expert team predictions and the bird migration prediction model initiated three curtailment signals during the autumn season, which were during the nights of 08/09 October, 16/17 October and 31 October / 01 November. As mentioned above, during none of these nights did the horizontal radar detect a peak. In contrast, the vertical radar did detect a peak during the curtailments of 08/09 and 16/17 October. This indicates that the horizontal radar might have erroneously missed a migration peak and the curtailment signals during these two nights were likely valid. Conceivably, high filtering activities by the horizontal radar might have played a role in missing the migration peak.

Wind conditions during the peak nights according to the model were variable, ranging from east to west. The most important weather pattern during the three peak nights detected by the horizontal radar was a sudden drop of wind speeds compared to the night before.

7.3 Future analyses

The scope of this validation report was limited to validating the model's performance and finding potential causes for mismatches between the measured MTRs by the horizontal radar and the model's predictions. The abovementioned findings of this study all help answering the question what the model is predicting and how migration over the North Sea works and how it is affected. However, even after this validation report, many questions on these topics remain. Future analyses could therefore try to answer the following questions:

- What is the effect of the threshold value for the radar and the trigger value for the model on the accuracy of the model?
- What bird species fly over the North Sea during the measured migration peaks? Could we identify the most common bird species based on migration counts at the coast?
- How can other radar systems located on the North Sea help to paint in the picture of nocturnal migration? How can these radar systems help to validate the model? Could bird radars at the coast aid in this procedure?
- How do the migration numbers measured at night compare to the migration numbers during the day?
- A more thorough analysis to find a pattern in false predictions (e.g. sudden changes in weather conditions, wind from XY direction)?
- Could it be helpful to adjust the trigger value after a few major migration events have happened?

References

Brabant, R., N. Vanermen, E.W.M. Stienen & S. Degraer, 2015. Towards a cumulative collision risk assessment of local and migrating birds in North Sea offshore wind farms. Hydrobiologia 756(1): 63-74.

Bradarić, M., 2022. On the radar: Weather, bird migration and aeroconservation over the North Sea. PhD Thesis. University of Amsterdam, Amsterdam.

Fijn, R.C., K.L. Krijgsveld, M.J.M. Poot & S. Dirksen, 2015. Bird movements at rotor heights measured continuously with vertical radar at a Dutch offshore wind farm. Ibis 157(3): 558-566.

Hersbach, H., B. Bell, P. Berrisford, G. Biavati, A. Horányi, J. Muñoz Sabater, J. Nicolas, C. Peubey, R. Radu, I. Rozum, D. Schepers, A. Simmons, C. Soci, D. Dee & J.-N. Thépaut, 2023. ERA5 hourly data on single levels from 1940 to present. Copernicus Climate Change Service (C3S) Climate Data Store (CDS).

Kraal, J.J., K.L. Krijgsveld, R.P. Middelveld, M. Japink, R.S.A. van Bemmelen & A. Gyimesi, 2023. Validation of the bird migration prediction model, Rapport 23-130. Waardenburg Ecology, Culemborg.

Krijgsveld, K., R.C. Fijn & R. Lensink, 2015. Occurrence of peaks in songbird migration at rotor heights of offshore wind farms in the southern North Sea. Report nr 15-119. Bureau Waardenburg, Culemborg.

Leemans, J.J., E.L.B. Rebolledo & A. Gyimesi, 2021. Validation of the offshore bird radars at Borssele Alpha, Rapport 21-109. Bureau Waardenburg, Culemborg.

Leemans, J.J., K. Kuiper & A. Gyimesi, 2022a. Additional validation of the offshore bird radars at Borssele Alpha, Rapport 22-005. Bureau Waardenburg, Culemborg.

Leemans, J.J., R.S.A. van Bemmelen, R.P. Middelveld, J.J. Kraal, E.L. Bravo Rebolledo, D. Beuker, K. Kuiper & A. Gyimesi, 2022b. Bird fluxes, flight- and avoidance behaviour of birds in offshore wind farm Luchterduinen, Rapport 22-078. Bureau Waardenburg, Culemborg.

Leemans, J.J., E.L. Bravo Rebolledo, K. Kuiper, N. Heida, R.S.A. van Bemmelen, G.J. IJntema, H. Madden & A. Gyimesi, 2024. Bird research in offshore wind farm Borssele. Fluxes, corridor use, flight- and avoidance behaviour, Rapport 24-084. Waardenburg Ecology, Culemborg.

Shamoun-Baranes, J. & H. van Gasteren, 2011. Atmospheric conditions facilitate mass migration events across the North Sea. Animal Behaviour 81(4): 691-704.

van Bemmelen, R.S.A., J. de Groeve & A. Potiek, 2022. Potential curtailment regimes for offshore wind farms: exploring the relation between wind speed, power yield and bird migration intensity. Spatial variation in migration intensity and optimization of curtailment threshold, Rapport 22-171. Bureau Waardenburg, Culemborg.

van Erp, J.A., E.E. van Loon, J. De Groeve, M. Bradarić & J. Shamoun-Baranes, 2023. A framework for post-processing bird tracks from automated tracking radar systems. Methods in Ecology and Evolution 15(1): 130-143.

Welcker, J., 2019. Patterns of nocturnal bird migration in the German North and Baltic Seas. Technical report. BioConsult SH, Husum.