# Validation of the bird migration prediction model


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***Wageningen Environmental Research** Droevendaalsesteeg 3A, 6708 PB Wageningen. Contribution regarding the predictions of the team of migration specialists.

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# Preface

Shutting down wind turbines during major bird migration events is expected to be an effective mitigation measure to reduce the number of bird casualties. Hence, this measure is proposed to be implemented at a large scale in Dutch offshore wind farms. 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 autumn module. This report summarizes the results of this validation and provides suggestions for the improvement of the bird migration forecast model. This version of the report is an update of the first concept after correcting for differences in how the ECMWF- and ERA5 weather models deal with the rain parameter.

# Summary

Large numbers of birds cross the North Sea during their migration to and from their wintering grounds. The rapid development of offshore wind farms leads to new risks along the migration path of these birds. Curtailment of offshore wind turbines during peak migration events is expected to be an effective mitigation measure to lower the number of collisions of migrating birds. In order to predict when curtailment needs to take place, a bird migration forecast model was developed by the University of Amsterdam (UvA) based on both actual radar measurements of offshore bird migration intensities and weather conditions at important regions along the flyway. The model predicts bird migration intensity (i.e., Mean Traffic Rate (MTR): the number of birds passing a line of 1 km) in the lower 300 meters above sea level and is trained on weather data from the ERA5 reanalysis model. This reanalysis combines model data with actual observations to provide the best possible location-specific estimate of weather circumstances. However, the network operators need to know the expected energy loss (i.e. the period of curtailment) two days in advance, which means the model needs to operate using weather forecasts instead of weather observations. Therefore, part of the validation of the bird migration forecast model encompassed evaluating eventual differences arising by the use of the ERA5 reanalysis weather data or the European Centre for Medium-Range Weather Forecasts (ECMWF-data).

First, this report presents the results of the validation of the bird migration forecast model for the autumn 2022 season (16 August – 30 November), using ECMWF weather forecast data as input instead of the ERA5 reanalysis data. While the migration occurs during this whole period, the most peaks are expected to occur during October and November. Therefore, the UvA decided to train the model only with data from these two months. This causes the model to underperform outside the periods on which it was trained, as one of the strongest predictors of migration in the current model setup is migration phenology.

In order to validate the predicted MTRs, the MTR predictions of the bird migration prediction model using ECMWF weather forecast data were compared with two data sources.

1. Actual measured MTRs within wind farm Luchterduinen, based on horizontal radar,
2. Actual measured MTRs within wind farm Luchterduinen, based on vertical radar.

This allowed for a comparison of the prediction model with both types of radar, but also for a comparison of both radars with each other. Hereby it needs to be considered that the prediction model is trained on data of the horizontal radar, which were assumed to be more reliable according to analyses from the UvA and contain more parameters of radar echo characteristics that help differentiating tracks of migratory birds. Therefore, comparing model outcomes with MTR measurements of the horizontal radar is probably the most valid comparison. Nevertheless, investigating MTR measurements of the vertical radar as well can be valuable when data of the horizontal radar are lacking or seem not to be reliable.

Furthermore, a group of expert ornithologists made predictions on the occurrence of nights with peak bird migration. These predictions were analysed and compared with the radar data as well as with the forecast model. Hereby, it should be taken into account that the

expert team used the 06:00 AM EMWCF forecast, while the model is ran with the 00:00 AM forecast.

For the ECMWF weather forecast data, three timings of weather forecast data were used as input in the model: 00:00 AM, 06:00 AM and 12:00 PM (UTC) of which the first is currently used as input. Finally, predictions of the bird migration forecast model generated based on the ECMWF weather forecast data were also compared with predictions based on actual ERA5 reanalysis data (i.e., the original weather data input for the model).

Our results show:

- In general, the MTRs produced by the bird migration forecast model were lower than the MTRs calculated using the radars.
- The radar data indicated ten nights with peak bird migration during the autumn of 2022. One of these nights also belonged to the top ten of nights according to the bird migration prediction model.
- In nine out of the top ten nights based on predicted MTRs by the bird migration forecast model, the radar data did not indicate a peak. However, in some of these cases mismatches occurred due to no radar data being available, either due to malfunctioning of the radars or heavy radar filtering caused by rain or high waves.
- Of the ten peak migration nights measured by the radars, five were also predicted by the expert team. Six nights that were predicted by the expert team as peak migration nights, did not match high MTRs measured by the radars. However, on some of the peak nights predicted by the expert team the radars were not operational. Also, lower values measured by the radars may have been caused by high waves or rain.
- Three out of eleven nights that were predicted to be a peak night by the expert group were also in the top ten most intense migration nights according to the model predictions.
- The model was originally only trained on October and November data, while the current validation was carried out also for the months August and September. Peaks predicted by the model in these latter months must be interpreted with care.
- We showed that relatively high waves lead to lower MTRs in the horizontal radar and therefore peaks could be missed under these conditions. Rainy periods are an important limiting issue for the vertical radar. Because of this, both radars have considerable periods without reliable data.
- Measurements of the horizontal radar on moments with relatively high waves are not always excluded by the standard data filtering steps, and hence predictions based on these data may falsely miss migration peaks.
- Instead of training the model only on the output of the horizontal radar, it is advised to consider training the model on MTR calculations from both the horizontal and vertical radars. This could result in a more complete picture of the migration season.
- To ensure the quality of the data of the horizontal radar, more strict filtering steps might be needed to filter out periods with falsely low MTRs.
- The bird migration forecast model was trained on an admittedly incomplete dataset (i.e., due to missing radar data) of a relative short research period with a limited number of migration peaks. With more seasons of bird migration data, the results will most likely improve.

# Content

# 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 (Krijgsveld *et al.* 2011). On their way, these birds encounter several risks. Because of the development of wind farms, also offshore, the possibility of colliding with one of the turbines has become one of those risks. The number of wind turbines is increasing rapidly, leading to increased danger of collisions for migrating birds.

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 created 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 bird migration prediction model was trained on weather data from the ERA5 reanalysis model (Hersbach *et al.* 2023a, 2023b). 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. This forms the starting point of the curtailment procedure of Dutch offshore wind farms. 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 these MTRs. For that reason, the model predictions of autumn 2022 were compared with radar measurements from the same bird radar in offshore wind farm Luchterduinen that was also used to train the bird migration prediction model.

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. Here, two methods to calculate the MTR for the autumn migration seasons of 2022 are used. On the one hand, the method used by Bradarić (2022), taking the density of bird tracks and the ground speed within an hour in consideration to quantify the number of birds that fly through the area. On the other hand, the method used by Leemans *et al.* (2022) 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 of the Robin 3D fixed system operating in wind farm Luchterduinen. Because the horizontal radar has no height information and the vertical radar lacks spatial information, the two radars are intended to work supplementary to each other to study migration patterns in detail.

The procedure of curtailing offshore wind farms starts with the bird migration prediction model outcomes. If the model outcome passes by a certain (still to be determined) MTR threshold value, the expert team will be notified. The expert team will then judge whether curtailment is necessary. This expert team consists of seven expert ornithologists from a variety of institutions. Being an important element in the curtailment procedure, the expert team predictions made for the autumn migration season of 2022 are also included in this report.

All in all, this report therefore aims to validate the UvA MTR predictions by comparing the model output with: radar measurements from the horizontal radar, radar measurements from the vertical radar and MTR predictions by the expert team.

**Reading guide**

- The methods of the analyses are presented in Chapter 2.
- In Chapter 3, we show the autumn 2022 migration as it was observed by the horizontal and vertical radar.
- The predictions by the expert group on peaks in bird migration are analysed in Chapter 4. Both Chapter 3 and 4 try to visualize the temporal pattern of the autumn migration season of 2022.
- In Chapter 5, the predictions by the bird migration prediction model are compared with the radar measurements described in Chapter 3.
- In Chapter 6, the data of all four data sources are put together and compared with each other, in order to find agreements and disagreements between the bird migration forecast model and the other sources.
- In chapter 7, it is discussed whether the accuracy of the model would improve with more recent weather forecasts (i.e. six and twelve hours later than used currently).
- An analysis of how the model is affected by using ECMWF weather forecasts instead of ERA5 reanalysis data is presented in Chapter 8.
- In the discussion, the results of the abovementioned analyses are put into perspective and recommendations for further research are provided.

# 2 Materials and methods

## 2.1 Radar measurements

As mentioned in the introduction, the horizontal and the vertical radar of the Robin 3D Fixed System in the Luchterduinen wind farm were used to calculate bird migration intensities in the form of MTR. The same method to calculate the MTR from the horizontal bird radar was used as was performed in (Bradarić 2022). Since the horizontal radar resembles a bird eye view of the study area, a density-based approach had to be used (§2.1.1). In contrast, the vertical radar looks like 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 was following (Leemans *et al.* 2022). Together, both radars provide detailed information about the flight behaviour of individual birds in the study area. The horizontal radar was used to calculate the MTRs the same way as was done before training the model, but also to show flight directions of the migrating birds. The vertical radar was used to study possible missed migration peaks by the horizontal radar and can be used to show flight height distributions during peaks.

### 2.1.1 Horizontal radar measurements

*Radar specification*

Two bird radars were installed on the railing of one of the turbines (WTG 42) in the offshore wind farm Luchterduinen at approximately 23 m above mean sea level. The installed radars are a so-called Robin 3D Fixed System, consisting of a horizontal Furuno magnetron-based S-band radar and a vertical radar which is specified in paragraph 2.2.1. The aim of the horizontal radar is to detect and measure the 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 (Leemans *et al.* 2022). All radar tracks observed by the horizontal radar were considered, including the so-called combined radar tracks. These latter are horizontal radar tracks that are also detected by the vertical radar and hence have an altitude component.

*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, the metric of displacement over time (DOT) was used to remove tracks that seemed to be rather locally oriented. 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 displacement over time were removed. The next step to remove tracks that were locally orientated was by deleting all tracks with a straightness of lower than 0.7. 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.

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. The wind speed and direction from the ERA5 weather model were used from the Copernicus website (Hersbach *et al.,* 2023b).

Finally, all minutes with high filtering activity by the radar were completely labelled as high-clutter minutes. Filtering by the radar is used to reduce the number of non-bird tracks ending up in the database; however, this usually leads to a lower detection probability of a real bird, and hence an underestimation of the number of birds during that minute. Therefore, all hours with 10 or less minutes of data were 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 an area left out due to the blanking sector of the radar towards the wind turbine it is installed on (Figure 2.1). The inner border of the donut is at 1,000 meters and the outer border at 2,000 meters from the radar. The surface area of the donut is 7.57 $km^2$. Every 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. 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.*

All tracks involved have a feature which is called 'the number of plots'. The number of plots stands for 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.

The 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 metres of the vertical column.

### 2.1.2 Vertical radar measurements

*Radar specification*

The vertical radar is the located at the same turbine as the horizontal radar and is a fixed vertical Furuno magnetron-based pulse X-band radar. The vertical radar works almost the same as 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 quite narrow. Again, combined tracks that were detected by both the horizontal and vertical radar were used.

*Data filtering*

To prevent any non-bird tracks from entering the dataset, several filtering steps were taken. These steps were based on (Leemans *et al.* 2022). Because the vertical radar has other characteristics than the horizontal radar, other filtering steps had to be used than during the calculation of MTRs with the horizontal radar. Especially rain showers are known to contaminate the data of the vertical radar. 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. Therefore, 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 more than 0.1 mm of rain. 252 of the 2568 hours in the autumn season of 2022 from the 16$^{th}$ of August until the 30$^{th}$ of November had at least 0.1 mm of rain.

For the final 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’ can be assigned. Each track that has multiple reflection centres is labelled with this property. A large proportion of the bird tracks generated by rain showers were found to have this label. Therefore, all hours with at least 50 tracks and of which more than 15% had the property ‘In Blob Formation’ at one of the two beams (Figure 2.2), were filtered out.

Based on track characteristics, each track is classified by the radar as, for example, small bird, large bird, airplane, or boat. Normally, only bird tracks were selected. However, in autumn 2022 some bird tracks were observed to be falsely classified as a 'Slow Target', indicating tracks with a low speed. Although these birds were flying at a normal speed, the radar indicated that these tracks seemed to move very slowly. This was likely caused by bird tracks that moved perpendicular to the vertical radar beam. As a result of how the radar projects each moving object, the estimated speed is very low. Migrating birds are likely to fly perpendicular to the vertical radar beam and therefore a certain proportion of these birds could be classified as 'Slow Target'. In order to avoid missing true bird tracks, these tracks were included in this analysis.

*MTR calculation*

Vertical radar measurements were done based on flux lines that were placed from 500 – 1000 meters from the radar, towards both sides of the beam (Figure 2.2). This is slightly closer to the radar than where the horizontal radar measurements were done, but this was done to prevent false tracks entering the data because of turbines. This also means that MTRs calculated from both radars are not comparable.

We present results using height bands, in order to show vertical layering of the flux. 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 Luchterduinen. 137-300 meters is the air layer just above rotor height that might still be visible by the horizontal radar. The rest of the vertical column, up to 1000 meters was divided in two layers, up to 500 meters and up to 1000 meters.

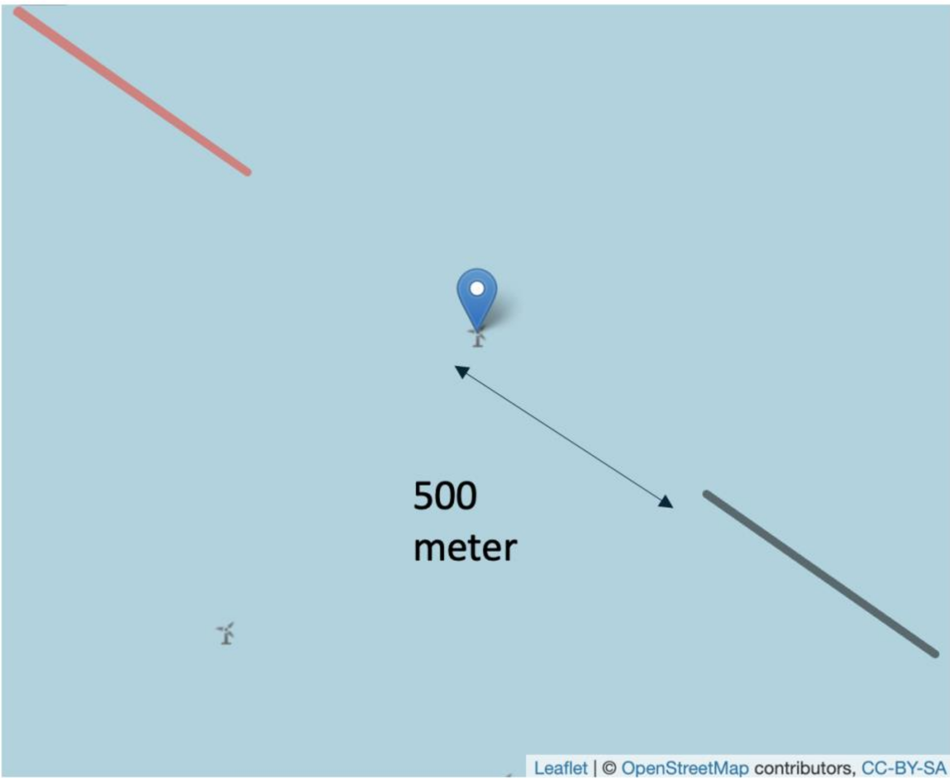


*Figure 2.2* *Fluxline placement around the radar to the northwest (red line) and southeast (black line). The marker depicts the radar location. Both flux lines are 500 meters long.*

## 2.2 Expert group predictions

A team of seven bird migration specialists predicted occurrence of migration peaks in the autumn of 2022, in order to offer an addition to the model predictions. Predictions were made for 70 nights, from 21 September 2022 to 30 November 2022. Predictions were given at 15:00 in the afternoon at the latest and were made for the night following 48 hours from the prediction. Thus, for instance, on Monday afternoon a prediction was made for the night from sunset on Wednesday to sunrise on Thursday. A warning for a migration peak was given when the team predicted a migration peak with a migration traffic rate (MTR) of more than 500 at altitudes up to ca 250 m, over the Dutch North Sea in the area south from Ijmuiden. In addition, these predictions were also made for the areas between IJmuiden and Texel and the area north of the Wadden Sea. Initially, predictions were made for the entire night, but from the end of October onwards a specification was made whether peaks would occur before midnight, after midnight, or during the entire night.

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 taken into account as well.

## 2.3 Bird migration prediction model

The bird migration prediction model needs several variables to generate its predictions. All steps described below were following (Bradarić 2022). First, a variety of weather variables were used as input into the model (§ 2.4.1). Next, using this weather data, the estimated wind assistance is calculated, indicating how much wind support there is for migrating birds (§2.4.2). Another variable that is calculated from the weather data, is the accumulation factor, which is a measure trying to capture how long birds delayed migration because of unfavourable weather conditions. Finally, the day of the year and hour after sunset are important factors within the model.

To compare the model predictions with the radar measurements described above, the weather forecast of 00:00 two days before the start of the night that is predicted by the model was used (Table 2.1). This is because the weather forecasts generated at 00:00 are used in the current procedure. However, the model predictions might improve with more recent and more accurate weather forecasts, which is why the model is also assessed with weather forecasts generated at 6 and 12 hours after midnight.

*Table 2.1 Timing of weather forecast as input into the bird migration prediction model.*

| Weather forecast | Night that is predicted |
|---|---|
| Date x – 2 days (00:00) | Night starting on date x |
| Date x – 2 days (06:00) | |
| Date x – 2 days (12:00) | |

### 2.3.1 Weather data

Weather data were taken from the ECMWF database. Weather data at the site of the radar were taken from the closest grid cell in the ECMWF dataset (52.25 N 4.00 E). Weather data from the departure locations, north of the Netherlands, Central Denmark and North-western Germany were averaged over all grid cells within the corresponding area and over the first two hours after sunset (Bradarić 2022). The weather variables that were used were the total precipitation (in mm) and mean sea level pressure (in hPa). Furthermore, both the wind components u (west to east) and v (south to north) at 100m above sea level were used (in m/s). The average air temperature (°C) from multiple pressure levels were extracted so that it corresponded with the air temperature from 100 to 300 meters above sea level. The altitude of these temperatures was calculated by dividing the geopotential height of a certain pressure level by the gravitation acceleration. Finally, the change of weather conditions between two subsequent nights, both at the radar site and on departure locations, was measured by calculating the difference in sea level pressure between two nights.

### 2.3.2 Other variables

The wind assistance that was used to indicate the support birds have from the wind, was calculated by multiplying the wind speed (m/s) by cos*difference in direction between wind and preferred migration routes. The latter was 214° at the radar location and 220° at the departure site for southward migrating birds (Bradarić 2022). To calculate the wind assistance for birds migrating towards the United Kingdom, the migration direction of 270° was used.

Bird accumulation was based on weather data as well, but only on weather data from departure locations. A binary variable was created, meaning that accumulation would take place when the hourly precipitation was above 0.01 mm and a lower wind assistance than -2 m/s. If both conditions were not favourable for migrating birds, a factor of ¾ was used to indicate the proportion of birds that do not depart in comparison to when these conditions were better. The accumulation factor ranged between zero and one, the latter indicating maximum accumulation. Finally, differences between subsequent nights in the accumulation factor were used as input in the model.

## 2.4 Weather of autumn 2022

The autumn of 2022 in the Netherlands was relatively mild and contained a lot of sunshine (KNMI, 2022). The mean temperature during the autumn of 2022 was 12.1°C which is warm in comparison to the long-term average autumn temperature based on data from 1991 to 2020 (10.9°C). Especially October was a month with high temperatures compared with the long-term average (13.1°C versus 10.9°C). For September (14.6°C versus 14.7°C) and November (8.6°C versus 7.0°C) the temperatures looked more like the long-term average. In October the highest temperature was in the last ten days of the month. On the 28th of October, a temperature of 24.6°C was measured in the Netherlands. These mild conditions stayed until the 19th of November, when cold weather arrived.

In September, there was a lot of precipitation in the Netherlands compared with the long-term average, 127 mm against 73 mm. This is in line with the precipitation in November 2022 (90 mm) compared to the long-term average (76 mm). October (38 mm) was less wet than normal (75 mm). Most precipitation was measured at the coastal region.

All months were exceptionally sunny, leading to the fourth most sunny autumn season since 1901. This reflects the mild character of the autumn of 2022. Mainly October was a relatively warm and dry month compared with the long-term average. September and November resembled more regular conditions based on temperature, but it was raining more than the long-term average.

# 3 Radar measurements

## 3.1 MTR calculations based on the horizontal radar

The total period of August 16th until November 30th consisted of 2568 hours. 725 hours were discarded, of which 92 hours the horizontal radar was turned off and 633 hours the filtering activities of the radar were too high for reliable results. This means that a total of 1,843 hours were used in this analysis. 1070 of these hours are nightly hours.

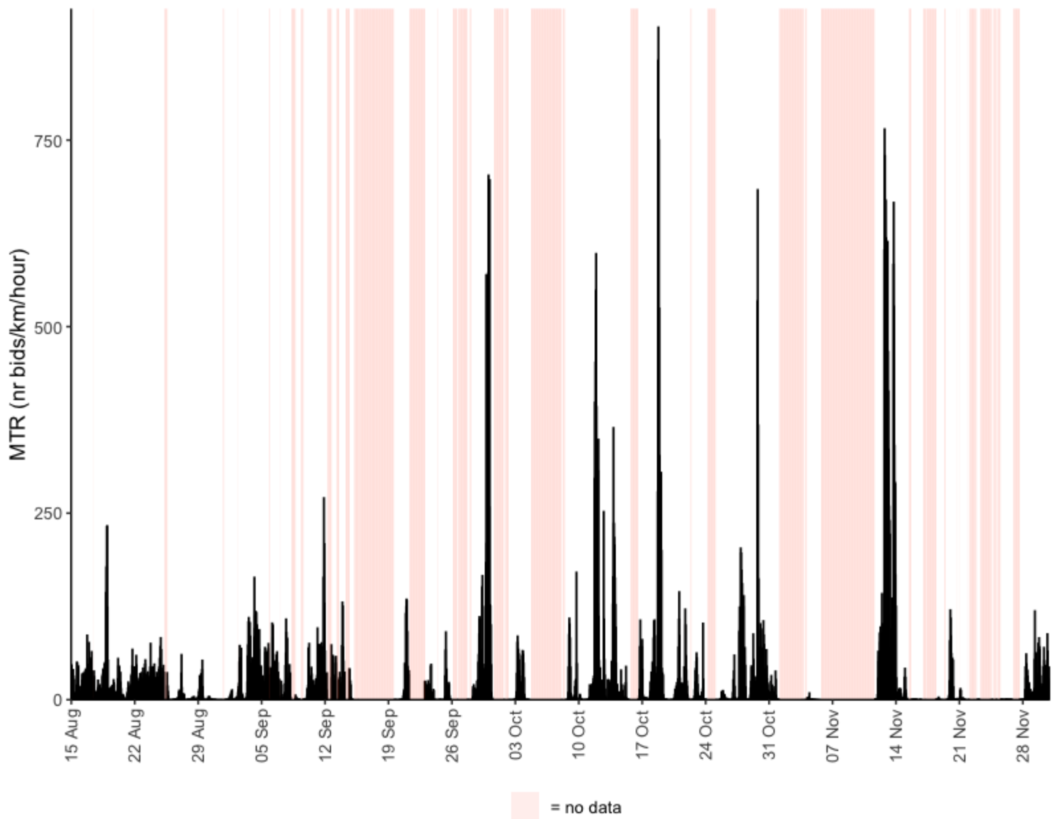


*Figure* 3.1 *The temporal pattern of the MTR (black bars) measured by the horizontal bird radar in the Luchterduinen wind farm in autumn 2022. Periods with no data due to filtering activities of the radar or inactivity of the radar are marked in light red.*

The horizontal radar measurements showed very high peaks of MTRs in the autumn of 2022 around the Luchterduinen wind farm (Figure *3.1*). The hour with the highest MTR was at the evening of 18 October from 9 to 10 pm (local time), with 901 birds/km/h. Interestingly, the hour with the second highest MTR was the hour before that, from 8 to 9 pm (856 birds/km/h), showing the concentrated character of bird migration. The third busiest hour was on 12 November from 7 to 8 pm, with 764 birds/km/h.

The night with the highest mean MTR was the night of November the 12th to the 13th of November when on average 465 birds/km/h crossed the study area. After that, the nights that began on 18 October, 29 September and 11 October were nights with high mean

MTRs. Besides these nights, the night starting on the 29th of October and on the 13th of November can be considered peak nights with at least two hours with an MTR above 500 birds/km/h (Table 3.1).

*Table 3.1 The average and maximum MTR measured by the horizontal radar during peak migration nights with an MTR above 500 birds/km/h.*

| Night | Average MTR (birds/km/hour) | Maximum MTR (birds/km/hour) |
|---|---|---|
| Sep 29 – Sep 30 | 322 | 703 |
| Oct 11 – Oct 12 | 283 | 598 |
| Oct 18 – Oct 19 | 325 | 901 |
| Oct 29 – Oct 30 | 162 | 683 |
| Nov 12 – Nov 13 | 465 | 765 |
| Nov 13 – Nov 14 | 192 | 666 |

The cumulative MTR over all 1,070 analysed hours was 48,886 birds/km. A total of 23 hours exceeded 500 birds/km/h (1.2% of total analysed hours). These 23 hours combined showed a cumulative MTR of 14,882 birds/km, which is 30 percent of the total cumulative MTR during analysed hours.

Our analysis was limited to periods when radar data was available. In some periods in November and October (when most peaks in bird migration occur) of 2022, no radar data was available due to rain or high waves (see §2.1.2 on radar filtering). However, during such conditions MTRs are generally expected to be lower and not exceeding 500 birds/km/h. But there are no field results to confirm this expectation yet.

### 3.1.1 Temporal patterns of peak nights

There were six peak migration nights that had hours with an MTR above 500 birds/km/h. The temporal pattern of bird migration during these nights were diverse (Figure 3.2). Similarities between the peak nights were that all of them had low MTRs in the hour of sunset, followed by an intensive period at the beginning of the night, shortly after sunset.

However, after this first peak, migration patterns differed. Some nights, like the night starting on the 29th of September, had an early peak, followed by a second peak later during that night. A possible explanation for this pattern could be that migrating birds are leaving the Netherlands first, followed by birds from further up north/northeast arriving later in the night. The same pattern was seen on the 11th of October and the 18th of October.

However, the second peak in MTR values was not present on the other three nights. On the 29th of October, a high peak in the beginning of the night was followed by a relatively calm migration night. Finally, the two last peak nights, the 12th and 13th of November, had a peak at the beginning of the night, after which the number of birds steadily decreased. However, the migration intensity can be considered as high during the whole night of the 12th of November, while on the 13th of November it was rather low after midnight.

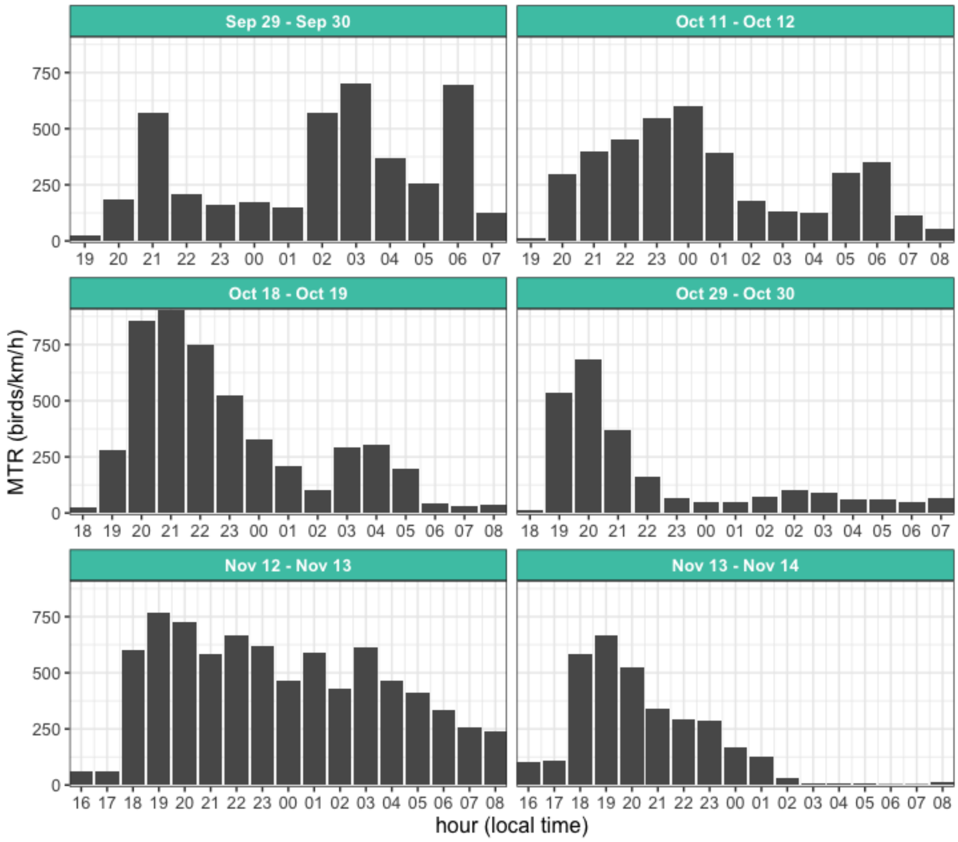


*Figure 3.2* *Temporal MTR pattern during the six peak migration nights with an MTR above 500 birds/km/h. Hours are in local time and span from the hour in which the sun sets until sunrise the next morning.*

### 3.1.2 Weather conditions on peak nights

The wind directions during peak migration hours were mostly from southeast (Figure 3.3), based on weather data gathered in the Luchterduinen Wind Farm. This is the case for most intense migration hours with MTRs above 500 birds/km/h, as well as for hours with MTRs above 250 birds/km/h. Considering that the main directions towards which birds fly during migration could be south (towards South-Europe and Africa) and west (towards the United Kingdom), these conditions seem most favourable for migration towards United Kingdom as it gives migrating birds a slight tail wind.

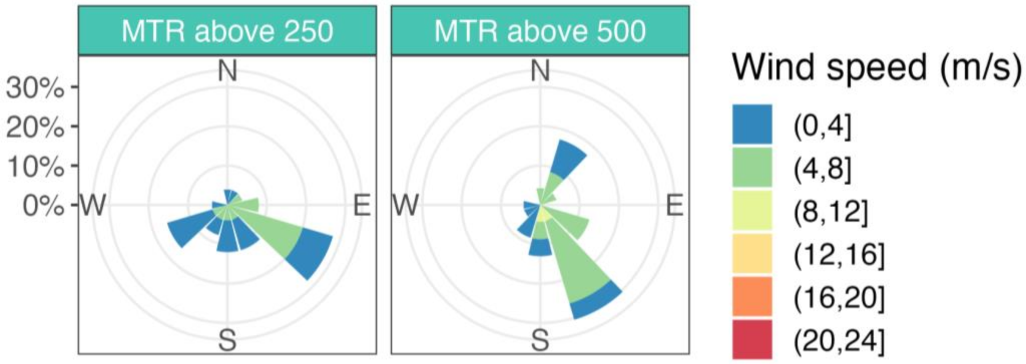


*Figure 3.3* *Wind directions during all peak migration hours considered together. Bar height is cumulative of all hours in which the wind had that direction. Colours within bars show wind speeds. Note 1: Wind directions show where the wind comes from and is therefore opposed to where it blows towards.* *<u>Note 2: The weather data used for this analysis came from a local weather station of wind farm Luchterduinen and is thus a different source than what was used as input in the bird migration prediction model. Such direct measurements of an instrument can differ substantially of the ERA5 data that is a model representation of the best estimated weather conditions.</u>*

Nonetheless, this does not mean that under these wind conditions birds can only migrate towards the United Kingdom. When looking at the wind directions and speed a week before the mass migration events compared to wind directions and speed during the peak night, it is obvious that wind direction changes are a likely factor driving mass migration events (Figure 3.4). This is especially highlighted by the night starting at the 12$^{th}$ of November (the busiest migration night of the season), before which a week long strong winds blew from the southwest (*i.e*. headwind for the main migration routes). Subsequently, on the night of 12 November, the wind direction turned towards southeast and reduced in strength, providing possible departure conditions for all the birds accumulated during the strong headwind conditions. Such changes in wind conditions seem to be an important trigger for mass migration moments.

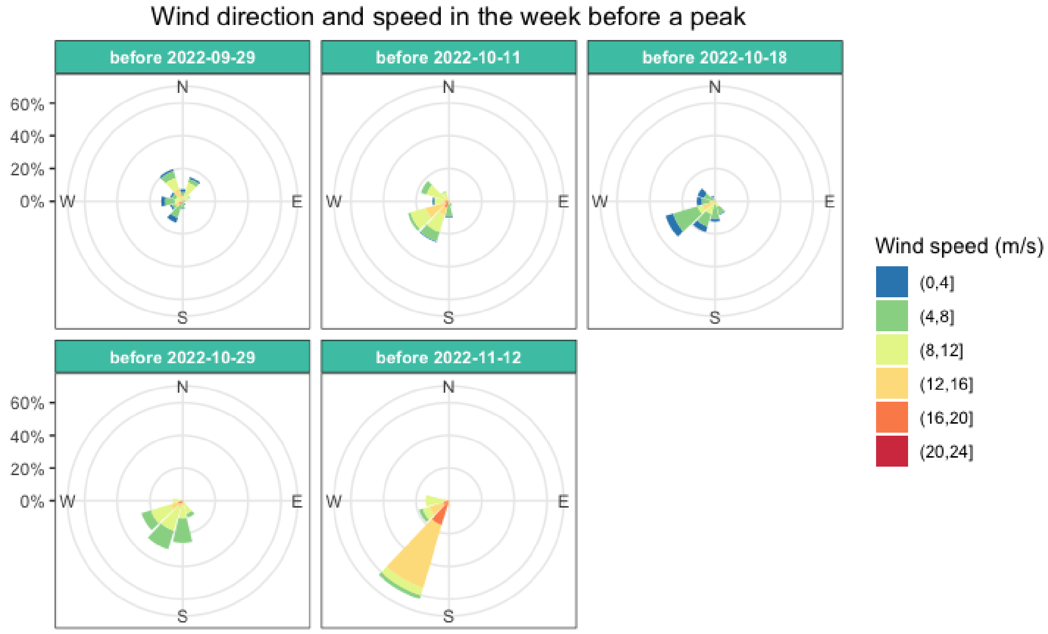


*Figure 3.4* *Wind direction in the weeks before peak migration nights. Colours within bars show wind speeds. Bar height is cumulative of all hours in which the wind had that direction. Wind directions show where the wind comes from and is therefore opposed to where it blows towards. Also note that of the peak nights the 13th of November is missing, because the week before that is mostly overlapping with that of 12th of November. Note: The weather data used for this analysis came from a local weather station of the Luchterduinen Wind Farm and is thus a different source than what was used as input into the bird migration prediction model. Such direct measurements of an instrument can differ substantially of the ERA5 data that is a model representation of the best estimated weather conditions.*

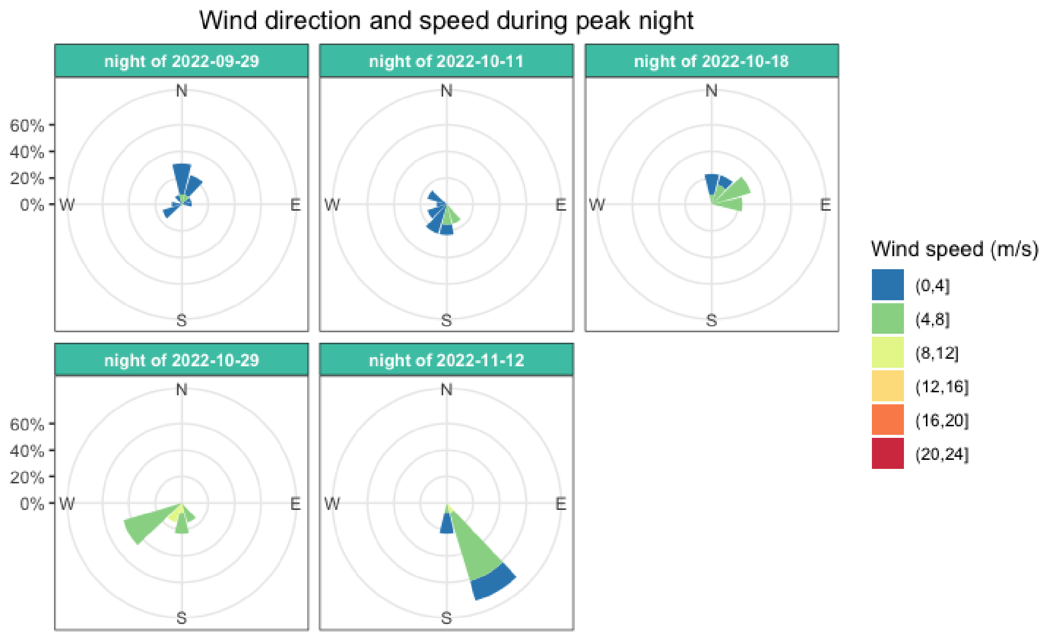


*Figure 3.5* *Wind direction during the individual nights with peak migration. Colours within bars show wind speeds. Bar height is cumulative of all hours in which the wind had that direction. Note that wind directions show where the wind comes from and is therefore opposed to where it blows towards. Note: The weather data used for this analysis came from a local weather station of the Luchterduinen Wind Farm and is thus a different source than what was used as input into the bird migration prediction model. Such direct measurements of an instrument can differ substantially of the ERA5 data that is a model representation of the best estimated weather conditions.*

The only peak migration night with obvious northern winds was the night of 29 September (Figure 3.5). Interestingly, this was also the only night in which the main flight direction of birds detected by the radar was clearly south (Figure 3.6). All other peak nights had a main axis of migration towards west or southwest. Overall, the main flight direction during peak nights seem to be parallel to the coast towards southwest.

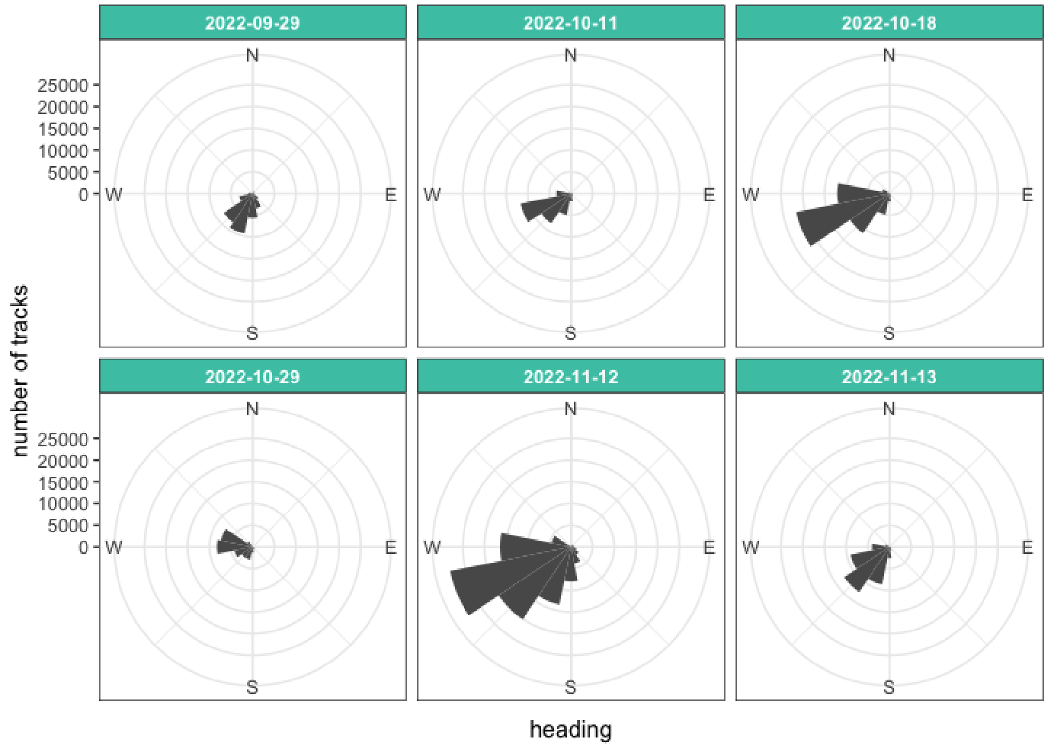


*Figure 3.6* *Flight direction based on horizontal radar data during peak nights. Number of tracks stands for the number of tracks in that night that were used in the analysis, i.e., after filtering. The date above the plot corresponds to the start of the night.*

### 3.1.3 Dataset cleaning

Understanding the behaviour of filtering by the radar and its effects on MTR calculations is crucial in the validation of the bird migration prediction model. To assess whether filtering steps of the radar data affected the model predictions, we analysed the effect of filtering due to waves and rain. A principal problem is that there is no predefined range of the extend of radar filtering within which the MTR calculations are reliable.

With increasing percentage of the total area filtered by the radar, the number of recorded tracks slightly decrease. This is clearly visible when comparing the wave height with the MTR in that hour (Figure 3.7). When the average wave height of an hour is below 100 cm, the filtering activities of the radar do not seem to affect the MTR. However, with waves above 100 cm, the radar seems to detect fewer bird tracks and above 125 cm there are almost no tracks recorded anymore. This indicates that calculated MTR during hours with wave heights above 100 cm should be judged very critically.

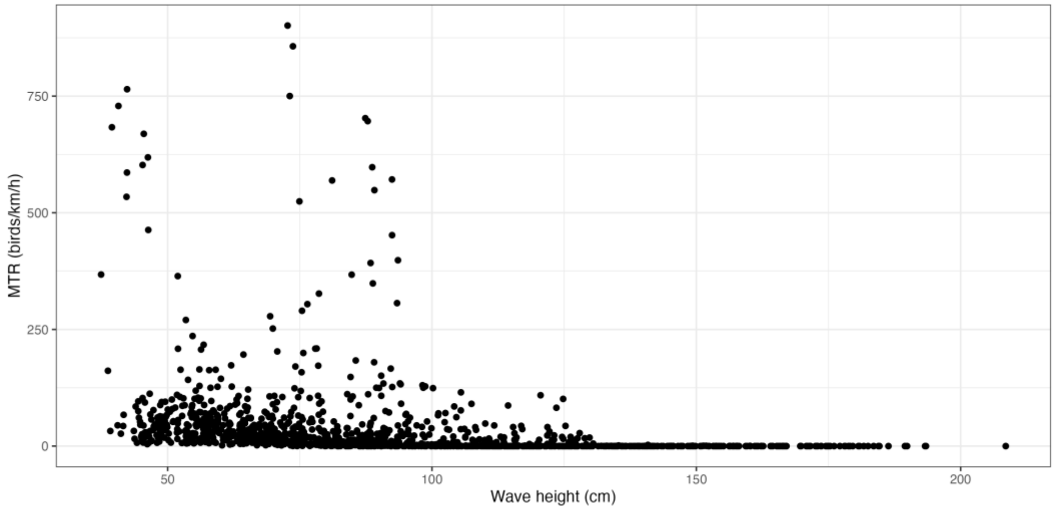


*Figure 3.7* *Wave height versus calculated MTR within an hour. Hours that are removed from the analysis because of high filtering are not shown here. Wave height was measured every minute and is subsequently averaged per hour.*

## 3.2 MTR calculations based on the vertical radar

Because there was no vertical radar data for the month of November, because of malfunctioning of the radar, the total period of analysis consisted of 1848 hours. 114 of which were filtered out because the radar was turned off and 426 hours were filtered out because of rain or rain filtering activities by the radar. This leaves 1308 hours in the dataset for the MTR calculations, with a total of 682 nightly hours.

Figure 3.8 shows the MTR calculated by the vertical radar for the different height bands. These patterns measured by the vertical radar were compared with the measurements from the horizontal radar to gain insight into the differences and similarities between the two types of radar. On both radars, the night of the 18th of October stands out as one of the busiest nights of the season. The same holds for the nights of the 29th of September, the 11th of October and the 29th of October. Because of missing data of the vertical radar in November, two peaks in the horizontal radar data could not be verified by the vertical radar. Note that the horizontal radar measures birds throughout the lower 300 meters. Therefore, from here, also when speaking of MTRs calculated by the vertical radar, the MTRs between 3 and 300 meters are meant, unless stated otherwise.

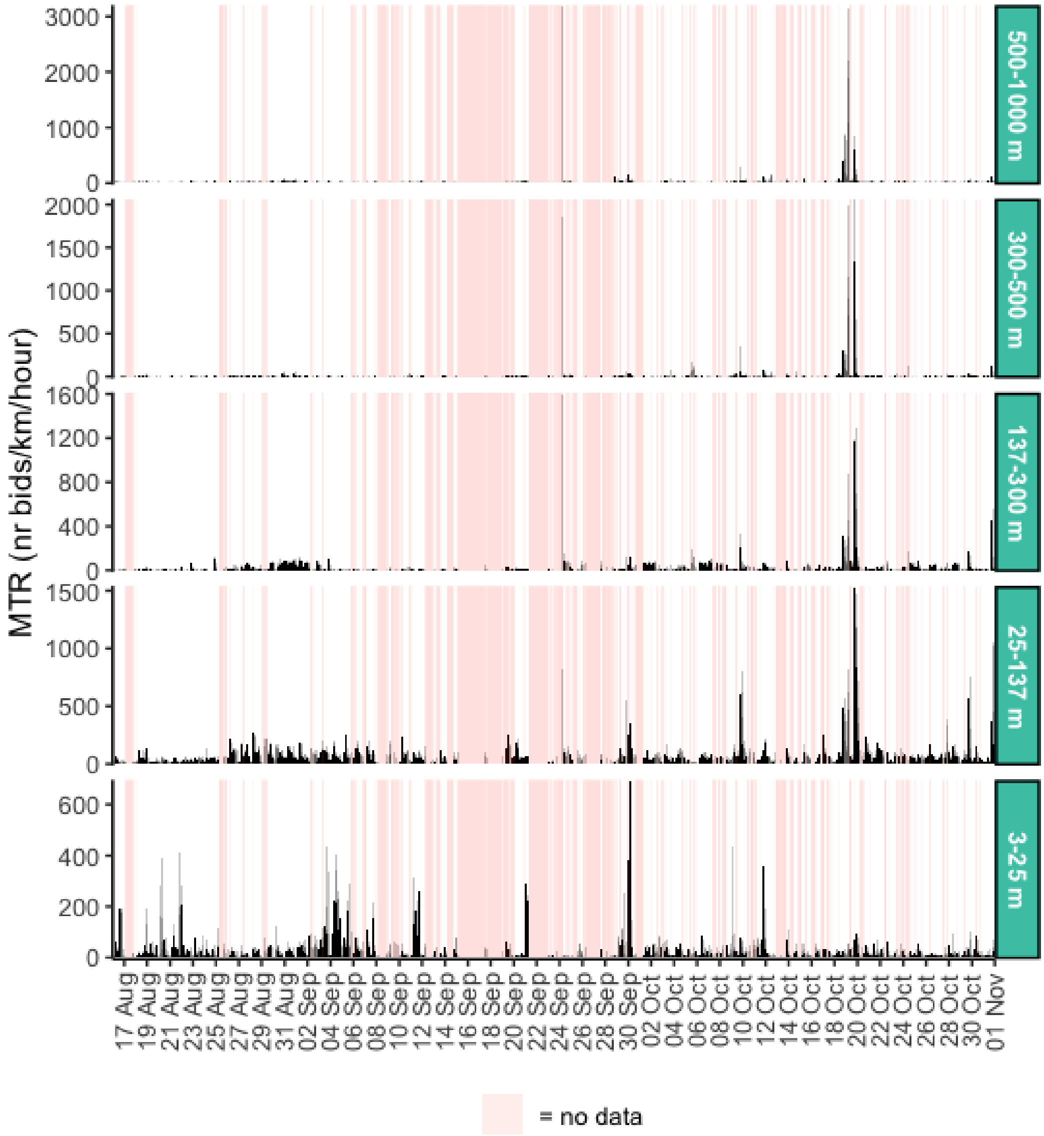


*Figure 3.8* *MTR (number of birds/km/h) calculated based on the vertical radar, per height band, for autumn 2022. Note that the scales on the y-axis differ per height band.*

In total, eight nights can be marked as peak nights based on the vertical radar data (Table 3.2). These nights were selected based on at least one hour with an MTR above 500 birds/km/h. 33 hours of the total of 723 hours in the analysis had an MTR above 500 birds/km/h, which is 4.6 percent. 33 percent of the total MTR in this analysis was measured durin these 33 hours.

Of those eight peak nights, four overlap with the peak nights based on the horizontal radar. The vertical radar was malfunctioning in November and hence we cannot verify whether the two peak nights in November based on the horizontal radar would have been detected by the vertical radar.

According to the vertical radar measurements, the night of the 23rd of September also had an hour with an MTR above 500 birds/km/h. However, this night will not be treated as a peak night, because there were only two hours in the dataset for that night. One was the peak hour with an MTR of 2420 birds/km/h at 06:00 in the morning, the other one had an MTR of only 5 birds/km/h which was earlier that night at 22:00. This could be the result of rain showers entering the dataset as bird tracks, despite several filtering steps. The horizontal radar had quite low MTRs during this night with a maximum MTR of only 47 birds/km/h. In addition, the half of the night was filtered out because of too heavy filtering by the radar. Finally, also the radar images indicated heavy rain showers just after 06:10 am. Therefore, this night was not marked as peak night.

*Table 3.2* *MTR measurements during the eight nights with the highest migration intensities according to the vertical radar. Nights were selected based on a maximum MTR above 500 birds/km/h.*

| Night | Average MTR (birds/km/hour) | Maximum MTR (birds/km/hour) | Nr hours above 500 birds/km/h |
|---|---|---|---|
| Sep 29 – Sep 30 | 528 | 1170 | 3 |
| Oct 08 – Oct 09 | 121 | 512 | 1 |
| Oct 09 – Oct 10 | 381 | 957 | 4 |
| Oct 11 – Oct 12 | 220 | 548 | 1 |
| Oct 18 – Oct 19 | 640 | 1753 | 9 |
| Oct 19 – Oct 20 | 1386 | 2858 | 8 |
| Oct 29 – Oct 30 | 208 | 990 | 2 |
| Oct 31 – Nov 01 | 749 | 1626 | 4 |

Based on our analysis, it is clear that some peak migration nights as identified by the vertical radar are missed by the horizontal radar. The most remarkable of these nights is the one starting on the 19th of October. According to the vertical radar, this was by far the night with the most intense bird migration, with an average MTR of 1,386 birds/km/h in the lower 300 meters, with a peak hour of 2,858 birds/km/hour at 9 pm local time. The hour before that had an MTR of 1,671 birds/km/hour, highlighting the mass migration occurring that night, distributed over the whole lower 1,000 meters (Figure 3.8).

In total, there were four nights that were indicated as peak nights by the vertical radar, but not by the horizontal radar. Besides the earlier mentioned 19 October, on the nights of 8, 9 and 31 October a large number of bird tracks were recorded by the vertical radar, while this was not the case for the horizontal radar. Those nights are further inspected to see what could have caused the horizontal radar to miss those nights.

Interestingly, Figure 3.9 shows that the night of 8 October deviates from the other missed peak nights. Most tracks recorded by the vertical radar were below twenty meters. The other three nights depicted in Figure 3.9 show a similar height profile in which the majority of recorded tracks were between 30 and 100 meters above sea level. However, the height profile of the four nights analysed do not indicate that a large proportion of the bird tracks are above the scope of the horizontal radar. Hence, the majority of bird tracks during these four nights was in the scope of the horizontal radar, but very few of them were detected.

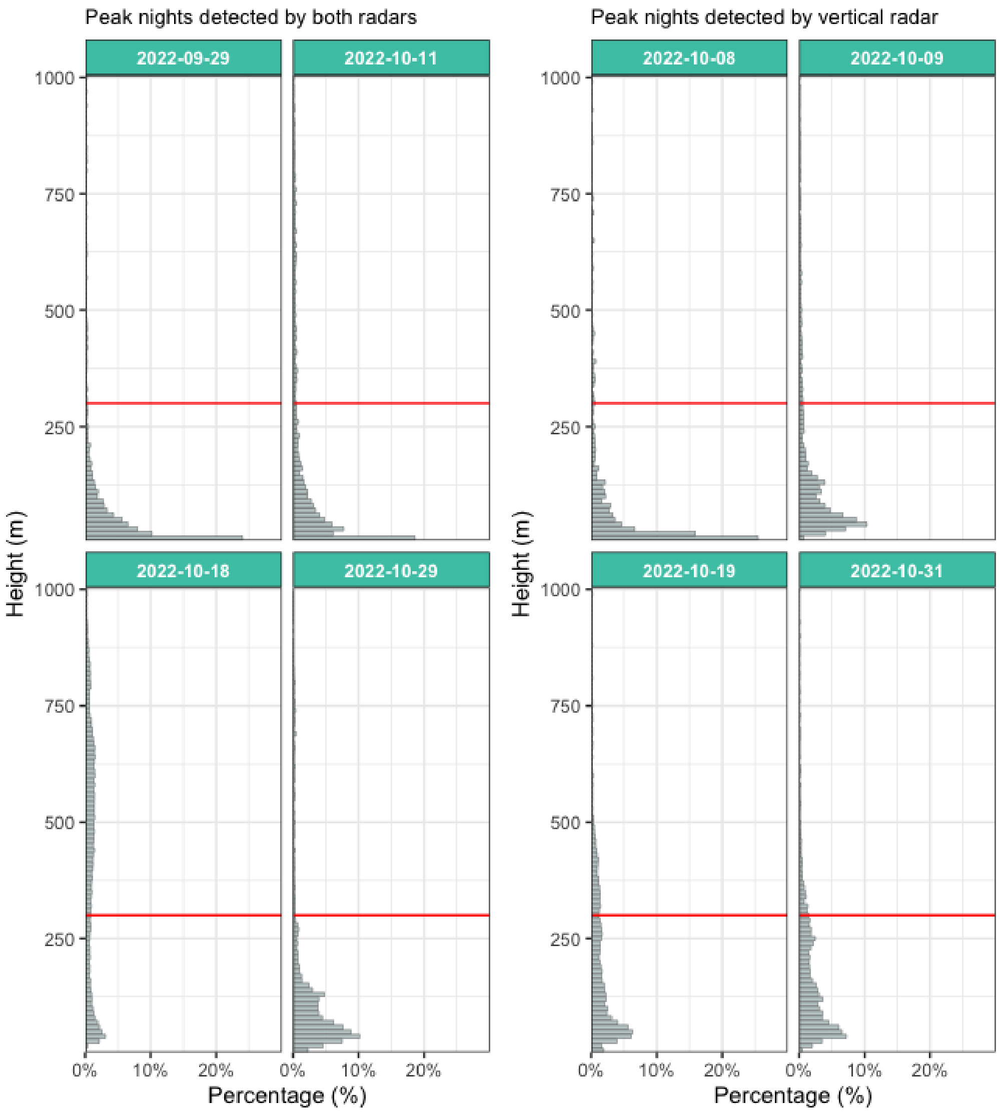


*Figure 3.9* *Height profile of four nights which were marked as peak night by the vertical radar, but not by the horizontal radar. Width of the bars is 10 meters. Red line shows the 300-meter line up to which the horizontal radar can (approximately) still record bird tracks.*

The night of 19 October was not filtered out by the standard filtering steps used for the horizontal radar but remained in the dataset as a night with lower MTRs. The reason why the horizontal radar did not measure high migration intensities was conceivably because of the high waves, with an average wave height above 1 meter that night. In paragraph 3.1.3 we show that data from the horizontal radar in periods with waves above 1 meter should be treated with caution. For the other nights, no waves above 1 meter were detected, and they were also not filtered out conform the filtering steps used for radar analysis. The night of 31 October however started with high filtering activities leading to filtering out most hours after midnight. This could have led to not detecting high MTRs that night. The reason why the horizontal radar detected no peak for the other two nights remains unclear.

# 4 Expert team predictions

Between 21 September and 30 November 2022, the expert team predicted peak migration at low altitudes on 11 nights out of 70. The evaluation of peaks predicted by the experts was based on both the horizontal and the vertical radar data. High MTRs as identified by either one or both radars was considered a peak night.

Predictions (either predicting a migration peak or the absence of it) were correct on 84% of nights (59 of 70 nights). Actual peaks as measured by the horizontal and/or vertical radar corresponded with expert team predictions on five nights, but did not on five nights, and on six nights a peak was predicted by the expert team that was not measured by the radars (Table 4.1). Generally speaking, during the majority of nights no peak migration at low altitudes occurs, so logically the majority of predictions involved predicting the lack of migration peak (59 of 70 nights). The lack of migration peaks is generally easier to predict than actual peaks, due to unfavourable weather conditions (e.g., rain, strong winds).

In the period that predictions were made by the expert team, the horizontal radar detected peak migration on six nights, while the vertical radar detected peak migration on eight nights. After November 3, the vertical radar was not operational. For the horizontal radar, there were no data available for several nights, either due to filtering steps (for example waves that were too high) or malfunctioning of the radar. Hence, there may have been peak migration nights that went undetected by the radars (see also Table 4.1). This was especially the case for the nights of 3 and 4 November. The vertical radar was off for the whole month of November and hence could not detect bird migration. From the horizontal radar dataset, the hours before midnight on 3 November were excluded from the analysis by the filtering steps of the bird migration forecast model due to too high filtering activities of the radar. However, radar measurements after midnight were not excluded, but these measurements should be treated with caution because wave height was still relatively high (above 1 meter). This could have been the case also on 4 and 15 November, when the horizontal radar measured extremely low MTRs during wave heights of above 1 meter. At these moments, the radar dataset is apparently being filled with valid measurements, but it could be that a large proportion of the flying birds is not detected the radar due to the large amount of clutter caused by waves (see Figure 3.7). Therefore, the mismatch on three out of the six nights for which the expert team predicted a peak not coinciding with high radar MTRs could be caused by unreliable radar measurements.

*Table 4.1 Overview of predictions made by the expert team and the matches with the peaks measured with the radar. Dates are given as the night before and after midnight, e.g 18-19 Oct stands for the night of the 18th to the 19th of October.*

| description | # nights | specifications |
|---|---|---|
| **Predictions expert team** | | number of nights predicted for autumn 2022 = 70 |
| peak predicted in general | 11 | |
| peak predicted north of Wadden Sea | 10 | |
| peak predicted between IJmuiden and Texel | 11 | |
| peak predicted south of IJmuiden | 11 | |
| uncertainty / discussion within team | 3 | in these cases a warning of a peak was given (13-14 & 16-17 Oct, 3-4 Nov) |
| **Measured peaks by the radar** | | |
| peak > 500MTR on radars Luchterduinen | 10 | 6 nights on hor. radar; 8 nights on vertical radar up to 3 Nov; 4 nights occur on both radars |
| **Results comparison** | | |
| prediction correct (either forecasting a peak or the lack of it) | 59 out of 70 | =84% |
| Matching peaks forecasted by expert team and also measured by the radar | 5 | Nights: 18-19 Oct, 12-13 Nov, 13-14 Nov |
| peak not forecasted by expert team but measured by the radar | 5 | Nights with peak measured with both radars: 29-30 Sep, 11-12 & 29-30 Oct<br>Nights with peak on vertical radar: 8-9, 9-10 Oct |
| peak predicted by expert team but not seen on radar | 6 | Nights: 13-14 Oct, 16-17 Oct, 3-4 Nov, 4-5 Nov, 15-16 Nov, 19-20 Nov;<br>Data from 3 Nov onward uncertain due to lack of vertical radar data. Reliability of horizontal radar data for nights of 4 and 15 Nov is questionable; data are missing for most hours in the night of 3-4 Nov (see table 6.2). |

All nights for which peaks were predicted correctly were nights with easterly to south-easterly winds, often with calm and high-pressure conditions in the departure areas. Stronger winds at sea (4-5 Bft) were considered low-altitude flying conditions.

Reasons that peak migration events were missed by the experts varied. On four of these nights (nights starting on 8, 9, 27 and 29 October), strong westerly or southerly winds (force 4-6 Bft) were thought to limit migration activity over sea. In addition, the focus of the expert team was on birds departing from Scandinavia, while birds departing from countries east of the Netherlands were erroneously mostly neglected during the expert team predictions. Departure conditions in these regions were more favourable with low easterly winds, resulting in an accumulation of birds on the Dutch coast. On two nights, a peak was predicted by the expert team but not at rotor height due to winds from favourable directions or low winds (nights starting on 29 Sep and 11 October). On both nights a peak was measured by both radars, at rotor height.

Nights on which peaks were incorrectly predicted concerned nights on which flight conditions were good in departure regions in Scandinavia, but worse conditions were predicted at sea in the Netherlands, forcing birds to fly at lower altitudes. For some of these nights, the team was doubtful whether a peak would occur or not. To be on the safe side, the expert team gave in those instances a warning of a peak (early November). An additional explanation for incorrectly predicted peaks could be that the predicted weather differed from the actual weather. Thus far, such a comparison between predicted and actual weather has not (yet) been made but could yield insight in the accuracy of the migration predictions.

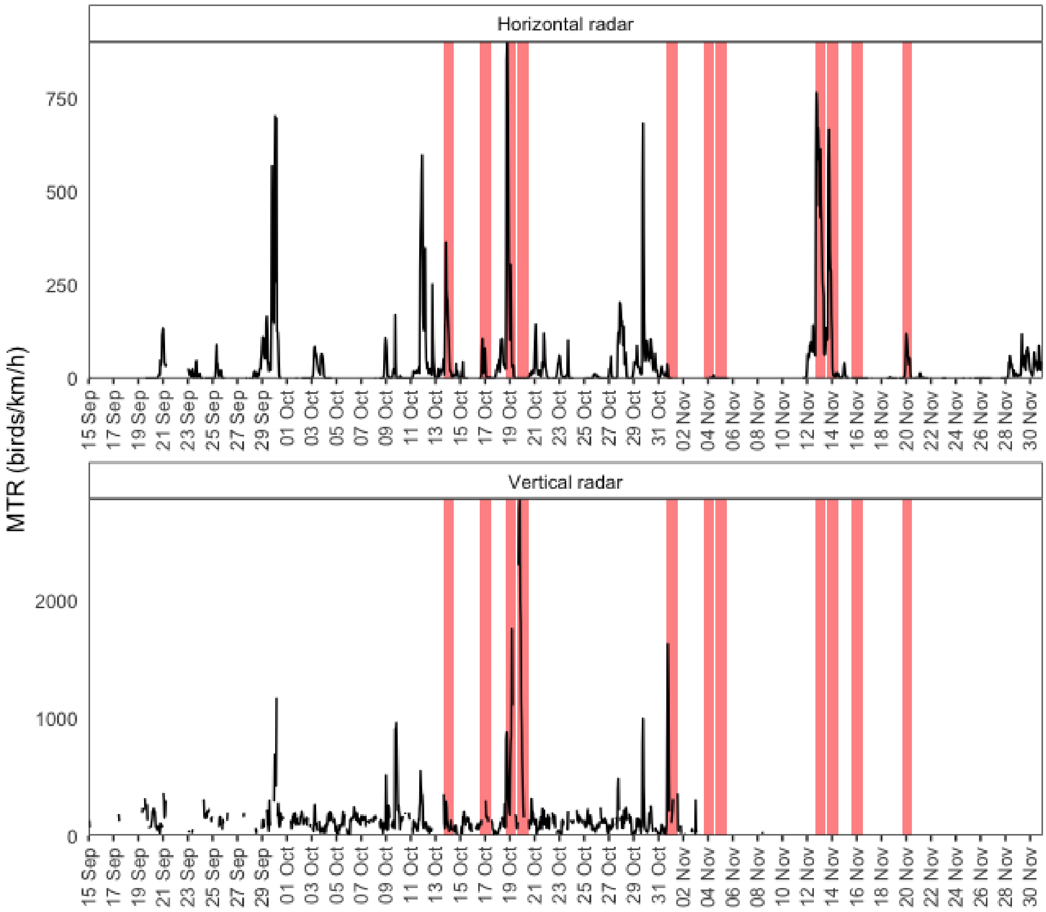


*Figure 4.1* *Upper plot: MTR (birds/km/h) as measured by the horizontal radar (black line) and the nights in which the expert group predicted a peak night (red rectangle; starting 21 Sep onwards). Lower plot: MTR (birds/km/h) as measured by the vertical radar (black line) and the nights in which the expert group predicted a peak night (red rectangle).*

# 5 Bird migration prediction model

## 5.1 Temporal pattern of the bird migration according to the bird migration prediction model

*The model predictions using weather data from midnight two days in advance show several peaks throughout the season of autumn 2022 (Figure 5.1). Most of these peaks lie in the second half of the season, mainly after mid-October. The model predicted November to be the month with the highest bird migration intensities, with the most remarkable peak being in the beginning of November, namely during the night from the $4^{th}$ to the $5^{th}$ of November. The maximum predicted MTR within that night was 378 birds/km/h, which occurred from 7pm to 8 pm (local time). The ten hours with the highest predicted MTR were all between 5 pm on 4 November and 3 am on 5 November, indicating how intensive bird migration was predicted to be on that night according to the bird migration prediction model. The top 10 nights with the highest predicted bird migration intensities all had a maximum MTR of 161 birds/km/h or more (*

Table 5.1).

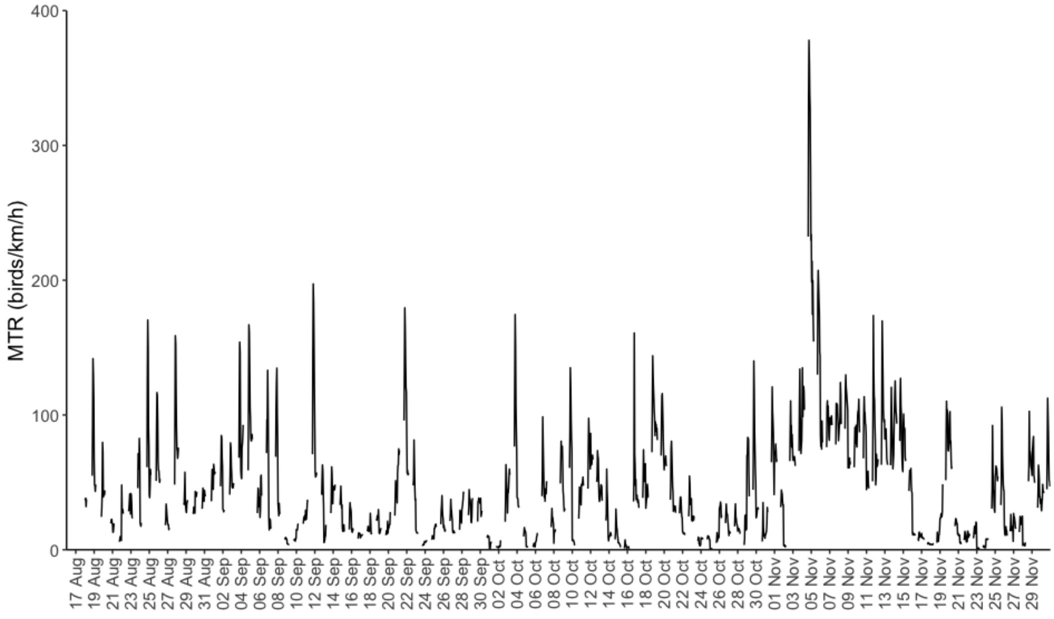


*Figure 5.1* *Temporal pattern of MTR values predicted by the bird migration prediction model. Daylight hours are not shown on the figure as the model was not trained and ran on these hours.*

*Table 5.1* *The ten nights of autumn 2022 with the highest bird migration intensities predicted by the bird migration prediction model. Nights were selected based on maximum MTR within that night. Note that these MTRs are predicted by the model, not measured by the radar.*

| Night | Average MTR (birds/km/hour) | Maximum MTR (birds/km/hour) |
|---|---|---|
| Aug 24 – Aug 25 | 84 | 170 |
| Sep 4 – Sep 5 | 103 | 167 |
| Sep 11 – Sep 12 | 104 | 197 |
| Sep 21 – Sep 22 | 101 | 180 |
| Oct 3 – Oct 4 | 78 | 175 |
| Oct 16 – Oct 17 | 52 | 161 |
| Nov 4 – Nov 5 | 256 | 378 |
| Nov 5 – Nov 6 | 130 | 207 |
| Nov 11 – Nov 12 | 84 | 174 |
| Nov 12 – Nov 13 | 95 | 170 |

## 5.2 Comparison of model predictions with radar measurements

In this paragraph, the performance of the bird migration prediction model is assessed by comparing it with the outcomes of flux calculations using both the horizontal and vertical radar. Generally, predictions of the bird migration prediction model were substantially lower than the measurements by the radars. The highest MTR predicted by the model was 378 birds/km/h, while the maximum MTRs measured by the horizontal and vertical radar were 901 birds/km/h and 2,858 birds/km/h respectively.

The highest peak predicted by the bird migration prediction model was not recorded by either one of the radars (Figure 5.2, night starting on 4 November). For the vertical radar the reason is simple: the radar was not operational during that night. However, the fact that the horizontal radar did not measure a peak during that night does not necessarily mean that the model wrongfully predicted high MTRs. High waves (above 1 meter), which occurred in the beginning of November, could have prevented the horizontal radar from measuring heavy migration, as was visualized in Figure 3.7. Interestingly, the expert group did also predict a peak for that night.

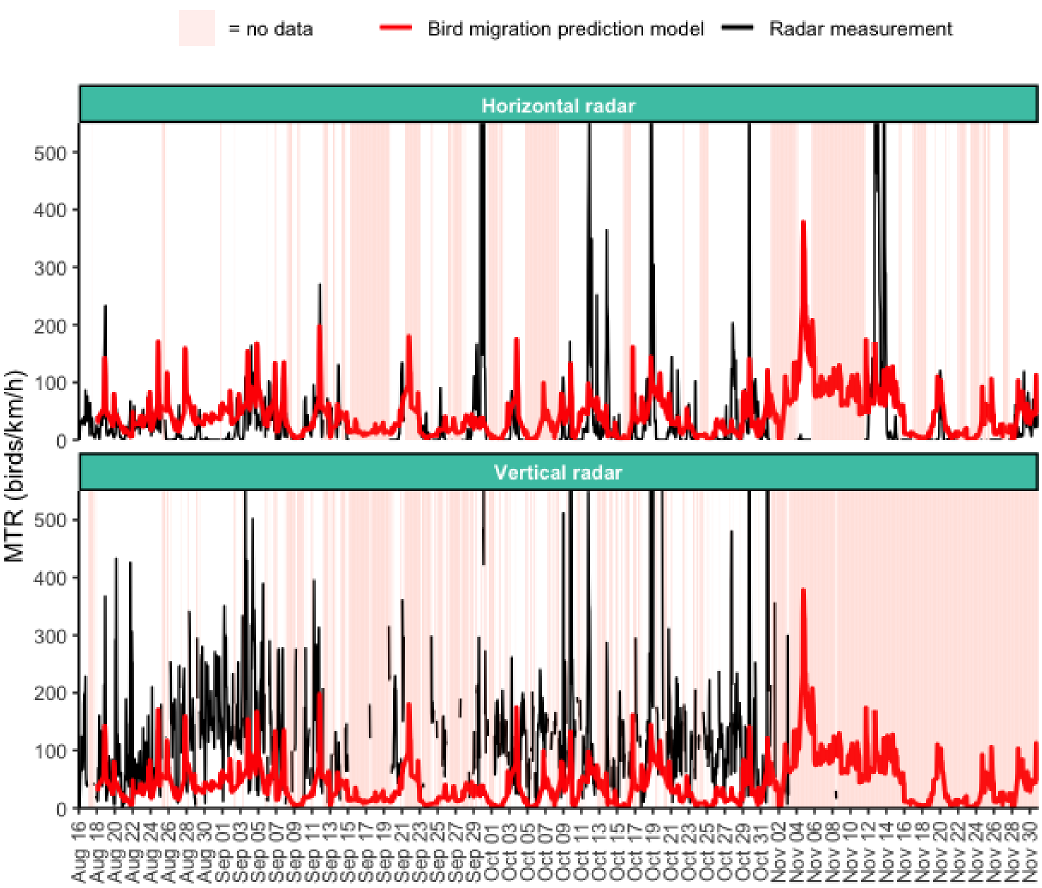


*Figure 5.2* *Temporal pattern of MTR measurements by radars (black bars; horizontal radar above, vertical below) and the bird migration prediction model outcomes (red line). Hours with no radar measurement are shaded in light red. Note that the y-axis are limited to MTRs of 550 birds/km/h to follow the dynamics of the bird migration prediction model outcomes.*

## 5.3 Model predictions for peak nights defined by radar measurements

A total of six nights were marked as a peak night by the horizontal radar, and eight nights by the vertical radar, both defined as migration intensities above 500 birds/km/h. As four of these nights overlapped, this resulted in a total of ten peak migration nights according to one or both of the radars being above 500 birds/km/h. When comparing the model predictions with the horizontal radar measurements (Table 5.2), only one of the six peak nights measured by the horizontal radar were also in the top 10 of the model predictions based on the maximum predicted MTR per night (see

Table 5.1). Furthermore, none of the peak nights measured by the vertical radar were in the top 10 of the model predictions (Table 5.2). In summary, only one night that was identified as a peak night based on one or both of the radars was also in the top 10 nights predicted by the model, namely the night starting on 12 November (Table 5.2). In the following chapters we discuss the possible reasons for this mismatch between model predictions and radar measurements.

*Table 5.2* *Nights in which intense bird migration was measured by one or both radars (above 500 birds/km/h) and the corresponding prediction by the bird migration prediction model. Green shading highlights the night that was also among the top 10 model predictions.*

| Night | Average predicted MTR (birds/km/hour) | Maximum predicted MTR (birds/km/hour) | Peak measured by |
|---|---|---|---|
| Sep 29 – Sep 30 | 32 | 38 | Both radars |
| Oct 09 – Oct 10 | 50 | 135 | Vertical radar |
| Oct 11 – Oct 12 | 71 | 98 | Both radars |
| Oct 18 – Oct 19 | 101 | 144 | Both radars |
| Oct 19 – Oct 20 | 79 | 116 | Vertical radar |
| Oct 29 – Oct 30 | 57 | 140 | Both radars |
| Oct 31 – Nov 01 | 78 | 121 | Vertical radar |
| Nov 12 – Nov 13 | 95 | 170 | Horizontal radar |
| Nov 13 – Oct 14 | 93 | 125 | Horizontal radar |

# 6 Comparison of radar measurements, expert group predictions and bird migration prediction model outcomes

## 6.1 Model predictions compared to radar data and expert group predictions

In Table 6.1 we provide an overview of all nights that are classified as peak nights based on radar measurements (one or both radars measured peak migration intensities (>500 birds/km/hour) for at least one hour) or based on predictions by the expert group. For each of these nights, we show the corresponding model predictions (mean hourly MTR and maximum MTR within that night). Furthermore, nights that belong to the top ten of nights according to the model predictions are also included in the table.

A total of six nights were marked as a peak night by the horizontal and eight by the vertical radars. Four of them overlapped, which resulted in a total of ten peak migration nights according to one or both radars during the autumn of 2022 (Table 6.1). Note that reliable radar data were available for the whole study period, so not necessarily all peak nights of bird migration are recorded by the radar measurements.

Eleven nights were marked by the expert group as potential peak nights. Five of these expert group forecasts matched the radar measurements. On the six other nights, the radar measurements did not indicate peak migration intensities, but on some of these nights the radars measurements were not reliable (see Chapter 4). Four of the nights when the radars measured peak migration intensities were not forecasted by the expert group (Table 6.1).

Based on this overview, we can clearly mark nights as true positives when a bird migration peak was measured by one or both radars. Ideally, the model would have predicted all these ten nights correctly. However, as mentioned before (see Table 5.2), only one night out of the top ten nights according to the bird migration prediction model matched with the peak migration nights based on radar measurements. Nevertheless, it is important to note that four of the top ten nights according to the bird migration prediction model fell in the period August – September, while the model was trained on the months October – November. Considering that this could have influenced the outcome of the model predictions, the relatively high predictions of the model in October and November could also be considered as a match with the radar measurements. If we disregard the high model forecasts in August and September that all delivered a mismatch with the radar measurements and the expert group forecasts, the model predictions on the 9$^{th}$, 18$^{th}$ and 29$^{th}$ of October and the 3$^{rd}$ of November with maximum MTRs of respectively 135, 144, 140 and 135 birds/km/hour would also belong to the top ten nights, all of them also indicated by the radar measurements or expert group forecasts as nights of intense migration.

*Table 6.1* *All nights when either of the radars measured peak migration intensities (>500 birds/km/hour, at least during one hour within that night) or the expert group forecasted peak migration events (green shadings), extended by nights that were among the top 10 nights of bird migration according to the bird migration prediction model generated with ECWMF weather forecasts at 00:00 two days in advance based on the maximum predicted MTR during that night (yellow shadings). For both radars the maximum and mean (between brackets) MTR during the night are presented. In addition, for all nights the corresponding model MTR (birds/km/hour) predictions are provided. Finally, the nights with missing radar data are shaded in light red and it is stated whether this data loss was for the whole night (no data) or just a part of the night (before/after midnight).*

| **Date** | **Horizontal radar**<br><br>Maximum MTR (mean MTR) | **Vertical radar**<br><br>Maximum MTR (mean MTR) | **Expert group** | **Mean MTR model prediction** | **Max. MTR model prediction** |
|---|---|---|---|---|---|
| 24 Aug | 83 (43) | 179 (92) | | 84 | 170 |
| 4 Sep | 93 (37) | 207 (97) | | 103 | 167 |
| 11 Sep | 85 (270) | 313 (99) | | 104 | 197 |
| 21 Sep | No data | No data | | 101 | 180 |
| 29 Sep | 703 (322) | 1170 (498) | | 32 | 38 |
| 3 Oct | 65 (27) | 101 (51) | | 78 | 175 |
| 8 Oct | 109 (38) | 512 (121) | | 53 | 81 |
| 9 Oct | 171 (18) | 957 (381) | | 50 | 135 |
| 11 Oct | 598 (283) | 548 (220) | | 71 | 98 |
| 13 Oct | 364 (124) | 350 (128) | | 20 | 60 |
| 16 Oct | 106 (32) | 296 (158) | | 52 | 161 |
| 18 Oct | 901 (325) | 1753 (640) | | 101 | 144 |
| 19 Oct | 0 (0) | 2858 (1386) | | 79 | 116 |
| 29 Oct | 683 (162) | 990 (208) | | 57 | 140 |
| 31 Oct | No data after midnight | 1626 (749) | | 78 | 121 |
| 3 Nov | No data before midnight | No data | | 102 | 135 |
| 4 Nov | 1 (0) | No data | | 256 | 378 |
| 5 Nov | No data | No data | | 130 | 207 |
| 11 Nov | 97 (33) | No data | | 84 | 174 |
| 12 Nov | 765 (465) | No data | | 95 | 170 |
| 13 Nov | 666 (192) | No data | | 93 | 125 |
| 15 Nov | 0 (0) | No data | | 32 | 60 |
| 19 Nov | 120 (40) | No data | | 82 | 110 |

Reliable radar measurements were not available for the whole study period, especially in November. If we consider the six peak nights predicted by the expert team in this month, the bird migration prediction model predicted relatively high MTRs (MTR above 100 birds/km/h) for five of these nights. Four of these nights also belonged to the top ten of busiest nights according to the model.

All in all, seven of the top ten nights according to the bird migration model predictions did not correspond with neither radar measurements nor expert group forecasts but four of these fell in August and September (Table 6.1), months for which the model was not trained. On all of the five nights with high predicted migration intensities according to the expert group and also confirmed by radars, the model forecasted relatively high MTRs (at least 116 birds/km/h).

## 6.2 Possible threshold values

In order to account for mismatches between model predictions and the real migration intensity, a threshold for initiating curtailment of offshore wind farms is needed, set to allow safe passage of birds during mass migration events. Whenever the model prediction for a certain hour is higher than this threshold, a signal for curtailment could be initiated.

Note that van Bemmelen et al. (2022) describe that the threshold for curtailment can be optimized between migration intensity and power yield by taking into account wind speed. If such optimization is taken into account, different thresholds would need to be chosen for different categories of wind speed (low, intermediate and strong wind speed). Within this current project, no differentiation has been made between wind speed categories.

In Table 6.2 we provide an overview of the number of nights when the maximum model predictions within a night were above different threshold values (and thus curtailment would be initiated) that confidently matched radar measurements in the autumn season of 2022.

*Table 6.2 Number of nights and hours in which one or both radars measured a peak and also predicted (maximal MTR) by the bird migration prediction model (true positives) and the percentage of hours within the total autumn 2022 season when curtailment would take place by different threshold values. Only night hours are considered.*

| Threshold | Number of true positive nights (out of 10 based on radar) | Number of true positive hours (out of 47 based on radar) | nr hours curtailed (% of total of 1456 hours) |
|---|---|---|---|
| 120 | 6 | 9 | 72 (4,9%) |
| 130 | 4 | 5 | 56 (3,8%) |
| 140 | 3 | 3 | 45 (3,1%) |
| 150 | 1 | 1 | 38 (2,6%) |
| 160 | 1 | 1 | 30 (2,1%) |

When zooming in on hours instead of complete nights, the radar measurements showed 47 nightly hours with an MTR above 500 birds/km/h based on either one or both radars.

Only 1 of these hours were predicted by the bird migration prediction model to have an MTR above 150 birds/km/h, while in total 9 hours were predicted to have an MTR above 120 birds/km/h (Table 6.2). The bird migration prediction model predicted a total of 72 hours to be above 120 birds/km/h.

The absence of reliable radar data during some nights in November might produce a distorted picture of the number of true positive predictions by the bird migration prediction model relative to the radar results. For instance, only 1 of the 30 hours that the model predicted an MTR above 160 birds/km/h for November matched with a peak hour based on radar data (Table 6.2). However, 14 of these 30 hours occurred during the night of 4 November. If these hours would have been a peak in the radar data, the number of true positive hours would considerably increase.

## 6.3 Potential of curtailing more than one hour

A potential way of increasing the accuracy of the model driven curtailment could be to increase the length of each curtailment. Because the predictions are made based on weather forecasts of 48 to 72 hours ahead of time, curtailment of only one hour might be too detailed. Therefore, it is interesting to see if the accuracy increases when each curtailment would not only contain the predicted peak hour itself, but also the hour before and after it.

When a safety range of one hour around the peak hour as predicted by the bird migration prediction model is used, more curtailed hours matched with peak hours based on radar (Table 6.3). However, also the number of false positives, when compared with radar results, increased. In a hypothetical situation of a threshold of 130 birds/km/h for the autumn of 2022 and a buffer of one hour, 12 curtailed hours would have matched with the 47 peak hours based on radar measurements. However, curtailment would have taken place during 96 hours, which is 6,6% of the total nightly hours within that season. When in that same situation a buffer of at least two hours was used, meaning a minimal curtailment of 5 hours, 23 hours had a match with radar peaks and in total 136 curtailment hours would have taken place.

With a threshold of 150 birds/km/h, only 3 hours matched with peak hours based on one or both radars, when a buffer zone of one hour was used. In total, curtailment would have taken place for 62 hours. With a buffer zone of two hours, a total of 4 hours would have matched, while curtailment would have taken place for 86 hours.

*Table 6.3* *Number of hours the bird migration prediction model predicted a peak which matched with a peak according to the radar results when curtailment was executed at least 3 and 5 hours around the predicted peak hour at different thresholds. Also the total number of curtailment hours are given for both situations.*

| Threshold | Nr of true positive hours when curtailing at least 3 hours (out of 47 based on radar) | Total number of hours curtailed when curtailing at least 3 hours | Nr of true positive hours when curtailing at least 5 hours (out of 47 based on radar) | Total number of hours curtailed when curtailing at least 5 hours |
|---|---|---|---|---|
| 120 | 19 | 126 | 23 | 178 |
| 130 | 12 | 96 | 15 | 136 |
| 140 | 8 | 75 | 10 | 105 |
| 150 | 3 | 62 | 4 | 86 |
| 160 | 2 | 50 | 3 | 70 |

# 7 Moment of weather forecast

The moment at which the weather forecast is generated can affect the accuracy of the forecast and therefore the accuracy of the bird migration prediction model outcomes. To test this, three moments of weather forecasts are assessed, namely at midnight, at 6 am and at 12 am, all from two days ahead of the day for which the MTRs are predicted. The ECMWF weather predictions come available only at certain moments. We are interested to know to what extend these differences in weather predictions influence the bird migration predictions.

The model outcomes produced using both the 00:00 forecast and the 06:00 forecast (from now on; 00:00 prediction and 6:00 prediction respectively) look very similar at a first glance (Figure 7.1). The highest peaks are almost equally high and peaks are almost at the same moments. The temporal patterns therefore seem to only differ at a more detailed level.

Nevertheless, those details are important. The most remarkable difference between the model outcomes in Figure 7.1 is the timing of the highest peak. Both the 00:00 prediction and the 06:00 prediction have their highest peak at the night starting on 4 November. However, according to the latter, the peak is spread out over two nights, with a similar peak on 3 November. In contrast, the 3$^{rd}$ of November was not even in the top 10 nights with intense migration based on the 00:00 prediction. The second highest peak night according to the 00:00 predictions is 5 November. In conclusion, both model runs show a migration peak of two nights, both including 4 November, but differ on whether the peak also include 3 or 5 November. Interestingly, the 12:00 prediction agrees with both model runs, and predicted peaks for all three nights. Due to the lack of data, the radar results unfortunately cannot help us in determining which prediction is the most accurate. The expert group however did predict a peak on 3 as well as the 4 November.

Overall, both the 00:00 and 06:00 prediction have one night in their top 10 of nights that are among the peak nights based on the radar calculations. In contrast, among the top 10 most intense migration nights according to the 12:00 predictions, three nights have a match with the peak nights based on either one or both radars. This indicates that the accuracy of the bird migration prediction model might benefit from more recent weather forecasts, but logically this depends on the accuracy of the weather forecast itself.

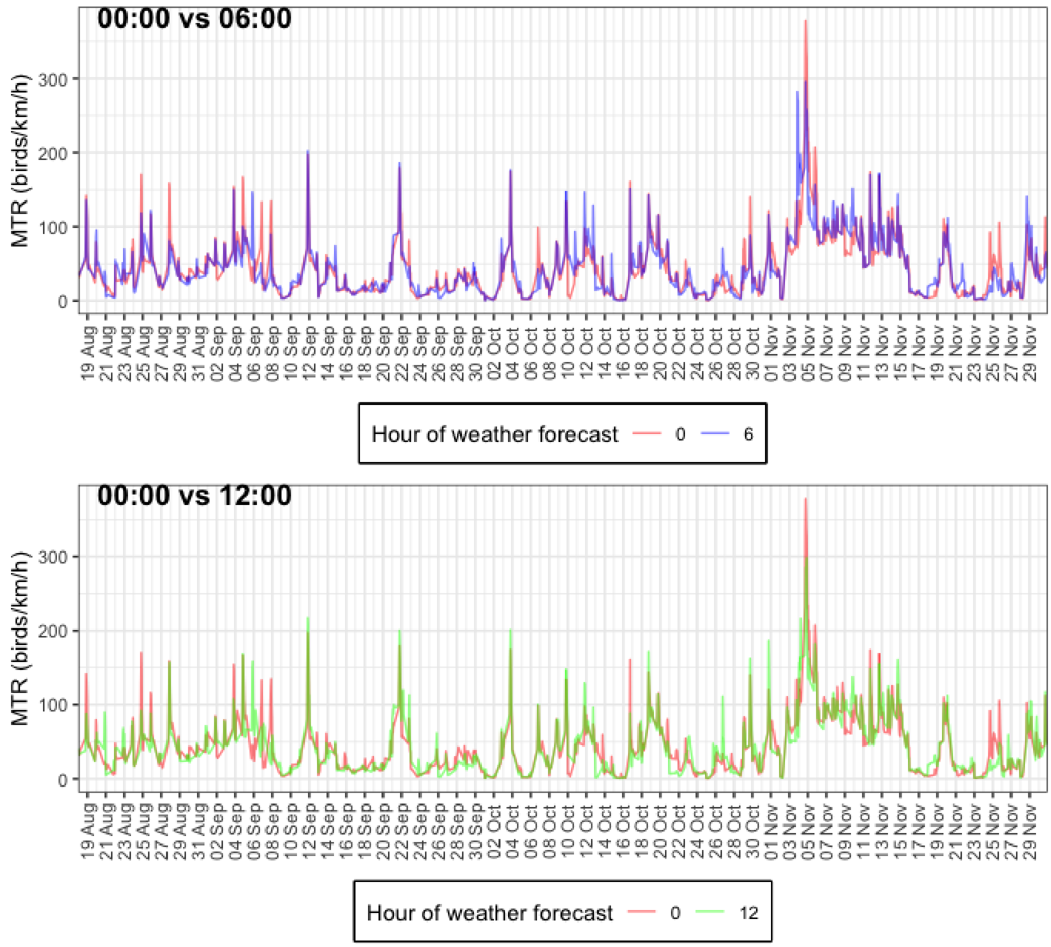


*Figure 7.1* *Upper plot: Temporal pattern of the bird migration model predictions generated with weather forecasts from 00:00 (red) and at 06:00 (blue) two days in advance. Middle plot: Temporal pattern of the bird migration model predictions generated with weather forecasts from 00:00 (red) and at 12:00 (green) two days in advance.*

That the differences are mainly in predicted peaks, is shown in the scatterplot of Figure 7.2. This figure shows the predicted MTR values for the 00:00 weather forecasts compared with the MTR predictions in that same hour using 06:00 and 12:00 weather forecasts. In this figure, a large proportion of the points are located very close to the x=y line, which visualises the points where the MTR predictions with weather forecasts of 00:00 matches precisely with either one of the later two timings of weather forecasts. Especially for hours with predicted MTR's below 50, the predictions between the different weather forecast timings are very small. Discrepancies between different model runs become more evident with higher predicted MTR values.

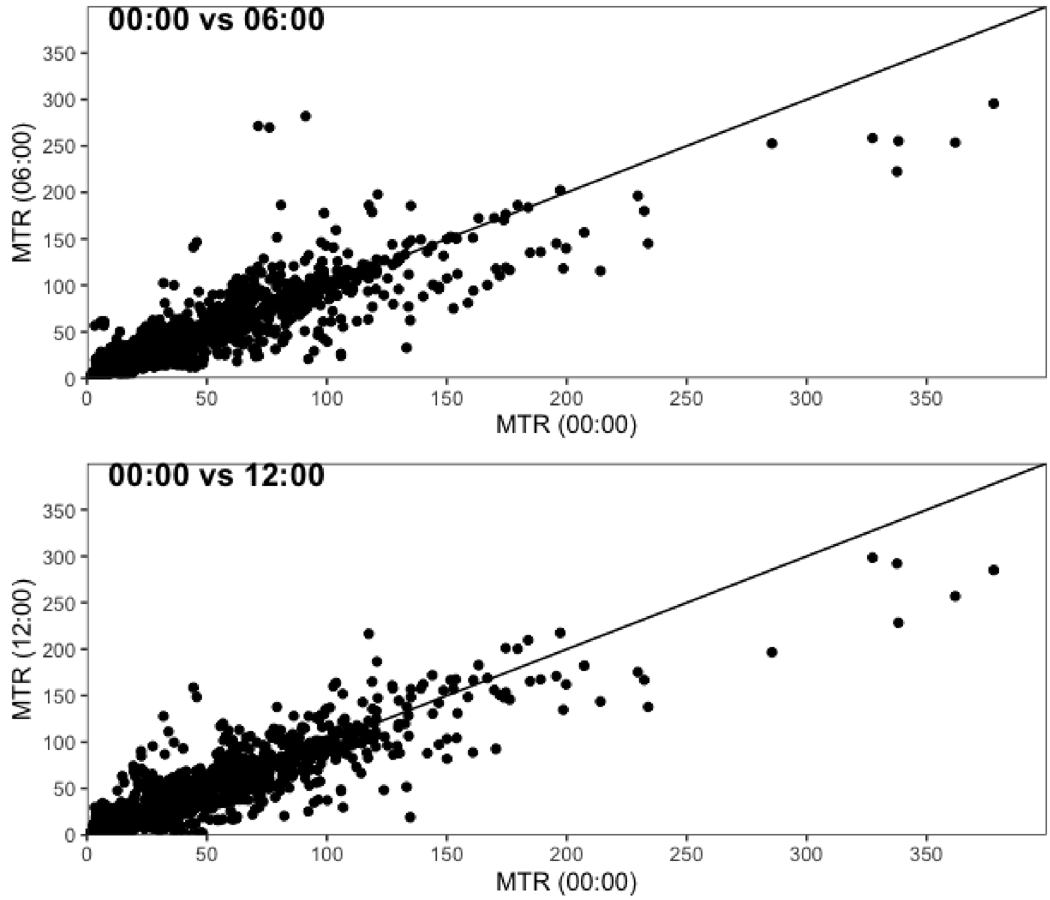


*Figure 7.2* *Upper plot: Scatterplot with MTR predictions for a model run with weather forecasts of 00:00 on the x-axis matched with MTR predictions for a bird migration prediction model run with weather forecasts of 06:00 on the y-axis of the same hour. Lower plot: Scatterplot with MTR predictions for a bird migration prediction model run with weather forecasts of 00:00 on the x-axis matched with MTR predictions for a model run with weather forecasts of 12:00 on the y-axis of the same hour. The line that is shown in both plots shows the x=y line, meaning the points where the MTR predictions with weather forecasts of 00:00 equal MTR predictions with the later weather forecasts.*

Zooming in on the abovementioned nights from 3 to 5 November, it is clear that the temporal pattern looked quite similar for 4 and 5 November according to the three model runs, although the magnitude of the peak differs (Figure 7.3). This means that if a hypothetical threshold would have been exceeded during these nights, curtailment would have taken place during the same part of the night for all three weather forecasts.

On 3 November, however, there was a high peak according to the 06:00 prediction, but not in the other two model runs. Although both the 06:00 prediction and the 12:00 prediction exceeded 200 birds/km/h during that night, both predictions do so in a different part of the night: the 06:00 prediction between 9 pm and 12 am (local time) and the 12:00 prediction at 6 am (local time). The predicted temporal pattern will be used to make the decision on when and for how many hours the curtailment procedure will be initiated. This means that the difference in timing between weather forecasts could result in a different timing and length of the curtailment procedure within a certain night.

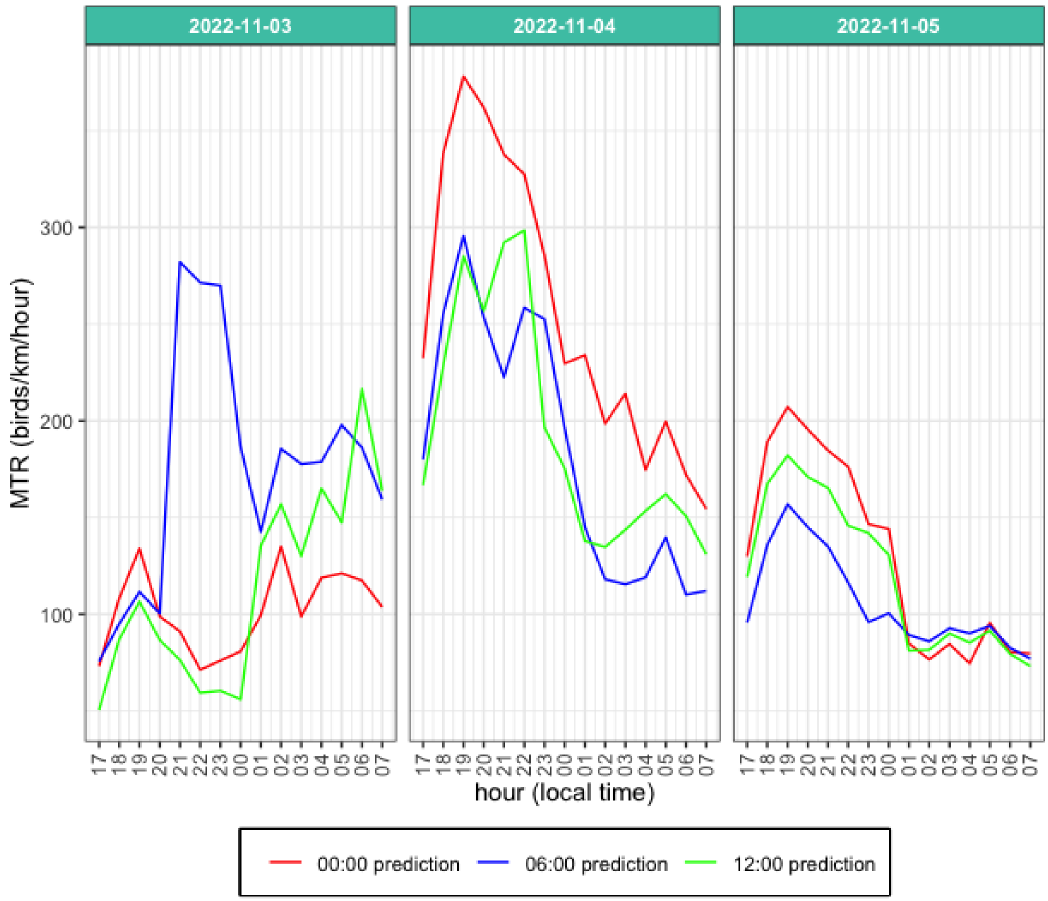


*Figure 7.3* *Temporal pattern differences between bird migration prediction model runs with different weather forecast timings in three nights that were predicted by the model as the most intense migration nights.*

# 8 Effect of weather predictions on bird migration prediction model outcomes

Weather forecasts of two days ahead can have a lot of uncertainty and may not predict the weather accurately. In the previous chapter, we showed that bird migration prediction model outcomes differed between weather forecasts of midnight and 06:00 and 12:00. If six hours of delay in weather forecasts already lead to a change in model outcomes (in particular timing of peaks), it can be expected that reanalysis weather data can impact the model outcomes even more. To test this, the reanalysis model data of the ERA5 weather model was used, on which also the bird migration prediction model was trained. The ERA5 +reanalysis data come from observations of a large variety of weather stations around the globe, which information is then combined into the weather computer model. This way the ERA5 reanalysis data contain a full picture spanning the entire world (Hersbach 2023a, 2023b).

Interestingly, model outcomes of the model with ECMWF weather forecasts as input were higher in general than when using ERA5 weather data (Figure 8.2), especially regarding the peaks in migration intensity forecasts (Figure 8.1). While the model outcomes with ECMWF weather forecasts of midnight two days in advance had their highest peak at 378 birds/km/h, the model with ERA5 data as input had their highest peak at 282 birds/km/h. The highest peak hour was the same in both model runs, namely 19:00 on 4 November, local time. The rest of the top five hours were also the same for both model runs; all hours from 18:00 to 22:00 on 4 November. This is in line with the general image; hours with high MTRs produced by the model with ECMWF weather forecasts of 00:00 two days in advance correlate well with hours with high MTRs produced by the model with ERA5 weather data as input (Figure 8.1).

This is also visible in Figure 8.2 where the temporal pattern of MTRs in the autumn season is depicted according to the bird migration prediction model using the ECMWF weather forecast and ERA5 weather reanalysis data as input. However, when looking at the top 10 of nights for both model runs, only 5 nights have a match. An important difference is 11 September. Here, the bird migration prediction model using the ECMWF weather forecast as input had the third highest peak with 103 birds/km/h on average over the whole night. The model that is run with ERA5 reanalysis data has only 59 birds/km/h on average for that night.

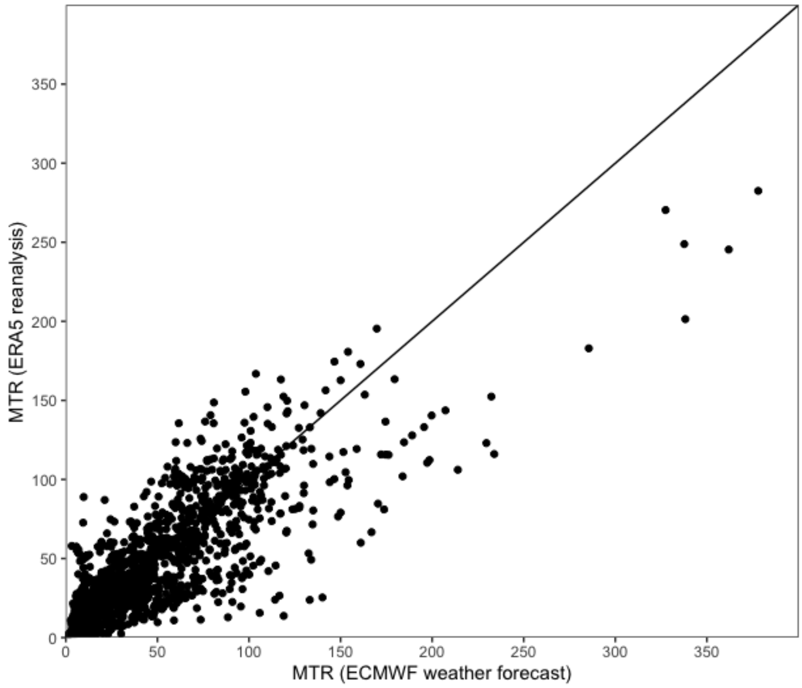


*Figure 8.1* *Scatterplot with MTR predictions for a bird migration prediction model run with ECMWF weather forecasts of 00:00 on the x-axis relative to MTR predictions for a model run with weather reanalysis data of the ERA5 weather model on the y-axis of the same hour. The line that is shown in the plot shows the x=y line, meaning the points where the MTR predictions with weather forecasts of 00:00 equal MTR predictions with the ERA5 weather model data as input.*

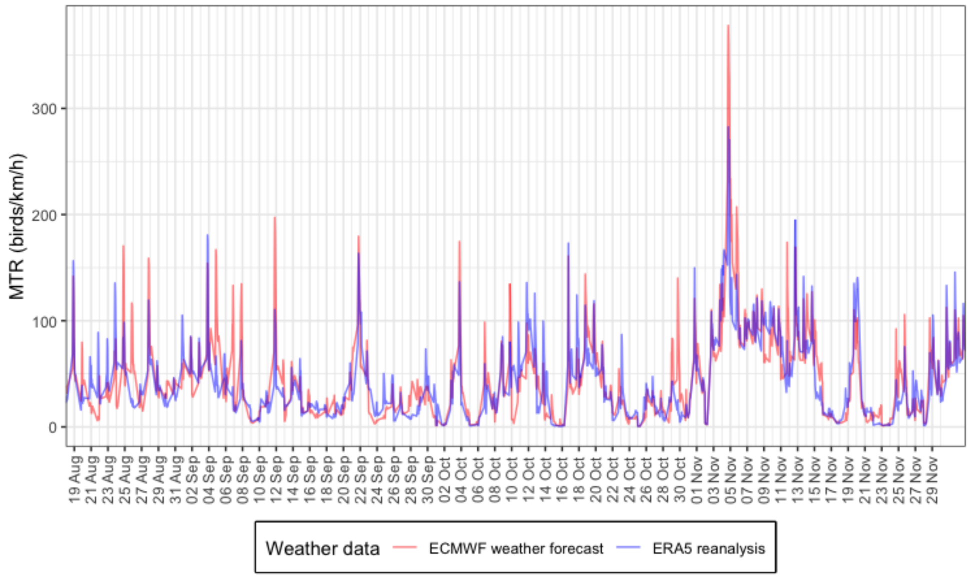


*Figure 8.2* *Temporal patterns of MTRs forecasted by the bird migration prediction model using ECMWF weather forecasts (red) of two days in advance at midnight and the ERA5 weather reanalysis (blue) as input.*

Table 8.1 is comparable to Table 6.1, but with model outcomes based on ERA5 reanalysis weather data. This table shows an overview of all nights which classify as peak night based on radar measurements (one or both of the radars measured peak migration intensities (>500 birds/km/hour) at least during one hour) or based on forecasts by the expert group. For each of these nights, we show the corresponding model predictions based on the ERA5 reanalysis weather data (mean hourly MTR and maximum MTR within that night).

Three of the nights when one or both radars measured a peak the bird migration prediction were also in the top ten of nights of model outcomes generated with ERA5 data. Because there are ten peak migration nights based on the radar measurements, seven of these nights were not predicted to be among the ten most intensive migratory nights according to the model. However, three of those nights were predicted by the ERA5-driven model to have a relatively high maximum MTR (>100 birds/km/h).

Finally, six of the top ten nights according to the ERA5-driven model were also predicted to contain a migration peak by the expert team. Out of the eleven nights that were predicted by the expert team to be a peak night, these six nights were in the top ten most intense migration night as predicted by the model. Moreover, three other nights also had relatively high MTRs (>100 birds/km/h).

Table 8.1 *All nights when either of the radars measured peak migration intensities (MTR for at least one hour above 500 birds/km/hour) or the expert group forecasted peak migration events (green shadings), completed by nights that were among the top 10 nights of bird migration according to the model generated with ERA5 reanalysis model data (yellow shadings). In addition, for all nights the corresponding model MTR (birds/km/hour) predictions are provided. Finally, for both radars the nights where data is missing are shaded in red and it is stated whether this data loss was for the whole night (no data) or just a part of the night (before/after midnight).*

| Date | Hor. radar | Vert. radar | Expert group | Mean MTR model prediction (ECMWF) | Max. MTR model prediction (ECMWF) | Mean MTR model prediction (ERA5) | Max. MTR model prediction (ERA5) |
|---|---|---|---|---|---|---|---|
| 18 Aug | 233 (104) | 367 (112) | | 79 | 142 | 84 | 156 |
| 24 Aug | 83 (43) | 179 (92) | | 84 | 170 | 67 | 98 |
| 3 Sep | 164 (59) | 318 (111) | | 89 | 154 | 91 | 181 |
| 4 Sep | 93 (37) | 207 (97) | | 103 | 167 | 42 | 67 |
| 11 Sep | 85 (270) | 313 (99) | | 104 | 197 | 59 | 111 |
| 21 Sep | No data | No data | | 101 | 180 | 112 | 163 |
| 29 Sep | 703 (322) | 1170 (498) | | 32 | 38 | 45 | 73 |
| 3 Oct | 65 (27) | 101 (51) | | 78 | 175 | 55 | 137 |
| 8 Oct | 109 (38) | 512 (121) | | 53 | 81 | 55 | 85 |
| 9 Oct | 171 (18) | 957 (381) | | 50 | 135 | 53 | 80 |
| 11 Oct | 598 (283) | 548 (220) | | 71 | 98 | 101 | 136 |
| 13 Oct | 364 (124) | 350 (128) | | 20 | 60 | 49 | 100 |
| 16 Oct | 106 (32) | No data before midnight | | 52 | 161 | 74 | 173 |
| 18 Oct | 901 (325) | 1753 | | 101 | 144 | 74 | 114 |
| 19 Oct | 0 (0) | 2858 (1386) | | 79 | 116 | 67 | 119 |
| 29 Oct | 683 (162) | 990 (208) | | 57 | 140 | 12 | 25 |
| 31 Oct | No data after midnight | 1626 (749) | | 78 | 121 | 71 | 150 |
| 3 Nov | No data before midnight | No data | | 102 | 135 | 124 | 167 |
| 4 Nov | 1 (0) | No data | | 256 | 378 | 168 | 282 |
| 5 Nov | No data | No data | | 130 | 207 | 102 | 144 |
| 11 Nov | 97 (33) | No data | | 84 | 174 | 49 | 81 |
| 12 Nov | 765 (465) | No data | | 95 | 170 | 108 | 195 |
| 13 Nov | 666 (192) | No data | | 93 | 125 | 84 | 142 |
| 15 Nov | 0 (0) | No data | | 32 | 60 | 21 | 38 |
| 19 Nov | 120 (40) | No data | | 82 | 110 | 116 | 141 |

# 9 Discussion and recommendations

## 9.1 Model performance

### 9.1.1 Model predictions versus radar predictions

Overall, the MTRs as predicted by the bird migration prediction model were lower than MTRs calculated by both radars Figure 9.1). The highest peak of the model was 378 birds/km/h while the highest peak within the horizontal radar was 901 birds/km/h. 23 hours exceeded 500 birds/km/h of the total of 1,843 hours that were analysed for the horizontal radar. For a machine learning model such as the bird migration prediction model, such rare events are extremely difficult to predict accurately. It is therefore crucial to look at the relative peaks and not at the actual MTR predictions per se.

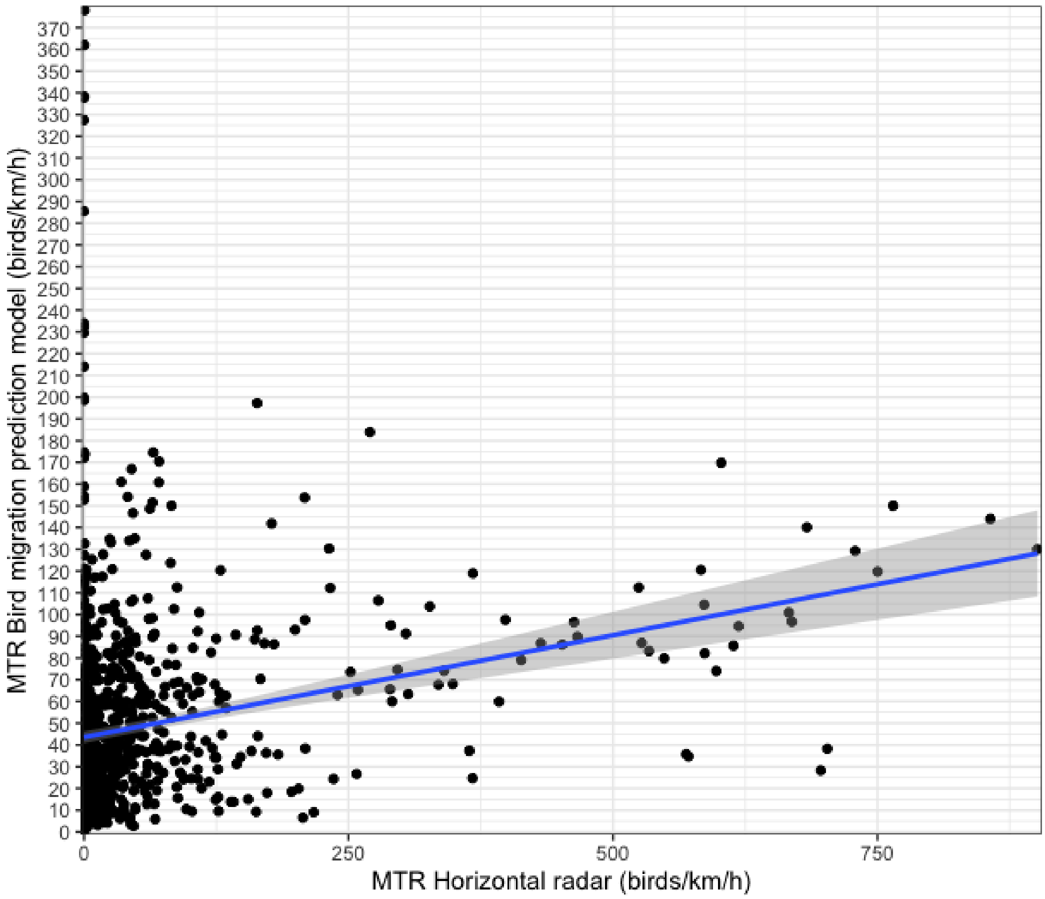


*Figure 9.1* *Scatterplot of the MTR of the horizontal radar matched with the bird migration prediction model predictions in that same hour. The blue line represents the best fitting line according to a linear model. Grey area around the blue line represents the 95% confidence interval.*

The bird migration prediction model forecasted one major peak within the first week of November. Unfortunately, these dates could not be analysed by radar data because of high filtering activities of the horizontal radar and malfunctioning of the vertical radar. The absence of reliable radar data during these nights greatly affected the outcome of the validation, especially the number of true positive hours. However, the expert group did predict a migration peak on the 4th of November.

Choosing a threshold to determine peak nights according to the bird migration prediction model is not straightforward. There are a lot of nights with relatively similar MTR predictions according to the model. The 10th night on the ranking of the bird migration prediction model had a peak of only 30 birds/km/h more than the 20th night on the ranking. Defining nights with peak migration intensities based on the model predictions and selecting a threshold based on these values is therefore difficult. For instance, we used the top ten nights based on the maximum MTR predicted by the model for an hour to identify positive matches with the radar data, but the differences in predicted MTRs are small and the ranking is also influenced by top nights predicted in August and September, months that the model was not trained on. Moreover, it is essential to keep the beforementioned limitations of the radar in mind when considering the number of true positives and choosing a threshold and based on the matches between radar data and model predictions.

The training period of October and November of the bird migration prediction model seems to have an important effect on the model outcomes. Since the implementation is going to be for the full period of mid-August until the end of November, we validated the model for that period. However, the radar results almost exclusively show peaks in October and November (one peak at the end of September), and hence the matches between the bird migration prediction model and the radar results could also only occur within these months. When only bird migration prediction model results in October and November are taken into account, and the top ten most intense migration nights are defined only for these months, four peaks match the radar measurements and three other the expert team forecasts, two of which did not have reliable radar measurements. This means that inaccuracy of the model is much larger in the months of August and September than in October and November, the months on which the model was trained.

### 9.1.2 Timing of weather forecast

Interestingly, the model that used weather forecast data of 00:00 of two days in advance, showed the highest MTRs on the 4th and 5th of November. However, when using weather data of six hours later, the peak already shifted towards the 3rd and 4th of November. The latter is in line with the expert group predictions, indicating that six hours more recent weather data seemed to have improved the accuracy of the outcome of the bird migration prediction model.

Outside of peak nights, the model predictions using input from either one of the three weather forecast timings look similar. Complete absence of predicted migration in the model using 00:00 weather forecasts as input will therefore not change into a prediction of intense migration in the more recent weather forecasts. However, this report shows that the timing of intense migration peaks can differ. Model predictions with different weather forecasts can therefore lead to exceedance of the curtailment threshold on a different (part of the) night.

The 12:00 prediction had the highest number of matches in peak nights when compared with the radar. This indicates that more recent weather forecasts might increase the reliability of the outcomes of the model. However, this was only based on one migration season, and it is therefore essential to test this during more migration seasons.

### 9.1.3 Threshold to determine peak nights in radar measurements

Choosing a valid threshold to determine peak nights on the basis of the radar results is a key step in validating the bird migration prediction model's performance. In this report, a night was labelled as peak night if it contained at least one hour with an MTR above 500 birds/km/h, conform curtailment thresholds defined earlier based on measurements in OWEZ (Krijgsveld *et al.* 2015). This method resulted in 23 peak hours (1.8% of all hours) divided over 6 peak nights in the horizontal radar database, and 33 peak hours (4.6% of all hours) divided over 8 peak nights in the vertical radar database. Within the whole study period of 1 August – 30 November, these hours accounted for 30 and 33% of the total bird flux measured by the horizontal and vertical radar respectively.

When a different threshold than 500 birds/km/h would have been chosen for both radars as a threshold, there would be different outcomes for the model validation as well. For instance, an arbitrary threshold of 300 birds/km/h would have led to 39 peak hours for the horizontal radar, which is 3.6% of all the hours analysed here. Comparably, 43% of the total bird flux would have passed by during these hours. However, only one of these hours would have occurred at a night that was not among the peak nights defined by the 500 birds/km/h threshold. The rest of the hours with an MTR between 300 and 500 according to the horizontal radar all fell within a night that was already labelled as peak night based on the threshold of 500 birds/km/hour. The added night to the analysis in this case is the $13^{th}$ of October. However, the model did not predict high MTRs for this night.

### 9.1.4 Migration patterns in relation to the bird migration prediction model

What drives birds to migrate all at once? This is an important question in creating and thus validating a bird migration prediction model. The most obvious factor driving bird migration are weather conditions, of which air pressure, wind and rain are important elements (Dokter *et al.* 2010; Rüppel *et al.* 2023). North-easterly winds may be considered the most promising for bird migration southwards (Bradarić *et al.* 2020; Manola *et al.* 2020). However, this wind direction is rare in autumn and most of the time the wind direction is southwest, which would mean head wind for southward migrating birds (Bradarić *et al.* 2020). Hence, birds have a limited number of days available on which conditions are suitable for migration. This may result in birds migrating under less favourable conditions, for instance when conditions remain unfavourable for an extended period of time (Manola *et al.* 2020; Kranstauber *et al.* 2022).

Results in this report show that wind directions during mass migration events have an eastern component most of the time. However, a possibly more important trigger for birds to migrate all at once is the sudden absence of bad wind conditions. Prior to almost every peak migration night, there was a relatively long period of southwestern winds, meaning head wind towards United Kingdom as well as to Southern Europe and Africa. This, in combination with the absence of rain, might increase the chances of intense migration. The accumulation factor within the model is therefore an essential element in predicting the migration patterns.

Two of the most important features for the model were the wind assistance within wind farm Luchterduinen for bird migration routes towards the southwest and the accumulation of migrating birds on the basis of wind assistance in Denmark. This corresponds to results of our study, although our analysis was done based on wind data collected by a weather station within the Luchterduinen wind farm instead of the ERA5 model data that was used for the training of the bird migration forecast model. This can differ substantially, because the weather station in Luchterduinen provides a direct measurement of that exact location and the ERA5 data is a model representation of the best estimated weather conditions. However, both results indicate the importance of wind assistance for bird migration peaks.

## 9.2 Horizontal radar data versus vertical radar data

A challenge of the current validation of the bird migration prediction model was the absence or unreliability of data of one or both radars at certain moments during the autumn 2022 season. As seen in Chapter 3 there can be large differences in the measurements of the two radars, despite operating at the same location. One important driver of these differences is that the horizontal and vertical radar differ in their filtering capacity to prevent non-bird objects, such as waves, entering the database. We showed that relatively high waves lead to lower MTRs in the horizontal radar and rainy periods are an important limiting issue for the vertical radar.

This means that for the horizontal radar, periods with waves above 1 meter seem not to be reliable when calculating MTRs. Moments at which the waves are higher than 1 meter are paired with strong wind conditions that might not be optimal for migrating birds. However, the vertical radar (from which the lowest 3 m was excluded to avoid contamination by wave clutter) also measured intense bird migration during nights with such conditions, e.g., on the 19$^{th}$ of October. Moreover, not only did the vertical radar measure a peak migration during that night, but also the expert team predicted a migration peak. Measurements of the horizontal radar during that night were not excluded by the standard data filtering steps of the model, and hence the MTRs from the horizontal radar data were presumably falsely not showing a migration peak.

## 9.3 Output variables of the bird migration prediction model

Every machine learning model is trained on a so-called ground-truthed dataset, which is known to be the real situation. The model is then trained to find patterns within the dataset based on features that might influence the output. The latter is in this case of MTR calculations performed on the dataset of the horizontal radar data in Luchterduinen. Because there are several gaps in the data of the horizontal radar, presumably because of too high waves, the question arises whether the horizontal radar dataset provides a correct reflection of the real situation.

### 9.3.1 Limitations of using only the horizontal radar for training the predictive model

How can the bird migration forecast model predict migration peaks on a night with waves above 1 meter, if it is trained on horizontal radar data that lacks migrations peaks in these conditions? That can occur when weather conditions (e.g., high waves) around the Luchterduinen wind farm where the radar is situated do not strongly correlate with weather conditions in departure areas. These conditions in departure areas, such as the Northern Netherlands and Denmark, are important features in predicting migration peaks, but may completely differ from conditions around Luchterduinen with high waves or rain.

Hence, training the machine learning model on incomplete data of a relative short research period with a limited number of migration peaks, will understandably not lead to the best results. There is however no ideal measurement equipment without any limitations. If the model would be trained on MTRs calculated with vertical radar data, the same issue would occur, but then with rain clutter. Even with perfect filtering steps, only keeping data from periods with good detection capabilities of the radar would lead to large data gaps.

### 9.3.2 Potential for training the model based on both horizontal and vertical radar data

As shown in this report, the use of the input parameters of wind assistance and accumulation factors are supported by the radar data analysis of autumn 2022. However, they might be an even better predictor if the model was not trained on only MTRs based on horizontal radar data, but also on data from the vertical radar. It is an advantage to have two radars with not only their own limitations but also their own strengths in one place. Thus, using input from both radars could lead to more redundant measurements and a more reliable ground-truthed dataset.

A possible output variable to train the model on, is the highest MTR from either of the radars. Since actual MTR numbers from the two radars can immensely differ, it is important to scale the MTRs to the maximum measured MTR of a season (for each type of radar specifically) when using such an approach. The increased redundancy in using measurements from two different radars ensures more reliable data in case there is an issue with one of the radars. Admittedly, periods with issues of both of the radars, and hence without reliable data, could still occur, but that would be expectedly significantly less often.

### 9.3.3 Level of detail

Another approach using data from both radars as output variable is by training the bird migration forecast model on periods of (half-)nightly data, instead of hourly data. Given the fact that the input features into the model are weather forecasts of two days ahead, the hourly predictions might be too detailed. It should be considered a great result if the model would be able to predict a migration peak during a certain night and it would occur in the first and/or second half of the night. The model reliability might improve by making the output variable categorical (peak or no peak, instead of the exact numbers) and not as detailed as it is now.

However, this would also influence the curtailment procedure. It would mean that the minimal period of curtailment would increase to half a night. Although it might make the model outcomes more reliable, it would also mean longer curtailments causing more potential energy loss.

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