Bat activity offshore

Analysis of data from passive acoustic monitoring, weather variables and wind turbine operations

Scientific note from DCE – Danish Centre for Environment and Energy

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AARHUS UNIVERSITY
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Data sheet

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Author(s):	Signe Marie Mygind Brinkløv, Klara Johanna Grethen, Astrid Særmark Uebel, Simeon Quirinus Smeele
Institution(s):	Aarhus University, Department of Ecoscience, Section for Wildlife Ecology
Referee(s):	Heidi Maria Thomsen and Morten Elmeros
Quality assurance, DCE:	Camilla Uldal
External comment:	Vattenfall A/S The comments can be found here
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Front page photo:	Horns Rev 3 wind farm. Photo by Signe M. M. Brinkløv
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1 Background and aims

The data analysis and outcomes presented in this scientific brief result from a request from Vattenfall A/S to DCE in the fall of 2024. The agreed task description included an analysis of a limited set of passive acoustic monitoring (PAM) data for bats, collected from buoys and wind turbines in select offshore wind farm areas. The data analysis included preliminary attempts to predict bat activity with parameters for weather, distance to coast and wind turbine operation, and thereby guide further data collection to substantiate the outcomes of the analysis.

The data for the study were collected as part of other projects in the Baltic Sea and the North Sea and were supplied by Aarhus University, Vattenfall A/S and the third-party consultant WSP. All data used in the final analysis were indexed, curated and quality assured by Aarhus University. The final dataset of audio files was then re-analysed with a bespoke convolutional neural network trained specifically on bat PAM data from Danish offshore stations to detect bat calls. All bat detections were manually verified and annotated, and the effect of the following parameters: time of year, distance to coast, temperature, wind speed, wind direction, precipitation, recording height, and turbine activity, was modelled to predict the probability of bat activity in general and, if data permitted, at species or species complex level.

Another aim of the study was to provide advice on how to improve further data and metadata collection protocols to facilitate reliable broad-scale quantitative analysis of bat activity offshore. This was done through ongoing dialogue with Vattenfall A/S, and relevant points are also summarised here.

2 Methods

The project involved the following components:

- Delivery of data for analysis
- Quality assurance, indexing and curation of data prior to further analysis
- Re-analyses of curated data with automated detection software
- Statistical analysis

Data were included from five sites (Fig. 2.1):

- Kriegers Flak I (KFI) in the western Baltic Sea, with recorders on the transition piece of ten wind turbines, five of which also had a recorder on the nacelle in 2024
- Kriegers Flak II (KFII) in the western Baltic Sea, with recorders on 16 buoys
- Horns Rev I (HRI) in the North Sea, with recorders on the transition piece of ten wind turbines
- Horns Rev III (HRIII) in the North Sea, with recorders on the transition piece of ten wind turbines
- North Sea I (NSI) in the North Sea, with recorders on 23 buoys

The data input for the analysis consisted of audio files collected during August 2022 to December 2024, from PAM stations on buoys and wind turbines, along with operational data from two of the sites (KFI and HRI). Data from HRIII and NSI were originally collected and analysed for the first year of the North Sea I baseline surveys and had already gone through quality assurance and automatic detection for bat call using the same methods as described below (Brinkløv et al. 2024). Data from KFII were originally collected and analysed by WSP for the first year of the Kriegers Flak II baseline surveys. Some of the data included for the KFI and KFII sites are included in WSP 2024a and WSP 2024b.

For the remaining data, during quality insurance, we removed all recordings that:

- were recorded before or on the reported deployment date, or after or on the reported retrieval date
- contained clear boat noise, music or speech, indicating the recorder was not at the station
- came from a deployment where we could manually verify from the data that the microphone or recorder was broken

Figure 2.1. Map of the five sites that supplied data for the analysis. Existing wind turbines were only present at Kriegers Flak I, Horns Rev I and Horns Rev III. For the Baltic Sea, the Kriegers Flak I site included data from ten wind turbines, mainly from transition piece height during a period of three years but also some from one year at nacelle height. Data from Kriegers Flak II were all from buoy stations. For the North Sea, the Horns Rev I and Horns Rev III data were from the transition piece of wind turbines, and the North Sea I data were from buoy stations.

After this quality insurance the dataset included 3,287,988 raw audio recordings and 10,506 filtered files with output from the commercial automated call detection and classification software *Kaleidoscope* (Wildlife Acoustics, Maynard, USA).

The data was recorded with two different hardware systems, the SM4BAT FS recorder (Wildlife Acoustics) and the SeaBat (AudioMoth, www.openacousticdevices.info, customized by WSP for offshore use). It should also be noted that we were not able to account for biases introduced by use of recording systems with different sensitivity thresholds and recording schedule settings. Further, as mentioned above, the data supplied for the analysis included a mix of raw audio data and pre-processed audio data in the form of audio files identified as containing bat calls by *Kaleidoscope*. For the pre-filtered audio data, files classified as noise by *Kaleidoscope* had not been saved. For these data, it was only possible to use *Animal Spot* to verify the presence of bat calls in the remaining files and discard false positives. It was not possible to test if any bat calls were missed by *Kaleidoscope*, introducing a potential bias in the analysis. To decrease bias in the results introduced by the automated software processing workflow, all data were re-analysed using one bat call detection model for all data based on the open-source and open-access *Animal Spot* software (Bergler et al. 2022). The model is based on a convolutional neural network and was trained specifically on call and noise examples from Danish offshore bat PAM. To ensure good performance on the new data from KFI, KFII and HRI, the model was retrained on examples from these sites before it was used for re-analysis.

For statistical analysis we developed bespoke Bayesian generalised additive mixed models (GAMMs). The response variable was the nightly presence/absence of bats. Bats were scored as present if at least one manually verified recording existed for that station and night. We used a directed acyclic graph for each focal variable and the backdoor criterion to decide which other variables to include to avoid spurious correlations. A directed acyclic graph represents all causal relationships in the form of arrows. The backdoor criterion is used to isolate the direct causal effect of the variable of interest from that of additional variables, e.g. to control for the fact that wind direction could both influence temperature (example: warmer winds from the south) and bat activity (example: less migration with head wind from the south or southwest). Bayesian models allow for the inclusion of prior information (e.g. that bat activity can only decrease with distance to coast) and are generally good at fitting sparse and unbalanced datasets.

All models were written in Stan (Gelman et al. 2015) with mildly informative priors centred around no effect. If positive effects could be ruled out (e.g. for distance to coast) priors only allowed for negative effects. Models were fitted using the R package *cmdstanr* (v. 0.8.1, Gabry et al. 2024) with four chains and default settings. Divergent transitions and Rhat values were monitored. All results are reported at the mean posterior prediction and the 89% posterior interval.

We first ran a model to summarise bat activity across spring, summer and fall. Day of the year was included as a B-spline smooth for each location, with 15 knots and a degree of three, using the function *bs* from the basic R package *splines* (R Core Team 2024, v. 4.3.3). Station, deployment and unique date were included as varying effects. For predictions, we only included day of the year. To summarise the activity for specific years for KFI, we ran the same model, but now including a varying offset B-spline smooth for each year and location.

We then tested the effects of distance to coast, temperature, wind direction, wind speed and precipitation. For this model we restricted the data to the period from 1st of August until 15th of October. We added the day of year as a B-spline smooth (with 10 knots) and station, deployment and unique date were included as varying effects. Temperature was included as a B-spline smooth with three knots and degree three. Wind direction was included as a linear predictor for the sine and cosine component. Wind speed was included as a linear predictor, with a prior only allowing for a decrease in activity with increasing speed. Precipitation was included as a linear predictor, with a prior only allowing for a decrease in activity with increasing precipitation. Predictions were made for a range of values of the variable of interest, while other variables were fixed at intermediate values where bat activity is likely to occur: 20 km off the coast, the date of peak migration as predicted by the model, 18 ˚C, northern wind, 3 m/s and no precipitation.

The effects of recording height (nacelle versus transition piece) and turbine activity (rounds per minute) were tested in separate models. For recording height, we restricted the data to nights and stations on KFI, where data were available from both the transition piece and nacelle recorder on the same turbine. Station, deployment and unique date were included as varying effects. Predictions were made for each recording height without including additional variables. For turbine activity we restricted the data to cases where turbine activity was available for KFI and used a model like the one used for the weather variable plus distance to coast, with rounds per minute added as a linear effect. Predictions were made as for the weather variables plus distance to coast.

Weather parameters, including precipitation (mm), temperature (2 m above sea level, converted from Kelvin to degrees Celcius), wind speed (10 m above sea level, converted to m/s), and wind direction (converted to degrees), were extracted from Copernicus (https://cds.climate.copernicus.eu/) for all locations and dates with curated audio data available based on the station coordinates, and summarised by taking the value at sunset for that location and date. Operational data from the wind turbines were supplied by Vattenfall A/S.

3 Results

An overview of the deployments, limited to the intervals for which data were included in the analysis after quality assurance and curation as outlined in the methods section, is presented in Fig. 3.1. Note that not all deployments were active for an equal time span. The data from KFII came from 16 buoy stations and was limited in coverage to part of 2023 (April to the end of September for 10 stations, April to the end of mid-July for 1 station and less than two months between August and October for five of the stations). For KFI, data was sampled across three years: during fall (August and September) 2022, from April to October 2023 (five of the 10 stations contributed data from less than two months during 2023), and from April to mid-November 2024. Most of the KFI data were from the transition piece of existing wind turbines but also included data from the nacelle on five of the wind turbines for 2024. The HRI data came from the transition piece of 10 wind turbines and were recorded between late April 2024 and either September, October or November 2024. The HRIII data came from the transition piece of 10 wind turbines with less than two months of coverage per station. The NSI data were from deployments on 23 buoys. The majority included up to one month of data from each of the four seasons over one year (April 2023 to April 2024). One was limited to winter 2023.

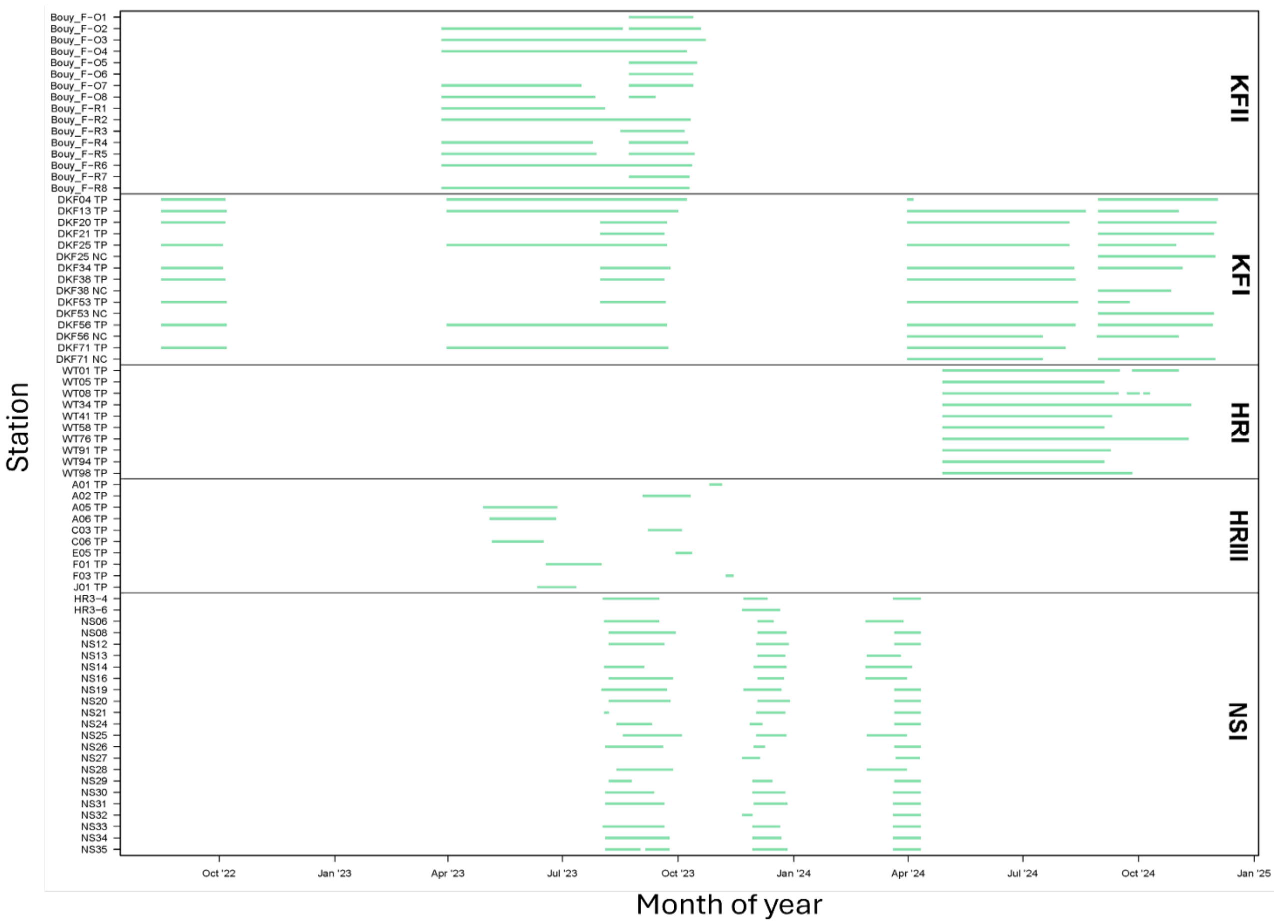

Figure 3.1. PAM deployments for which data were included in the analyses. Data was included from five sites, two in the western Baltic Sea: Kriegers Flak I (KFI) and Kriegers Flak II (KFII), and three in the North Sea: Horns Rev I (HRI), Horns Rev III (HRIII) and North Sea I (NSI). For wind turbine stations, the recording height is indicated after the station name: TP = transition piece, NC = nacelle.

Across species and sites, bat activity was highest, with a clear activity peak, during fall (Fig. 3.2 and 3.4). Figure 3.3. shows the model prediction zoomed in on fall separately for each of the three deployment years in KFI. The three years were combined into the overall model shown in the top left subplot of Fig. 3.2. A smaller activity peak was also present for Nathusius' pipistrelle in both KFI and KFII during spring (Fig. 3.2) but was almost undetectable in the analysis of available data from the North Sea areas (HRI, HRIII and NSI) (Fig. 3.4). For the ENV species complex, a small spring activity peak was only evident from the KFI area but absent for the KFII area, where predictions were modelled based on data from a single year. The analysis did not reveal any apparent differences in the timing of the pronounced activity peak in fall and the minor activity peak in spring between species and between sites. The fall activity peak consistently occurred during August through October. The spring peak, where present, occurred during May. The overall seasonal model (Figs. 3.2 - 3.4) includes both spring and fall, all other models are restricted to the fall season.

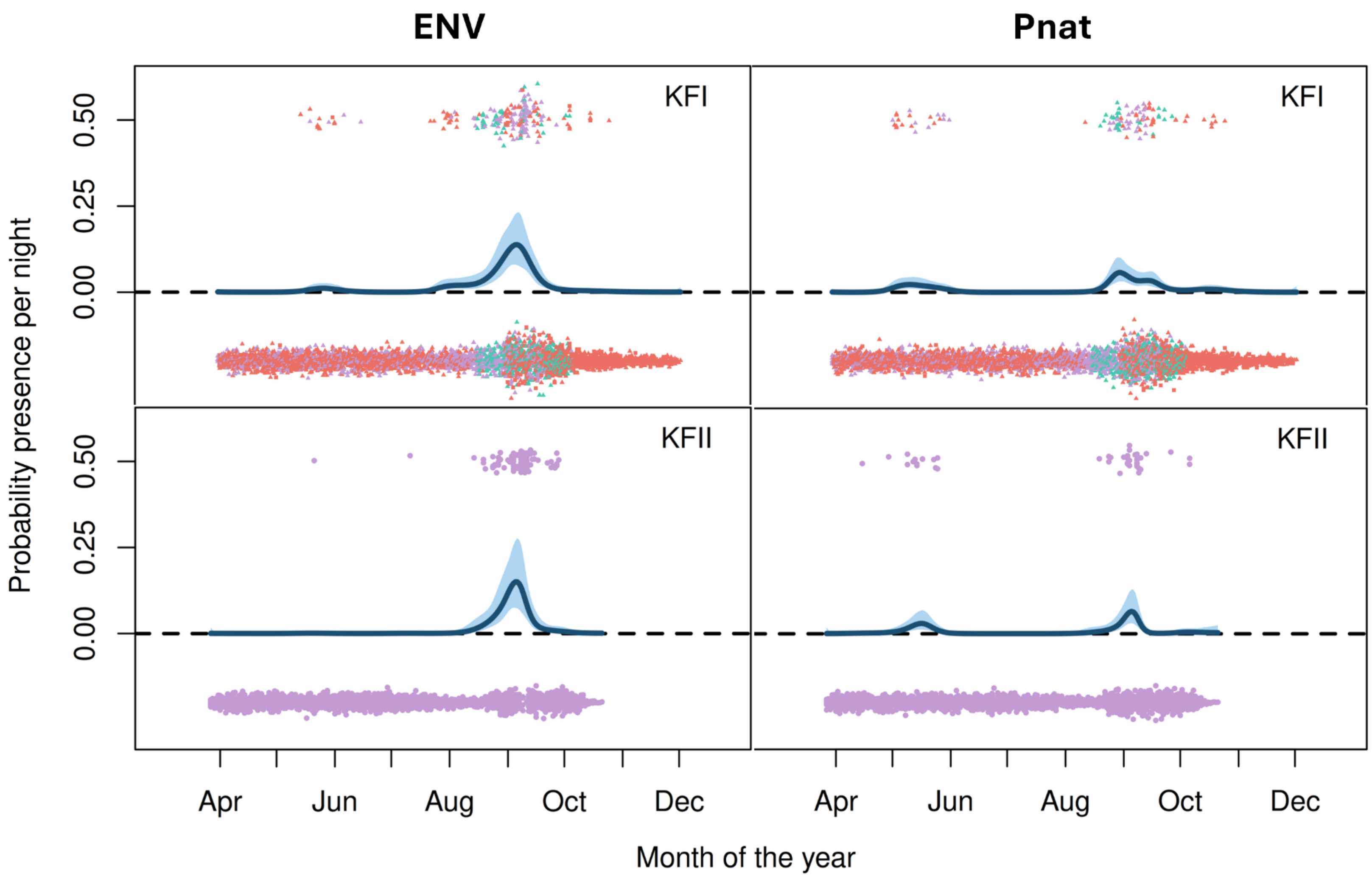

Figure 3.2. Probability of bat presence across the month of year in the Kreigers Flak area. Two sets of models were developed from the data from Kriegers Flak I and II, one for presence of the ENV species complex (left column) and one for presence of Nathusius\ pipistrelle (Pnat, right column). Dark blue solid line: mean posterior prediction of bat presence. Blue shaded area: model uncertainty (89% posterior interval). Black dashed line indicates 0. Coloured data markers represent bat presence (= bat activity on that night, above black dashed line) and absence (= no bat activity on that night, below dashed black line). Data marker shape indicates type of station: round = buoy, triangle = wind turbine transition piece and square = wind turbine nacelle. Colour of data markers indicates different deployment years: green = 2022, purple = 2023 and red = 2024.

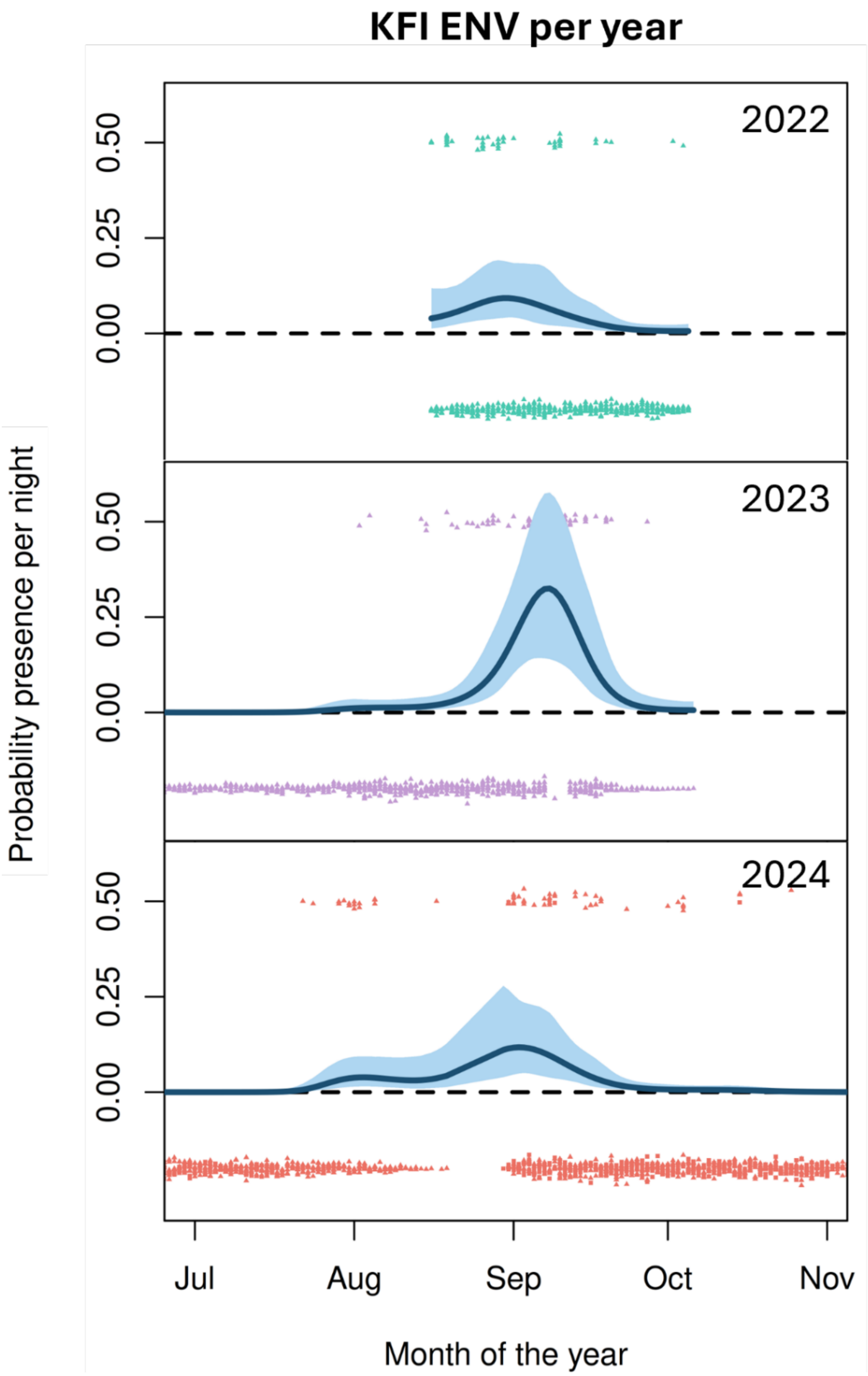

Figure 3.3. Probability of ENV presence across the month of year for three consecutive years in Kriegers Flak I. The yearly plots are based on the same model used in the overall plot in figure 3.2 but only show the fall season. Dark blue solid line: mean posterior prediction of bat presence. Blue shaded area: model uncertainty (89% posterior interval). Black dashed line indicates 0. Coloured data markers represent bat presence (= bat activity on that night, above black dashed line) and absence (= no bat activity on that night, below dashed black line). Data marker shape indicates type of station: round = buoy, triangle = wind turbine transition piece and square = wind turbine nacelle. Colour of data markers indicates different deployment years: green = 2022, purple = 2023 and red = 2024.

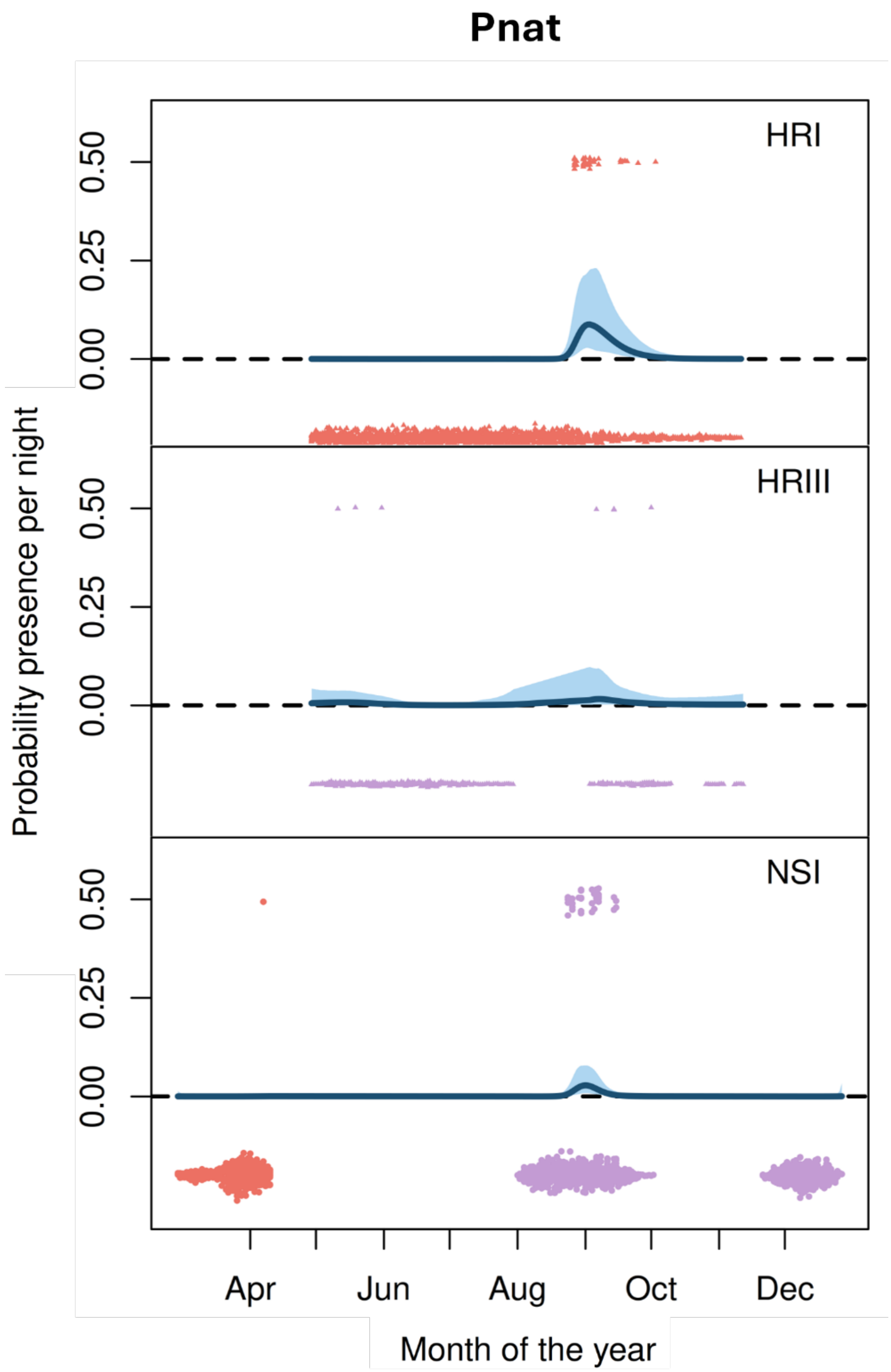

Figure 3.4. Probability of bat presence across the month of year in the North Sea. It was only possible to model the presence of Nathusius' pipistrelle (Pnat) for the North Sea: Horns Rev I (HRI), Horns Rev III (HRIII) and North Sea I (NSI), due to a lack of data for other species. Dark blue solid line: mean posterior prediction of bat presence. Blue shaded area: model uncertainty (89% posterior interval). Black dashed line indicates 0. Coloured data markers represent bat presence (= bat activity on that night, above black dashed line) and absence (= no bat activity on that night, below dashed black line). Data marker shape indicates type of station: round = buoy and triangle = wind turbine transition piece. Colour of data markers indicates different deployment years: purple = 2023 and red = 2024.

On Kriegers Flak, bat activity showed a decrease with increasing distance to the coast. However, bat activity remained present even at the stations furthest from the coast (see Fig. 3.5). Data from the North Sea were too limited to obtain meaningful predictions of bat activity with distance to the coast for this area.

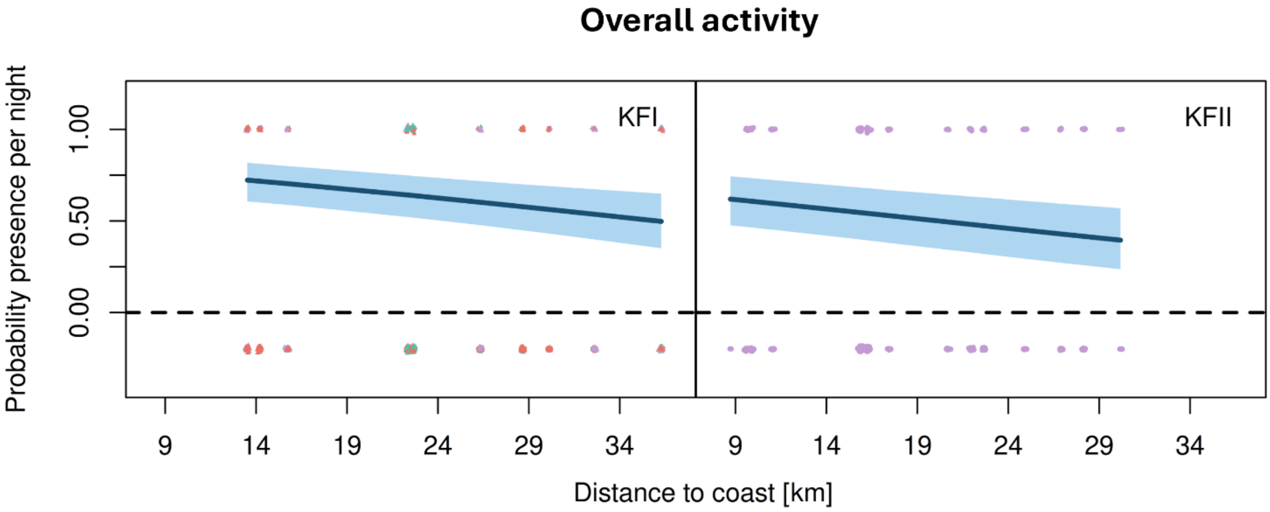

Figure 3.5. Probability of overall bat presence with distance to the coast in the Kriegers Flak area. Predictions for presence with distance to the coast were made for overall bat activity across species separately for each of the two Kriegers Flak sites (KFI and KFII). Dark blue solid line: mean posterior prediction of bat presence. Blue shaded area: model uncertainty (89% posterior interval). Black dashed line indicates 0. Coloured data markers represent bat presence (= bat activity on that night, above black dashed line) and absence (= no bat activity on that night, below dashed black line). Data marker shape indicates type of station: round = buoy, triangle = wind turbine transition piece and square = wind turbine nacelle. Colour of data markers indicates different deployment years: green = 2022, purple = 2023 and red = 2024.

On Kriegers Flak, activity of the ENV species complex started to increase around 14-16˚C and appeared to peak around 20-21˚C (Fig. 3.6), although uncertainty was so great that neither the start of the increase nor the presence of an optimal temperature could be estimated precisely. For Nathusius' pipistrelle, no consistent effect of temperature was established for KFI while an increase in activity was predicted with increasing temperature for KFII, with high uncertainty (Fig. 3.6). There were not enough data available for the North Sea to obtain meaningful estimates.

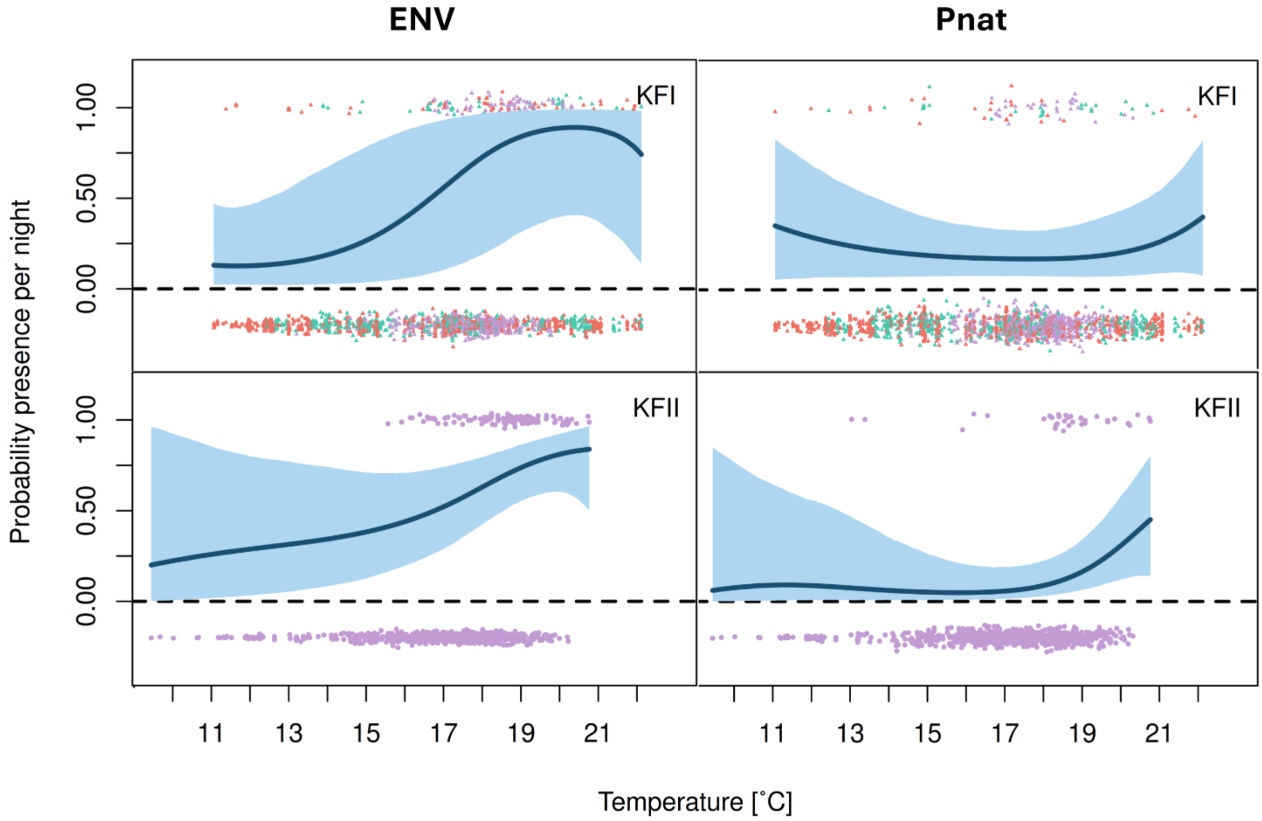

Figure 3.6. Probability of bat presence with temperature in the Kriegers Flak area. Two sets of models were developed from the data from Kriegers Flak I and II, one for presence of the ENV species complex (left column) and one for presence of Nathusius' pipistrelle (Pnat, right column). Dark blue solid line: mean posterior prediction of bat presence. Blue shaded area: model uncertainty (89% posterior interval). Black dashed line indicates 0. Coloured data markers represent bat presence (= bat activity on that night, above black dashed line) and absence (= no bat activity on that night, below dashed black line). Data marker shape indicates type of station: round = buoy, triangle = wind turbine transition piece and square = wind turbine nacelle. Colour of data markers indicates different deployment years: green = 2022, purple = 2023 and red = 2024.

The model could not predict any clear effect of wind direction on the activity of the ENV species complex for KFI, whereas most activity was predicted around SW-W-NW winds for Kriegers Flak II (Fig. 3.7, left column). For Nathusius' pipistrelle, the model predicted most activity when a northern wind component was present for KFI (Fig. 3.7, right column). A similar trend may be present for Nathusius' pipistrelle at KFII but with too high uncertainty to be conclusive. The effect of wind direction on bat activity over the North Sea was only modelled for Nathusius' pipistrelle based on fall data and, accordingly, predicted activity to increase with eastern wind components (NE-E-SE) with the activity peak displaced slightly towards more southern winds for HRIII. However, uncertainty was also very high for these predictions (Fig. 3.8).

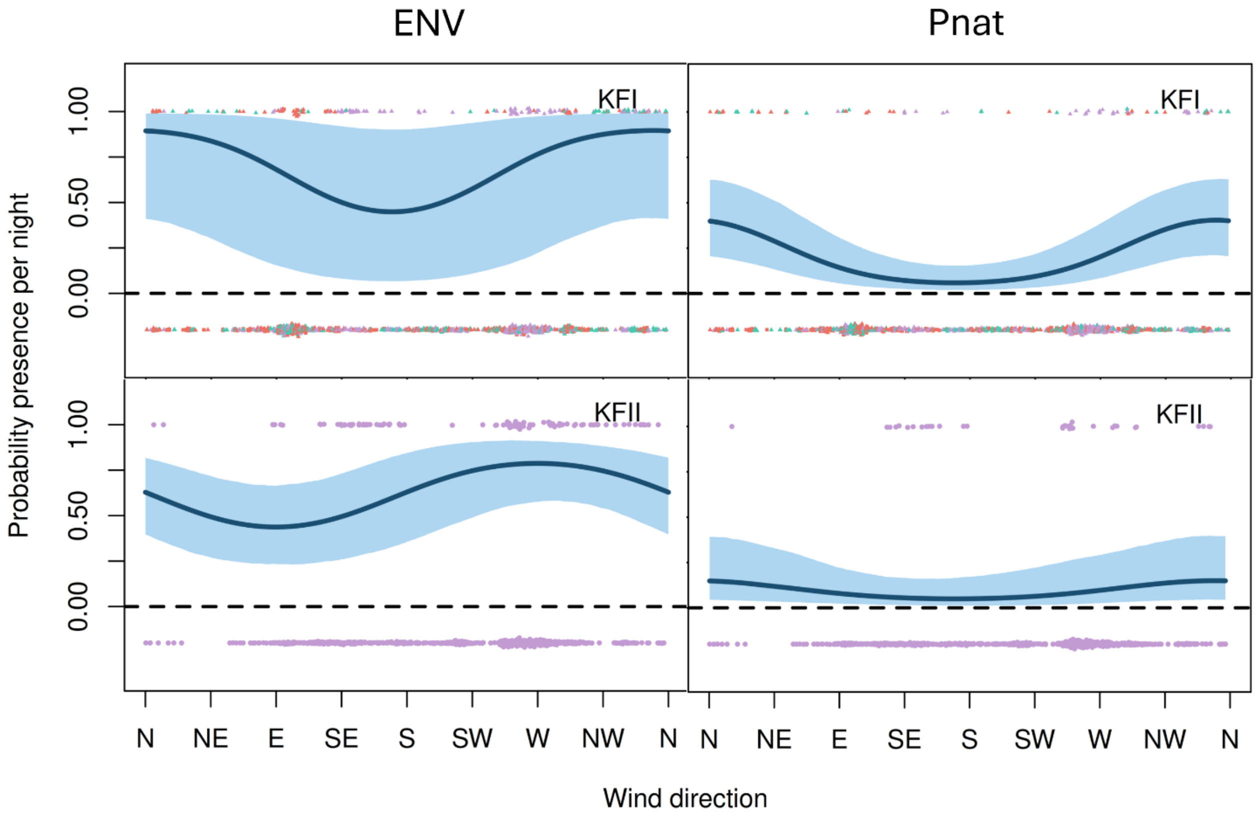

Figure 3.7. Probability of bat presence with wind direction in the Kriegers Flak area. Two sets of models were developed from the data from Kriegers Flak I and II, one for presence of the ENV species complex (left column) and one for presence of Nathusius' pipistrelle (Pnat, right column). Dark blue solid line: mean posterior prediction of bat presence. Blue shaded area: model uncertainty (89% posterior interval). Black dashed line indicates 0. Coloured data markers represent bat presence (= bat activity on that night, above black dashed line) and absence (= no bat activity on that night, below dashed black line). Data marker shape indicates type of station: round = buoy, triangle = wind turbine transition piece and square = wind turbine nacelle. Colour of data markers indicates different deployment years: green = 2022, purple = 2023 and red = 2024.

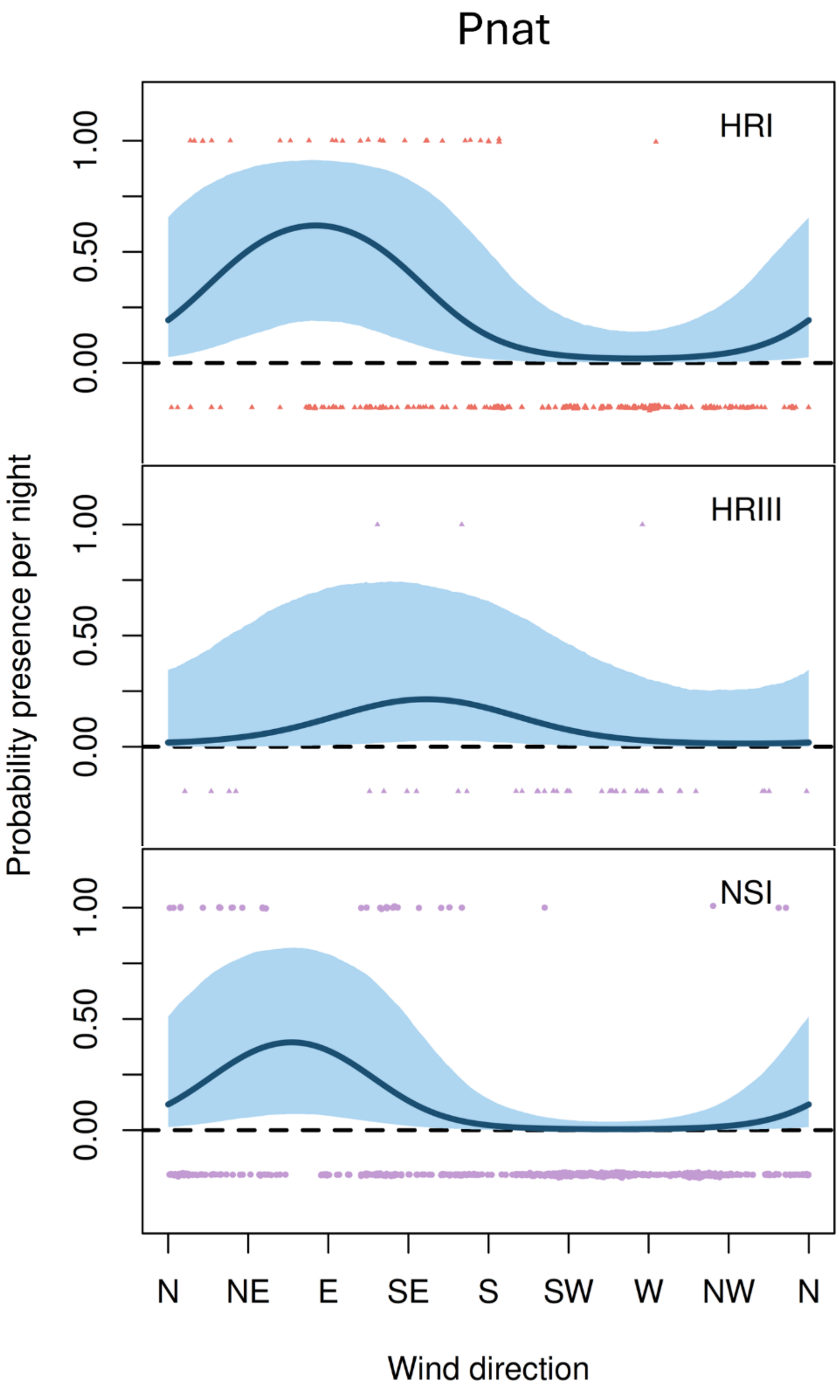

Figure 3.8. Probability for presence of Nathusius' pipistrelle (Pnat) with wind direction in the North Sea. Black line: mean posterior prediction of bat presence. Dark blue solid line: mean posterior prediction of bat presence. Blue shaded area: model uncertainty (89% posterior interval). Black dashed line indicates 0. Coloured data markers represent bat presence (= bat activity on that night, above black dashed line) and absence (= no bat activity on that night, below dashed black line). Data marker shape indicates type of station: round = buoy and triangle = wind turbine transition piece. Colour of data markers indicates different deployment years: purple = 2023 and red = 2024.

Wind speed has a clear negative effect on the activity of both ENV species and Nathusius' pipistrelle at Kriegers Flak, consistent for both KFI and KFII (Fig. 3.9). The probability for bat activity dropped steeply as wind speeds increased to 10 m/s. Some, but lower, activity was predicted for wind speeds of 10-15 m/s for the ENV species complex, but the predictions for KFI were associated with high uncertainty. For the North Sea, not enough data were available to obtain meaningful estimates. The cumulative relative presence of ENV and Pnat species in Kriegers Flak I and II is shown in Figure 3.10.

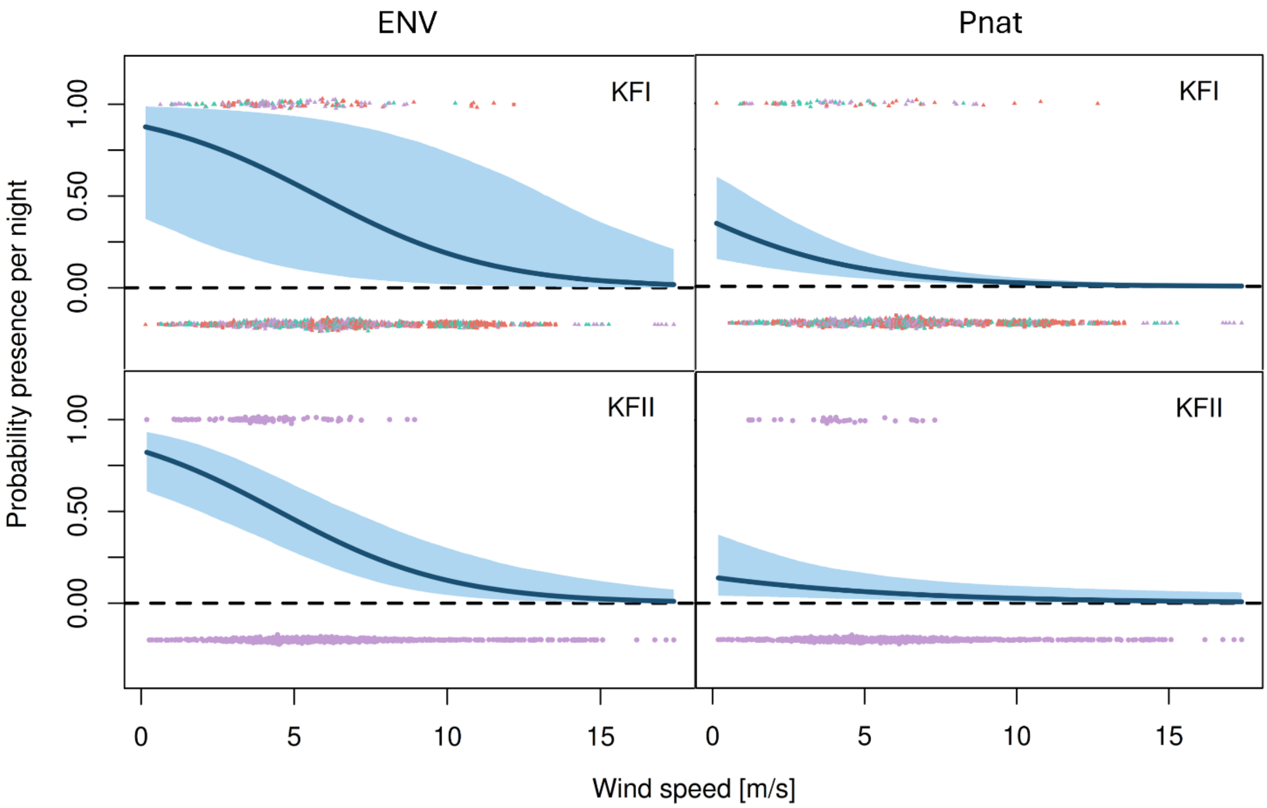

Figure 3.9. Probability of bat presence with wind speed in the Kriegers Flak area. Two sets of models were developed from the data from Kriegers Flak I and II, one for presence of the ENV species complex (left column) and one for presence of Nathusius' pipistrelle (Pnat, right column). Dark blue solid line: mean posterior prediction of bat presence. Blue shaded area: model uncertainty (89% posterior interval). Black dashed line indicates 0. Coloured data markers represent bat presence (= bat activity on that night, above black dashed line) and absence (= no bat activity on that night, below dashed black line). Data marker shape indicates type of station: round = buoy, triangle = wind turbine transition piece and square = wind turbine nacelle. Colour of data markers indicates different deployment years: green = 2022, purple = 2023 and red = 2024.

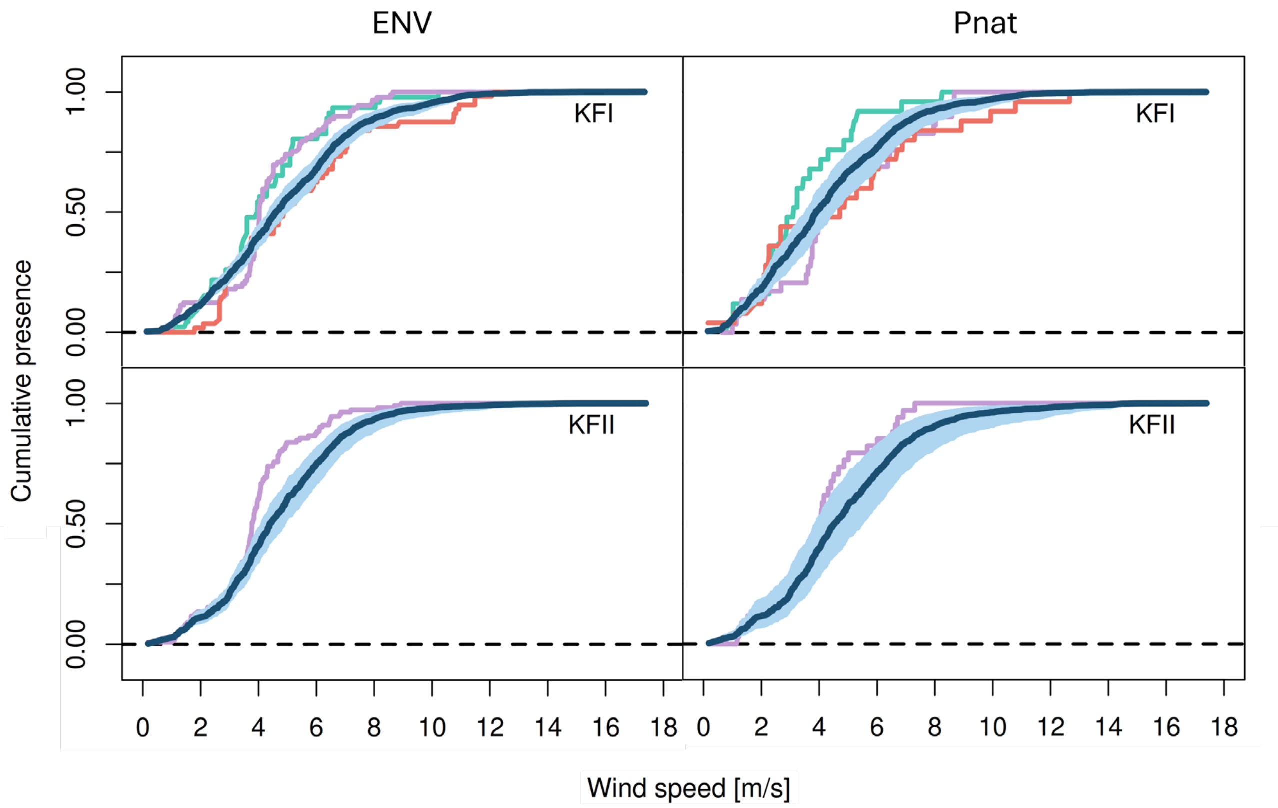

Figure 3.10. Cumulative bat presence across windspeeds. For each windspeed (x-axis) we summed the observed bat activity up to and including that wind speed and normalised by the total number of observations. Coloured lines are for the raw data, dark blue line is based on the model predictions. Shaded light blue is the 89% posterior interval.

The predicted effect of precipitation on bat activity was only modelled for the ENV species complex at the two Kriegers Flak sites and the model did not detect a clear effect, as illustrated in Fig. 3.11.

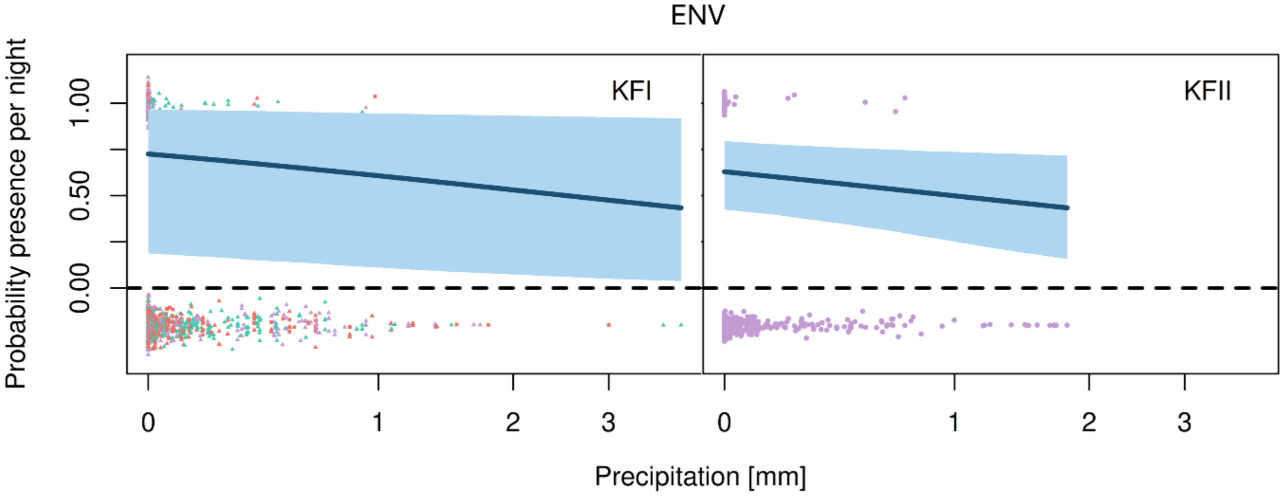

Figure 3.11. Probability of presence of the ENV (*Eptesicus*, *Nyctalus* and *Verspertilio*) species complex with precipitation in the Kriegers Flak area. Dark blue solid line: mean posterior prediction of bat presence. Blue shaded area: model uncertainty (89% posterior interval). Black dashed line indicates 0. Coloured data markers represent bat presence (= bat activity on that night, above black dashed line) and absence (= no bat activity on that night, below dashed black line). Data marker shape indicates type of station: round = buoy, triangle = wind turbine transition piece and square = wind turbine nacelle. Colour of data markers indicates different deployment years: green = 2022, purple = 2023 and red = 2024.

ENV species were observed both at the transition piece and at nacelle height, whereas the Nathusius' pipistrelle was only observed at transition piece height. This was also reflected in the model results, where there was a strong contrast between the probability for activity of the Nathusius' pipistrelle at the transition piece and nacelle height, with virtually no activity predicted at nacelle height. There was no such strong contrast for the ENV species complex (Fig. 3.12), and the confidence interval of the contrast overlaps zero, indicating that the model could not detect a difference. This indicates that ENV species are more likely than Nathusius' pipistrelle to be active within the acoustic range of the nacelle at the Kriegers Flak I site, the only site where it was possible to attempt this comparison.

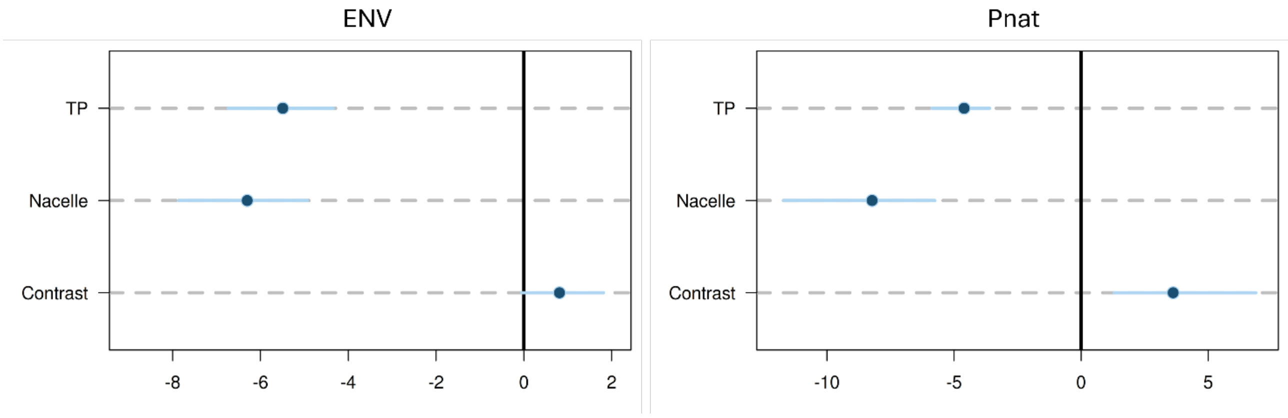

Figure 3.12. Effect plot of the modelled effect of recording height on bat presence. The effect estimates for transition piece and nacelle recording height and the estimated difference (contrast) between the two. Points are model averages; lines are model uncertainty (89% posterior interval).

Turbine activity had no effect on the predicted activity of ENV species, and model uncertainty was high (Fig. 3.13, left). In contrast, a negative effect of turbine operation was predicted with high uncertainty for Nathusius' pipistrelle (Fig. 3.13, right).

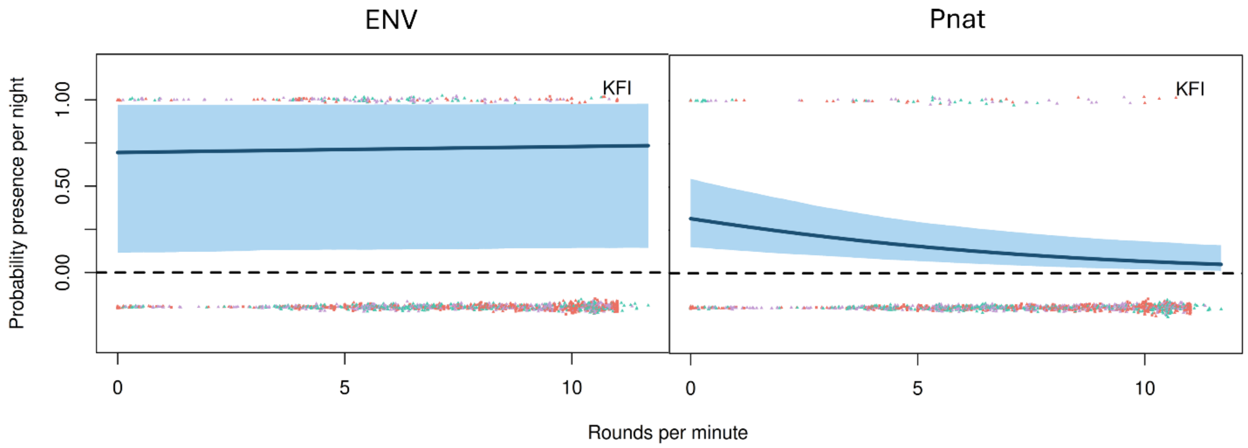

Figure 3.13. Probability of bat presence with wind turbine operation in the Kriegers Flak area. Two models were developed, one for presence of the ENV species complex (left column) and one for presence of Nathusius' pipistrelle (right column). Dark blue solid line: mean posterior prediction of bat presence. Blue shaded area: model uncertainty (89% posterior interval). Black dashed line indicates 0. Coloured data markers represent bat presence (= bat activity on that night, above black dashed line) and absence (= no bat activity on that night, below dashed black line). Data marker shape indicates type of station: round = buoy, triangle = wind turbine transition piece and square = wind turbine nacelle. Colour of data markers indicates different deployment years: green = 2022, purple = 2023 and red = 2024.

4 Discussion

The project involved analysis of data collected by Aarhus University, Vattenfall A/S and WSP. The process of acquiring, indexing and curating the data was labourious and highlights a strong need for dialogue and guidelines to help contributing parties align

a) what defines raw data,

b) how data should be stored, named and organised to facilitate later sharing and analysis by those other than the data collectors,

c) which essential metadata should be documented and saved with the collected datasets.

These points are not specific to this project but are broadly relevant, e.g. for the purposes of cumulative impact assessments and for using multi-source data in a comprehensive analysis to guide curtailment efforts (Brinkløv et al. 2025, Asmus et al. 2025). To improve proper documentation of further offshore bat PAM efforts, it is advisable that specific metadata is always documented and made available with the raw data. Aarhus University drafted and provided a preliminary template for this purpose for use by the wind turbine operator and technicians on-site (Appendix 1).

The client (Vattenfall A/S) was responsible for the data delivery, which was initially planned for completion by December 2024. Following several delays, the data delivery was not completed before March 2025, and some metadata were never delivered. The delays were caused by several factors, including communication lags with WSP, a lack of IT infrastructure and restrictions imposed by IT security policy, necessitating physical transport of data on hard drives rather than simple and fast online transfers. Although basic, such issues are important to consider for future and timely data sharing and analysis workflows based on data input from multiple sources. It is advisable to store all raw data and metadata on a secure server, to which third-party access can be granted through a share-link with fast read-access.

We used generalised additive mixed models (GAMMs) to estimate the effect on bat activity from specific predictors (e.g. weather parameters and turbine activity) to account for high complexity and multiple dependencies in the data. The presented results are the outcomes of a Bayesian approach to GAMM, where prior assumptions are used to inform the posterior distributions. This allows prior information to be included (e.g. if a similar analysis has been run for another location or if certain relationships are not possible) and makes model results more robust, especially with limited data (Gelman et al. 2013). Outcomes were compared to a frequentist approach (maximum likelihood-based inference) which resulted in similar model predictions and robustness.

A fall activity peak between August and October, and the highest probability for activity in late August into the first half of September was consistent for all sites and for both the ENV species complex and Nathusius' pipistrelle (Figs. 3.2 - 3.4). Spring activity was predicted, but with a much less pronounced peak than fall activity, and only for Nathusius' pipistrelle at the KFI and KFII sites. These results could reflect better foraging opportunities offshore for bats in fall or be related to geographical or population dynamic differences in migration activity or movement patterns between the fall and spring season, e.g. bats staying over land on the west coast of Jutland or northeast migration being more scattered and difficult to monitor in spring (Ahlén et al. 2009).

The predictions for bat activity with distance to coast corroborated that bat activity decreases with increasing distance to land but also showed that bat activity persists up to 30-40 km from the coast at the two Kriegers Flak sites (Fig. 3.5). These results agree with observations from the first year of the North Sea I baseline surveys (Brinkløv et al. 2024), although they were too limited for modelling efforts.

Overall, the predictions for bat activity based on weather parameters are aligned with earlier offshore findings (Lagerveld et al. 2021, Brabant et al. 2021). The predictions for increased activity of Nathusius' pipistrelle during the fall season offshore over the North Sea coincide with wind directions including an eastern component (Fig. 3.8), corresponding to tailwind for bats leaving the coast of west Jutland. It is uncertain whether the activity arises from intermittent offshore foraging bouts or is related to offshore migration activity. Curtailment is relevant for periods of significant activity regardless of the nature of the activity, but foraging activity could involve higher risk if bats stay near or in the rotor-swept area for longer than during migration flights. If further data across multiple years corroborate the low probability of activity with western winds, this result could be used to tailor site-specific curtailment efforts, in combination with additional relevant predictors. The results for the Kriegers Flak sites were less clear. However, wind direction appeared to influence the ENV activity more strongly than the activity of Nathusius' pipistrelle at Kriegers Flak (Fig. 3.7). Predictions for activity based on wind speed were limited to the Kriegers Flak sites where they showed a consistent decrease in bat activity with increasing wind speed (Figs. 3.9 and 3.10). Yet, some activity was estimated to persist at wind speeds above 10 m/s, even up to 15 m/s for ENV species, indicating a potential species-dependent tolerance (Hatch et al. 2013). The predicted activity up to and beyond wind speeds of 10 m/s implies that wind speed may be more useful as a variable for curtailment in combination with other parameters (Barré et al. 2023). It should, however, also be noted that higher wind speeds increase the ambient noise, consequently increasing the risk of missing bats in the detection effort. For both the modelled and cumulative presence plots, it is still unknown how the relative levels of activity (e.g. 5% or 90% of the total activity) translate into bat density. In the modelled plots, the effect of wind speed was predicted with other variables fixed, including wind direction (fixed to northern wind, see methods). Depending on the prevalent wind direction in a given year, the model curve may move up and down without changing the slope but resulting in a different y-axis intercept (higher or lower presence at a wind speed of 0 m/s, see Fig. 3.2 top left subplot), but the cumulative plots (Fig. 3.10) would not reflect this change. If the broader scope of data comparisons across sites is properly considered in the data collection process per site, it should be possible to use the modelling approach to tailor curtailment schemes based on multiple variables and predict more accurate thresholds or upper and lower boundaries for when curtailment is relevant.

Estimates of the effect of wind turbine operation (based on rounds per minute as predictor variable in the GAMM) indicate that activity of Nathusius' pipistrelle is more likely to be influenced by blade rotation than the activity of ENV species (Fig. 3.13). However, these results are associated with high uncertainty and are highly preliminary.

As expected, the dataset was limited for the scope of the task (few data per site and year) and further reduced in size by the quality assurance process. There is also a risk of bias in the results since a proportion of the input data was recorded using duty cycling (five out of every fifteen seconds monitored were recorded) and/or only supplied as detections with further raw data discarded without the possibility of verifying that they contained no bat calls (Brinkløv et al. 2025, Smeele et al. In prep.). Accordingly, the outcomes of the analyses are associated with high uncertainty of the model predictions and should be interpreted with due caution. Yet, we were able to establish proof-of-concept, and from the process identify the main barriers for a comprehensive analysis. Further data and a coordinated effort are needed to streamline the workflow and refine the approach. This type of comprehensive analysis, regardless of the choice of statistical analysis, should be emphasised as a dynamic tool to be updated with additional data input over time, firstly to improve resolution of, and track potential changes in, the predicted patterns at the species, geographical and temporal level.

5 References

Ahlén I, Baagøe HJ & Bach L 2009. Behavior of Scandinavian Bats during Migration and Foraging at Sea, Journal of Mammalogy: 90(6), 1318–1323. https://doi.org/10.1644/09-MAMM-S-223R.1

Asmus, J., K.-H. Frommolt, and M. Knörnschild. 2025. "Lost in Translation—How Transparency Can Improve Comparability and Reusability in Acoustic Bat Research." *Ecology and Evolution* 15, no. 8: e71883. https://doi.org/10.1002/ece3.71883.

Barré K, Froidevaux JSP, Sotillo A, Roemer C, Kerbiriou C. 2023. Drivers of bat activity at wind turbines advocate for mitigating bat exposure using multicriteria algorithm-based curtailment. Science of The Total Environment 866, 161404. https://doi.org/10.1016/j.scitotenv.2023.161404

Bergler C, Smeele SQ, Tyndel SA, Barnhill A, et al. 2022. ANIMAL-SPOT enables animal-independent signal detection and classification using deep learning. Sci Rep 12, 21966. https://doi.org/10.1038/s41598-022-26429-y

Brabant R, Laurent Y, Poerink BJ & Degraer S 2021. The relation between migratory activity of pipistrellus bats at sea and weather conditions offers possibilities to reduce offshore wind farm effects. Animals 2021, 11(12), 3457. https://doi.org/10.3390/ani11123457

Brinkløv SMM, Smeele SQ, Uebel AS, Fjederholt ET, Elmeros M. 2024. Bat Surveys – North Sea I. Bat surveys - pre-investigations for offshore wind farms in the area North Sea I. Commissioned by Energinet Eltransmission A/S. https://dce.au.dk/fileadmin/dce.au.dk/Udgivelser/Eksterne_udgivelser/2024/Bat_surveys.pdf

Brinkløv SMM, Uebel AS, Fjederholt ET, Elmeros M. 2025. Sensitivity mapping of relative risks to bats from Danish offshore wind energy. Aarhus University, DCE – Danish Centre for Environment and Energy, 55 pp. Technical Report No. 332. Commissioned by The Danish Energy Agency. https://dce.au.dk/fileadmin/dce.au.dk/Udgivelser/Tekni-ske_rapporter_300-349/TR332.pdf

Gabry J, Češnovar R, Johnson A, Bronder S 2024. cmdstanr: R Interface to 'CmdStan'_. R package version 0.8.1, https://discourse.mc-stan.org, https://mc-stan.org/cmdstanr/

Gelman, A., Carlin, J. B., Stern, H. S., Dunson, D. B., Vehtari, A., & Rubin, D. B. (2013). *Bayesian Data Analysis* (3rd ed.). CRC Press.

Gelman A, Lee D, Guo J. 2015. Stan: A Probabilistic Programming Language for Bayesian Inference and Optimization. *Journal of Educational and Behavioral Statistics*, *40*(5), 530-543. https://doi.org/10.3102/1076998615606113 (Original work published 2015)

Hatch SK, Connelly EE, Divoll TJ, Stenhouse IJ & Williams KA 2013. Offshore Observations of Eastern Red Bats (*Lasiurus borealis*) in the Mid-Atlantic United

States Using Multiple Survey Methods. PLoS ONE, 8, e83803. https://doi.org/10.1371/journal.pone.0083803

https://doi.org/10.1371/journal.pone.0083803Lagerveld S, Poerink BJ & Geelhoed SCV 2021. Offshore occurrence of a migratory bat, Pipistrellus nathusii, depends on seasonality and weather conditions. Animals 11, 3442. https://doi.org/10.3390/ani11123442

R Core Team (2024). _R: A Language and Environment for Statistical Computing [computer software]. R Foundation for Statistical Computing, Vienna, Austria. https://www.R-project.org/

Smeele et al (In Prep). Modelling offshore bat activity over Danish waters. Aarhus University, DCE – Danish Centre for Environment and Energy. Technical Report. Commissioned by The Danish Energy Agency.

WSP 2024a. Flagermus ved Kriegers Flak Havmøllepark 2022 og 2023. https://ens.dk/sites/ens.dk/files/Vindmoller_hav/flagermus_ved_kriegers_flak_havmoellepark_2022_2023_maj2024.pdf

WSP 2024b. Kriegers Flak II. Technical report - Bats. Energinet. https://ens.dk/sites/ens.dk/files/Vindmoller_hav/techincalreport-batskriegersflakii.pdf

6 Appendix 1

Data sheet – offshore bat monitoring

*SITE/WIND FARM:*______________________________

To be filled by technician on site
(where possible, document with photos to provide overview of location and orientation)

Order	**Deployment**		**Recovery**		**Station Type** *buoy/WT TP/ WT nacelle/other*	**Horizontal microphone orientation** *microphone faces N/NW/other*	**Vertical microphone orientation** *X degrees down/up from horizontal*
	Date *first dd:mm:yy on station*	**Local time** *hh:mm*	**Date** *last dd:mm:yy on station*	**Local time** *hh:mm*			
1							
2							
3							
4							
5							
6							
7							
8							
9							
10							

Comments (*height above sea, distance from nacelle, equipment damage, other…)*

To be filled by office

Order	**Station ID** *WT/buoy #*	**Coordinates**		**Recorder ID** *serial #/ consultant identifier*
		Lat (N)	*Long (E)*	
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				

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Figure 6.1. Preliminary metadata template.