



OPEN Seasonal and diel acoustic activity of sei whales (*Balaenoptera borealis*) in the New York Bight

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High levels of anthropogenic activity in the northwest Atlantic may have impacts on marine species. As such, it is important to document species distribution in order to monitor behavioral responses to changes in these activities or the environment. Sei whales (*Balaenoptera borealis*) are an endangered species consistently documented in the New York Bight (NYB), though they are understudied in this region. Here, we used passive acoustic monitoring from 2017 to 2020 to investigate sei whale acoustic presence and vocal activity in the NYB, as well as the relationship between seasonal acoustic presence and environmental variables [sea surface temperature (SST) and chlorophyll-a concentration (Chl-a)]. Sei whales were primarily present in spring, exhibiting low levels of activity in other seasons, potentially reflecting migratory patterns. Vocal activity was higher during daylight, supporting growing evidence that vocalizations are reduced at night when sei whales are thought to forage. Presence and vocal activity were highly correlated with SST, particularly in spring; both tended to decrease once temperatures reached around 9°C. However, acoustic activity was not significantly related to Chl-a. These findings suggest that the NYB may be an important spring habitat and potential feeding ground for sei whales in the northwest Atlantic.

Keywords Baleen whales, Northwest Atlantic, Baselines, Environmental covariates, Passive acoustic monitoring

The northwest Atlantic experiences high levels of anthropogenic activity, including shipping, commercial fishing, recreational activities, and the development of offshore wind (OSW) energy to meet growing energy needs^{1–3}. These activities may have potential impacts on numerous marine mammal species that utilize these waters. For example, baleen whales (Mysticetes), including humpback whales (*Megaptera novaeangliae*), fin whales (*Balaenoptera physalus*), North Atlantic right whales (NARW; *Eubalaena glacialis*) and sei whales (*Balaenoptera borealis*), are at risk of vessel strikes, entanglement in fishing gear, and behavioral or physiological changes from exposure to high anthropogenic noise levels^{4–8}. Therefore, it is vital to establish baseline information in species presence and habitat use, and to monitor species distribution and behavior over time, to better interpret environmental and/or anthropogenic factors influencing variability. Baseline information can inform the development of effective mitigation or conservation practices to limit impacts on vulnerable species.

In the northwestern Atlantic, baleen whales generally migrate along the Atlantic coast of the United States and Canada⁹. Visual and acoustic surveys are valuable methods for monitoring the presence and behavior of these whales throughout their migratory routes, including in areas with intense anthropogenic activity^{10–12}. Visual surveys of baleen whales can be used to document behavior at or near the surface of the water (e.g., lunge feeding in humpback whales¹³) and provide information on an animal's identity (via photo-identification^{14–16}) and health (via body condition^{17,18}). However, whales can only be detected visually over short distances and while at the surface. Furthermore, visual surveys are dependent on weather conditions and can be challenging or impossible during certain times of day or year (e.g., nighttime and winter¹⁹). Passive acoustic monitoring (PAM) allows for the continuous recording of the underwater soundscape, providing an alternative, indirect method for documenting species presence and behavior during times and over timescales that are challenging or impossible with visual surveys. Baleen whales produce acoustic signals or vocalizations as a method of communication that facilitate social interactions, such as reproductive displays and maintaining contact among individuals and groups^{20,21}. While detection by PAM requires animals to be acoustically active (non-vocalizing animals will be

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missed), PAM nevertheless provides valuable information about species acoustic presence throughout all times of day and seasons. Moreover, PAM can be a useful tool for monitoring anthropogenic activity and concurrent changes in acoustic behavior of vocal animal species^{22,23}.

Sei whales are an endangered species that demonstrate seasonal variation in presence^{24,25}. Sei whales migrate annually from tropical and subtropical breeding grounds during winter to subpolar feeding grounds during summer²⁶. Temporal variation in sei whale presence and distribution may be related to oceanographic conditions such as sea surface temperature (SST) and chlorophyll-*a* concentration (Chl-*a*)^{27–33}. SST and Chl-*a* have commonly been used as proxies for prey productivity as they have been found to affect the abundance of baleen whale prey species, thus influencing baleen whale foraging locations^{28,32,34}. Correlations between oceanographic conditions and sei whale presence and distribution have been found in both acoustic and visual studies^{27–33}. However, the relationships are not always consistent; the correlation between SST and sei whale presence varies spatially and seasonally^{30,31}. Sei whales are detected at a wide range of SSTs (2.5–25°C^{28,32,35}), with peaks in presence reported during SSTs ranging from 5–17°C (*sensu*^{28,30–35}). The relationship between Chl-*a* and sei whale presence also varies; some studies found a temporal lag between increased Chl-*a* and increased sei whale presence^{27,32,36}, while others found no significant correlations³⁰.

In addition to seasonal variations in presence, diel patterns in sei whale vocal activity have varied across studies. Sei whales produce downsweeping vocalizations (henceforth, “downsweeps”) in various low-frequency bandwidths^{25,37–41}. The most common and well-known sei whale vocalization is the 82–34 Hz downsweep³⁹. These downsweeps have been detected during all times of year in the Atlantic^{9,12,24,25} and are an effective indication of sei whale presence³⁹. Sei whales in the Falkland Islands produced these downsweeps at similar rates throughout a 24-hour period²⁵. In Massachusetts and in the Azores Archipelago, however, sei whales produced downsweeps more frequently during daylight hours^{24,42}, potentially reflecting prey behavior, which in turn may influence sei whale foraging and vocal behavior^{42,43}.

Diel patterns of sei whale vocal activity can also vary seasonally; in the Azores Archipelago, sei whales exhibited a bias towards daytime vocalizations during spring at one study site and during autumn at another²⁴. These daytime vocalizations were hypothesized to serve as contact calls^{24,39} rather than being used to communicate prey patches²⁴. Though satellite telemetry, isotope analysis, and behavioral observations all suggest that sei whales migrate through the region during spring and autumn, they also indicate that sei whales do not forage in these waters^{24,44,45}.

The New York Bight (NYB), which encompasses the busiest port in the United States⁴⁶, is also a documented habitat for sei whales. Sei whales are one of seven cetacean species designated as a ‘Species of Greatest Conservation Need’ by the New York State Department of Environmental Conservation^{1,47} and have been sighted and acoustically detected at varying levels near the continental shelf break (between 50 and 120 km from shore)^{9,12,19}. However, data on sei whale distribution nearshore (< ~ 50 km from shore) is limited. Aerial surveys conducted in 2017–2020 (36 days of survey effort, one per month) and 2024 (three days of survey effort, one per month of May, June, and July) included a total of four days with visual sightings of sei whales in the continental shelf/slope area of the NYB in April, May, June, and July^{19,48}. Similarly, the peak in sei whale acoustic presence closer to shore occurred from March to mid-June, though they have been acoustically detected in the outer reaches of the NYB in all months^{9,12}. Given that sei whales in the NYB have never been sighted during vessel-based surveys and are rarely observed in aerial-based surveys, PAM provides a critically important alternative method for detecting and monitoring sei whales in this region.

While previous visual and acoustic surveys have established a spring peak in sei whale presence in the NYB^{9,12,19,48}, little is known about how sei whale presence relates to changes in the environment. This study corroborates previously established trends in acoustic activity and builds upon previous research by investigating sei whale acoustic activity in relation to environmental variables (i.e. SST and Chl-*a*) to better understand sei whale habitat use. This is important given the ongoing and forthcoming anthropogenic activities in the NYB including vessel traffic, commercial fishing, and OSW activities^{6,10}. Given the potential impacts of these anthropogenic activities, it is imperative to establish baselines and potential drivers of sei whale presence in the NYB to inform mitigation and management efforts.

Here we propose to investigate: (1) the seasonal and diel patterns of sei whale acoustic presence and vocal activity in the nearshore region of the NYB and (2) whether SST and Chl-*a* are correlated with sei whale seasonal acoustic presence in the study area. These results will contribute to the currently limited understanding of sei whale acoustic activity in the NYB and form a baseline for sei whale presence as anthropogenic activity continues to increase in the region.

Results

Seasonal presence and vocal activity

Downsweeps were recorded in all months except January and December, and both acoustic presence (number of days per week with downsweeps detected; Fig. 1) and vocal activity (number of downsweeps per week) peaked in spring each year (Fig. 2), with 95% of downsweeps detected between March and May. Both acoustic presence and vocal activity significantly varied with SST ($p < 0.001$; see Supplementary Materials I for more details). Vocal activity was highest during weeks 12–14 (late March to mid-April) before decreasing to very low levels in subsequent weeks in 2017, 2019, and 2020 (Fig. 2). In 2018, however, vocal activity was relatively consistent with other years through weeks 12–14 but peaked in weeks 15–18 (mid-April to mid-May), and acoustic presence was significantly higher in 2018 than in other years ($p = 0.005$). Acoustic presence throughout all years decreased substantially in spring once SST reached around 9°C, which occurred four weeks later in 2018 than in other years (Fig. 1). The temperatures at which spring acoustic presence began varied between years, but presence was rarely detected when SST < 5°C. However, acoustic activity was detected at low levels at both extremes of the SST

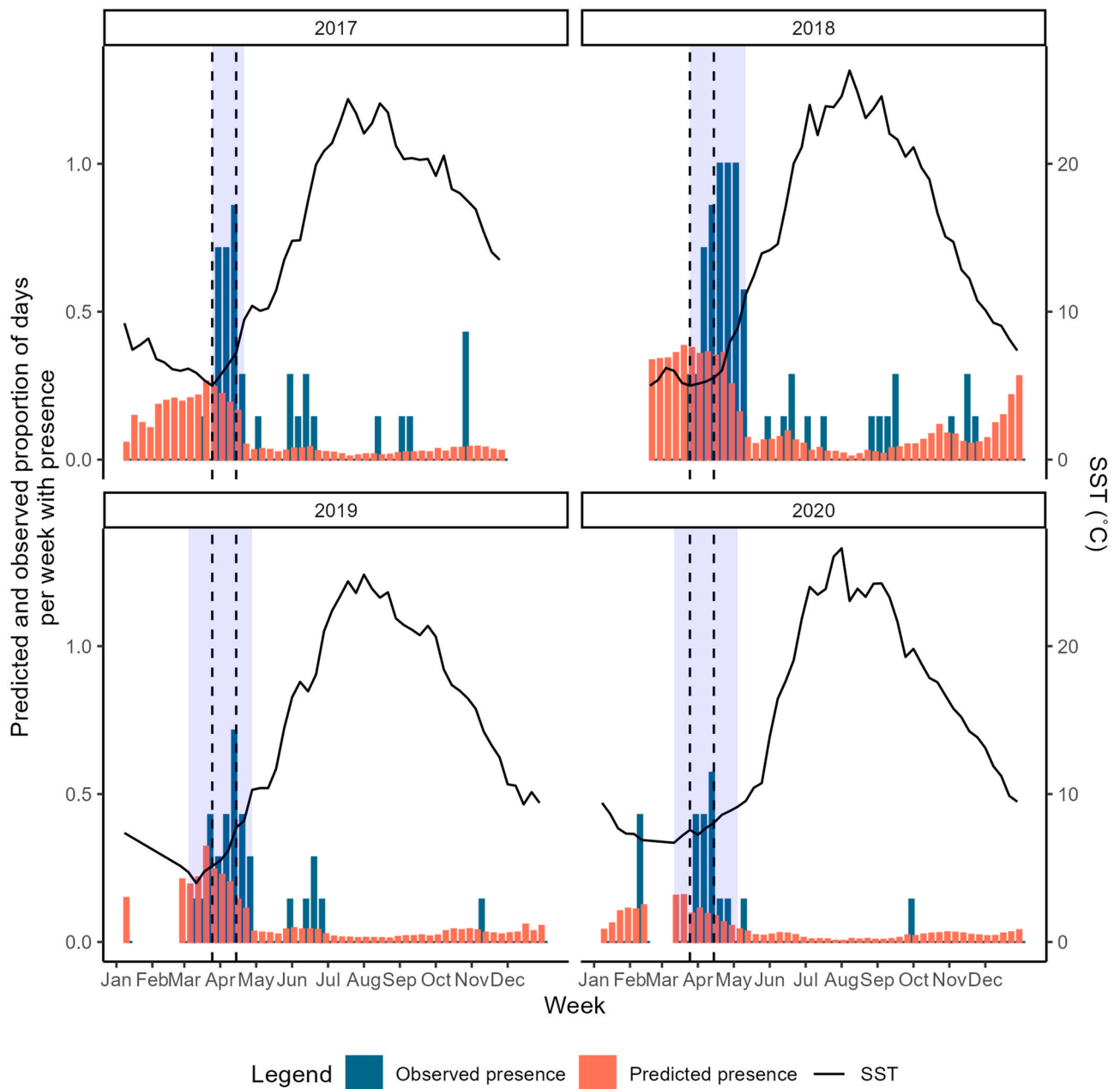


Fig. 1. The predicted (orange) and observed (blue) proportion of days per week with presence, separated by year. Sea surface temperature (SST) is represented by the black trendline, weeks 12–14 (late March to mid-April) are shown between the vertical dashed black lines, and weeks with a mean SST between 5 and 9°C are highlighted within the shaded blue rectangle. The y-axis on the left of the figure describes the proportion of days per week with presence (both predicted and observed), while the y-axis on the right of the figure describes the SST (°C).

range during the survey period (4.0–26.6°C). Presence was only detected when SST < 5°C in late February and early March, while presence was typically detected between August and November when SST > 15°C.

Neither acoustic presence nor vocal activity were found to be significantly correlated with Chl-a ($p = 0.362$ and $p = 0.071$, respectively; Figs. 3 and 4; see Supplementary Materials I for more details). Interestingly, though, acoustic presence in spring and winter months was predicted to be highest when Chl-a was lowest (surface Chl-a < 0.05 mg m⁻³), which coincided with weeks 12–20. Based on the observed data, the peaks in spring vocal activity, which coincided with low Chl-a levels, occurred around two or three weeks after a peak in Chl-a in early to mid-March each year. In 2018 this peak in Chl-a reached only 2.5 mg m⁻³, but in other years the peak in Chl-a was > 5 mg m⁻³. Acoustic presence was predicted to be highest in summer and autumn when Chl-a levels were around 2 mg m⁻³, though Chl-a ranged from 0.42 to 6.16 mg m⁻³ in summer and 0.49–5.86 mg m⁻³ in autumn.

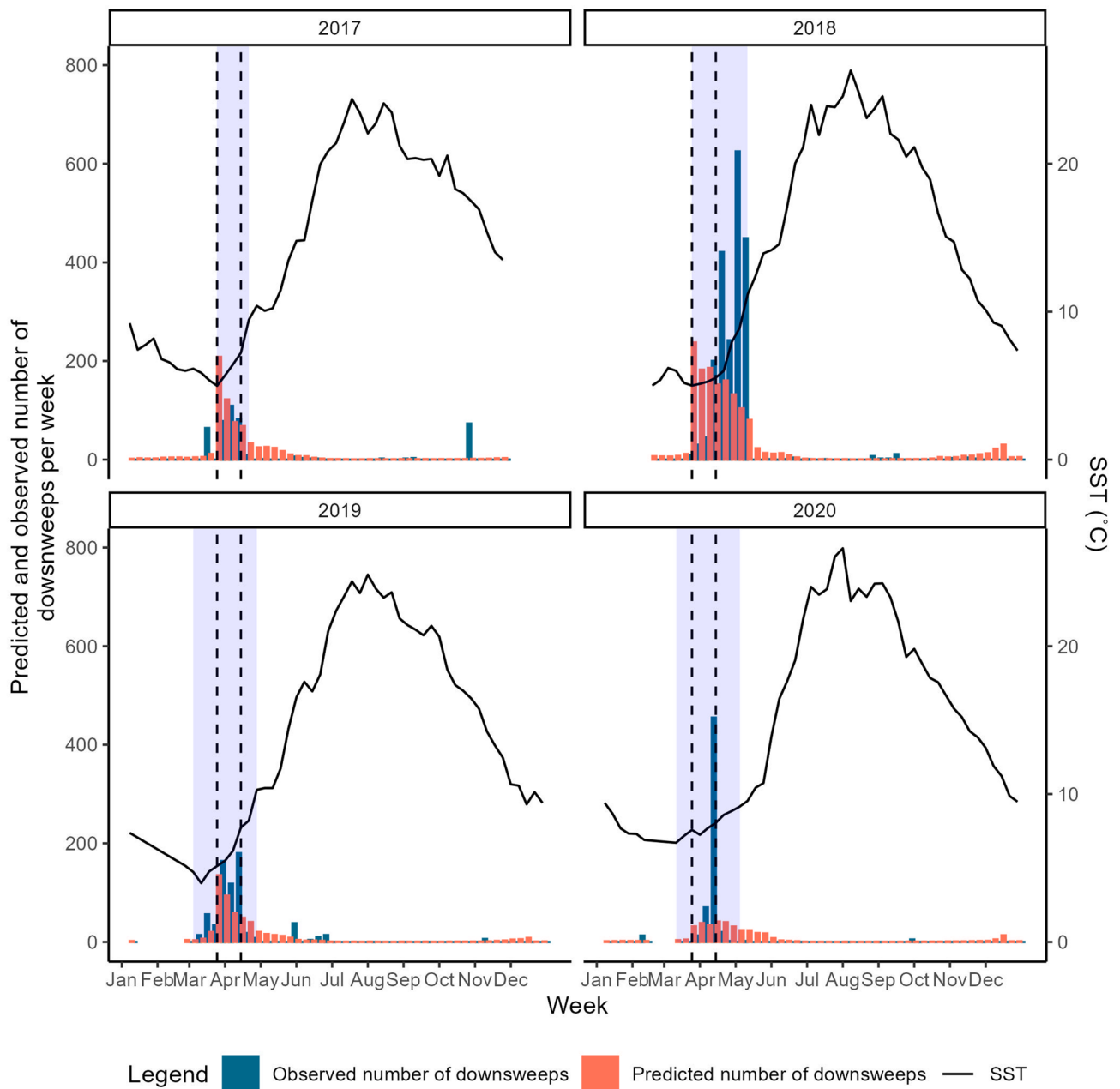


Fig. 2. The predicted (orange) and observed (blue) number of downsweeps per week, separated by year. Sea surface temperature (SST) is represented by the black trendline, weeks 12–14 (late March to mid-April) are shown between the vertical dashed black lines, and weeks with a mean SST between 5 and 9 °C are highlighted within the shaded blue rectangle. The y-axis on the left of the figure describes the proportion of days per week with presence (both predicted and observed), while the y-axis on the right of the figure describes the SST (°C).

Diel presence and vocal activity

Downsweeps were recorded in all 24 hours of the day, and both acoustic presence and vocal activity were found to be significantly different at different times of day ($p < 0.0001$ and $p = 0.006$, respectively; Figs. 5 and 6; see Supplementary Materials I for more details). Acoustic presence was higher during the day than at night and twilight, while daytime vocal activity was only significantly higher than twilight vocal activity ($p < 0.006$). Interestingly, daytime downsweeps were predicted to be more frequent in all seasons, even though the observed data showed that downsweeps were more frequent at night during autumn (Fig. 6).

Discussion

Consistent seasonal patterns were detected in sei whale acoustic presence and vocal activity across years in the NYB. Sei whale downsweeps were detected in all seasons over the study period, with the primary peak in activity from late winter into spring and a smaller peak from late August to mid-November. However, the vast majority

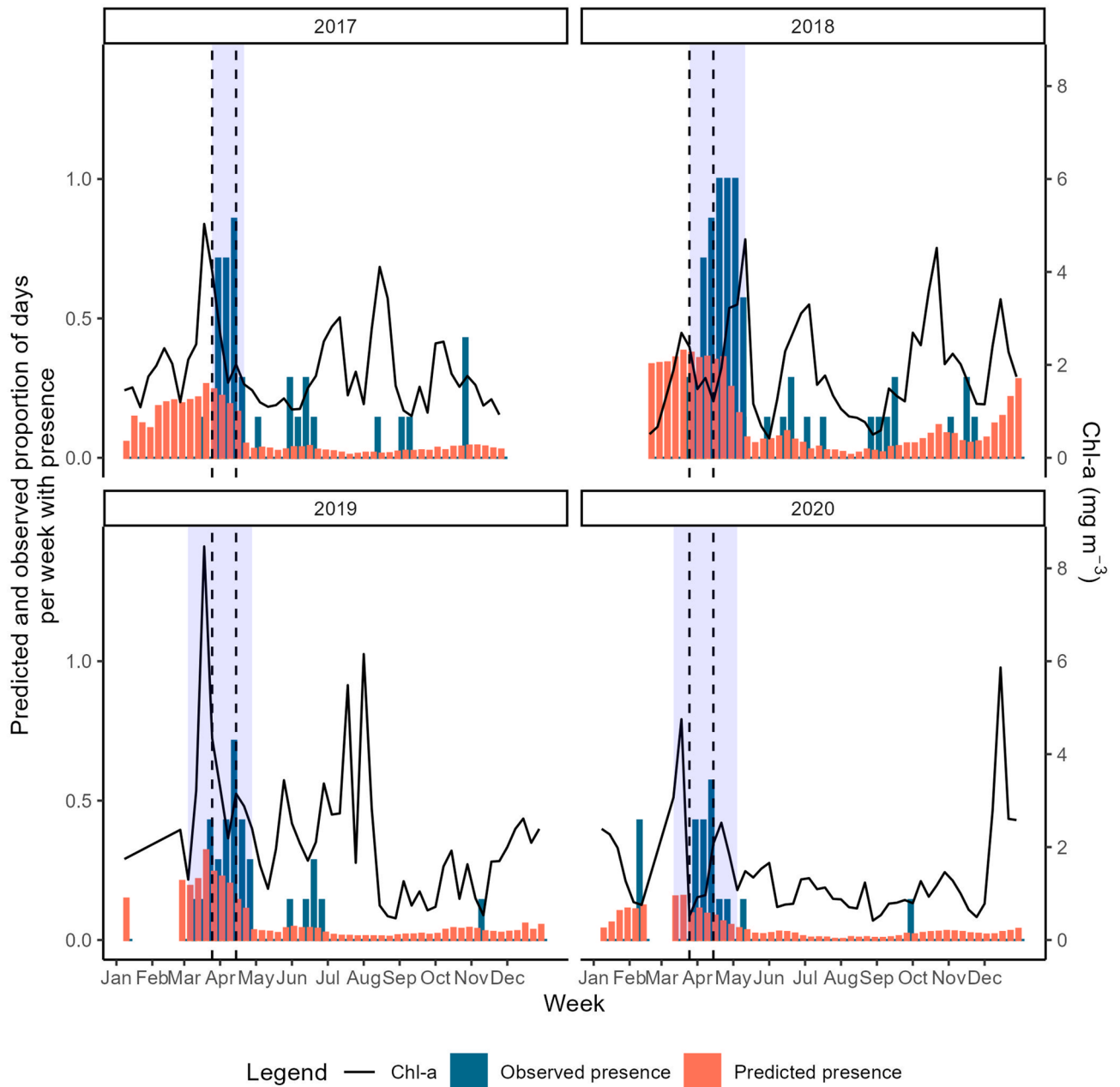


Fig. 3. The predicted (orange) and observed (blue) proportion of days per week with presence, separated by year. Chlorophyll-a concentration (Chl-a) is represented by the black trendline, weeks 12–14 (late March to mid-April) are shown between the vertical dashed black lines, and weeks with a mean sea surface temperature (SST) between 5 and 9°C are highlighted within the shaded blue rectangle. The y-axis on the left of the figure describes the proportion of days per week with presence (both predicted and observed), while the y-axis on the right of the figure describes the Chl-a (mg m^{-3}).

(95%) of downsweeps were detected between March and May. These results build upon previous PAM efforts within the NYB^{9,12}, with a consistent peak in acoustic presence in spring. This trend was corroborated by aerial surveys conducted from 2017 to 2020¹⁹ and 2024⁴⁸.

These spring peaks in sei whale activity may be due to some portion of the Northwest Atlantic sei whale population using the NYB along their migratory path. Sei whale migration routes in the Atlantic Ocean are not fully understood, but sei whale acoustic presence in the western Atlantic has distinct seasonality; detections peak in summer at higher latitudes (e.g., between the NYB and Greenland) and in winter at lower latitudes (e.g., Cape Hatteras⁹). Sei whale acoustic presence in the present study increased considerably in week 12 (mid-March) each year, regardless of SST and Chl-a concentration, and dropped to very low levels by week 14 (early April) in all years except 2018. Acoustic presence did not fluctuate with these environmental proxies for foraging opportunities (except in 2018) and was concentrated in early spring. Given that early spring is when sei whales

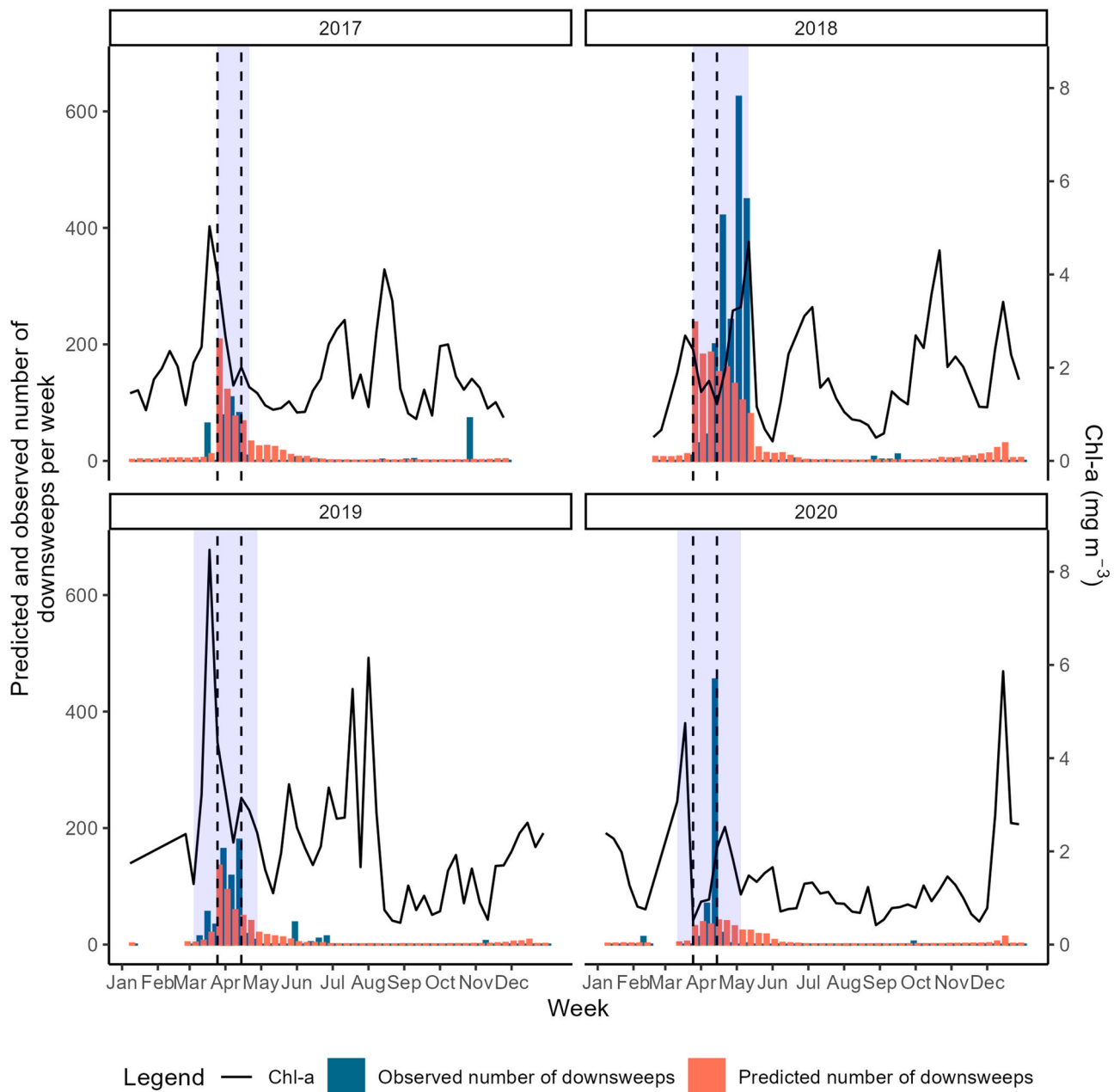


Fig. 4. The predicted (orange) and observed (blue) number of downsweeps per week, separated by year. Chlorophyll-a concentration (Chl-a) is represented by the black trendline, weeks 12–14 (late March to mid-April) are shown between the vertical dashed black lines, and weeks with a mean SST between 5 and 9 °C are highlighted within the shaded blue rectangle. The y-axis on the left of the figure describes the proportion of days per week with presence (both predicted and observed), while the y-axis on the right of the figure describes the Chl-a (mg m⁻³).

are known to migrate north, this short and regular period of acoustic presence in the NYB may be primarily due to migration.

Though migration is hypothesized to be the primary driver for the spring peak in sei whales in the NYB, these animals may forage opportunistically in this region if there is sufficient prey, as may have been the case in 2018. Thus far, no sei whale foraging behavior has been reported in the NYB, though this may be due to the rarity of visual sightings. For example, during aerial surveys from 2017 to 2020, sei whales were only sighted twice in the NYB [one solitary whale and one group of six whales¹⁹]. However, an aggregation of sei whales was observed near Hudson Canyon during aerial surveys on May 29, 2024 ($n = 31$ whales) and June 1, 2024 ($n = 20$ whales) alongside a large number of NARW [$n = 35$ and 33, respectively, representing ~ 9–10% of the world's NARW population⁴⁸]. Given that both species aggregated in similar areas and have similar diets⁴⁹, these aggregations may reflect increased prey abundance and thus additional foraging opportunities. Moreover, a necropsy of a

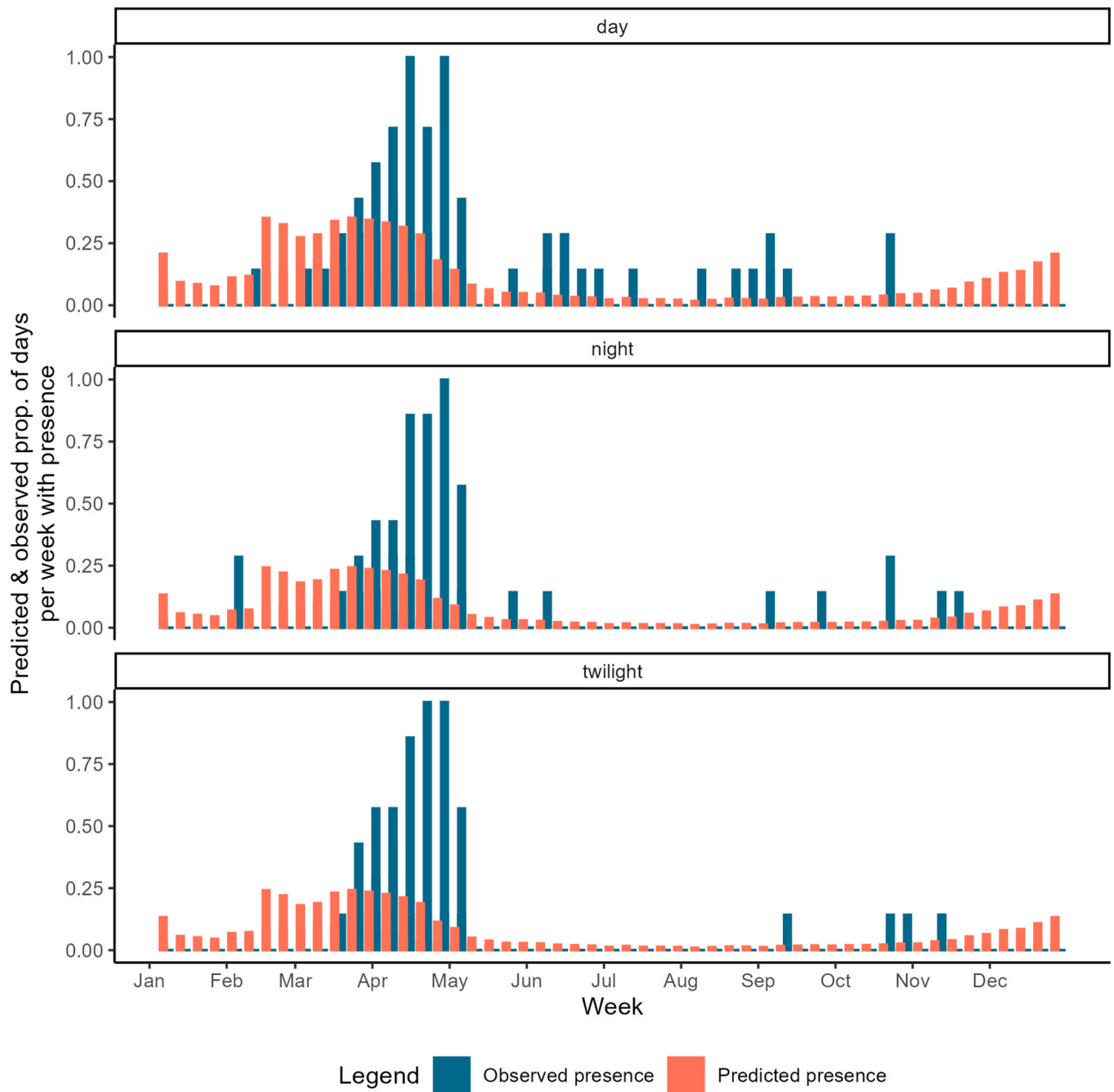


Fig. 5. The weekly predicted (orange) and observed (blue) days of presence, separated by time of day (day, night, and twilight).

sei whale found deceased on the bow of a ship in the Port of Brooklyn in May 2024 revealed that the whale's stomach was "full of food"⁵⁰[personal communication with Kim Durham], indicating recent foraging activity. If sei whale digestion rates are similar to rates of digestion for other baleen whales, this whale is estimated to have been feeding within the 10 hours prior to its death^{51,52}, potentially within the NYB.

Though sei whales are generally an oceanic species^{26,53}, past studies have indicated that increased prey availability draws sei whales to the continental shelf^{49,54,55}. In the NYB, sei whales are rarely detected nearshore (< ~ 50 km from shore) in seasons other than spring, when nearshore and offshore (200–250 km from shore) detection rates are relatively similar^{12,19} [present study]. As such, the spring peak in acoustic activity documented in the mid-shelf region [50–200 km from shore; present study] may relate to movement between nearshore and offshore habitats, as whales may move to follow the distribution of their prey. Movements between regions may increase overlap between sei whales and vessel traffic (see Supplementary Materials II for more details). Nearshore regions of the NYB are heavily dominated by anthropogenic activity, including recreational and commercial vessel traffic. In other baleen whale species, overlap with areas of high vessel traffic density has been shown to increase population mortality rates⁵⁶; therefore, it is possible that sei whales in the NYB are at higher risk for vessel strike during periods when they are closer to shore.

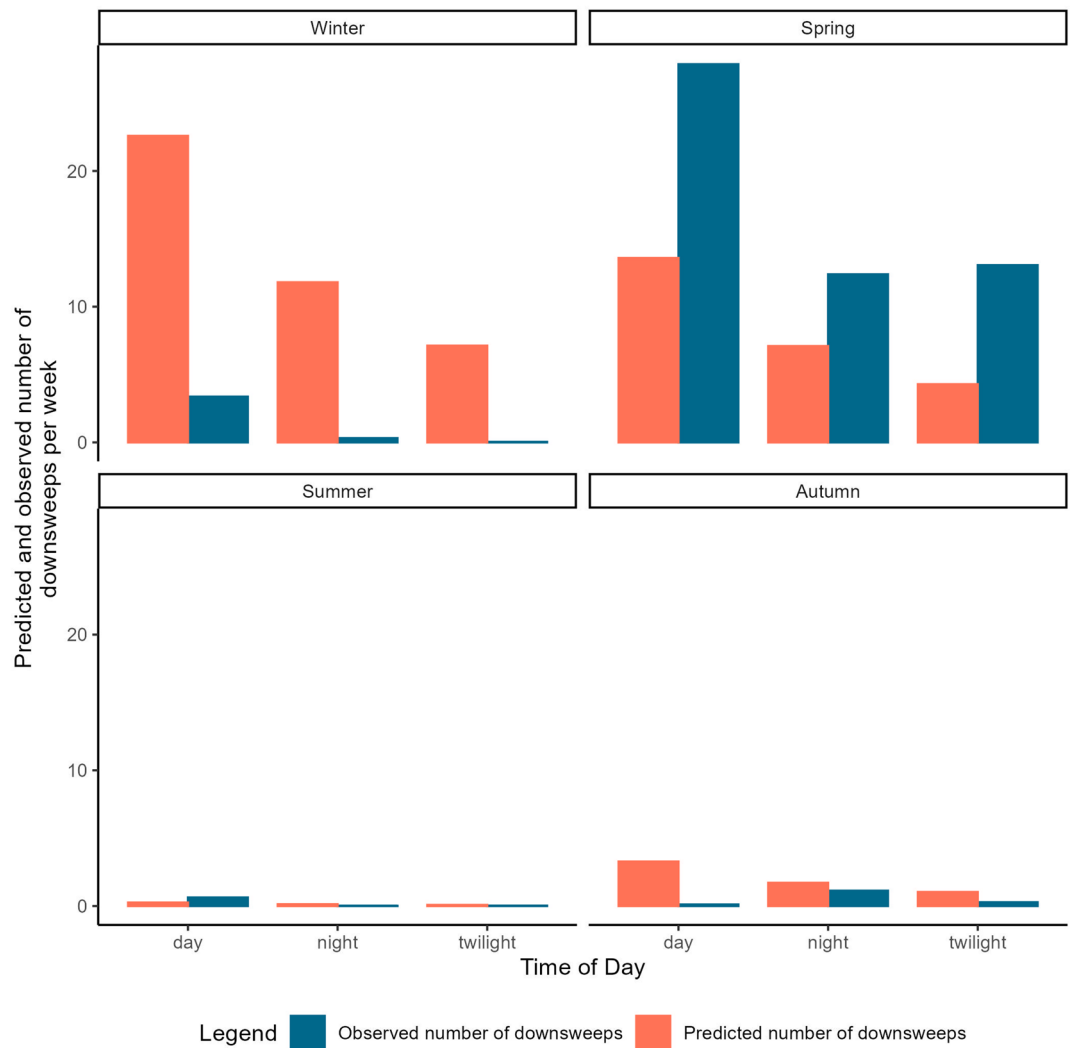


Fig. 6. The mean predicted (orange) and observed (blue) number of downsweeps per week during each time of day (day, night, and twilight), separated by season.

Overlap between sei whales and anthropogenic activity may also vary annually due to differences in environmental factors (i.e., SST and prey availability). While population abundance cannot be determined from the number of downsweeps recorded, the increased vocal activity documented in 2018 (~ 5x more downsweeps compared to other years) may reflect a higher abundance of whales. Furthermore, vocal activity in 2018 was primarily concentrated in April and early May, which differed from the peak vocal activity in late March and April documented in all other years (i.e., 2017, 2019–2020). This 2018 anomaly in vocal activity could be due to a weak La Niña event that took place from late 2017 into early spring 2018⁵⁷. Though La Niña is mainly thought to affect the Pacific Ocean, it also influences weather patterns in the Atlantic Ocean⁵⁸, and may have affected the timing and magnitude of the spring bloom in 2018. For example, spring 2018 had a mean SST of 10.32 °C (0.7–1 °C lower than other years), and temperatures did not rise above 9 °C until mid-May (around 3 weeks later than in other years). SST can serve as a proxy for baleen whale prey distribution due to its effects on the spring bloom, which temporarily increases prey availability in a region²⁷, and sei whales may follow the distribution of their prey as temperature increases through spring.

In the North Atlantic, sei whale's preferred prey is *Calanus finmarchicus*^{53,59}, a large species of copepod. Notably, copepods were the primary prey group found in the stomach of the deceased sei whale discovered in the Port of Brooklyn in May 2024 [Kim Durham, Pers. Comm.], though they were not identified to the species level. *C. finmarchicus* are found primarily in offshore environments (> 50 m depth), but during spring, they are also found in mid-shelf and some nearshore areas of the NYB, particularly near the buoy used in the present study⁶⁰. A second, smaller species of copepod, *Centropages typicus*, were also found in high abundance in the NYB⁶⁰ and could serve as sei whale prey; however, the seasonal and temperature preferences of *C. finmarchicus* more closely mirror sei whale presence in the NYB than those of *C. typicus* [highest abundance in February and in waters > 15 °C⁶¹. *C. finmarchicus* exhibit maximum abundance in the NYB in March through May⁶⁰, and in regions around the world with SSTs from 5–10 °C^{34,62,63}. SSTs in the study area generally reached 10 °C by late April, thus sei whales may move on to different areas at that time following the distribution of *C. finmarchicus*.

However, because SSTs remained low ($< 10^{\circ}\text{C}$) from late April through mid-May in 2018, there may have been a shift in *C. finmarchicus* occurrence this year, resulting in increased sei whale acoustic presence and vocal activity during this time. A similarly dramatic increase in sei whale presence was recorded in 1986 on Stellwagen Bank in the Gulf of Maine, when the abundance of *C. finmarchicus* was a magnitude higher than in other years⁴⁹, and such events have been reported in various places worldwide⁵³.

In addition to SST, Chl-a is another common proxy for baleen whale prey distribution and is often evaluated as a predictor for baleen whale presence^{27–33}. Most studies have documented a temporal lag between peaks in Chl-a and increased sei whale presence, likely because sei whales are secondary consumers^{27,32,36}. While a temporal lag between Chl-a concentration and sei whale acoustic presence in spring was documented, the lag in this study had a much shorter time span (i.e., 2–4 weeks) compared to others (e.g., 16-week²⁷, two-month³², and three-month³⁶ lags). This suggests Chl-a is a poor indicator for sei whale presence in this region.

Sei whale acoustic presence was significantly higher during the day than at night or twilight, particularly during spring (when most downsweeps were detected). This is consistent with the diel pattern of sei whale downsweep production recorded in the Great South Channel of Massachusetts, in spring at the Condor site of the Azores Archipelago, and in autumn at the Gigante site of the Azores Archipelago^{24,42}, though it contrasted with patterns observed in the Falkland Islands²⁵ and in Massachusetts Bay⁶⁴. Elevated production of sei whale downsweeps during the day may relate to foraging behavior. For example, sei whales may produce fewer downsweeps at night while they are feeding on prey that exhibit diel vertical migration (DVM) as these prey are distributed in shallower depths of the water column (and thus more available) at night^{42,43}. The increase in sei whale downsweep production during the day may be related to social behaviors, such as communicating the location of sparse daytime prey patches⁴² or producing contact calls during migration²⁴.

Interestingly, while vocal activity was highest during the day in spring, vocal activity was highest at night in autumn. Diel patterns of vocal activity can change between seasons, as was observed in the Azores archipelago²⁴, and a preference for the nighttime production of downsweeps was observed in Massachusetts Bay⁶⁴. Differences in diel vocal activity patterns may indicate that sei whales are feeding on different prey species between seasons. While daytime rates of downsweep production may be higher in spring if sei whales are feeding on copepods (e.g. *C. finmarchicus*) or euphausiids that perform DVM^{43,65}, a preference for nighttime downsweep production in autumn could reflect sei whales foraging on a prey type that does not perform DVM, such as fish⁶⁶. However, it is also possible that most of the sei whale population does not forage in the NYB in autumn, and instead simply pass through the area as they migrate south. Sei whale downsweeps are less frequent in the NYB in autumn, potentially reflecting a shorter period of presence than in spring, or that sei whales are primarily closer to the continental shelf break during autumn and winter, as was documented in Davis et al.⁹. Together, diel and seasonal patterns of vocal activity in autumn and the habits of various prey species suggest that sei whales likely are not foraging in the surveyed section of the NYB in autumn, and if they are, it is likely not on copepods or euphausiids.

These patterns in sei whale vocalizations may also be influenced by the type of vocalization assessed. Here, we focused solely on one type of sei whale vocalization, the 82–34 Hz downsweep, as this is the only sei whale vocalization that has been documented in the NYB thus far^{9,12}. Studies in other regions have recorded several other sei whale vocalization types^{25,37,38,40,41,64}, and it is possible that excluding these other vocalization types may decrease detection rates. Diel patterns in downsweep production vary by location, but diel trends in downsweeps differ from diel trends of other vocalization types within the same region^{25,64}, suggesting they may serve different functions. Downsweeps were also produced at consistently lower rates than other vocalization types when more than one vocalization type was investigated^{25,64}, raising questions about the efficacy of using solely downsweeps to determine sei whale presence/vocal activity. Further study is necessary to determine whether other sei whale vocalization types are being used in the NYB and whether patterns of sei whale acoustic activity vary between vocalization types.

Conclusion

This study provides novel insight into sei whale acoustic presence and vocal activity in the NYB. The seasonal presence of sei whales in early spring, as well as their tendency to vocalize more frequently during the day, are important contributions to our understanding of sei whale behavior in the northwestern Atlantic. Further research on sei whales in the NYB may build upon these results by conducting targeted efforts (e.g., PAM, vessel surveys, and aerial surveys) during periods with peaks in acoustic presence. Given the already high levels of anthropogenic activity in the NYB, it is important to establish baselines on the presence and habitat use of these endangered whales to inform mitigation and monitoring efforts related to forthcoming developments.

While this is the only known study investigating the diel patterns of sei whale vocal activity in the NYB, Murray et al.⁶⁷ posited that their findings on NARW seasonal trends in presence and diel trends in vocal activity in the NYB could have implications for mitigating the incidence of vessel strikes with NARW⁶⁷. For example, Murray et al.⁶⁷ found that NARW were acoustically detected but not visually detected in concurrent aerial surveys, suggesting that acoustic detections could serve as supplementary triggers for dynamic management areas designed to protect NARW. Sei whales may benefit from similar mitigation protocols, as they are likely to be at increased risk for vessel strikes during spring months. Median vessel speeds in the study area during peak periods of sei whale presence were generally higher than the recommended 10 kts for reducing the risk of vessel strike that are seasonally in place for the NY Seasonal Management Area for NARWs [including cargo ships, passenger vessels, and recreational vessels; Kügler et al. in prep; see Supplementary Materials II for details]. Although there is little, if any, information available on how sei whales may react to close vessel encounters, these higher vessel speeds highlight an urgent need for further research on this topic since higher vessel speed has been linked to elevated risk of vessel strike in other species (e.g., NARW^{56,68}). If the lower levels of acoustic activity during nighttime are due to the DVM of prey species moving closer to the surface, sei whales may be

spending more time at shallower depths while foraging. Considering that at night sei whales exhibit relatively low vocal activity, an increased amount of time at the surface and reduced detectability due to limited sighting availability may lead to sei whales being more vulnerable to vessel strikes during nighttime hours.

Right Whale Slow Zones (established by NOAA) are currently triggered when NARW are detected by the near-real time baleen whale Low Frequency Detection and Classification System (LFDCS) detectors on the two buoys deployed by the Woods Hole Oceanographic Institution (WHOI)^{69,70} as well as long-endurance Slocum gliders⁷¹ in the NYB. One of the WHOI buoys was also used to collect the archival data used in this study. Given that sei whales are routinely acoustically detected in near-real time by these autonomous platforms, it is possible that periods of high sei whale vocal activity (i.e. spring) could serve as an early warning for sei whale presence and offer this species further protection during vulnerable nighttime hours. This information could be relayed to management authorities and marine resource users to help mitigate anthropogenic impacts on sei whales in the NYB.

Materials and methods

Data collection

A PAM buoy was deployed in the Empire Wind Lease Area approximately 40 km from the entrance to the New York/New Jersey Harbor and between two major shipping lanes (Fig. 7). In addition to detecting and transmitting information about whale vocalizations to shore in near-real time, the buoy recorded audio from June 2016 to December 2020 with the exception of December 3, 2017 – February 12, 2018 and January 1, 2019 – February 19, 2019, when the buoy was not operational. The acoustic monitoring system consisted of a surface buoy connected with stretch hoses to an aluminum frame on the sea floor (see^{67,70} for further system details). Audio was recorded by a digital acoustic monitoring (DMON^{72,73}) instrument mounted on the aluminum frame at a 2000 Hz sampling rate and 16-bit depth with a duty cycle of 30 min every 60 min for 2017 to 2019⁶⁷. In 2020, audio was recorded continuously, but only the first 30 min of each hour were reviewed to maintain consistency across years⁶⁷.

Acoustic analysis

Data collected from January 1, 2017 to December 31, 2020 were first analyzed using the LFDCS⁶⁹. The LFDCS automatically detected and categorized sounds that fit the parameters for sei whale downsweeps. These LFDCS detections were then reviewed in Raven Pro⁷⁴ using spectrograms (Hanning window, 1024 FFT, 90% overlap) set to a frequency range of 10–100 Hz with a frequency resolution of 1.95 Hz and time resolution of 0.0510 s. The sounds were then labeled by analysts as either a true positive (TP) or a false positive (FP), and any sei whale downsweeps temporally close to LFDCS detections, but that were missed by the detector, were added manually. Vocalizations marked as TP for sei whales were then manually verified twice to confirm the species classification. Because the characteristics of sei whale downsweeps are similar to the characteristics of some

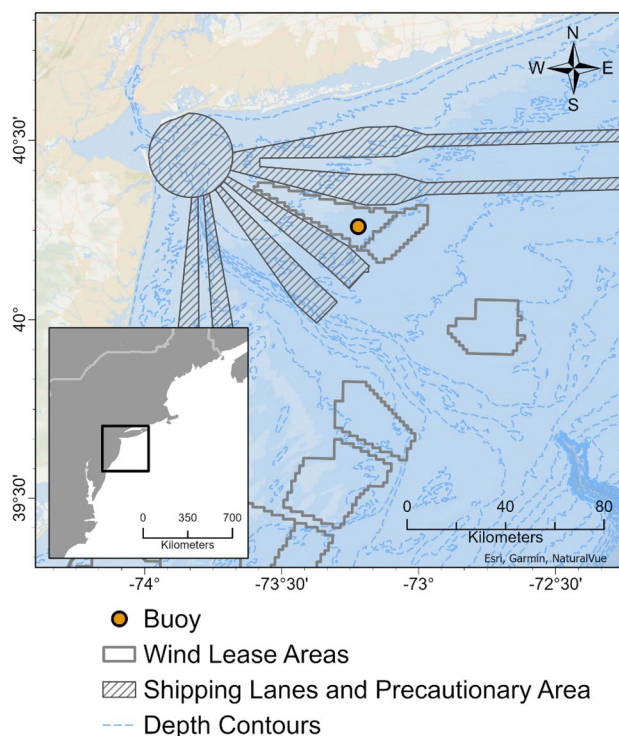


Fig. 7. A map of the study area, the New York Bight (NYB), shipping lanes, wind lease areas, and the location of the buoy.

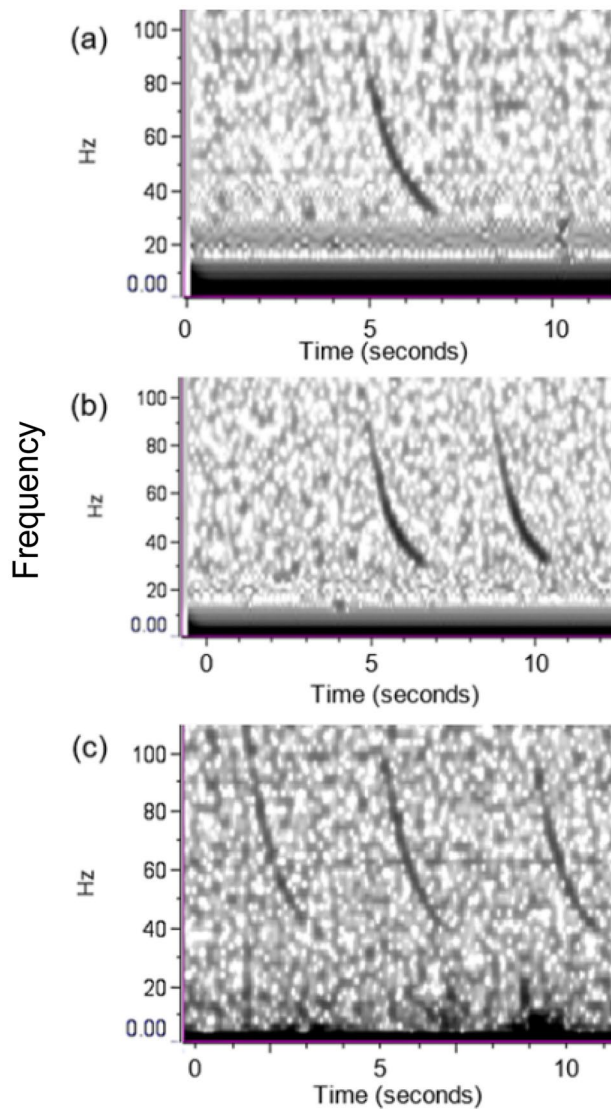


Fig. 8. Examples of (a) singlet, (b) doublet, and (c) triplet sei whale downsweeps.

humpback whale song units documented in the NYB, sei whale downsweeps were verified by looking at both the low- and high-frequency contexts of the sound using two time-linked spectrogram windows: the first following the spectrogram parameters outlined above and the second following the same parameters, but with a frequency range of 10–1000 Hz and an FFT of 256 to incorporate frequency bandwidths relevant for humpback whale vocalizations.

Manual classification of sei whale downsweeps was conducted using guidelines outlined in Baumgartner et al.⁴³ and as follows. The sei whale vocalizations included in this study were stereotyped, low-frequency downsweeps that can be present in singlets, doublets, or triplets^{39,45}. They can sweep from 100 to 30 Hz, but on average will sweep from 82 to 34 Hz for a duration of 1.4 s (Fig. 8). Doublets and triplets have an average inter-note interval (INI) of 3.5 s³⁹. As the 82–34 Hz downsweeps are the only sei whale vocalizations documented in the NYB thus far, they are the only sei whale vocalization type included in this study. These downsweeps, particularly when present in doublets or triplets, are unique to sei whales and are a reliable proxy for sei whale presence³⁹.

Statistical analysis

Seasonal presence and vocal activity

To determine the seasonal pattern of sei whale acoustic activity, data were processed in RStudio using R version 4.3.2⁷⁵. Both vocal activity and acoustic presence were investigated at a weekly resolution rather than a daily resolution to allow for the observation of more gradual seasonal changes and to reduce zero-inflation. Vocal activity was represented by the number of sei whale downsweeps per week, hereafter termed number of downsweeps. If a doublet or triplet was detected, each individual vocalization (two for a doublet, three for a triplet) was marked as a separate downsweep. Acoustic presence was calculated as a ratio of the number of days

per week with sei whale downsweeps detected divided by the number of days with recording effort per week. Acoustic presence was therefore represented by the proportion of days per week with presence, i.e. by values bounded by 0 (no presence that week) and 1 (acoustic presence in every recording day that week). Any weeks without recording effort were removed from the dataset, as no audio was available for review for these weeks and presence could therefore not be determined. The astronomical season (winter, spring, summer, autumn) of each week was also noted.

Remotely sensed SST and surface Chl-a data have been used in previous studies as proxies for baleen whale prey availability due to their relationship to marine ecosystem productivity^{27–33}. Sei whales are secondary and tertiary consumers, meaning they feed on (and often follow the distributions of) organisms such as krill and fish whose populations depend on the primary production of phytoplankton²⁷. Chl-a is a byproduct of primary production, and peaks in primary productivity often occur during spring (i.e. the spring bloom), when various layers of the water begin to mix and the water temperature becomes less stratified²⁷. Given their relationship to primary production and therefore sei whale prey distribution, SST and Chl-a were also included in this study to investigate a possible link between sei whale presence and prey distribution in this region. Daily values for SST (°C, 1 km resolution) and surface Chl-a (mg m^{-3} , 750 m resolution) were retrieved from images taken by the Multi-scale Ultra-high Resolution Sea Surface Temperature (MUR SST) dataset produced by the NASA Jet Propulsion Laboratory and the Visible Infrared Imager Radiometer Suite (VIIRS) dataset by the National Oceanic and Atmospheric Administration (NOAA), respectively. It is important to note here that both environmental factors were measured only at the surface of the water due to the nature of remote sensing; Chl-a will therefore refer to surface Chl-a from here on. Though public-access remotely sensed data are limited in scope (i.e. limited to surface measurements), they are cost-effective, require little to no labor for collection, and allow for wide regions to be monitored on a long time scale^{76,77}. Both datasets were accessed through the NOAA Coastwatch DataPortal (SST data at <https://www.star.nesdis.noaa.gov/pub/socd1/ecn/data/podaac-mur/sst/daily/conus/> and Chl-a data at <https://www.star.nesdis.noaa.gov/pub/socd1/ecn/data/viirs/chl/daily/ma/>). Missing Chl-a values were interpolated using the RStudio package *zoo*. The median weekly values for both SST and Chl-a were used as explanatory variables.

Two generalized additive mixed models (GAMMs) were run and analyzed in RStudio (package: *mgcv*) to investigate the pattern of seasonal sei whale vocal activity and acoustic presence, using a tweedie and binomial distribution, respectively (See Supplementary Materials I for model results). The tweedie distribution was chosen because it is appropriate for zero-inflated count data and there were many weeks where there was no vocal activity (number of downsweeps = 0), while the binomial distribution was chosen because the acoustic presence was calculated as a proportion bounded by 0 (no presence that week) and 1 (acoustic presence in every recording day that week).

The response variable for the tweedie-distributed GAMM was the number of downsweeps, while the response variable for the binomial-distributed model was acoustic presence. In both models, year was included as parametric predictor variables to account for variability in interannual vocal activity and presence, while SST and Chl-a were added as smoothed variables and fit as thin plate regression splines (TPRS). Season was not included as a variable due to its correlation with SST in this region; therefore, seasonal trends were analyzed through the examination of SST. Recording effort (i.e., number of days of recording each week) was included as a weighting factor for both models and an autocorrelation term centered around week (correlation = $\text{corAR1}(\text{form} = \sim 1 \mid \text{Week2})$) was included to reduce the effects of overfitting due to temporal correlations. The best models were then chosen based on the function `gam.check()` and an analysis of generated residual plots. Weekly predicted values for seasonal presence and vocal activity were generated using the `predict()` function in the *stats* package.

Diel presence and vocal activity

Diel acoustic presence and vocal activity of sei whales was investigated using each day of data (January 1, 2017 – December 31, 2020) divided into three bins (day, night, or twilight) that determined the light availability at a particular hour. These bins are hereafter referred to as time of day. The times of sunrise and sunset in the NYB throughout the year was determined using the package *suncalc*. *Suncalc* uses the angle of the sun in relation to the Earth, the coordinate location, and the date to determine the exact time at which the top of the solar disk meets the horizon both in the morning (sunrise) and in the evening (sunset) on any given day. In this study, the hours of sunrise and sunset were both given the designation of twilight, as crepuscular animals are active at both times of day⁷⁸. For example, if sunset occurred at 18:50, the hour from 18:00 to 18:59 would be designated as twilight. The number of downsweeps and acoustic presence were then aggregated to a weekly resolution, divided into the three bins of day, night, twilight (i.e. the number of downsweeps refers to the number of downsweeps detected during a particular time of day in a particular week, and presence refers to the presence of downsweeps during a particular time of day in a particular week). As such, each week had three values for number of downsweeps and acoustic presence, respectively, one for each time of day.

Similar to the seasonal presence analysis, two generalized additive mixed models (GAMMs) were run in RStudio (package: *mgcv*). A tweedie distribution was used to investigate the diel pattern of sei whale vocal activity, while a binomial distribution was used to investigate the diel pattern of acoustic presence (see Supplementary Materials I for model results). The best model was then chosen based on the comparison of the function `gam.check()` and an analysis of generated residual plots.

For the tweedie-distributed GAMM, the response variable was the number of downsweeps, while the response variable for the binomial-distributed model was acoustic presence. In both models, time of day and year were included as parametric predictor variables and SST was included as a smoothed variable with a TPRS due to it being a strong predictor for sei whale vocal activity and presence in the seasonal models. Recording effort (i.e., number of days of recording per week) was included as a weighting factor for both models and an autocorrelation term centered around week (correlation = $\text{corAR1}(\text{form} = \sim 1 \mid \text{Week2})$) was included to reduce

the effects of overfitting due to temporal correlations. Resulting plots were then compared using the package *ggplot2*. Weekly predicted values for diel presence and vocal activity during each time of day were generated using the `predict()` function in the *stats* package.

In summary, a total of four GAMMs were used to analyze the seasonal and diel trends in sei whale vocal activity and acoustic presence: (1) a tweedie GAMM for seasonal vocal activity, (2) a binomial GAMM for seasonal acoustic presence, (3) a tweedie GAMM for diel vocal activity, and (4) a binomial GAMM for diel acoustic presence. Model fit was evaluated using the `gam.check()` function in package *mgcv* to ensure no model assumptions were violated.

Data availability

The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request. Sea surface temperature and surface chlorophyll-a concentration data are publicly available on the NOAA Coastwatch DataPortal (SST data at <https://www.star.nesdis.noaa.gov/pub/socd1/ecn/data/podaac-mur/sst/daily/conus/> and Chl-a data at <https://www.star.nesdis.noaa.gov/pub/socd1/ecn/data/viirs/chl/daily/ma>).

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Author contributions

All authors have contributed significantly by conceiving of the research idea (MP, AM), conducting (MP) and advising in the acoustic (MR, AM, CKN, ST, HR) and statistical analyses (MR, AM, CKN, ST, SS, MB, HR), writing the R code for statistical analysis (MP), creating figures (MP, CKN), writing (MP) and reviewing previous (MP, MR, CKN, ST, HR) and final (MP, MR, AM, CKN, ST, MB, SS, HR) drafts of the manuscript, securing funding support (MR, HR), providing and collecting data for the study (MB, HR), and creating the methodology for data collection (MB).

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Declarations

Competing interests

The authors declare no competing interests.

Additional information

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