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A methodological approach for determining sea turtle responses to vessel traffic using passive *in situ* monitoring

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Abstract

Vessel strikes are the leading cause of sea turtle strandings. However, there is limited information on how the presence of vessel traffic can impact sea turtle behavior and space use. Currently, research into these responses consists primarily of lab studies, as *in situ* studies pose logistical challenges. In this study, we present a method to understand these responses in the field using both acoustic telemetry and passive acoustic monitoring to quantify turtle movement and vessel traffic, respectively. Between 2019 and 2022, we tracked green (*Chelonia mydas*, n = 7) and loggerhead (*Caretta caretta*, n = 6) turtles within Biscayne National Park (Florida, United States). We used two miniature acoustic telemetry arrays (5 receivers each), with a central passive acoustic recorder in each array to quantify vessel traffic. In addition to recording turtle presence, data from transmitters containing tri-axial accelerometers allowed us to quantify turtle activity. We used generalized linear models to determine the relationship of turtle residency and activity to hourly and daily vessel traffic. Our results indicated a weak but significant negative relationship between turtle residency and vessel traffic. We also observed reduced activity levels in response to increased vessel presence. This study demonstrates a viable *in situ* method for quantifying the sub-lethal impacts of vessel traffic to sea turtles, revealing that even vessel presence alone can alter sea turtle behavior. These findings provide critical information for managing vessel activity in protected areas to mitigate behavioral disturbances, not just direct mortality.

Introduction

The rapid urbanization of coastal areas intensifies human-induced pressures on nearshore ecosystems, threatening their ecological health and sustainability via heightened resource exploitation, habitat degradation, pollution, and ocean sprawl (Todd et al. 2019). Among these pressures, increased vessel activity is a pervasive threat, causing habitat damage (Zieman 1976), noise pollution (Popper et al. 2003), and collisions with wildlife (Fuentes et al. 2025). As a result, vessel traffic poses a significant threat to sea turtles as vessel strike injuries are a leading cause of sea turtle strandings (Fuentes et al. 2025). While the threat of vessel strikes on sea turtles are increasingly studied (Fuentes et al. 2025), there is limited information regarding vessel activity impacts on sea turtle behavior and movement patterns.

Until recently, knowledge of sea turtle behavioral responses to vessel activity was limited to laboratory studies examining turtles exposed to anthropogenic noises (e.g. boat engine noise; Samuel 2004). While this work was critical in highlighting the overlap between turtle hearing sensitivities and boat noise, it remained difficult to quantify behavior in the wild. Innovations in biologging have made recording behavioral responses of sea turtles in the wild more feasible; tracking devices equipped with acoustic recorders and accelerometers have been successfully deployed on sea turtles to determine fine-scale, acute responses to vessel passages (Tyson et al. 2017; Garzon et al. 2024). More recently, studies have implemented animal-borne video surveillance to further characterize these acute responses.

While animal-borne sensors allow for direct observation, short deployment periods limit their ability to determine the long-term impacts of vessel activity on a population. A potential solution is the use of passive monitoring techniques, such as acoustic telemetry and underwater recorders. By combining these methods, it is possible to monitor both animal movement and vessel activity simultaneously for longer periods of time (i.e. months to years). Indeed, these methods have successfully determined relationships between vessel traffic and shark habitat use (Rider et al. 2021). However, they have not yet been applied to sea turtles, whose behaviors—particularly surfacing and responses to sound—may be distinctively altered by vessel presence (Hazel et al. 2007; Tyson et al. 2017; Garzon et al. 2024).

Here, we present a combined methodological approach for the long-term, *in situ* monitoring of sea turtle behavior in relation to vessel activity. Our methods integrate acoustic telemetry, to track turtle residency and activity, with passive acoustic monitoring, to record ambient sound and identify vessel presence. We demonstrate the application of this approach with green (*Chelonia mydas*) and loggerhead (*Caretta caretta*) sea turtles within Biscayne National Park (southeastern Florida, USA). The park is an ideal test site as it experiences high recreational and fishing vessel traffic (Ault et al. 2017) and supports a large abundance of turtles that use the bay both year-round and as a migratory stopover (Hart et al. 2023).

This integrated monitoring approach is key to understanding how the spatiotemporal overlap between vessel activity and turtle habitat use affects population abundance and distribution.

Methods

Study area

Biscayne Bay is a subtropical bay along the southeastern coast of Florida, USA. The Bay ranges from 2 to 18 m deep and consists mostly of a carbonate sand substrate that promotes several species of seagrass (Zawada and Brock, 2009). At the north end, the Bay is surrounded by the extensive metropolitan area of Miami and Coral Gables, while the southern end borders part of the Everglades and the beginning of the Florida Keys. Biscayne National Park occupies the central and southern portions of the Bay and extends further east offshore towards the Gulf Stream. Activities like diving and fishing are permitted within the park's boundaries, which can lead to high amounts of recreational vessel activity. High concentrations of traffic occur in the eastern half of the Bay, especially along the western shores of Boca Chita, Sands, and Elliot Keys (Ault et al., 2017; Rider et al., 2021). The Intracoastal waterway bisects the Bay and brings a high amount of traffic from Miami as well as several large marinas along the southwest shores (see dashed lines in Figure 1).

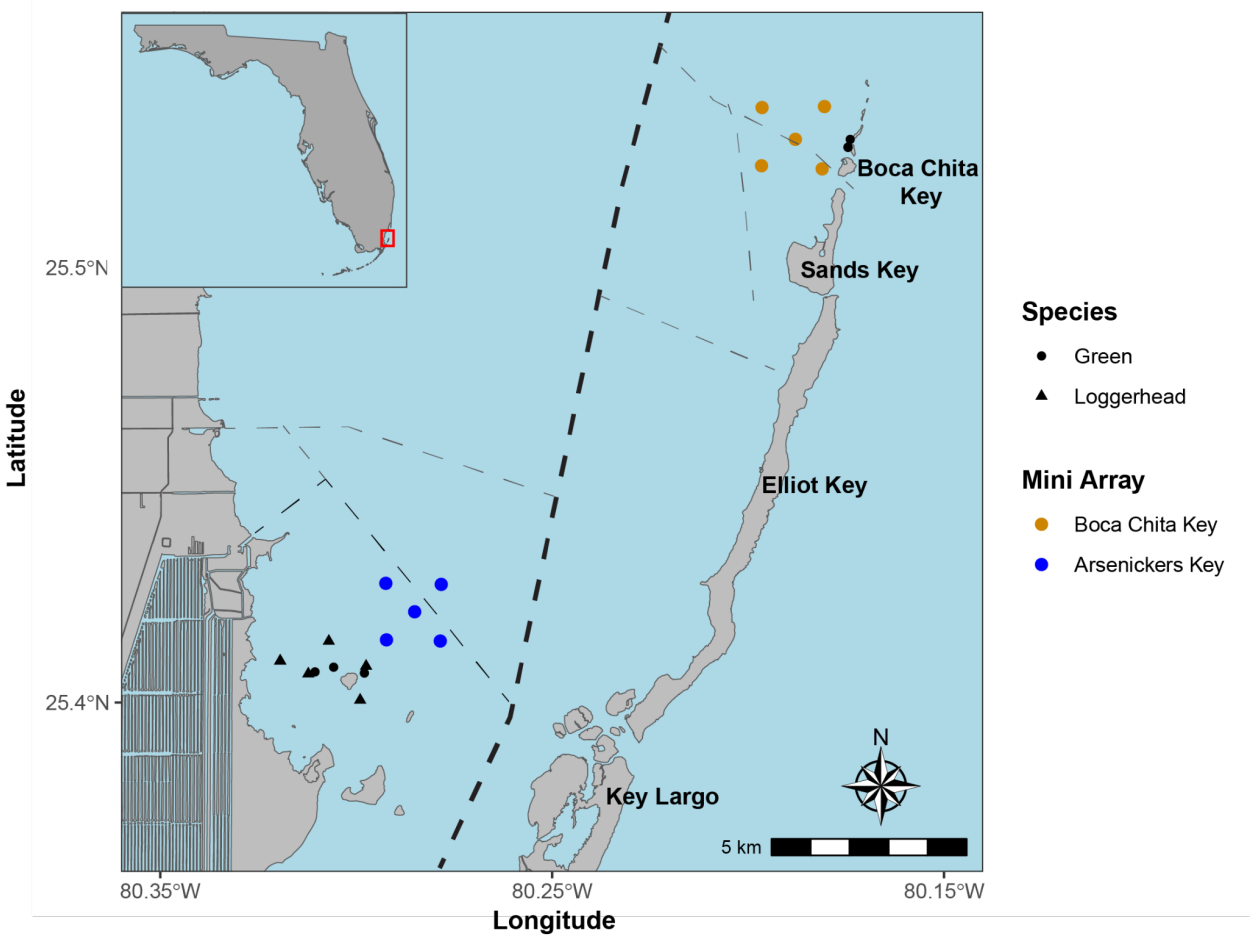


Fig 1 Map of the southern portion of Biscayne Bay, Florida, showing the two mini arrays located at Boca Chita and Arsenickers Keys along with the tagging locations of turtles detected on each array between 2019 and 2022. At each array, the points represent the location of an acoustic telemetry receiver. The central point at each mini array also contained the passive acoustic monitoring station that was used to detect boat traffic. The dashed lines represent popular routes used by recreational boaters, with the bold line representing the Intracoastal Waterway that bisects Biscayne Bay.

Since we had a pre-existing array of animal tracking and passive acoustic monitoring stations set up to determine the relationship between vessel traffic and shark habitat use (see Rider et al., 2021), we focused our efforts on two particular areas within the Bay that had both varying amounts of vessel traffic and presence of sea turtles: Boca Chita Key and Arsenickers Key. Boca Chita Key is located along the eastern boundary of the Bay and contains a park that is a popular destination for recreational boaters as well as a channel that connects the bay to offshore reef areas. The area around Arsenickers Key is located in the southern portion of the Bay and given its location, experiences occasional vessel traffic that is traveling from Biscayne National Park Headquarters either towards outlets to the open ocean at Caesars Creek, or they are accessing the Intracoastal Waterway.

Turtle capture and tracking

Turtles were captured using the rodeo method (See Ehrhart and Ogren 1999) with a diver positioned on the bow of a small vessel, with the aid of other onboard observers, scanning the water for hardshell turtles. When a turtle was located, the vessel pursued the turtle until in a position for the diver to dive into the water and capture the turtle by hand. Once at the surface, the onboard crew lifted the turtle over the gunwale with the aid of the diver in the water. Upon boarding, each turtle was flipper and PIT tagged, biopsied from the trailing edge of the rear flipper using a sterile biopsy punch, photographed, measured, and released.

To track movements and activity, we attached acoustic transmitters to posterior marginal scutes, over the rear leg at a location where the shell is flattest, and secured them with both epoxy and nylon coated wire (Stokes et al. 2008). We used two models of individually-coded acoustic transmitters from Innovasea Systems Inc. (Halifax, Nova Scotia, Canada): V13-1x (nominal delay = 80–160 s, battery life = 602-631 days) and V13A-1x (nominal delay = 60–120 s, battery life = 98-234 days). The V13A-1x models contained a tri-axial accelerometer (Measurement Range = ± 3.43 m s^{-2}), which measured acceleration on three axes either five or 12.5 times per second over a 57-second sampling interval. Using the acceleration values measured across all three axes over the sampling interval, these tags transmitted the root mean square acceleration value, which represented the general body acceleration of the turtle.

Reliable estimates of turtle presence, activity, and residency patterns were obtained using passive acoustic receivers located in two locations within Biscayne Bay: Boca Chita Key and Arsensickers Key (Figure 1). Beginning in March 2019, we deployed Innovasea VR2W – 69 kHz receivers (Innovasea Systems Inc., Halifax, Nova Scotia, Canada) at each location. In March 2022, we deployed four more receivers at each location to increase the detectability of tagged turtles. The four additional receivers were arranged in a square formation surrounding the existing receiver station (Figure 1). Each new receiver was placed ~400 m from the existing station since the 50% detection range was ~250 m (based on range testing conducted by Rider et al. 2021). Receivers were anchored to the substrate at depths ranging from 1.5 to 2.5 m using a concrete stand. Maintenance was performed and detection data were retrieved from each receiver every six months.

Vessel traffic via passive acoustic monitoring

We quantified vessel traffic at each location using underwater acoustic recorders (i.e., Snap Recorder from Loggerhead Instruments, Sarasota, Florida, United States). The recorders were affixed to the same stand as the central acoustic telemetry receiver at each location using cable ties. This attachment allowed for simultaneous recording of both turtle and vessel presence. The recorder at Arsenickers Key was established in March 2018 as part of Rider et al. (2021), while the recorder at Boca Chita Key was implemented in May 2022. Each recorder was programmed to record 10 seconds every minute with a sample rate of 32 kHz (decimated once), and a sensitivity of -169.4 dBV/uPa. Selected sample rates allowed recorders to log frequencies up to 16 kHz, which is well-within the range of recreational engines (Barlet and Wilson, 2002; Fischer and Brown, 2005). In August 2022, the recorders were reprogrammed to record five seconds every two minutes to increase battery life. This did not impact the detectability of vessel traffic as a similar rate of vessel passages were recorded regardless of the recording interval. We performed routine maintenance and downloaded data at each recording station every 20 to 60 days.

Following methods outlined in Rider et al. (2021), we quantified vessel traffic using vessel engine noise recorded by the underwater acoustic recorders. We used a vessel detection software developed by the Marine Environmental Research Infrastructure for Data Integration and Application Network (MERIDIAN) at Dalhousie University (Nova Scotia, Canada). The software took the sound clips and processed them through two separate functions: a 'filter analyzer' and an 'anomaly detector'. The filter analyzer determined the 'normal' level of background noise by transforming an audio signal using a Fast Fourier Transform to create a spectrogram, which was split into six frequency bands with central frequencies of 31.2, 62.5, 125, 250, 500, and 1000 Hz. The running median of sound pressure level was computed for each frequency band using a window size of three seconds and a step size of one second. For each frequency band, the filter analyzer produced a time series of median sound pressure levels. The median was computed using a window size of one minute and subtracted from the median values for each frequency band. This produced a time series of background-subtracted median values for each frequency band with which the anomaly detector function could be used to identify the presence of vessel engine noise.

The anomaly detector searched for instances of unusually high sound levels (i.e., peaks) in the time series of background-subtracted median sound pressure values. For the purpose of this study, only the median value from frequency bands of 125, 250, and 500 Hz were used as they closely aligned with the frequencies produced by recreational vessel engines. A positive vessel detection was counted if a peak met four specific criteria: 1) it was separated by at least two minutes from any other peak (to prevent repeated detections of the same vessel), 2) it occurred in a minimum of two of the three frequency bands, 3) it exhibited a minimum height above the background fluctuations (i.e., prominence), and 4) it did not exceed a certain threshold level (to account for miscellaneous high-amplitude sounds such as those

produced by snapping shrimp). The minimum height was computed as $h_{min} = p * M(|x - M(x)|)$, where p was the specified prominence, and M(x) was the median operator. Specified prominence was manually adjusted for each station to account for differences in background noise. We cross-validated vessel detections by analyzing spectrograms from multiple random samples of sound clips for each recorder using the sound analysis software Raven Pro 1.4 (Cornell Lab of Ornithology, New York, USA). The final product of the anomaly detector were date-time stamps of vessel detections. We determined the detection range of the underwater acoustic recorders to be ~600 m (see Rider et al., 2021 for more details).

To understand the temporal patterns of daily vessel traffic, we compared daily vessel presence patterns across array locations and between weekdays and weekends/holidays using a two-way analysis of variance (ANOVA) with a Tukey's *post hoc* test. We defined weekdays as Monday through Friday, weekends as Saturday and Sunday, and holidays as major boating holidays including Columbus Day, Fourth of July, Labor Day, Memorial Day, and Lobster Mini Season (third Wednesday and Thursday of July). Daily passages were log-transformed to meet assumptions of equal variance and normality.

Turtle residency in response to vessel traffic

While it is customary to pre-filter acoustic telemetry data to remove any instance of false detections (i.e., detections occurring from either environmental noise or overlap between two or more acoustic transmitter signals, which were defined if the time between transmissions were greater than a given threshold; Kessel et al. 2014), we manually filtered out any lone detections on a case by case basis due to a limited temporal overlap when both acoustic telemetry receivers and passive acoustic monitors were operational. Using the detection data from the acoustic telemetry array, we were able to calculate reliable estimates of turtle residency by measuring the time during specific detection events. A detection event was defined as the time from when a turtle arrived at one of the two arrays to the last time it was detected. We determined when the turtle was no longer present if an hour had passed before the next detection. For instances where only one detection was recorded, we labeled the residency time as 10 seconds which corresponds to the amount of time it takes for a complete transmission to be recorded by a receiver.

To understand the potential relationship between vessel traffic and turtle residency, we evaluated turtle residency dependent on vessel passages with a temporal resolution of one hour. Hourly turtle residency was determined by taking each detection event and calculating the proportion of the hour that the turtle was present. To account for absences without causing zero inflation, we included all hours of the day for each day that a turtle was present. We evaluated the relationship between hourly turtle residency dependent on hourly vessel passages with the interactions of diel period and array locations

(Boca Chita and Arsenickers) using a generalized linear model (GLM) with a Tweedie error distribution using the R package 'glmmTMB' (Brooks et al. 2017). We defined diel periods as sunrise to sunset (day) and sunset to sunrise (night) using the 'suncalc' package in R (Thieurmel and Elmarhraoui). We initially included turtle ID as a random effect to account for repeated measures in a generalized linear mixed model (GLMM), but this resulted in a singular fit. We applied data dredge statistics to run the GLM with all valid combinations of parameters using the dredge function from the R package 'MuMIn' (Bartoń 2023). This allowed us to test every possible combination of fixed effects and generate Akaike's information criterion (AIC) and AIC weights for every model. The preferred model was selected based on the lowest AIC. Models with a $\Delta AIC < 2$ were considered to be equivalent to the best fitting model.

In addition to assessing the direct relationship between turtle residency and vessel traffic, we also evaluated patterns in turtle residency at each mini array location using detection data from the entire deployment period independent of when vessel monitoring stations were operational. We evaluated the relationship between turtle residency (i.e., time of a detection event) and the interaction of diel period, location of array, and day types (weekdays and weekend/holidays) using a generalized linear mixed model with a lognormal distribution. Turtle ID was included as a random effect to account for repeated measurements among individuals (Bolker et al. 2009). Similar to the GLM describing hourly residency, data dredge statistics were also applied to find the best fitting GLMM to describe general patterns in turtle residency. Diagnostic plots using empirical quantile residuals were generated using the R package 'DHARMa' (Hartig 2012) to assess model fit.

Turtle activity in response to vessel traffic

Given the limited data from the accelerometer tags, we were not able to evaluate the potential relationship between turtle activity and vessel traffic like we did for turtle residency. However, we were able to analyze a direct relationship by 1) assessing turtle activity based on the immediate presence of a vessel passage, and 2) estimating the relationship between the acceleration and hourly vessel passages. To determine the immediate response of a turtle to the presence of a vessel, we compared the root mean square acceleration values of the turtles whether or not a vessel was present 15 minutes or less before a turtle was detected using a Welch's two sample t-test. To determine the potential relationship between activity and hourly vessel passages, we used linear regression to test if mean daily acceleration values could be explained by mean hourly vessel passages in a given day.

Similar to analyzing the overall patterns in turtle residency, we assessed patterns in turtle activity using detection data from the entire deployment period independent of vessel traffic data. More specifically, we evaluated the relationship between turtle acceleration and the interaction of diel period

and day types using a GLMM. Given the relatively shorter tag life of the accelerometer, we did not have enough data to compare activity between locations. Turtle ID was included as a random effect to account for repeated measurements among individuals (Bolker et al. 2009). Model fit was assessed using the same methods described above.

Results

Turtle captures

Between 2018 and 2022, a total of 29 turtles were captured and affixed with acoustic transmitters. Of those 29, six loggerhead and seven green turtles were detected at either the Boca Chita (n = 6) or Arsenickers (n = 7) mini arrays (Table 1; Online Resource 1). Four of the detected turtles (one loggerhead and three green) were affixed with accelerometer tags.

Table 1: Summary of turtles affixed with acoustic transmitters and detected within at least one of the mini arrays.

ID	Species	Date tagged	Tagging location	Accelerometer?	Estimated tag life	Total detections	Days detected
CC1	Loggerhead	11/18/2018	Arsenickers	N	602	391	38
CC2	Loggerhead	12/3/2018	Arsenickers	N	602	12	1
CC3	Loggerhead	9/26/2019	Arsenickers	N	602	11	2
CC4	Loggerhead	10/10/2019	Arsenickers	N	602	232	9
CM1	Green	10/17/2019	Arsenickers	Y	98	16	2
CC5	Loggerhead	10/17/2019	Arsenickers	Y	98	1	1
CM2	Green	12/16/2019	Boca Chita	Y	98	346	38
CC6	Loggerhead	3/1/2022	Arsenickers	N	631	692	77
CM3	Green	3/1/2022	Boca Chita	N	631	2	2
CM4	Green	3/1/2022	Boca Chita	N	631	2	1
CM5	Green	3/17/2022	Boca Chita	N	631	54	10
CM6	Green	3/17/2022	Boca Chita	N	631	100	50

CM7	Green	3/17/2022	Boca Chita	Y	234	35	20

Vessel traffic patterns

The two-way ANOVA revealed that both location ($F = 46.3$, $p < 0.001$) and day type ($F = 30.1$, $p < 0.001$) had significant effects on the total number of daily vessel passages while there was no significant interaction between the location and type of day ($F_{1,255} = 0.705$, $p = 0.402$). The Tukey's *post hoc* test indicated a greater amount of vessel activity both at Boca Chita Key ($p < 0.001$) as well as on weekends/holidays ($p < 0.001$; Figure 2).

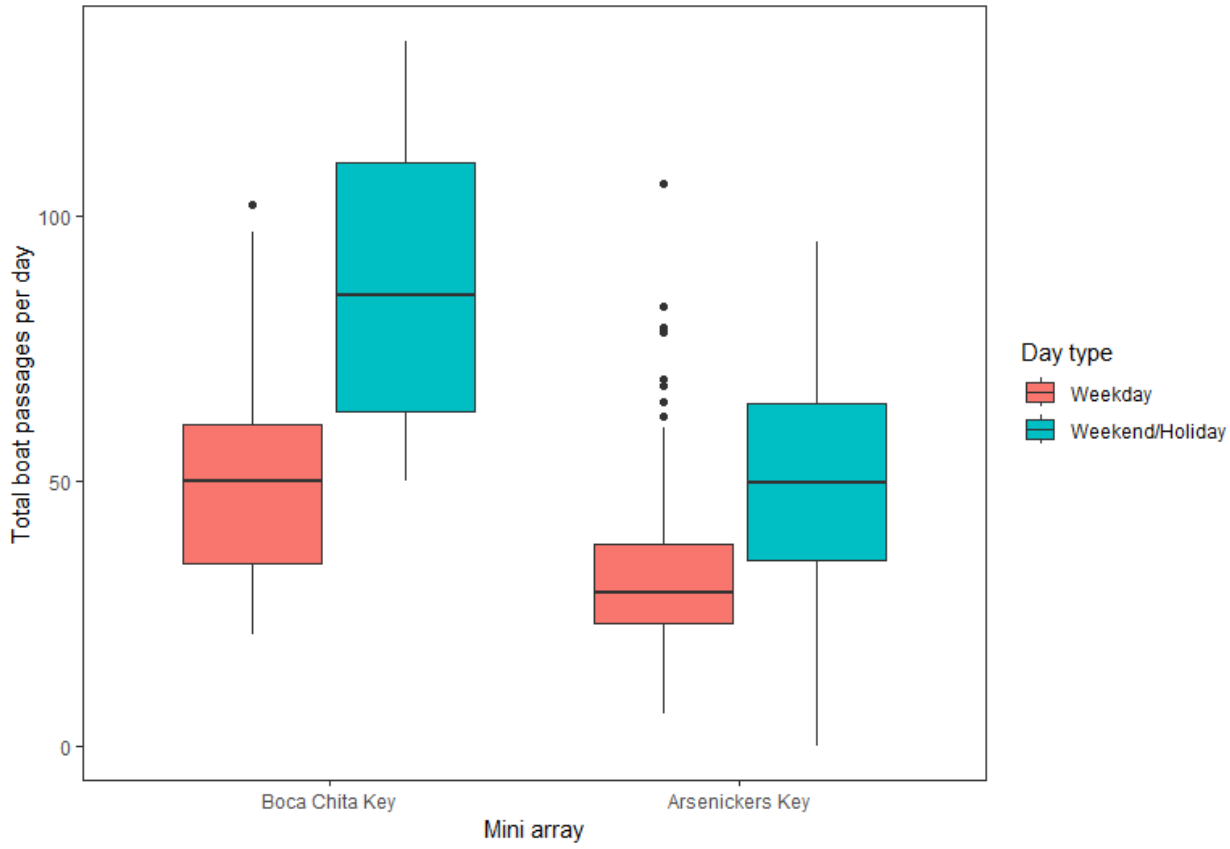


Fig 2 Boxplots showing daily boat traffic trends between mini arrays, and day type. Major boating holidays including Columbus Day, Fourth of July, Labor Day, Memorial Day, and Lobster Mini Season (third Wednesday and Thursday of July) were paired with weekends.

Turtle residency in response to vessel traffic

There were four models explaining hourly turtle residencies that fell within two delta AIC, each of which included the array location and hourly vessel passages. The best fit GLM for explaining hourly turtle residency consisted of hourly vessel passages, array location, and their interaction (Online Resource 2). The model indicated both a significant inverse relationship between hourly residency and hourly vessel passages and significantly higher residency at Arsenickers Key (Figure 3; Table 2). However, the model did not detect a significant interaction between vessel passages and array location. The predictive power of the model was relatively low ($R^2 = 0.018$).

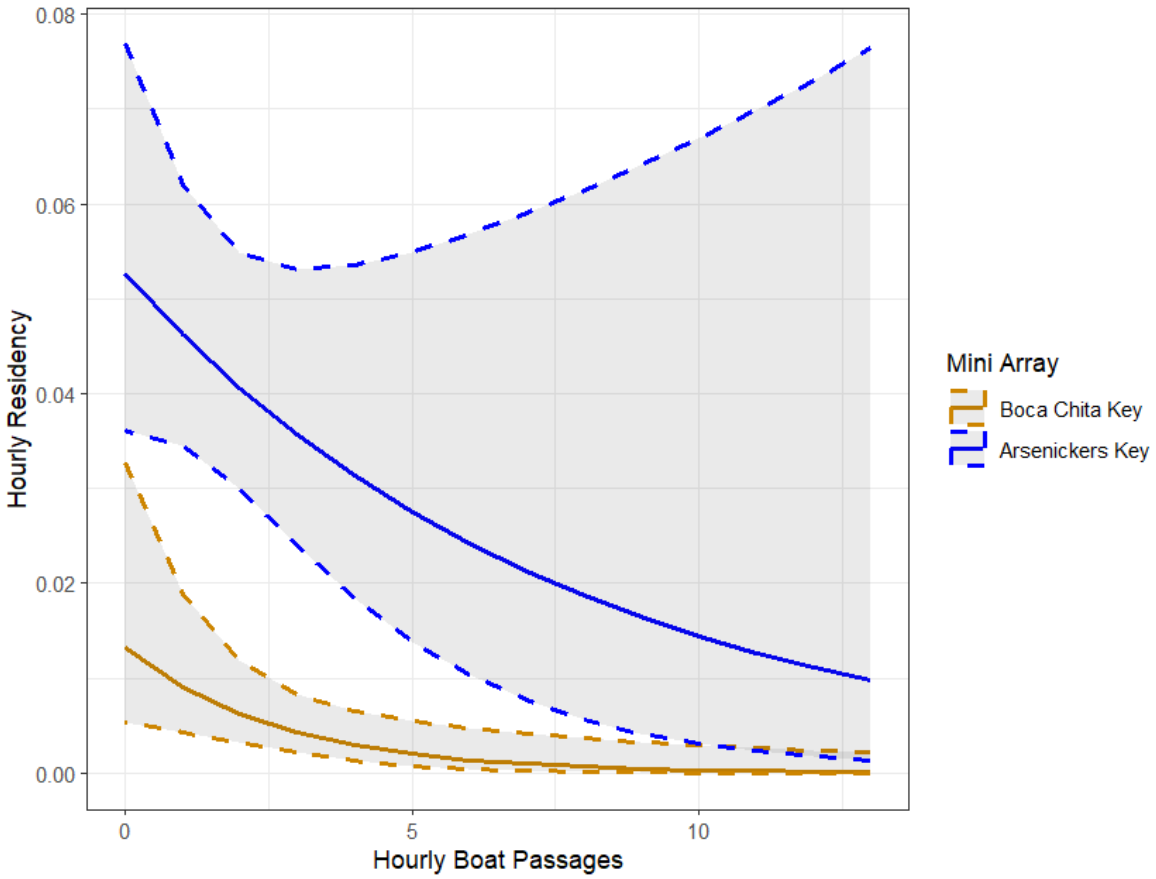


Fig 3 Predicted values of the hourly residency with respect to hourly boat passages at a given mini array as determined by the preferred generalized linear model with a tweedie distribution that included array location, hourly boat passages, and their interaction. Hourly residency was calculated as the percent time spent at a receiver station within a given hour. The shaded area represents the 95% confidence interval.

Table 2: Generalized linear model parameter estimates of hourly residency dependent on hourly boat passages and location of array location. Boca Chita Key was the reference level for array location. An asterisk represents an interaction term.

Parameter	Estimate	Std. Error	z value	p value
Intercept	-4.276	0.472	-9.057	<0.001
Hourly boat passages	-0.372	0.147	-2.537	0.011
Array location	1.331	0.510	2.611	0.009
Hourly boat passages * Array location	0.243	0.172	1.413	0.158
			R^2	0.018

For estimating general patterns in turtle residency, there were four models that fell within two delta AIC, each including array location as a predictor. The best fit GLMM only contained array location as a fixed effect (Online Resource 3). The model indicated that residency at Arsenickers Key was significantly higher than at Boca Chita Key (Table 3).

Table 3: Parameter estimates for the best fit generalized linear mixed model estimating turtle residency dependent on array location. The reference levels for array location was Boca Chita Key.

Predictors	Estimates	Std. Error	z value	p value
(Intercept)	0.71	0.22	-1.09	0.276
Array location	2.46	0.69	3.21	0.001
Random Effects				
σ^2	26.29			
$\tau_{00\ \text{Turtle ID}}$	0.11			
ICC	0.00			

$N_{\text{Turtle ID}}$	13
Observations	395
Marginal R^2 / Conditional R^2	0.007 / 0.012

Turtle activity in response to vessel traffic

On days that both vessels and turtles with accelerometer transmitters were detected, we were not able to detect a significant difference in turtle acceleration if a vessel was present before the detection event ($t_{2.4} = 0.73$, $p = 0.53$). There were only three instances where a vessel was detected within 15 minutes before a turtle with an accelerometer tag was detected.

We were able to determine the relationship between mean daily acceleration and mean hourly vessel passages for one green turtle (i.e., CM7) detected at Boca Chita Key in May and June of 2022. The linear model indicated a significant inverse relationship where mean hourly vessel passages explained 59.0% of the variation in mean daily acceleration ($F_{1,4} = 8.20$, $p = 0.046$; Figure 4).

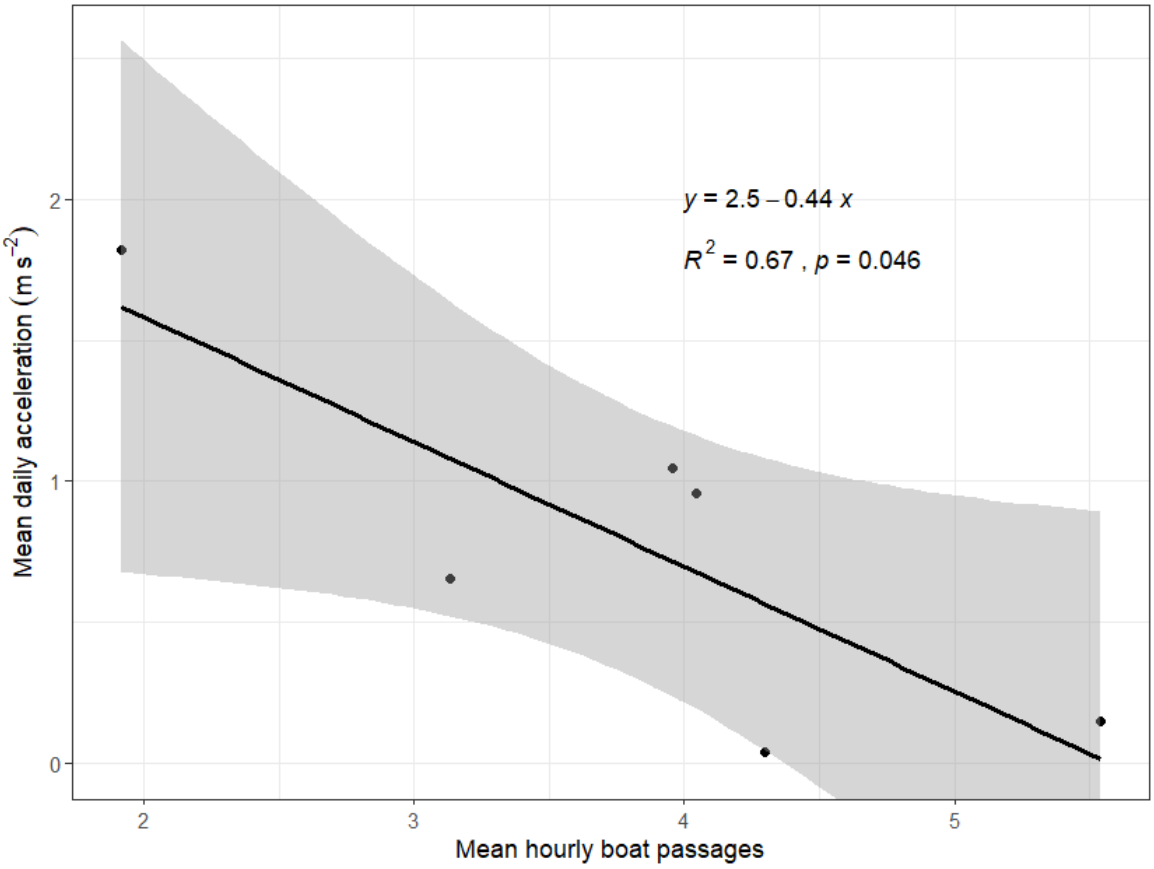


Fig 4 Mean daily acceleration of one green turtle (CM7) was inversely related to the mean hourly boat passages as determined by a linear model. This is based on one green turtle (CM7) detected at Boca Chita Key in May and June of 2022. The shaded area represents the 95% confidence interval.

Turtle activity, regardless of when vessels were detectable, was significantly higher on weekdays as well as during the day (Figure 5; Table 4). There was no significant interaction detected between day type and diel period.

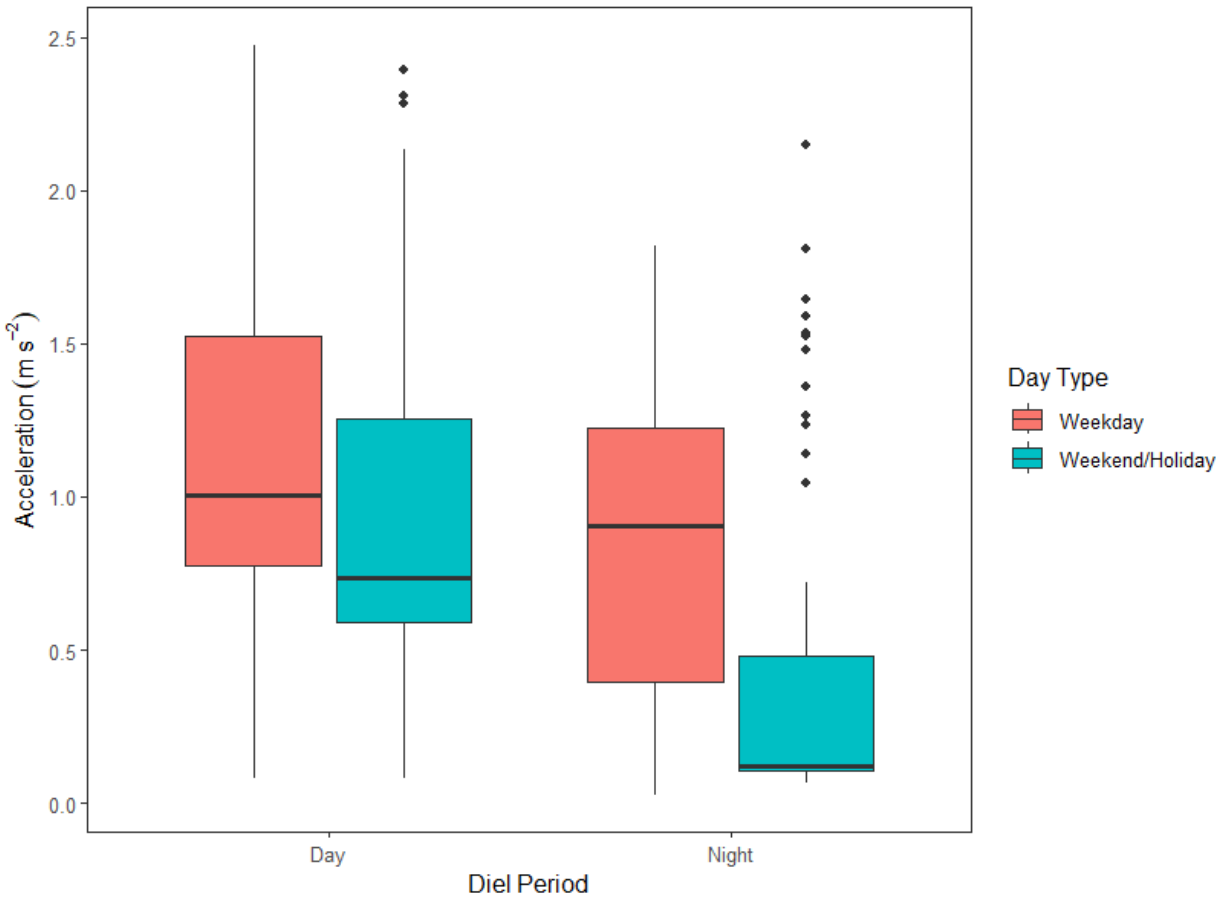


Fig 5 Boxplots of acceleration for tagged turtles grouped by diel periods and day types. Major boating holidays including Columbus Day, Fourth of July, Labor Day, Memorial Day, and Lobster Mini Season (third Wednesday and Thursday of July) were paired with weekends.

Table 4: Generalized linear mixed model parameter estimates of turtle acceleration dependent on diel period and day type (i.e., weekdays vs. weekends/holidays). The reference levels for diel period and day type were day and weekday, respectively. An asterisk represents an interaction term.

Predictors	Estimates	Std. Error	z value	p value
(Intercept)	1.11	0.21	0.52	0.602
Diel period	0.43	0.08	-4.83	<0.001
Day type	0.63	0.04	-7.34	<0.001

Diel period * Day type	1.20	0.23	0.95	0.344

Random Effects

σ^2	0.61
$\tau_{00\ \text{Turtle ID}}$	0.09
ICC	0.12
$N_{\ \text{Turtle ID}}$	4
Observations	398
Marginal R^2 / Conditional R^2	0.226 / 0.323

Discussion

In this study, we integrated passive acoustic tracking with sound recordings of vessels to present a methodological approach for evaluating the relationship between sea turtle movement behavior and vessel activity in the wild. While we were able to identify some acute relationships that align with findings from other studies, sample size limitations prevented us from the ability to perform more robust analyses. However, we demonstrate an effective approach for measuring behavioral responses of sea turtles to boat traffic in the wild and believe the methods here should be further applied and developed. Below we discuss preliminary findings from this work and the utility of our approach in future research with procedural recommendations.

Turtle residency in response to vessel *traffic*

We observed lower turtle residency at a high vessel traffic site (i.e., Boca Chita) along with a general decline in residency with higher vessel presence across both locations. This finding was consistent with past studies that observed turtle behavioral shifts in the presence of vessels. For example, turtles were observed to reduce their home range size in response to the onset of the scallop fishing season, which may be explained by the increase in vessel presence and fishing activity (Wilderman et al.

2018). Additionally, animal-borne cameras logged an increase in swimming activity with increased head movement indicative of surveying as vessel noise persisted (Diaz et al. 2024). The increased disturbance in the water may cause turtles to evade the surrounding area especially given the shallow conditions of the study area. It's possible that they are moving the deeper water to avoid any disturbance on the surface. Further, research has shown that turtles are less likely to evade oncoming traffic when speeds are greater than 4 km/hr. Since both sites do not have speed restrictions, it is possible that turtles have acclimated to avoid this area during periods of heightened activity such as during the day or weekend.

While it is possible that turtle residency was higher at Arsenickers due to the lower amounts of vessel traffic, there are too many confounding variables that could contribute to this pattern such as prey availability and overall habitat. Regardless, the increased residency in an area with lower amounts of traffic is beneficial to survivability as sea turtles have a higher probability of being stuck by a vessel the closer the habitat they are occupying is to a navigable waterway or marina (Foley et al. 2019).

Turtle activity in response to vessel *traffic*

Based on the accelerometry data, we did observe a decrease in activity during increased levels of vessel traffic. This behavioral pattern aligns with several studies that tracked turtle behavior in response to vessel activity. Diaz et al. (2024) attached camera tags to green turtles and observed increased time on the sea bed as the duration of boat noise increased. However, the authors also noted that unlike times when turtles were traveling, time spent scanning for threats did not significantly increase when they were sedentary on the bottom; noting that this may be due to resting in deeper waters where threats of vessels are of smaller concern. Given the relatively shallow bathymetry of our study area (1-4 m), it is more likely that the turtles are actively avoiding vessel traffic by remaining sedentary. Further, since green sea turtles have been observed to be less active at night (Christiansen et al. 2017), it is likely that the reduction in activity is occurring due to vessel presence as vessel traffic should inherently increase during the day given the location in the Bay. While we were only able to gather sufficient data from one individual, these results do warrant further investigation into long term effects of heightened vessel traffic on turtle behavior as it is possible that turtles have acclimated to the sustained human presence (Todd et al. 2019; Wright et al. 2020).

Applicability of passive monitoring for future research

Our array design was built off that from Rider et al. (2021) who assessed the relationship between vessel presence and shark residency patterns but only combined the use of one acoustic telemetry receiver

with one underwater recorder at each location. Given the limitations that come with tracking sea turtles via acoustic telemetry, such as relatively shorter days at liberty given attachment methods (Hardin and Fuentes, 2021), we surrounded the central receiver/recorder with four additional telemetry receivers to maximize the detectability of our tagged turtles. While this idea was good in theory, we have some suggestions for future iterations of this array design. First and foremost, we suggest that tagging take place within the array. While tagging took place in proximity to each mini array in this study, all turtles were tagged just outside the boundary. This could potentially explain the relatively small number of detections received given the number of turtles tagged. However, it could also be due to the overall residency patterns of the turtles in the region. Hart et al. (2023) indicates that there are year-round and seasonal populations of both green and loggerhead turtles in Biscayne Bay. It is possible that turtles with 10 or fewer days detected (n = 24) were using the Bay as a stopover site during their seasonal migrations. Thus, future studies should target more residential populations by tagging during times of the year when seasonal migrators are not as abundant. This tactic would also help further understand the long-term relationship of sea turtles and vessel activity by assessing those turtles that have appeared to acclimate to the increased human presence.

We also recommend using passive acoustic recorders with longer battery life. Here we used Snap Recorders from Loggerhead Instruments. These recorders were great for regular maintenance in the field (i.e., battery memory card exchange, programming, and initialization) and were similar sizes to the VR2W's which made for easier implementation at each station. However, due to their smaller size, their battery life was not long enough for us to perform routine maintenance on a monthly basis. We tried to address this by switching the recording rate from 10 seconds every minute to 5 seconds every two minutes as this did not change the ability or rate of recording boat passages. Thus, we suggest methods be altered to either reduce the rate of recording even further and test its ability to record vessel passages or use large recorders with the capacity to hold more batteries (e.g., Loggerhead Instruments LS1 or LS2).

Using acoustic telemetry to understand acute responses in animal behavior can be challenging as it produces only presence data. For example, we are not able to determine the exact position of the turtle or boat given the detection range of each type of acoustic recorder, so it is possible that boats and turtles were almost 1 km apart. Thus. Additionally, when turtle residency was to decrease, our confidence that the turtle was truly absent from the area only extended to the detection range (i.e. ~1000 m). However, given the fine spatiotemporal scale of this study and our array design that accounted for detection range, this turned out to be a suitable setup. We suggest that future research employ the use of positioning systems (i.e., VPS arrays) that use triangulation to estimate the actual position and track, which would allow for an even more fine scale analysis of turtle responses to vessel passes.

Conclusions

The use of passive monitoring can be a useful methodology when trying to answer questions related to long-term behavioral responses to a stimulus such as boat traffic in the wild. While the methods presented here had limitations, we were successful in identifying relationships between sea turtle behavior and vessel traffic on par with short-term *in situ* studies and believe that these methods can be further adapted to collect more detailed information on these interactions. These results can be useful in mitigating the interactions between sea turtles and vessel traffic not only to reduce risk of collisions, but also dampen any behavioral effect that vessels can have on sea turtle well-being.

Compliance with Ethical Standards

All applicable international, national and/or institutional guidelines for sampling, care and experimental use of organisms for the study have been followed and all necessary approvals have been obtained through Permits NMFS 21233, NMFS IACUC 21233, MTP-19-030, MTP-20-30, MTP-21-30, MTP-22-30, MTP-23-30, BISC-2019-SCI-0013, BISC-2020-SCI-009, BISC-2021-SCI-0011, BISC-2022-SCI-0017, BISC-2023-0022.

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Competing interests

The authors have no competing interests to declare that are relevant to the content of this article.

Author contributions

All authors contributed to the study conception and design. Data collection and analysis were performed by Mitchell Rider. The first draft of the manuscript was written by Mitchell Rider and Chris Sasso and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data availability

The datasets generated and analyzed during the current study are not publicly available as they are in the process of being made available on the National Centers for Environmental Information. However, data for this study are available from the corresponding author on reasonable request.

Consent to participate

This article does not contain any studies with human participants performed by any of the authors.

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This article does not contain any studies with human participants performed by any of the authors.

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