An Ecological and Oceanographic Baseline to Inform Offshore Wind Development Over the Continental Shelf Off the Coast of New Jersey

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Visit the Research and Monitoring Initiative website: https://dep.nj.gov/offshorewind/rmi/

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Executive Summary

New Jersey has set a goal to procure half of its energy from renewable resources by 2030, which includes the development and operation of offshore wind energy.[1] Offshore energy developments would occur in a coastal shelf that is characterized by remarkable variability across time scales from days and weeks to seasons, years, and decades. This intense ocean variability drives an equally variable ecosystem from the primary producers to the highly migratory fisheries and marine mammals found throughout the existing and planned lease areas. The tight coupling between the ocean conditions and the habitat preference of local and migratory species leads to distributions that can significantly vary from season to season and year to year. Furthermore, the Mid-Atlantic Bight (MAB) is situated in one of the most rapidly warming regions in the world and is vulnerable to both ocean and coastal acidification. These long-term environmental trends are associated with observed and projected changes in species distributions, biomass, and diversity. Therefore, it is critical to monitor ongoing oceanographic and ecological change in New Jersey's productive coastal waters to support an environmentally responsible offshore wind (OSW) planning process and examine potential effects during development, operation, and decommissioning phases. The oceanographic and ecological effects of OSW development are likely to be complex and vary at different spatiotemporal scales which, without long-term regional monitoring programs, would make it difficult to tease apart OSW effects from other natural and anthropogenic effects.

To address these needs, this project implemented a comprehensive, non-extractive monitoring program through the New Jersey Research and Monitoring Initiative (RMI) using deployments of autonomous underwater vehicles (AUVs) called gliders in coastal shelf waters off New Jersey. We conducted a total of twenty deployments (ten per year, for two years) that included a seasonal baseline survey with a pair of gliders deployed in each season, and additional deployments to fill coverage gaps between Spring and Fall. A full complement of available sensors were integrated into the gliders to simultaneously map oceanographic and ecological variables. The gliders surveyed the full water column from surface to near bottom and traversed the shelf from nearshore-inner shelf to offshore-outer shelf. RMI gliders traversed coastal shelf waters 368 out of 708 days (52% coverage) and traveled a total of 10,651 km. Data collected through this initial project provided a seasonally-resolved 3D view of regional ocean and ecological conditions that includes physical and chemical variables, as well as biological variables spanning multiple trophic levels – from phytoplankton and zooplankton to pelagic fish and marine mammals.

The high temporal resolution of the data revealed both high seasonal and interannual variability in all variables measured, with dramatic differences between 2023 and 2024, that were driven by changes in sources and properties of different water masses and regional atmospheric activity. Seasonally, we observed the evolution of water column structure from Spring to intensified Summer stratification, to Fall stratification breakdown and Winter full water column mixing. With these physical transformations, we observed simultaneous seasonal changes in water chemistry (dissolved oxygen, pH, aragonite saturation state) and chlorophyll-a, as well as event-based oceanographic changes (upwelling, Nor'easters, the passage of tropical storms and hurricanes, multi-stressor events). Compared to Summer 2024, lower bottom water dissolved oxygen concentrations were observed during Summer 2023 and were associated with fish, crab, and lobster

[1]https://dep.nj.gov/cleanenergy/nj/

mortalities in the sampling area. This was likely the result of warmer bottom temperatures and higher surface and subsurface maximum chlorophyll-a concentrations in 2023 that acted to increase bottom water microbial activity, resulting in lower dissolved oxygen. In contrast, lower bottom temperature, salinity, and aragonite saturation states, and relatively higher dissolved oxygen concentrations in 2024 are attributed to an unusually high-volume flux of Labrador Slope water flowing southward onto the New Jersey shelf.

This project also highlighted the response of the region's ecology to differences in the timing and intensity of these events and to variability in the magnitude of oceanographic variables. Zooplankton and pelagic fish and squid distribution in New Jersey coastal shelf waters exhibited high spatiotemporal variability. Overall, zooplankton and pelagic fishes/squid exhibited similar seasonal and interannual trends, and their interannual trends tracked with significant differences in oceanographic conditions between the two observation years. Zooplankton and fish concentrations were lower in 2024 Spring and Summer, respectively, compared to 2023. This could be the result of a number of factors, both bottom-up (physical drivers) or top-down (predation). Lower overall concentration of pelagic fishes in 2024 could have been a response to colder temperatures, or other drivers associated with the higher influx of the Labrador Slope water mass, affecting timing of seasonal migrations. High predation rates of copepods by baleen whales may explain the dramatic decline in large copepod concentrations between Winter and Spring 2024, aligning with the observations of the highest marine mammal total detection number and detection days in Spring 2024.

The high spatiotemporal resolution of the monitoring strategy employed in this study increases our ability to characterize natural variability of the system throughout a year. These observations can be used as a baseline for detecting potential effects of offshore wind development and operation and/or comparison against future observations of environmental and biological fluctuations and long-term changes in New Jersey's coastal system. These results demonstrate the important role oceanographic conditions and variability play in driving the distributions and concentrations of zooplankton, fishes, and marine mammals. The data produced as a result of this project has provided comprehensive datasets that serve many users and support a wide breadth of ongoing research. For example, this project provides contextual data and information for other funded RMI projects, and baseline information to support future hypothesis-driven research within the RMI research priority areas. Continuing to collect high resolution observation data will be critical for understanding how the timing and magnitude of oceanographic variables, combined with predator-prey interactions, may influence populations of ecologically and commercially important marine organisms.

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Introduction and Motivation

The Mid-Atlantic Bight (MAB) is bounded by Massachusetts to the north and North Carolina to the south, and is separated by the Hudson Shelf Valley extending from the mouth of the Hudson River out to the continental shelf-break. The physical oceanography of this region is influenced by local topography, freshwater input from rivers and estuaries, large scale atmospheric patterns over the North Atlantic, and tropical or Winter coastal storm events. Therefore, the ocean characteristics on the MAB shelf, including in the planned offshore wind energy areas, undergoes remarkable variability across time scales from days and weeks to seasons, years, and decades. The "Cold Pool", a region of cold remnant Winter water near the bottom of the water column, develops seasonally and persists from Spring to Fall on the continental shelf in the Northeast US (Houghton et al., 1982), and is an important driver of biological patterns (e.g., Malone et al. 1983, Sullivan et al. 2000, Steves and Cowen 2000, Sullivan et al. 2005). This intense ocean variability drives an equally variable ecosystem from primary producers to highly migratory fishes and marine mammals. The tight coupling between the ocean conditions and the habitat preference of local and migratory species leads to distributions that can significantly vary between seasons and years. Furthermore, the MAB is situated in one of the most rapidly warming ocean regions in the world and is vulnerable to both ocean and coastal acidification. The continental shelf off of New Jersey has been experiencing ocean warming since the 1970's, and the environmental phenology of the system has shifted to include earlier Spring transitions and later Fall cooling (Friedland and Hare, 2007). Notably, the overall warming trend is projected to continue, where under a doubling of CO_2, warming could increase by 3-4°C in the next 70 years (Saba et al., 2016). These long-term environmental changes are associated with observed and projected changes in species distributions, biomass, and diversity. Therefore, time scales of variability – from seasons (at a minimum) to years - must be considered in approaches to quantify, and potentially isolate, potential offshore wind effects on marine ecosystem processes from long-term changes.

New Jersey has set a goal to procure half of its energy from renewable resources by 2030.[2] Even though there is currently a pause in development due to a recent Federal executive order, New Jersey remains focused on offshore wind power playing a critical role in achieving renewable energy goals and creating a more sustainable economy in the state (NJ Executive Order No. 8, 2018). New Jersey fisheries also play a critical role in the state economy; landings generated $166 M in revenues in 2015, with sea scallop ($98 M) and ocean quahog ($11 M) accounting for close to two-thirds of landings revenues for the year. Including importers, fisheries industries account for over 31,000 New Jersey jobs and almost $1.3 B in income for the State (NMFS, 2017). Ocean warming has led to vulnerability in approximately half of the U.S. Northeast Shelf species (Hare et al., 2016), and the dominant response of fish species to ocean warming has been distribution range shifts poleward. Furthermore, NJDEP published the 2020 New Jersey Scientific Report on Climate Change which states, "New Jersey is at increased risk to the effects of ocean acidification due to its economic dependence on shellfish harvests, with southern New Jersey counties ranking second in the United States in economic dependence on shelled mollusks" (New Jersey Department of Environmental Protection, 2020).

With offshore wind construction planned for New Jersey, it is critical that oceanographic and ecological baseline monitoring begin immediately. Leveraging our significant experience and existing

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[2]https://dep.nj.gov/cleanenergy/nj/

resources, this project implemented comprehensive, non-extractive monitoring of the coastal waters off New Jersey, overlapping with planned offshore wind development areas, using autonomous underwater vehicles (AUVs) called gliders. Throughout this project, we provided baseline monitoring data to support the offshore wind planning process and allow for the examination of potential changes during development and operational phases, as well as provided valuable information relevant to ongoing environmental and ecological changes in New Jersey' productive coastal waters. The resulting seasonally-resolved 3D view of regional ocean and ecological conditions includes physical and chemical variables, and biological variables spanning multiple trophic levels – from phytoplankton and zooplankton to pelagic fish and marine mammals.

By providing comprehensive oceanographic and ecological measurements, this project advances the mission of the New Jersey Offshore Wind Research and Monitoring Initiative (RMI). Several RMI objectives are met with this scientifically rigorous, hypothesis-based, and scientifically defensible research, including these short-term highest-priority research areas: 2 (Environmental Change), 3 (Benthos), 7 (Fishes & Invertebrates), and 10 (Marine Mammals), and several other RMI projects are supported by these data (see Section 'Conclusions and Recommendations for Future Research'). The RMI glider data are also informing each of the following RMI research priorities: 1) Establish an adaptable framework for future offshore wind research and monitoring efforts; 2) Contribute to and leverage the greater regional research effort; 3) Identify and inform actions for adaptive management; 4) Examine seasonal habitat use of organisms and drivers of those patterns; and 5) Examine the potential impacts of OSW on oceanographic variables and organism biomass, distribution, and connectivity. The latter two priorities are also shared by several other entities, including the recently released Regional Wildlife Science Collaborative for Offshore Wind (RWSC) science plan, the Responsible Offshore Science Alliance (ROSA), the Bureau of Ocean Energy Management (BOEM), and National Marine Fisheries Service (NMFS). All data collected under this RMI-funded project are openly accessible so that all regional projects will have the ability to integrate these oceanographic and ecological data into their data synthesis. The importance of continued oceanographic and ecological monitoring is recognized by New Jersey and RMI has awarded funding to maintain the high resolution, glider-based observing program initiated by this project through 2028.

Project Design and Methods

This project supported the procurement of observing platforms, specifically three gliders and several science payload bays and associated sensors, that were used to conduct ten glider deployments per year for two years in New Jersey coastal shelf waters, with greater than seasonal resolution. Data analysis efforts and data products thus far have focused on the examination of seasonal progressions and interannual variability in oceanographic and ecological data and developing a better understanding of spatiotemporal distribution of pelagic organisms (zooplankton, squid, fishes) and marine mammal presence.

Equipment Purchasing

Three Slocum gliders with integrated science bays (ru39, ru40, ru41), three spare science bays, and associated sensors were ordered in June 2022, obtained in February-March 2023, and prepped and tested in the Rutgers University glider laboratory prior to the first paired glider seasonal survey (April-May 2023) (Fig. 1).

The paired gliders for the first seasonal mission (ru39, ru41; Spring 2023) were deployed out of Sandy Hook, New Jersey on April 20, 2023. Unfortunately, contact with ru41 was lost after only four days (April 24, 2023), and the glider was never found/retrieved. No alerts or warnings (e.g., drop weight, abort) were received from the glider before the communication loss. From the Rutgers University glider team's extensive glider experience, three possibilities could have been responsible for the loss of ru41: 1. entanglement at depth in fishing gear, 2. vessel strike or interaction with ocean organism (i.e. shark or other large predator), or 3. a software failure (rare and least likely). The glider was formally designated lost at the end of May, over a month after contact was lost. The glider and sensors were insured. The Rutgers University team submitted the insurance claim in early June, and a replacement glider was ordered on August 2, 2023 upon insurance payout. Given the contingencies we included in this project, including a third glider and additional sensor bays and another leveraged glider, Rutgers devised a plan forward to adapt to this unfortunate circumstance and maintain the deployment schedule. The new replacement glider (ru43) was received in February 2024 and was equipped with the same sensors that were integrated in ru41: a Sea-Bird CTD, a Wetlabs FLBBCD-SLC ECOpuck, an Aanderaa optode, a WHOI DMON, a Vemco Rx-Live passive receiver, and rechargeable lithium batteries. RU43 was worked into the RMI deployment rotation shortly after.

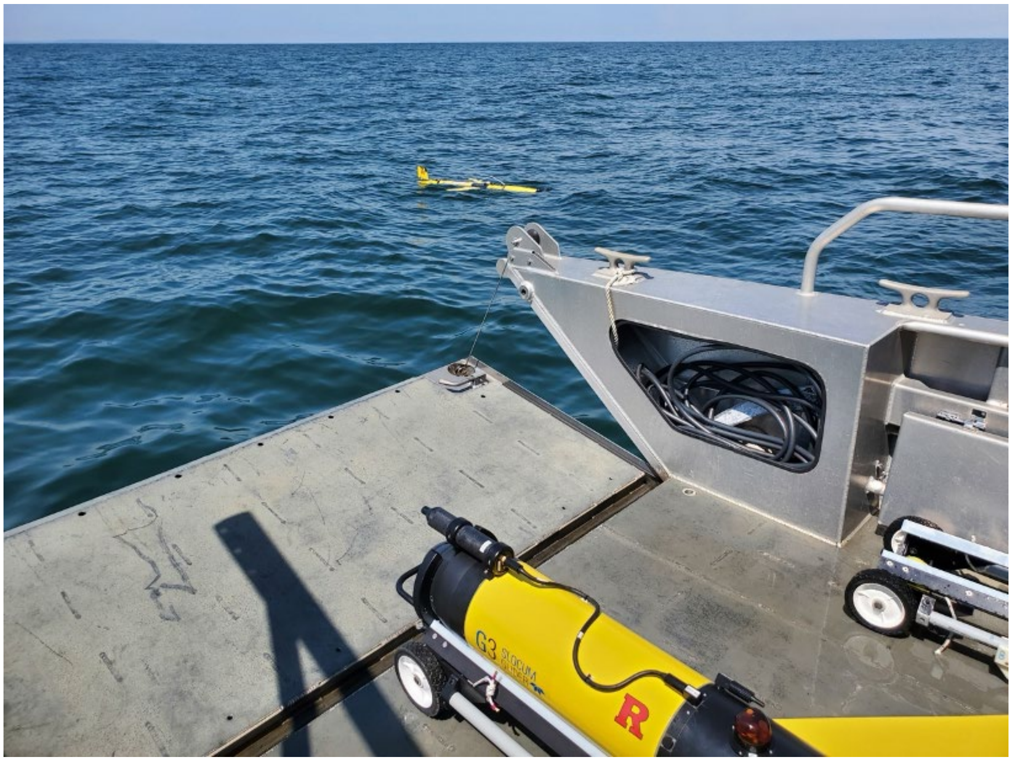


Figure 1. RMI gliders during deployment on a paired seasonal mission. Photo credit: Chip Haldeman, Rutgers University.

Glider Deployments

Slocum gliders are AUVs that navigate ocean waters collecting high-resolution data at various depths throughout the water column (Schofield et al., 2007). Gliders have proven to be particularly robust vehicles in the coastal waters of the MAB, completing missions supporting hurricane response (Glenn et al., 2016), water quality monitoring for federal and state agencies (Kohut et al., 2014), and numerous other scientific insights about this complex coastal system (Castelao et al., 2008; Glenn et al., 2008; Oliver et al., 2013; Miles et al., 2015; Glenn et al., 2016; Oliver et al., 2017). Sensors integrated into the gliders are capable of sampling multiple parameters approximately every one to two seconds along the glider transects. Gliders operate, or 'fly', in a see-saw pattern; therefore, data can be collected from surface to bottom, east to west, and north to south providing a detailed 3D view of ocean and ecological conditions within and around a study area, such as designated offshore wind lease areas.

We implemented a comprehensive deployment strategy that optimized and maximized measurements for oceanographic and ecological baseline assessment in relation to New Jersey's offshore wind development activity. The deployment schedule and sensor configuration considered the significant seasonal variability in both the oceanography and ecology within the region of interest, the large suite of parameters that are needed to address the full scope of the RMI research priorities, and the known realities of operating a glider monitoring program off the New Jersey coast, including required maintenance and calibration schedules, glider endurance, and mitigating sensor interference.

Seasonal Paired Missions: We conducted a seasonal baseline survey with a pair of gliders deployed in each season over two years with a full complement of available sensors to simultaneously map oceanographic and ecological variables (Table 1). Each mission lasted 3-4 weeks. Two gliders were paired for each seasonal mission to accommodate the larger sensor suite and mitigate interference between active and passive sensors. One glider was equipped with a CTD sensor (to determine water depth, temperature, salinity, and density), an optics puck measuring chlorophyll-a and colored dissolved organic matter (CDOM) fluorescence, an optode measuring dissolved oxygen, and a DMON passive acoustics sensor for marine mammal monitoring and detection (Baumgartner et al. 2019, 2020). The second glider was equipped with an optics puck and an Acoustic Zooplankton Fish Profiler (AZFP; Chave et al., 2018) multi-frequency echo sounder for active acoustic detection of pelagic organisms. Similar to the first glider, the second glider contained a CTD, but this CTD package also included an integrated deep ISFET-based pH sensor for ocean acidification applications. Both gliders also carried a VEMCO acoustic telemetry receiver to track acoustically tagged species moving through the region.

Glider Endurance and Sensor Interference: To simultaneously measure all of the above listed variables without sacrificing data quality and resolution and glider endurance, two separate gliders were deployed in tandem for the seasonal missions. Sensor interference must be considered when deploying this specific suite of sensors. For example, interference can occur when active and passive acoustic sensors are integrated and operating on the same glider, unless sampling the respective sensors is alternated (which will reduce spatiotemporal resolution of both sensor measurements). Additionally, the more sensors deployed on a single glider will require more battery capacity, reducing the glider deployment endurance. Under our executed configuration, our tandem glider deployments maximized the suite of sensors deployed at the highest resolution, ensured the necessary endurance to complete the mission, and mitigated known or expected interference between sensors.

Active Acoustic Configuration: Depending on the configuration of the transducers' frequencies, the AZFP sensor can be used to detect with higher confidence either (but not both) smaller organisms like zooplankton or larger organisms like pelagic fish. Zooplankton (e.g., copepods) are a major food source for many pelagic fish and squid species and some baleen whales (e.g., North Atlantic right whale) and therefore are a key link in the trophic food chain. Therefore, understanding zooplankton distributions and abundance could inform locations of North Atlantic right whale foraging hotspots relative to offshore wind development areas. Pelagic squid and fish, specifically small bodied species such as herring, mackerel, butterfish, and menhaden, are not only another major food source for other fish and mammal (e.g., humpback whale) species, but are also targets of local fisheries. Therefore, we selected specific acoustic frequency ranges for different seasonal surveys to target dominant predator-prey interactions. Specifically, we proposed to deploy the zooplankton-configured AZFP unit (with 125, 200, 455 kHz frequencies) during months when North Atlantic right whales are actively migrating through the area (November – April) to capture interactions with copepods and other zooplankton. The pelagic fish-configured AZFP unit (with 38, 125, 200 kHz frequencies) was planned for deployments during Summer and Fall to capture humpback whale interactions with sandlance and/or menhaden. There were some deployments where we had to deviate from this plan (e.g., when the pelagic fish-configured AZFP malfunctioned and had to be repaired) (Table 1).

Gap Fill Missions: In addition to the paired seasonal missions, we deployed a single glider twice in each year that was equipped with the CTD/pH or CTD and DMON, optics puck, optode, and VEMCO acoustic receiver. These deployments filled coverage gaps between seasonal glider deployments from the onset of seasonal stratification associated with the Cold Pool formation in the Spring to the physical breakdown in the Fall. Recognizing that the exact timing of Cold Pool formation and breakdown varies from one year to the next (Chen and Curchitser, 2020), this deployment strategy ensured that the 2-year baseline contributed to Cold pool/offshore wind research priorities (Miles et al., 2021) by capturing these key ocean events and the concurrent ecological response.

Deployment Schedule: The exact timing of each 3-4 week deployment was determined jointly by Rutgers University and the RMI team based on weather, environmental, and other logistical variables. We conducted a total of 20 glider deployments for this project. We conducted a paired-glider Spring 2023 mission (4/20 - 5/12), an Early Summer 2023 single-glider mission (06/29 - 08/02), a Summer 2023 paired-glider mission (08/17 - 09/20), an Early Fall 2023 single-glider mission (09/20 - 10/19), a Fall 2023 paired-glider mission (11/03 – 12/05), a Winter 2024 paired-glider mission (02/15 - 03/14), a Spring 2024 paired-glider mission (04/29 – 05/29), an Early Summer 2024 single-glider mission (06/12 – 07/09), a Summer 2024 paired-glider mission (07/23 – 08/23), an Early Fall 2024 single-glider mission (09/04 – 10/05), a Fall 2024 paired-glider mission (10/21 – 11/19), and a Winter 2025 paired-glider mission (02/26 – 03/28). These 20 deployments conclude two full annual cycles of data collection. Sensors aboard each glider and mission are included in Table 1.

Table 1. Summary of the 20 RMI glider deployments from Spring 2023 – Winter 2025, including season, glider name, and identification of the sensors integrated and ocean variables measured.

		Ocean Variables Measured							
Deployment time	Glider name	Salinity, Temperature, Depth[a]	pH[b]	Chlorophyll, backscatter, CDOM[c]	Dissolved oxygen[d]	Zooplankton biomass (active acoustics)[e]	Fish biomass (active acoustics)[f]	Marine mammal detection[g]	Tagged fish detection[h]
Spring 2023	ru39	X	X	X		X			X
Spring 2023	ru41*	X		X	X			X	X
Gap fill: Early Summer 2023	ru40	X		X	X			X	X
Summer 2023	ru39	X	X	X			X		X
Summer 2023	ru40	X		X	X			X	X
Gap fill: Early Fall 2023	ru34	X	X	X	X				X
Fall 2023	ru39	X	X	X		X			X
Fall 2023	ru40	X		X	X			X	X
Winter 2024	ru39	X	X	X		X			X
Winter 2024	ru40	X		X	X			X	X
Spring 2024	ru39	X	X	X		X			X
Spring 2024	ru40	X		X	X			X	X
Gap fill: Early Summer 2024	ru43	X	X	X	X				X
Summer 2024	ru39	X	X	X			X		X
Summer 2024	ru40	X		X	X			X	X
Gap fill: Early Fall 2024	ru43‡	X	X	X		X			X
Fall 2024	ru39	X	X	X			X		X
Fall 2024	ru40	X		X	X			X	X
Winter 2025	ru39	X	X	X			X		X
Winter 2025	ru40	X		X	X			X	X

[a]Sensor = Sea-Bird CTD
[b]Sensor = deep-sea ISFET based pH sensor, coupled with [a]CTD
[c]Sensor = Wetlabs FLBBCD-SLC ECOpuck
[d]Sensor = Aanderaa optode
[e]Sensor = ASL Acoustic Zooplankton Fish Profiler (AZFP), a multi-frequency echosounder configured for zooplankton (120, 200, 455, 769 kHz)
[f]Sensor = ASL Acoustic Zooplankton Fish Profiler (AZFP), a multi-frequency echosounder configured for pelagic fishes (38, 120, 200 kHz)
[g]Sensor = WHOI DMON
[h]Sensor = Vemco Rx-Live or Vemco VMT
*glider lost; replacement ordered

‡ru43 = new glider (replacement to lost glider ru41)

Survey Design

All proposed glider missions covered approximately the same spatial extent and transect (Fig. 2). The zig-zag path of the glider missions covered an area from Sandy Hook down to Atlantic City throughout the New Jersey outer continental shelf (OCS), from coastal nearshore extending to the shelf break. This ensured that the monitoring occurred both along established long-term transects for historical context and within multiple offshore wind lease areas.

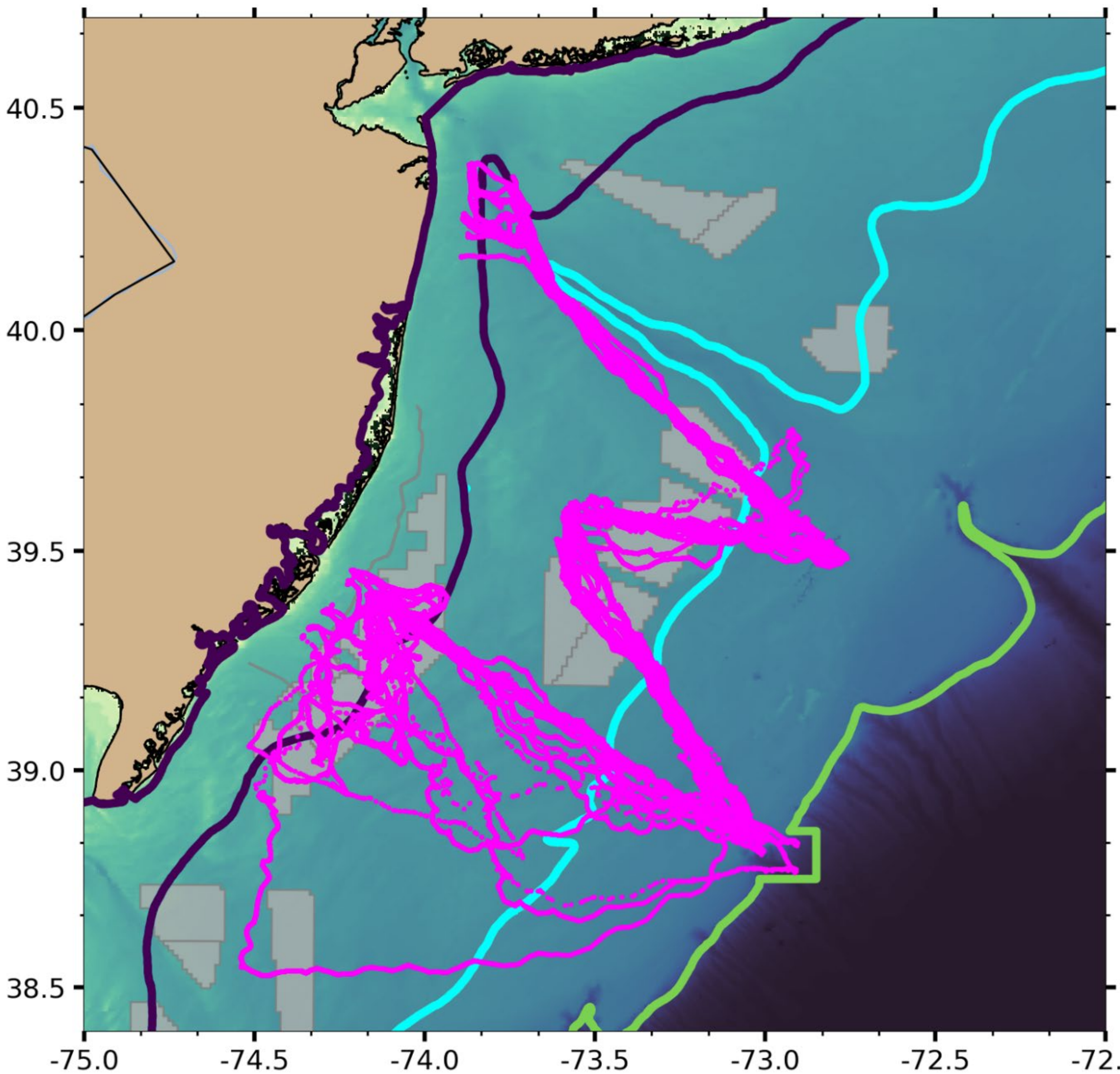


Figure 2. Map depicting the transects from 20 RMI glider deployments (magenta lines) on the New Jersey coastal shelf. Colored bathymetry lines indicate Inshore-Midshelf-Offshore strata used in data analyses (modified from the standard NOAA NEFSC strata), where the area bounded inside the dark purple lines represents the Inshore stratum, the area between the farthest offshore dark purple line and the cyan line represents the Midshelf stratum, and the area between the cyan line and the green line represents the Offshore stratum (see Section 'Results'). Gray polygons represent the Bureau of Ocean Energy Management (BOEM) wind lease areas.

Spring, Summer and Fall paired RMI deployments were coordinated with nearshore glider deployments funded by NJDEP's Bureau of Marine Water Monitoring (BMWM), which allowed for synchronous observations over a larger area of the OCS to better understand spatial variation in oceanographic conditions off of New Jersey. In 2024, funding from BMWM supported the addition of a pH sensor to some deployments of the nearshore NJDEP glider to expand the spatial coverage of carbonate chemistry monitoring and to monitor for potential multi-stressor conditions (low pH/Ω and dissolved oxygen), similar to what was observed during the Summer 2023 missions (see 'Results – Multi-stressor Events' below).

Vessel-Based Sampling: For glider surveys that included pH measurements (see Table 1), discrete water samples were collected at glider deployment and recovery. These samples were used to assess carbonate chemistry (pH, total alkalinity, dissolved inorganic carbon) and to ground truth the glider pH sensor (i.e., to calculate the field accuracy of the glider-based pH sensor). Ship-based water samples were collected at multiple depths (surface, near-bottom, and the thermocline, if present) via Niskin bottles mounted on a CTD-rosette, or via individual Niskin bottle casts, and preserved with saturated mercuric chloride until analysis. pH (on the Total pH scale) of water samples was measured spectrophotometrically at 25°C with purified meta-cresol purple (mCP, Liu et al. 2011) using 10 cm pathlength cylindrical glass cells and an Agilent Technologies Cary 8454 UV-Vis spectrometer. pH was calculated according to the equations presented in Douglas and Byrne (2017). Total alkalinity (TA) open-cell titrations for water samples were performed by a custom-built titration apparatus, following the approach of Standard Operating Procedure 3b (Dickson et al. 2007). DIC was quantified using a non-dispersive infrared method (Chen et al., 2015; Huang et al., 2012). TA and DIC accuracies were determined using Certified Reference Materials (CRMs) from Andrew Dickson's group at the Scripps Institution of Oceanography. Analyses were performed by the Stony Brook University Coastal Fluxes Lab.

For glider surveys where the zooplankton-configured AZFP was operating (see Table 1), net tows were conducted at glider deployment and recovery to collect species, abundance, and size information for dominant zooplankton present. Zooplankton data from net tows were used to help inform the acoustic models (with length frequency distribution and shape- and taxon-specific scattering properties) to identify the dominant scattering organisms responsible for the acoustic signatures observed. Zooplankton were collected by performing replicate oblique tows from the surface to approximately 5 m above the seafloor with a 0.25 m2, 200 micron mesh net with filtering cod-end and preserved in 10% buffered formalin. Net depth was estimated using wire angle and length of wire until April 2025 when the depth was measured using a HOBO Titanium 250-Foot Depth Water Level Data Logger attached to the net. In the lab, each tow was split to obtain a representative sample, and individual zooplankton were identified to lowest feasible taxonomic group and counted using a dissecting stereo microscope.

Data Quality Assurance and Quality Control

Principal Investigators (PIs) Saba and Kohut prepared a project-specific Quality Assurance Project Plan (QAPP) that was reviewed and approved by NJDEP in March 2023. This plan contains highly detailed information on sampling procedures for each glider sensor and for vessel-based measurements, sample custody procedures, data processing procedures, analytical procedures, data quality requirements and assessments, sensor calibration procedures and preventative maintenance, and documentation and reporting. The QAPP for this project is provided below as Appendix 1.

Data Analyses

Oceanographic Data Analyses: For each glider profile, surface data were defined as the average of the data collected between 1-5m depth and bottom data were defined as the average of the data collected between the maximum profile depth and 4m above. The bottom depth of the profile was compared to GEBCO's gridded bathymetry data (https://www.gebco.net/) to ensure that the maximum profile depth was within +/- 20% of the water depth at the profile coordinates from the global bathymetry file. If the glider profile depth was not within +/- 20% of the bathymetry depth, the data were not included in the bottom data analysis. If the profile had a defined mixed layer depth (calculated as the depth of max Brunt-Vaisala frequency squared (N^2) from Carvalho et al. 2017), the profile data were binned into 1-m depth bins to find the chlorophyll-a maximum value and depth. The associated dissolved oxygen and pH maximum values were located within +/- 3m of the chlorophyll-a maximum value depth. If there was no defined mixed layer, the data from the profile were not included in the chlorophyll-a maximum analysis.

Data from each glider sensor profile were binned according to region (Inshore, Midshelf, Offshore, based on modified NOAA bottom trawl survey strata downloaded from https://github.com/NOAA-EDAB/FisheryConditionLinks/tree/master/NES_BOTTOM_TRAWL_STRATA), and season (Spring: Mar-Apr, Summer: June-Aug, Fall: Sept-Nov, Winter: Dec-Feb) based on the profile timestamp. These binned data were used to develop boxplots for data visualization and comparison between seasons and years. Significant seasonal differences between region and year were determined using Kruskal-Wallis analysis with a Dunn post hoc test. Unless otherwise specified, all statistical analyses were performed using scipy (version 1.15.1) and skikit-posthocs (version 0.11.4) in Python 3.13.1, and a p-value of <0.05 was considered statistically significant. The scripts for the oceanographic data analyses are available in Github here.

Passive Acoustic Detections of Marine Mammals and Tagged Individuals: Glider-based marine mammal monitoring was conducted using the digital acoustic monitoring instrument (DMON), a passive acoustic instrument that records and processes audio in real-time. A low-frequency detection and classification system (LFDCS; Baumgartner and Mussoline, 2011) uses spectrograms to produce pitch tracks of sounds, or changes in the pitch of a call over time. The LFDCS identifies simple statistics for each pitch track, including duration, average frequency, and rate of change of frequency, using a discriminant function analysis to classify each call based on a known set of pre-defined calls. A subset of LFDCS-detected pitch tracks are sent back to a shore-based computer in real-time and evaluated by an expert human analyst at least once per day. Detections confirmed by the analyst are then posted to the Robots4Whales website in near real-time. Each of these detections indicates a whale call, but distinctions between individual whales (as opposed to multiple calls from a single whale) cannot be defined in this analysis. The specific location of each whale detected also cannot be determined, and in some cases may be occurring very far from the hydrophone, as detection range is dependent on several factors including glider orientation, seasonal changes in water properties that affect sound propagation, differences in call behavior, and species-dependent call range which can vary from approximately 10km for right whales to 100s-1000s of km for fin whales (Harris et al., 2018; Johnson et al., 2022; Pepper, 2023). More information on the process, and example spectrograms, are available at https://robots4whales.whoi.edu/about/how-it-works/.

Glider deployments carrying a Vemco Rx-LIVE acoustic receiver provide real-time detection of acoustic transmitters on tagged wildlife as ASCII files, which include detection time, a tag ID unique to an individual, and several other status fields. When paired with a DMON, these detections are mapped to location by interpolating to the glider path and are plotted on Robots4Whales. Gliders deployed with a Vemco Mobile Transceiver (VMT) do not provide data availability in real-time, but collect similar data fields as the Rx-LIVE. Upon recovery, raw receiver download files from Rx-LIVE and VMT are sent to the Mid-Atlantic Acoustic Telemetry Observation System (MATOS), the Atlantic Cooperative Telemetry Network's interoperable database, along with all associated metadata including glider path, deployment and recovery location and time, and project information. MATOS stores receiver array and tag information from several researchers, and every 4 months, cross-matches tag and receiver information and sends any matches back to data providers. The returned data extraction for receivers includes time, derived location, and tag ID for each detection. For any tags with information in the MATOS database, contact information and project ID are also provided; however, the tag owner needs to be contacted for any additional information, including species. If a tag ID is not registered in MATOS, it is not always possible to identify the tag owner(s) to contact. More information on MATOS processing is provided at https://matos.asascience.com/home/about.

Active Acoustic Data Analysis: For each deployment with either a zooplankton- or pelagic-fish configured AZFP (Fig. 3), pitch, roll, GPS fixes, and depth data were calculated from glider measurements and converted into tab delimited *.csv files compatible with Echoview software (v. 15.1.68). Raw acoustic data were linked to the pitch, etc. data by time stamp and processed using Echoview software. Glider downcasts were isolated by masking out portions of the data with pitch outside the range of -15 and -30 degrees, roll outside the range of -7 to 7 degrees, near-field echoes (3-4 m from the transducer) and the ocean bottom (where applicable), which were removed from analyses. The AZFP is mounted at a 22° angle on the glider, so it is directly perpendicular to the seafloor only on glider dives. The pitch and roll constraints are to filter out upcasts and any times during downcasts when the glider was rolled too far to one side or another for the AZFP to be pointed directly downwards. It is standard procedure to remove near-field echoes, as their physical properties are different from echoes obtained further away from the AZFP. Calibration parameters and offsets retrieved during AZFP calibrations were applied to the echogram, including speed of sound and absorption coefficients calculated from five-day averages of glider CTD data. Echoview's Background Noise Removal (De Robertis and Higginbottom, 2007), Impulse Noise Removal, and Transient Noise Removal (Ryan et al., 2015) algorithms were used to clean the raw acoustic data from each frequency.

After the removal of background and impulse noise, the acoustic data were exported from Echoview by integrating over cells 1 m deep and 0.1 nautical miles long (measured along the glider track). This method creates vertical profiles for each 0.1 nautical mile segment of the glider track by averaging horizontally across each 1 m depth bin contained within that segment. This is similar to the dive-to-vertical-profile method described in Reiss et al. (2021), except that a given horizontal integration cell may contain varying amounts of glider dives (including less than one dive) depending on the depth of the water column, which varied from 15 m to over 200 m over the course of most deployments. Because of this water depth variation, creating vertical profiles from distance along the glider track, instead of on a per-dive basis, were more expedient.

For data obtained from the zooplankton-configured AZFP (Fig. 3, left panel), each integration cell was assigned a species label based on dB differencing methods - Large Copepod, Gelatinous Zooplankton, or Empty Cell. Attempts were made to quantify small zooplankton using acoustics, specifically small copepods that are historically highly abundant in the region and observed in high numbers in our reported discrete zooplankton tow data. However, due to the much wider variety of fluid-like scattering animals in the same size range as small zooplankton, we encountered difficulties creating a robust target strength model for use in concentration and biomass estimates. For this reason, and because the large copepods in the MAB are more ecologically relevant to whale populations (especially North Atlantic right whales), we elected to focus solely on large copepods for acoustic concentration and biomass estimates. We specifically targeted *C. finmarchicus* as that was the only copepod species we encountered in the discrete zooplankton tows that is considered "large" (prosome length consistently >1 mm), and there are established acoustic models for this species. For each large copepod cell, large copepod concentration and biomass were calculated from the measured volume backscatter strength (S_v) value via the forward problem method and using target strength and individual dry weight values for *C. finmarchicus* stage IV-VI (Simmonds and MacLennan, 2005). These are presented as estimates of individuals (concentration) or grams (biomass) per meter cubed.

For data obtained from the pelagic fish-configured AZFP (Fig. 3, right panel), echoes were first categorized using dB differencing into one of four types: Gelatinous zooplankton, fish with an air-filled swim bladder, fish without an air-filled swim bladder, or empty cell. Specific species were then assigned based on the time of year the deployment was conducted, with these assignments based on dominant species collected in historical trawl data from NJDEP[3] and NOAA's Northeast Fisheries Science Center (NEFSC)[4] surveys conducted in the same geographical area as the glider deployments. During Summer and Fall months (June-November), all fish with air-filled swim bladder echoes were assigned the label "Menhaden", and all fish without air-filled swim bladder echoes were assigned the label "Longfin Squid". During Winter and Spring months (December-May), all fish with air-filled swim bladder echoes were assigned the label "Atlantic Herring", and all fish without air-filled swim bladder echoes were assigned the label "Atlantic Mackerel". It should be noted, however, that this is a very large assumption and may not be consistently accurate. Nevertheless, such an assumption was required for the use of specific target strength and weight values to derive estimates of concentration and biomass via the forward problem as described above. Some progress has been made using broadband echosounders to determine the community composition of a mixed-species assemblage (Loranger et al., 2022); however, because the glider-mounted echosounder is solely narrowband frequencies, this level of species identification was not possible.

In order to get depth-integrated measurements for both zooplankton and fish data, the data were first averaged into larger horizontal bins (expanding the horizontal measurement from 0.19 km to 6 km), then integrated over the depth range to obtain measurements with units of individuals or grams per meter squared. Similar to the oceanographic data, abundance and biomass data were binned according to season, region (Inshore, Midshelf, Offshore), location relative to wind farm lease area (Inside or Outside), and time of day (Day or Night) to compare the spatiotemporal distributions of concentration and biomass.

[3] https://dep.nj.gov/njfw/fishing/marine/ocean-stock-assessment-program/
[4] https://www.fisheries.noaa.gov/inport/item/22557

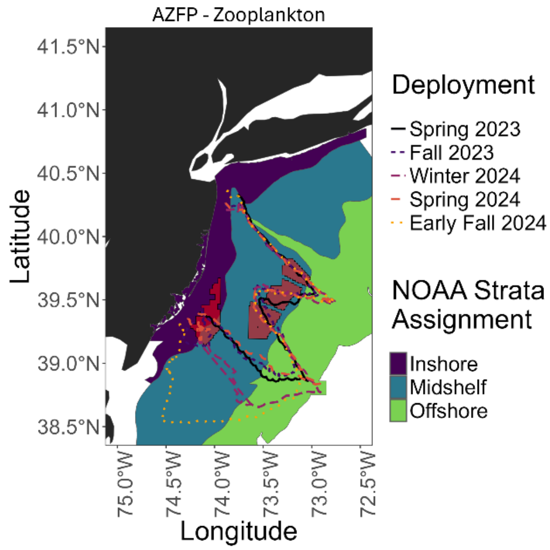


Figure 3. Map depicting the transects from RMI deployments of gliders equipped with Acoustic Zooplankton Fish Profiler (AZFP) active acoustic multi-frequency echosounders. Left panel: Deployments with zooplankton-configured AZFP; Right panel: Deployments with fish-configured AZFP. Colored bathymetry indicates Inshore-Midshelf-Offshore strata used in data analyses (modified from the standard NOAA NEFSC strata to account for deployments which extended over the continental shelf break), where the dark purple area represents the Inshore stratum, the dark cyan area represents the Midshelf stratum, and the green area represents the Offshore stratum (see Section 'Results – Active Acoustic Detections of Scattering Organisms'). Red polygons represent the Bureau of Ocean Energy Management (BOEM) wind lease areas.

Because shelf strata and offshore wind lease areas are both spatial variables, the percentages of the glider transect within each shelf strata, and the offshore wind lease areas within each shelf strata, were calculated. Across the distance traveled over all deployments, 23.9% was in the Inshore strata, 46.7% was Midshelf, and 29.4% was Offshore. Over all deployments, 25.1% of the glider's transect distance was within the lease areas. Of the distance traveled within the lease areas, 13% was in the Inshore strata, 86.2% was Midshelf, and 0.8% was Offshore. As construction has not yet commenced in this region, any differences in concentration observed inside vs. outside the lease likely reflect natural variability and patchiness of zooplankton, pelagic fishes, and squid. The scripts for the active acoustics data analyses are available in Github here.

Results

Oceanographic Data

Seasonal Progressions

Through the 20 deployments conducted in this project, RMI gliders were in coastal shelf waters 368 out of 708 days (52% coverage) and traveled 10,651 km. With this high temporal resolution (> seasonal), we observed the evolution of water column structure from Spring to intensified stratification in Summer to stratification breakdown in Fall and full water column mixing through Winter. With these physical transformations, we also observed simultaneous changes in water chemistry (dissolved oxygen, pH, aragonite saturation state) and chlorophyll-a (a proxy for phytoplankton biomass) (Figs. 4-7). Low concentrations of bottom water dissolved oxygen were observed and are further discussed in Sections 'Interannual variability' and 'Multi-stressor Events'. Event-based oceanographic changes were also observed (upwelling, Nor'easters, and the passage of tropical storms and hurricanes).

Seasonal Progressions in 2023: During the first deployment in Spring 2023, the initiation of seasonal thermal heating in surface waters was observed. This highlighted the start of a two-layer system that became more pronounced throughout the summer season (Fig. 4). Upwelling was observed during early Summer of 2023 (late July/early August), highlighted by sudden cooling of surface water which was likely due to injections of cold bottom water to the surface Inshore (Fig. 4, middle column). A majority of shelf bottom waters during Summer 2023 had dissolved oxygen concentrations < 5 mg/L, and near hypoxic levels of dissolved oxygen (concentrations < 3 mg/L) were observed in the shallowest, Inshore waters in Summer (Fig. 4). Dissolved oxygen concentrations at or below 5 mg/L are considered problematic for marine life due to negative impacts on metabolism, feeding, growth, and reproduction (Murawski et al., 1989; USEPA, 2000; Levin et al., 2009) and have been designated as limiting to marine organisms in New Jersey coastal shelf waters (Weis et al., 2017). Chronic exposure (>24 hours) to dissolved oxygen concentrations <3 mg/L have been shown to compromise juvenile growth and function (USEPA, 2000; Ramey, 2011; Taghon, 2017). The water column was temporarily mixed during the offshore passage of Hurricane Lee around 09/16/23 (Fig. 4, right column) which replenished bottom water dissolved oxygen. The water column re-stratified briefly before becoming fully mixed again after a strong hybrid storm (Nor'easter and Tropical Storm Ophelia) drove the Fall water column turnover on 09/26/23. The water column remained well-mixed through the Fall/Winter seasons (Fig. 5). The gradual ocean cooling from late Fall 2023 through Winter 2024 was also observed.

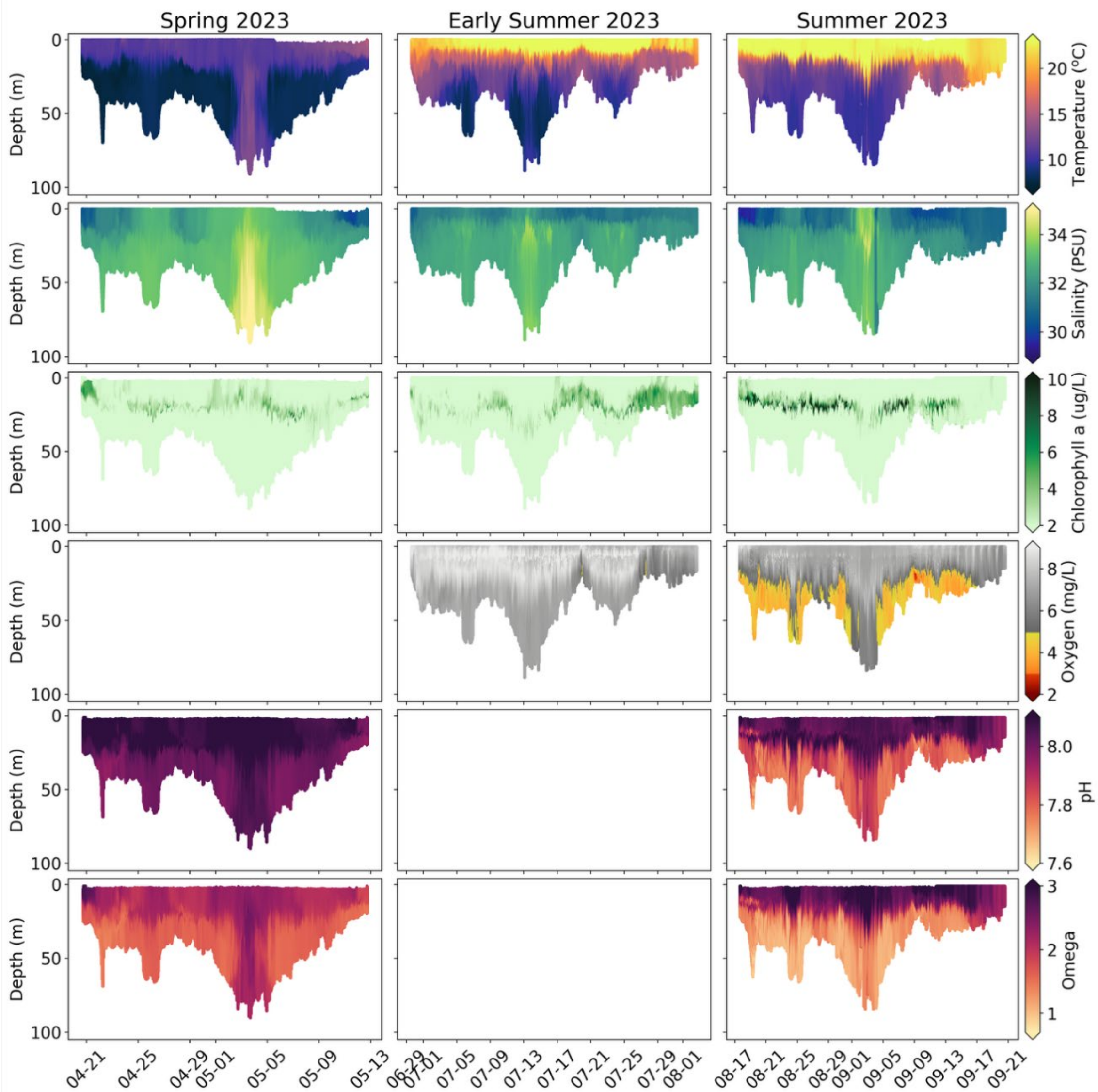


Figure 4. Complete vertical profiles of oceanographic variables measured along glider mission tracks through the New Jersey outer continental shelf (OCS; see mission tracks in Figure 2) during Spring 2023 (left column), Early Summer 2023 (middle column), and Summer 2023 (right column) glider deployments. Oceanographic measurements shown (from top to bottom row) are temperature, salinity, chlorophyll-a concentrations, dissolved oxygen concentrations, pH, and derived aragonite saturation state (Omega). Empty panels represent the lack of a sensor measuring that variable during that specific deployment.

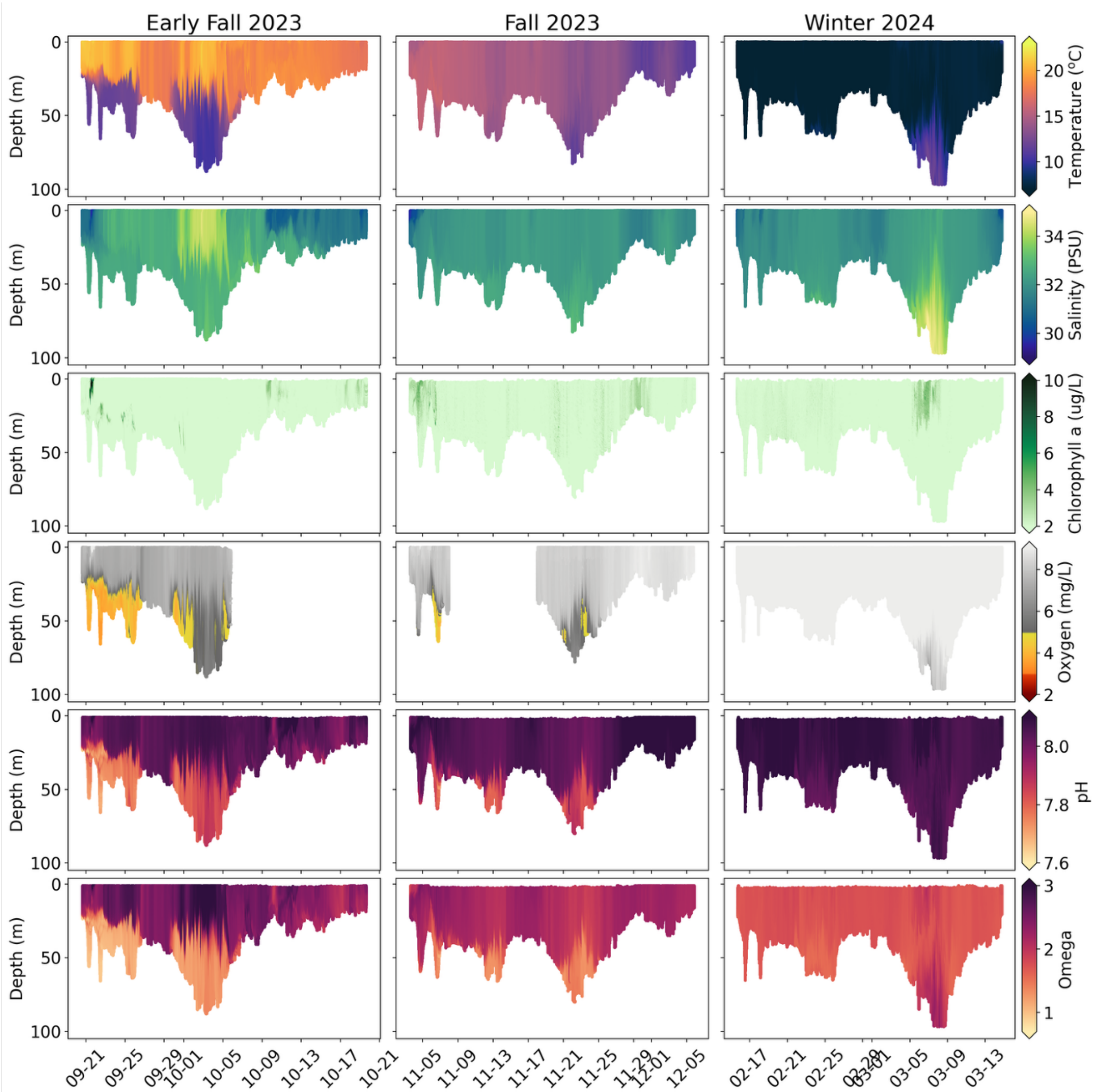


Figure 5. Complete vertical profiles of oceanographic variables measured along glider mission tracks through the New Jersey outer continental shelf (OCS; see mission tracks in Figure 2) during Early Fall 2023 (left column), Fall 2023 (middle column), and Winter 2024 (right column) glider deployments. Oceanographic measures shown (from top to bottom row) are temperature, salinity, chlorophyll-a concentrations, dissolved oxygen concentrations, pH, and derived aragonite saturation state (Omega). Gaps in data during a deployment represent sensor malfunctions that prevented measurements from being recorded.

Seasonal Progressions in 2024: The minimum bottom temperature during the Spring 2024 mission was measured at 6.09˚C, and the Cold Pool average temperature stayed near 7-8˚C through the early Summer and Summer 2024 missions (Figs. 6, 7; Table A3.1; See also Section 'Interannual Variability'). Typically, average Cold Pool temperature during this time of year is between 8-10˚C. Spring bottom waters were also relatively fresh, particularly Inshore and Midshelf which averaged 30.79 and 31.6 PSU, respectively (Table A3.2). Bottom seawater pH and aragonite saturation state (Omega) during Summer 2024 were the lowest we have observed in our history of glider-based ocean acidification monitoring (since 2018). Minimum bottom pH values (7.6) and aragonite saturation state (Omega) values (0.65) were observed across a large proportion of the shelf, particularly in the shallower areas. However, bottom dissolved oxygen remained above hypoxic levels (>5 mg/L; Fig. 6). Seasonal water-column stratification was strong throughout the first half of the early Fall mission and co-occurred with high subsurface concentrations of chlorophyll. This stratified, 2-layer system eroded in late September signifying the Fall turnover which, unlike in 2023, immediately homogenized the water column temperature, chlorophyll, pH, and aragonite saturation state (Omega) profiles resulting in warmed bottom water and increased bottom water pH and aragonite saturation state (Fig. 7). This occurred during stormy weather resulting from post-tropical cyclone Helene. The gradual seasonal cooling of shelf water and increases in pH and omega were observed during the Fall 2024 paired mission. The Winter 2025 glider mission, which covered part of the Spring 2025 season, observed anomalously cool ocean temperatures (averaging 5-6˚C) and the highest dissolved oxygen concentrations measured during the 2-year monitoring period (Figs. 6-7; Tables A3.1, A3.5).

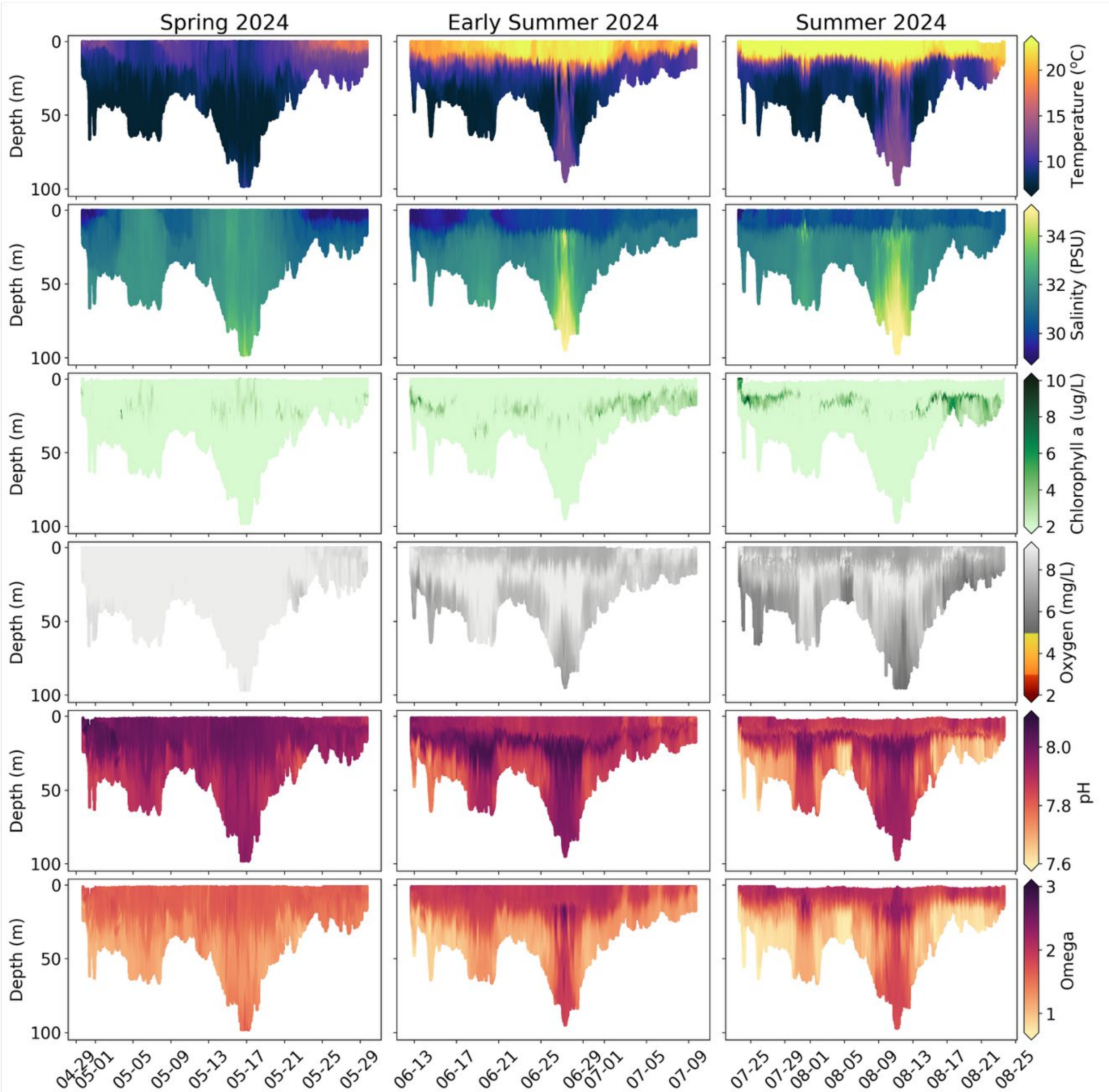


Figure 6. Complete vertical profiles of oceanographic variables measured along glider mission tracks through the New Jersey outer continental shelf (OCS; see mission tracks in Figure 2) during Spring 2024 (left column), Early Summer 2024 (middle column), and Summer 2024 (right column) glider deployments. Oceanographic measures shown (from top to bottom row) are temperature, salinity, chlorophyll-a concentrations, dissolved oxygen concentrations, pH, and derived aragonite saturation state (Omega).

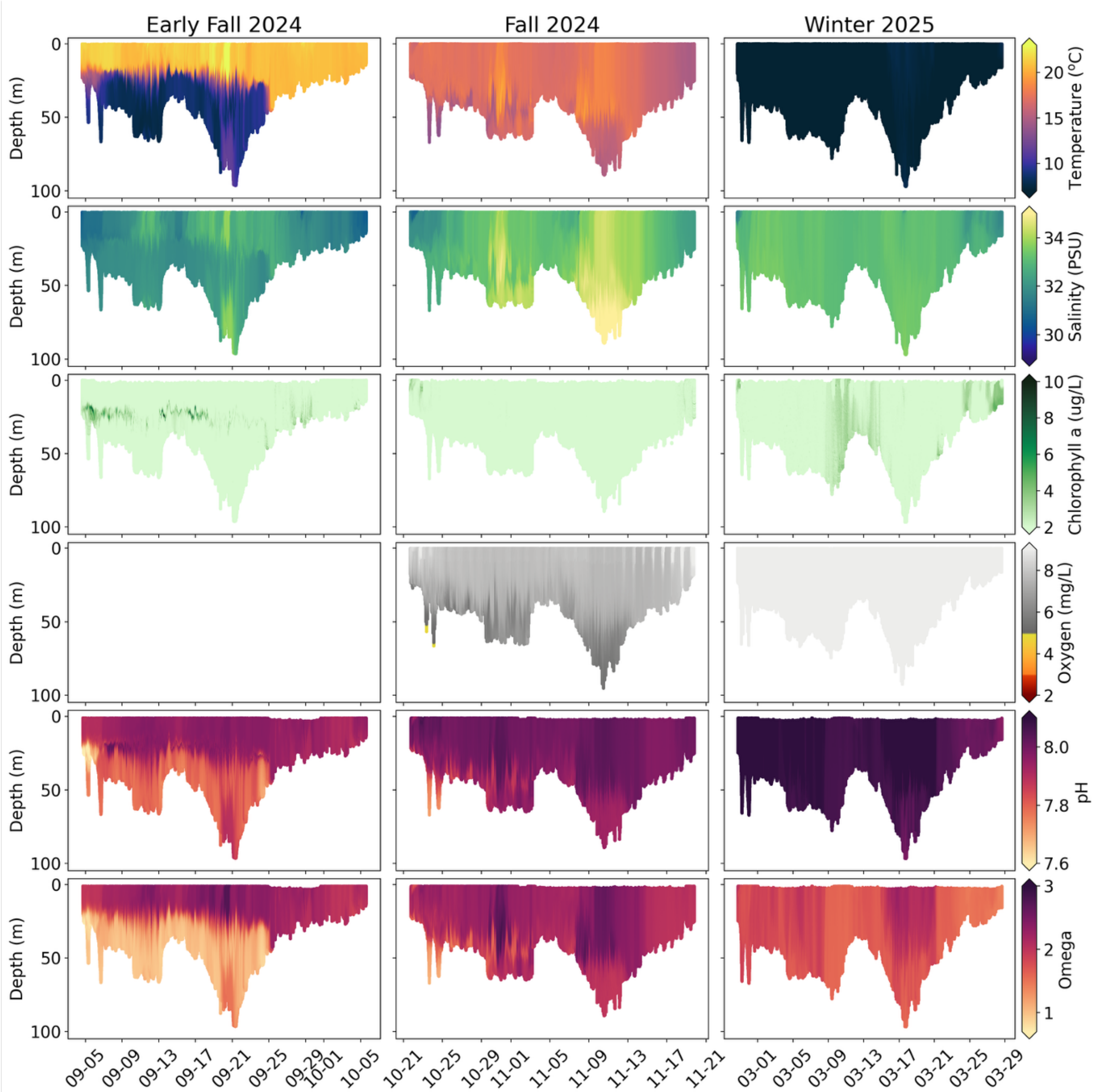


Figure 7. Complete vertical profiles of oceanographic variables measured along glider mission tracks through the New Jersey outer continental shelf (OCS; see mission tracks in Figure 2) during Early Fall 2024 (left column), Fall 2024 (middle column), and Winter 2025 (right column) glider deployments. Oceanographic measures shown (from top to bottom row) are temperature, salinity, chlorophyll-a concentrations, dissolved oxygen concentrations, pH, and derived aragonite saturation state (Omega). Empty panels represent the lack of a sensor measuring that variable during that specific deployment.

Interannual Variability

The progression from Summer 2022 (pre-RMI) to Summer 2024 in the Mid-Atlantic is characterized by an intense switch from a warmer bottom temperature anomaly in 2022 to a colder bottom temperature anomaly in 2024 (Fig. 8, row A).

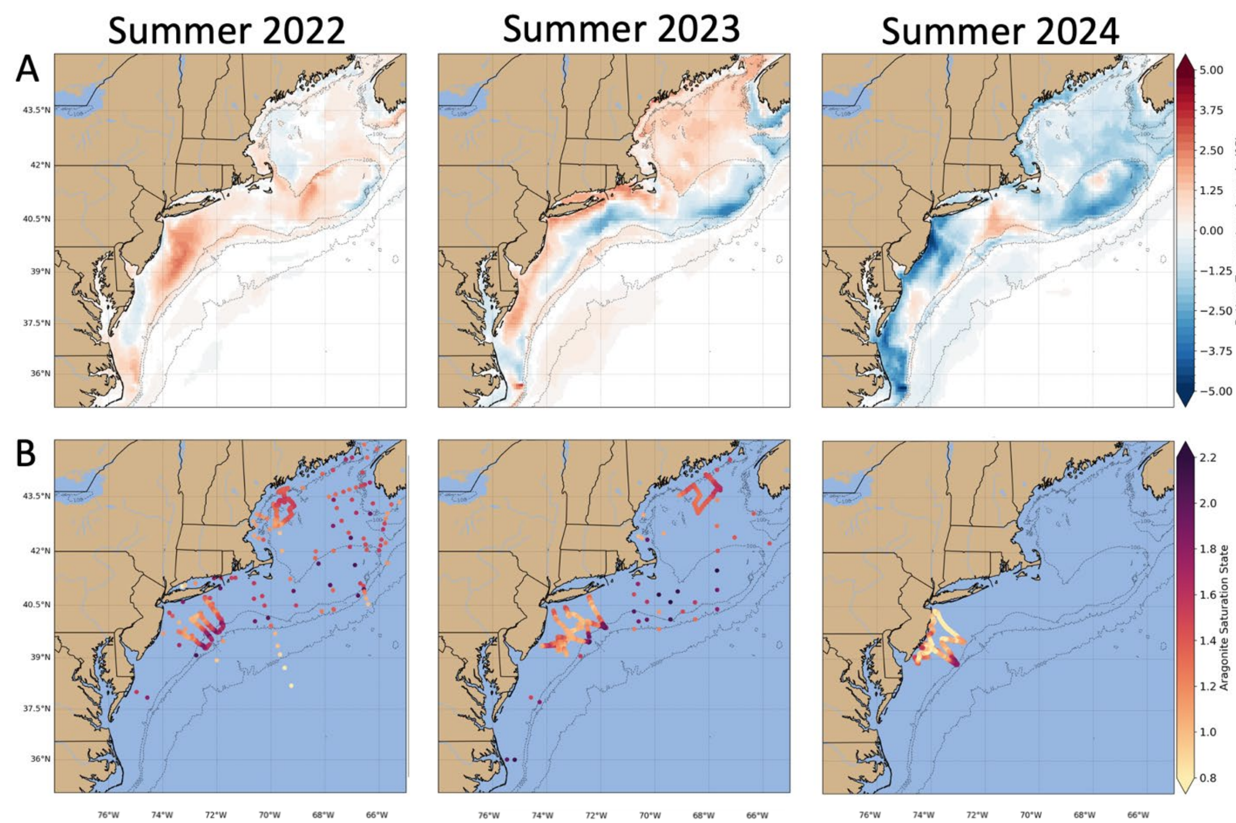


Figure 8. Bottom temperature anomaly (row A) and bottom aragonite saturation state (row B) for the Summers of 2022 (left column; before the start of this RMI glider project), 2023 (middle column), and 2024 (right column). The bottom temperature anomaly for each Summer-year was calculated as the difference from the Summer mean 2012-2024. Bottom temperature data courtesy of the E.U. Copernicus Marine Service Information (CMEMS): Global Ocean Physics Reanalysis (GLORYS12V1) dataset. The bottom aragonite saturation state values were those observed from available vessel- and glider-based efforts during the Summers of 2022, 2023, and 2024, including RMI gliders in 2023 and 2024. (Figure from the NOAA State of the Ecosystem Northeast US Ecosystem Indicator Catalog (#63 Ocean Acidification and other Stressors): https://noaa-edab.github.io/catalog/ocean_acidification.html)

Consistent with this trend, RMI gliders observed significantly decreasing average bottom temperatures in Spring (2023 to 2025; Midshelf and Offshore), Summer (2023 to 2024; full shelf), and Winter (2024 to 2025; Inshore and Midshelf, no Offshore data available) (Fig. 9, Table A3.1). The coldest ocean temperatures were recorded during Winter-Spring 2025, with averages between 5-6 °C across the shelf (Table A3.1). The relatively freshest bottom water was observed during 2024 in all seasons except for Fall (Fig. 10, Table A3.2).

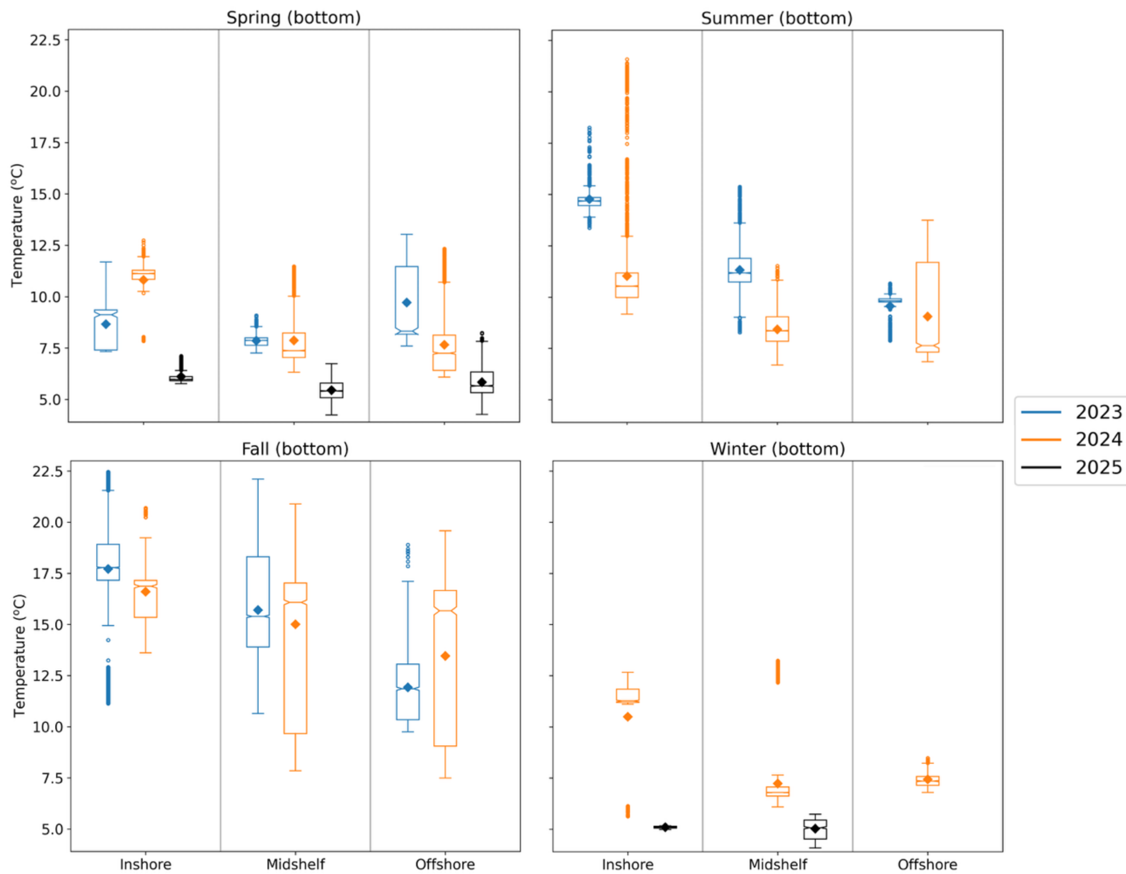


Figure 9. Bottom water temperature across the New Jersey coastal shelf for Spring (top left), Summer (top right), Fall (bottom left), and Winter (bottom right) of 2023, 2024, and 2025. The box limits extend from the lower to upper quartiles (25%, 75%), with a line at the median and a diamond symbol at the mean. The whiskers extend from the box by 1.5x the inter-quartile range (IQR). Circles indicate outliers and notches indicate 95% confidence interval around the median. (Note: The Winter 2025 deployment that occurred 02/26-03/28 extended into the Spring period (Mar – May); therefore, Spring 2025 boxes were included to capture the full deployment period.)

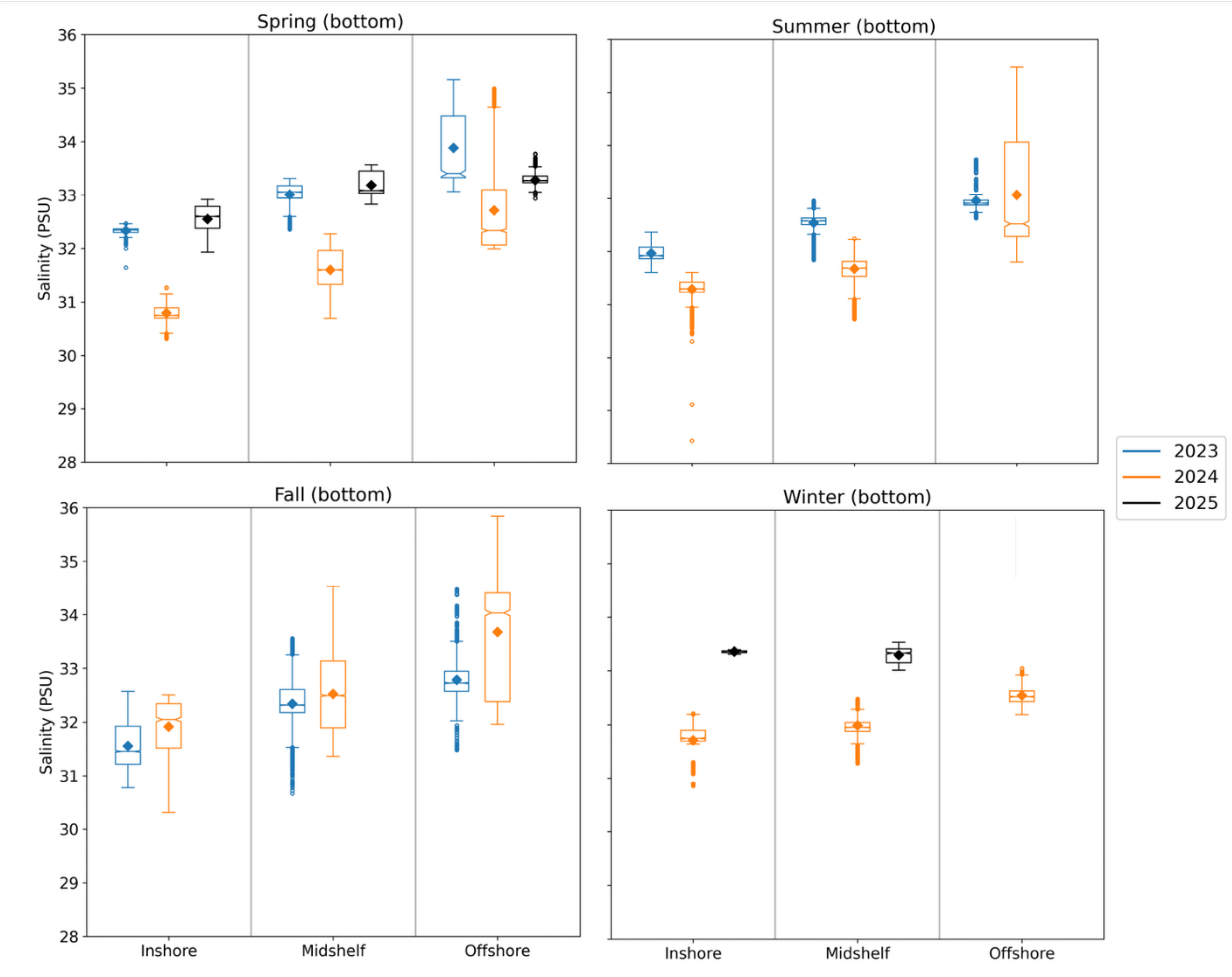


Figure 10. Bottom water salinity (PSU) across the New Jersey coastal shelf for Spring (top left), Summer (top right), Fall (bottom left), and Winter (bottom right) of 2023, 2024, and 2025. The box limits extend from the lower to upper quartiles (25%, 75%), with a line at the median and a diamond symbol at the mean. The whiskers extend from the box by 1.5x the inter-quartile range (IQR). Circles indicate outliers and notches indicate 95% confidence interval around the median. (Note: The Winter 2025 deployment that occurred 02/26-03/28 extended into the Spring period (Mar – May); therefore, Spring 2025 boxes were included to capture the full deployment period.)

Although there are gaps in temporal observations during the Spring seasons of 2023 and 2024, the data (Fig. A3.1) indicate that stratification may have set up a few weeks earlier in Spring 2023 compared to 2024. In Spring 2023 there was a gradual shallowing of the mixed layer depth, and strengthening of stratification (indicated by increasing Max N2 values), going into Summer. In comparison, Spring 2024 was characterized by much shallower mixed layer depths, which deepened going into Summer but exhibited stronger stratification than in 2023.

In the Mid-Atlantic, the cooling and freshening of coastal and offshore waters between Summer 2022 and 2024 corresponds with decreasing Summer bottom aragonite saturation state values (Fig. 8, row B), suggesting increased Summer bottom water acidification over time. However, the significantly lower aragonite saturation states measured by RMI gliders in 2024 compared to 2023 were persistent across the shelf Spring-Fall even in the surface (Fig. 11, Table A3.3). Bottom aragonite saturation states were significantly lower in 2024 compared to 2023 across the shelf in Spring and in the Inshore and Midshelf regions through Summer and Fall (Fig. 12, Table A3.4). The bottom aragonite saturation state observed on the Mid-Atlantic coastal shelf during Summer 2024 (minimum value = 0.65) are the lowest values recorded for this region by vessels or gliders since 2007 (Gaichas et al., 2025). Winter surface aragonite saturation states were statistically similar between years 2024 and 2025; however, bottom aragonite saturation states were lower in the Inshore stratum in 2025 compared to 2024 (Figs. 11-12, Tables A3.3 and A3.4).

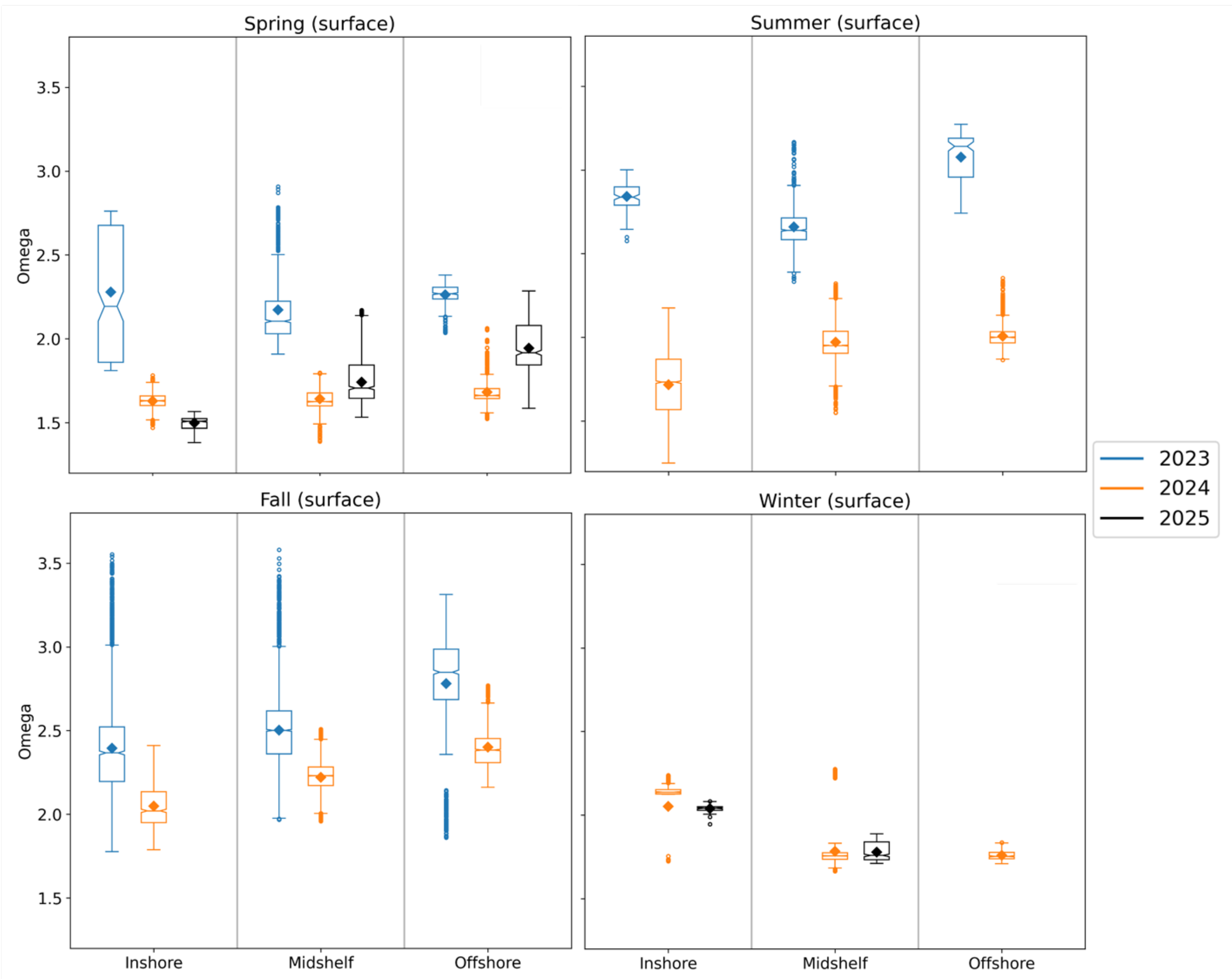


Figure 11. Surface aragonite saturation state (Omega) across the New Jersey coastal shelf for Spring (top left), Summer (top right), Fall (bottom left), and Winter (bottom right) of 2023, 2024, and 2025. The box limits extend from the lower to upper quartiles (25%, 75%), with a line at the median and a diamond symbol at the mean. The whiskers extend from the box by 1.5x the inter-quartile range (IQR). Circles indicate outliers and notches indicate 95% confidence interval around the median. (Note: The Winter 2025 deployment that occurred 02/26-03/28 extended into the Spring period (Mar – May); therefore, Spring 2025 boxes were included to capture the full deployment period.)

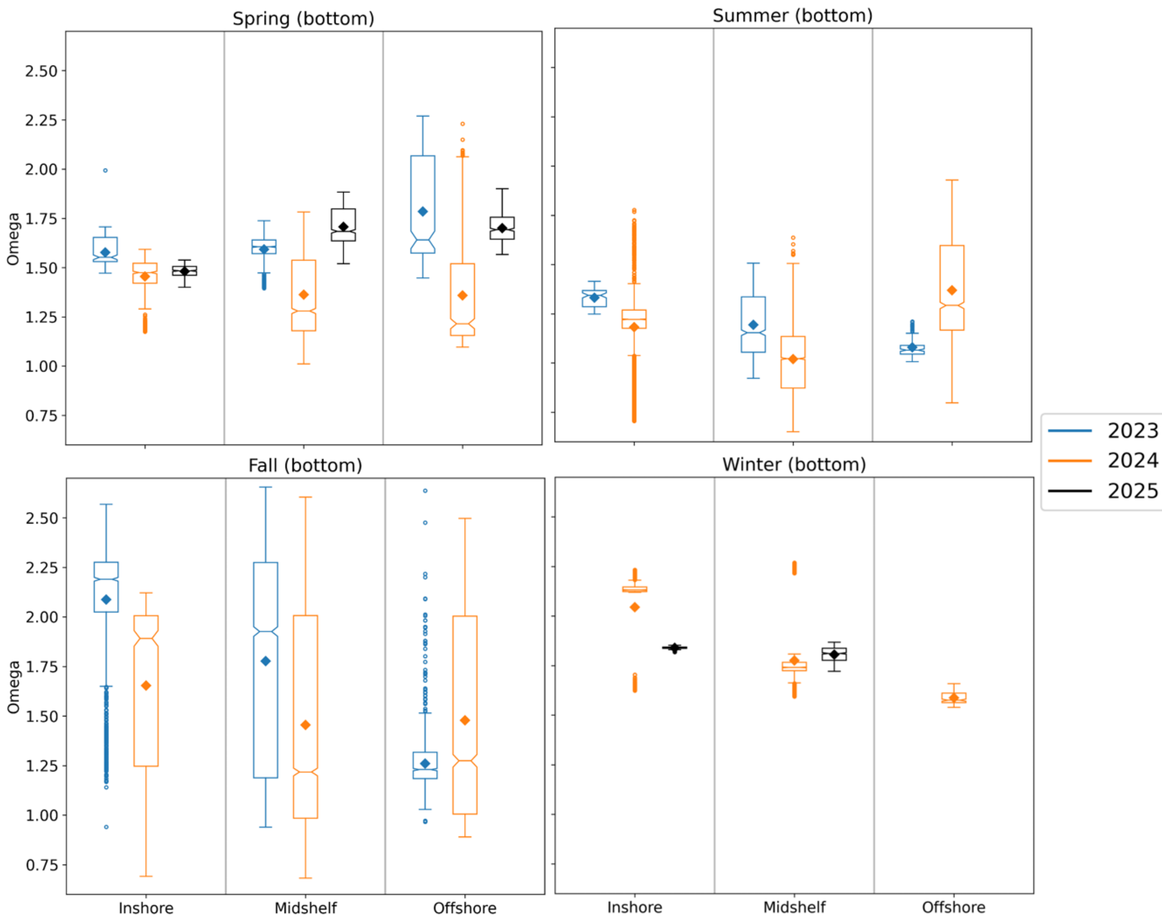


Figure 12. Bottom aragonite saturation state (Omega) across the New Jersey coastal shelf for Spring (top left), Summer (top right), Fall (bottom left), and Winter (bottom right) of 2023, 2024, and 2025. The box limits extend from the lower to upper quartiles (25%, 75%), with a line at the median and a diamond symbol at the mean. The whiskers extend from the box by 1.5x the inter-quartile range (IQR). Circles indicate outliers and notches indicate 95% confidence interval around the median. (Note: The Winter 2025 deployment that occurred 02/26-03/28 extended into the Spring period (Mar – May); therefore, Spring 2025 boxes were included to capture the full deployment period.)

Conversely, bottom dissolved oxygen concentrations across the New Jersey shelf were significantly lower in the Summer and Fall of 2023 compared to 2024 (Fig. 13, Table A3.5). A majority of shelf bottom waters during Summer 2023 had dissolved oxygen concentrations < 5 mg/L, and hypoxic levels of dissolved oxygen (concentrations < 3 mg/L) were observed in the shallowest, Inshore waters in Summer (Fig. 4). In contrast, there were no observations of dissolved oxygen concentrations < 5 mg/L in bottom water throughout 2024 (Fig. 6). The highest dissolved oxygen concentrations recorded in the 2-year observation period occurred Winter-Spring 2025, and these values were significantly higher than those measured during Winter-Spring 2024 (Fig. 13, Tables A3.5).

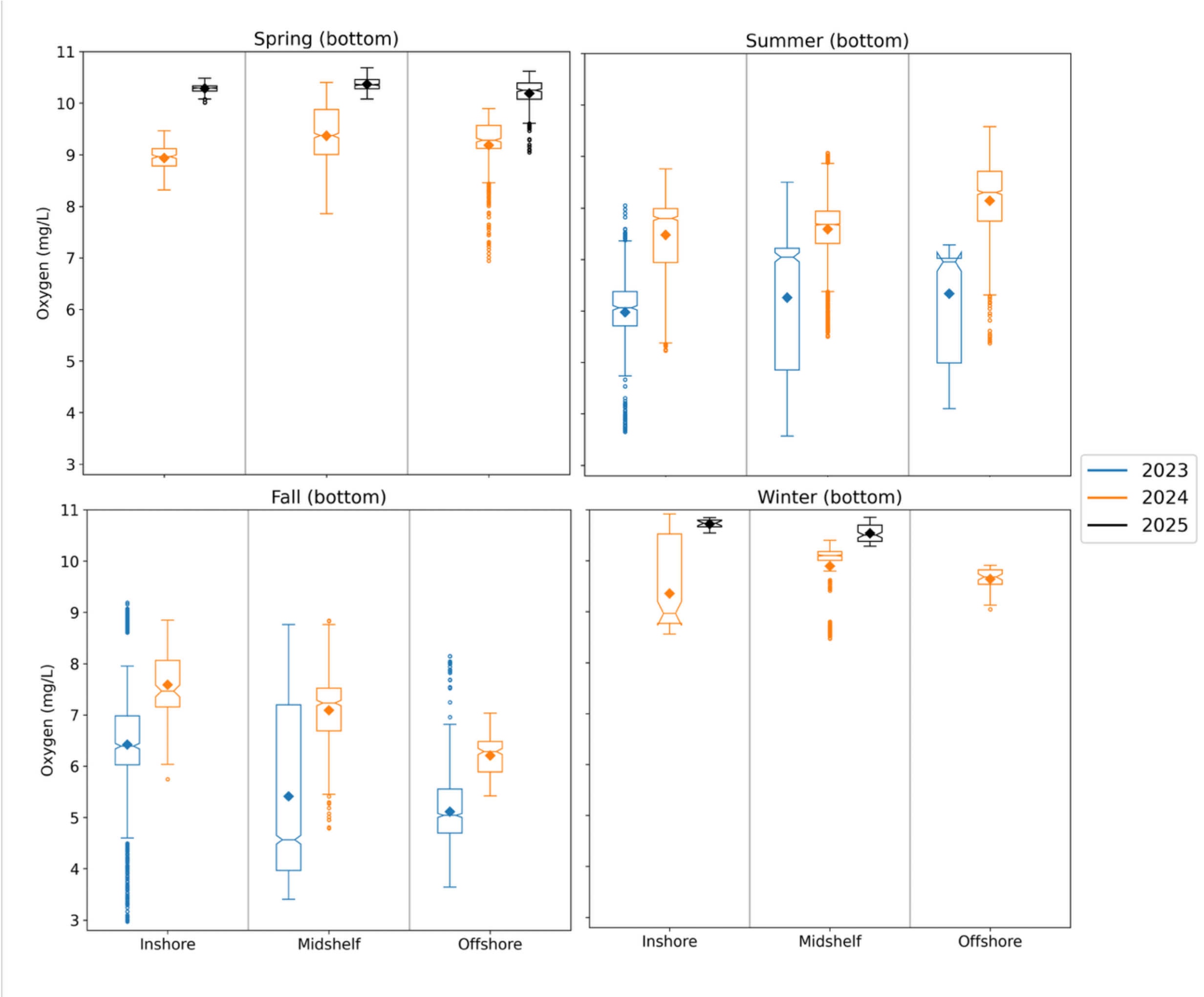


Figure 13. Bottom water dissolved oxygen concentration across the New Jersey coastal shelf for Spring (top left), Summer (top right), Fall (bottom left), and Winter (bottom right) of 2023, 2024, and 2025. The box limits extend from the lower to upper quartiles (25%, 75%), with a line at the median and a diamond symbol at the mean. The whiskers extend from the box by 1.5x the inter-quartile range (IQR). Circles indicate outliers and notches indicate 95% confidence interval around the median. (Note: The Winter 2025 deployment that occurred 02/26-03/28 extended into the Spring period (Mar – May); therefore, Spring 2025 boxes were included to capture the full deployment period.)

Higher chlorophyll-a concentrations occurred in the surface and at the subsurface chlorophyll-a maximum (chla-max) in the Spring and Summer of 2023 (compared to 2024) (Figs. 14 and 15, Table A3.6 and A3.7). Additionally, in 2023 the chlorophyll-a subsurface maximum was present throughout Spring across the shelf and particularly persisted throughout Summer (Fig. 4). Conversely, the presence of a chlorophyll-a subsurface maximum during Spring 2024 was sparse, and its presence in Summer was primarily limited to shallower areas (Figs. 6, 15). The well-mixed water column in Winter homogenized the chlorophyll-a vertical profiles, but concentrations were still comparable to other seasons. Winter 2024 chlorophyll-a concentrations were relatively consistant across the shelf, but in Winter-Spring 2025, chlorophyll-a concentrations were relatively higher in the Inshore stratum (Figs. 5, 7, 14, 15; Table A3.6).

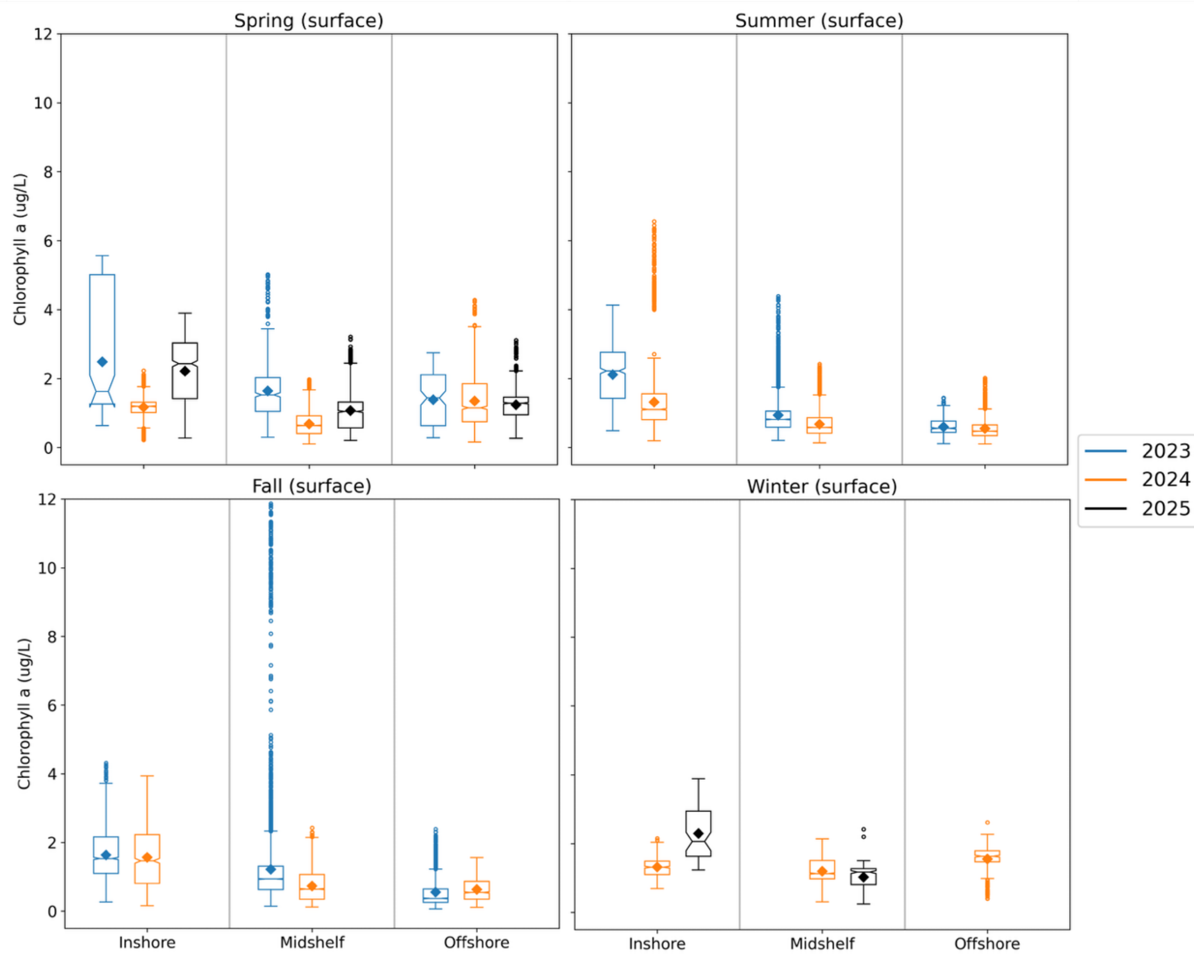


Figure 14. Chlorophyll-a concentration in surface water across the New Jersey coastal shelf for Spring (top left), Summer (top right), Fall (bottom left), and Winter (bottom right) of 2023, 2024, and 2025. The box limits extend from the lower to upper quartiles (25%, 75%), with a line at the median and a diamond symbol at the mean. The whiskers extend from the box by 1.5x the inter-quartile range (IQR). Circles indicate outliers and notches indicate 95% confidence interval around the median. (Note: The Winter 2025 deployment that occurred 02/26-03/28 extended into the Spring period (Mar – May); therefore, Spring 2025 boxes were included to capture the full deployment period.)

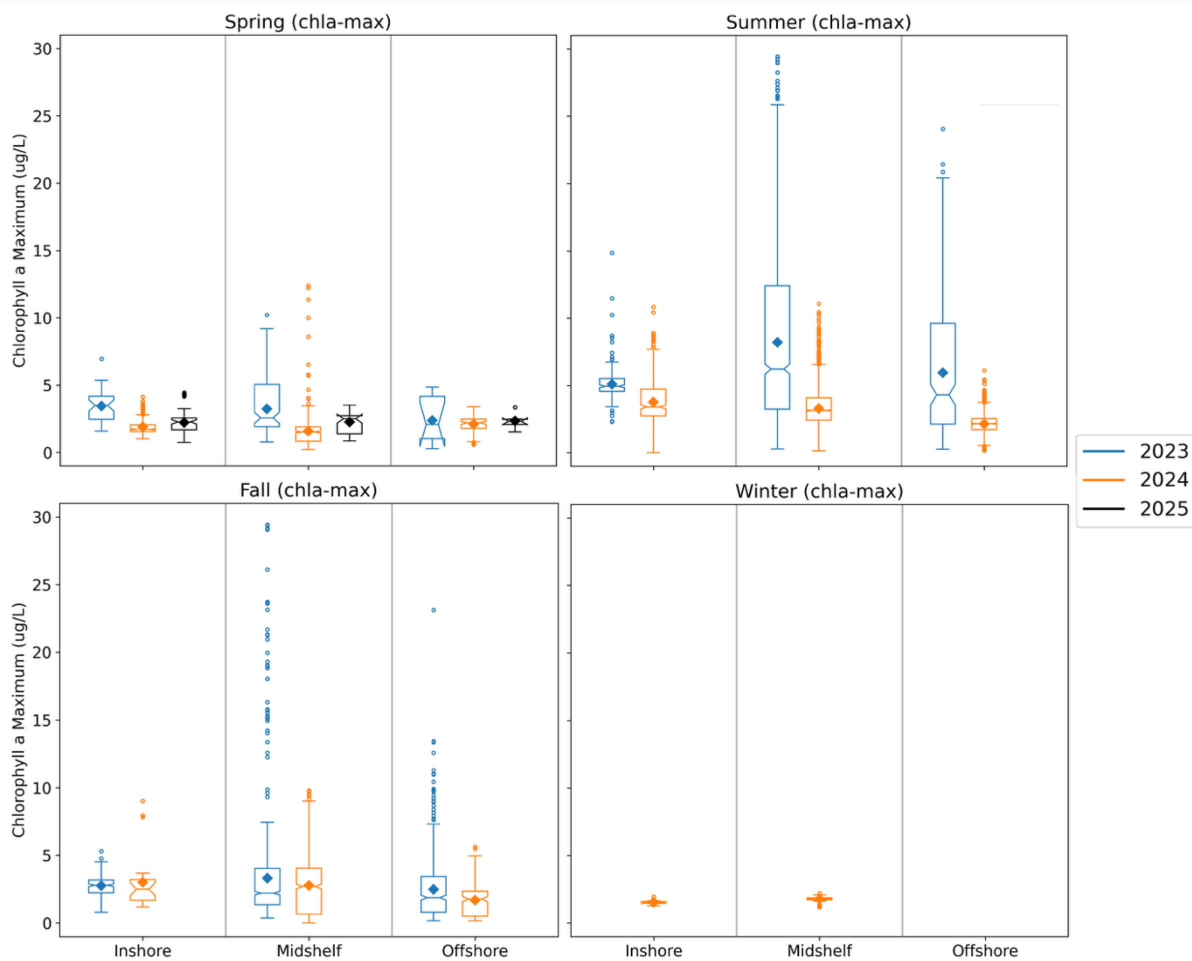


Figure 15. Chlorophyll-a concentration in the chlorophyll-a subsurface maximum across the New Jersey coastal shelf for Spring (top left), Summer (top right), Fall (bottom left), and Winter (bottom right) of 2023, 2024, and 2025. Data from Winter 2024 (Offshore only) and 2025 are not shown due to low sample sizes of defined mixed layer depths and the presence of a chlorophyll-a subsurface maximum. The box limits extend from the lower to upper quartiles (25%, 75%), with a line at the median and a diamond symbol at the mean. The whiskers extend from the box by 1.5x the inter-quartile range (IQR). Circles indicate outliers and notches indicate 95% confidence interval around the median. (Note: The Winter 2025 deployment that occurred 02/26-03/28 extended into the Spring period (Mar – May); therefore, Spring 2025 boxes were included to capture the full deployment period.)

Multi-stressor Events

From August-September 2023, much of the bottom water sampled along the coast, from Sandy Hook to Tuckerton, and across the OCS, from nearshore (15 meter water depth) to offshore (60 meter water depth), exhibited low dissolved oxygen concentrations, pH, and aragonite saturation levels (Figs. 16, 17). Dissolved oxygen concentrations < 5 mg/L, pH values < 7.75, and aragonite saturation states calculated to be <1, were observed at shallow, inshore locations by RMI gliders, as well as by a shallow-water glider (ru28) deployed at the same time (funded by NJDEP BMWM). Conditions in these areas are indicative of ocean acidification as normal (optimal) seawater is typically characterized by dissolved oxygen concentrations > 7 mg/L, pH of ~8.1, and aragonite saturation states > 3.

During the time when low dissolved oxygen, pH, and aragonite saturation state were observed, numerous mortalities of fish, lobsters and crabs were reported within the sampling area (Figs. 16 and 17). The mortalities were observed in bottom waters primarily off the coast of Monmouth and Ocean Counties across an area that included the Mud Hole, as far east as Lillian wreck, and southward to Sea Girt and Axel Carlson Reefs, as well as the surrounding areas. Mortalities were reported by commercial and recreational fisherman to NJDEP for American lobsters, Jonah crab, Atlantic rock crab, spider crabs, black sea bass, and tautog. Mortalities were observed in pots, where trapped organisms would not have been able to escape poor conditions, as well as on the open bottom. This observation suggests that if low dissolved oxygen and/or pH were the cause of these reported mortalities, the area affected may have been extensive enough that organisms could could not escape these physiological stressors.

Normal, more optimal dissolved oxygen, pH, and aragonite saturation state levels were restored in bottom waters temporarily (9/16/2023-9/21/2023) during the offshore passage of Hurricane Lee. However, the water restratified shortly after with bottom dissolved oxygen concentrations returning to values < 5 mg/L. These conditions persisted until during a strong hybrid storm fully mixed the Inshore and Midshelf water column around 9/26/2023, which increased bottom dissolved oxygen concentrations above hypoxic levels for the remainder of the sampling period (See Section 'Seasonal Progressions').

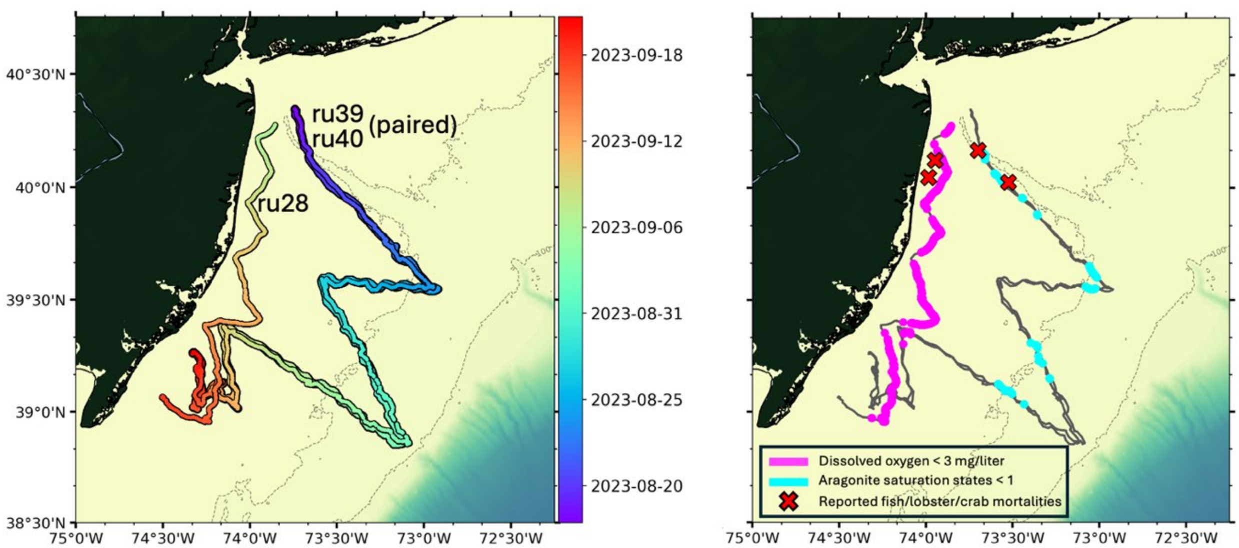


Figure 16. Summer 2023 glider missions along the coast of New Jersey. Left: Mission tracks of three gliders (ru28, ru39, ru40) deployed off the coast of New Jersey in August and September. RMI gliders ru39 and ru40 were deployed as a pair along the same mission track. All gliders had sensors measuring temperature and salinity. NJDEP glider ru28 and RMI glider ru40 each had an additional sensor measuring dissolved oxygen (no pH or aragonite saturation state), and RMI glider ru39 had an additional sensor measuring pH (no dissolved oxygen). Right: Locations of hypoxic levels of dissolved oxygen (magenta; < 3 mg/liter) and low aragonite saturation state (cyan; < 1) measured along the glider mission tracks and locations of reported fish, lobster, and/or crab mortalities (red X). (Figure from: Northeast Fisheries Science Center, 2024)

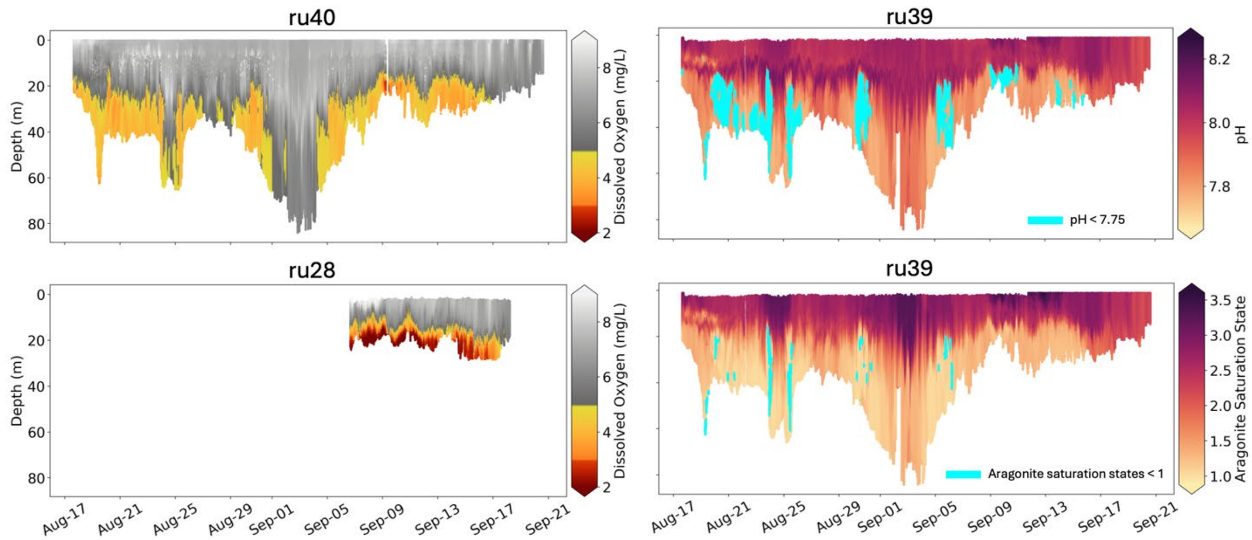


Figure 17. Complete cross-sections of dissolved oxygen concentrations (left top and bottom), pH (right top), and aragonite saturation state (right bottom) measured along the mission tracks during the deployments of the three gliders (ru28, ru39, ru40) during August and September. Dissolved oxygen concentrations between 3-5 mg/liters are expressed as orange and yellow, and hypoxic concentrations < 3 mg/liter are expressed as red. pH values < 7.75 and aragonite saturation states < 1 are highlighted in cyan. (Figure from: Northeast Fisheries Science Center, 2024)

Acoustic Data

Passive Acoustic Detections of Marine Mammals and Tagged Individuals

Over the course of 20 deployments, RMI gliders detected at least 20 different species via telemetry, primarily sandbar shark (34 individuals), Atlantic sturgeon (21 individuals), black sea bass (17 individuals), tautog (12 individuals), and striped bass (10 individuals). Other tagged species detected included dusky shark (9), bluefin tuna (7), Summer flounder (6), white shark (5), smooth dogfish (4), shortfin mako (3), clearnose skate (3), sand tiger (2), blacktip shark (2), and a single little tunny, common thresher, southern stingray, Atlantic cod, yellowfin tuna, and loggerhead sea turtle. Of the tags detected during this project, 55 have not yet been identified by RUCOOL. Additional details are provided in Table 2, excluding the specifics of species information as those data are owned by the tag owners. The presence of four marine mammal species – Humpback, Fin, Sei, and the critically endangered North Atlantic Right Whale (NARW) – were also detected for a total of 157 detection days, but we are unable to determine the number of distinct individuals using the hydrophone data. The passive acoustic data and the status of data retrieval and processing are summarized in Table 2. Locations for marine mammal detections can be viewed in Figs. 18-21, Appendix 4, and on the links provided in Table 2. These links also contain maps showing locations and tag identification for telemetered detections (scroll to bottom of page and select 'VEMCO tag detection data'). These maps are also openly accessible at http://robots4whales.whoi.edu/. Information on the voluntary North Atlantic Right Whale Slow Zones managed by NOAA Fisheries and referenced in the table can be found at https://www.fisheries.noaa.gov/feature-story/help-endangered-whales-slow-down-slow-zones.

Table 2. Summary of passive acoustic (telemetry and DMON) detections during 20 RMI glider deployments.

Deployment/glider name	**Telemetry detection data info and/or status**	**DMON detection data info and status**
Spring 2023 paired		
ru39	No detections	N/A. No DMON sensor.
ru41	No detections	3 humpback detection days
Early Summer (June/July) 2023 gap fill		
ru40	109 detections from 10 tags; contact information is available for 9 tags (90 detections), 7 of which (59 detections) RUCOOL has species information for.	2 fin whale detection days
Summer 2023 paired		
ru39	27 detections from 6 tags; contact information is available for 5 tags (19 detections), 4 of which (10 detections) RUCOOL has species information for.	N/A. No DMON sensor.
ru40	81 detections from 14 tags; contact information is available for 13 tags (75 detections), 9 of which (40 detections) RUCOOL has species information for.	18 fin whale detection days
Early Fall (September/October) 2023 gap-fill		
ru34	849 detections from 46 tags; contact information is available for 40 tags (554 detections), 39 of which (509 detections) RUCOOL has species information for.	N/A. DMON swapped for pH to continue monitoring dissolved oxygen and pH
Fall 2023 paired		
ru39	72 detections from 16 tags; contact information is available for 12 tags (44 detections), 11 of which (35 detections) RUCOOL has species information for.	N/A. No DMON sensor.
ru40	56 detections from 12 tags; contact information is available for 10 tags (50 detections), 9 of which (43 detections) RUCOOL has species information for.	15 total whale detection days including fin whales (11 detection days), humpback whales (2 detection days), and North Atlantic right whales (NARW, 5 detection days). *Note: Due to the detection of NARW presence from this glider, NOAA Fisheries triggered a voluntary Right Whale Slow Zone in the detection area, effective 11/17-12/2.
Winter 2024 paired		
ru39	18 detections from 4 tags; all of which RUCOOL has species information for. Some identified tags are receiver array transmitters (2 tags, 6 detections).	N/A. No DMON sensor.
ru40	143 detections from 12 tags; contact information is available for 11 tags (142 detections), all of which RUCOOL has species information for. Some identified tags are receiver array transmitters (5 tags, 50 detections).	24 total whale detection days including sei whales (1 detection day), fin whales (19 detection days), and humpback whales (16 detection days).
Spring 2024 paired		
ru39	124 detections from 10 tags; contact information is available for 7 tags (31 detections), all of which RUCOOL has species information for. Some identified tags are receiver array transmitters (5 tags, 26 detections).	N/A. No DMON sensor.
ru40	373 detections from 36 tags; contact information is available for 30 tags (329 detections), 29 of which (295 detections) RUCOOL has species information for. Some identified tags are receiver array transmitters (7 tags, 108 detections).	22 total whale detection days, including sei whales (12 detection days), fin whales (14 detection days), North Atlantic right whales (1 detection day), and humpback whales (22 detection days). *Note: Due to the detection of NARW presence from this glider, NOAA Fisheries triggered a voluntary Right Whale Slow Zone in the detection area, effective 5/18-6/2.
Early Summer (June/July) 2024 gap-fill		
ru43	92 detections from 19 tags; contact information is available for 17 tags (86 detections), all of which RUCOOL has species information for. Some identified	N/A. No DMON sensor.

	tags are receiver array transmitters (5 tags, 14 detections).	
Summer 2024 paired		
ru39	77 detections from 11 tags; contact information is available for 9 tags (51 detections), all of which RUCOOL has species information for. Some identified tags are receiver array transmitters (4 tags, 15 detections).	N/A. No DMON sensor.
ru40	394 detections from 35 tags; contact information is available for 34 tags (393 detections), 32 of which (344 detections) RUCOOL has species information for. Some identified tags are receiver array transmitters (7 tags, 98 detections).	19 total whale detection days, including sei whales (1 detection day), fin whales (19 detection days), North Atlantic right whales (2 detection days), and humpback whales (5 detection days). *Note: Due to the detection of NARW presence from this glider, NOAA Fisheries triggered two voluntary Right Whale Slow Zones in the detection area, effective 7/31-8/15 and 8/11-8/26.
Early Fall (September) 2024 gap-fill		
ru43	106 detections from 14 tags; contact information is available for 10 tags (72 detections), all of which RUCOOL has species information for. Some of the identified tags are receiver array transmitters (6 tags, 48 detections).	N/A. No DMON sensor.
Fall 2024 paired		
ru39	52 detections from 12 tags; contact information is available for 10 tags (44 detections), 9 of which (37 detections) RUCOOL has species information for. Some of the identified tags are receiver array transmitters (2 tags, 10 detections).	N/A. No DMON sensor.
ru40	234 detections from 25 tags; contact information is available for 24 tags (222 detections), 7 of which RUCOOL has species information for. Some of the identified tags are receiver array transmitters (4 tags, 40 detections).	26 total whale detection days, including sei whales (1 detection day), fin whales (21 detection days), and humpback whales (26 detection days)
Winter 2025 paired		
ru39	Data is submitted to MATOS and data extraction is underway at the time of this report.	N/A. No DMON sensor.
ru40	173 detections from 14 tags; contact information is available for all tags, 13 of which (158 detections) RUCOOL has species information for. Some of the identified tags are receiver array transmitters (6 tags, 46 detections).	28 total whale detection days, including sei whales (3 detection days), fin whales (24 detection days), North Atlantic right whales (5 detection days), and humpback whales (20 detection days). *Note: Due to the detection of NARW presence from this glider, NOAA Fisheries triggered two voluntary Right Whale Slow Zones in the detection area, effective 3/3-3/18 and 3/12-3/27.

Fin, humpback, and North Atlantic right whales were detected in all seasons; however, the highest number of detection days for each species, and highest total number of detections, occurred during Spring (primarily Spring 2024) (Table 3; Figs. 18, 19, and 21). Sei whales were also detected in all seasons except Winter; however, with few total detections observed, most of which occurred in a single deployment (Spring 2024), it is difficult to discern any clear seasonal pattern in total detections or detection days (Fig. 20). Fin whales and humpback whales were detected more frequently than North Atlantic right whales or sei whales (Table 3). Humpback whales (Fig. 19) were detected in highest numbers primarily during the transition seasons (Spring and Fall). Direct comparisons between whale species, and analyses based on specific location and even time of year, are difficult due to differences in call behavior, variability in sound propagation based on water properties, glider orientation relative to whale location, and species-specific detection ranges (e.g. approximately 10 km for right whales to 100s-1000s km for fin whales; Harris et al., 2018; Johnson et al., 2022; Pepper, 2023).

Table 3. Seasonal summary of fin whales, humpback whales, North Atlantic right whales, and sei whales detected by DMON hydrophone. Far right column (PAM Days) describes the number of days within each season that a glider carrying a DMON sensor was deployed. Seasons are defined as Winter: December-February, Spring: March-May, Summer: June August, Fall: September-November.

	Fin Whales	**Humpbacks**	**NARW**	**Sei Whales**	**PAM Days**	**Total Detections**
	Detection Days (Total Number of Detections)					
Winter	15 (217)	5 (40)	1 (2)	0 (0)	21	259
Spring	46 (1053)	56 (787)	7 (14)	17 (85)	75	1939
Summer	33 (489)	5 (14)	2 (3)	1 (1)	79	507
Fall	32 (674)	29 (333)	3 (9)	1 (1)	71	1017

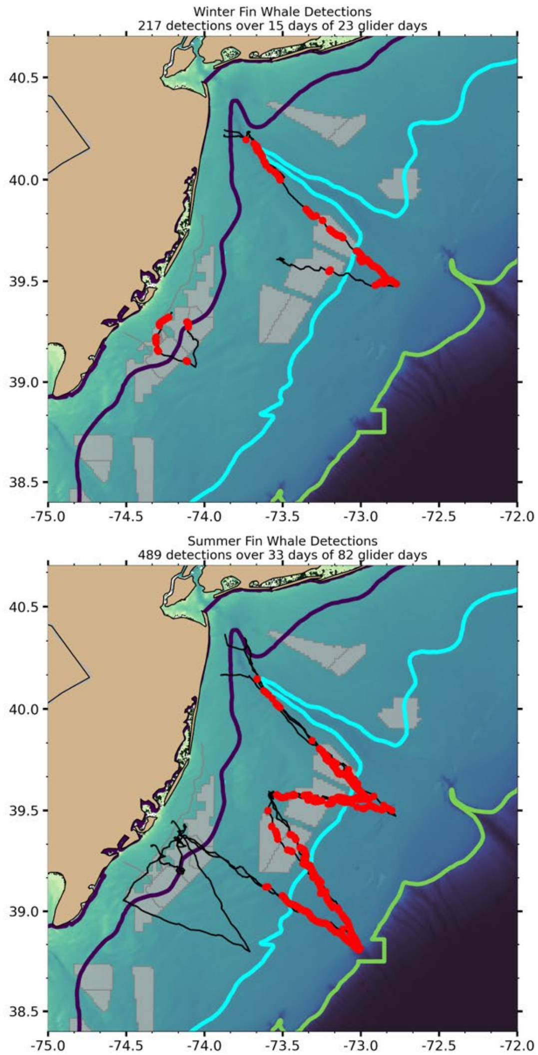


Figure 18. Seasonal distribution of fin whale detections. Glider survey path carrying DMON within each season is shown with a black line, whale detections are represented with red markers, and Inshore-Midshelf-Offshore strata are colored as in Figure 2. Gray polygons represent the Bureau of Ocean Energy Management (BOEM) wind lease areas. Seasons are defined as Winter (upper left): December-February, Spring (upper right): March-May, Summer (lower left): June-August, Fall (lower right): September-November. Note: the Spring 2023 deployment only contained 4 days of detection data due to the loss of RMI glider ru41, so most of the Spring data shown are from 2024.

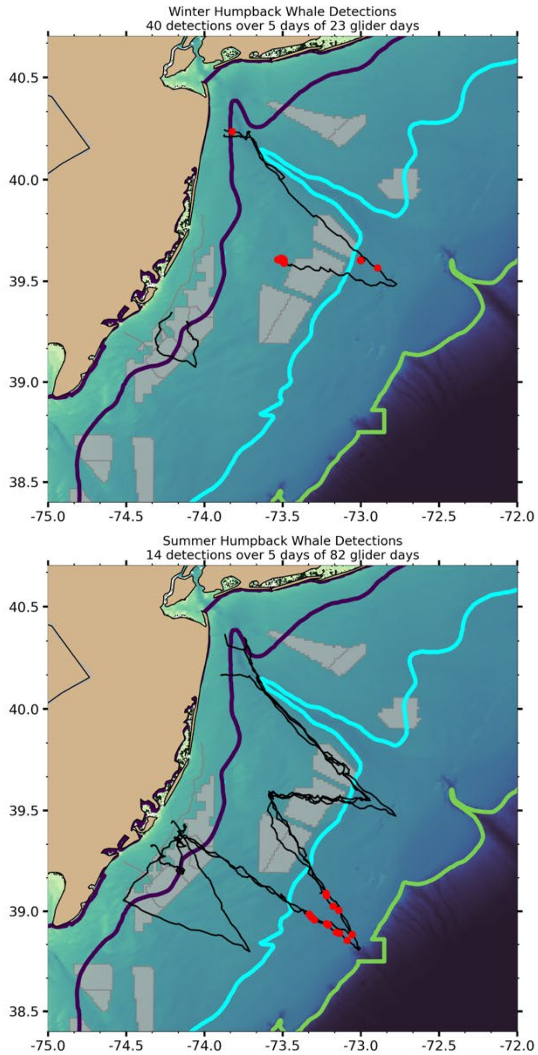


Figure 19. Seasonal distribution of humpback whale detections. Glider survey path carrying DMON within each season is shown with a black line, whale detections are represented with red markers, and Inshore-Midshelf-Offshore strata are colored as in Figure 2. Gray polygons represent the Bureau of Ocean Energy Management (BOEM) wind lease areas. Seasons are defined as Winter (upper left): December-February, Spring (upper right): March-May, Summer (lower left): June-August, Fall (lower right): September-November. Note: the Spring 2023 deployment only contained 4 days of detection data due to the loss of RMI glider ru41, so most of the Spring data shown are from 2024.

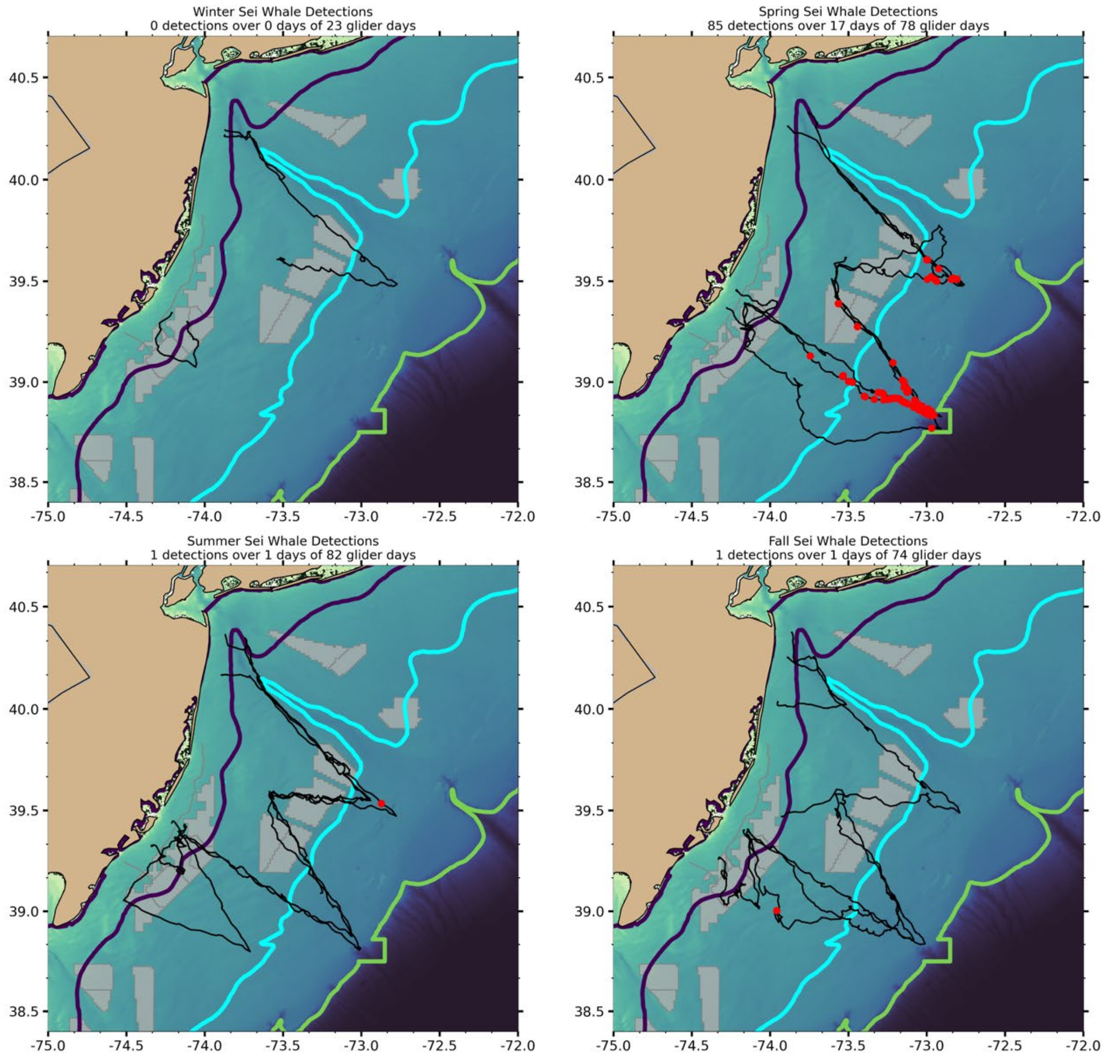


Figure 20. Seasonal distribution of sei whale detections. Glider survey path carrying DMON within each season is shown with a black line, whale detections are represented with red markers, and Inshore-Midshelf-Offshore strata are colored as in Figure 2. Gray polygons represent the Bureau of Ocean Energy Management (BOEM) wind lease areas. Seasons are defined as Winter (upper left): December-February, Spring (upper right): March-May, Summer (lower left): June-August, Fall (lower right): September-November. Note: the Spring 2023 deployment only contained 4 days of detection data due to the loss of RMI glider ru41, so most of the Spring data shown are from 2024.

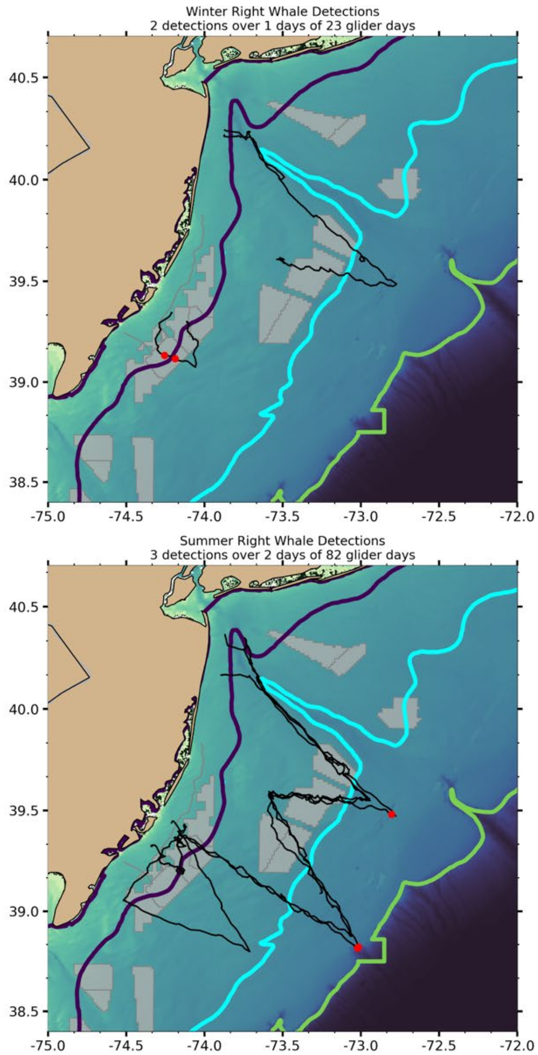


Figure 21. Seasonal distribution of North Atlantic right whale detections. Glider survey path carrying DMON within each season is shown with a black line, whale detections are represented with red markers, and Inshore-Midshelf-Offshore strata are colored as in Figure 2. Gray polygons represent the Bureau of Ocean Energy Management (BOEM) wind lease areas. Seasons are defined as Winter (upper left): December-February, Spring (upper right): March-May, Summer (lower left): June-August, Fall (lower right): September-November. Note: the Spring 2023 deployment only contained 4 days of detection data due to the loss of RMI glider ru41, so most of the Spring data shown are from 2024.

Active Acoustic Detections of Scattering Organisms

Eight active acoustic missions that occurred during the study period were paired deployments with a second glider carrying a DMON for marine mammal detections (see above section). Only one active acoustic mission was a gap-fill mission without a paired DMON sensor (Early Fall 2024). Of the nine total active acoustic missions, five were with the zooplankton-configured AZFP and four were with the pelagic fish-configured AZFP (Fig. 3).

Zooplankton: Discrete tow data collected at each zooplankton-configured AZFP deployment and recovery, indicated that small copepods (copepods with prosome length <1 mm) were consistently the most abundant taxon in the tows, with the exception of the Early Fall 2024 tow, when organisms in the 'Other' taxa group were more abundant (Fig. 22). The 'Other' category included non-decapod larvae, fish eggs, amphipods, and other rarer taxa. Across all tows, large copepods (>1 mm) consisted solely of *C. finmarchicus*. This species was most abundant in Winter 2024, but was also observed in Spring 2023 and 2024 and Early Fall 2024 (Fig. 22). The Spring and Fall seasons exhibited the greatest range of taxon groups. A link to the full dataset of discrete zooplankton data is available in 'Data Storage and Accessibility'.

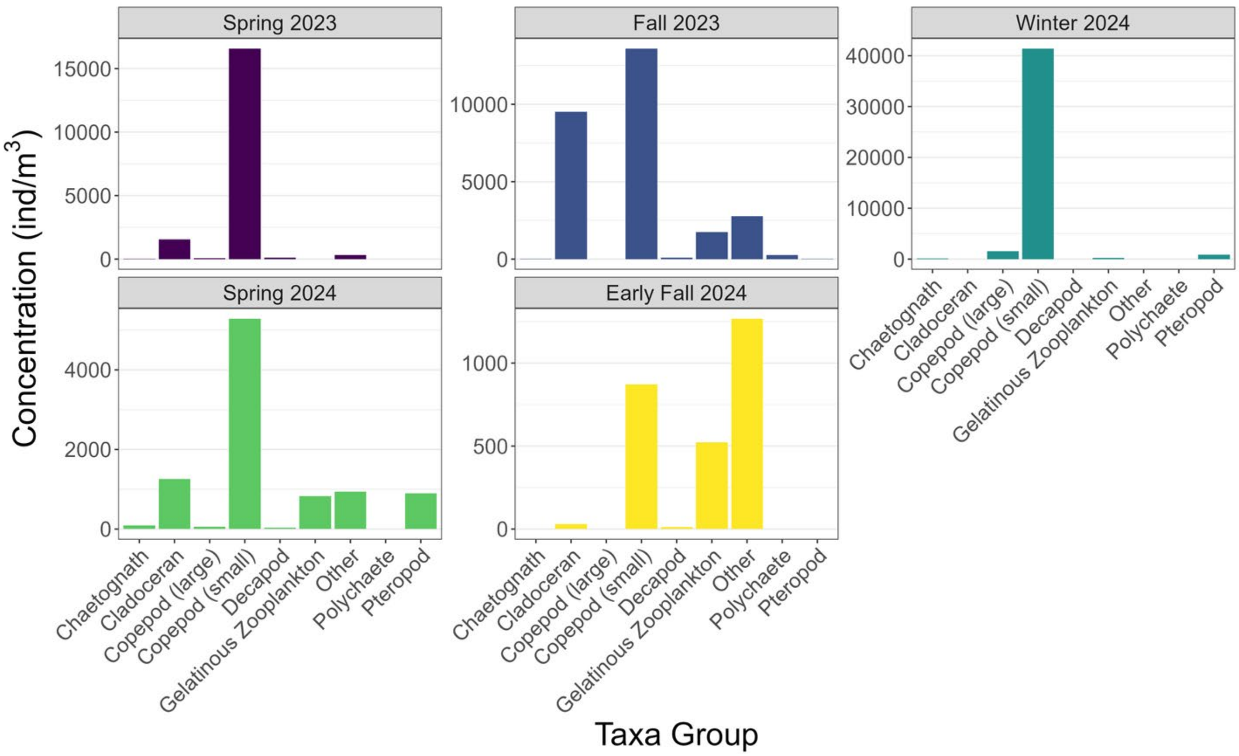


Figure 22. Derived concentration data (individuals/m^3) from oblique zooplankton tows, collected into high-level taxa groups. Note that the y-axis scale is not consistent across all four panels, in order to show the variation in concentration values when overall concentrations were low in the Summer tow. All tows were performed in the Inshore stratum, where the glider was being either deployed or recovered.

In order to understand general patterns of distribution and patchiness of zooplankton communities, the volume backscatter strength (S_v) of non-empty integration cells (e.g. cells that were identified as having echoes consistent with either *C. finmarchicus or* gelatinous zooplankton) was examined over time and depth. S_v generally strengthened (increased) as frequency increased, with the exception of the Early Fall 2024 deployment. Within each frequency, stronger S_v values indicate more concentrated zooplankton. Additionally, non-empty integration cells were primarily observed during nighttime hours through most of the water column and concentrated near the surface or near the seafloor during daytime hours. Finally, the strongest S_v values in each frequency were usually observed where the seafloor was 40-80 m deep (Figs. 23-27). All of these characteristics are typical for the MAB zooplankton community, particularly when *C. finmarchicus* is present (Baumgartner et al., 2003).

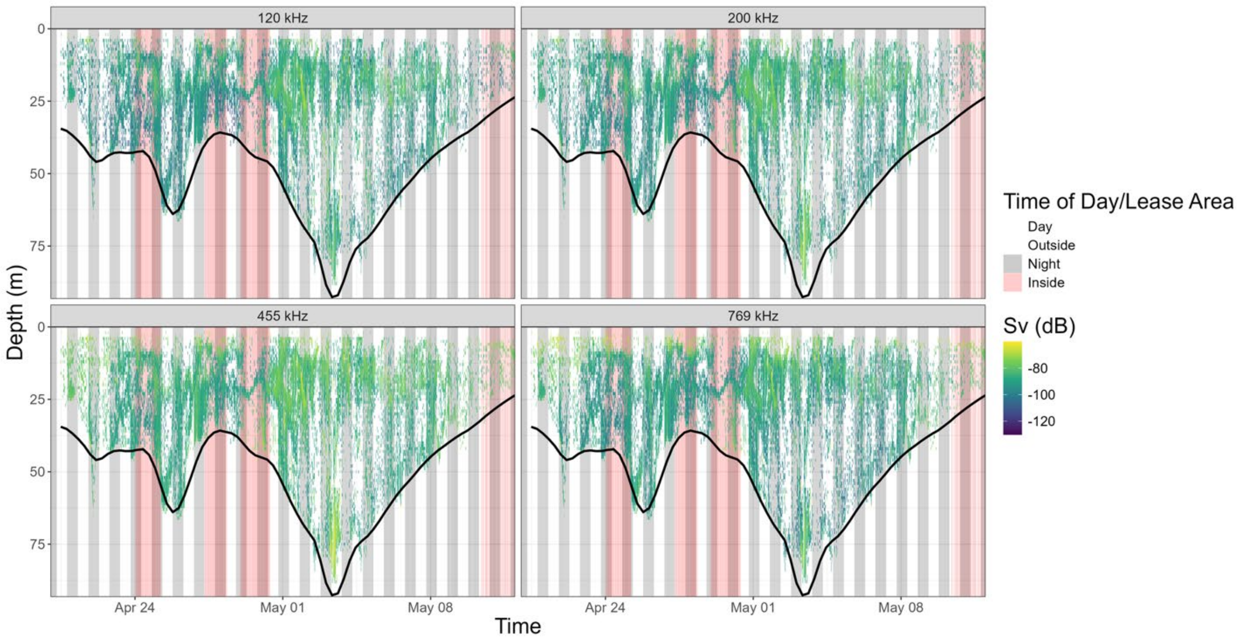


Figure 23. S_v (volume backscatter strength, dB) at 120 (top left), 200 (top right), 455 (bottom left), and 769 (bottom right) kHz from the zooplankton-configured AZFP during the Spring 2023 glider mission. The white and gray bands indicate day and night, respectively, and the pink bands indicate when the glider was within a Bureau of Ocean Energy Management (BOEM) wind lease area.

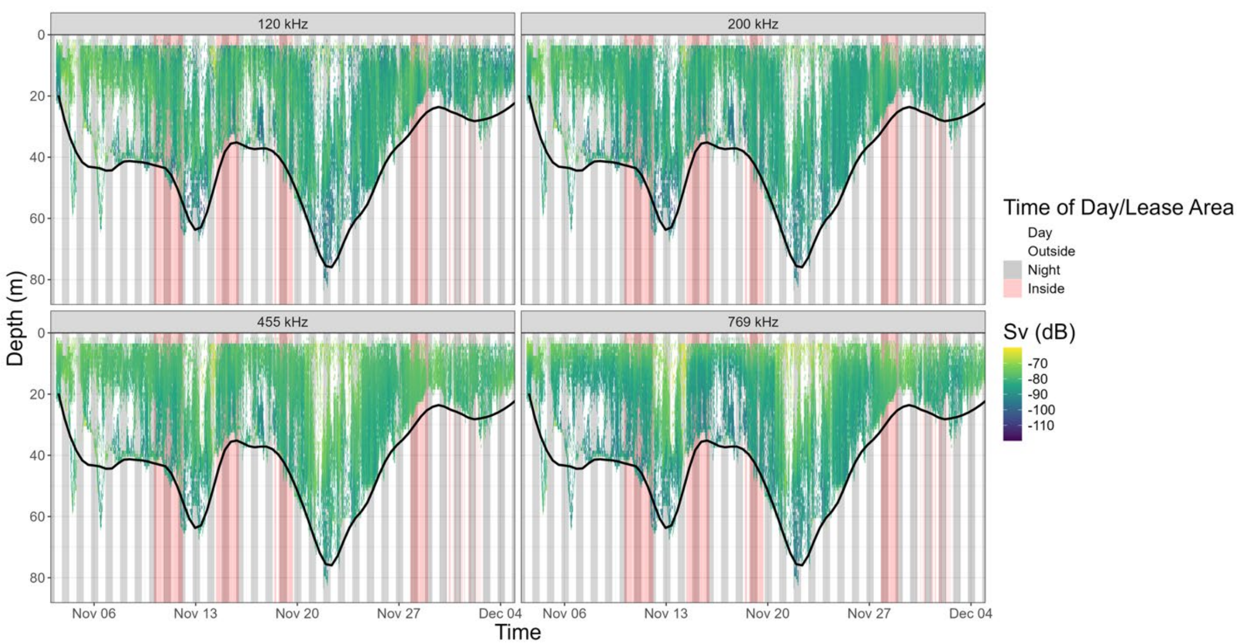


Figure 24. S_v (volume backscatter strength, dB) at 120 (top left), 200 (top right), 455 (bottom left), and 769 (bottom right) kHz from the zooplankton-configured AZFP during the Fall 2023 glider mission. The white and gray bands indicate day and night, respectively, and the pink bands indicate when the glider was within a Bureau of Ocean Energy Management (BOEM) wind lease area.

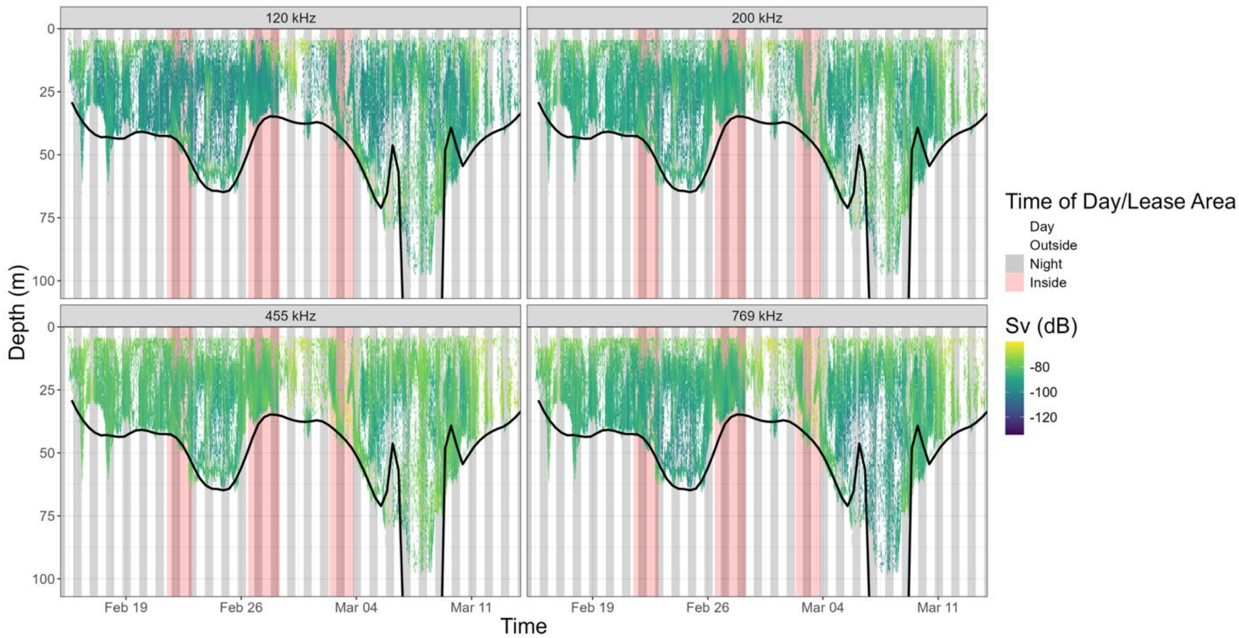


Figure 25. S_v (volume backscatter strength, dB) at 120 (top left), 200 (top right), 455 (bottom left), and 769 (bottom right) kHz from the zooplankton-configured AZFP during the Winter 2024 glider mission. The white and gray bands indicate day and night, respectively, and the pink bands indicate when the glider was within a Bureau of Ocean Energy Management (BOEM) wind lease area.

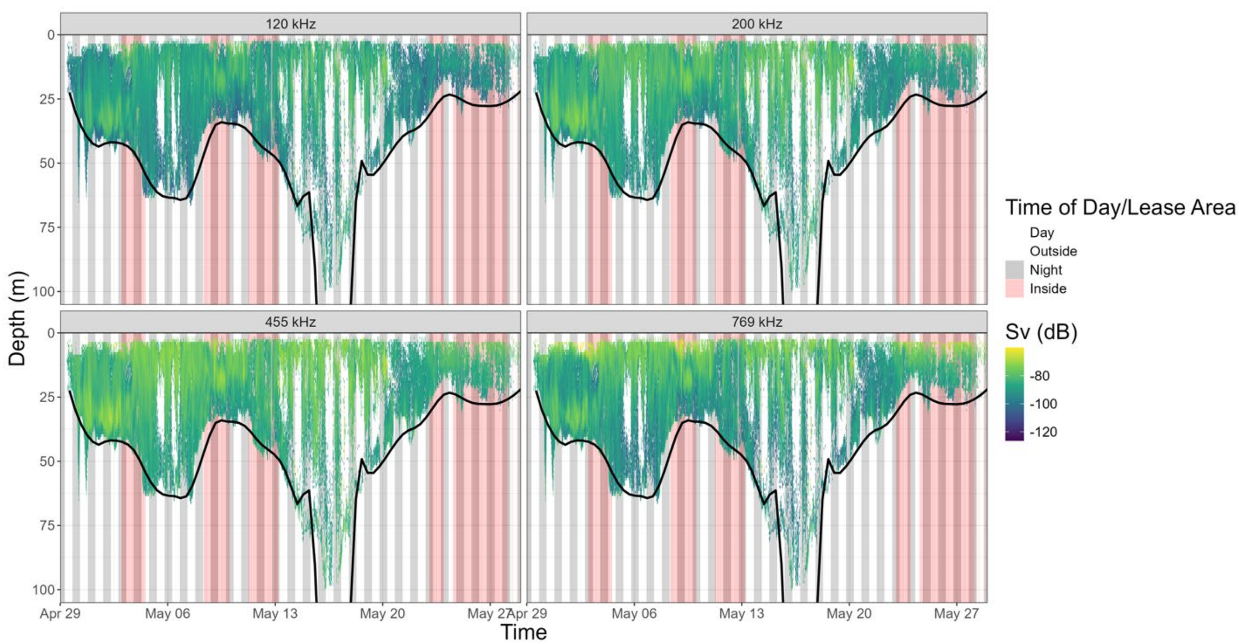


Figure 26. S_v (volume backscatter strength, dB) at 120 (top left), 200 (top right), 455 (bottom left), and 769 (bottom right) kHz from the zooplankton-configured AZFP during the Spring 2024 glider mission. The white and gray bands indicate day and night, respectively, and the pink bands indicate when the glider was within a Bureau of Ocean Energy Management (BOEM) wind lease area.

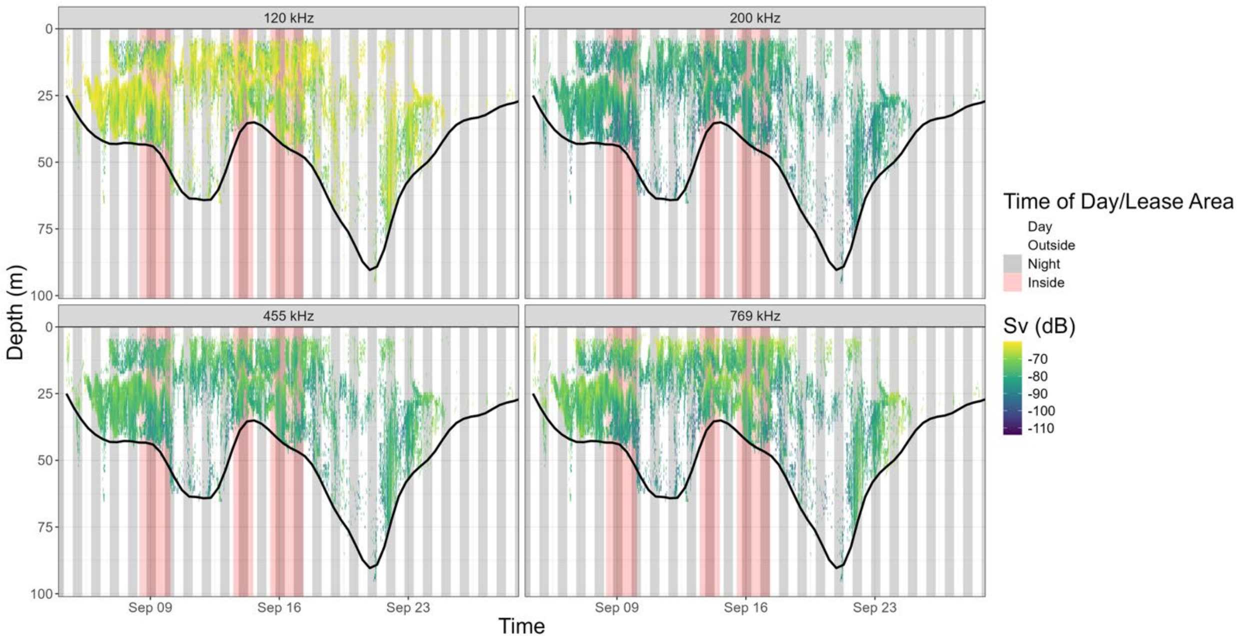


Figure 27. S_v (volume backscatter strength, dB) at 120 (top left), 200 (top right), 455 (bottom left), and 769 (bottom right) kHz from the zooplankton-configured AZFP during the Early Fall 2024 glider mission. The white and gray bands indicate day and night, respectively, and the pink bands indicate when the glider was within a Bureau of Ocean Energy Management (BOEM) wind lease area.

We utilized established acoustic target strength models of the only large copepod we detected in the discrete tows, *C. finmarchicus,* to derive estimates of their concentration and biomass from S_v. All deployments observed patchy distribution of large copepods, which were primarily concentrated along specific isobaths that changed between seasons (Figs. 28-32). During the Spring and early Fall deployments, large copepods were primarily located in the Inshore and/or Midshelf strata, but during the Fall (late Fall) and Winter deployments, large copepods occurred in higher concentrations in the Midshelf and Offshore strata. Copepods were distributed vertically throughout the water column with peak concentrations between depths of approximately 5 to 50 m, except for Spring 2024 (Appendix 5). Spring 2024 differed from Spring 2023, with fewer large copepods detected, which tended to be more inshore and in surface waters. The highest number of large copepods was observed in Winter 2024, contained entirely in the Midshelf and Offshore strata, with no observations recorded in the Inshore stratum. The high concentration Winter 2024 season was followed by the lowest concentration observed in Spring (2024) (Table 4).

More copepods were observed during daylight hours, except for the Fall 2023 deployment, when slightly more copepods were observed at night (Table 5). Analyses are ongoing to determine whether a diel vertical migration of zooplankton is observed in the data, whereby zooplankton concentrations may increase in the surface layer at night. Copepod concentrations were lower along the glider transects within the offshore wind lease areas compared to outside in every season (Table 6), but this could be the result of a higher proportion of the glider transect occurring outside of the lease areas.

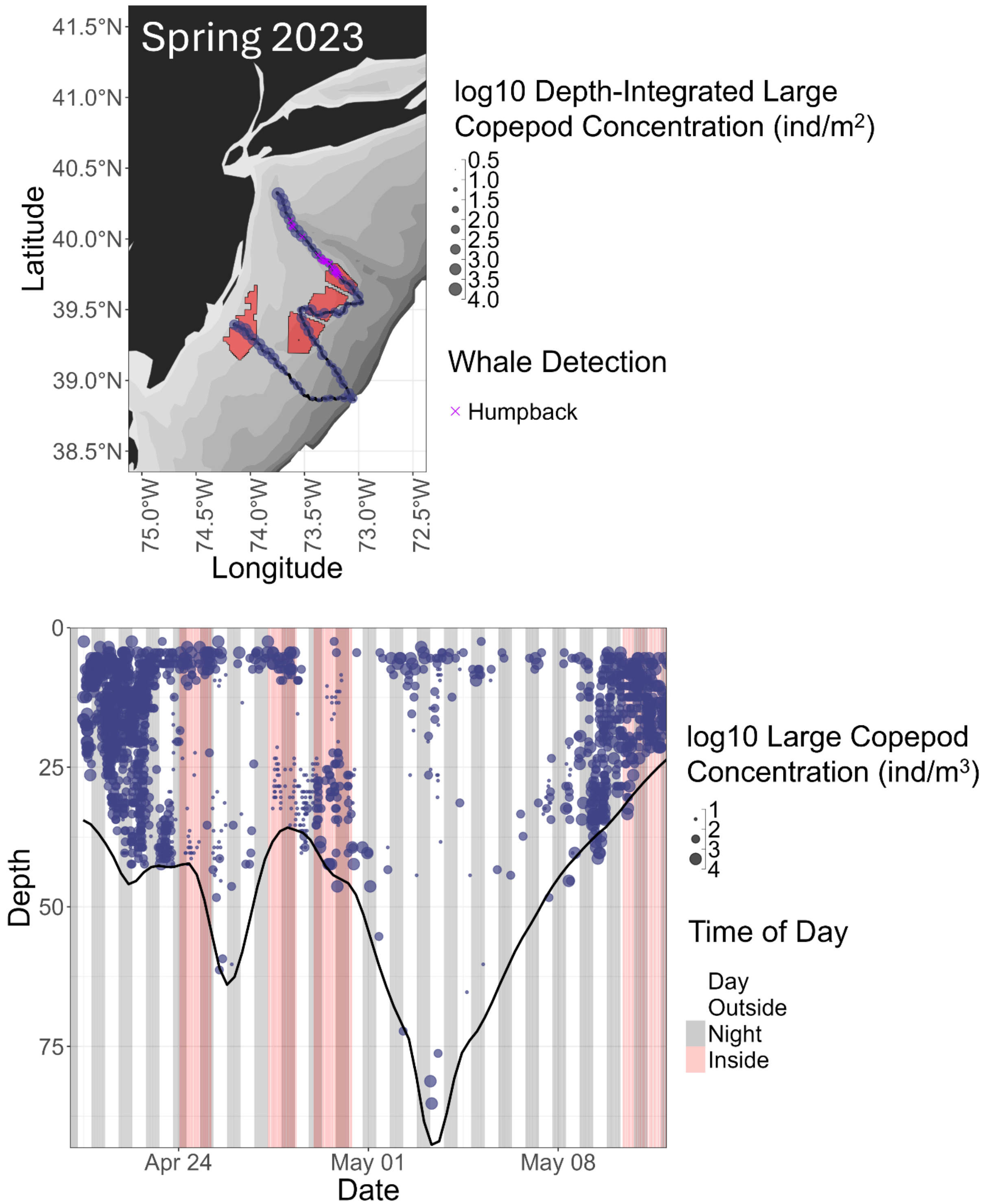


Figure 28. Large copepod concentrations from the Spring 2023 glider mission. The top panel also shows whale detections from the paired DMON glider (purple markings). The white and gray bands indicate day and night, respectively, and the pink bands indicate when the glider was within a Bureau of Ocean Energy Management (BOEM) wind lease area (red polygons in top panel).

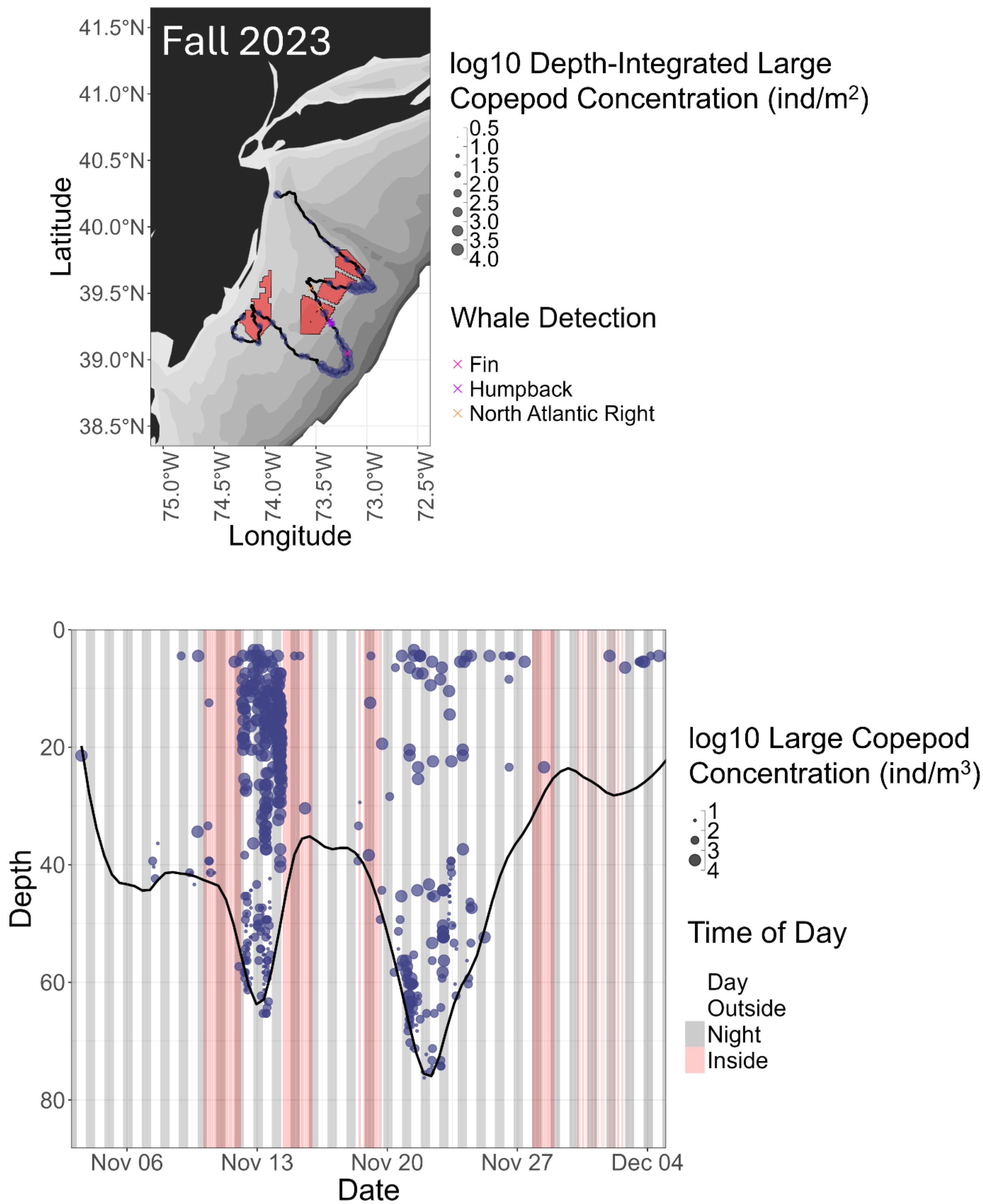
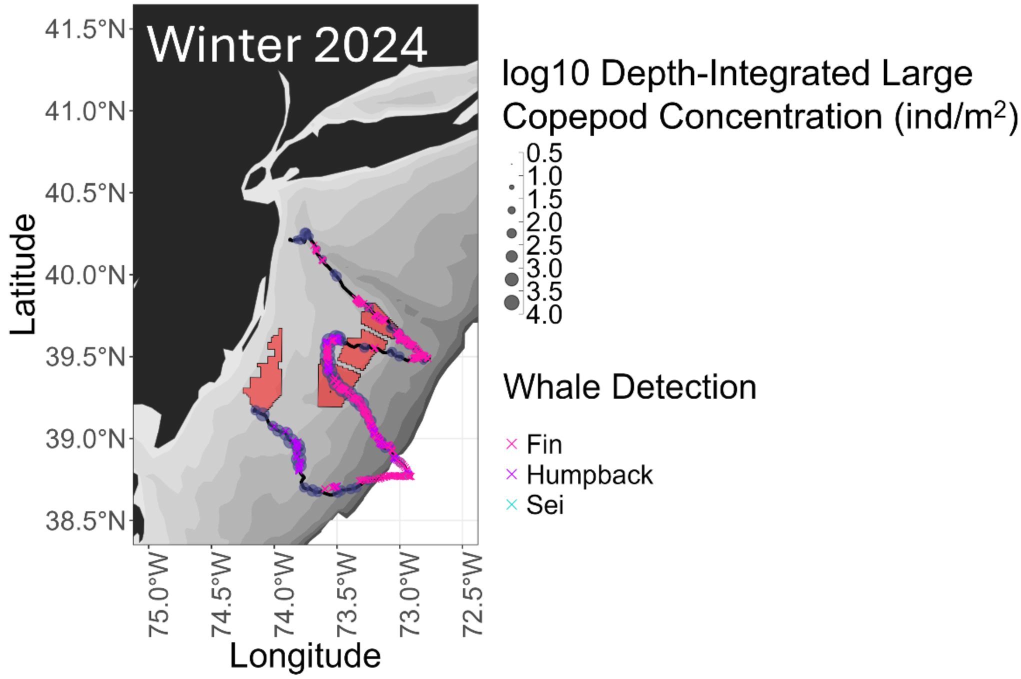


Figure 29. Large copepod concentrations from the Fall 2023 glider mission. The top panel also shows whale detections from the paired DMON glider (pink, purple, orange markings). The white and gray bands indicate day and night, respectively, and the pink bands indicate when the glider was within a Bureau of Ocean Energy Management (BOEM) wind lease area (red polygons in top panel).



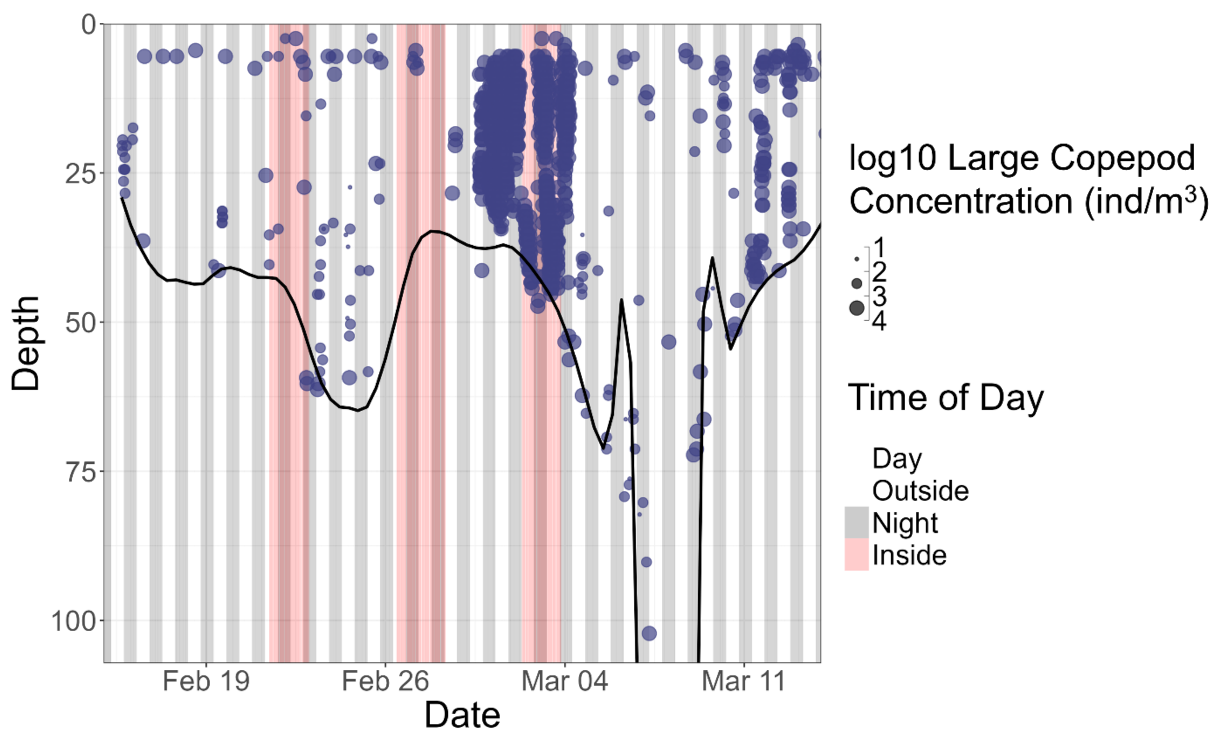


Figure 30. Large copepod concentrations from the Winter 2024 glider mission. The top panel also shows whale detections from the paired DMON glider (pink, purple, cyan markings). The white and gray bands indicate day and night, respectively, and the pink bands indicate when the glider was within a Bureau of Ocean Energy Management (BOEM) wind lease area (red polygons in top panel).

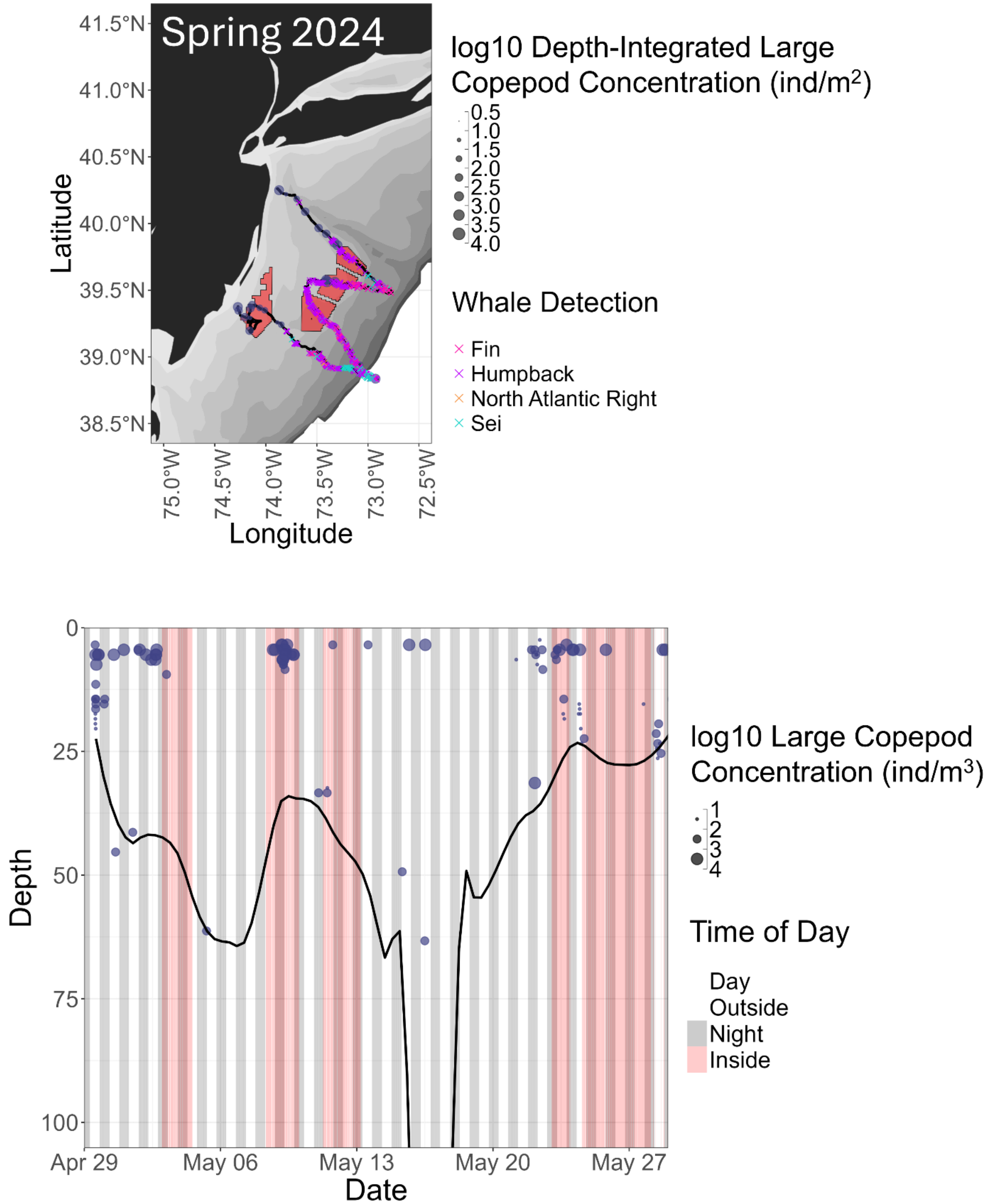


Figure 31. Large copepod concentrations from the Spring 2024 glider mission. The top panel also shows whale detections from the paired DMON glider (pink, purple, orange, cyan markings). The white and gray bands indicate day and night, respectively, and the pink bands indicate when the glider was within a Bureau of Ocean Energy Management (BOEM) wind lease area (red polygons in top panel).

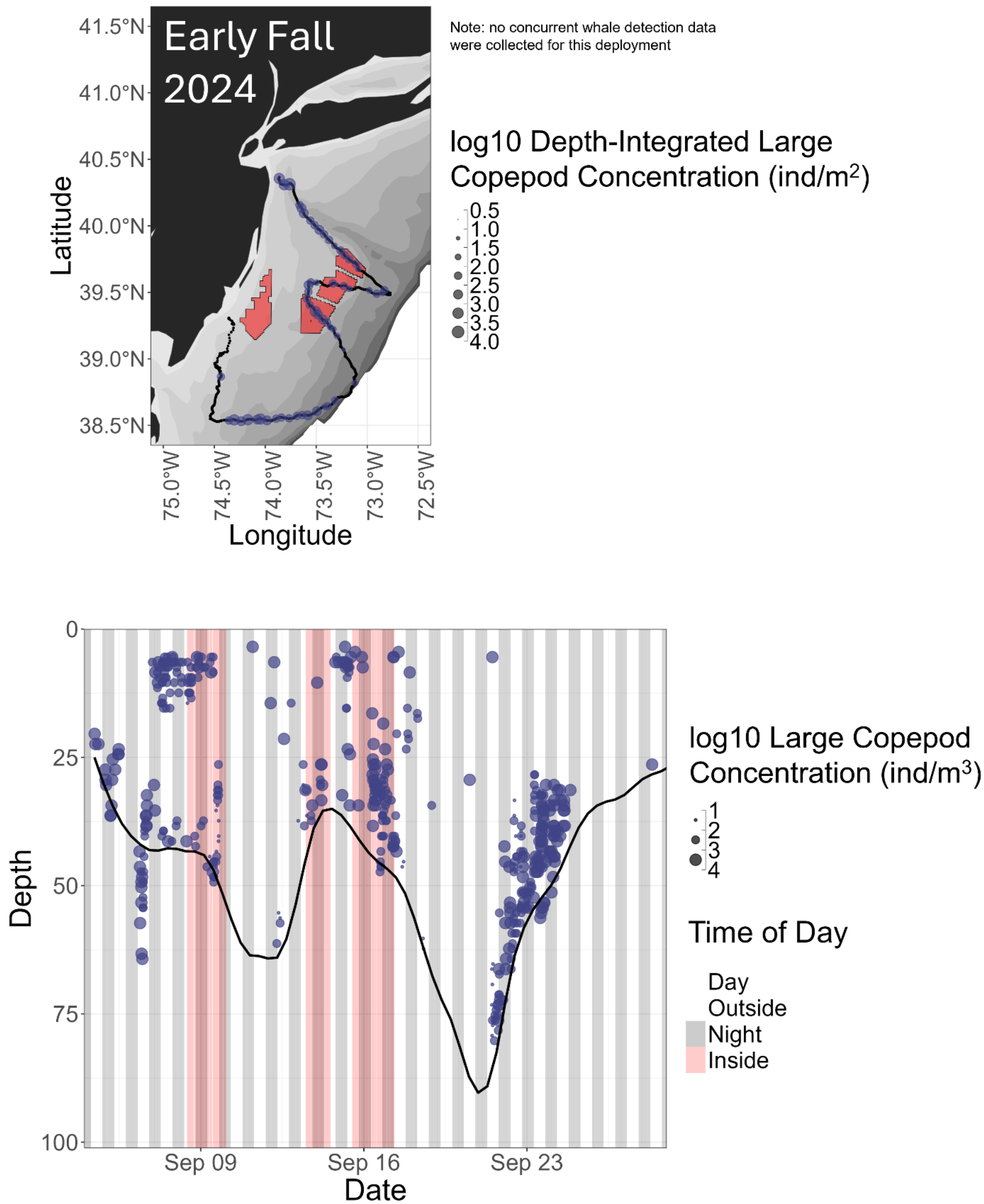


Figure 32. Large copepod concentrations from the Early Fall 2024 glider mission. Note that this was a solo, gap-fill mission without a paired DMON glider for whale detections. The white and gray bands indicate day and night, respectively, and the pink bands indicate when the glider was within a Bureau of Ocean Energy Management (BOEM) wind lease area.

Table 4. Sum of depth-integrated large copepod concentrations (individuals/m^2) estimated from glider acoustics for each season and each season/shelf strata combination.

	Total	Inshore	Midshelf	Offshore
Spring 2023	1.6×10^6	3.5×10^5	1.2×10^6	1.4×10^5
Fall 2023	2.5×10^6	2.0×10^4	1.3×10^6	1.2×10^6
Winter 2024	7.5×10^6	0	7.0×10^6	4.9×10^5
Spring 2024	2.5×10^5	6.4×10^4	1.5×10^5	3.4×10^4
Early Fall 2024	1×10^6	8.8×10^4	8.6×10^5	9.4×10^4

Table 5. Sum of depth-integrated large copepod concentrations (individuals/m^2) estimated from glider acoustics for each season during day and night hours.

	Day	Night
Spring 2023	9.9×10^5	6.5×10^5
Fall 2023	1.0×10^6	1.5×10^6
Winter 2024	4.4×10^6	3.1×10^6
Spring 2024	1.7×10^5	8.1×10^4
Early Fall 2024	7.0×10^5	3.4×10^5

Table 6. Sum of depth-integrated large copepod concentrations (individuals/m^3) estimated from glider acoustics for each season inside and outside the wind farm lease areas.

	Inside	Outside
Spring 2023	4.3×10^5	1.2×10^6
Fall 2023	7.7×10^5	1.7×10^6
Winter 2024	3.4×10^6	4.1×10^6
Spring 2024	1.0×10^5	1.5×10^5
Early Fall 2024	1.3×10^5	9.1×10^5

Fishes: Patterns of volume backscatter strength (S_v) were examined for fish-configured AZFP deployments. Patches of S_v that were not removed by the noise filters, and therefore are likely to be biological echoes, occurred during night-time hours closer to the surface (Figs. 33-36). These patches dissipated after sunrise, likely indicating diel vertical migration of pelagic fishes. The patches of near surface night-time S_v occurred consistently across the entire glider track through all three shelf strata. Values of S_v were strongest in Summer 2023 and Fall 2024 and relatively weak in Summer 2024 and Winter 2025.

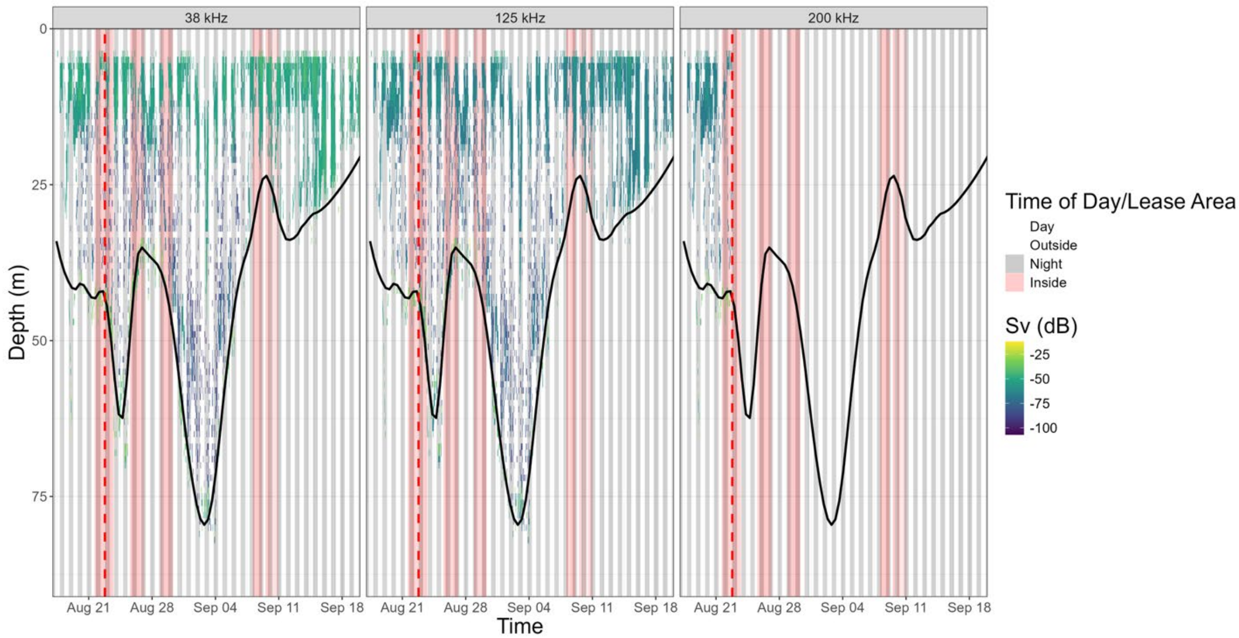


Figure 33. S_v (volume backscatter strength, dB) at 38, 125, and 200 kHz from the fish-configured AZFP during the Summer 2023 glider mission. The white and gray bands indicate day and night, respectively, and the pink bands indicate when the glider was within a Bureau of Ocean Energy Management (BOEM) wind lease area.

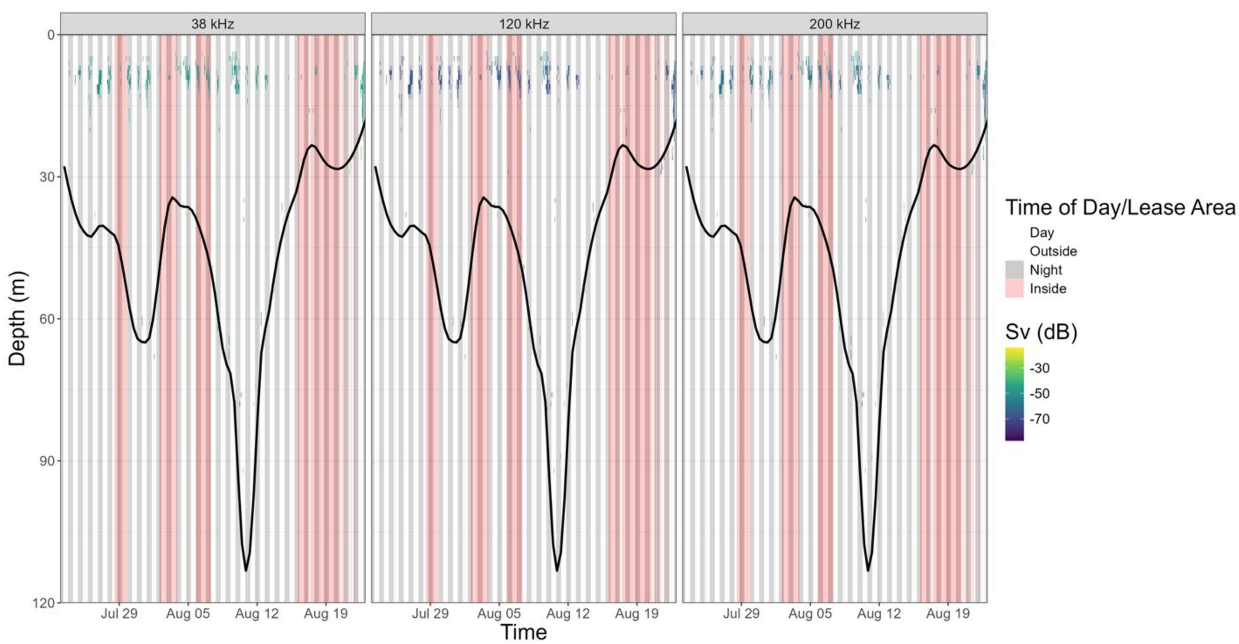


Figure 34. S_v (volume backscatter strength, dB) at 38, 125, and 200 kHz from the fish-configured AZFP during the Summer 2024 glider mission. The white and gray bands indicate day and night, respectively, and the pink bands indicate when the glider was within a Bureau of Ocean Energy Management (BOEM) wind lease area.

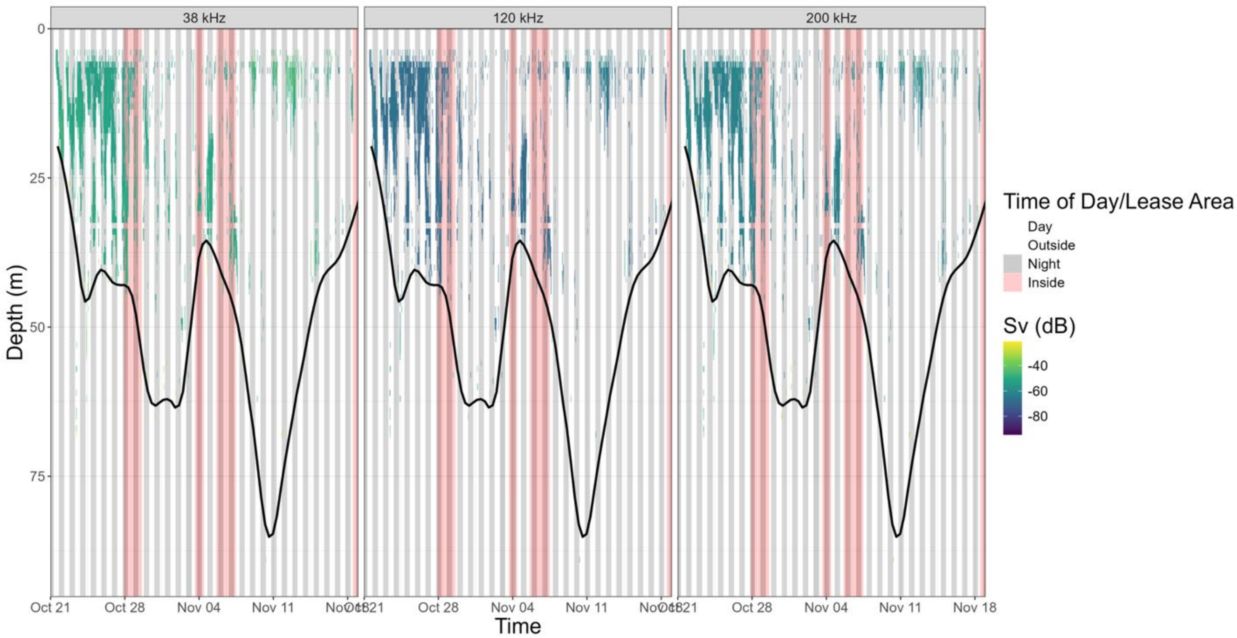


Figure 35. S_v (volume backscatter strength, dB) at 38, 125, and 200 kHz from the fish-configured AZFP during the Fall 2024 glider mission. The white and gray bands indicate day and night, respectively, and the pink bands indicate when the glider was within a Bureau of Ocean Energy Management (BOEM) wind lease area.

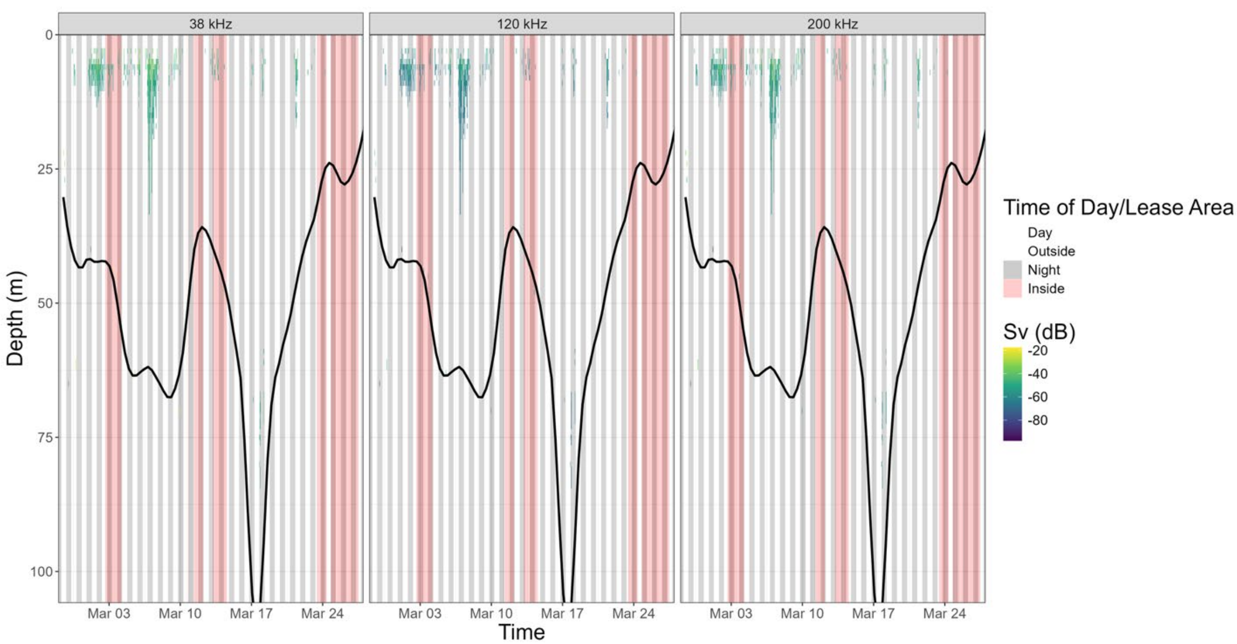


Figure 36. S_v (volume backscatter strength, dB) at 38, 125, and 200 kHz from the fish-configured AZFP during the Winter 2025 glider mission. The white and gray bands indicate day and night, respectively, and the pink bands indicate when the glider was within a Bureau of Ocean Energy Management (BOEM) wind lease area.

We utilized acoustic target strength models from the literature for each of the four species potentially detected by the fish-configured AZFP: menhaden (Lucca and Warren, 2019), longfin squid (Simmonds and MacLennan, 2005), Atlantic mackerel (Scoulding et al., 2017), and Atlantic herring (Ona, 2003). Pelagic fish and squid distributions were less patchy in the horizontal dimension (along the glider track) compared to zooplankton (Figs. 37-40) and did not exhibit any clear seasonal trends in their vertical distribution (Table 8; Appendix 5). While detections of longfin squid were observed in Summer and Fall deployments, they predominantly occurred in measurable concentrations only in the Summer 2023 deployment. During the Summer and Fall deployments, fish were primarily concentrated in the Midshelf strata; however, during the Winter deployment, they were observed in highest concentrations Offshore (Figs. 37-40, Table 7). Similar to large copepods, the highest observed concentrations of fish occurred during Winter, and fish were more common outside the wind farm areas across all seasons (Table 9). There was a noticeable difference in the number of fish detected between the two observed Summers. Total fish concentrations in Summer 2024 were two orders of magnitude lower than those in Summer 2023 (Table 7), which is mirrored by the difference in large copepod concentrations between Spring 2023 and 2024 (Table 4).

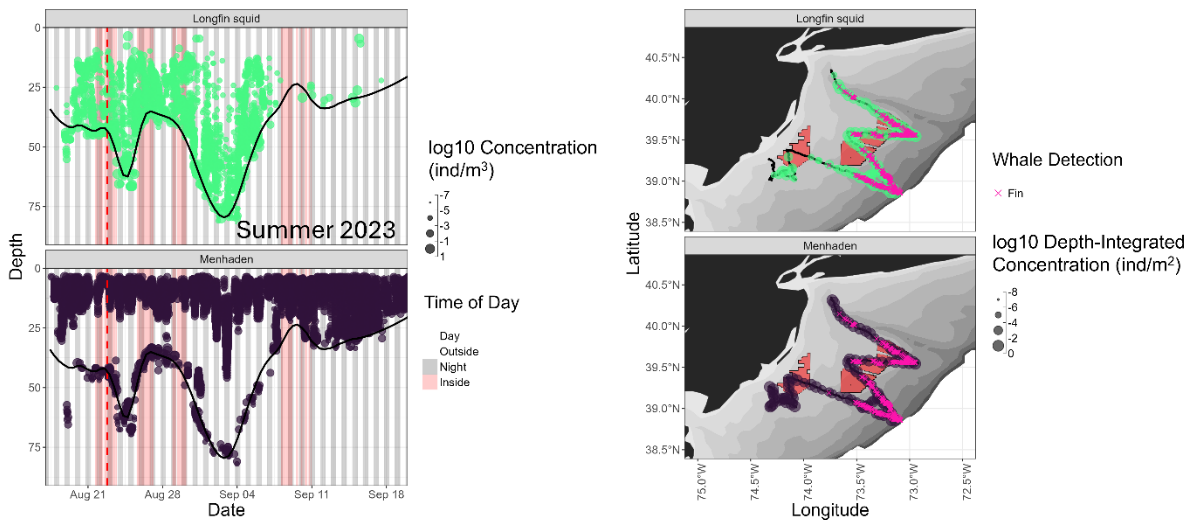


Figure 37. Fish species and concentrations from the Summer 2023 glider mission. Left panels are depth stratified: white and gray bands indicate day and night, respectively, and the pink bands indicate when the glider was within a Bureau of Ocean Energy Management (BOEM) wind lease area (red polygons in right panels). The red dotted line indicates when the 200 kHz channel ceased functioning during the deployment. Right panels are depth integrated and display whale detections from the paired DMON glider. Note log scale for concentrations: negative logs correspond to positive concentrations less than 1.

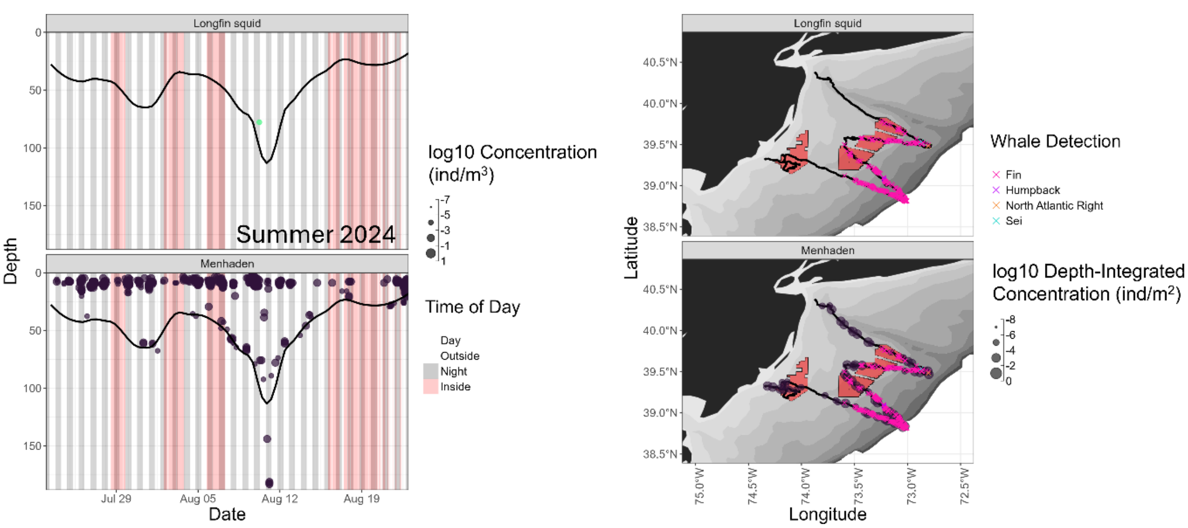


Figure 38. Fish species and concentrations from the Summer 2024 glider mission. Left panels are depth stratified: white and gray bands indicate day and night, respectively, and the pink bands indicate when the glider was within a Bureau of Ocean Energy Management (BOEM) wind lease area (red polygons in right panels). Right panels are depth integrated and

display whale detections from the paired DMON glider. Note log scale for concentrations: negative logs correspond to positive concentrations less than 1.

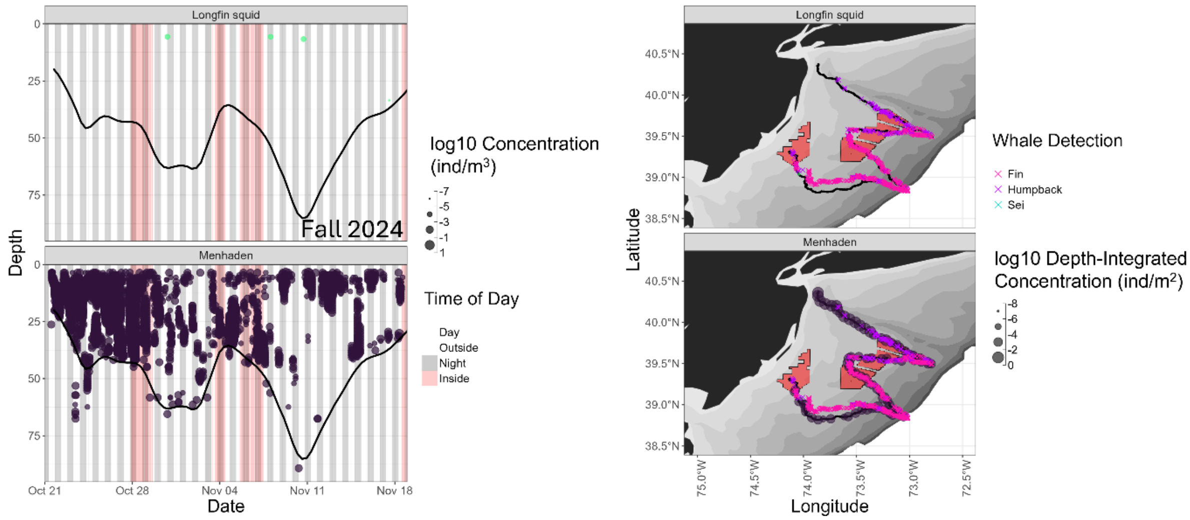


Figure 39. Fish species and concentrations from the Fall 2024 glider mission. Left panels are depth stratified: white and gray bands indicate day and night, respectively, and the pink bands indicate when the glider was within a Bureau of Ocean Energy Management (BOEM) wind lease area (red polygons in right panels). Right panels are depth integrated and display whale detections from the paired DMON glider. Note log scale for concentrations: negative logs correspond to positive concentrations less than 1.

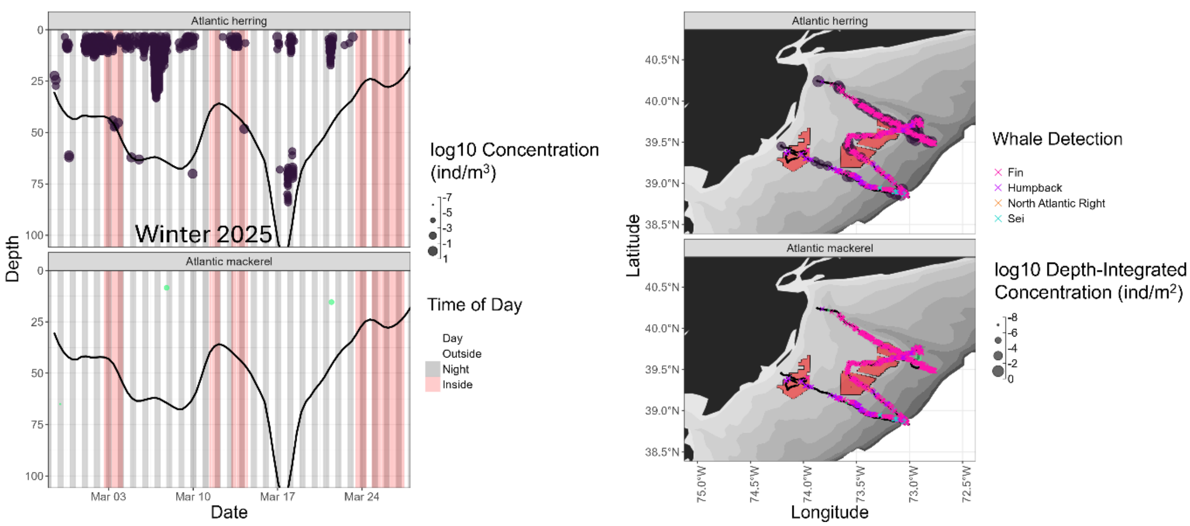


Figure 40. Fish species and concentrations from the Winter 2025 glider mission. Left panels are depth stratified: white and gray bands indicate day and night, respectively, and the pink bands indicate when the glider was within a Bureau of Ocean Energy Management (BOEM) wind lease area (red polygons in right panels). Right panels are depth integrated and display whale detections from the paired DMON glider. Note log scale for concentrations: negative logs correspond to positive concentrations less than 1.

Table 7. Sum of depth-integrated fish (fishes and squid combined) concentrations (individuals/m^2) across all species estimated from glider acoustics for each season and each season/shelf strata combination.

	Total	Inshore	Midshelf	Offshore
Summer 2023	181	12	126	43
Summer 2024	3	0	1	2
Fall 2024	17	2	13	3
Winter 2025	235	5	71	159

Table 8. Sum of depth-integrated fish (fishes and squid combined) concentrations (individuals/m^2) across all species estimated from glider acoustics for each season during day and night hours.

	Day	Night
Summer 2023	84	97
Summer 2024	1	1
Fall 2024	6	11
Winter 2025	102	132

Table 9. Sum of depth-integrated fish (fishes and squid combined) concentrations (individuals/m^2) across all species estimated from glider acoustics for each season inside and outside the wind farm lease areas.

	Inside	Outside
Summer 2023	41	139
Summer 2024	0	2
Fall 2024	2	15
Winter 2025	35	199

Discussion

The oceanography and ecology of the New Jersey coastal shelf system is highly variable and complex at both seasonal and interannual scales. This ecosystem is also situated in one of the most rapidly warming regions in the world and is vulnerable to both ocean and coastal acidification. Yet the range of variability on these different spatiotemporal scales is not well understood because there are limited multi-year seasonal observations of combined oceanographic and ecological variables. Glider deployments conducted by this RMI project revealed both high seasonal and interannual variability in the physical, chemical, and biological variables measured. These results demonstrate the important role that oceanographic conditions and variability play in driving the distributions and concentrations of zooplankton, fishes, and marine mammals. Continued observations and more in-depth analyses utilizing the growing RMI ecoglider dataset will be key to improving our understanding of how the timing and magnitude of oceanographic variables, combined with predator-prey interactions, may influence populations of ecologically and commercially important marine organisms.

Our efforts through this project are contributing to the establishment of an oceanographic and ecological baseline prior to the construction of offshore wind in the region. Patterns of organism distribution driven by variability in oceanographic conditions may be challenging to elucidate from distribution patterns brought on by offshore wind development and operation. High-density data collection over multiple years increases the ability to quantify the region's natural oceanographic and ecological spatiotemporal variability, which can then be compared to observations taken post-development with increased statistical confidence. Therefore, assessing the distribution and spatiotemporal variability in physical, chemical, and biological ocean conditions are particularly important to study now, *before* the construction of offshore wind in local coastal shelf waters, so that future assessments can be made to determine whether and/or how offshore wind may impact the region's ecology.

Seasonal Trends in Oceanographic and Biological Data

The physical seasonal dynamics observed during this project followed known historical trends, including development of a stratified water column in the Spring and early Summer, stratification breakdown in the Fall, and full water column mixing in the Winter (Castelao et al., 2008, 2010). However, intermittent events such as coastal upwelling and storms (tropical storms, hurricanes, Nor'easters) created sudden and significant changes to water column structure and oceanographic conditions. At times, these changes were short-lived and the system reset within days, but higher frequency events, or more intense storms during the fall, contributed to full water column mixing that persisted until Spring. These events can be ecologically important due to the replenishing of nutrients to the ocean's surface (from subsurface water or via runoff) and increasing biological productivity (e.g., Glenn et al., 2004; Shi and Wang, 2007), alleviating bottom water hypoxia or acidification conditions (e.g., Wright-Fairbanks et al., 2020), and triggering seasonal migrations of fishes (Secor et al., 2018).

During Summer, low dissolved oxygen concentrations in coastal bottom waters are typically driven by a combination of warmer ocean temperatures that decrease the saturation of dissolved oxygen and increase respiration rates, strong and/or long duration of stratification that reduces the ability for bottom waters to mix with oxygenated surface waters, and high phytoplankton biomass and productivity in the surface that sinks to subsurface waters and fuels high respiration rates by bacteria that deplete dissolved oxygen (e.g., Diaz, 2001). While heterotrophic bacteria consume dissolved oxygen, they also produce carbon dioxide which can contribute to lower pH and aragonite saturation states that could increase stress exposure to local organisms and exacerbate negative responses when paired with low dissolved oxygen concentrations, (Saba et al., 2019). Carbonate chemistry seasonal dynamics also followed similar trends as those observed by previous glider-based efforts in the region (Wright-Fairbanks et al., 2020), including lowest values of pH and aragonite saturation state generally occurring in summer-time bottom waters.

This project highlighted that the region's ecology responds to differences in timing, and variability, in the magnitude of physical variables. Both zooplankton and pelagic fish/squid distributions in New Jersey coastal shelf waters exhibited high spatiotemporal variability. Throughout Spring and early Fall, large copepods were most abundant in the Inshore and/or Midshelf strata, but occurred in greater abundance Midshelf and Offshore during the late Fall and Winter. These observations align with copepod distributions reported in prior studies where high densities of *C. finmarchicus* were previously observed along the Mid-Atlantic shelf break (Durbin and Kane, 2007; Grieve et al., 2017). However, while previous observations of *C. finmarchicus* concentrations were higher in Spring and lower in Winter (Grieve et al., 2017), data collected during this project showed the opposite trend. The difference in observed *C. finmarchicus* temporal dynamics could be the result of historically low sampling efforts conducted during the Winter season and high variability (halving or doubling) in concentrations from year to year (Grieve et al., 2017). This emphasizes the need for continued seasonal observations, particularly as *C. finmarchicus* densities are projected to decrease by up to 50% in the Mid-Atlantic by 2100 under ongoing climate change (Grieve et al., 2017). More comprehensive groundtruthing of the active acoustic data also needs to be conducted in future research to reduce assumptions and increase confidence in acoustically-identified zooplankton (and pelagic fish/squid) species and their respective concentration and biomass estimates.

Higher concentrations of pelagic fish/squid Offshore in Winter and Midshelf in Summer and Fall likely represent seasonal migratory patterns of many mobile marine species (e.g., Eklund and Targett, 1991). Our data are consistent withprevious studies that have reported menhaden primarily occupying surface waters, except in Winter where they are found in deeper, subsurface waters (Liang et al., 2020). One exception observed in this study was in Fall 2024, when estimated menhaden concentrations exhibited deeper distributions more similar to those observed in Winter 2025. Because the menhaden fishery largely operates inshore in the Mid-Atlantic, the extent and duration of menhaden distribution offshore is not well-defined in the literature (Ahrenholz, 1991; Simpson et al., 2017), however, menhaden tend to be distributed north/inshore on the New Jersey shelf during Spring and Summer and then migrate south/offshore in the Fall where they remain through the Winter (Liljestrand et al., 2019). Other species of pelagic fishes like Atlantic herring and mackerel also perform extensive north-south migrations. Herring (and northern populations of mackerel) spawn in Gulf of Maine and Georges Bank in the Spring and then overwinter offshore in Southern New England and the Mid-Atlantic Bight (e.g., Stevenson and Scott, 2005). Similarly, longfin squid are generally distributed Inshore during Spring and Summer, migrate Offshore in the Fall, and overwinter in warmer waters off the shelf break (Jacobson 2005). In this study, we observed high estimated concentrations of squid across the shelf during Summer 2023, with few detections and low concentrations in Summer 2024, Fall, 2024, and Winter 2025. The latter two observations could be explained by not extending our glider tracks far enough offshore to sample them acoustically. The low detections/estimated concentrations in Summer 2024 could be a result of delayed inshore migrations reported that year by the fishing community (Gaichas et al., 2024; see 'Interannual Trends in Oceanographic and Biological Data' below). In addition to cross-shelf migration, some local pelagic fish species also perform diel vertical migrations (Brown et al., 2025; Stevenson and Scott, 2005), which were observed in the volume backscatter profiles from our acoustic data.

Humpback whale total number of detections and detection days were highest during transition seasons (Spring, Fall), which is consistent with previous observations and modeled surface density estimates (Roberts et al., 2016; Marine Geospatial Ecology Lab, 2022). Interestingly, these detection peaks occurred at the same time as the Spring inshore migration, and Fall offshore migrations, of many pelagic fish species (e.g., Eklund and Targett, 1991). Coupling of these datasets should be the focus of future research. While not detected by our gliders, a large and persistent marine mammal aggregation that included North Atlantic right whales, fin whales, and humpback whales, was observed at the Hudson Canyon and at the shelf break south of Long Island during the Summer of 2024. While the critically endangered North Atlantic right whale was previously thought to mostly be observed in the New York Bight during brief migratory periods in the Winter and Spring, this observation highlighted new patterns that may be observed in future surveys of this monitoring project.

Interannual Trends in Oceanographic and Biological Data

Dramatic oceanographic differences observed between 2023 and 2024 were likely driven by changes in sources and proportions of different water masses and regional atmospheric activity. When compared to 2023, we attribute the relatively lower bottom temperature, salinity, and aragonite saturation states, and higher dissolved oxygen concentrations observed in 2024 to an unusually high-volume flux of Labrador Slope water (a relatively cool, fresh, oxygenated water mass) flowing southward through the Scotian Shelf, Gulf of Maine, southern New England, and onto the New Jersey shelf (Drinkwater et al., 2002; Record et al., 2024). The glider-based observations in this study are consistent with historical vessel-based datasets synthesized by Wang et al. (2013) and Wanninkof et al. (2015) who observed lower total alkalinity and aragonite saturation state, and higher dissolved inorganic carbon concentrations, in northern waters compared to southern waters along the U.S. East coast. These trends were associated with coastal currents, influenced by the less buffered Labrador Sea, that flow southward through U.S. Northeast shelf waters. Changes in source water from warm to cold regimes flowing from the Northeast Channel into the Gulf of Maine (and eventually southward into New Jersey waters) have coincided with ecosystem regime shifts in the Gulf of Maine on decadal scales (Greene and Pershing, 2007; Meyer-Gutbrod et al., 2021) and before 2024, similar cold-water influx had not occurred since the warmer regime began in 2011 (Record et al., 2024). Furthermore, recent projections released by NOAA's Northeast Fisheries Science Center predict this cooling will continue possibly for the next several years, indicating a regime shift (Koul et al., 2024). They attribute this cooling to more frequent injections of cold water into the Gulf of Maine and a southward movement of the Gulf Stream. Therefore, it is pertinent to continue high-resolution ocean observations to better understand any resulting impacts on ocean habitats and their inhabitants.

The Winter of 2024 was less windy and warmer than average for New Jersey, while Winter 2025 was windier and colder than average (Rutgers New Jersey Weather Network). These differences in weather conditions likely explain the significantly colder surface and bottom temperatures observed in the Winter of 2025 (compared to Winter 2024) as well as the significantly higher surface and bottom pH and dissolved oxygen concentrations, which are likely due to increased wind-driven ocean mixing (Wright-Fairbanks et al. 2020).

During the Summer of 2023, most of the bottom water observed by RMI gliders exhibited dissolved oxygen concentrations < 5.0 mg/L. When compared to Summer 2024, the lower dissolved oxygen concentrations that RMI gliders observed during the Summer 2023 were likely the result of warmer bottom temperatures (i.e., less influence of more oxygenated Labrador Slope water) and higher surface and subsurface maximum chlorophyll a concentrations. Higher chlorophyll-a concentrations likely provided more organic matter that supported bacterial production and, combined with warmer bottom water, increased respiration rates that consumed and depleted dissolved oxygen. Low dissolved oxygen concentrations can cause significant negative impacts on organism metabolism, feeding, growth, reproduction, and even mortality (e.g., Diaz and Rosenberg, 2008; Levin et al., 2009). For example, a meta-analysis study determined that fish exhibited negative growth and food consumption at dissolved oxygen concentrations < 4.5 mg/L (Hrycik et al., 2016), including the growth of Winter and Summer flounder (Steirhoff et al., 2006). Fish, lobster, and crab mortalities were reported at the same time we observed low bottom water dissolved oxygen concentrations during Summer 2023. These mortalities could have resulted from low absolute dissolved concentrations (< 3 mg/L in shallow, nearshore waters; 3-5 mg/L in more offshore waters of the shelf), the long duration of exposure to hypoxic conditions (<5 mg/L for most of the shelf from mid-August to late-September), or a combination of low dissolved oxgen and low pH/aragonite saturation state. Gaining a better understanding of the mechanistic drivers that cause anomalous years of low dissolved oxygen as well as a better understanding of organism tolerance to environmental stressors, will help in developing predictive models that could create a warning system for management applications.

Overall, zooplankton and pelagic fishes/squid exhibited interannual trends that reflected the significant differences in oceanographic conditions between the two observation years. However, because active acoustic measurements for zooplankton and pelagic fish/squid distributions were not conducted in every season and year, we were unable to fully interpret interannual variability. Due to the limited dataset, we could only compare Spring zooplankton and Summer pelagic fish/squid between the two survey years. Compared to Spring 2023, zooplankton concentrations were dramatically lower in Spring 2024, which could be the result of a number of bottom-up (physical drivers) or top-down (predation) factors. Lower overall zooplankton concentrations in 2024 could be a response to colder temperatures, or other drivers associated with the higher influx of the Labrador Slope water mass (e.g., lower salinity). However, *C. finmarchicus* is a cold-water adapted copepod species and therefore, higher abundances would be expected in colder years. In this case, high predation rates of these copepods by baleen whales may explain the dramatic decline in large copepod concentrations between Winter and Spring 2024. This also aligns with the observations of the highest marine mammal total detection number and detection days in Spring 2024.

Temperature is an important environmental driver of seasonal migration patterns for fish and squid (Dryfoos et al. 1973; Jacobson, 2005; Anstead et al., 2021). The reduced concentration of pelagic fish/squid from Summer 2023 to 2024 observed in this study may be due to the colder bottom water temperatures observed in Summer 2024. Furthermore, delayed Inshore migrations of longfin squid (as well as black sea bass and haddock) were reported by the fishing community in Spring 2024, and measurements of energy density of longfin squid were lower in Spring 2024 compared to Spring 2023 (Gaichas et al., 2025).

Direct comparisons between whale species, and analyses based on specific location and even time of year, are difficult due to differences in call behavior, variability in sound propagation based on water properties, glider orientation relative to whale location, and species-dependent differences in detection range (approximately 10 km for right whales to 100s-1000s km for fin whales; Harris et al., 2018; Johnson et al., 2022; Pepper, 2023). However, gliders reported the highest total number of detections and detection days for humpback whales during transition seasons (spring, fall), which is consistent with previous observations and modeled densities (Roberts et al., 2016; Marine Geospatial Ecology Lab, 2022). These humpback whale detection peaks co-occurred with the inshore and offshore migration of pelagic fish in the spring and fall, respectively, which suggests that coupling these datasets with the zooplankton data would be be a valuable focus area for future research. There were a greater number of detection days for fin, humpback, and sei whales in Summer, Fall, and Winter 2024 compared to 2023. Limited PAM data collection in Spring 2023 prevents interannual comparison for this season. The number of NARW detection days was higher in 2024 compared to 2023 in Summer and Winter seasons, but lower in Fall. While the critically endangered North Atlantic right whale was previously thought to mostly be observed in the New York Bight during brief migratory periods in the winter and spring, the reports of a large, multi-species marine mammal aggregation in Summer 2024 suggests that new patterns in movement may be observed by future surveys of this monitoring project. Continued observations are needed to better understand interannual variability in marine mammal presence and distribution, as well as what environmental conditions drive those patterns.

Deliverables

The project has supported two completed Masters student theses (Nicholas Occhiogrosso, Scott Pescatore) with two currently in progress (Jessica Leonard, Teemer Barry), and three PhD student dissertations that are currently in progress (Isabella Moore, Jacob Kuenzli, Ashley Hann). As data analyses for these ongoing theses and dissertations progress, several manuscripts will be published in the next few years as a result. Additionally, several undergraduate students and graduate students in our Masters in Operational Oceanography program have been engaged in the project by participating in field, laboratory, or data processing.

The data from this project has contributed to the development of data products that have been included in two NOAA Northeast Fisheries Science Center annual State of the Ecosystem reports. The hypoxic levels of dissolved oxygen concentrations and low pH/aragonite saturation state observed by RMI gliders in Summer 2023 was correlated with the reported fish mortalities as the subject of a Rutgers University press release. Several (total of 26 so far) project presentations have been made, including presentations to regional offshore wind networks (ROSA), NJDEP, and RMI, as well as presentations at regional and national science conferences.

Student Theses and Dissertations:

1. Occhiogrosso, N.S. 2024. Glider-observed seasonal and spatial distributions of zooplankton in the Mid-Atlantic Bight. Thesis for the Master of Operational Oceanography Program. Graduate Program in Oceanography, Rutgers University. 20 p. Appendix 1.
2. Pescatore, S. 2024. Associating fish tag detections to satellite derived water masses and ocean front gradients. Thesis for the Master of Operational Oceanography Program. Graduate Program in Oceanography, Rutgers University. 19 p. Appendix 2.

Reports:

1. Northeast Fisheries Science Center and contributors. 2025. State of the Ecosystem 2025: Mid-Atlantic. Northeast Fisheries Science Center. Access report: https://doi.org/10.25923/23nx-qf59. **G. Saba is a contributing author**.

2. Northeast Fisheries Science Center and contributors. 2024. State of the Ecosystem 2024: Mid-Atlantic. Northeast Fisheries Science Center. Access report: https://doi.org/10.25923/vz5a-d111. **G. Saba is a contributing author**.

Press Releases:

1. Saba, G., Kohut, J. 2023. Rutgers Scientists Observe Unusual Ocean Conditions Possibly Linked to Mortality in Marine Life off New Jersey. Article written for Rutgers Today and the Rutgers School of Environmental and Biological Sciences (SEBS) and New Jersey Agricultural Experiment Station (NJAES) Newsroom. Available here.

Project Presentations:

1. Saba, G., Kohut, J. 2025. An Autonomous-based Oceanographic and Ecological Baseline to Inform Offshore Wind Development. Talk presented at the Regional Wildlife Science Collaborative for Offshore Wind (RWSC) Habitat & Ecosystem Subcommittee meeting. May 2025. Virtual.
2. Kohut, J., Saba, G., Lawrence, K., McGarigal, C. 2024. An autonomous-based oceanographic and ecological baseline to inform offshore wind development. NAWEA Windtech Conference. October 2024. New Brunswick, NJ.
3. Mossman, D., Kohut, J.T., Saba, G.K. 2024. Examining the Seasonal Relationships Between Oceanographic Variables and Echosounder-Derived Zooplankton Abundance Estimates Using an Autonomous Underwater Glider. Poster presented at the Mid-Atlantic Chapter of the American Fisheries Society Annual Meeting. October 2024. New Brunswick, NJ.
4. Nazzaro, L., Kohut, J., Saba, G., Mossman, D., Baumgartner, M., & Wilder, J. Physics, plankton, and whales, oh my! 2024 North Atlantic Right Whale Consortium Annual Meeting. October 2024. Providence, RI.
5. Saba, G. 2024. 'Eco-gliders' as novel platforms for ocean health and ecosystem monitoring and research. Invited talk presented at the Mid-Atlantic Ocean Conservation Symposium. October 2024. Monmouth, NJ.
6. Saba, G. 2024. Why measure coastal acidification? What can it tell us? Insight from a New Jersey case study. Invited talk presented at the Mid-Atlantic Ocean Acidification Workshop. September 2024. Baltimore, MD.
7. Kohut, J.T., McGarigal, C., Lawrence, K., Saba, G.K. 2024. An autonomous-based oceanographic and ecological baseline to inform offshore wind development. Talk presented at the Underwater Gliders User Group Workshop. September 2024. Ann Arbor, MI.
8. Garzio, L., Nazzaro, L., Kohut, J.T., Saba, G.K. 2024. 2023 Seasonal Mid-Atlantic Ocean Temperatures and Stressors. Talk presented at the State of the Climate: New Jersey 2023 webinar. July 2024. Virtual.
9. Saba, G.K., McGarigal, C., Lawrence, K., Kohut, J.T. 2024. An autonomous-based oceanographic and ecological baseline to inform offshore wind development. Poster presented at NYSERDA's State of the Science 2024 Workshop Taking an Ecosystem Approach: Integrating Offshore Wind, Wildlife, and Fisheries. July 2024. Long Island, NY.

10. Kohut, J.T., McGarigal, C., Lawrence, K., Saba, G.K. 2024. An autonomous-based oceanographic and ecological baseline to inform offshore wind development. Talk presented at the International Underwater Glider Conference. June 2024. Gothenburg, Sweden.
11. Kohut, J.T., McGarigal, C., Lawrence, K., Saba, G.K. 2024. An autonomous-based oceanographic and ecological baseline to inform offshore wind development. Talk presented at the Mid-Atlantic Ocean Forum. May 2024. Lewes, DE.
12. Kohut J., Saba, G., McGarigal, C., Lawrence, K. 2024. An Autonomous-based Oceanographic and Ecological Baseline to Inform Offshore Wind Development. Presented at the World Fisheries Congress. March 2024. Seattle, WA.
13. Saba, G., Kohut, J., McGarigal, C., Lawrence, K. 2024. An Autonomous-based Oceanographic and Ecological Baseline to Inform Offshore Wind Development. Invited talk presented to the New Jersey Department of Environmental Protection's Division of Science and Research. March 2024. Virtual.
14. Kohut J., Saba, G., McGarigal, C., Lawrence, K. 2024. An Autonomous-based Oceanographic and Ecological Baseline to Inform Offshore Wind Development. Invited talk presented at the New Jersey Coastal and Climate Resilience Conference. March 2024. Long Branch, NJ.
15. Saba, G., Kohut, J. 2024. An Autonomous-based Oceanographic and Ecological Baseline to Inform Offshore Wind Development. Talk presented at the Ocean Sciences 2024 meeting. February 2024. New Orleans, LA.
16. Kohut, J. and Zemeckis, D. 2023. What's happening with offshore wind off New Jersey. Talk presented to the general public as part of the Rutgers Cooperative Extension ReNew Jersey Series. Virtual. October 2023.
17. Kohut, J., Saba, G., Nazarro, L., Baumgartner, M., Wilder, J., Lawrence, K., McGarigal, C. 2023. Exploring overlap between NARW and ocean features: An autonomous-based oceanographic and ecological baseline. Talk presented at the NARW Consortium Science Meeting. October 2023. Halifax, Nova Scotia, Canada.
18. Saba, G., Kohut, J., Lawrence, K., McGarigal, C. 2023. An autonomous-based oceanographic and ecological baseline to inform offshore wind development over the continental shelf off the coast of New Jersey, northeast U.S. Talk presented at BPU in-house visit. October 2023. Rutgers University, NJ.
19. Kohut, J., Crowley, M., Coleman, K., and Saba, G. 2023. RUCOOL Offshore wind habitat and ecosystem efforts. Talk presented to the RWSC Habitat and Ecosystem Subcommittee. Virtual. September 2023.
20. Kohut, J. and Saba, G. 2023. An autonomous-based oceanographic and ecological baseline to inform offshore wind development. Invited graduate student seminar series at New Jersey Institute of Technology. September 2023, Newark, NJ.
21. Kohut, J. and Munroe D. 2023. Offshore wind, the environment, and the ecology. Talk presented to teachers participating in the 2023 RECharge Workshop sponsored by NJEDA. August 2023. Atlantic City, NJ.
22. Saba, G., Kohut, J., Lawrence, K., Reilly, R. 2023. An autonomous-based oceanographic and ecological baseline to inform offshore wind development over the continental shelf off the coast of New Jersey, northeast U.S. Talk presented at the Rutgers University Offshore Wind Symposium. January 2023. New Brunswick, NJ.
23. Saba, G., Kohut, J., Lawrence, K., Reilly, R. 2022. An autonomous-based oceanographic and ecological baseline to inform offshore wind development over the continental shelf off the coast of New Jersey, northeast U.S. Talk presented to the state Offshore Wind Environmental Resources Working Group. September 2022. Virtual.

24. Saba, G., Kohut, J., Lawrence, K., Reilly, R. 2022. An autonomous-based oceanographic and ecological baseline to inform offshore wind development over the continental shelf off the coast of New Jersey, northeast U.S. Talk presented at the ICES Annual Science Conference. September 2022. Dublin, Ireland.
25. Saba, G., Kohut, J. 2022. Autonomous solutions responding to the oceanographic and ecological monitoring needs of offshore wind development. Talk presented at NYSERDA's State of the Science Workshop on Wildlife and Offshore Wind Energy. July 2022. Tarrytown, NY.
26. Saba, G.K. 2022. 'Eco-gliders' as novel platforms for ocean health and ecosystem monitoring and research. Invited talk presented at the Ocean Carbon & Biogeochemistry meeting. June 2022. Woods Hole, MA.

Recommendations for Future Research

The data produced as a result of this project has already provided comprehensive datasets serving many users and is supporting a wide breadth of ongoing research and offshore wind energy development planning and monitoring. RMI will continue to support ecoglider-based oceanographic and ecological monitoring for three additional years of deployments (Spring 2025 through Winter 2028). The resulting five-year data sets will enable development of seasonally-resolved climatologies that will improve understanding of average conditions and variability as well as potentially identify anomalous conditions that may be attributed to climate conditions and/or future potential offshore wind impacts. Longer-term data for co-located physical, chemical, and biological variables will also provide the means to investigate the mechanistic drivers of the patterns and variability of marine organism distributions, inguding for phytoplankton, zooplankton, pelagic fishes and squid, and marine mammals. These data will allow for a more thorough examination of multi-stressor dynamics, organism biomass, distribution, and connectivity, and will be particularly useful for identifying physical oceanographic conditions that may concentrate prey and create foraging 'hot spots' in future studies. Without a more complete understanding of the natural variability and mechanistic drivers of oceanographic and ecological conditions, it would be difficult to attribute changes in any of these variables directly to offshore wind development and operation.

Future field efforts are needed throughout the New Jersey OCS to co-locate glider surveys with vessel-base, depth-stratified zooplankton sampling and mid-water trawls for pelagic fishes and squid. Increased sampling, and at denser spatiotemporal resolution, would greatly improve identification of community composition and dominant scattering species throughout the full water column and OCS. Additionally, direct, lab-derived measurements of acoustical properties of small copepods would greatly expand the capacity of the zooplankton-configured AZFP by allowing for the development of reliable target strength acoustic models to quantify their concentration and biomass. This is particularly important for the New Jersey coastal shelf because small copepods consistently dominated the community composition in our discrete tow data. These efforts together would limit assumptions, increase confidence in the identification of dominant scatterers, and greatly improve accuracy of taxon-specific concentration and biomass estimates.

Additionally, the data from this project are providing contextual data and information for other funded RMI projects, including the eDNA and fish telemetry surveys and the marine mammal tagging and tracking studies among others (Fig. 41). Specifically, oceanographic data collected by these RMI glider missions are providing environmental context that can be used in those and future studies for interpretation of sampling conducted in the aforementioned surveys. Physical oceanographic measures of temperature and water column structure can provide information on how marine species, specifically higher trophic groups including fishes and marine mammals, are occupying and utilizing dynamic pelagic habitat. Glider Rx-LIVE and VMT receivers are providing data on fish species tagged with acoustic transmitters for the ongoing RMI telemetry project, and a current Rutgers PhD student is developing a spatial probability model using these datasets to determine how oceanographic variables influence the distribution and habitat use of elasmobranchs. Glider-based marine mammal detection data will be useful to the RMI whale tagging study by providing general location information for targeted species for tagging, and the visual location, identification, and possibly enumeration of the whales in the tagging study will provide more specific metrics to inform and better interpret the glider-based passive acoustic data. Ocean temperature and chemistry data produced by this project are currently being utilized to develop openly accessible data products focused on how these variables may be impacting habitats and physiological responses of commercially important marine species as part of the NOAA Northeast Fisheries Science Center's annual State of the Ecosystem reports.

Our recommendations for future research support the need for continued oceanographic and ecological observations as offshore wind footprints grow. Future studies should continue integrating relevant oceanographic information with organism abundance and distribution data to elucidate potential responses to climate variability and change, environmental stressors, and offshore wind development and operation. These studies will help guide management and conservation efforts as well as support the responsible development and operation of offshore wind.

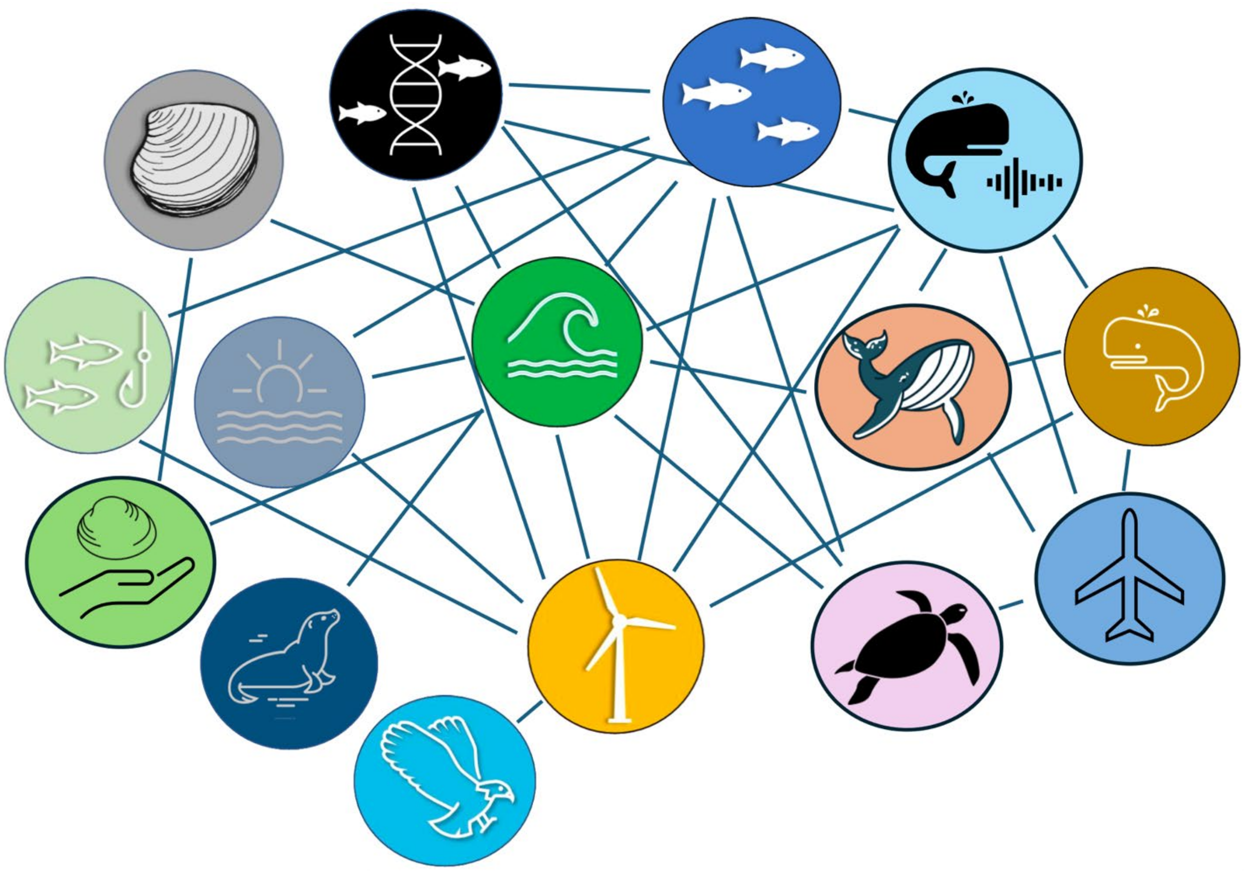


Figure 41. Project data sharing and connectivity between this RMI ecoglider project (green circle with wave) and other funded RMI projects. Credit: NJ RMI.

Data Storage and Accessibility

All raw and processed glider data, as well as sensor data that are recorded externally (e.g. AZFP, DMON, Vemco) are stored on Rutgers DMCS servers and are backed up regularly. Processed glider data files can be publicly accessed via the Environmental Research Division Data Access Program (ERDDAP) and links to the full-resolution delayed-mode glider datasets for each deployment are provided in the section below. The "Delayed Mode Science Profiles" datasets for each deployment contain all profile-based measured and derived science variables that are reported through the glider, as well as the associated QC variables that can be applied to the variables for quality control. All associated variable and deployment metadata are provided in each dataset in ERDDAP. To access and download these datasets, navigate to the Data Access Form by clicking on "data", select desired variables and constraints, choose desired File type and click "Submit" (Fig. 42). A more detailed video tutorial of downloading data from ERDDAP can be found here, and example code to programmatically download glider data files using Python is available in the RUCOOL Github repo.

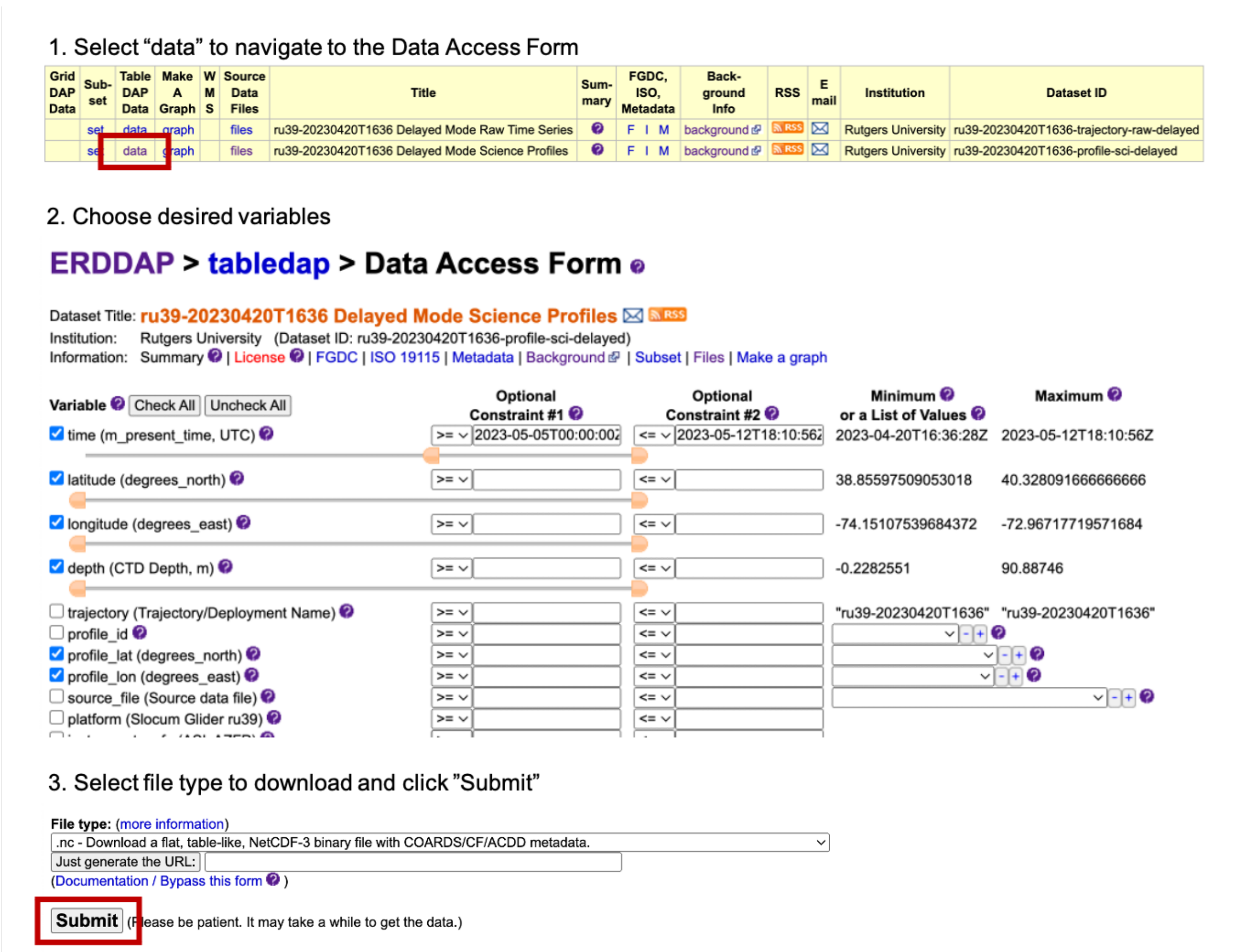


Figure 42. Example screen shots for accessing and downloading glider data from ERDDAP.

Glider datasets that have integrated pH sensors have been further quality controlled (post-processing code here) and archived at NCEI's Ocean Carbon and Acidification Data System (OCADS) (Table 10).

Acoustically-derived datasets that record data external to the glider and require additional processing have been submitted to NCEI's Water Column Sonar Data repository (AZFP, post-processing instructions and code here) and NCEI's Passive Acoustic Data Archive (DMON, post-processing instructions and code here).

Telemetry tag detections from Innovasea Rx-LIVE and VMT receivers are sent to the Mid-Atlantic Acoustic Telemetry Observation System (MATOS), a data portal designed to support the Atlantic Cooperative Telemetry Network, under project "RUCOOL NJRMI Eco-glider Surveys" (code RMIgliders).

Vessel-based sampling data collected at glider deployments and recoveries for ground-truthing the glider-based pH and AZFP sensors have been processed and are publicly available via ERDDAP. Zooplankton tow data are available here, carbonate chemistry water sampling data are available here, and the pH glider and water sampling comparison tables are available here.

Table 10. Accession Numbers assigned to glider datasets with integrated pH sensors that have been archived at NCEI's Ocean Carbon and Acidification Data System (OCADS)

Glider Mission	Glider	Glider-deployment ID	Accession Number and Hyperlink
Spring 2023 paired	ru39	ru39-20230420T1636	0300778
Summer 2023 paired	ru39	ru39-20230817T1520	0306235
September 2023 gap-fill	ru34	ru34-20230920T1506	0306334
Fall 2023 paired	ru39	ru39-20231103T1413	0306288
Winter 2024 paired	ru39	ru39-20240215T1646	0306290
Spring 2024 paired	ru39	ru39-20240429T1522	0306276
June 2024 gap-fill	ru43	ru43-20240612T1658	0306279
Summer 2024 paired	ru39	ru39-20240723T1442	0306278
September 2024 gap-fill	ru43	ru43-20240904T1539	0306280
Fall 2024 paired	ru39	ru39-20241021T1717	0306285
Winter 2025 paired	ru39	ru39-20250226T1700	0306287

Data Management

The data are reported in two ways. Real-time data are those data sent back to shore via the satellite connection during the mission and may not include the full dataset. Delayed mode data are those data recovered from the glider once it is recovered and include the full dataset. The QA/QC associated with both data reporting are described in the project QAPP document. The status of data reporting for each mission is summarized below.

- Spring 2023 paired
    - ru39: delayed mode data are available on ERDDAP
    - ru41 (lost): real-time raw data are available on ERDDAP
- June/July 2023 gap-fill
    - ru40: delayed mode data are available on ERDDAP

- Summer 2023 paired
  - ru39: delayed mode data available on ERDDAP
  - ru40: delayed mode data available on ERDDAP
- September/October 2023 gap-fill
  - ru34: delayed mode data available on ERDDAP
- Fall 2023 paired
  - ru39: delayed mode data available on ERDDAP
  - ru40: delayed mode data (pre-brake failure) and delayed mode data (redeploy after fix of glider brake) available on ERDDAP
- Winter 2024 paired
  - ru39: delayed mode data available on ERDDAP
  - ru40: delayed mode data available on ERDDAP
- Spring 2024 paired
  - ru39: delayed mode data available on ERDDAP
  - ru40: delayed mode data available on ERDDAP
- June 2024 gap-fill
  - ru43: delayed-mode data available on ERDDAP
- Summer 2024 paired
  - ru39: delayed-mode data available on ERDDAP
  - ru40: delayed-mode data available on ERDDAP
- September 2024 gap-fill
  - ru43: delayed-mode data available on ERDDAP
- Fall 2024 paired:
  - ru39: delayed-mode data available on ERDDAP
  - ru40: delayed-mode data available on ERDDAP
- Winter 2025 paired:
  - ru39: delayed-mode data available on ERDDAP
  - ru40: delayed-mode data available on ERDDAP

Developments in Real-time Data Visibility

As part of our ongoing effort to ensure real-time data availability and quality control, we added calculations of preliminary time-lag adjusted pH and dissolved oxygen (in units of mg/L), QARTOD gross range and spike tests for pH, and Total Alkalinity and Aragonite Saturation State for the New Jersey/New York Bight region to our glider data processing pipeline. These data products are available in our real-time datasets that are distributed on RUCOOL's glider ERDDAP server while the glider is actively deployed, and are also plotted in real-time on our operational glider website for each relevant deployment. The code for these improvements is publicly available in our rugliderqc Github repository. Once the glider is recovered, the full-resolution delayed-mode dataset is processed and shared via ERDDAP, and replaces the real-time dataset, which is simply a subset of the full-resolution delayed-mode dataset. The real-time plots and operations are preserved on the RUCOOL operational glider website indefinitely.

In order to add calculations of Total Alkalinity and Aragonite Saturation State, we updated our Total Alkalinity (TA)-salinity regression analysis to incorporate more vessel-based data in the New Jersey/New York Bight region (Fig. 43). The previous analysis included discrete samples collected during the Summer 2015 East Coast Ocean Acidification (ECOA) cruise. This dataset was paired with water sampling done during seasonal glider deployments and recoveries, and the linear relationship between TA and salinity was calculated for each season. Any seasonal differences in the TA-salinity relationship were based solely on the glider-based water sampling due to a lack of vessel-based data.

To incorporate more vessel-based data into the analysis, we used the 2021 CODAP-NA dataset in addition to publicly available cruise data downloaded from the NCEI Ocean Carbon and Acidification Data System (OCADS) data portal. These datasets were filtered to include sampling locations within the New York Bight at depths less than 200m (maximum glider depth), and salinity/TA QC flags were applied (when available).

The resulting vessel-based New York Bight dataset includes Niskin bottle samples as well as surface flow-through and underway samples from 31 oceanographic cruises from 2006-2022 (Fig. 43). This expansion of the vessel-based dataset now allows for more robust seasonal TA-salinity regressions that are used to estimate TA in glider datasets.

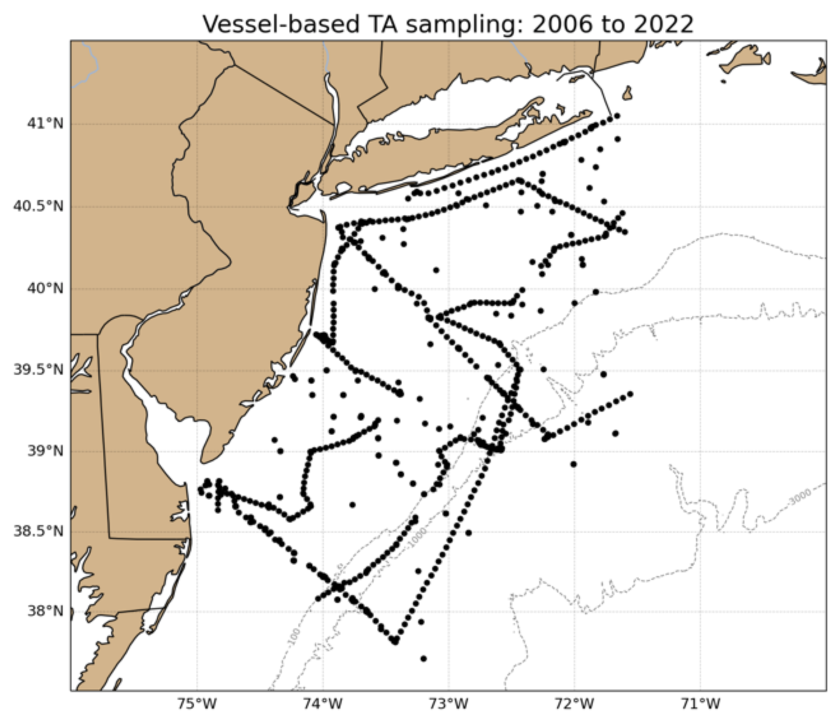


Figure 43. All publicly available vessel-based TA data from 2006-2022 harvested from the CODAP-NA dataset and NCEI OCADS and incorporated into an updated TA-salinity regression analysis.

Leveraged Products

The resulting data from this project is starting to be utilized for research and the development of data products by data analysts from our Masters in Operational Oceanography program and graduate students in our Graduate Program in Oceanography. Our team is currently working on two manuscripts that will be submitted to peer reviewed journals over the next year: one that highlights the effectiveness of a glider-based monitoring program to evaluate coastal oceanographic and ecological dynamics serving many needs and one that will present a full seasonally resolved description of zooplankton abundance, biomass, and distribution (vertical and horizontal) patterns in New Jersey shelf waters. We are applying generalized linear models to the data to determine if ocean physical features (e.g., fronts) play a role in driving zooplankton aggregations or patches, and this work is being led by a new PhD student Ashley Hann. This manuscript is an expansion of initial efforts conducted by Nicholas Occhiogrosso, a student advised by PI Saba who completed our Masters in Operational Oceanography (MOO) program in the Summer of 2024. Additionally, these efforts build off of another MOO student, Scott Pescatore, who developed software tools and utilized VEMCO telemetry data from five previous (non-RMI) glider deployments on the New Jersey shelf to investigate how tagged fish distributions were related to satellite-derived oceanographic features (specific water masses, frontal locations). The tools Scott developed can be applied to the RMI glider telemetry data for this specific manuscript and will also provide routine products that present the overlap of these ecological trophic groups to observed ocean characteristics and features. There are many more manuscripts planned that will utilize this project's data. Another Rutgers PhD student, Isabella Moore, is focusing part of her dissertation research on determining potential oceanographic drivers of whale distributions, in particular satellite-based and surface current-based frontal metrics. Isabella's research will build on work from MOO students Courtney Dreyfus and Rhyan Grech, and will in part use oceanographic data and whale detections collected by this ecoglider monitoring program. Additionally, the marine mammal data collected through the RMI glider passive acoustic sensors are contributing to the larger community effort to inform probability maps of North Atlantic Right Whales in and around planned offshore wind projects. Current Masters students are using RMI glider data, along with other complementary datasets, to test how different glider flight patterns can improve sensor equilibration times (Jessica Leonard) and to examine Summer variability in bottom oxygen in the Mid-Atlantic Bight measured by gliders (Teemer Barry). Finally, PhD student Jacob Kuenzli (advised by PI Saba and collaborating with Drs. Keith Dunton and Jason Adolf) at Monmouth University) and other external collaborators is currently conducting research that is utilizing moored- and glider telemetry receiver data (from this RMI ecoglider project, the RMI telemetry project, and other ongoing and historical projects) to determine historical presence/absence, distribution, and habitat use of tagged elasmobranchs. These research efforts are just beginning.

This project's data are also being integrated into data products that are routinely being developed for the NOAA Northeast Fisheries Science Center annual State of the Ecosystem reports. These data products are specifically focused on ocean acidification and other environmental stressors in the New England and Mid-Atlantic regions and were specifically requested by the New England and Mid-Atlantic Fisheries Management Councils. Data products include the development of maps of bottom water pH and aragonite saturation states as well as maps depicting locations where bottom aragonite saturation state reached lab-derived sensitivity levels within the habitat depth range of designated target species in the Mid-Atlantic Bight (Atlantic sea scallop and longfin squid; see example Fig. 44) and Gulf of Maine (Atlantic cod and American lobster). The RMI glider data have been integral in highlighting multi-stressor interactions (e.g., Summer 2023) and localized seasonal ocean acidification. Specifically, it was data from the RMI gliders that were able to reveal the lower aragonite saturation state conditions that occurred in the Mid-Atlantic coastal shelf during the two most recent years (2023 and 2024) which not only increased the spatial range of potentially unfavorable habitat for Atlantic sea scallops and longfin squid in the Summer-time compared to the observed past years, but also marked the first time these sensitivity levels were reached in observations outside of the Summer season: Fall for both species and Spring for Atlantic sea scallops. These latter findings would not have been possible without the seasonal-resolution observations of this RMI ecoglider program, as no existing vessel-based programs conduct consistent, seasonally resolved carbonate chemistry sampling efforts.

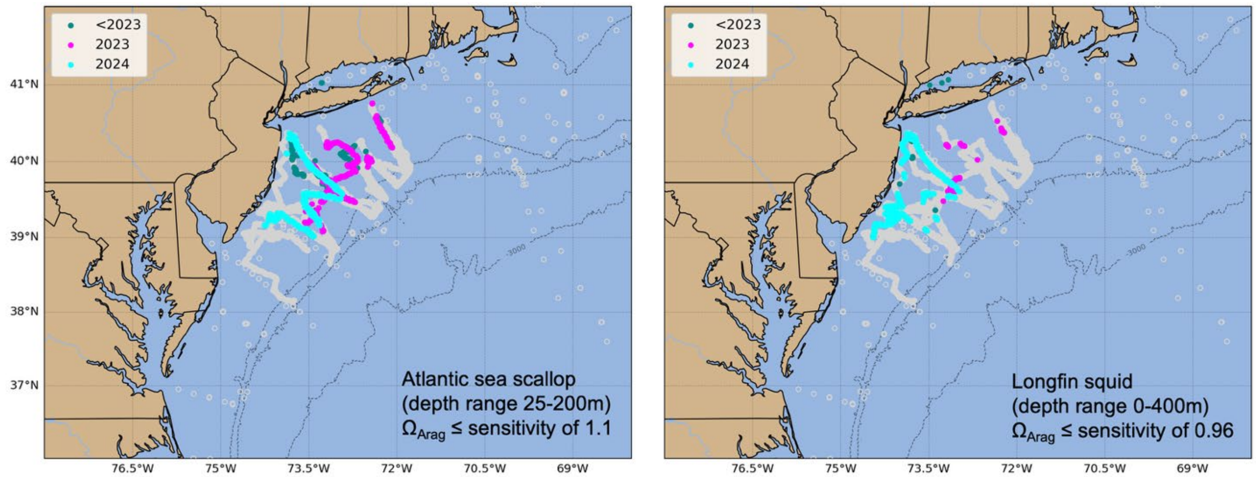


Figure 44. Locations where bottom aragonite saturation state (ΩArag; Summer only: June-August) were at or below the laboratory-derived sensitivity level for Atlantic sea scallop (left panel) and longfin squid (right panel) for the time periods 2007-2022 (dark cyan), 2023 only (magenta) and 2024 only (cyan). Gray circles indicate locations where bottom ΩArag values were above the species-specific sensitivity values (Figure from: Gaichas et al., 2025).

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Appendices

Appendix 1: QAPP

New Jersey Department of Environmental Protection

Division of Science and Research (DSR)

Quality Assurance Project Plan (QAPP)

for

An ecological and oceanographic baseline to inform offshore wind development over the continental shelf off the coast of New Jersey

Contract No. BC22-001-002

Project Information Page:

1. Project Name: An ecological and oceanographic baseline to inform offshore wind development over the continental shelf off the coast of New Jersey

2. Date of Project Initiation: November 17, 2022 (effective date)

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6. Project Description

   A. **Objective and Scope Statement**

   The Mid-Atlantic Bight (MAB) is bounded by Long Island, New York to the north and New Jersey to the west, and is separated by the Hudson Shelf Valley extending from the mouth of the Hudson River out to the continental shelf-break. The physical oceanography of this region is influenced by local topography, freshwater input from rivers and estuaries, large scale atmospheric patterns over the North Atlantic, and tropical or winter coastal storm events. Therefore, the ocean characteristics on the MAB shelf, including the planned offshore wind energy areas, undergoes remarkable variability across time scales from days and weeks to seasons, years, and decades. The Mid-Atlantic "Cold Pool", a region of cold remnant winter water near the bottom of the water column, develops seasonally, persisting from spring to fall on the continental shelf in the Northeast US (Houghton et al. 1982, Chen and Curchitser 2020), and is an important driver of biological patterns (e.g., Malone et al. 1983, Sullivan et al. 2000, Steves and Cowen 2000, Sullivan et al. 2005). This intense ocean variability drives an equally variable ecosystem from the primary producers to the highly migratory fisheries and marine mammals throughout the existing and planned lease areas. The tight coupling between the ocean conditions and the habitat preference of local and migratory species lead to a distribution that can significantly vary from season to season and year to year. Furthermore, the MAB is situated in one of the most rapidly warming regions in the world and is vulnerable to both ocean and coastal acidification. These long-term environmental changes are associated with observed and projected changes in species distributions, biomass, and diversity. Therefore, these time scales of variability – from seasons (at a minimum) to years - must be considered in approaches to quantify and potentially isolate potential offshore wind impacts on these marine ecosystem processes and changes.

New Jersey has set a goal to procure half of its energy from renewable resources by 2030. Offshore wind power will play a critical role in achieving the renewable energy goal to create a more sustainable economy in the state (NJ Executive Order No. 8, 2018). Fisheries also play a critical role in the state economy. New Jersey fisheries landings generated $166 M in revenues in 2015, with sea scallop ($98 M) and ocean quahog ($11 M) accounting for close to two-thirds of landings revenues for the year (NMFS 2017). The continental shelf off New Jersey has been experiencing ocean warming since the 1970's, and the phenology of the system has also shifted including earlier spring transitions and later fall cooling (Friedland and Hare 2007). Notably, the overall warming trend is projected to continue where under a doubling of CO_2 warming could increase by 3-4°C in the next 70 years (Saba et al. 2016). Ocean warming has led to vulnerability in approximately half of the U.S. Northeast Shelf species (Hare et al. 2016), and the dominant response of fish species to ocean warming has been distribution range shifts poleward. Furthermore, NJDEP published the 2020 New Jersey Scientific Report on Climate Change which states, "New Jersey is at increased risk to the effects of ocean acidification due to its economic dependence on shellfish harvests, with southern New Jersey counties ranking second in the United States in economic dependence on shelled mollusks" (New Jersey Department of Environmental Protection 2020).

With offshore wind construction scheduled to begin in the next couple years, it is critical that oceanographic and ecological baseline monitoring begin immediately. The deployment of a glider-based program will simultaneously map oceanographic and ecological parameters that will inform each of the New Jersey Offshore Wind Research and Monitoring Initiative's (RMI) research priorities[1]. Leveraging significant glider experience of the Principal Investigators (PIs) and existing resources at Rutgers University, this effort will efficiently stand up a comprehensive monitoring program specific to the coastal waters off New Jersey that overlap with planned offshore wind development areas. The project consists of three tasks: Task 1 is the glider deployments themselves; Task 2 is the data management including archive, access, and quality control; and Task 3 is the data analysis relevant to RMI research priorities.

Task 1: Glider deployments

In this effort, a glider-based ocean monitoring program will sample the necessary oceanographic and ecological parameters to provide a baseline dataset that will inform the responsible development of offshore wind. Slocum gliders are autonomous underwater vehicles that navigate ocean waters collecting high-resolution data at various depths throughout the water column (Schofield et al. 2007). The gliders have proven to be particularly robust vehicles in the coastal waters of the NYB, completing missions supporting hurricane response (Glenn et al. 2016), water quality monitoring for federal and state agencies (Kohut et al. 2014, Saba et al. 2019, Wright-Fairbanks et al. 2020), and numerous other scientific insights about this complex coastal system (Castelao et al. 2008, Glenn et al. 2008, Oliver et al. 2013, Miles et al. 2015, Glenn et al. 2016, Oliver et al. 2017).

A comprehensive deployment strategy will optimize and maximize measurements for oceanographic and ecological baseline assessment in relation to New Jersey's offshore wind development activity. The deployment schedule and sensor configuration consider the significant seasonal variability in both the oceanography and ecology within the region of interest, the large suite of parameters that are needed to address the full scope of the RMI research priorities, and the known realities of operating a glider monitoring program off the NJ coast including required maintenance and calibration schedules, glider endurance, and mitigating sensor interference. Rutgers has been operating gliders in this region since 1999 with well over 200 of our over 500 global deployments occurring in this region. This work includes annual deployments

[1] dep.nj.gov/offshorewind/rmi/#research-and-monitoring-priorities

coordinated with the NJDEP. These missions have been governed by an existing quality assurance project plan (Kohut et al. 2014) that has been updated here to reflect the additional sensors and mission objectives of this RMI project These deployments include experience with all sensors described below.

Task 2: Data QA/QC, Management, and Sharing

The data quality assurance/quality control (QA/QC) and management for this project will be based on the considerable infrastructure already in place at Rutgers. This project will provide for the preservation, documentation, and sharing of data collections, and other related research and education products. The project will generate new data (near real-time and delayed mode QC'd datasets), and the specific data sets managed by this project include physical, chemical, and biological variables sampled by both glider and vessel platforms.

Task 3: Reporting, Data Product Development, and Deliverables

In addition to the real-time and post mission baseline data delivery outlined in task 2, the PIs will prepare progress reports, a draft final report, and a final report for submission to the RMI leadership team.

B. **Data Usage**

This project provides an opportunity for baseline monitoring and research to not only support the offshore wind planning process, but also provide valuable information relevant to ongoing environmental and ecological change in New Jersey' productive coastal waters. This study will provide observations of water quality parameters, including temperature, salinity, dissolved oxygen, and carbonate chemistry profiles, and biological metrics (chlorophyll, zooplankton and pelagic fish biomass, marine mammal presence) along the New Jersey shelf inside and outside of several existing and planned offshore wind lease sites. These environmental observations will contribute to the NJDEP database of water quality and ecological observations in the coastal ocean. The data provided by this study will help the NJDEP understand the interactions and impacts of offshore wind energy projects on environmental (water quality) and living marine (zooplankton, fishes, marine mammals) resources.

The data collected during this project will not be used for regulatory/compliance purposes.

C. **Data Quality Objectives**

Data generated during the glider deployments (near real-time) and post-processed (during data analysis and quality-control, Task 2) as well as data products developed in Task 3 fall in Level 3 because they can be used to help better define the coastal ocean water quality and ecological conditions. Data collected and analyzed in Tasks 1 and 2 include physical (temperature, salinity depth), chemical (dissolved oxygen, pH, colored dissolved organic matter), and biological (chlorophyll a, zooplankton/fish biomass, marine mammal detection/presence, fish detection) variables. Data provided by this glider monitoring program will be used as input to conduct a series of analyses and develop relevant products. The specific products and analysis completed will be determined following consultation with the RMI leadership team.

D. Observation Design and Rationale

A seasonal baseline survey will be conducted with a pair of gliders deployed in each season over two years with a full complement of available sensors to simultaneously map oceanographic and ecological variables. One glider will be equipped with a Conductivity, Temperature, and Depth sonde (CTD) to determine water depth, temperature, salinity, and density, an optics puck measuring chlorophyll-a and colored dissolved organic matter (CDOM) fluorescence, an optode measuring dissolved oxygen (DO), and a Digital Acoustic Monitoring (DMON) passive acoustics sensor for marine mammal monitoring and detection. The second glider will be equipped with an optics puck and an Acoustic Zooplankton Fish Profiler (AZFP) multi-frequency echo sounder for active acoustic detection of pelagic organisms. Like the first glider, the second glider will have a CTD, but this CTD package will also include an integrated pH sensor for ocean acidification applications. Both gliders will also carry an Innovasea acoustic telemetry receiver to track tagged species moving through the region.

Glider Endurance and Sensor Interference: To simultaneously measure all of these above listed variables without sacrificing data quality and glider endurance, two separate gliders deployed in tandem are required.

Active Acoustic Configuration: Given the focus areas of the RMI and the tendency for current offshore wind monitoring programs, the Rutgers team will use two AZFP sensor units with a configuration that would dedicate one unit for zooplankton (with 125, 200, 455, and 769 kHz frequencies) and one unit for pelagic fishes (with 38, 125, 200 kHz frequencies). The usage of each AZFP will be rotated seasonally to target dominant predator-prey interactions. The zooplankton-configured AZFP will be deployed during the winter-spring seasons (zooplankton are primary prey for the North Atlantic right whale), and the pelagic fish-configured AZFP will be deployed during the summer-fall seasons (primary prey for humpback whales).

In addition to these paired seasonal missions, a third glider equipped with the CTD/pH, optics puck, optode, and Innovasea acoustic telemetry receiver will be deployed 3 times each year. These deployments will fill coverage gaps in the seasonal glider deployments from the onset of seasonal stratification associated with the Cold Pool formation in the spring to the physical breakdown in the fall. This deployment strategy will ensure that the 2-year baseline contributes to cold pool/offshore wind research priorities (see Miles et al. 2021) by capturing these key ocean events and the concurrent ecological response.

All proposed glider missions will cover the same spatial extent and transect, covering an area from Sandy Hook down to Cape May, from near shore extending out across the shelf. This will ensure that the monitoring occurs both on established long-term transects for historical context and within offshore wind lease areas.

Vessel-based sampling will also be conducted during glider deployments and recoveries. These sampling efforts include discrete water samples for carbonate chemistry (pH, total alkalinity, dissolved inorganic carbon) to groundtruth the glider pH sensor (i.e., to calculate the field accuracy of the glider-based pH sensor) (all deployments and recoveries), and net tows to collect species, abundance, and size information for dominant zooplankton species/scatterers present that will inform the zooplankton active acoustic data (only for winter-spring glider deployments when the zooplankton-configured AZFP is operating).

E. Sampling Procedures

Sensors integrated into the glider sample multiple parameters approximately every one to two seconds along the glider transects. Data will be collected from surface to bottom, east to west, and north to south providing a detailed three-dimensional view of ocean and ecological conditions within and around the existing and planned offshore wind lease areas.

<u>Glider CTD</u>

For each deployment the glider will be equipped with a pumped Sea-Bird CTD. The CTD will sample conductivity, temperature and pressure at a rate of 0.5 Hz throughout the mission. Salinity will be calculated based on glider-measured conductivity, temperature, and pressure. The pressure will be used to calculate depth. These data will be used to map ocean temperature, salinity and density along the track.

Glider DO

For each deployment the glider will also be equipped with an Aanderaa optode. The optode will measure raw phase shifts across a calibrated foil that when combined with measured temperature from the CTD will give measures of DO concentration and percent saturation at a rate of 1 Hz.

Glider optics

For each deployment the glider will be equipped with a Sea-Bird EcoPuck. Each sensor includes three channels - chlorophyll fluorescence, Colored Dissolved Organic Material (CDOM) fluorescence, and backscatter - and samples at a rate of 0.5 Hz along the glider path.

Glider pH

Glider pH will be calculated on the total hydrogen concentration scale using glider-measured reference voltage (sampled every 0.5-1.0 Hz), salinity, pressure, temperature, and sensor-specific calibration coefficients (Johnson et al. 2017, Saba et al. 2019, Wright-Fairbanks et al. 2020).

Active acoustics (AZFP)

For each of the seasonal paired missions, one glider will be deployed with an active acoustics sensor (AZFP). The winter and spring missions will deploy a unit configured for zooplankton (with 125, 200, 455, and 769 kHz frequencies). The summer and fall missions will deploy a unit configured for pelagic fishes (with 38, 125, 200 kHz frequencies). Data in each frequency will include a profile of acoustic backscatter. The AZFPs will be configured to transmit pulses of 500 µs on all three frequencies at an interval of 2 s with one transmission (ping) during each interval.

Passive acoustics (DMON)

The WHOI-developed digital acoustic monitoring (DMON) instrument running the low-frequency detection and classification system (Baumgartner and Mussoline 2011) was integrated into the Slocum glider a decade ago (Baumgartner et al. 2013) and has been used on over 90 glider missions in U.S., Canadian, and Chilean waters to date. The accuracy of the DMON for baleen whale detection from gliders and buoys is well characterized (Baumgartner et al. 2019, 2020). Right whale acoustic presence data from DMON-equipped gliders and buoys are currently being used to trigger voluntary ship speed restrictions as part of the National Oceanic and Atmospheric Administration's (NOAA) Slow Zones for Right Whales Program on the U.S. east coast, as well as mandatory ship speed restrictions and fishery closures in Canadian waters. Each DMON-equipped glider will monitor multiple marine mammal species in near real time, including fin, sei, humpback, blue and North Atlantic right whales (NARW). In addition to facilitating near real-time detection, the DMON will also continuously record audio at a 2 kHz sampling rate, allowing the detection of other species in post-processing, including minke and sperm whales.

<u>Fish telemetry receiver</u>

Acoustic telemetry has become an increasingly important tool to study migration patterns, habitat use and preferences, mortality, and general population monitoring of fish (Hussey et al. 2015, Block et al. 2016). Gliders with their autonomous nature, adaptive sampling capabilities, and sustained power capacity, have been recognized as a promising tool that can target specific ocean and biological features outside of fixed acoustic arrays for long periods of time (Oliver et al. 2013, Haulsee et al. 2015, Whoriskey 2015, Breece et al. 2016, Oliver et al. 2017). All gliders deployed through this effort will be equipped with an Innovasea acoustic telemetry receiver. The passive acoustic glider (the glider equipped with a DMON sensor) and the gap-fill glider (the third glider with no passive or active acoustics) will each have an integrated Rx-LIVE cabled receiver that allows real-time communication and data transfer. The Rx-LIVE has a depth rating of 500m and offers detection of multiple frequencies (51-81 kHz) with the capability of detecting, in its presence, organisms (fish, elasmobranchs, and other macrofauna) tagged with Vemco transmitters and other coded transmitters at 69 kHz. The active acoustic glider (the glider equipped with an AZFP sensor) will have a forward-facing acoustic telemetry receiver (VMT Mobile Acoustic Transceiver; 69 kHz) with a depth rating of 1000m for use with 69 kHz coded tags. This receiver is attached externally to the glider (not integrated and cabled); therefore, there is no access to real-time data and collected data are stored in the receiver internally until the glider is recovered and the data are downloaded. During deployments, the receiver data logs and stores decipherable acoustic codes that include information on date/time, organism identity, signal power, and the number of logged occurrences of that code within a specified amount of time. To our knowledge, several fish tagging efforts are underway in and around New Jersey wind energy areas (lease areas and export cable routes) and in areas of biological significance (i.e, migration corridors) (Thomas Grothues and Keith Dunton, pers. comm.). Common tagged species in the region through these efforts include smooth dogfish and skates, the benthic summer flounder, windowpane, horseshoe crab, and black sea bass. Many other species, such as Atlantic sturgeon, striped bass, and numerous elasmobranchs tagged with Vemco tags are also at liberty in the study area and will likely be detected (e.g., Dunton et al. 2015, Frisk et al. 2019, Rothermel et al. 2020).

Vessel-based sampling

Glider pH groundtruthing: Upon each deployment and recovery of the glider with integrated pH sensor, discrete water samples for pH, total alkalinity, and dissolved inorganic carbon will be collected near the glider for groundtruthing the glider pH sensor This approach follows best practice guidelines for autonomous pH measurements with DuraFET-based sensors (Bresnahan et al. 2014, Johnson et al. 2016, Martz et al. 2015, Saba et al. 2019, Thompson et al. 2021). Immediately upon reaching the deployment and recovery locations, a cast using an SBE19 conductivity, temperature, and depth sensor (CTD) will be conducted from the vessel within 100 meters of the glider (with integrated pH sensor) to select depths of interest for collection of discrete water samples. At a minimum, a surface and near bottom water sample are recommended (in duplicate), but additional sample depths are encouraged if there are features of interest (e.g., thermocline, intrusion of a water mass) (Wright-Fairbanks et al. 2020, Thompson et al. 2021). Discrete samples will be collected within 100 meters from the glider at pre-selected target depths either by a hand-lowered individual 5-L Niskin or using an SBE55 6-Niskin bottle rosette with an SBE19 CTD attached. Discrete water samples from each depth will be collected into 300 ml borosilicate glass bottles (duplicate for each parameter: 2 bottles for pH, 2 bottle for total alkalinity and dissolved inorganic carbon at each depth) and preserved with saturated mercuric chloride (final concentration of 0.02%; Dickson et al. 2007) then transported to PI Saba's laboratory for refrigerator storage prior to shipping to the analytical laboratory. Discrete sample analyses are described in H. Analytical Procedures. Between field uses, the Niskin bottles used for discrete sample collection are rinsed thoroughly inside and outside with freshwater and allowed to dry before closing. The 300 ml borosilicate glass bottles can be reused after sample analysis following a cleaning procedure that includes a soap soak, rinsing with deionized water, a drying period, then placed in a muffle furnace to remove organics.

Glider active acoustics-zooplankton groundtruthing: Upon each deployment and recovery of the glider with integrated zooplankton-configured AZFP sensor (winter-spring deployments only), duplicate oblique tows (surface to 5 meters above bottom) will be conducted with a 0.5 meter diameter, 200μm mesh net fitted with a flow meter at net opening and a filtering cod end at net bottom. Nets will be towed at a speed of 1-2 knots for 15-30 minutes depending on depth and expected biomass. The contents of the cod-ends will be rinsed with filtered seawater from the cod-ends into glass collection jars, preserved in a 10% formalin solution (equivalent to 4% final concentration of buffered formaldehyde), and refrigerated until analysis in the laboratory. Zooplankton sample analyses are described in section 6-H.

F. **Sample Custody Procedures**

These procedures are not applicable to the autonomous glider-based observations, and only apply to the vessel-based sampling efforts. Discrete seawater samples preserved for pH, total alkalinity (TA), and dissolved inorganic carbon (DIC) analysis at each glider deployment and recovery will be placed in a cooler with ice for transport to PI Saba's Rutgers laboratory. Once there, they will be stored in a refrigerator at 4˚C until shipment to the analytical lab (Dr. Baoshan Chen; School of Marine and Atmospheric Sciences, Stony Brook University, Stony Brook, NY). Preserved zooplankton samples will be placed in a sample box and sealed for transport to PI Saba's laboratory where they will be stored in a refrigerator at 4˚C until analysis in the laboratory. All discrete water samples and zooplankton tow samples that will be returned to the lab will be logged into an electronic master record upon collection and storage (see also Section 11. A.) The master record will include the unique sample name as labeled on the bottle (date, depth, parameter [pH, TA/DIC, or surface zooplankton], replicate number, method of preservation), time, and station or latitude/longitude (via vessel GPS) where the collection was made, and name of the technician who handled the collection and storage. After every glider deployment and recovery, this master sample log will be used to check every sample that is offloaded for transport to the lab against the master log to ensure all samples are recovered from storage on the vessel. A copy of the master sample log will be sent to the lab and technician analyzing the samples (applicable only for the carbonate chemistry samples), and they will enter the specific analysis information for each sample (date of sample analysis, measurements of pH, TA/DIC, lab temperature, and metadata information and measurement data for the certified reference materials used during sample analysis).

G. **Monitoring Sites and Frequency of Sample Collection**

All proposed glider missions would cover the same spatial extent and transect (Fig. 1). The zig-zag glider missions will cover an area from Sandy Hook down to Cape May, from near shore extending out across the shelf.

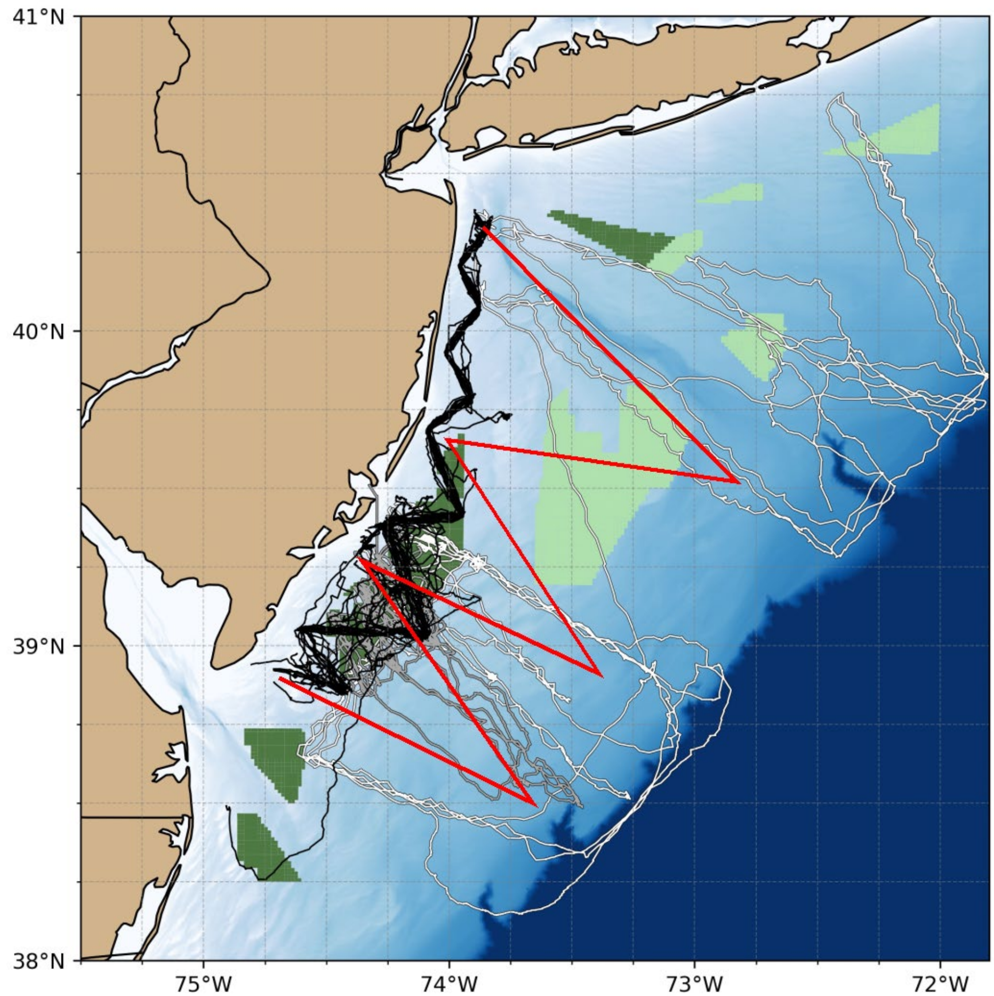

Figure 1. Map indicating the coverage of three relevant glider missions including NJDEP water quality (black), NOAA and NYSDEC pH (white), and Ørsted Marine Mammal Monitoring (Grey). The proposed environmental coastal survey track is shown in red. All these deployments occur within the footprint of a nested HF

The targeted paired deployment dates for each year will be: January-February (Deployment 1), April-May (Deployment 2), July-August (Deployment 3), and October-November (Deployment 4). The three targeted cold pool resolving deployment dates for each year will be: 3 deployments between May-October to fill the coverage gaps between the seasonal paired deployments listed above.

To summarize, this deployment strategy will provide seasonal resolution data that allows for a large range of parameters that will support multiple RMI research priorities – including physical and chemical variables, and biological variables spanning from phytoplankton and zooplankton to pelagic fish and marine mammals. The additional spring through fall deployments will provide baseline physical, chemical, and biological information but with greater temporal coverage. This will allow us to resolve the evolution of the local seasonal stratification (formation and breakdown of the Cold Pool) as well as the ability to capture distinct, biologically-important episodic events (e.g., upwelling, storms, intrusion of warm core rings and the onset and breakdown of the Cold Pool) that might otherwise not be detected in the more punctuated seasonal monitoring program. This monitoring strategy increases our ability to characterize the true variability of the system throughout a year, which can then be used as a baseline to observe potential impacts of offshore wind development and operation and/or compare to observations of future environmental and biological fluctuations and long-term changes in New Jersey's coastal system. These data will also provide baseline information to support future hypothesis-driven research within the RMI research priority areas.

H. Analytical Procedures

Glider pH: Resolving other carbonate chemistry variables

Total alkalinity and salinity exhibit a conservative relationship in U.S. East Coast waters (Cai et al. 2010, Wang et al. 2013), and seasonal relationships between salinity and total alkalinity have been reported (Wright-Fairbanks et al. 2020). Therefore, total alkalinity will be estimated using glider-derived salinity (Saba et al. 2019, Wright-Fairbanks et al. 2020). The remaining carbonate system parameters will be calculated using PyCO2SYS (Humphreys et al. 2020) with glider temperature, salinity, pressure, pH, and salinity-derived total alkalinity as inputs (Lewis and Wallace 1998, Sharp et al. 2020, van Heuven et al. 2011). Other CO2SYS inputs will include total pH scale (mol kg^{-1}-SW), K_1 and K_2 constants of Mehrbach et al. (1973) with refits by Dickson and Millero (1987), KSO_4 dissociation constant of Dickson (1990), KHF dissociation constant of Uppstrom (1974), and borate-to-salinity ratio of Perez and Fraga (1987).

Vessel-based sampling

Glider pH groundtruthing: Discrete carbonate chemistry water samples, including dissolved inorganic carbon (DIC), total alkalinity (TA), and pH, are collected aboard the vessel during each glider deployment and recovery. Samples will be analyzed for pH spectrophotometrically using purified meta-Cresol Purple dye (Clayton and Byrne 1993, Liu et al. 2011), total alkalinity via open cell Gran titration (Dickson et al. 2007, Chen et al. 2015), and dissolved inorganic carbon using a coulometric method (Dickson et al. 2007)) (Table 1).

Samples will be analyzed by chemist Dr. Baoshan Chen, a Research Assistant Professor at the School of Marine and Atmospheric Sciences, Stony Brook University (Stony Brook, NY) who operates a carbonate chemistry laboratory. pH accuracy is guaranteed by purified meta-Cresol Purple obtained from Bob Byrne at University of South Florida and will be calibrated against Tris buffer obtained from Andrew Dickson at UCSD Scripps Institution of Oceanography (DelValls and Dickson 1998). As a one-point check, Tris buffer is analyzed as a pH sample to check the difference between the theoretical and instrument reported pH values. The pH offset is then applied to the instrument reported pH values. The precision of pH analysis is ±0.0005 pH units. At present, the likely bias of accuracy for pH is estimated to be less than 0.005 pH units. DelValls & Dickson 1998). Additionally, discrete DIC and TA measurements will be used to calculate pH and check the internal accuracy of spectrophotometric measurements. This lab uses community-accepted quality control protocols (Dickson et al. 2007) and certified reference materials (CRMs; for testing accuracy of DIC and TA) obtained from Andrew Dickson at UCSD Scripps Institute of Oceanography. DIC and TA are analyzed using an automated analyzer (VINDTA 3C, Marianda) with accuracy and precision both at ± 1 μmol kg^{-1}. Fresh CRM is used every day and at the beginning of sample analyses to calibrate the analyzer. Dr. Chen has also participated in a blind calibration inter-laboratory comparison procedure, in collaboration with Andrew Dickson's lab, to ensure high analytical accuracy and precision.

Table 1

Parameter	**Number of samples**	**Sample Matrix**	**Analytical Method**	**Sample Preservation (vol/vol)**	**Holding Time**
pH	*4-6 samples (including duplicates)	seawater	spectrophotometric	Saturated mercuric chloride (0.02%)	< 2 months
Total alkalinity	*4-6 samples (including duplicates)	seawater	open cell Gran titration	Saturated mercuric chloride (0.02%)	< 2 months
Dissolved inorganic carbon	*4-6 samples (including duplicates)	seawater	coulometric method	Saturated mercuric chloride (0.02%)	< 2 months
Zooplankton	**2 samples (duplicates)	seawater	Dissecting microscope	Formalin solution (10% concentration)	< 6 months

*Per glider deployment or recovery (all deployments and recoveries)
** Per glider deployment or recovery (only winter-spring)

Discrete pH measurements will be converted to *in situ* pH values using *in situ* depth-specific temperature and salinity measured by SBE19 CTD. Discrete pH will then be compared to glider pH measurements at the same, or closest, depth from the glider's first profile at deployment and its last profile before recovery to determine glider pH sensor field accuracy.

Glider active acoustics-zooplankton groundtruthing: As soon as possible after collection at glider deployment and recovery (winter-spring only), each set of duplicate preserved zooplankton samples will be processed for species identification, abundance, and size. Using a dissecting microscope, the samples will be sorted and morphologically identified by species, and those individuals will be counted (Table 1). Abundances will be reported in number m^{-3} (based on counts and volume of water flowing through the net during sampling). Individuals from a subset of each species will be measured for prosome length (copepods), standard and uropod length (euphausiids), or total body length (other zooplankton).

7. Data Quality Requirements

The quality objectives for this project apply to sensor real-time and post processed data and discrete carbonate chemistry data. The real-time data are those subset of data that are sent back to Rutgers during the mission via the satellite link. The transmission is a data subset to reduce file size that will 1) reduce time on the surface when the glider is most vulnerable to damage and 2) reduce the airtime on the expensive satellite link. During each deployment the data will be logged locally on the glider with the glider manufacturer software. The glider engineering data will be logged every 4 seconds and the science data will be logged at the sample rate for each sensor. Following recovery of the glider the entire dataset logged locally on the glider will be recovered and used to construct the post-processed dataset. Sensor quality assurance and data quality control will be conducted and documented. These techniques will be followed based on the scientific literature and manufacturer recommendations. Quality assurance procedures for each sensor include calibrations, regular sensor cleaning, and comparability/bias tests (see Table 2 below and sections 8, 9, and 10).

Table 2				
	CTD	Optics	pH	DO

Comparability or Accuracy *based on manufacturer claims*	Temp.: ±0.005 °C Cond.: ±0.0003 S/m Pres: ±0.1% of full scale range	Chl-a: 0.02 μg/L Backscatter: 0.003 m^{-1}	±0.05	Conc: <2 μM
Resolution *based on manufacturer claims*	Temp.: ±0.001 °C Cond.: ±0.00001 S/m Pres.: 0.002% of full scale range	Chl-a: ±0.03 ug Chl/l Backscatter: 1.84E-06 m^{-1} sr^{-1}	±0.001	Conc.: < 0.1 μM
Bias	Bias will be determined through the direct comparisons with simultaneous tank tests with another factory calibrated SBE-19 CTD.	Gross MIN and MAX tests before each deployment	Bias will be determined through comparison to pH of discrete seawater samples.	Bias will be determined through comparison to winkler titrations

Table 3			
	Discrete pH	**Discrete Total Alkalinity (TA)**	**Discrete Dissolved Inorganic Carbon (DIC)**
Accuracy	±0.005	±1 μmol kg^{-1}	±1 μmol kg^{-1}
Precision	±0.0005	±1 μmol kg^{-1}	±1 μmol kg^{-1}

8. Data Quality Assessments

A. Data Representativeness

Each glider deployment follows the standards used by the international glider community (Underwater Glider User Group: https://underwatergliders.org/index.php/glider-best-practices/; OceanGliders: https://www.oceangliders.org/taskteams/best_practices/). These standards are designed to ensure sampling coverage and accuracy to ensure the data represent the structure of observed parameters along the mission path. Therefore, the data will represent the vertical and horizontal structure with resolution of 0.5 m and 120m in the vertical and horizontal, respectively. Given that we are following the same protocols and will use the same sensor configuration as other nationally certified glider missions, we anticipate the same level of precision and accuracy for this project in determining the vertical and horizontal structure of the parameters sampled by each glider.

B. **Data Comparability**

The glider deployments and sensor calibration and maintenance will be conducted following national and international standards. Rutgers University supports glider operations as part of the U.S. Integrated Ocean Observing System (IOOS). Saba and Kohut contribute to both of these programs. This involvement will ensure that the glider datasets will be managed in a way consistent with the IOOS federally certified process. Consequently, data collected under this project will be directly comparable to other similarly certified missions around the world, including missions funded by other state, federal, and private sector entities.

9. Calibration Procedures and Preventive Maintenance

Calibration Procedures

Sensor quality assurance and data quality control will be conducted and documented. These techniques will be followed based on the scientific literature and manufacturer recommendations. Quality assurance procedures for each sensor include calibrations, regular sensor cleaning, and comparability/bias tests (Tables 2 and 4).

CTD, DO, optical, and pH sensors: The CTD, DO, optical, and pH sensors will be calibrated by the factory annually. This is in accordance with recommended annual factory calibrations from the manufacturers.

pH/CTD: The combined pH/CTD sensor may be cleaned and factory calibrated more frequently depending on field accuracy or level of biofouling upon inspection after each deployment (Saba et al. 2019, Thompson et al. 2021).

Active Acoustics (AZFP): Annual calibrations of the glider AZFP sensors will be conducted according to Reiss et al. (2021) in collaboration with bioacoustic experts at the Antarctic Ecosystem Research Division team at the NOAA Southwest Fisheries Science Center in La Jolla, San Diego. Their facility's seawater tank, measuring 10 meters x 20 meters x 10 meters (width x length x depth) is large enough to conduct the calibrations without interference from tank walls and its bottom and therefore, is routinely used in glider-based acoustic calibrations. Acoustic calibrations will be conducted using a tungsten carbide sphere (12.7-38.1 mm diameter), following Foote et al. (1987) and Taylor and Lembke (2017). For calibration, each glider will be suspended at an angle of 22.7° and lowered until the transducers are 1 m below the surface. The target sphere will be suspended by monofilament line directly below the glider AZFP sensor. The sphere will be suspended approximately 3–4 m from the transducers, avoiding the 5m range where echoes from the tank surface might interfere with the calibration. The upper 10% of on-axis acoustic returns from the beam of each transducer will be used to determine gains and offsets for calibration (Demer et al. 2015), and glider CTD-measured *in situ* salinity and water temperature will be used to adjust the sound speed in calculations using the echosounders. This calibration process will be repeated for each individual frequency channel on each AZFP sensor. dB offsets for each channel will be recorded and applied to the data collected during the New Jersey coastal shelf glider deployments within that calibration year.

DMON (Passive Acoustics): The ceramics within the sensor are calibrated as described by the manufacturer, from which calibration data are derived for hydrophones after pre-amp and system gains are applied.

Table 4

Analyte	**DQI**	**Field QC Check**	**Frequency of Collection**	**Acceptance Criteria**	**Corrective Actions**
CTD	Comparability and bias	*In situ* comparison with a second, factory calibrated CTD	At the time of each glider deployment & recovery	Within 'Comparability or Accuracy' range listed in Table 2	Suspect values are flagged as described in this document.
CTD	All	Manufacturer Factory Calibration and cleaning	Annually	Within 'Comparability or Accuracy' range listed in Table 2	Recalibrate until data quality meets criteria listed in Table 2
pH	Comparability and bias	Discrete seawater sample collection	At the time of each glider deployment & recovery	Within 'Comparability or Accuracy' range listed in Table 2	Suspect values are flagged as described in this document.
pH	All	Manufacturer Factory Calibration and cleaning	Annually, or more frequently depending on field accuracy or level of biofouling upon	Within 'Comparability or Accuracy' range listed in Table 2	Recalibrate until data quality meets criteria listed in Table 2

			inspection after each glider mission		
DO	All	In-house calibration verification	Before and after each glider deployment	Within 'Comparability or Accuracy' range listed in Table 2	Suspect values are flagged as described in this document.
DO	All	Manufacturer Factory Calibration and cleaning	Annually	Within 'Comparability or Accuracy' range listed in Table 2	Recalibrate until data quality meets criteria listed in Table 2
Optics	All	Manufacturer Factory Calibration and cleaning	Annually	Within 'Comparability or Accuracy' range listed in Table 2	Recalibrate until data quality meets criteria listed in Table 2
Optics	Comparability and bias	In-house verification of factory calibration	Before each deployment	Within 'Comparability or Accuracy' range listed in Table 2	Recalibrate until data quality meets criteria listed in Table 2
AZFP active acoustics	All	In-house calibration	Annually	N/A	N/A
Passive Acoustics (DMON)	All	Manufacturer Factory Calibration	At the time of manufacture	N/A	N/A

Preventative Maintenance

CTD, DO, pH sensors: In addition to annual factory calibrations, comparability and bias testing will be conducted for CTD, pH, and DO sensors (Table 4). These procedures as followed are outlined in the manual drafted by the manufacturers and will be used to confirm the factory calibration. The glider CTDs will be referenced to a second, stand-alone factory calibrated SBE-19 CTD at each glider deployment and recovery. The DO sensor calibration will be verified before and after each deployment with in-house Winkler titrations (described in section 10 of this document). The depth-specific glider pH sensor data will be compared to discrete seawater pH measurements (to determine field accuracy of the sensor). If any values are found out of the acceptable range reported by the component manufacturers ('Comparability or Accuracy' range listed in Table 2), the sensors will be recalibrated.

Optical sensors: The calibration of the optical sensors is verified through Gross MIN and MAX tests to get baseline values (in air) and MAX for proper sensor response to certain wavelengths (described in section 10 of this document).

Active Acoustics (AZFP): Direct comparability/bias tests are not applicable for the AZFP sensors. Estimated zooplankton biomass from the acoustically derived measurements can be directly compared to zooplankton biomass estimates from net tows; however, there are no standardized approaches to conduct these comparisons because the challenges and limitations are very different between the methods. For instance, acoustic approaches may not allow high levels of taxonomic differentiation, but net tows are limited by the size of organisms they can collect (i.e., avoidance of larger zooplankton, dependent on net mesh size) and are inherently more subject to patchiness in sampling. Therefore, zooplankton data from net tows are not typically used to directly compare acoustically-derived biomass estimates, but instead are used to help inform the acoustic models (with length frequency distribution and shape- and taxon-specific scattering properties) to identify the dominant scattering organisms responsible for the acoustic signatures observed.

Passive Acoustics (DMON): Direct comparability/bias tests are not applicable for the DMON sensors. Sensor calibration will be verified through spot checks throughout the project. For validation of instrument performance while at sea, consistency in the background noise spectra collected by the instrument will be used to identify hydrophone issues.

10. Quality Control Checks

<u>All glider data</u>

Each time the glider surfaces throughout a mission, a subset of collected data will be sent to shore via an Iridium satellite phone located in the tail of the glider. This allows for preliminary inspection of all science data and software metrics to assess glider functionality. Full data sets will be collected post-recovery from memory cards stored in the glider. Data will be processed using Slocum Power Tools (https://github.com/kerfoot/spt/) and analyzed using Python data analysis software (see https://github.com/rucool/rugliderqc).

<u>Glider CTD, DO, and optical sensors</u>

The CTD, DO, and optical data will be run through appropriate quality assurance/quality control (QA/QC) guidelines as outlined in an Environmental Protection Agency (EPA) QA Project Plan for glider deployments along the coast of New Jersey (Kohut et al. 2014) and the variable specific quality control manuals issued by the Integrated Ocean Observing System (https://ioos.noaa.gov/project/qartod/). The procedures include pre- and post- deployment steps for each sensor to ensure data quality for each deployment. The CTD and DO sensors will be factory calibrated annually, and data will be verified for each deployment (Kohut et al. 2014). DO sensor calibration will also be verified in-house. Before and after each deployment, Winkler titrations using 2-point oxygen tests will be conducted to verify the calibration of the glider optode. The optode end points are checked in 100% saturated water (with an aquarium bubbler) and in 0% oxygen water (using sodium sulfite). If the values are off the calibration by more than 3%, a calibration will be conducted in-house. The analytical methods and quality control for these titrations will be carried out using LaMotte DO kits as described in EPA Method 360.2 (Kohut et al. 2014). Factory calibration of the optical sensors will also be verified before each deployment. The glider optical sensors, upon delivery from the manufacturer, are accompanied by colored disks that are used to conduct in-house verifications that the sensor can read the maximum values. Before deployment, dark counts on the sensor are taken by covering the optical sensor with electrical tape to black it out and record the readings. Then the tape is removed, and the colored disks are placed over the sensor to verify that it maxes out for CDOM and chlorophyll readings. For backscatter, a solid object is held in front of the sensor to check if it maxes it out.

Glider pH

The glider-based pH/CTD sensor will be factory calibrated annually, or more frequently depending on level of biofouling upon inspection after each glider mission, and data will be verified by comparisons of pH measured from discrete samples during each glider mission.

The pH data will be run through quality assurance/quality control (QA/QC) guidelines outlined in a recently published standard operating procedure for glider-based pH sensors (Thompson et al. 2021). These are described briefly in the following paragraphs.

Glider-based pH data will be initially inspected for sensor time lags, which are identified as skewed upcast and downcast profiles in pH reference voltage data and are often associated with areas of steep gradients in salinity or temperature. To correct for sensor lag, upcast and downcast pairs will be run through potential time shifts from 0 to 60 s at 1-s intervals. The optimal time shift determined will be applied for each glider sampling segment to minimize the difference between reference voltage at a certain depth in the upcast/downcast pairs (Saba et al. 2019, Wright-Fairbanks et al. 2020, Thompson et al. 2021). Python data analysis software scripts for this QC time shift procedure are available here: https://github.com/rucool/rugliderqc.

After time shifts are applied, pH data will be run through QA/QC measures based on the Integrated Ocean Observing System (IOOS) Manual for Real-Time Quality Control of pH Data Observations (U.S. Integrated Ocean Observing System 2019, Thompson et al. 2021). pH reference voltage data will be flagged and removed in instances where more than 1 hr has passed between observations (≪1% of observations) or in instances without a valid time stamp (~20% of observations). Next, observations of other scientific variables without both a corresponding pH reference voltage and pressure value will be removed (~40% of observations). Observations outside of the latitude and longitude bounds of the study area will be flagged and removed (≪1% of observations). pH values will be validated in a gross range test, flagging and removing values outside the measurement bounds of the glider pH sensor (pH < 6.5 and pH > 9; ≪1% of observations). As more deployments of the pH glider provide a mean climatology for the study area, the gross range test can be restricted to a user-specified local or seasonal pH range. Next, a spike test will identify and remove single value spikes in pH reference voltage observations (≪1% of observations). Lastly, data will be inspected visually for unrealistic rates of change, flat-lining, and attenuated signals, which would indicate decreased sensor function or sensor failure.

Quality control procedures for data produced from the glider-based pH sensors also entail evaluations of sensor field accuracy (see section 6-H). Here, glider-based pH measurements will be compared to discrete seawater pH at the same, or closest, depth from the glider's first profile at deployment and its last profile before recovery. Groundtruthing offsets will be determined as glider pH-discrete pH at each depth. Glider agreement will be calculated as the average absolute offset between all depths at deployment or recovery. Uncertainty in glider agreement will be calculated as one standard deviation between glider pH measurements in the surface layer during the discrete sampling period.

Suspect values outside of the field accuracy range will be flagged. Following each deployment, the final quality-controlled data will be within the 'Comparability or Accuracy' range listed in Table 2 of this document. If a value is found outside these criteria, it will be flagged in the final dataset. Each data point will be treated independently so that any one point flagged will not restrict use of the other quality data from the same deployment.

<u>Active Acoustics (AZFP)</u>
As mentioned in section 9, annual in-house calibrations of the glider AZFP sensors will be conducted, and dB offsets will be applied to the relevant datasets.

Pitch, roll, GPS fixes, and depth data will be calculated from glider measurements and converted into tab delimited *.csv files compatible with Echoview software. Raw acoustic data will be linked to the other glider sensor data (temperature, salinity, etc.) by time stamp and processed using Echoview software. Glider downcasts will be isolated by masking out portions of the data with pitch outside the range of -15 and -30 degrees, and surface noise (top 2 m) and the ocean bottom (where applicable) will be removed from analyses. Calibration parameters and offsets will be applied to the echogram, including speed of sound and absorption coefficients calculated from five-day averages of glider CTD data. Echoview's Background Noise Removal (De Robertis and Higginbottom 2007), Impulse Noise Removal, and Transient Noise Removal (Ryan et al. 2015) algorithms will be used to clean the raw acoustic data from each frequency. Then from each frequency, mean volume backscattering strength (MVBS or Sv, dB) and area backscatter coefficient (ABC or sa, m^2 m^{-2}) will be exported in 1 m × 1 m bins (e.g., Reiss et al. 2021) for additional MATLAB processing of zooplankton or fish identification, school detection, and biomass. Length-frequency distributions of dominant zooplankton collected in the net tows may be used to estimate species-specific biomass (e.g., Kitamura et al. 2017, Sakinan & Gücü 2017). Additionally, length-frequency distributions of fish obtained from bottom trawl and structure-associated fish surveys from other projects may also be used to assist in estimations of fish biomass if they are conducted during the same season and in the same sampling area (e.g., Demer et al. 1999, Fernandes et al. 2002, Gorska et al. 2005, Jech and Michaels 2006).

One of the major challenges of bioacoustics is classifying the organisms that are responsible for producing the acoustic scatter. Target classification is an important step in the analysis of bioacoustics data because it allows for converting the backscatter data into more confident estimates of abundance or biomass (see Berger et al. 2018). Using multi-frequency echosounders, as opposed to single frequency echosounders, is one way we are addressing this issue in this project. Multi-frequency bioacoustic data allow for calculating the differences in volume backscattering strength between multiple frequencies and therefore differentiating between different major taxa and different sizes of organisms with different scattering properties. Secondly, we will utilize length-frequency distributions of dominant zooplankton collected in the net tows to help improve our models for volume backscatter and biomass estimates. To the best of our ability, and if data from bottom trawl and/or structure-associated fish surveys that are conducted during the same season and in the same sampling area are available, we will also use length-frequency distributions of fish from these surveys to assist in estimations of fish biomass.

Passive Acoustics (DMON)

As described in section 9, the ceramics of the DMON sensor are calibrated following manufacturer recommendations. Sensor calibration is validated in periodic spot checks and continuously during each mission based on consistency of the recorded background noise. Additionally, the analysts that verify individual detections in the data are certified through a training program that they must go through and a protocol that they must follow.

11. Documentation, Data Reduction, and Reporting

A. Documentation

Glider-based sampling

The project will generate a packet for each deployment. The deployment packet will document all glider and sensor preparation, maintenance, calibration, and inspection. The calibration, testing, maintenance for each deployment will be documented. This documentation includes:

1) a pre-deployment check out
2) a pre-deployment check out for the optode
3) a deployment checklist
4) a recovery checklist
5) a post-deployment checklist
6) manufacturer calibration documentation

A deployment packet will be made up of all the above documents. For each deployment the Rutgers team will ensure that all are filled out completely and accurately. A copy of this packet will be stored at Rutgers in both hard copy and online on a server located in the Department of Marine & Coastal Sciences at Rutgers and will be available upon request.

Vessel-based sampling

Aboard the vessel, a master sample log (chain of custody form – see Appendix A) of all the discrete water and zooplankton tow samples collected will be maintained on a physical datasheet (on waterproof paper). The written information will include the unique sample name as labeled on the bottle (date, depth, parameter [pH, TA/DIC, or surface zooplankton], replicate number, method of preservation), time, and station or latitude/longitude (via vessel GPS) where the collection was made, and name of the technician who made the collection. All discrete water samples collected at each station will be returned to the lab and stored before shipping to the analytical laboratory. The paper datasheet will be logged into an electronic master record. All physical data records (written sample logs) will be held on site at Rutgers, and digital master records will be stored on a server located in the Department of Marine & Coastal Sciences at Rutgers University. After every glider deployment and recovery, this master sample log will be used to check every sample that is offloaded for transport to the lab against the master log to ensure all samples are recovered from storage on the vessel. A copy of the master sample log will be sent to the lab, detailing sample relinquishing and receipt, and technician analyzing the samples (applicable only for the carbonate chemistry samples), and they will enter the specific analysis information for each sample (date of sample analysis, measurements of pH, TA/DIC, lab temperature, and metadata information and measurement data for the certified reference materials used during sample analysis).

B. Data Reduction and Reporting

Data Reduction

Glider CTD, DO, optical, and pH sensors: The data management for the physical data will be based on the considerable infrastructure already in place at Rutgers University to support glider operations as part of Integrated Ocean Observing System (IOOS). Kohut, Miles and Flagg are part of the Mid Atlantic regional component of IOOS, MARACOOS. This involvement will ensure that the glider datasets will be managed in a way consistent with the IOOS federally certified process. This approach is based on a centralized data service that provides quality control standards and easy access to data and metadata. For each deployment the complete dataset will be stored locally on the glider. In addition, a subset of the data files recorded by the glider will be transferred back to shore via the Iridium satellite communication system in near real-time. These files are then archived to a fileserver at Rutgers University, where they are backed up daily. These surfacing events will occur approximately every 2 to 3 hours during the mission. With each connection, email will be automatically sent to our glider team with information on glider health (battery voltage, vacuum pressure, and location). The raw data stream will be processed to be consistent with both the IOOS national glider plan and the NSF Ocean Observing Initiative (OOI) data management plans. Scientific parameters will be merged with the glider navigational parameters (i.e., location and time) and are stored in organized data structures, which are saved to the RU fileserver in near real-time. Real-time glider health and deployment status will be available at: https://marine.rutgers.edu/cool/data/gliders/. This webpage will include plots of relevant scientific parameters (temperature, salinity, density, chlorophyll concentration, etc.) and maps showing the glider's path and intended waypoints. These processed datasets will be made available in near real-time in the trajectory NetCDF file format via the Thematic Real-time Environmental Data Distribution System (THREDDS). While the glider is on a mission, the real-time distributed data will be considered provisional until the complete dataset is quality controlled after recovery. Once the glider has been recovered, files containing the full datasets will be downloaded and the previous steps repeated, providing the end user with the complete scientific and navigational data streams in Environmental Research Division's Data Access Program (ERDDAP).

Active Acoustics (AZFP): Glider AZFP raw data binary files (*.01A and *.01B files) will be stored hourly on a data card that will be removed after deployment for processing. These raw data files will be archived in the relevant data portals (e.g., ERDDAP, NCEI). Data processing steps will be conducted from the raw data to ensure removal of non-relevant data and clean the dataset. These include removing glider downcasts outside a certain pitch range, linking time stamps of raw acoustic data with other glider sensor data, removing ocean surface and bottom noise, and removing background, impulse and transient noise. These processing steps are described in section 10. Quality Control Checks. Both raw and processed datasets will be stored according to NOAA's National Centers for Environmental Information (NCEI) national archive for water column sonar data: https://www.ncei.noaa.gov/products/water-column-sonar-data.

Passive Acoustics (DMON): The near real-time detection data from the glider-mounted DMON will be reviewed twice daily by an analyst after Baumgartner et al. (2019, 2020) and the results of the analysis will be available on the robots4whales.whoi.edu website, displayed in the Whale Alert app, and disseminated by text and email messages to stakeholders and other interested parties. We will make the near real-time analyst results available automatically for display in other data distribution platforms, including the Mid-Atlantic Regional Association Coastal Ocean Observing System (MARACOOS) website and Mysticetus platform (an application used to track wildlife detections by the wind energy sector). Recorded audio from the DMON will be archived with the NOAA Northeast Fisheries Science Center's PAM data repository and displayed on their Passive Acoustic Cetacean Map (PACM).

Vessel-based data: Carbonate chemistry parameters (pH, total alkalinity, and dissolved inorganic carbon) will be compiled into separate tables for each glider mission, with each table reporting data from glider deployment and recovery. Each table will be included in the glider metadata submitted with the final delayed mode, QC'd dataset in ERDDAP. Processed zooplankton abundance data will be compiled into separate tables for each glider mission and submitted with the final delayed mode, QC'd dataset in ERDDAP (will all glider data) and NCEI (with only active acoustic data).

Reporting

Progress Reports: Every five months, following approval of the QAPP, a prepared summary of glider surveys completed will be submitted. Progress reports shall be submitted by the end of the calendar month for the previous reporting period's activities. Each report will summarize the mission data collected and status of data Quality Assurance/Quality Control, delivery, and access, and will include applicable data products.

Draft Final Report: Upon completion of the contract period, a draft Final Report will be prepared. The report will include a summary of the missions completed in task 1 and a summary of the data shared via the various entities described in task 2. This report will be submitted within 4 months of the completion of the 3rd Progress Report.

Final Report: Upon approval of the Draft Final Report, a nonproprietary/non-confidential Final Report will be submitted. The report will reflect any updates requested and recommendations for future missions along with the summary of missions completed in task 1 and of the data shared via the various entities described in task 2. This report will be submitted within 4 months of the approval of the Draft Final Report.

12. Data Validation

Data validation, quality control procedures and documentation for the data collected through this project are described in above Sections 6-11.

13. Performance and Systems Audits

Project performance will be monitored by the lead researchers (Kohut and Saba). Josh Kohut, Grace Saba, and technical staff will ensure that all testing, maintenance, and inspection are completed before and after each deployment. These steps will be documented and compiled in the deployment reports described in section 11 of this document. The checkout and checklist documents referenced in section 11 will ensure that all steps are included. Grace Saba and technical staff will ensure the QAPP is followed for the laboratory-focused analysis and data quality control. Grace Saba, Josh Kohut, and members of our data processing technical staff will ensure that all quality control processing and assessment is carried out on all real-time and post-processed data prior to submission to data portals. Any deviations from the QAPP/SOPs will be documented. A list of key project personnel and their corresponding responsibilities is provided in section 16.

The NJDEP Office of Quality Assurance may contact project participants for deployment/retrieval dates to allow for compliance to audit compliance with the QAPP.

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15. Schedule of Tasks

Project Activity	Dates
QAPP Development/Approval	November 2022 – March 2023

Glider Deployment (Quarterly)	Spring 2023 – Winter 2025 (April 2023 – February 2025
Final Report Submittal to NJDEP	June 2025

16. **Project Operations and Responsibility**

A list of key project personnel and their corresponding responsibilities is included below:

Sampling operations: Grace Saba, Josh Kohut, Dave Aragon, Nicole Waite, Kaycee Coleman, Brian Buckingham
Sampling QC: Grace Saba, Josh Kohut, Delphine Mossman, John Kerfoot, Laura Nazzaro, Lori Garzio
Laboratory analysis: Grace Saba, Delphine Mossman, Nicole Waite
Laboratory QC: Grace Saba, Delphine Mossman, Nicole Waite
Data processing activities: Lori Garzio, John Kerfoot, Delphine Mossman, Laura Nazzaro
Data processing QC: Lori Garzio, John Kerfoot, Delphine Mossman, Laura Nazzaro
Data quality review: Grace Saba, Josh Kohut, Lori Garzio, John Kerfoot, Delphine Mossman, Laura Nazzaro
Performance evaluation/auditing: Grace Saba and Josh Kohut
Overall QA: Grace Saba and Josh Kohut
Principal investigator: Grace Saba

17. **Training**

PIs Saba and Kohut co-manage our hardware and software technical staff, who run the operations in our Center for Ocean Observing Leadership (COOL). COOL maintains the world's most advanced coastal ocean observatory. Training for new employees is conducted by our advanced hardware and software technical staff. Only trained, qualified personnel will handle sensor calibrations and verifications, glider prep and deployment/recovery, and data processing, analysis, and quality control. These activities will be overseen by PIs Saba and Kohut.

Appendix 2: Data Structure Guidance

During a glider deployment, data files are sent to shore via satellite, processed in near real-time, served via RUCOOL's slocum-data ERDDAP server, and plotted in the deployment-specific page in RUCOOL's glider operations website. Once a glider is recovered, the full resolution datasets are processed and shared publicly via ERDDAP, and relevant datasets are post-processed and archived at NCEI.

In ERDDAP, glider datasets are organized by glider deployment ID (e.g. ru39-20250226T1700). Two different types of datasets are provided, Science Profiles and Raw Trajectories, and detailed descriptions of each dataset type can be found here. Each glider dataset served in ERDDAP (real-time or delayed) contains the complete and relevant metadata describing the deployment, sensors, variables and QC variables (if applicable). Data served in ERDDAP can be downloaded in any user-specified format that is supported by ERDDAP.

Data available in ERDDAP allows for easy, quick, and modifiable imagery based on glider data that is delivered in real-time. Figures on the RUCOOL glider operations website are also updated in real-time. These features allow the entire team from data managers and pilots to PIs, funders, and external collaborators to quickly review data, adapt sampling if necessary, and examine anomalous event information such as low dissolved oxygen and/or pH, storm cooling, etc. Several of the quality control tests implemented can also alert the team to anomalous data in addition to poor quality data.

Once a glider is recovered, the full-resolution delayed-mode dataset is processed and shared via ERDDAP. This dataset replaces the real-time dataset which is simply a subset of the full-resolution delayed-mode dataset. The real-time plots and operations are preserved on the RUCOOL operational glider website indefinitely.

Table A2.1. Glider missions, deployment ID and hyperlinks to each full resolution delayed mode dataset in ERDDAP.

Glider Mission	Glider	Glider-deployment and Hyperlink
Spring 2023 paired	ru39	ru39-20230420T1636
	ru41	ru41-20230420T1638
June/July 2023 gap-fill	ru40	ru40-20230629T1430
Summer 2023 paired	ru39	ru39-20230817T1520
	ru40	ru40-20230817T1522
September 2023 gap-fill	ru34	ru34-20230920T1506
Fall 2023 paired	ru39	ru39-20231103T1413
	ru40	ru40-20231103T1421 and ru40-20231115T1612
Winter 2024 paired	ru39	ru39-20240215T1646
	ru40	ru40-20240215T1642
Spring 2024 paired	ru39	ru39-20240429T1522
	ru40	ru40-20240429T1528
June 2024 gap-fill	ru43	ru43-20240612T1658

Summer 2024 paired	ru39	ru39-20240723T1442
	ru40	ru40-20240723T1600
September 2024 gap-fill	ru43	ru43-20240904T1539
Fall 2024 paired	ru39	ru39-20241021T1717
	ru40	ru40-20241021T1654
Winter 2025 paired	ru39	ru39-20250226T1700
	ru40	ru40-20250226T1704

Table A2.2. Examples of metadata included in glider datasets

Global Attributes	**Sensor Attributes**	**Variable attributes**
Project description	Make and model	Long name
Funding acknowledgement	Sensor description	Standard name
Contributors	Serial number	Description
Deployment region	Calibration date	Units
File creator and contact information		
Deployment summary		

Vessel-based sampling data collected at glider deployments and recoveries for ground-truthing the glider-based pH and AZFP sensors (zooplankton tows, carbonate chemistry water samples, pH glider groundtruthing) are publicly available via ERDDAP. Each dataset contains complete and relevant metadata and can be downloaded in any user-specified format that is supported by ERDDAP

Table A2.3. Examples of metadata included in the vessel-based sampling datasets

Global Attributes	**Variable attributes**
Project description	Long name
Funding acknowledgement	Standard name
Contributors	Description
Sampling and analysis methods	Units
File creator and contact information	

PAM data is analyzed by an expert acoustician at least once daily and marine mammal detections are updated on https://robots4whales.whoi.edu in real-time, along with additional plots of oceanographic data and real-time fish tag detections (if there is an Rx-LIVE receiver mounted to the glider). The rapid response time means these detections are often used to quickly trigger voluntary slow zones by NOAA Fisheries if a right whale is detected. Detections can be downloaded in real-time and are being shared within the MARACOOS OceansMap viewer.

Telemetry tag detections from Innovasea Rx-Live and VMT receivers are sent to the Mid-Atlantic Acoustic Telemetry Observation System (MATOS) project "RUCOOL NJRMI Eco-glider Surveys", along with all required metadata including glider trajectories required to determine the locations of detections. MATOS accepts data and metadata from receivers and transmitters, and 3-4 times a year runs a data extraction to match all detections from receivers to transmitters that have been submitted to the database. Following the extraction all detections are shared with tag owners, and contact information for tag owners is shared with the owners of receivers that detect their tags. Species information is not included in the returned datasets, but can be requested from tag owners.

Relevant project details and metadata are included in the Responsible Offshore Science Alliance (ROSA) FishFORWRD database (project ID Ex-33) and in the Regional Wildlife Science Collaborative (RWSC) research database under the marine mammals, protected fish species, and habitat & ecosystem topic categories. Our team works closely with leadership from both organizations and has contributed to plans for including mobile receivers as part of the RWSC Research Planning Map which currently includes only stationary receivers but is in the process of adding standard paths for recurring mobile receivers for this and other projects (draft shown in Figure A1.1).

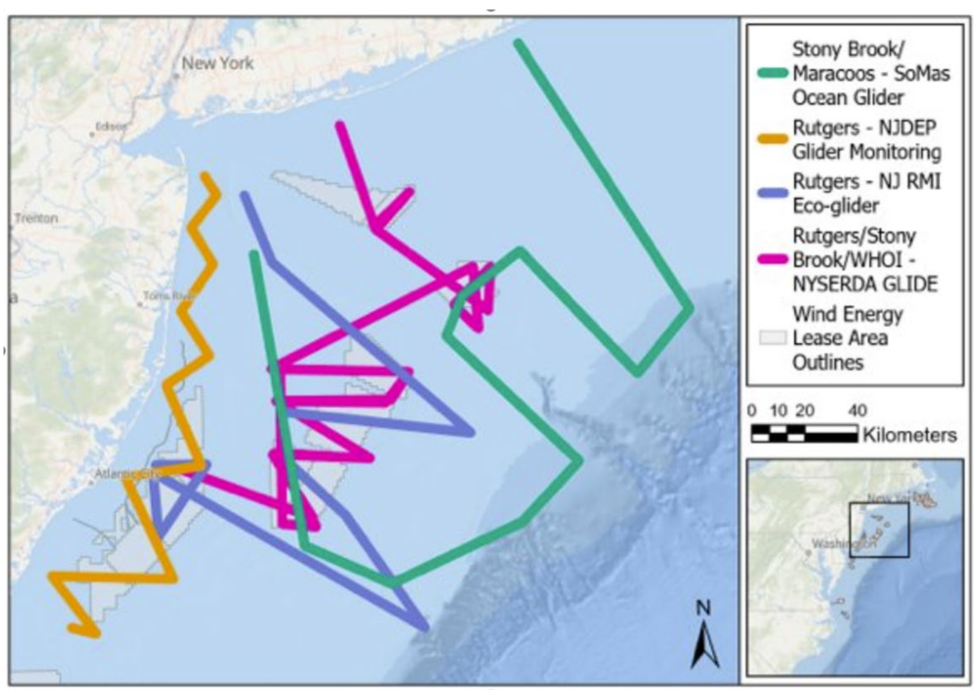

Figure A2.1. Draft RWSC Research Planning map that includes relevant glider transects for acoustic telemetry receivers.

Appendix 3: Supplemental Oceanography Interannual Variability Tables and Figures

Table A3.1. Bottom water temperature (°C) seasonal average ± standard deviation across the New Jersey coastal shelf measured by RMI gliders for 2023, 2024, and 2025. ns = not sampled. Note: The Winter 2025 deployment that occurred 02/26-03/28 extended into the Spring period (Mar – May); therefore, Spring 2025 data were included to capture the full deployment period.

	Spring			Summer		Fall		Winter	
	2023	2024	2025	2023	2024	2023	2024	2024	2025
Inshore	8.66 ± 0.94	10.81 ± 1.03	6.11 ± 0.34	14.77 ± 0.64	11.03 ± 2.07	17.71 ± 2.52	16.6 ± 1.65	10.5 ± 2.3	5.09 ± 0.05
Midshelf	7.85 ± 0.33	7.87 ± 1.28	5.45 ± 0.47	11.32 ± 1.05	8.42 ± 0.9	15.7 ± 2.43	15 ± 4.22	7.24 ± 1.57	5.03 ± 0.47
Offshore	9.72 ± 1.85	7.66 ± 1.63	5.83 ± 0.84	9.56 ± 0.72	9.04 ± 2.33	11.92 ± 1.57	13.45 ± 3.84	7.43 ± 0.38	ns

Table A3.2. Bottom water salinity (PSU) seasonal average ± standard deviation across the New Jersey coastal shelf measured by RMI gliders for 2023, 2024, and 2025. ns = not sampled. Note: The Winter 2025 deployment that occurred 02/26-03/28 extended into the Spring period (Mar – May); therefore, Spring 2025 data were included to capture the full deployment period.

	Spring			Summer		Fall		Winter	
	2023	2024	2025	2023	2024	2023	2024	2024	2025
Inshore	32.33 ± 0.07	30.79 ± 0.16	32.55 ± 0.28	31.96 ± 0.14	31.28 ± 0.2	31.55 ± 0.46	31.91 ± 0.48	31.71 ± 0.3	33.36 ± 0.02
Midshelf	33.0 ± 0.22	31.6 ± 0.42	33.18 ± 0.21	32.54 ± 0.17	31.67 ± 0.19	32.34 ± 0.4	32.52 ± 0.65	31.98 ± 0.19	33.29 ± 0.14
Offshore	33.88 ± 0.67	32.71 ± 0.8	33.28 ± 0.11	32.96 ± 0.2	33.06 ± 1.05	32.78 ± 0.37	33.67 ± 1.11	32.54 ± 0.19	ns

Table A3.3. Surface water omega seasonal average ± standard deviation across the New Jersey coastal shelf derived from data measured by RMI gliders for 2023, 2024, and 2025. ns = not sampled. Note: The Winter 2025 deployment that occurred 02/26-03/28 extended into the Spring period (Mar – May); therefore, Spring 2025 data were included to capture the full deployment period.

	Spring			Summer		Fall		Winter	
	2023	2024	2025	2023	2024	2023	2024	2024	2025
Inshore	2.28 ± 0.36	1.63 ± 0.05	1.5 ± 0.04	2.84 ± 0.09	1.72 ± 0.2	2.39 ± 0.35	2.05 ± 0.12	2.05 ± 0.18	2.04 ± 0.02
Midshelf	2.17 ± 0.22	1.64 ± 0.06	1.74 ± 0.14	2.66 ± 0.12	1.97 ± 0.1	2.5 ± 0.22	2.22 ± 0.11	1.78 ± 0.12	1.78 ± 0.05
Offshore	2.26 ± 0.07	1.68 ± 0.08	1.94 ± 0.18	3.08 ± 0.14	2.01 ± 0.07	2.78 ± 0.32	2.4 ± 0.12	1.76 ± 0.03	ns

Table A3.4. Bottom water omega seasonal average ± standard deviation across the New Jersey coastal shelf derived from data measured by RMI gliders for 2023, 2024, and 2025. ns = not sampled. Note: The Winter 2025 deployment that occurred 02/26-03/28 extended into the Spring period (Mar – May); therefore, Spring 2025 data were included to capture the full deployment period.

	Spring			Summer		Fall		Winter	
	2023	2024	2025	2023	2024	2023	2024	2024	2025
Inshore	1.58 ± 0.07	1.45 ± 0.09	1.48 ± 0.03	1.33 ± 0.05	1.18 ± 0.17	2.09 ± 0.32	1.65 ± 0.47	2.04 ± 0.2	1.84 ± 0.01

Midshelf	1.59 ± 0.07	1.36 ± 0.23	1.71 ± 0.09	1.19 ± 0.16	1.02 ± 0.18	1.78 ± 0.55	1.45 ± 0.5	1.78 ± 0.15	1.81 ± 0.04
Offshore	1.78 ± 0.25	1.36 ± 0.26	1.7 ± 0.08	1.08 ± 0.05	1.37 ± 0.27	1.26 ± 0.16	1.48 ± 0.5	1.59 ± 0.03	ns

Table A3.5. Bottom water dissolved oxygen (mg/L) seasonal average ± standard deviation across the New Jersey coastal shelf measured by RMI gliders for 2023, 2024, and 2025. ns = not sampled. Note: The Winter 2025 deployment that occurred 02/26-03/28 extended into the Spring period (Mar – May); therefore, Spring 2025 data were included to capture the full deployment period.

	Spring			Summer		Fall		Winter	
	2023	2024	2025	2023	2024	2023	2024	2024	2025
Inshore	ns	8.93 ± 0.23	10.28 ± 0.09	5.97 ± 0.79	7.47 ± 0.77	6.42 ± 1.39	7.59 ± 0.68	9.36 ± 0.82	10.72 ± 0.09
Midshelf	ns	9.37 ± 0.5	10.37 ± 0.14	6.26 ± 1.33	7.59 ± 0.59	5.41 ± 1.61	7.09 ± 0.66	9.89 ± 0.54	10.54 ± 0.17
Offshore	ns	9.19 ± 0.57	10.19 ± 0.3	6.33 ± 1.02	8.14 ± 0.72	5.11 ± 0.71	6.21 ± 0.37	9.64 ± 0.22	ns

Table A3.6. Surface chlorophyll-a (ug/L) seasonal average ± standard deviation across the New Jersey coastal shelf measured by RMI gliders for 2023, 2024, and 2025. ns = not sampled. Note: The Winter 2025 deployment that occurred 02/26-03/28 extended into the Spring period (Mar – May); therefore, Spring 2025 data were included to capture the full deployment period.

	Spring			Summer		Fall		Winter	
	2023	2024	2025	2023	2024	2023	2024	2024	2025
Inshore	2.48 ± 1.77	1.17 ± 0.35	2.21 ± 1.05	2.11 ± 0.83	1.32 ± 0.95	1.63 ± 0.75	1.56 ± 0.84	1.31 ± 0.29	2.29 ± 0.8
Midshelf	1.64 ± 0.9	0.68 ± 0.34	1.07 ± 0.59	0.94 ± 0.57	0.68 ± 0.35	1.21 ± 1.38	0.73 ± 0.44	1.2 ± 0.4	1.02 ± 0.36
Offshore	1.39 ± 0.74	1.34 ± 0.8	1.24 ± 0.47	0.6 ± 0.23	0.55 ± 0.31	0.55 ± 0.46	0.63 ± 0.34	1.55 ± 0.39	ns

Table A3.7. Seasonal average ± standard deviation of chlorophyll-a (ug/L) at the subsurface chlorophyll-a maximum across the New Jersey coastal shelf measured by RMI gliders for 2023, 2024, and 2025. ns = not sampled. low n = data not reported due to very low sample sizes (a well-mixed water column in Winter means the mixed-layer depth and chlorophyll-a maximum are not calculated).

	Spring			Summer		Fall		Winter	
	2023	2024	2025	2023	2024	2023	2024	2024	2025
Inshore	3.46 ± 1.19	1.9 ± 0.57	2.22 ± 0.81	5.1 ± 1.28	3.77 ± 1.79	2.76 ± 0.77	3.03 ± 2.03	1.54 ± 0.16	low n
Midshelf	3.24 ± 1.81	1.6 ± 1.23	2.27 ± 0.75	8.2 ± 6.49	3.3 ± 1.53	3.32 ± 3.86	2.78 ± 2.12	1.77 ± 0.21	low n
Offshore	2.38 ± 1.67	2.1 ± 0.62	2.34 ± 0.55	5.94 ± 4.87	2.16 ± 0.86	2.49 ± 2.41	1.7 ± 1.26	low n	ns

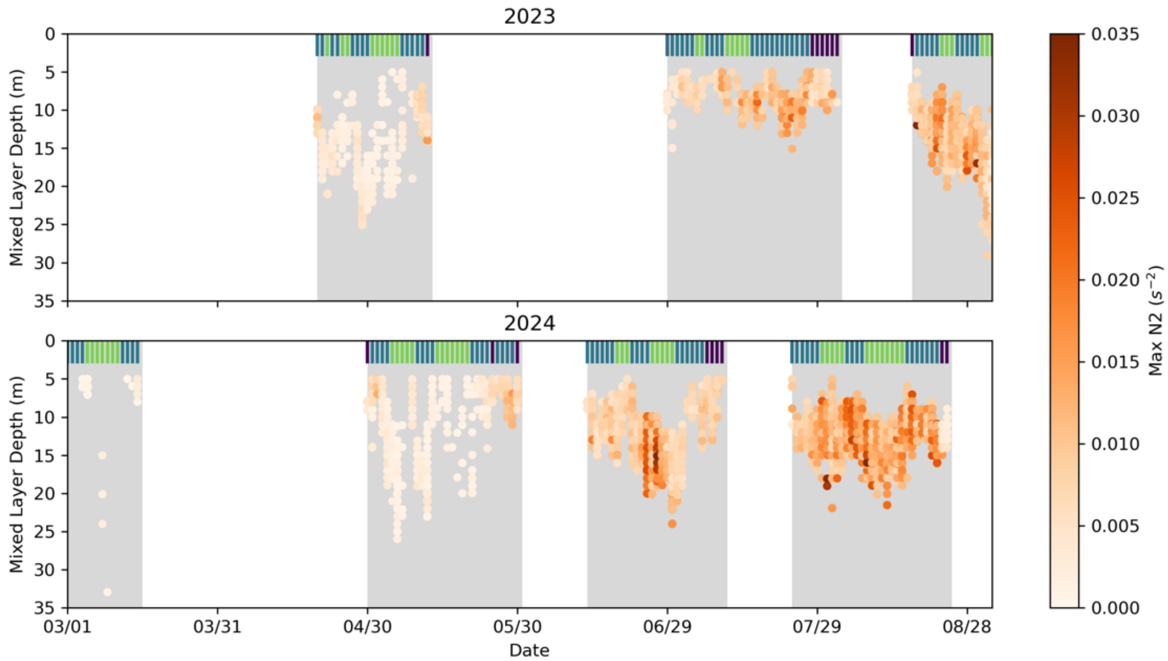

Figure A3.1. Spring and Summer stratification metrics for 2023 and 2024 deployments. Shaded area indicates times when glider was deployed, markers are located mixed layer depth (MLD) calculated for each profile, and color indicates maximum buoyancy frequency (Max N2, higher values meaning stronger stratification). MLD and Max N2 are calculated for each profile. Colored area at surface indicates whether the glider is present in Inshore (dark blue), Midshelf (medium blue), or Offshore (green) strata as shown in Figure 2.

Appendix 4: Robots4Whales Whale Detections For Each PAM Deployment

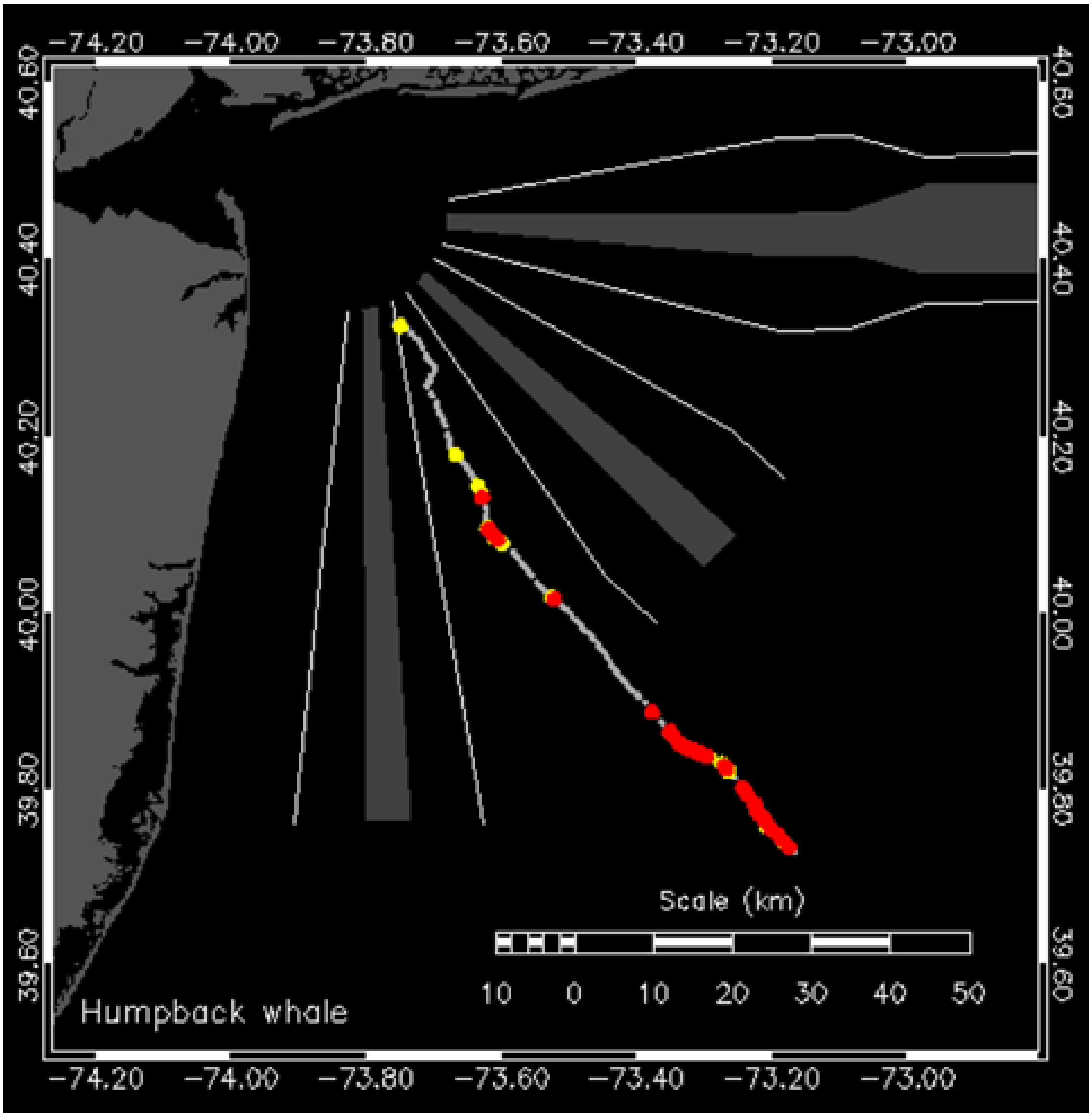

Figure A4.1. Marine mammal detections observed during the Spring 2023 glider mission. Red = detected; yellow = possibly detected; gray = not detected. Note: The near real-time data for the 4 days and 90 km ru41 was in operation prior to being lost provided valuable marine mammal detection data, particularly highlighting the presence of humpback whales in the deployment area. Image from http://robots4whales.whoi.edu/.

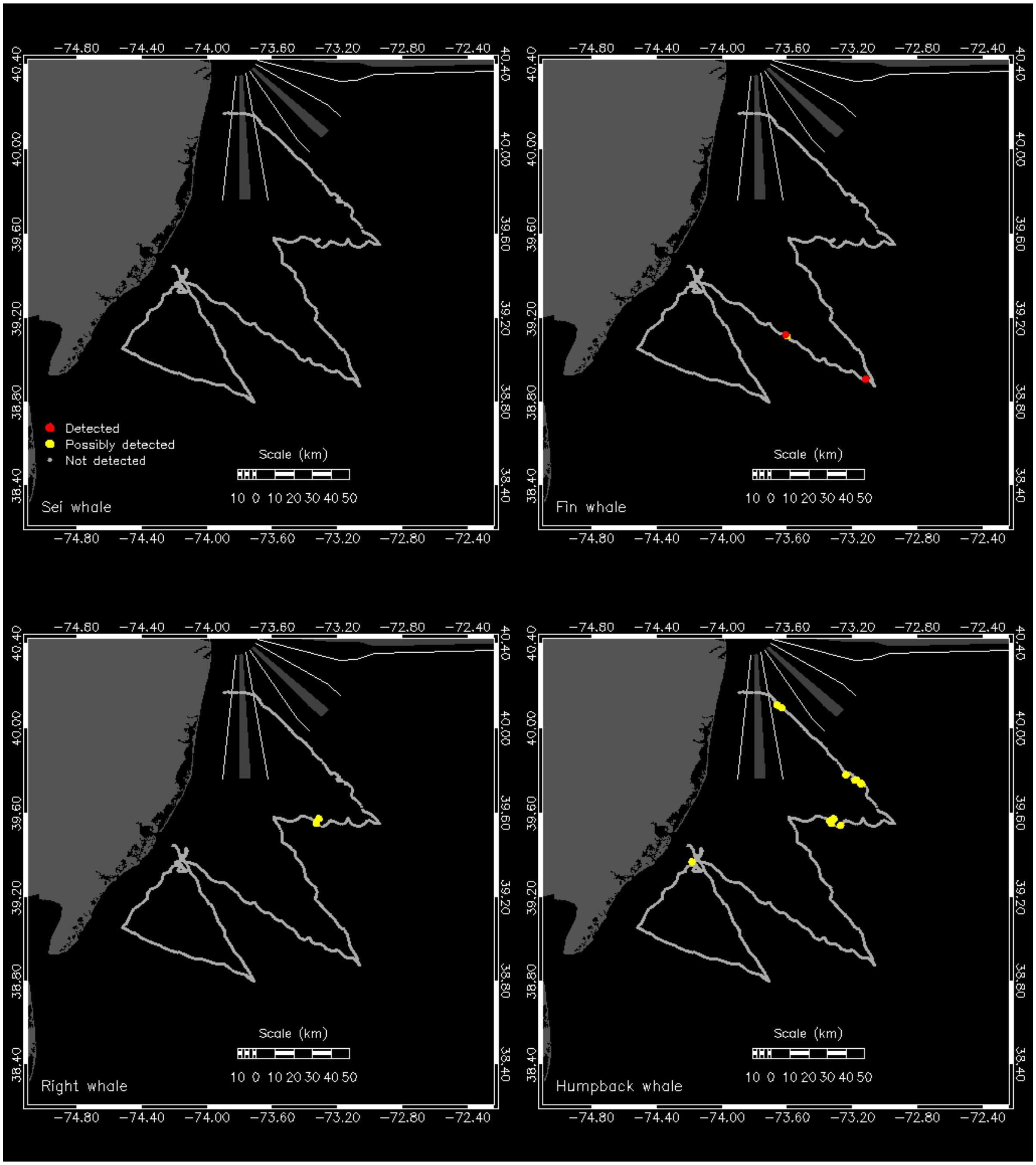

Figure A4.2. Marine mammal detections observed during the Early Summer 2023 glider mission. Red = detected; yellow = possibly detected; gray = not detected. Image from http://robots4whales.whoi.edu/.

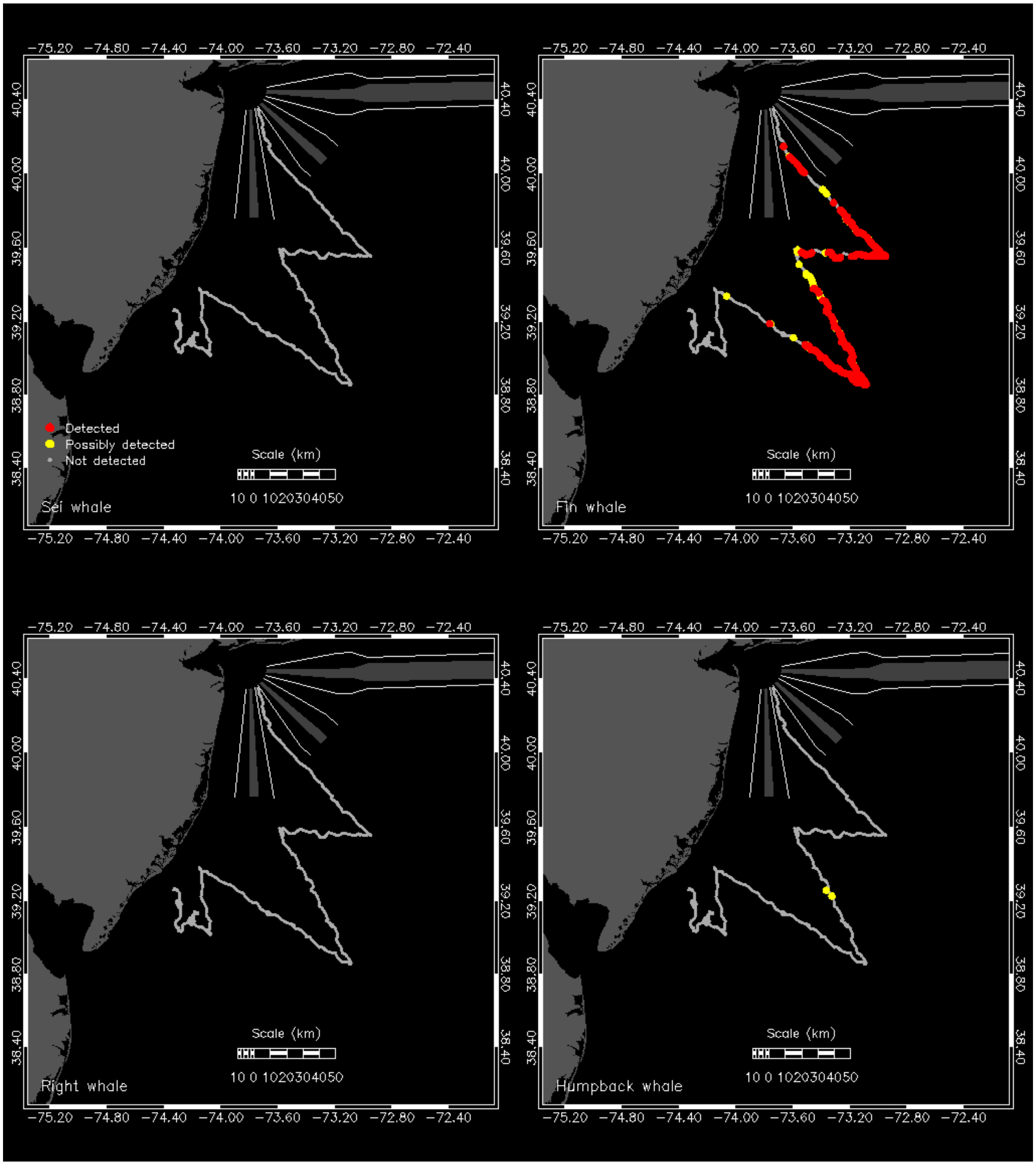

Figure A4.3. Marine mammal detections observed during the Summer 2023 glider mission. Red = detected; yellow = possibly detected; gray = not detected. Image from http://robots4whales.whoi.edu/.

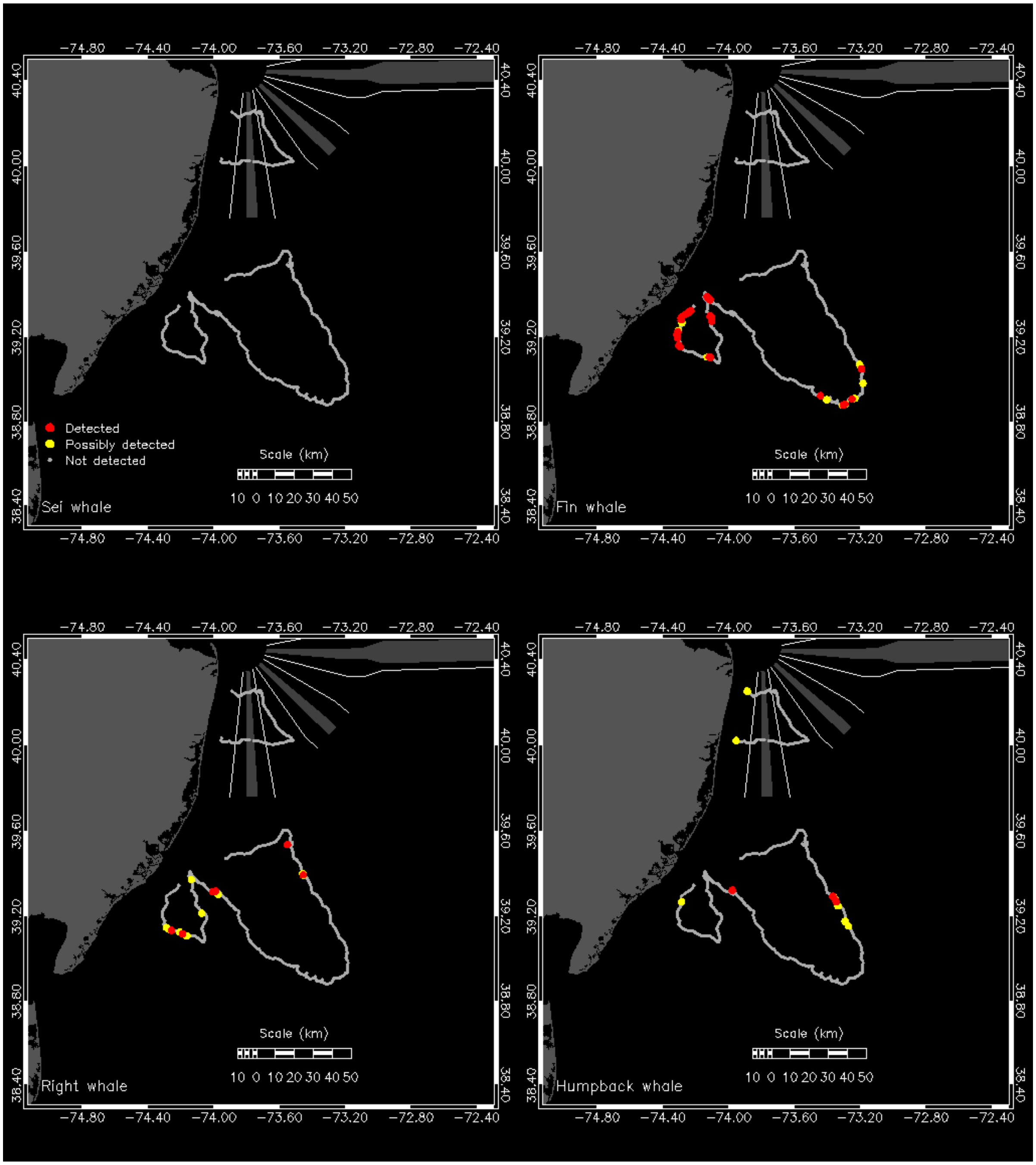

Figure A4.4 Marine mammal detections observed during the Fall 2023 glider mission. Red = detected; yellow = possibly detected; gray = not detected. Note: Near the beginning of the Fall 2023 paired mission (deployed on 11/03), ru40 experienced a glider brake issue on 11/08, making it difficult to complete its vertical profiles. Therefore, it was recovered on 11/10 out of Manasquan, repaired in-house, then redeployed near ru39 on 11/15 out of Tuckerton. Image from http://robots4whales.whoi.edu/.

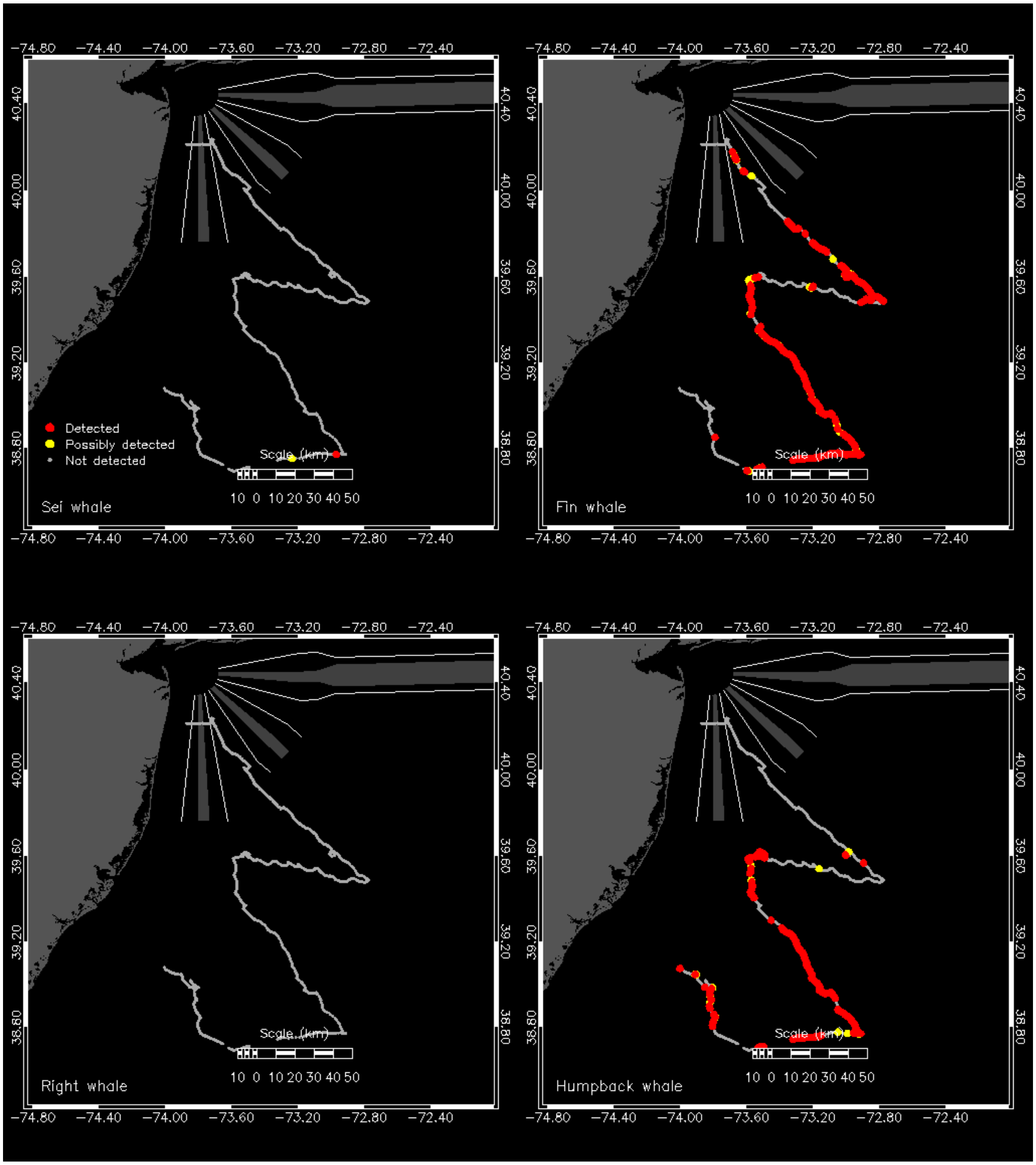

Figure A4.5. Marine mammal detections observed during the Winter 2024 glider mission. Red = detected; yellow = possibly detected; gray = not detected. Image from http://robots4whales.whoi.edu/.

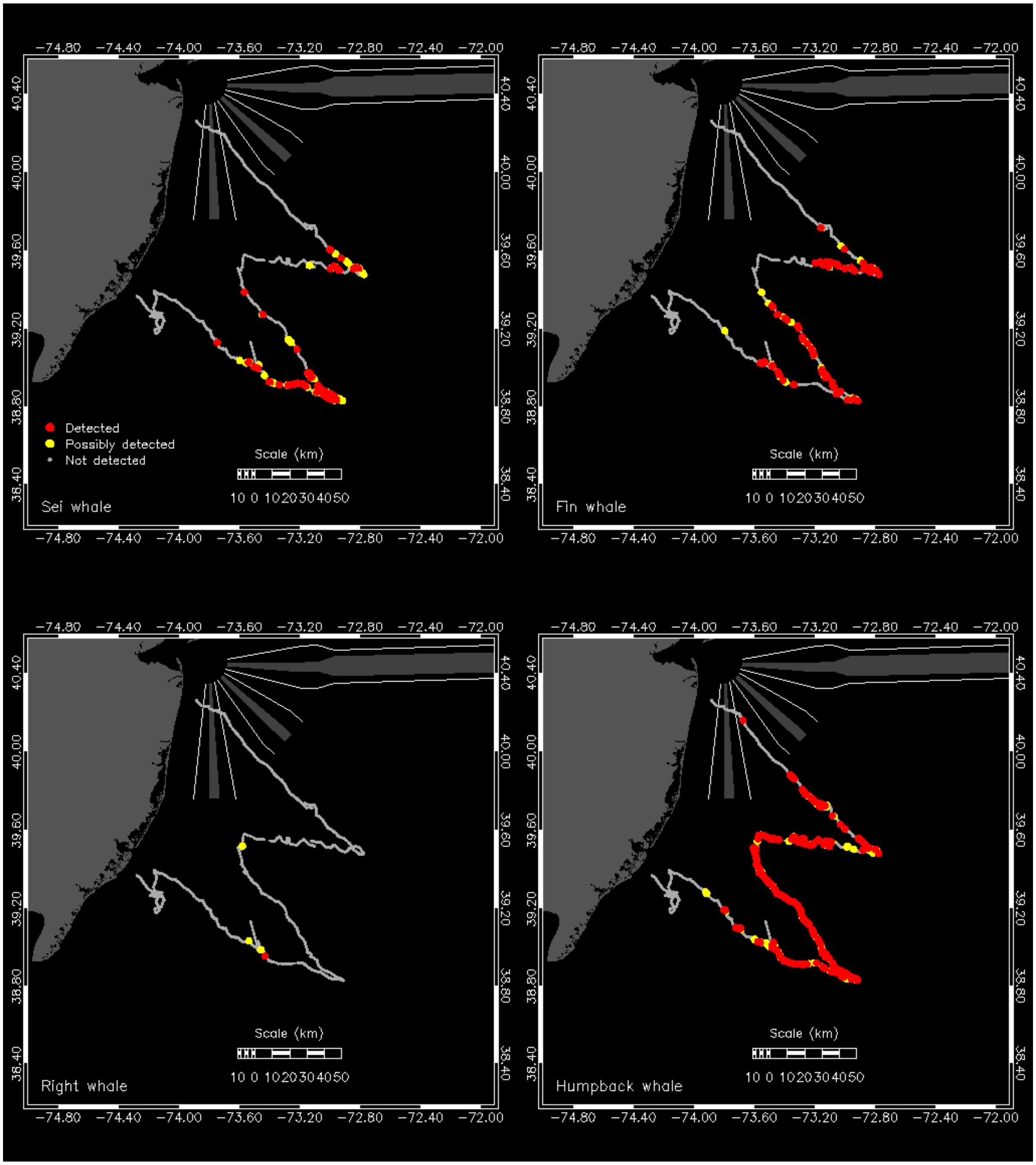

Figure A4.6. Marine mammal detections observed during the Spring 2024 glider mission. Red = detected; yellow = possibly detected; gray = not detected. Image from http://robots4whales.whoi.edu/.

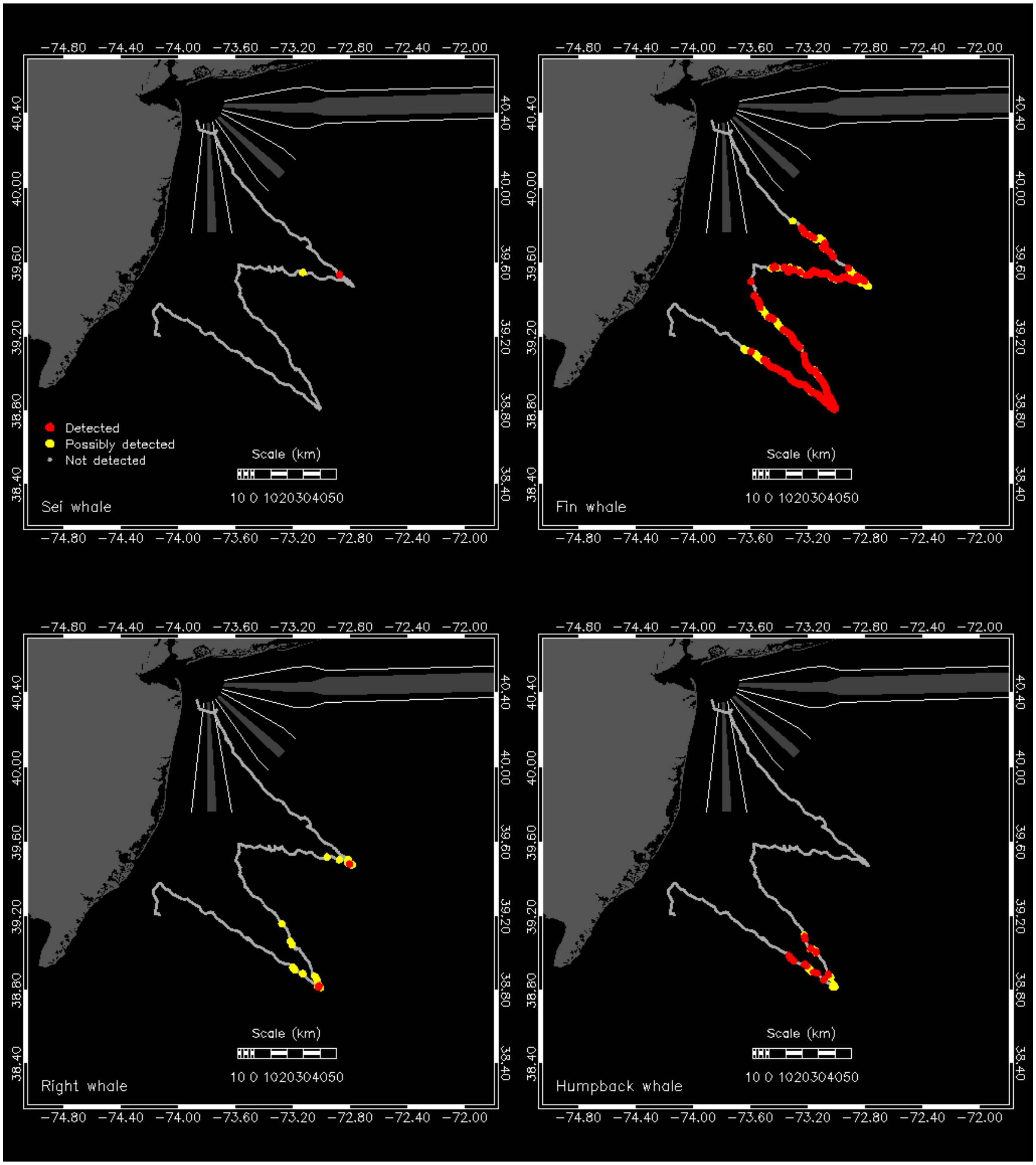

Figure A4.7. Marine mammal detections observed during the Summer 2024 glider mission. Red = detected; yellow = possibly detected; gray = not detected. Image from http://robots4whales.whoi.edu/.

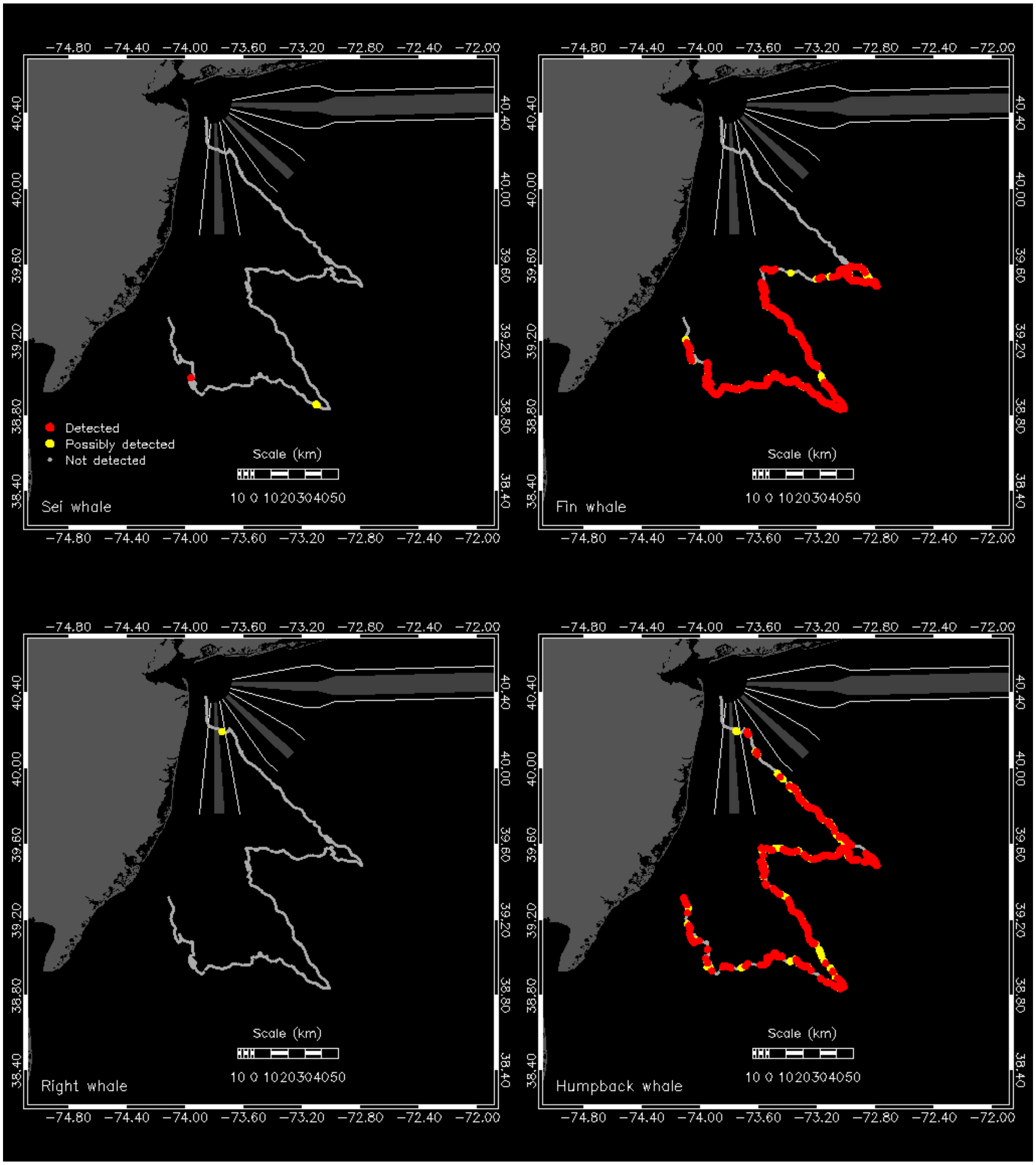

Figure A4.8. Marine mammal detections observed during the Fall 2024 glider mission. Red = detected; yellow = possibly detected; gray = not detected. Image from http://robots4whales.whoi.edu/.

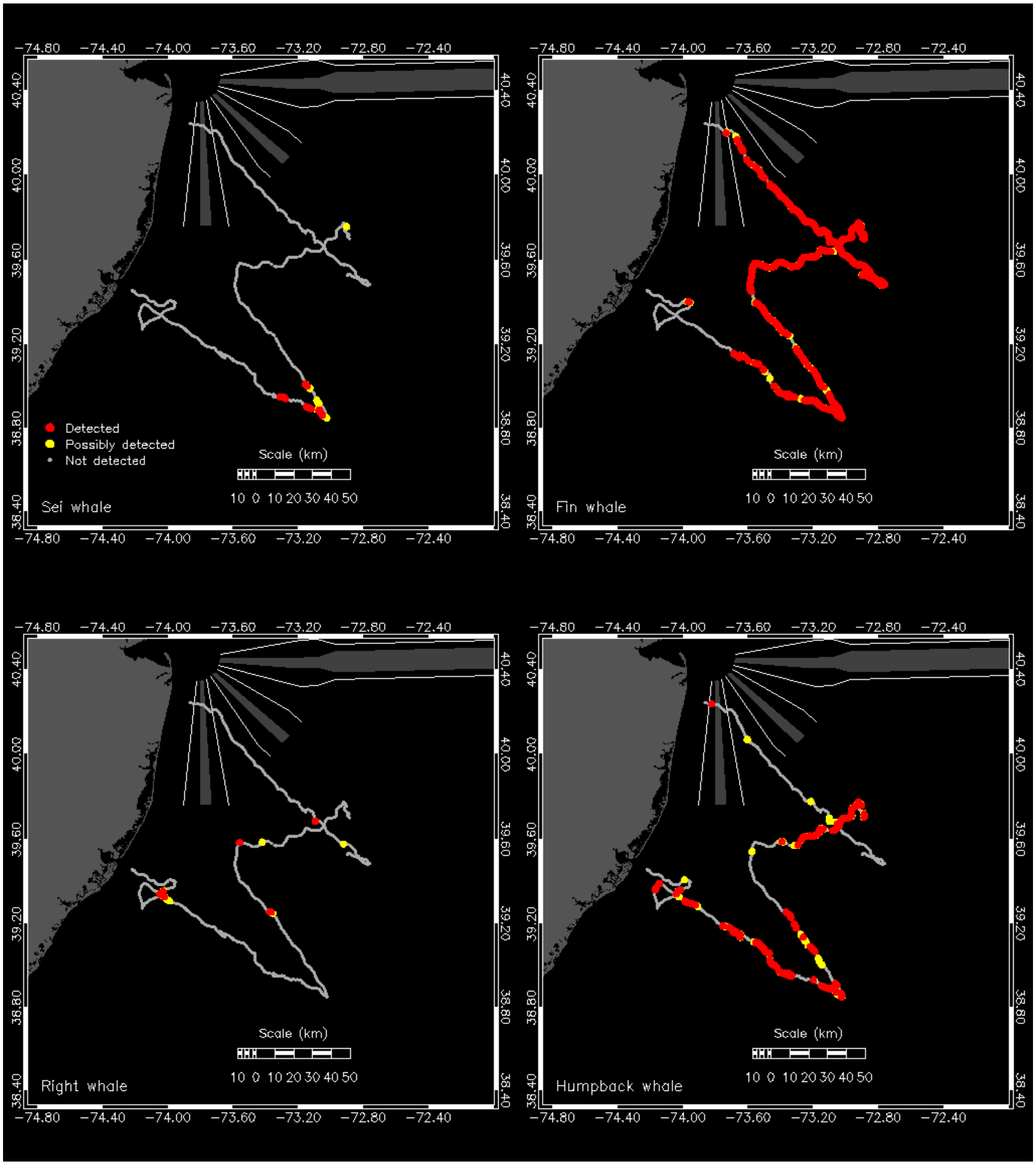

Figure A4.9. Marine mammal detections observed during the Winter 2025 glider mission. Red = detected; yellow = possibly detected; gray = not detected. Image from http://robots4whales.whoi.edu/.

Appendix 5: Supplemental Active Acoustics Figures and Tables

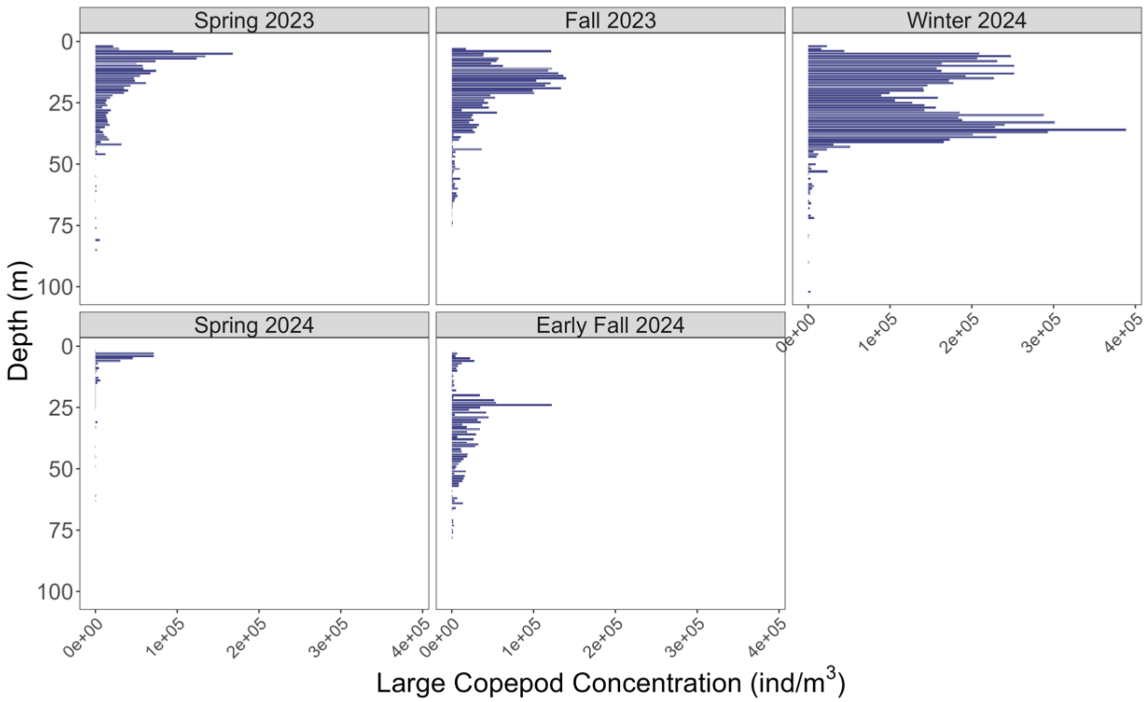

Figure A5.1. Vertical distribution of the sum of large copepod concentration for each seasonal deployment.

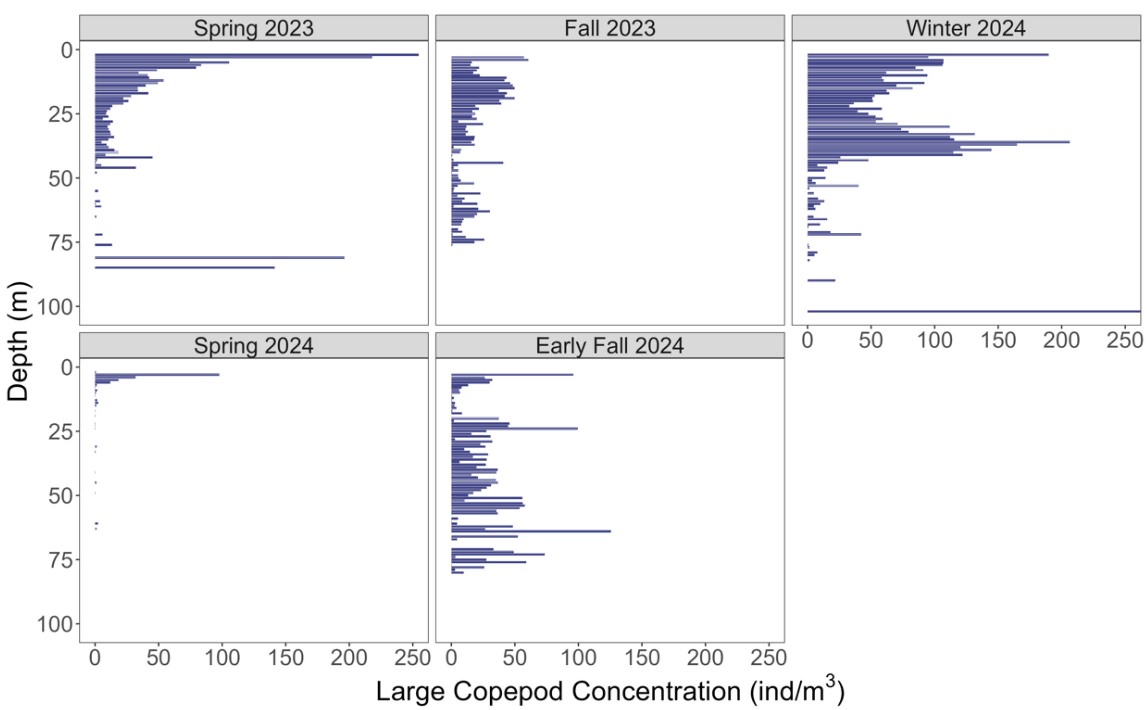

Figure A5.2. Vertical distribution of the mean large copepod concentration for each seasonal deployment. Note that the lowest bar on the Winter 2024 panel has a value of roughly 3000 individuals/m^3 and was cut off to better visualize the rest of the data.

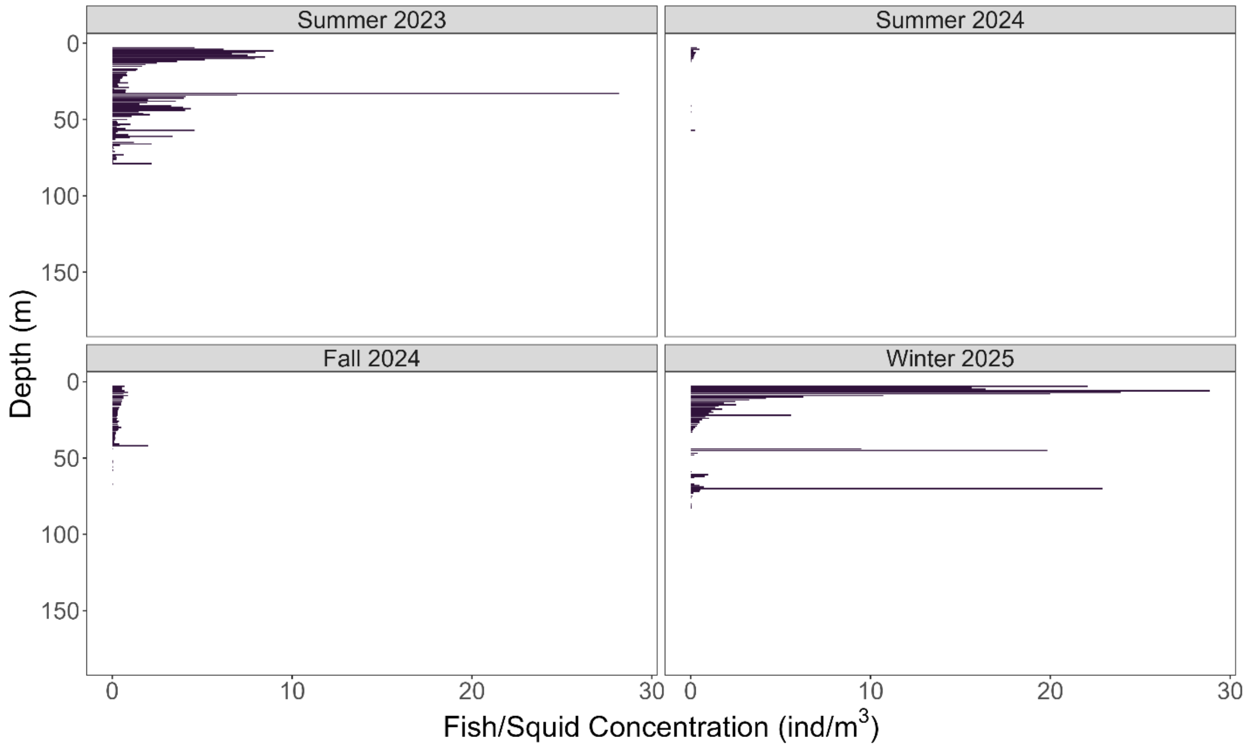

Figure A5.3. Vertical distribution of the sum of pelagic fish and squid concentration across all species for each seasonal deployment.

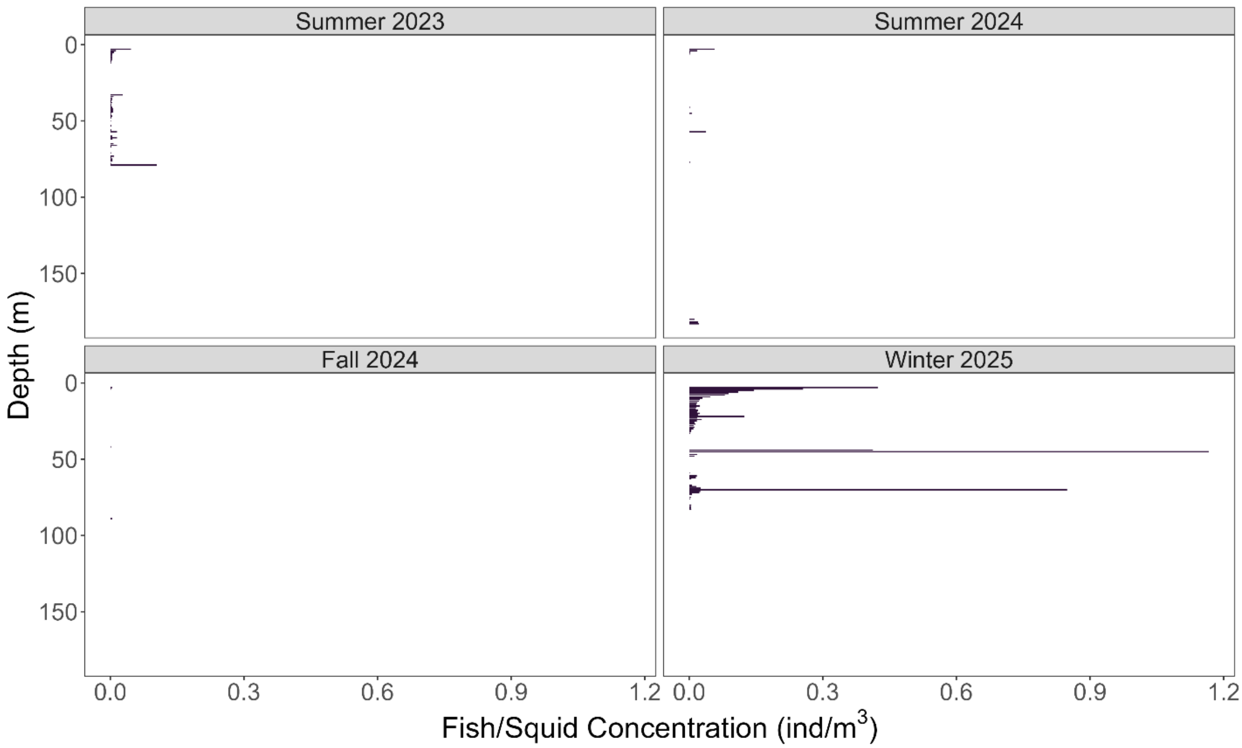

Figure A5.4. Vertical distribution of the mean fish and squid concentration across all species for each seasonal deployment.

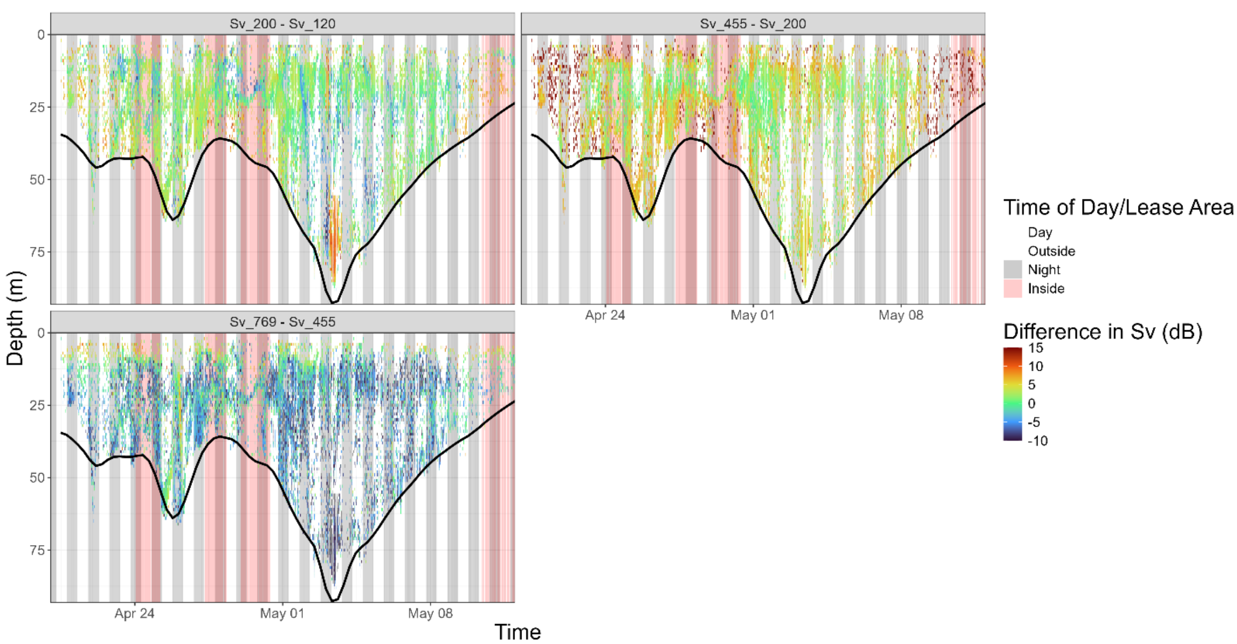

Figure A5.5. The difference in S_v (volume backscatter strength, dB) between adjacent frequencies from the zooplankton-configured AZFP during the Spring 2023 glider mission. The white and gray bands indicate day and night, respectively, and the pink bands indicate when the glider was within a Bureau of Ocean Energy Management (BOEM) wind lease area.

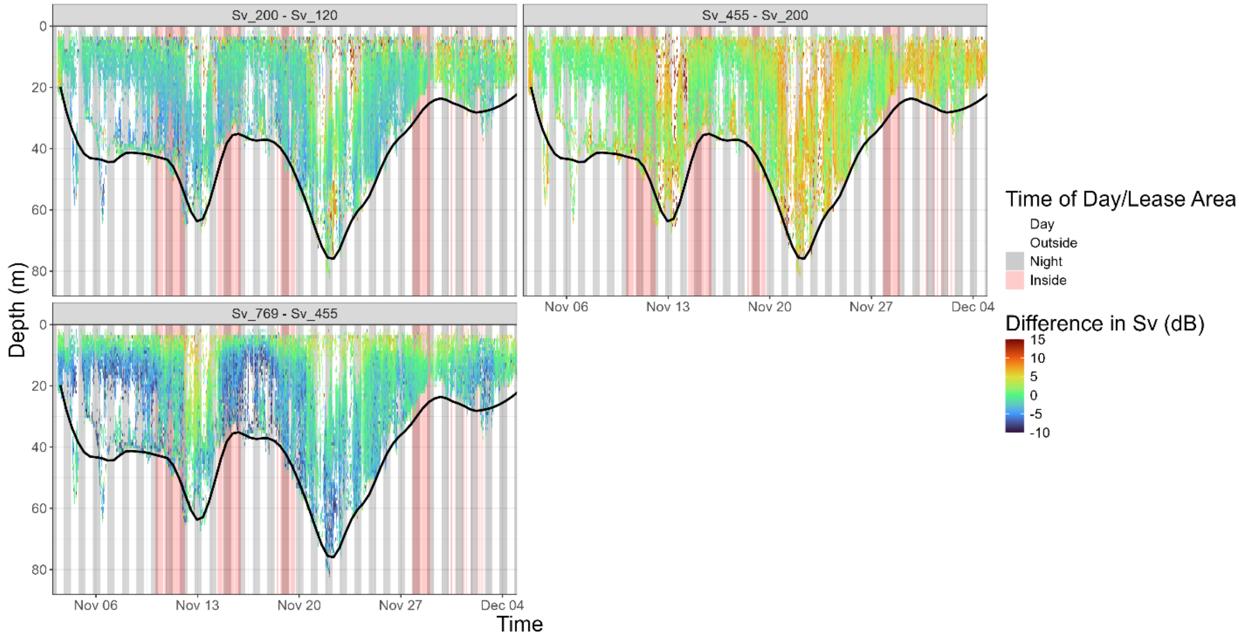

Figure A5.6. The difference in S_v (volume backscatter strength, dB) between adjacent frequencies from the zooplankton-configured AZFP during the Fall 2023 glider mission. The white and gray bands indicate day and night, respectively, and the pink bands indicate when the glider was within a Bureau of Ocean Energy Management (BOEM) wind lease area.

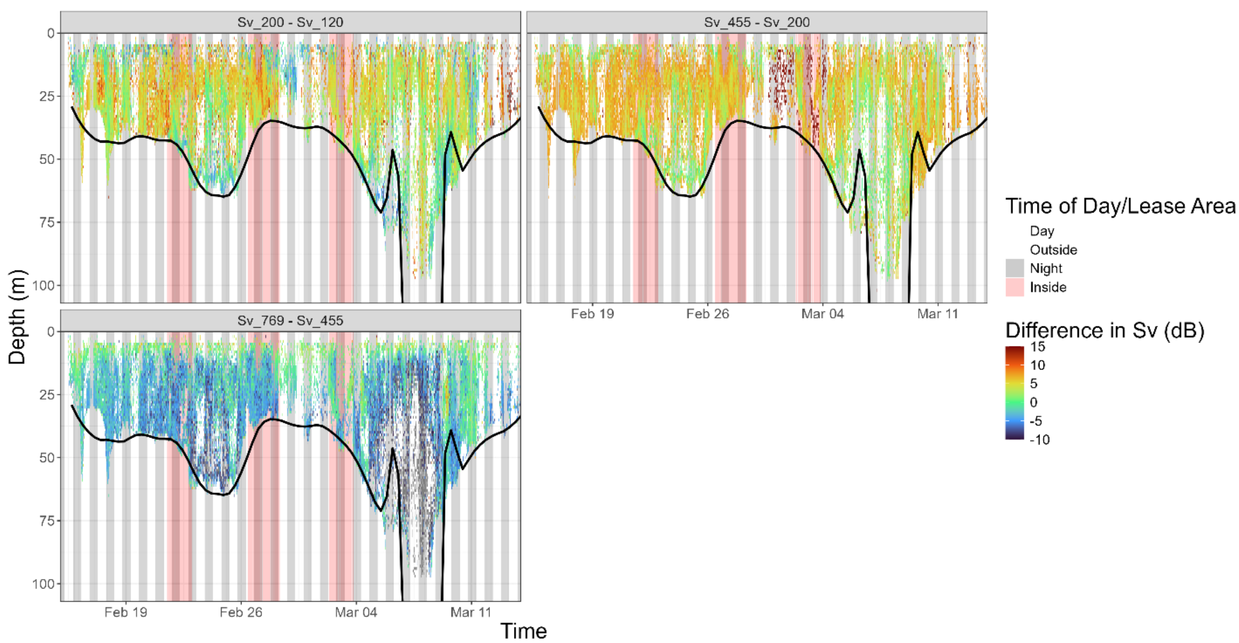

Figure A5.7. The difference in S_v (volume backscatter strength, dB) between adjacent frequencies from the zooplankton-configured AZFP during the Winter 2024 glider mission. The white and gray bands indicate day and night, respectively, and the pink bands indicate when the glider was within a Bureau of Ocean Energy Management (BOEM) wind lease area.

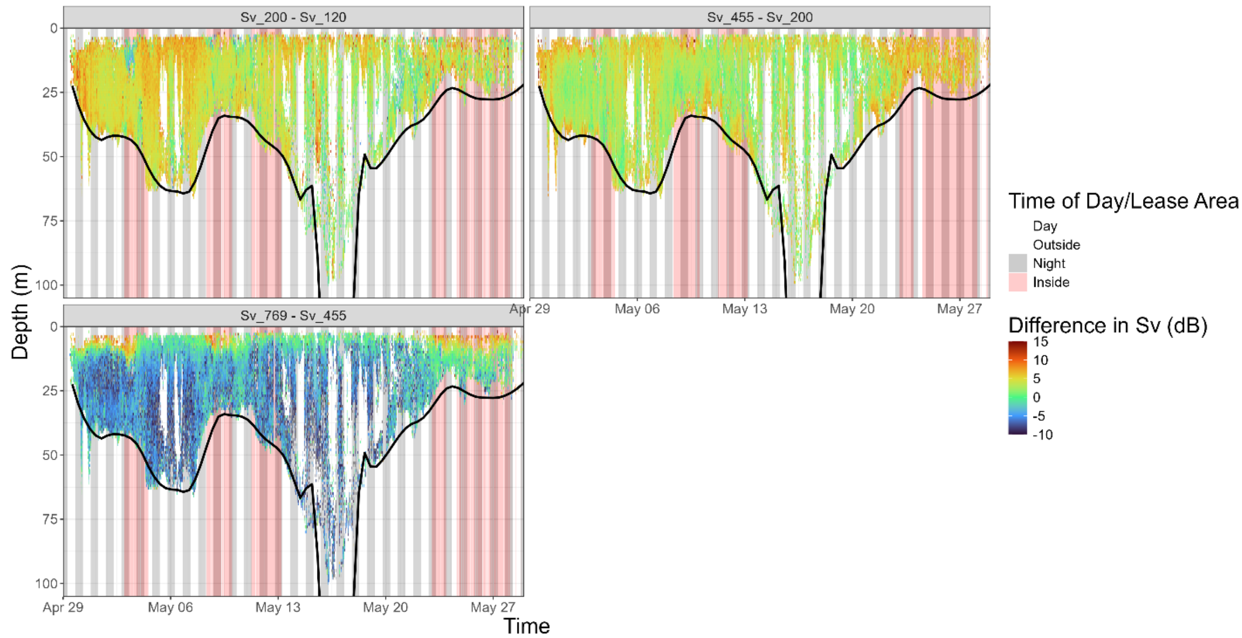

Figure A5.8. The difference in S_v (volume backscatter strength, dB) between adjacent frequencies from the zooplankton-configured AZFP during the Spring 2024 glider mission. The white and gray bands indicate day and night, respectively, and the pink bands indicate when the glider was within a Bureau of Ocean Energy Management (BOEM) wind lease area.

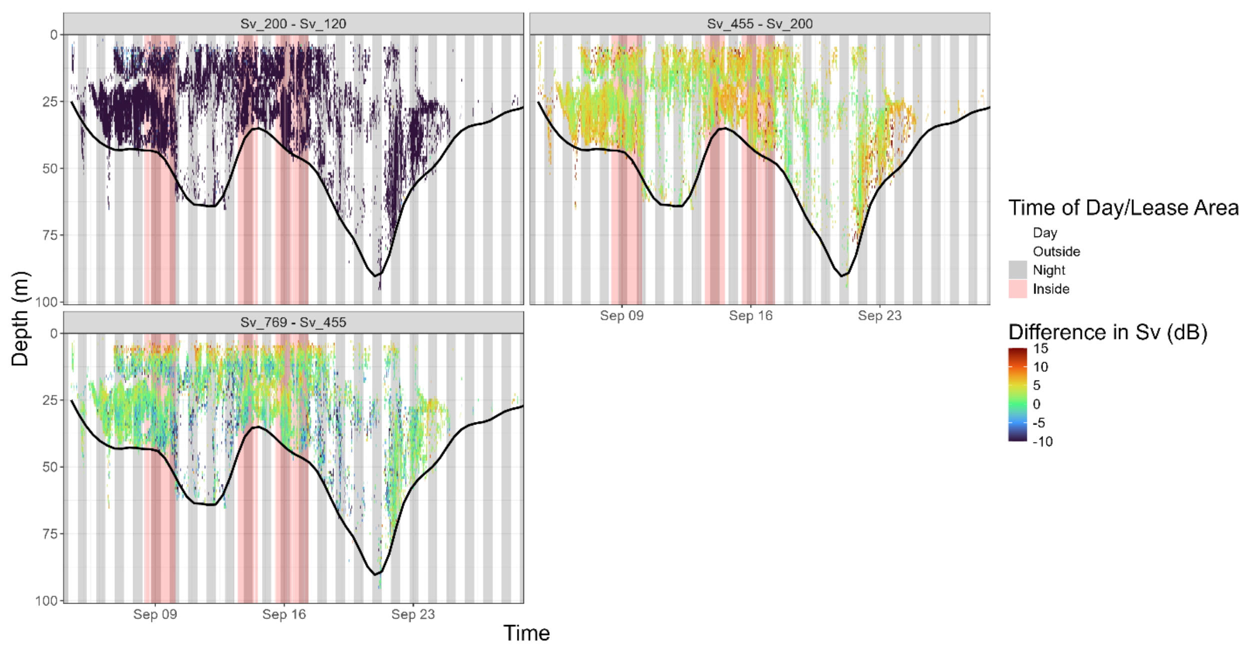

Figure A5.9. The difference in S_v (volume backscatter strength, dB) between adjacent frequencies from the zooplankton-configured AZFP during the Early Fall 2024 glider mission. The white and gray bands indicate day and night, respectively, and the pink bands indicate when the glider was within a Bureau of Ocean Energy Management (BOEM) wind lease area.