GLIDER-OBSERVED SEASONAL AND SPATIAL DISTRIBUTIONS OF ZOOPLANKTON IN THE MID-ATLANTIC BIGHT

By

NICHOLAS S. OCCHIOGROSSO

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ABSTRACT OF THE THESIS

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Thesis Directors:

Grace Saba and Josh Kohut

As secondary producers, zooplankton are essential in the energy flow within marine ecosystems, acting as a trophic link between photosynthetic primary producers and predatory organisms, such as migratory fishes and marine mammals, including the critically endangered North Atlantic right whale (*Eubalaena glacialis*). However, the distribution of zooplankton, and drivers of those distributions, are not well studied in the highly productive Mid-Atlantic Bight coastal shelf ecosystem. This region exhibits strong variability that occurs over multiple time scales, from seasons to years to decades, and is located within the broader U.S. Northeast shelf that is rapidly warming and is susceptible to ongoing ocean acidification. Furthermore, offshore wind construction is scheduled to begin in New Jersey coastal shelf waters within the next few years, and potential impacts of offshore wind construction and operation on the oceanography and local ecology are currently unknown. Therefore, establishing a baseline dataset of oceanographic and ecological parameters is crucial to inform not only future studies focused on determining trends in zooplankton distribution but also the offshore wind planning process toward responsible development. Autonomous underwater vehicles (AUVs) called gliders can reliably collect high-resolution data over a wider depth range and often at a lower cost compared to vessel-based sampling. Active acoustic approaches using multi-frequency echosounders make it possible for AUVs to observe marine pelagic species' distributions more directly, and when paired with other oceanographic and ecological sensors, provide insight into how seasonal changes in ocean conditions overlap with the distribution of fish, marine mammals, and their prey. In this study, gliders were used to collect a suite of oceanographic and ecological variables covering three distinct seasons (Spring 2023, Fall 2023, Winter

2024). Variables measured and included in this analysis were temperature, salinity, depth, chlorophyll-a, pH, colored dissolved organic matter, and zooplankton abundance and biomass.

From integrated glider-based acoustic and discrete tow data, small copepods were the most abundant taxa, while large copepods dominated total zooplankton biomass for all seasons. Zooplankton abundance and biomass were lowest in the spring across all depth bins. In fall, the highest depth-integrated biomass and abundance values were in the mid- and outer-shelf waters, while in the spring and winter seasons, highest values were nearshore. Average ocean temperatures were observed to be highest in the fall and lowest in the winter, while salinity was the highest in the outer-shelf waters during the spring. No statistically significant correlations were found between zooplankton abundance and biomass values and measured oceanographic variables. Future research should be directed to determine other potential physical or biological drivers of zooplankton distributions that were outside the scope of this study. Data produced here will assist in developing predictive models that could inform “hot spots” of prey distributions and respective predator feeding locations and provide a baseline from which to analyze potential impacts of offshore wind on zooplankton distributions.

Acknowledgments

I would like to thank everyone at the Rutgers University Center for Ocean Observing Leadership (RUCOOL) for allowing me the opportunity to observe and work with live data from the Slocum Gliders. I especially thank and acknowledge my thesis advisors, notably Dr. Grace Saba as well as Dr. Josh Kohut for their support and encouragement throughout the development of my thesis. I also want to thank Delphine Mossman who played a crucial role in the data management and processing of the raw echosounder data. I also thank software technician Lori Garzio for the mixed layer depth code. Finally, I thank Dr. Alex Lopez for his additional review and overall guidance throughout the Masters of Operational Oceanography program.

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Introduction

Pelagic zooplankton are considered one of the most critically important organisms in the flow of energy across nearly every marine ecosystem, and as a primary consumer, contribute directly to the productivity of pelagic fish populations (Debertin et al. 2018) and the presence of baleen whales, including the critically endangered North Atlantic right whale (NARW; *Eubalaena glacialis*) (Nøttestad et al. 2015). Zooplankton are also notoriously challenging to quantify using traditional vessel-based methods due to their patchy distribution, and the mechanisms in which large spatial aggregations occur remain poorly understood in marine ecology (Basedow et al. 2019). This "patchiness" in spatio-temporal distribution impedes the capability of research into behavioral and physical drivers in which these aggregations occur, and in turn, limits the ability to accurately model and predict how they may be affected by changes in their environment (Franks 1992). These dynamics are of particular interest in regions that exhibit high spatio-temporal variability of temperature and salinity, including the Mid-Atlantic Bight (MAB) coastal shelf ecosystem (Castelao et al. 2008, Mountain 2003).

Offshore wind (OSW) development in MAB coastal shelf waters is set to begin during the next few years. Both New York and New Jersey have established collective targets of 20,000 MW of energy by 2050 and 11,000 MW by 2040 respectively (Musial et al. 2023). As of 2023, the existing leases issued by the Bureau of Ocean Energy Management (BOEM) near both states cover approximately 911,284 acres (3,688 km^2) of federal waters (BOEM 2023). Several studies describing potential environmental changes from OSW infrastructure and development discuss whether changes in hydrodynamic patterns around wind farm areas may alter local currents, circulation patterns, or mixing dynamics (Methratta et al. 2020, Miles et al. 2021, Christiansen et al. 2023), and if these potential physical dynamics might affect planktonic communities (i.e., injecting higher concentrations of nutrients into the upper water column that would promote phytoplankton productivity). One study conducted at the Longyuan Offshore Wind Farm in Rudong, China, pointed to water temperature, dissolved oxygen, pH, and suspended solids as the most important factors affecting the local zooplankton community, with a notable increase in suspended solids concentration when comparing the ocean state before and after construction (Wang et al. 2018).

To conduct an effective oceanographic and ecological baseline monitoring program, it is crucial to consider a specific region's physical conditions and oceanographic variability alongside ecological metrics, including zooplankton distribution. Faculty at Rutgers University recently established an autonomous-based ‘ecoglider’ oceanographic and ecological monitoring program over the New Jersey coastal shelf that is providing a seasonally-resolved 3D view of MAB ocean and ecological conditions that includes physical and chemical variables, and biological variables spanning multiple trophic levels – from phytoplankton and zooplankton to pelagic fish and marine mammals. Autonomous underwater vehicles (AUVs), including gliders, have demonstrated an ability to reliably collect high-resolution data throughout the water column and for longer intervals compared to traditional vessel-based sampling (Schofield et al. 2007). Integrated multi-frequency echosounders allow AUVs to observe pelagic species more directly using active acoustic detection (Chave et al. 2018, Reiss et al. 2021). The main goal of this thesis is to conduct an analysis on the ecoglider data to determine spatio-temporal variability in the distributions of zooplankton abundance and biomass within the MAB. The outcomes of this study will inform not only future studies focused on seasonal, interannual, and long-term trends in zooplankton but also will provide a baseline for future studies that investigate potential impacts of OSW on plankton communities.

Methods

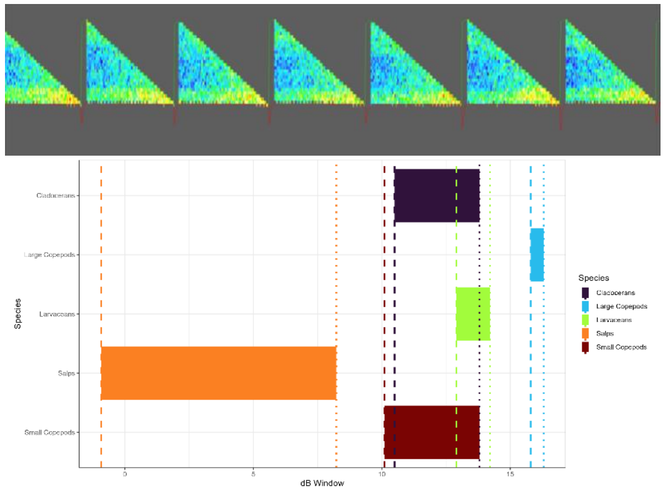

Figure 1. Echogram image of AZFP backscatter on March 1, 2024, as seen on Echoview. Note the near-bottom layer of copepods in yellow (top). The dB windows with all five taxa represented for Fall 2023 (bottom).

A Rutgers University G3 Slocum electric glider (RU39) was equipped with a multi-frequency echosounder unit, the Acoustic Zooplankton Fish Profiler (AZFP; 120, 200, 455, 769 kHz) manufactured by ASL Environmental Sciences Inc. The glider was equipped with a pumped CTD to determine water depth, temperature, salinity, and density, a deep ISFET-based pH sensor, and a BB2FL ECO optics puck measuring chlorophyll-a fluorescence, colored dissolved organic matter (CDOM), and backscatter. The glider conducted three missions, running zig-zags nearshore-to-offshore along the New Jersey coast during April-May 2023 (Spring), November-December 2023 (Fall), and February-March 2024 (Winter) (Fig. A1). The glider was flown alongside a second glider (RU40) that was outfitted with a CTD, an optics puck, an Aanderaa optode for measuring dissolved oxygen, and a DMON passive acoustic sensor for marine mammal detection. These seasons were chosen to coincide with months during the migration of the NARW through the MAB area (November through April). The AZFP measured raw acoustic backscatter signals (Fig. 1, top), which were then processed using a MATLAB script to identify backscatter signals (D. Mossman, personal communication).

Data was processed in Echoview to remove background noise, impulse noise, and noise below a line one meter above the seafloor. In addition, data within a certain distance from the transducer was removed to get rid of near-field scattering (Reiss et al. 2021, Watkins and Brierley 2002). The following formula was used to calculate the near-field boundary, where *a* is the linear distance across the transducer face:

$$R_b = a^2/\lambda$$

Because the transition from near- to far-field conditions occurs gradually around R_b, it is best practice to only analyze acoustic data at a range $2R_b$ of the transducer based on the highest frequency being used (Simmonds and MacLennan 2005). For this data, the value of $2R_b$ was two meters. To identify major taxon/size groups of the dominant zooplankton scatterers, frequency differencing between adjacent frequencies was performed by subtracting the higher frequency ping values from the lower frequency ping values in decibel space, then using these differences in target strengths to locate observed data of the higher frequency with a difference in scattering consistent with a certain target group or species using calculated decibel windows (e.g., ~ 9 and 14 dB for large copepods; Fig. 1, bottom) (Simmonds and MacLennan 2005). Zooplankton abundance in individuals/m^3 for each taxa *Z* was then calculated with the following formula, using data from only the 455 kHz frequency:

$$[Z] = 10^{\frac{S_{v(Z)} - TS_Z}{10}}$$

Zooplankton biomass estimates were then obtained using the product of abundance and the individual dry weight (IDW) of a single zooplankton obtained from literature review. Zooplankton species, abundance, and biomass were further corroborated using discrete vessel-based tow samples conducted at all glider deployments and recoveries.

For the sake of simplifying and maintaining a consistent dataset across all three seasons, only datapoints associated with copepods were analyzed. Prior surveys describe copepods as the most dominant and diverse component within zooplankton assemblages and, therefore, particularly useful to examine how changes in zooplankton assemblage structure reflect the underlying oceanography (Friedland et al. 2015, McCosker et al. 2020). In late 2023, the model used in the acoustic-to-biomass calculations was modified to better reflect the composition of tow samples during both the deployment of the glider in November and its recovery in December. This model was subsequently used to analyze data across all seasons. The datapoints analyzed within all three season datasets (and their associated taxa) are thus labeled "Large Copepod" (primarily *Calanus finmarchicus*), or "Small Copepod" (primarily *Paracalanus spp., Pseudocalanus spp., Centropages spp.,* or any combination thereof).

To determine spatial distributions of zooplankton over the MAB shelf, both abundance and biomass data were further divided into three distinct depth bins, defined by a specified depth range that correspond to the glider's position in the MAB (nearshore, 0-40 m; mid-shelf, 40-70 m; and outer-shelf, >70 m). The depth bins are used as the basis for conducting various statistical tests using the SciPy library for Python. To measure the difference in zooplankton abundance and biomass between different depth bins within each season, a Welch's ANOVA test was performed using the mean values of abundance and biomass within each consolidated depth bin. A Games-Howell post-hoc test ($\alpha < 0.05$) was used to compare means. For examining differences in the zooplankton abundance and biomass means between seasons for each depth bin, a test of normality, Welch's ANOVA test, and a Games-Howell post-hoc test ($\alpha < 0.05$) were used.

Results

Zooplankton spatial distributions along the glider transects were relatively homogenous in spring and winter, but in the fall, zooplankton spatial distributions were more concentrated in deeper isobaths over the mid- to outer-shelf (Fig. 2). Zooplankton were present in the water column both within and outside OSW wind lease areas, and their distributions within lease areas was most prevalent during winter (pink = inside wind lease areas, Fig. 2). From both the deployment and recovery net tow samples, small copepods were typically the most abundant zooplankton taxa in all seasons based on concentration in individuals m^{-3}, representing 39.8%, 66.3%, and 70.6% of total individual zooplankton in spring, fall, and winter, respectively. By contrast, large copepods were the dominant taxa in terms of biomass in spring, fall and winter, representing 98.1%, 93.1%, and 88.3% of the total copepod biomass and 97.7%, 92.4%, and 87.1% of the total zooplankton biomass, respectively. Patches of dense depth-integrated zooplankton biomass and abundance were also observed along the glider track, with the largest patches occurring in mid- to outer-shelf waters in all three seasons (Fig. 3).

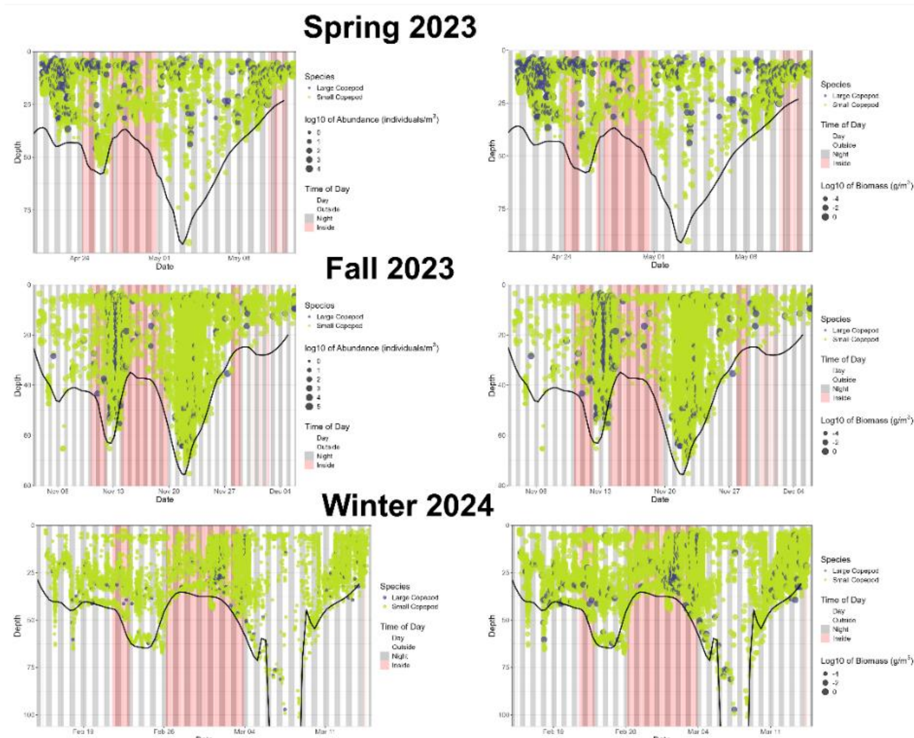

Figure 2. Distribution of abundance (left panels) and biomass (right panels) of small and large copepods in relation to ocean depth and time during the spring, fall, and winter glider missions. Datapoints may not necessarily correlate with bathymetry (black line). Areas in pink represent time spent inside offshore wind lease areas.

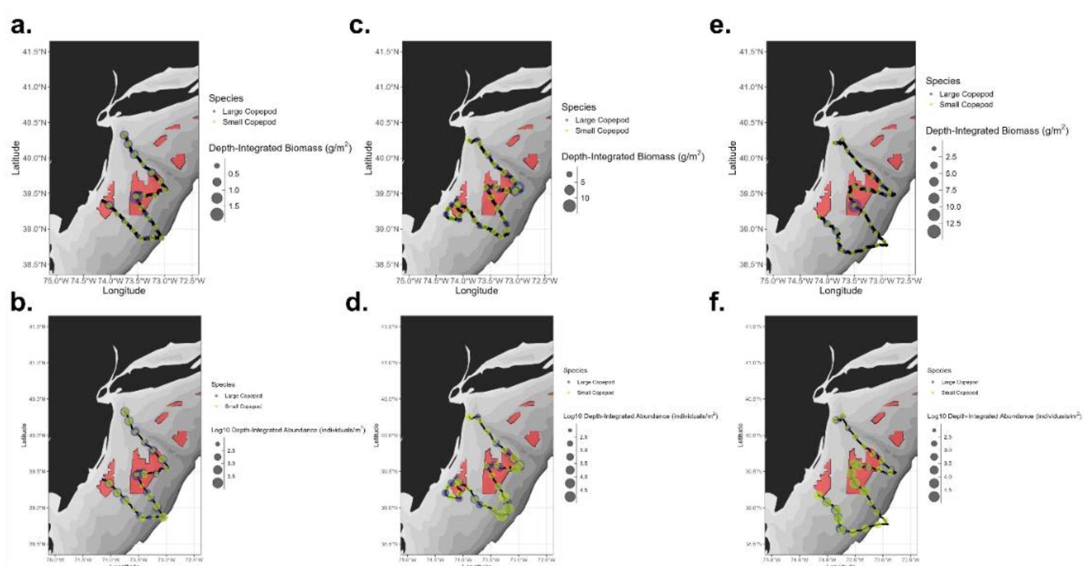

Figure 3. Depth-integrated biomass (a, c, e) and abundance (b, d, f) values over the three seasonal glider deployments (left panels: Spring 2023; middle panels: Fall 2023; right panels: Winter 2024). Note salmon-colored areas represent offshore wind lease areas. Purple bubbles represent large copepods, and green bubbles represent small copepods.

The raw zooplankton biomass and abundance values were highest in mid-shelf waters in the fall (Welch's ANOVA test, $p = 4.139610\times10^{-29}$ for biomass and $p = 9.896922\times10^{-287}$ for abundance), while depth-integrated values were highest in mid- and outer-shelf waters during the fall (Log_{10} Abundance; $f = 558.563449$, $p = 1.526346\times10^{-185}$ in mid-shelf and $f = 147.327423$, $p = 1.767826\times10^{-56}$ for outer shelf) (Fig. 4). Both Spring and Winter seasons exhibited the most similarity between zooplankton biomass and abundance values (Games-Howell post-hoc analysis, $p = 0.405959$ for biomass and $p = 3.954477\times10^{-1}$ for abundance). Biomass and abundance were also highest in nearshore waters compared to mid- and outer-shelf, even though the depth-integrated values were lowest in the Spring compared to Fall and Winter (ANOVA test; $f = 50.158499$, $p = 1.106026\times10^{-20}$) (Fig. 4). Using an ANOVA test for the mean values of different depth bins per season, the ratio of variances for both zooplankton biomass and abundance was highest in the Fall ($f = 39.605022$ for biomass and $f = 782.382065$ for abundance).

Oceanographic variables measured by the glider (temperature, salinity, density, chlorophyll-a, pH, CDOM are shown in contour plots along the glider track (Fig A2). As was done for the zooplankton abundance and biomass variables, oceanographic variables were also analyzed by depth bins and represented as box plots (Fig. 4, Fig. A3). Average ocean temperature values were highest in the fall season across all three depth bins (Games-Howell test, $\bar{x} = 14.0217$) whereas the winter season had the lowest average ocean temperature values (Games-Howell test, $\bar{x} = 7.1120$) (Fig. 4, Fig. A3). Although average salinity was homogeneous across all three seasons, there was a notable trend where salinity increased from nearshore to the outer shelf (Fig. 4, Fig. A3). This was especially noticeable in the spring, where the highest average salinity value was observed in outer-shelf waters. By contrast, the lowest salinity value was observed nearshore during the fall. Across all seasons, average chlorophyll-a was highest in the nearshore ($\bar{x} = 1.9058$), and lowest in the outer-shelf (Games-Howell test, $\bar{x} = 1.2409$) (Fig. A3). No statistically significant correlations were found between zooplankton abundance and biomass values and measured oceanographic variables.

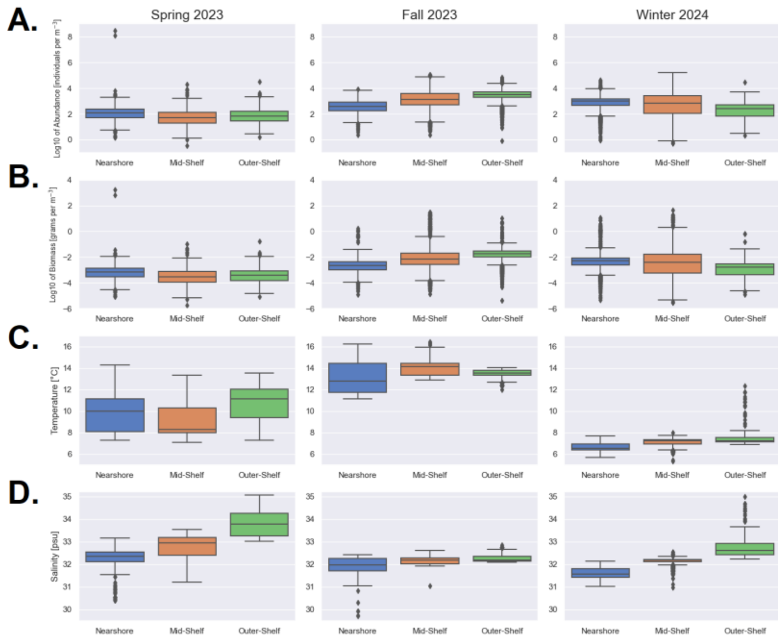

Figure 4. Comparisons of Log10 abundance, (A.) Log10 biomass, (B.) water temperature, (C.) and salinity (D.) during the three seasonal glider deployments (from left to right: Spring 2023, Fall 2023, Winter 2024) at three different depth bins (Nearshore = 0-40m; Mid-Shelf = 40-70m; Outer Shelf = >70 m). Box represent the 25th and 75th percentiles, line within the boxes represent the medians, whiskers represent the full range of the data. Black dots outside whiskers represent outliers.

Discussion

Zooplankton distribution in New Jersey coastal shelf waters exhibited high spatio-temporal variability, where highest observed abundance and biomass of zooplankton occurred in mid- to outer-shelf waters in the fall, and for both spring and winter, relatively higher zooplankton abundance and biomass occurred in nearshore waters. These observations align with prior studies, where species of copepods like *Centropages typicus* appeared to decline in relative abundance in tandem with warmer temperatures during the summer months. At the same time, the highest abundances for *C. typicus* were observed in the shallower inshore shelf regions rather than in deeper waters (Durbin & Kane 2007). Although analyses conducted in the present study determined that no significant correlations occurred between the depth-integrated biomass and abundance values with any of the oceanographic parameters, there could be other parameters controlling observed zooplankton distributions. This includes changes in phytoplankton distribution and spring blooms, as Flagg et al. (1994) described through the examination of spring bloom data from two successive springs (1988-1989), which showed a relationship between primary and secondary production and other features including horizontal or vertical gradients or fronts, season-specific (nearshore v. offshore) and species-specific favorable habitats (Flagg et al. 1994). Correlations of zooplankton biomass and abundance using these metrics was beyond the scope of this study but should be a focus of future work.

The glider-based data demonstrate the potential for which AUV-based echosounder surveys can provide high-resolution zooplankton measurements throughout the water column over time and space. This approach could therefore be applied to augment vessel-based surveys and provide more biomass and abundance data compared to surveys only collecting zooplankton information via net tows at discrete, individual stations with low spatial resolution (Powell & Ohman 2012). Another benefit of using glider platforms is the co-measurement of other oceanographic variables, that over time and with more statistical power, may reveal relationships that were not identified in the present study. The primary limitation with using AUVs in sampling populations of pelagic zooplankton is that the data, as is the case with all acoustically derived zooplankton data, does not provide species-specific information compared to alternative methods such as discrete net tows or Continuous Plankton Recorder (CPR) surveys (Melle et al. 2014). Therefore, conducting net tows near the glider to collect discrete zooplankton data for size and species composition, as was done in the present study, is imperative to ensure the acoustic models are accurately representing the dominant zooplankton scatterers.

The results of both the statistical analysis and spatial binning demonstrates the challenge of mapping the overlap between physical ocean characteristics and zooplankton patches that can regularly fluctuate due to changes in grazing, growth, and transport of water masses via major ocean currents. The results also demonstrate the difficulty of collecting zooplankton data over a large spatio-temporal scale, which is needed to relate observed data to key regional and global ocean processes (Ruckdeschel et al. 2020). Considering the ability of these ecogliders to provide the high-resolution measurements of zooplankton on the MAB shelf, some of these challenges can be overcome, allowing for a more standardized set of data for use in statistical analysis.

Conclusion

The data presented here could assist in identifying foraging hotspots of predators, including the NARW, and could identify where such locations are in proximity to OSW development areas. Identifying the availability of NARW prey in the MAB is beneficial for conservation efforts, as it can also be used to predict shifts in the range of other whale species and predatory organisms, more specifically through the development of a predictive model that could identify overlap of prey hotspots and the feeding locations of predators (Pendleton et al. 2020). The results of this study also connect with the broader long-term goal of examining the potential impacts that OSW development can have on biomass, distribution, connectivity, and other physical and biological variables. These specific impacts will vary depending on the location, scale, and design of wind farms, in addition to changes in water circulation patterns, turbulence, and mixing dynamics caused by wind farm infrastructure, which could also influence nutrient availability and phytoplankton productivity (Messié & Chavez 2017).

Glider deployments could also be useful in continued research focused on changes in zooplankton population and distribution due to climate change, especially as it relates to changes in habitat (Ruckdeschel et al. 2020). Climate change is expected to have a substantial impact on the distribution, species and/or size composition, migration behaviors, and aggregation of zooplankton (Debertin et al. 2018), in addition to reduction in body size, egg production and overall population density in the case of *C. finmarchicus*, a primary food source for the NARW (Pendleton et al. 2020, Melle et al. 2014). This will be due to rising sea surface temperatures limiting their potential distribution within their ideal temperature range and forcing migration to northern latitudes, thereby limiting overall space and access to resources. This would have negative impacts on the marine food web, affecting both commercial fisheries and even NARW survival (Beaugrand et al. 2014, Grieve et al. 2017). Because the effects of climate change may vary depending on their sensitivity to environmental changes and fluctuating oceanographic conditions, ongoing research and monitoring will be required to better understand and predict its effect on zooplankton population dynamics.

Appendix.

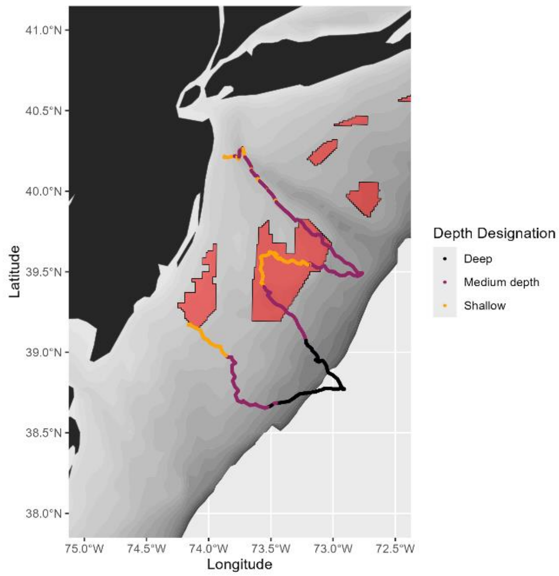

Figure A1. Exemplary glider track for the glider run of Winter 2024. Note the varying depth along the glider path (See "Depth Designation" legend).

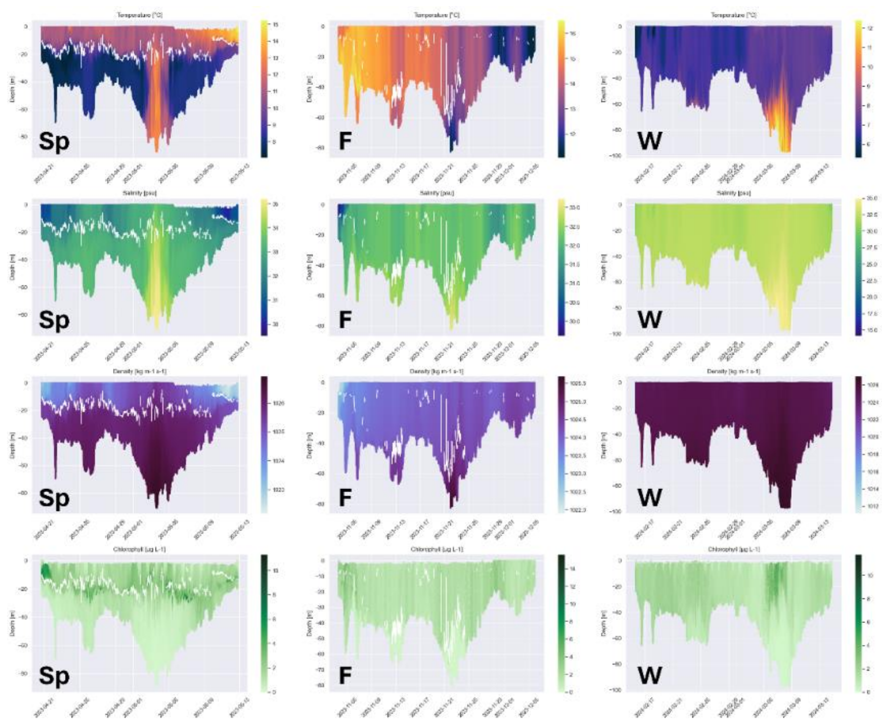

Figure A2. Contour plots of temperature, salinity, density, and chlorophyll-a from three seasonal glider deployments (Sp = spring 2023, F = fall 2023, W = winter 2024). Mixed layer depth (MLD) for each profile is plotted in white. Winter has no significant mixed layer.

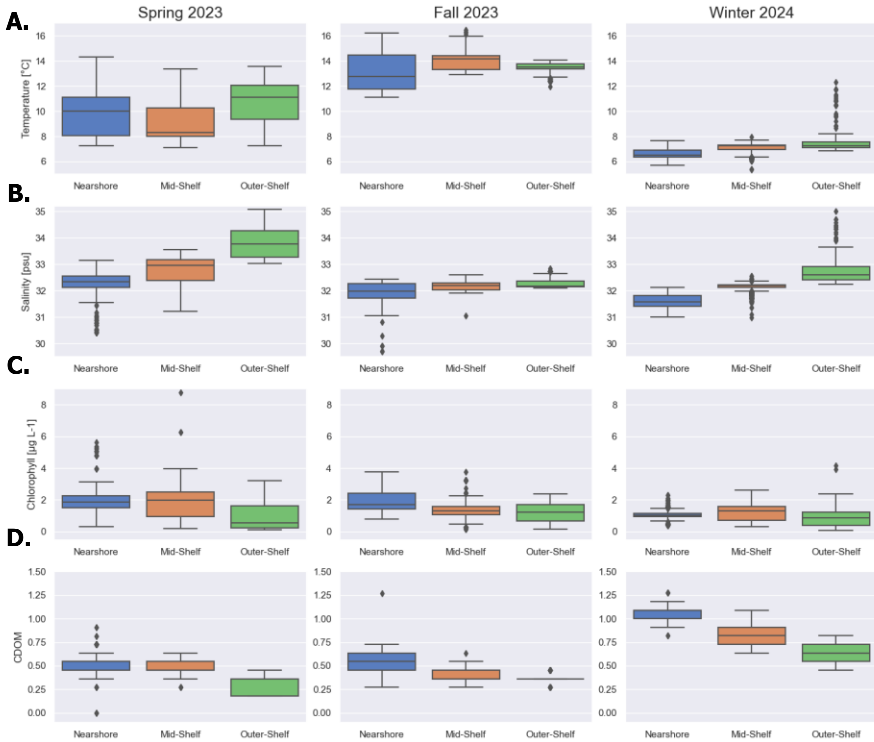

Figure A3. Box-plot comparisons of various ocean conditions, temperature (A), salinity (B), chlorophyll-a (C), and CDOM (D) during the three seasonal glider deployments (from left to right: Spring 2023, Fall 2023, Winter 2024) at three different depth bins (Nearshore = 0-40m; Mid-Shelf = 40-70m; Outer Shelf = >70 m).

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