

TEMPORAL AND SPATIAL VARIABILITY IN  
EUPHAUSIID ABUNDANCE, BIOMASS, AND  
SPECIES COMPOSITION AT THE NORTHWEST  
ATLANTIC SHELF BREAK AND ITS CANYONS

A Thesis

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## ABSTRACT

Submarine canyons contain dense aggregations of euphausiids and are ecologically important for many marine predators. At the Northwest Atlantic shelf break, euphausiids play a critical role, supporting diets for top predators and many commercially important species of fish, yet their distribution is poorly understood. The species composition of euphausiid aggregations was examined relative to abrupt changes in topography and variations in environmental conditions along the Northwest Atlantic shelf break. Net sampling was conducted on seven occasions from 2004-2013 within three canyons and two non-canyon sites along the New England shelf break. The objective was to determine if euphausiid biomass and abundance are greater within canyons than at non-canyon sites along the shelf break, and investigate temporal variation in the aggregation structure over five years of repeat sampling within a single canyon. Additionally, we investigated the impact of a warm-core ring on one canyon region during its presence from June to August 2010. Twenty species were identified, of which 6 were cold-water species and 14 were warm-water species. Cold-water species dominated all samples, but only *Meganyctiphanes norvegica* was significantly more abundant at shallow sites than deep sites. Species distribution and abundance was significantly related to bottom depth, with no significant difference between canyon and non-canyon sites. Interannual sampling showed high variability between years. There appeared to be a relationship between biomass and temperature, though an increased sample size is needed to improve the strength of statistical testing.

## BIOGRAPHICAL SKETCH

Robert Levine received his Bachelor of Science degree in Interdisciplinary Studies in Agricultural and Life Sciences, with a minor in Science of Earth Systems, from Cornell University in May 2012. As an undergraduate, he participated in the Cornell Earth and Environmental Science Field Program in Hawaii, where he first became interested in oceanography. Following his semester in Hawaii, he attended the Marine Bioacoustics course at the Friday Harbor Laboratories before finishing his undergraduate coursework. He completed his undergraduate degree while a guest student in the Biology Department at the Woods Hole Oceanographic Institution where he participated in various projects related to zooplankton ecology, eventually using the data he worked with for his graduate research. As a graduate student, Robert has assisted in teaching undergraduate introductory courses, as well as graduate workshops in satellite oceanography and marine bioacoustics.

This document is dedicated to my family and friends who have supported me throughout my graduate work.

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CHAPTER 1  
TEMPORAL AND SPATIAL VARIABILITY IN EUPHAUSIID ABUNDANCE,  
BIOMASS, AND SPECIES COMPOSITION AT THE NORTHWEST  
ATLANTIC SHELF BREAK AND ITS CANYONS

## 1.1 Background

### 1.1.1 Continental Shelf Breaks

Continental shelf-break regions, the area where the continental shelf abruptly changes to the continental slope, are ecologically important areas for marine organisms, particularly marine predators, throughout the world, and serve as key regions for commercial fisheries. The presence of zooplankton at the edge of the continental shelf is believed to attract planktivorous fish, including commercially important species to the area [59]. Large euphausiid aggregations have been reported in various shelf-break regions, including aggregations along Bransfield Strait [30], the Western Antarctic Peninsula shelf [27], Baja California [40], the Gulf of St. Lawrence [44], and along Vancouver Island [45].

Many shelf breaks are characterized by steep-walled canyons which cut into the shelf break. These submarine canyons which bisect the steep slope of the shelf break contain concentrated aggregations of zooplankton in many of these regions [11, 20, 27]. Canyons have been observed with higher abundances of top

marine predators [11, 18]. The presence of top predators appears to be associated with zooplankton aggregations, with higher densities of fish [9] and whales [49] that show preferences to feed within canyons.

Occurrences of upwelling in shelf break canyons are due to the interaction between a coastal current and the abrupt topography [31], and this vertical flow coupled with vertical swimming behaviors may be an important mechanism for the aggregation of zooplankton at shelf breaks [17].

### **1.1.2 Northwest Atlantic**

The Gulf Stream creates a narrow oceanographic barrier in the Northwest Atlantic, resulting in biological variability between the cold-water organisms north of the Gulf Stream, and the warm-water species present in the Sargasso Sea to the south [21]. While the species distribution is not strictly confined by region, species ranging from Arctic boreal waters to the Slope Water, the region between the continental shelf and the Gulf Stream [23], and are typically restricted to waters north of the Gulf Stream. Along the New England shelf break, abrupt topography creates an interaction of distinctive water masses and the temporary frontal features along the Gulf Stream [10], and shelf break zooplankton may be influenced by the changing water conditions. Warm-core rings (WCR) form as a northerly meander separates from the Gulf Stream, resulting in cores with water of Sargasso Sea origin. The rings occur in the Slope Water and result in increased productivity and

altered environmental conditions through exchange of water [13, 38, 55]. WCRs have been found to play a role in changing the composition of zooplankton at the shelf break [12, 13, 22, 57], transporting organisms from the waters of the Sargasso Sea which had become contained within the meander of the Gulf Stream.

The study region examined here is the continental shelf-break of the northern Mid-Atlantic Bight south of New England, an important region for commercial fisheries and feeding area for top predators. Odontocetes have been frequently observed along the shelf break [49], and some are known to reside along the shelf break and continental slope for most of the year [50]. Along the New England shelf break, dense aggregations of euphausiids have been observed within canyons [20, 24]. Relative to other shelf-break regions, the canyons south of New England have received little attention. Previous studies of zooplankton community structure have been few [20, 26], primarily reporting on the structure inside of WCRs and the species present in the Slope Water [12, 13, 57], with little investigation of the communities directly at the shelf break. Euphausiids are a key part of the shelf-break ecosystem, contributing to 5-10% of the total zooplankton biomass [32]. They may be important in creating a favorable habitat for the multi-species assemblages of predators in the New England shelf break and Slope Water region, and previous studies indicate the need for a more thorough understanding of the bio-physical processes of the area to determine their availability as a food resource to predators [19, 20].

### **1.1.3 Objectives**

In this study, we characterize the spatial variability in euphausiid populations along the New England shelf break to better understand the role of euphausiids and their relationship to the region's ecosystem. This included testing the hypotheses that euphausiid biomass and abundance is greater within the canyons than outside of the canyons, and that there is significant variability in the presence of euphausiids within the canyons themselves, with euphausiid aggregations expected to be greater within the shallow canyon heads. We also investigated the impact of a warm-core ring at the shelf break on the euphausiid population structure as it intruded into the region. To determine temporal variability of the euphausiids at the shelf break, we used a multi-year time series to identify changes in the euphausiid populations within a single canyon.

## **1.2 Methods**

### **1.2.1 Sample Collection**

Samples were collected aboard 7 research cruises to the continental shelf break south of New England between 2004 and 2013 (Table 1.1, Figure 1.1). Temporal sampling includes a five-year time series of samples collected in Atlantis Canyon, and spatial variability was investigated using samples from two canyons and ad-

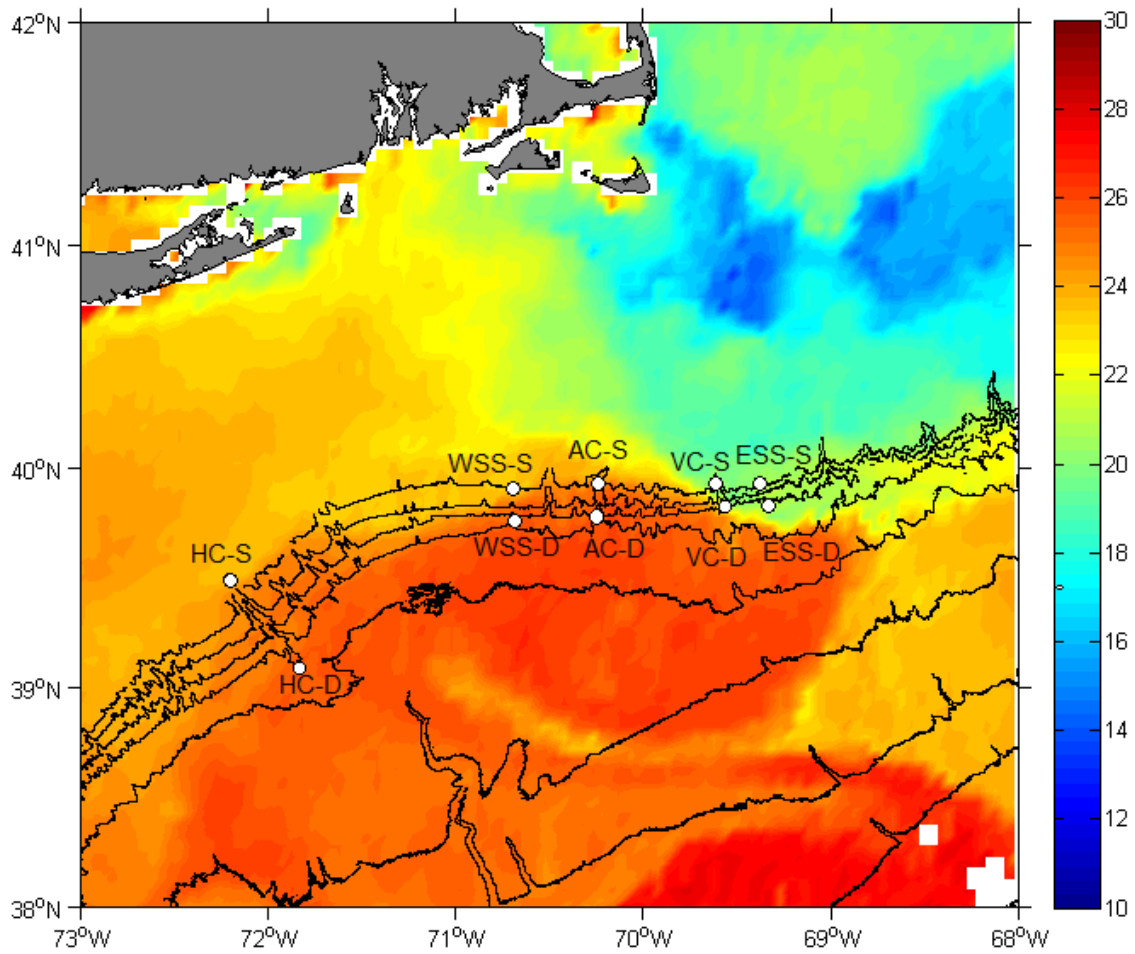


Figure 1.1: Study region, showing the continental shelf break region south of New England in the northern portion of the Mid-Atlantic Bight. Average sea surface temperature ( $^{\circ}\text{C}$ ) during the duration of sampling in early July of 2010 is shown overlaying bottom contours of the New England Shelf Break region, with the location of net tow sites indicated. Abbreviations for sites, HC: Hudson Canyon, VC: Veatch Canyon, ESS: Eastern Slope Site (non-canyon), WSS: Western Slope Site (non-canyon), AC: Atlantis Canyon, Alv: Alvin Canyon, S: Shallow, D: Deep. Sea surface data courtesy of NASA NESDIS, 100-m resolution bottom depth courtesy of USGS [3].



jacent non-canyon areas.

### ***R/V Connecticut***

Sample collection was completed from 7 to 16 July 2010 aboard the R/V *Connecticut*. The survey design included sampling at shallow and deep locations within two canyons along the New England shelf break, and corresponding shallow and deep sampling of two adjacent non-canyon sites for comparison. Zooplankton were collected within Veatch Canyon and at a corresponding non-canyon site to the east, and within Atlantis Canyon and a corresponding non-canyon site to the west. At the time of the cruise, a warm-core ring that developed from a northern meander of the Gulf Stream was impacting sea surface temperatures and much of the water column at the Atlantis Canyon and at the western non-canyon sites (Figure 1). Sampling was done using a nine-net Multiple Opening/Closing Net and Environmental Sensing System (MOCNESS) [57] with a mouth area of 1-m<sup>2</sup> and 335- $\mu$ m nets, equipped with electronic sensors for pressure, temperature, conductivity, and volume filtered. The MOCNESS allows for depth stratified sampling of eight depth bins, though depth ranges varied between sites due to sampling depth. Narrowband acoustics were collected during net sampling using a surface-towed body with four single-frequency transducers operating at 43, 120, 200, and 420 kHz.

Table 1.1: Tow information for the 20 net tows included in this study. Abbreviations for cruise, CT: R/V *Connecticut*, C: SSV *Corwith Cramer*, EN: R/V *Endeavor*. For tow number, MOC1: 1-m2 MOCNESS, TT: Tucker trawl; for site, HC: Hudson Canyon, VC: Veatch Canyon, ESS: Eastern Slope Site (non-canyon), WSS: Western Slope Site (non-canyon), AC: Atlantis Canyon, S: Shallow, D: Deep, 09-13 represents the yearly sampling completed on the SSV *Corwith Cramer* in Atlantis Canyon.

Site	Cruise	Month	Day	Year	Local Time		Latitude (°N)	Longitude (°W)	Bottom Depth (m)	Sampled Depth (m)
					Hour	Minute				
AC-D	CT2010	7	9	2010	20	21	39.85	70.2	1027	710
AC-S	CT2010	7	10	2010	21	12	39.97	70.14	236	270
VC-S	CT2010	7	11	2010	20	31	39.95	69.95	293	290
VC-D	CT2010	7	13	2010	12	49	39.88	69.54	644	690
ESS-S	CT2010	7	13	2010	20	15	39.94	69.36	283	300
ESS-D	CT2010	7	14	2010	16	27	39.89	69.29	1206	720
WSS-D	CT2010	7	15	2010	7	39	39.81	70.67	1119	720
WSS-S	CT2010	7	15	2010	18	46	39.96	70.69	348	300
09-S	C223A	6	30	2009	22	4	39.98	70.31	382	200
09-D	C223A	7	1	2009	4	30	39.78	70.17	1540	400
10-S	C230A	7	26	2010	1	46	39.95	70.31	457	200
10-D	C230A	7	25	2010	21	15	39.76	70.22	1968	490
11-S	C235A	7	3	2011	5	41	39.96	70.3	485	150
11-D	C235A	7	2	2011	21	58	39.78	70.19	1609	390
12-S	C241A	7	1	2012	23	22	39.96	70.28	490	210
12-D	C241A	7	2	2012	4	10	39.81	70.17	1185	200
13-S	C248B	7	8	2013	3	39	40	70.3	317	170
13-D	C248B	7	9	2013	2	45	39.82	70.16	1083	320
HC-D	EN388	1	11	2004	21	32	39.05	71.88	2365	900
HC-S	EN388	1	12	2004	19	57	39.44	72.19	793	400

### ***SSV Corwith Cramer***

Samples were collected aboard the *SSV Corwith Cramer* as part of an annual 10-day student orientation cruise to the New England shelf break conducted by the Sea Education Association and the MIT-WHOI Joint Program. The timing of the cruises varied between late June and late July (Table 1.1). Each year, zooplankton sampling was completed at two stations within Atlantis Canyon, at the mouth and head, using a three-net 1-m<sup>2</sup> version of a Tucker trawl [47] with 335- $\mu$ m nets and instrumented in most years with a time-depth recorder. Sampling was stratified using two nets, with the first ranging from the maximum sampling depth to approximately 100m, and the second sampling to the surface. Measurements of conductivity, temperature, and pressure were made to the maximum depth of the net sampling near the start and end of the tow. The sampling depth varied yearly, and samples from 2009-2013 were available for analyses.

### ***R/V Endeavor***

Two sites were sampled for zooplankton between 10 and 14 January 2004, one at the mouth of Hudson Canyon and the other at the canyon's head using a 1-m<sup>2</sup> MOCNESS with sensors for pressure, temperature, conductivity, and volume filtered and 335- $\mu$ m mesh nets.

## Net Correction

Due to mechanical failures, poor preservation, or damage during transport, various samples were lost, damaged, or never collected. Acoustic data were used to guide interpolation of biomass and abundance to in order to accommodate for missing samples.

### 1.2.2 Krill Measurements and Identification

All samples were preserved in a 5% or 10% buffered formalin solution immediately after collection. In the laboratory, total zooplankton biovolume [1] was measured for all nets prior to any additional processing. Samples were split using either a Folsom [35] or Motoda splitter [36] and sub-samples were randomly selected for silhouette analyses [12] and animal identification. All euphausiids were separated from the sub-sample and identified to species under a compound light microscope. Individuals were imaged using a 1200 dpi resolution scanner and lengths were measured using WHOI Silhouette DIGITIZER (v1.1) [29] for MATLAB. Lengths were measured from the base of the eye-stalk to the posterior margin of the 6th abdominal segment [33]. Biomass as wet weight in milligrams for all species was calculated using a length to weight relationship for North Atlantic euphausiids ( $\text{Wet Weight} = 0.0138 \times \text{Length}^{3.071}$ ) [12]. Euphausiids of temperate or arctic origin were classified as cold-water species, while those of tropical and subtropical origin were categorized as warm-water species according to previous

work [8, 13, 34].

### 1.2.3 Biomass and Abundance

Using digitized length and weight measurements, abundances and biomasses for the integrated water column were calculated for each tow location. For MOCNESS samples, flow meter measurements were used to estimate animal abundance per unit volume filtered. For samples collected using a Tucker trawl, estimates of volume filtered were made using the length of the tow based on the ship track, and a time-depth recorder when available to determine the additional setback of the net. Due to variable depths of tows and the different depth stratification available from each net system, biomass and abundance were determined as an average for the entire water column sampled in order to compare sites.

Euphausiids, particularly larger species, are known to avoid capture by zooplankton sampling nets [42, 52, 54, 56]. To determine the potential impact of net avoidance on the samples, sensitivity analyses were conducted for a subset of the statistical tests where abundance of *Meganyctiphanes norvegica* and *Nematoscelis megalops* were increased by a factor of 4.5 and 11 for night and day tows, respectively. Biomass values were increased by a factor of 2.2 for night sampling, and 5.5 for during the day. These values were based on the net avoidance observations made by Wiebe et al., (2013) [56], which were made in the Gulf of Maine based on catches dominated by *Meganyctiphanes Norvegica*. Totals corrected for avoid-

ance were used to determine if the adjusted values varied the significance of the analyses relative to the uncorrected data.

#### **1.2.4 Environmental Conditions**

In order to investigate the impact of the environmental variability on the euphausiid population, as well as monitor the presence and influence of the warm-core ring, environmental data were collected in conjunction with all net tows. For sampling conducted on the R/V *Endeavor* and R/V *Connecticut*, salinity and temperature measurements from the instruments mounted on the MOCNESS frame were used in the analysis. Conductivity, temperature, and depth (CTD) measurements corresponding with Tucker Trawl net tows on the SSV *Corwith Cramer* were taken from casts nearest to the starting point of each net tow, as well as immediately after.

The CTD measurements were used to determine the following environmental conditions tested for their relationships to the euphausiid aggregations:

- Mean temperature to 10m      - Depth of the 15 °C isotherm
- Mean temperature to 50m      - Mean salinity to 10m
- Mean temperature to 300m      - Mean salinity to 50m
- Depth of the 10 °C isotherm

Sea surface temperature and surface chlorophyll concentration corresponding to all shipboard sampling events were obtained from the NASA Moderate Res-

olution Imaging Spectroradiometer (MODIS) sensor on the Aqua satellite. Sea-surface temperature, in conjunction with the depth of the 10 °C isotherm, was used to define the edge and center of the WCR in distinct time frames corresponding with net sampling events to define the distance to the nearest edge of the ring, as well as the distance to the center of the ring for each tow. Bottom depth values were interpolated from a 100-m resolution bathymetric data set [3] for each tow site.

### **1.2.5 Statistics**

Statistical analyses were completed in MATLAB and R, utilizing the vegan package [37] to perform species by site analyses and examine the relationship between the environmental variables and the individual species, as well as all species grouped as either cold or warm-water in origin. Abundance in animals per cubic meter and biomass in grams per cubic meter were totaled at two levels: for individual species and for cold or warm-water classes.

Simple and multiple linear regression tools in the native statistical package in R were used to model the response of abundance and biomass to individual and groupings of environmental variables. Multivariate regression models were calculated to determine significance of independent environmental variables and their efficacy as predictors when grouped to address specific questions. The MASS package in R [48] was used to determine the optimal multivariate regression based

on an Akaike information criterion [2], and residuals were checked for normality.

Patterns in species contribution and distribution were investigated with non-metric multidimensional scaling (NMDS) using the Bray-Curtis similarity index [7]. Abundance and biomass were explored as both independent species and temperature groups. Analyses of similarity were used to investigate the relationships between the samples and predetermined factors including integrated temperature to the thermocline, canyon head versus canyon mouth, canyon versus non-canyon, and year.

### **1.3 Results**

Abundance, biomass, and species composition all exhibited strong variability across the spatial scale sampled during surveying in 2010, and similarly, strong variability was evident between the five successive years of temporal sampling in Atlantis Canyon. Cold-water species composed the majority of both the euphausiid abundance and biomass in all sampling events, and of the environmental conditions tested, only a limited set showed a correlation with the amount of organisms at each site.

Overall, the shallow sampling sites tended to have both greater abundance and biomass than the deep sites. The one pair of net samples in which the deep site exhibited greater abundance or biomass than the shallow site occurred in the



2011 Atlantis Canyon samples. Of all the sampling events, the abundance was the greatest at the shallow sampling site of Atlantis Canyon collected in 2013, however the composition was dominated by a small species *Thysanoessa gregaria* and therefore the greatest biomass was found at the shallow sampling site within Veatch Canyon due to the greater presence of *Meganyctiphanes norvegica* and *Nematoscelis megalops* (Table C.4).

### **1.3.1 Horizontal Distribution and Canyon Associations**

At both canyon and non-canyon sites, a similar trend in greater total abundance and total biomass at the shallow sites occurred. In a comparison of all shallow sites to all deep sites, combining both canyon and non-canyon sites, mean euphausiid abundance and biomass were significantly greater at shallow sampling sites than deep sites ( $p = 0.01124$  for abundance,  $p = 0.001946$  for biomass; Figure 1.2). There was similar abundance and greater biomass in the canyons than away from the canyons, driven primarily by high biomass at the Veatch Canyon shallow site. However, there was no significant difference between the total values at both canyons and the non-canyon sites ( $p = 0.591$  for abundance,  $p = 0.5307$  for biomass). No significant variability was found in either abundance or biomass when separately comparing the heads of canyons to the shallow sites along the shelf ( $p = 0.5657$  for abundance,  $p = 0.7029$  for biomass), or the mouths of canyons to the deep sites along the shelf ( $p = 0.2313$  for abundance,  $p = 0.2955$  for biomass).

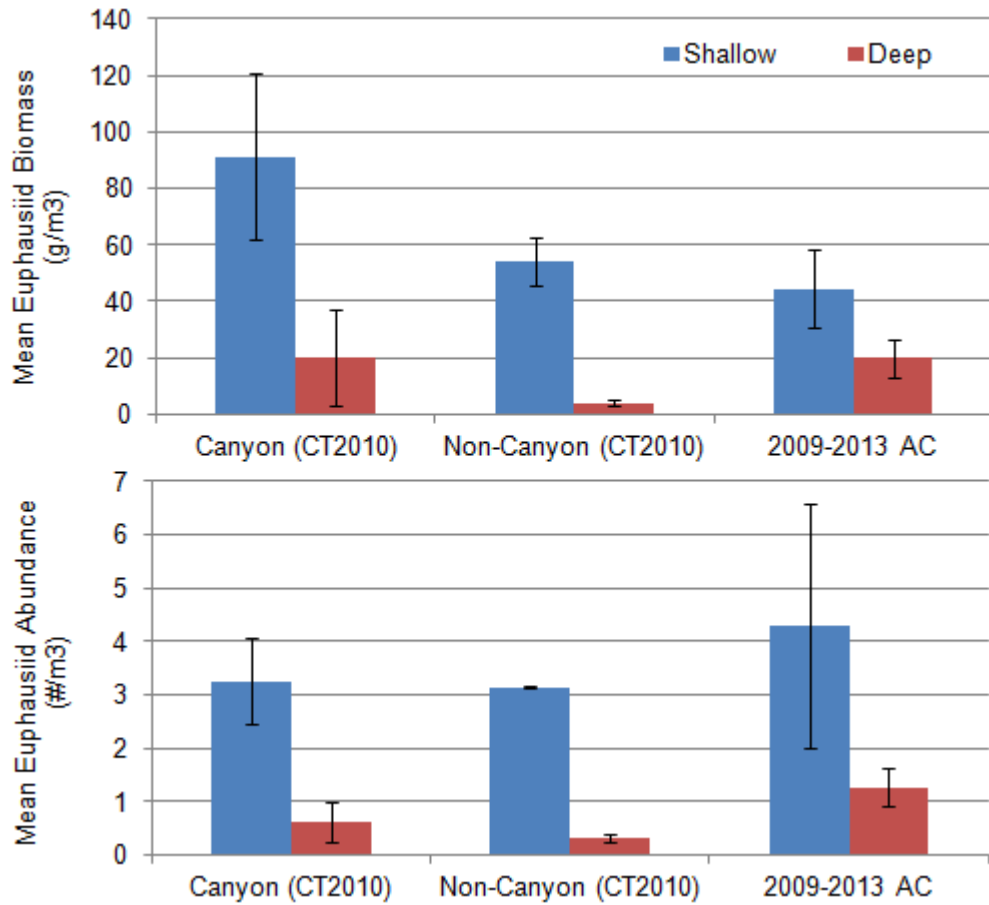


Figure 1.2: Mean euphausiid biomass (top) and abundance (bottom) for shallow and deep samples at canyon and noncanyon sites from the R/V *Connecticut* (CT2010), and the 5-year mean for Atlantis Canyon (2009-2013 AC) based on SSV Corwith Cramer sampling. Bars represent standard error.

Using all values of abundance and biomass for individual species at every site instead of cumulative totals of all euphausiids, biomass was significantly different ( $p = 0.0125$ ) between all shallow and deep sites, while abundance showed little evidence of correlation ( $p = 0.504$ ). Adjusting for potential avoidance, the level

of significance was not affected when looking at the difference between shallow and deep sites for both abundance ( $p = 0.8879$ ) and biomass ( $p = 0.03002$ ) for all species. Although six of the seven most frequently caught species had a greater abundance and biomass at the shallow sites than the deep sites, when examining species separately, *M. norvegica* was the only species to exhibit significantly higher abundance ( $p = 0.02048$ ) and biomass ( $p = 0.00913$ ) at the shallow sites within canyons and along the shelf compared to the deep sites. Between the canyon and non-canyon sites, there was no significant difference in *M. norvegica* abundance ( $p=0.3836$ ) or biomass ( $p=0.5614$ ). The cold-water species were responsible for the majority of the biomass and abundance among all sites and contributed most to the variability (Figure 1.3, Figure 1.4)

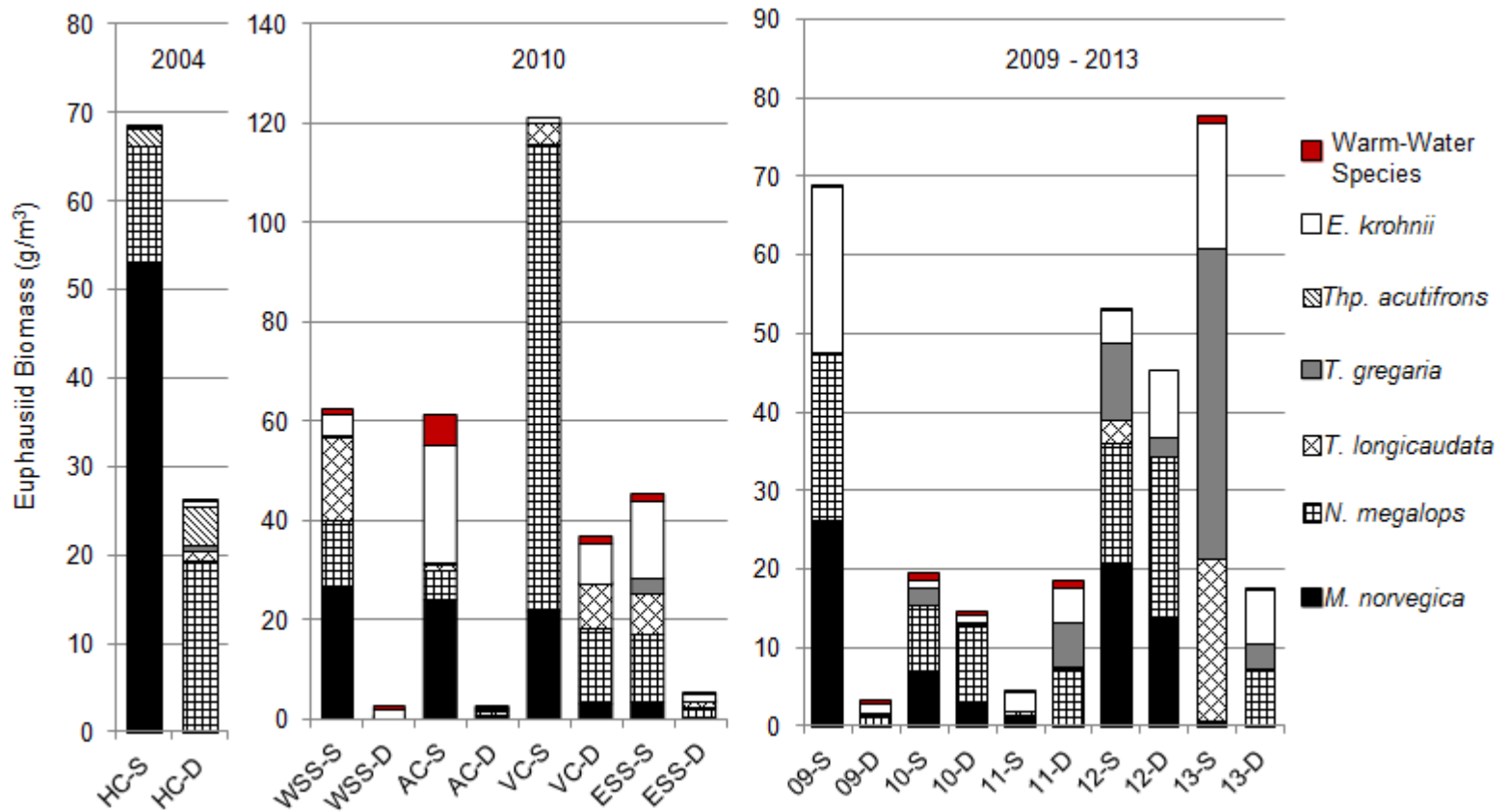


Figure 1.3: Total euphausiid biomass in mg/m<sup>3</sup> at each site (not adjusted for avoidance estimation). The contributions of the six cold-water species are shown, as well as the cumulative contribution of all warm-water species. HC: Hudson Canyon, VC: Veatch Canyon, ESS: Eastern Slope Site (non-canyon), WSS: Western Slope Site (non-canyon), AC: Atlantis Canyon, S: Shallow, D: Deep, 09-13 represents the yearly sampling completed on the SSV Corwith Cramer in Atlantis Canyon.

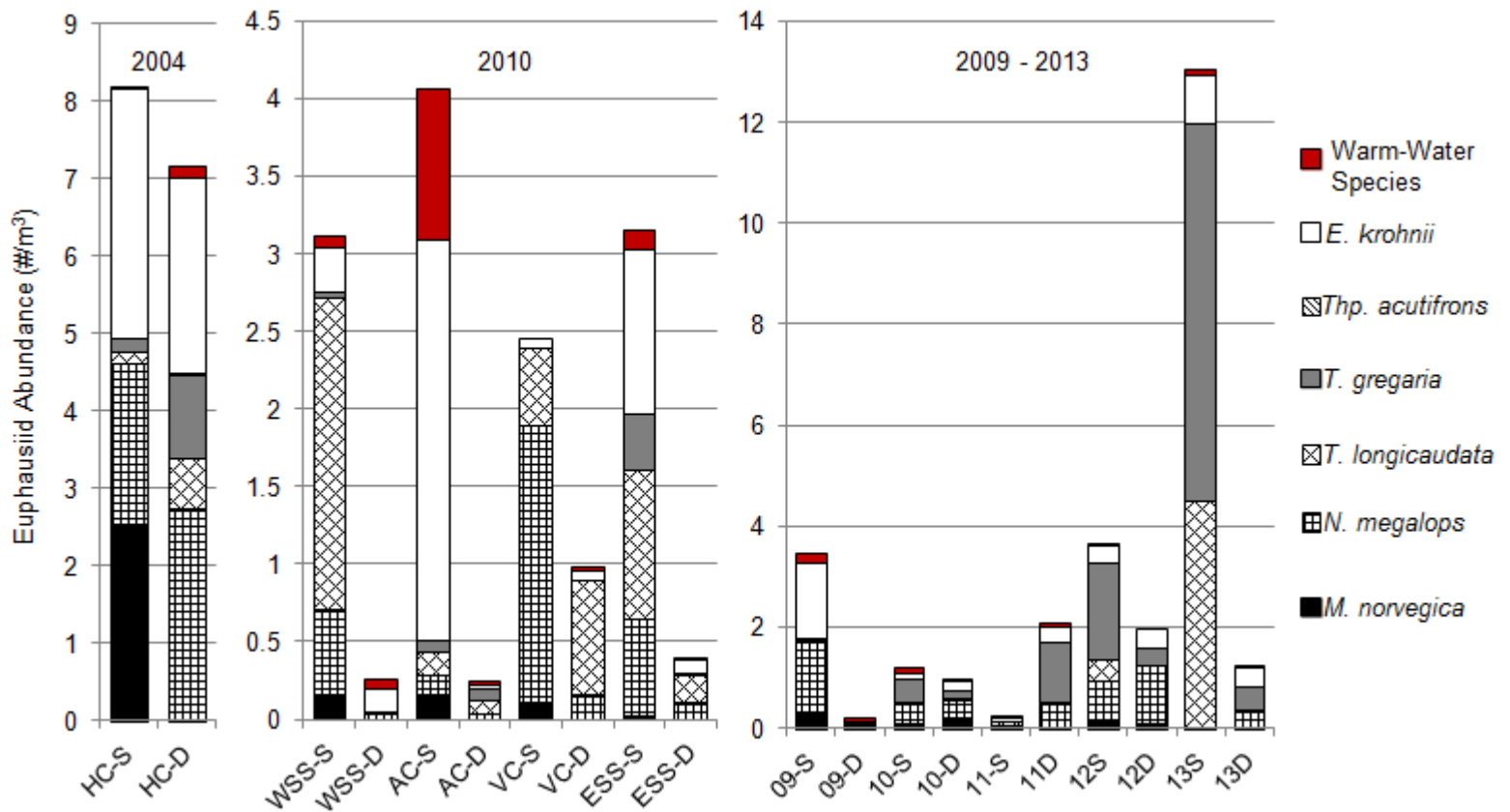


Figure 1.4: Total euphausiid abundance in animals/m<sup>3</sup> at each site (not adjusted for avoidance estimation). The contributions of the six cold-water species are shown, as well as the cumulative contribution of all warm-water species. HC: Hudson Canyon, VC: Veatch Canyon, ESS: Eastern Slope Site (non-canyon), WSS: Western Slope Site (non-canyon), AC: Atlantis Canyon, S: Shallow, D: Deep, 09-13 represents the yearly sampling completed on the SSV Corwith Cramer in Atlantis Canyon.

### 1.3.2 Species Composition

In total, 20 species from 6 genera were recorded among the 20 sampling sites, of which 6 species were considered cold-water, and 14 were warm-water. Cold-water Slope Water species on average comprised greater than 91% of euphausiid abundance and 92% of euphausiid biomass. Of the 20 species, *E. krohnii* had the most widespread presence, being found within the samples from 19 of the 20 sites. *M. norvegica*, *N. megalops*, *T. longicaudata*, *T. gregaria*, *E. mutica*, and *N. microps* were present within more than half of the samples. The remaining 13 species were present at less than half of the sampling sites and 4 were only present at a single site (Tables C.1-C.8).

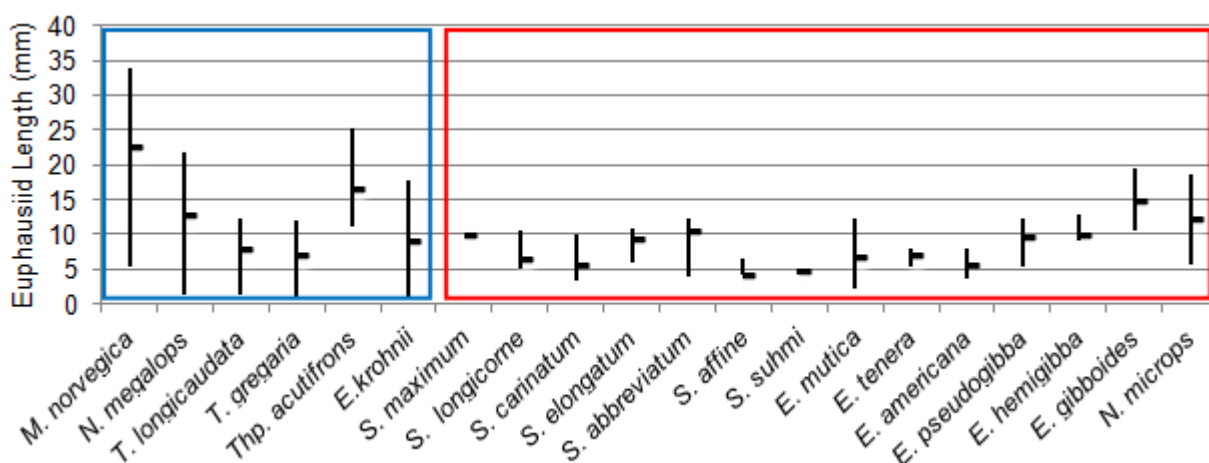


Figure 1.5: Range of euphausiid length by species for all samples. Median length value is indicated. Cold-water species (blue) and warm-water species (red) are grouped.

The size-frequency distribution for all species varied between tows, with a

greater range of median lengths occurring at shallow sites (Figure 5, Table 1.2). Comparing pairs of shallow and deep sites, shallow sites tended to have the larger animals, however, no significant relationship existed between length and bottom depth.

Table 1.2: Euhausiid length statistics by tow. Measurements are in mm.

Site	Minimum	Median	Maximum
AC-S	3.6763	7.90025	25.705
AC-D	2.2226	7.6071	18.892
VC-S	1.343	11.798	33.867
VC-D	1.1334	8.42845	27.679
ESS-S	0.0855	8.9091	29.248
ESS-D	2.1354	8.3184	20.347
WSS-S	3.8213	9.0948	30.326
WSS-D	3.4053	7.3127	17.354
HC-S	3.7558	12.7065	29.781
HC-D	3.7509	11.7721	18.8731
09-S	2.0001	11.5178	32.8732
09-D	4.4211	10.0551	20.7065
10-S	2.8176	8.5838	27.4984
10-D	2.9138	11.38	25.8374
11-S	6.666	10.4269	13.6376
11-D	20.0193	8.0979	14.8752
12-S	5.9117	8.9512	27.5167
12-D	6.9038	10.6714	27.6479
13-S	2.0255	6.8066	15.5879
13-D	4.6999	8.3343	15.7788

Cluster analysis for biomass of all species collected on the R/V *Connecticut* resulted in three distinct groupings; the three deepest sites, all of which were greater than 1000m depth, the shallow site within Veatch Canyon, and the remaining three shallow sites with the addition of the deep Veatch Canyon sample,

which was the shallowest of the samples from the outer shelf break at 644m bottom depth (Figure 1.6). Cluster analyses based on species abundances indicated a distinction between the head and mouth of Atlantis Canyon, and a differentiation between Atlantis Canyon and all other sites. However, further investigation through NMDS showed no link between the presence of particular species and location, with no significant linkages between sites or distinct species groups (cold- and warm-water). Environmental conditions show no significant relationship to species composition among the sites sampled on the spatial survey.

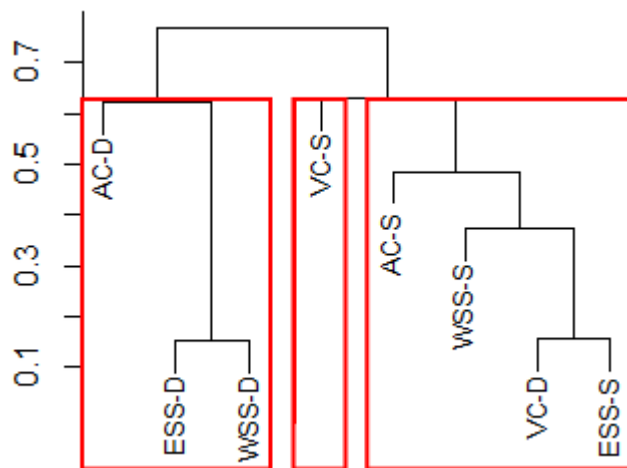


Figure 1.6: Similarity from cluster analysis of species biomass for all sites sampled on the R/V *Connecticut*, based on the distances between cluster centroids using Bray-Curtis Dissimilarities.



### 1.3.3 Environmental Relationships

Statistical analyses linking the euphausiid abundance and biomass at all sites to particular environmental conditions resulted in the identification of a subset of variables with the greatest explanatory power. Total euphausiid biomass at each site showed a high correlation with bottom depth ( $p = 0.008023$ ,  $r^2 = 0.2797$ , Figure 1.7).

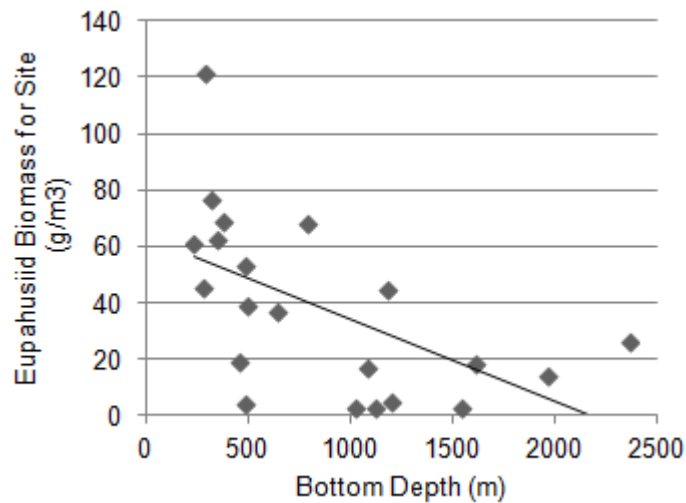


Figure 1.7: Relationship between euphausiid biomass and bottom depth. Total euphausiid biomass for each site is significantly related to decreasing depth ( $r^2 = 0.2797$ ,  $p = 0.008023$ ).

This trend is driven by cold-water species, having a greater presence and contribution to biomass (Figure 1.8). Separately, cold-water species show a significant correlation to depth ( $p = 0.00747$ ), while warm-water species exhibit no significant relationship ( $p = 0.1505$ ).

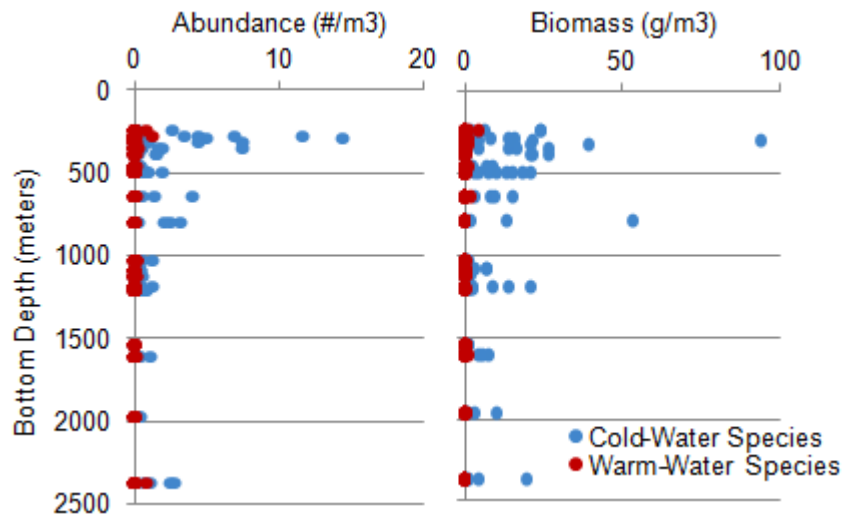


Figure 1.8: Abundance (left) and biomass (right) for all species of euphausiids relative to bottom depth of site. Cold-water species are indicated by blue, warm-water species by red.

In 2010, total euphausiid biomass and abundance decreased with distance from the ring edge, both away from and into the ring, with a significant decrease in biomass occurring the farther the sampling was from the ring edge ( $p = 0.02767$ ,  $r^2 = 0.4084$ , Figure 1.9).

Using all environmental variables collected, separate linear models were determined as the optimal predictors for total euphausiid abundance (Table 1.3) and biomass (Table 1.4). Hudson Canyon samples were not included in models due to temperature variation of winter sampling.

Table 1.3: Optimal model for total euphausiid abundance.

Total Abundance (AIC = 37.9, $r^2 = .5242$ , $p = .002626$ )		
<i>Variable</i>	<i>Coefficient</i>	<i>Significance</i>
Bottom Depth	-0.0021	0.047
Surface Chlorophyll Concentration	11.313	0.0118
Mean Salinity to 10m Depth	-0.9686	0.0266
Depth of 10 °C Isotherm	0.02444	0.022

Table 1.4: Optimal model for total euphausiid biomass.

Total Biomass (AIC = 129.68, $r^2 = .5842$ , $p = .0004107$ )		
<i>Variable</i>	<i>Coefficient</i>	<i>Significance</i>
Bottom Depth	-0.0425	0.00007
Mean Temperature to 10m Depth	-3.7084	0.00263
Depth of 10	0.23613	0.01096

### 1.3.4 Temporal Variability

Short-term temporal variation was investigated by comparing the sampling of Atlantis Canyon in early July and late July in 2010, which showed dominance of biomass by similar species, *M. norvegica*, *N. megalops*, and *E. krohnii*. There was a factor of 5 increase in biomass at the mouth of the canyon, from 2.73 to 14.59 grams per cubic meter, between the two sampling events.

Strong interannual variability was observed in both euphausiid abundance and biomass over the 5-year sampling of Atlantis Canyon, with greater than a 17-fold difference in biomass between the smallest and largest sample sizes at shallow sites, and 14-fold difference at deep sites (Figure 1.10). There was signifi-

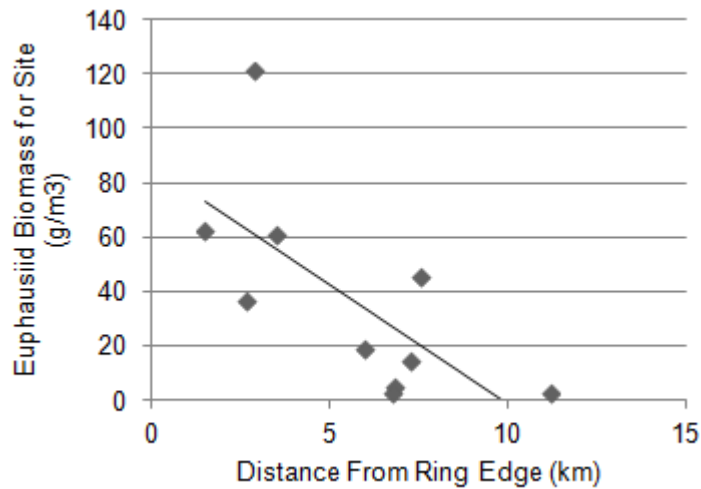


Figure 1.9: Change in total euphausiid biomass with increasing distance from ring edge. All samples collected in 2010 are included. The solid line represents the linear relationship  $\text{Biomass} = 86.544 - (8.783 \times \text{Distance from ring edge})$ ,  $r^2 = 0.4084$ ,  $p = 0.02767$ .

cant decrease in species richness among the sites sampled over the five-year sampling period ( $p=0.02178$ ,  $r^2=.44$ ) due to the presence of more warm water species in 2009 and 2010, however there was no relationship between species richness and abundance ( $p=0.3223$ ,  $r^2=0.0021$ ) or biomass ( $p=0.5828$ ,  $r^2=-0.0807$ ). The samples revealed a possible trend between increasing water temperature and decreasing biomass at the deep sampling sites, though the linear relationship was not significant ( $p = 0.4307$  with surface temperature,  $p = 0.4051$  with mean temperature to 300m depth), and shallow samples showed high variability in biomass over five years, with no simple linear correlation to temperature ( $p = 0.9241$  with surface temperature,  $p = 0.6969$  with mean temperature to 300m depth).

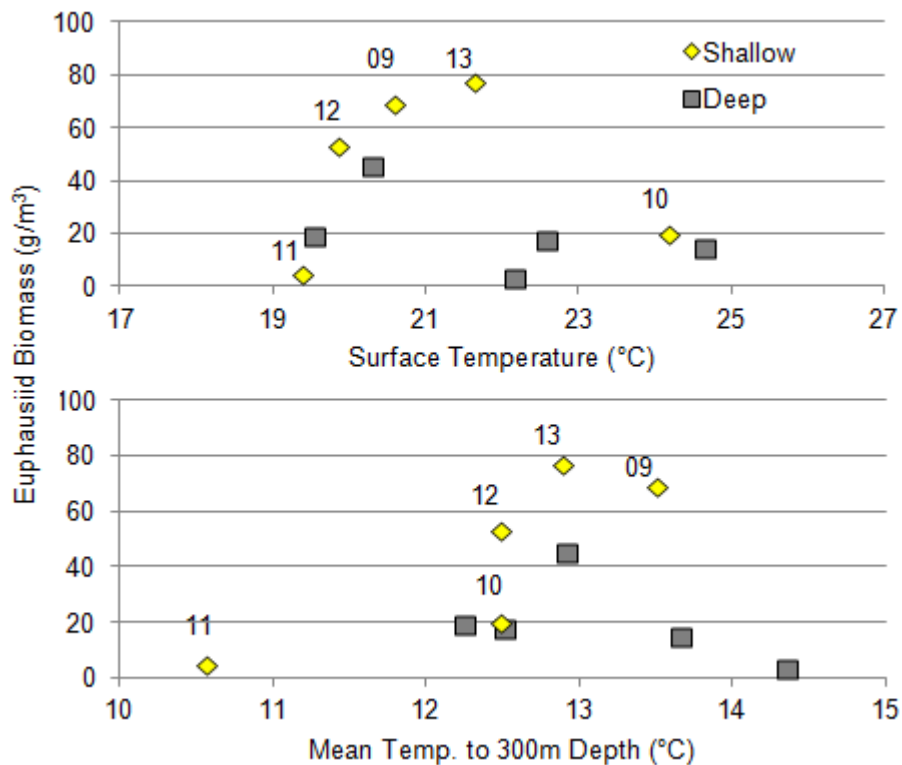


Figure 1.10: Total euphausiid biomass vs. surface temperature (top) and mean temperature to 300m depth (bottom) for shallow and deep sampling sites within Atlantis Canyon as collected aboard the SSV Corwith Cramer. Years are indicated for shallow sites.

## 1.4 Discussion

Euphausiid presence was much greater at shallow sites just at the edge along the shelf break, however there was little difference between the euphausiid aggregation size and composition inside and outside of the canyons. This variability was correlated to bottom depth, and though biomass tended to be greater within the

heads of the canyons than the shallow non-canyon sites, the trend was not significant. Canyon heads exhibited larger aggregations than canyon mouths, and this same relationship was present along the shelf at non-canyon sites. Expatriates from the Sargasso Sea were present in various samples during the 2010 sampling but contributed little to the abundance and biomass. Any changes between sites and years were primarily driven by the presence of the 6 cold-water species at the majority of sites, and the variation in biomass was dominated by the presence of the larger cold-water species.

### **1.4.1 Spatial Distribution**

Contrary to our expectations, total euphausiid abundance and biomass were not significantly greater in canyons than at nearby non-canyon sites, though topography did affect their distribution. Bottom depth was the primary correlate in the spatial distribution of the euphausiids in this Northwest Atlantic study site, primarily driven by the presence of the two largest species, *M. norvegica* and *N. megalops*. Although it may be possible that there is no canyon effect, alternatively, the small sample size of sites may have limited our ability to detect significant variation between the canyon and non-canyon sites. Additionally, our intention to test a canyon effect might have been disrupted by the intrusion of the warm-core ring. The presence of the ring during June/July 2010 may have restricted the distribution of euphausiids along the shelf break, impacting any preference for the canyons that might have been observed of the euphausiid aggregations un-

der normal environmental conditions. The movement of the ring and change in temperature at both surface and depth may have resulted in displacement of the animals, and possibly moving more animals along the ring edge.

It is possible that the patchiness of the aggregations in the area is responsible for site-to-site variability in abundance and biomass. Multiple species in this study have distributions that are known to be patchy and site-to-site variation in total euphausiid biomass might be due to patchiness and the differences in sampling technique between the data sets. Additionally, a few of the species exhibit diel vertical migration, moving position in the water column throughout the day, and therefore variability in time of sampling is likely to show variation of in abundance and biomass based on sampling depth relative to the dispersion of animals throughout the water column [16].

The relationship between biomass and distance to the edge of the ring may be explained by the location of the sites. Of the sampling conducted during the presence of the ring during the 2010 R/V *Connecticut* survey, the three sites with the greatest biomass are shallow sites, as well as the three sites closest to the edge of the ring. These sites are the head of both Veatch and Atlantis Canyon (VC-S, AC-S), and the shallow western non-canyon site (WSS-S). There is a moderate correlation ( $\rho = 0.5245$ ) between distance from the edge of the ring and bottom depth. However, based on the weak correlation between the observed temperature variables and biomass, there is a high likelihood that bottom depth is the underlying cause of the statistical significance between total biomass and the distance to the

front.

As the sampling for this study was focused at the shelf break and not within the Slope Water, the location of the sampling sites only allows us to see the effect of the edge of the WCR rather than the ring's center. Based on previous observations of rings during the Warm-Core Ring Program, the sampling conducted during the presence of the ring in 2010 would be classified as in the edge of the ring or in unaltered Slope Water [5] (Figure 1.11). This categorization of the sampled water body may explain the dominance of Slope Water species at all sampling sites, as the influence of the ring in this area would have been minimal and the community structure may have been mostly undisturbed. Within warm-core rings, the species of cold-water origin, particularly *M. norvegica*, *N. megalops*, *T. longicaudata*, and *E. krohni* tend to be very limited in abundance relative to the Slope Water [13], and would be expected to contribute to a smaller portion of abundance and biomass than the warm-water species.

#### **1.4.2 Temporal Variability**

There were differences in euphausiid biomass collected between the sampling of Atlantis Canyon in early and late July 2010, though the dominant euphausiids in all tows were cold-water species that would be expected to be found in the waters along the continental shelf-slope region. Samples collected later in the month were dominated by *N. megalops*, while those collected earlier were dominated primarily



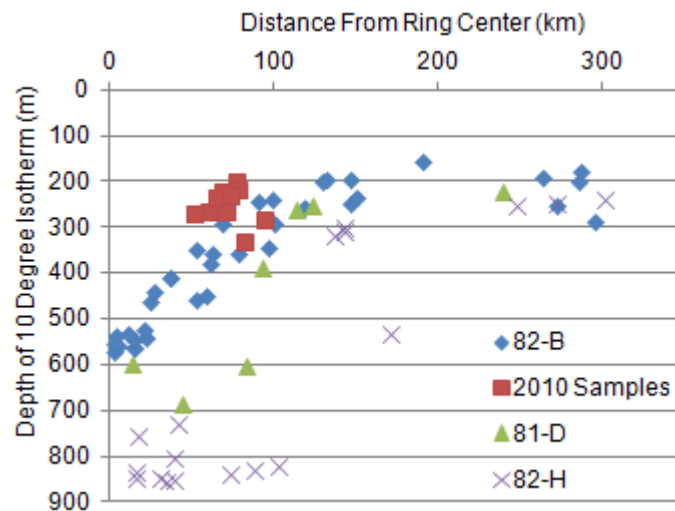


Figure 1.11: Relationship between distance from the center of the ring and the depth of the 10 degree isotherm for warm-core rings 81-D, 82-B, and 82-H based on data presented by Barber and Wiebe (1985) [5]. Samples collected during the 2010 collection fall within the range of previous collection sites classified as high velocity region and Slope Water.

by *M. norvegica*. As both of these species are likely not to be found within the water of the WCR, the variation may not be due to the movement of the ring. There was an order of magnitude difference in biomass collected at the mouth of the canyon between the two events as well, so although that biomass at the shallow site may have decreased over the three-week time period, biomass at the mouth increased. However, it is difficult to make direct comparisons between the two sampling events due to the differences in sampling equipment and sampling procedure on the two cruises. As with the spatial comparison, the patchiness of the aggregations can also lead to considerable variability in the catch.

No significant correlation was found between abundance or biomass and the environmental conditions measured for the time-series samples from Atlantis Canyon. There is a possible inverse relationship between euphausiid biomass and temperature at the deep sampling sites, however with a small sample size of only 5 periods, there is no quantitative correlation. The shallow sites are more variable than the deeper sites both for surface temperature and temperature of the water column.

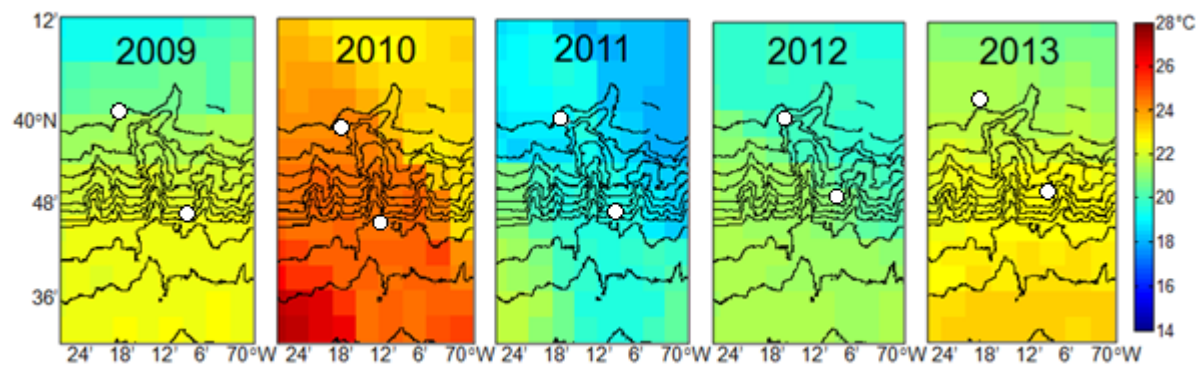


Figure 1.12: Sea surface temperature corresponding to sampling of Atlantic Canyon aboard the SSV *Corwith Cramer* during summer sampling from 2009-2013. Net sampling sites are indicated by a white circle.

Based on the temperature observations, the low biomass found during the 2010 sampling, which occurred during the intrusion of the warm-core ring into the area, may be due to the high surface temperature. The temperature of the water column was more consistent in 2009, 2012, and 2013, all of which exhibited similar biomass to each other and the sampling conducted at shallow sites earlier in 2010. Biomass collected at the shallow sampling site in 2011 was also low, however contrary to

the previous year, sea surface temperatures were similar to 2009, 2012, and 2013, while the water column temperature was much lower than the other sampling periods. The decreased biomass at the shallow site in Atlantis Canyon in 2010 may be explained by the anomalously warm surface temperature, while the low biomass in 2011 may be a result of an overall colder water column. Low biomass at the shallow site in 2011 may also be due to insufficient sampling. Net tows at the head of the canyon occurred during the day to a depth of only 150m in an area with a bottom depth of 480m. It is possible that the sampling depth did not reach the euphuasiid layers that exhibit diel vertical migration and remain deep during daylight, resulting in significant under sampling.

In 2010, the warmer surface temperature might be indicative of relative flow of surface waters as a result of the presence of the ring which is displacing the organisms, as opposed to directly driving a reduction in abundance and biomass. One potential explanation is that *M. norvegica*, which was responsible for much of the variability in biomass due to their size and therefore contribution to total biomass, might move along the shelf-slope into more favorable conditions.

### **1.4.3 Future Work**

Continued efforts to measure the variability between canyon and non-canyon sites along the shelf break require expanded data collection and more replicate tows of comparable canyon and non-canyon sites. In order to further investigate

the limited differences between canyons and non-canyons as preferred sites of euphausiid aggregation, sampling in a similar spatial distribution collected without the influence of a warm-core ring in the area would be needed to determine whether the limited variation between sites was potentially a result of the frontal features of the ring. Investigation into historic data sets containing time series of the zooplankton communities in the Slope Water will better illustrate the variability in the community when undisturbed by a warm-core ring. Additionally, the use of a sampling method with higher spatial resolution and coverage, such as using active acoustics to detect zooplankton biomass, would provide more support in determining spatial variability.

Though there may be a trend between the water column temperature and the biomass at deep sites within Atlantis Canyon over our five-year sampling period, the current sample size is not sufficient to allow for strong enough statistical testing to support or refute that a relationship exists. Continued expansion of this time series would be ideal, and higher frequency sampling, such as seasonal catches, with variable water column temperature would also provide a necessary data set to further test this hypothesis.

The relationship between topography and the euphausiid community structure at the shelf break raises questions about how their distribution may influence predators in the region. Top predators had previously been seen associated with canyons, and the region is already known to be a key feeding area. Additional work to incorporate these findings into work investigating other animals in

the area will help to clarify the relationship between the euphausiid communities and higher trophic levels. Two marine mammal observers and a seabird observer were aboard during sampling on the R/V *Connecticut* in 2010, and observations from the sampling showed greater abundance of Odontocetes and birds at the colder sampling sites, particularly within the shallow Veatch Canyon site where zooplankton biomass was greatest [51]. Preliminary analyses of acoustic data also show greater mean volume backscattering at the head of Veatch Canyon, supporting the net samples analyzed in this work, and inferring higher biomass at the canyon heads in conjunction with top predator observations. Analyses showed high density of sea birds along the edge of the ring, and future work should investigate the similarities between the concentration of euphausiid biomass and the concentration of birds along the ring edge.

In addition to top predators, to understand the whole system of trophic interactions occurring at the shelf-break, the spatial relationship between the euphausiid population and commercially sought fish should additionally be investigated. Commercial fishing fleets from New Jersey to Massachusetts operate at the New England shelf break, targeting a variety of fish and squid, and the area is fished year-round using a wide array of gear, including a range from large bottom and mid-water trawls to rod and reel, as well as benthic traps and pots for lobster and crab. Greene et al. (1988) have suggested that the squid and fish on Georges Bank subsidize their diet with the high krill production found in the canyons surrounding the bank, and that the excess fish production can be attributed to these canyon aggregations, particularly of *M. norvegica* [20]. Similarly, the importance

of *M. norvegica*'s contribution biomass at the edge of the shelf break supported in this study suggests that the aggregations may play a role in supporting those fish stocks that visit the shelf break.

Anecdotal evidence from commercial fisherman supports a theory of seasonal spatial variation of the aggregation of euphausiids, in which euphausiids found within Atlantis Canyon have been observed to aggregate on the canyon sides favoring the down-current side. The location of the aggregations was observed to alternate seasonally, being present on one side in spring and on the other in fall [41]. The presence of euphausiids impacts the decision by fisherman of where to focus their efforts, as euphausiids may make up a significant portion of the prey for their target fish species. It is important to identify the potential roles the zooplankton, particularly in the canyons, have in the activities of these commercial fisheries.

APPENDIX A  
NET CORRECTIONS AND SAMPLING ERROR

### A.1 Atlantis Canyon Acoustic Correction

Acoustic observations were used to guide the interpolation of missing samples. For R/V *Connecticut* tow 12 (WSS-S), only samples within the 300-150 meter and 25-0 meter depth intervals were available for analysis. Tow 12 was a daytime sample, and based on the expected diel vertical migration pattern and known depth ranges of the species collected, the biomass of the euphausiids at the time of the tow would have been assumed to be concentrated at depth within the nets that were successfully preserved. In order to correct for missing samples in R/V *Connecticut* tow 12, the acoustic profile during sampling was matched with the trajectory of the net to determine the relative total volume backscattering of each depth bin. Echograms of the four frequencies were visually inspected to determine if the net passed through areas meeting a threshold scattering level typically associated with euphausiid aggregations. Mean volume backscattering for 5-meter bins bounding the net track were compared, and based on the observations of the acoustic profile, data for tow 12 was calculated based on the assumption of no euphausiid presence between 150 and 25 meters depth (Figure A.1).

Of the three species with the greatest contribution to biomass at the site, *M. norvegica* is the only species that migrates daily. *T. longicaudata* has been found to

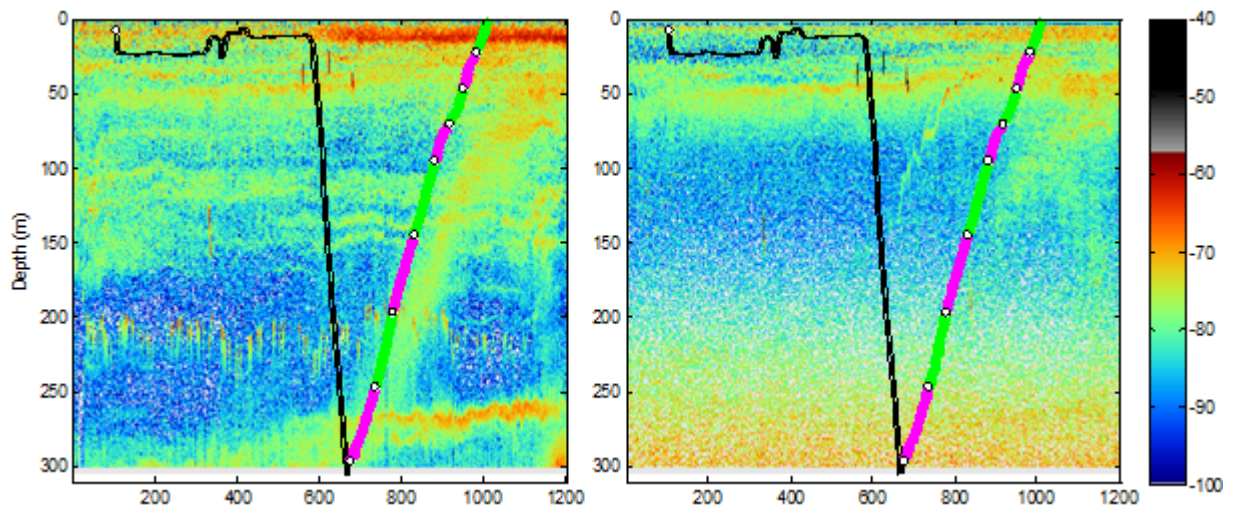


Figure A.1: CT2010 Tow 12 profiles overlaid on acoustic echograms of volume backscattering strength at 43kHz (left) and 120kHz (right).

have similar distributions during both day and night [6, 28, 58], and while it has been observed to be concentrated between 0-100m, is known to extend in range deeper than 350m [6] *N. megalops* showed no shift in vertical distribution in the Slope Water and the central 50% of the population tends to concentrate in a narrow depth range around 200m [53, 54]. The abundance and biomass values used can be considered the minimum possible values for the tow, and along with observed volume backscatter from acoustic data, it was assumed there was negligible euphausiid presence in the water column where samples were missing. If the abundance of the missing nets were of equal value to the most abundant sample from the tow, the maximum abundance would be 8.27 animals per cubic meter, an increase by a factor of 2.66. The maximum biomass determined on the same



basis would be 86.49 grams per cubic meter, an increase by a factor of 1.38. Using the maximum values as the assumed abundance and biomass, the abundance for tow 12 would be the most abundant sample from the R/V *Connecticut*, more than double what would be the second most abundant catch from the head of Atlantis Canyon. These adjusted values would further decrease any variability observed between the canyon and non-canyon sites.

## **A.2 Differences in Sampling Technique**

Volume filtered for samples collected using a MOCNESS was determined using a flow meter attached to the MOCNESS frame, which was either calibrated during the course of the cruise or a prior calibration was used to convert flow meter rotations to volume based on the distance the net has traveled. For sampling of Atlantis Canyon conducted aboard the SSV *Corwith Cramer*, volume filtered by each net of the Tucker trawl was determined based on GPS position of the vessel to determine the distance the net traveled through water. Discrepancies in the amount of water sampled by each net impact abundance and biomass calculations that are determined based on unit volume. It is possible that while the sampling was consistent within the data sets utilizing different net systems, differences between the two introduce additional uncertainty when making comparisons between them. For this reason, most analyses used the data sets independently.

### **A.3 Avoidance Mitigation**

Euphausiids are known to be able to avoid capture in standard net tows [42, 52, 54]. It has been shown that the use of a strobe light system to limit avoidance can lead to a significant increase in euphausiids abundance captured [42, 46, 52, 56]. Using a MOCNESS equipped with an LED-based strobe system, Wiebe et al. (2013) determined appropriate factors for biomass and abundance for day and night sampling [56]. Avoidance estimates are biased due to greater ability of larger zooplankton to swim more quickly away from the net. The avoidance corrections were applied to *M. norvegica* as well as *N. megalops*, the two largest species found and those known to exhibit avoidance [42, 54]. Although it did increase the expected abundance and biomass, particularly at sites dominated by the two species, the correction for avoidance had little effect on the strength of the correlation between abundance and biomass and the environmental conditions considered.

### **A.4 Biomass Calculation**

The length to wet weight regression used to determine biomass was based on euphausiids sampled in a warm-core Gulf Stream ring 82-B and derived by Davis and Wiebe (1985) [12]. This regression is based on formalin preserved samples similar to the ones used in this study. An alternative regression (wet weight =

$0.0055 \times \text{length}^{3.2059}$ ) was used by Wiebe et al. (2013) [56] in determining biomass for euphausiids collected at three sites within the Gulf of Maine, originating from measurements of *Euphausia superba* from the western Antarctic continental shelf [52]. The regression used in this study is steeper and therefore has a greater impact on the wet weight of an organism as it increases in length, possibly overestimating the contribution of the larger organisms to total biomass (Figure A.2). It

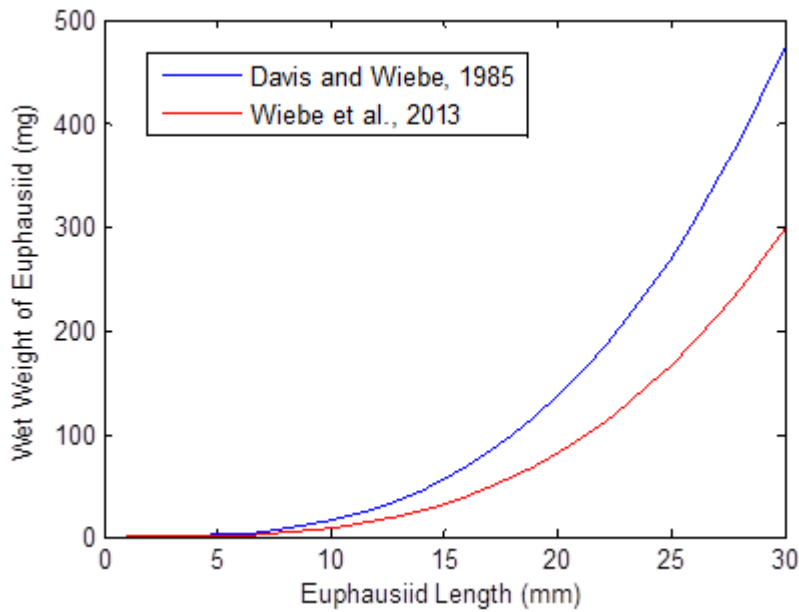


Figure A.2: Regressions for calculating biomass based on euphausiid length used for organisms in the Northwest Atlantic.

is possible to then over predict biomass and overestimate the influence of species with the greatest length. Though multiple studies have calculated length-weight relationships for the North Atlantic [4, 12, 14, 25, 43], species-specific regressions for the Slope Water are needed to precisely determine biomass from length measurements for future research in the region.

## APPENDIX B

### ENVIRONMENTAL VARIABLES

Table B.1: Environmental conditions collected and considered for statistical analyses.

Environmental Condition	Unit	Collection	Description
Mean Temperature to 10m	°C	in situ	Temperature in the upper surface of the water column
Mean Temperature to 50m	°C	in situ	Temperature down to the thermocline
Mean Temperature to 300m	°C	in situ	Temperature of the water column, using 300 meters as a consistent proxy due to the variability of sampling depth
Depth of the 10 °C isotherm	meters	in situ	Used to determine the influence of the warm-core ring [5]
Depth of the 15 °C isotherm	meters	in situ	Additional proxy to determine the influence of the warm-core ring
Mean Salinity to 10m	ppt	in situ	Salinity in the upper surface of the water column
Mean Salinity to 50m	ppt	in situ	Salinity down to the thermocline
Sea Surface Temperature	°C	NASA MODIS- Aqua	Sea surface temperature at a .05 degree resolution [15]
Sea Surface Chlorophyll	mg/m <sup>2</sup>	NASA MODIS- Aqua	Chlorophyll-a concentration at .025 degree resolution as a proxy of primary productivity at the surface [39]
Bottom Depth	meters	USGS	100m-resolution bathymetric data collected using hydroacoustic mapping [3]

APPENDIX C  
SPECIES TABLES

**C.1 Abundance**

Table C.1: Abundance (#/m<sup>3</sup>) by species collected on the R/V *Endeavor*.

	HC-S	HC-D
<b>Cold-Water Species</b>		
<i>Meganyctiphanes norvegica</i>	2.531345	0
<i>Nematoscelis megalops</i>	2.081969	2.727399
<i>Thysanoessa longicaudata</i>	0.1379879	0.6709749
<i>Thysanoessa gregaria</i>	0.1946362	1.054198
<i>Thysanapoda acutifrons</i>	0	0.0404313
<i>Euphausia krohnii</i>	3.227321	2.526191
<i>Distribution Totals</i>	8.173259	7.019194
<b>Warm-Water Species</b>		
<i>Stylocherion maximum</i>	0	0
<i>Stylocherion longicorne</i>	0.0020708	0
<i>Stylocherion carinatum</i>	0	0
<i>Stylocherion elongatum</i>	0	0
<i>Stylocherion abbreviatum</i>	0	0.0074627
<i>Stylocherion affine</i>	0.0012711	0
<i>Stylocherion Suhmi</i>	0	0
<i>Euphausia mutica</i>	0	0.010437
<i>Euphausia tenera</i>	0	0
<i>Euphausia americana</i>	0	0.8562315
<i>Euphausia pseudogibba</i>	0	0.0229793
<i>Euphausia hemigibba</i>	0	0
<i>Euphausia gibboides</i>	0.0050505	0
<i>Nematoscelis microps</i>	0	0.0024876
<i>Distribution Totals</i>	0.008392	0.899598
<i>Euphausia spp.</i>	0	0
<i>Stylocherion spp.</i>	0	0
<i>Thysanapoda spp.</i>	0.0052994	0
<i>Total Abundance</i>	8.18695	7.91879

Table C.2: Abundance (#/m<sup>3</sup>) by species collected on the SSV *Corwith* Cramer, 2009-2011.

	09-S	09-D	10-S	10-D	11-S	11-D
<b>Cold-Water Species</b>						
<i>Meganyctiphanes norvegica</i>	0.24346	0	0.0629773	0.1946886	0.0312348	0
<i>Nematoscelis megalops</i>	1.476188	0.0483627	0.4204847	0.34687	0	0.4363715
<i>Thysanoessa longicaudata</i>	0	0	0	0.0441853	0.0624695	0.0664063
<i>Thysanoessa gregaria</i>	0.0221327	0.036272	0.4621514	0.1257642	0	1.156368
<i>Thysanapoda acutifrons</i>	0	0	0	0	0	0
<i>Euphausia krohnii</i>	1.518586	0.0322418	0.1003135	0.1956332	0.0937043	0.3215198
<i>Distribution Totals</i>	3.260368	0.116877	1.045927	0.907141	0.187409	1.980666
<b>Warm-Water Species</b>						
<i>Stylocherion maximum</i>	0	0	0	0	0	0
<i>Stylocherion longicorne</i>	0	0.0080605	0	0	0	0
<i>Stylocherion carinatum</i>	0	0	0	0	0	0
<i>Stylocherion elongatum</i>	0	0	0	0	0	0
<i>Stylocherion abbreviatum</i>	0	0	0	0.0139738	0	0
<i>Stylocherion affine</i>	0	0	0	0	0	0
<i>Stylocherion Suhmi</i>	0	0	0	0	0	0
<i>Euphausia mutica</i>	0.0221327	0.0040302	0.1504702	0.0069869	0	0.0757891
<i>Euphausia tenera</i>	0	0.0080605	0	0	0.0312348	0
<i>Euphausia americana</i>	0.109684	0.0201511	0	0	0	0
<i>Euphausia pseudogibba</i>	0.0333215	0.0120907	0	0	0	0
<i>Euphausia hemigibba</i>	0	0	0	0	0	0
<i>Euphausia gibboides</i>	0	0	0	0	0	0
<i>Nematoscelis microps</i>	0	0	0	0.0200161	0	0
<i>Distribution Totals</i>	0.165138	0.052393	0.15047	0.040977	0.031235	0.075789
<i>Euphausia spp.</i>	0	0	0	0	0	0
<i>Stylocherion spp.</i>	0	0	0	0	0	0
<i>Thysanapoda spp.</i>	0	0	0	0	0	0
<i>Total Abundance</i>	3.42551	0.16927	1.1964	0.94812	0.21864	2.05646

Table C.3: Abundance ( $\#/m^3$ ) by species collected on the SSV *Corwith Cramer*, 2012-2013.

	12-S	12-D	13-S	13-D
<b>Cold-Water Species</b>				
<i>Meganyctiphanes norvegica</i>	0.1305057	0.0558464	0.0034	0
<i>Nematoscelis megalops</i>	0.7830343	1.172775	0	0.3248847
<i>Thysanoessa longicaudata</i>	0.4176183	0	4.464153	0.0271397
<i>Thysanoessa gregaria</i>	1.905383	0.3350785	7.466643	0.4380988
<i>Thysanapoda acutifrons</i>	0	0	0	0
<i>Euphausia krohnii</i>	0.3393148	0.390925	0.9674759	0.3911981
<i>Distribution Totals</i>	3.575856	1.954625	12.89827	1.181321
<b>Warm-Water Species</b>				
<i>Stylocherion maximum</i>	0	0	0	0
<i>Stylocherion longicorne</i>	0	0	0	0
<i>Stylocherion carinatum</i>	0.0261011	0	0	0
<i>Stylocherion elongatum</i>	0	0	0	0
<i>Stylocherion abbreviatum</i>	0	0	0	0
<i>Stylocherion affine</i>	0	0	0	0
<i>Stylocherion Suhmi</i>	0	0	0	0
<i>Euphausia mutica</i>	0	0	0.1382712	0
<i>Euphausia tenera</i>	0	0	0	0
<i>Euphausia americana</i>	0	0	0	0
<i>Euphausia pseudogibba</i>	0	0	0	0
<i>Euphausia hemigibba</i>	0	0	0	0
<i>Euphausia gibboides</i>	0	0	0	0
<i>Nematoscelis microps</i>	0	0	0	0.0135699
<i>Distribution Totals</i>	0.026101	0	0.138271	0.01357
<i>Euphausia spp.</i>	0	0	0	0
<i>Stylocherion spp.</i>	0	0	0	0
<i>Thysanapoda spp.</i>	0	0	0	0
<i>Total Abundance</i>	3.60196	1.95463	13.0365	1.19489

Table C.4: Abundance (#/m<sup>3</sup>) by species collected on the R/V *Connecticut*.

	WSS-S	WSS-D	AC-S	AC-D	VC-S	VC-D	ESS-S	ESS-D
<b>Cold-Water Species</b>								
<i>Meganyctiphanes norvegica</i>	0.149732	0	0.155907	0.000587	0.099319	0.008839	0.018853	0
<i>Nematoscelis megalops</i>	0.547747	0.028414	0.116931	0.02681	1.782619	0.137969	0.62462	0.103106
<i>Thysanoessa longicaudata</i>	2.00984	0.008183	0.155907	0.090543	0.504101	0.745936	0.956051	0.177963
<i>Thysanoessa gregaria</i>	0.037405	0.000609	0.077954	0.076942	0	0.002391	0.359628	0.010072
<i>Thysanapoda acutifrons</i>	0	0	0	0	0	0	0.000653	0
<i>Euphausia krohnii</i>	0.286337	0.150958	2.572473	0.017104	0.056714	0.05066	1.06722	0.083864
<i>Distribution Totals</i>	3.03106	0.18816	3.07917	0.21199	2.44275	0.94579	3.02703	0.37501
<b>Warm-Water Species</b>								
<i>Stylocherion maximum</i>	0	0	0	0	0	0	0	0.000125
<i>Stylocherion longicorne</i>	0	0.002571	0	0	0	0	0	0
<i>Stylocherion carinatum</i>	0.034088	0.006349	0	0.005046	0	0.000319	0	0
<i>Stylocherion elongatum</i>	0	0	0	0.002342	0	0	0	0
<i>Stylocherion abbreviatum</i>	0.009351	0.001426	0.038977	0.001754	0	0	0	0
<i>Stylocherion affine</i>	0	0.000189	0	0	0	0	0	0
<i>Stylocherion Suhmi</i>	0	0.000675	0	0.002808	0	0	0	0
<i>Euphausia mutica</i>	0.02727	0.007915	0.857491	0.001535	0	0	0.104957	0.002034
<i>Euphausia tenera</i>	0	0.023142	0	0.001112	0	0	0	0
<i>Euphausia americana</i>	0	0	0	0	0	0	0	0
<i>Euphausia pseudogibba</i>	0	0	0	0	0	0	0	0
<i>Euphausia hemigibba</i>	0	0.006866	0	0.00562	0	0	0	0
<i>Euphausia gibboides</i>	0	0	0	0	0	0	0	0
<i>Nematoscelis microps</i>	0.009351	0.011161	0.077954	0.007268	0	0.025626	0.013169	0.007703
<i>Distribution Totals</i>	0.08006	0.0603	0.97442	0.02749	0	0.02595	0.11813	0.00986
<i>Euphausia spp.</i>	0	0	0	0	0	0.000478	0	0
<i>Stylocherion spp.</i>	0	9.43E-05	0	0	0	0.000797	0	0
<i>Thysanapoda spp.</i>	0	0.000862	0	0	0	0	0	0
<i>Total Abundance</i>	3.11112	0.24942	4.05359	0.23947	2.44275	0.97302	3.14515	0.38487



## C.2 Biomass

Table C.5: Biomass (g/m<sup>3</sup>) by species collected on the R/V *Endeavor*.

	HC-S	HC-D
<b>Cold-Water Species</b>		
<i>Meganyctiphanes norvegica</i>	53.080715	0
<i>Nematoscelis megalops</i>	13.000798	19.422317
<i>Thysanoessa longicaudata</i>	0.121523	0.924338
<i>Thysanoessa gregaria</i>	0	0.665931
<i>Thysanapoda acutifrons</i>	1.936386	4.474183
<i>Euphausia krohnii</i>	0.145627	0.489612
<i>Distribution Totals</i>	68.28505	25.97638
<b>Warm-Water Species</b>		
<i>Stylocherion maximum</i>	0	0
<i>Stylocherion longicorne</i>	0.001649	0
<i>Stylocherion carinatum</i>	0	0
<i>Stylocherion elongatum</i>	0	0.007732
<i>Stylocherion abbreviatum</i>	0	0
<i>Stylocherion affine</i>	0	0.065826
<i>Stylocherion Suhmi</i>	0	0.042597
<i>Euphausia mutica</i>	0	0.010514
<i>Euphausia tenera</i>	0	0
<i>Euphausia americana</i>	0	0.028695
<i>Euphausia pseudogibba</i>	0.001346	0
<i>Euphausia hemigibba</i>	0	0
<i>Euphausia gibboides</i>	0	0
<i>Nematoscelis microps</i>	0.0058	0
<i>Distribution Totals</i>	0.008795	0.155363
<i>Euphausia spp.</i>	0	0
<i>Stylocherion spp.</i>	0	0
<i>Thysanapoda spp.</i>	0.118649	0
<i>Total Abundance</i>	68.2938	26.1317

Table C.6: Biomass (g/m<sup>3</sup>) by species collected on the SSV *Corwith Cramer*, 2009-2011.

	09-S	09-D	10-S	10-D	11-S	11-D
<b>Cold-Water Species</b>						
<i>Meganyctiphanes norvegica</i>	26.135411	0	6.96343	2.887933	1.316126	0
<i>Nematoscelis megalops</i>	21.211211	1.21543	8.38541	9.698752	0	7.139803
<i>Thysanoessa longicaudata</i>	0	0	0	0.179944	0.492561	0.16239
<i>Thysanoessa gregaria</i>	0.071507	0.251217	2.060835	0.266184	0	5.68911
<i>Thysanapoda acutifrons</i>	0	0	0	0	0	0
<i>Euphausia krohnii</i>	21.03513	1.210513	1.153971	0.966594	2.425823	4.369043
<i>Distribution Totals</i>	68.45326	2.67716	18.56365	13.99941	4.23451	17.36035
<b>Warm-Water Species</b>						
<i>Stylocherion maximum</i>	0	0	0	0	0	0
<i>Stylocherion longicorne</i>	0	0.034684	0	0	0	0
<i>Stylocherion carinatum</i>	0	0	0	0	0	0
<i>Stylocherion elongatum</i>	0.031638	0.115191	0.760135	0.014096	0	1.197252
<i>Stylocherion abbreviatum</i>	0	0.043649	0	0	0.224071	0
<i>Stylocherion affine</i>	0.253902	0.110301	0	0	0	0
<i>Stylocherion Suhmi</i>	0.05549	0.157541	0	0	0	0
<i>Euphausia mutica</i>	0	0	0	0.508341	0	0
<i>Euphausia tenera</i>	0	0	0	0	0	0
<i>Euphausia americana</i>	0	0	0	0.071134	0	0
<i>Euphausia pseudogibba</i>	0	0	0	0	0	0
<i>Euphausia hemigibba</i>	0	0	0	0	0	0
<i>Euphausia gibboides</i>	0	0	0	0	0	0
<i>Nematoscelis microps</i>	0	0	0	0	0	0
<i>Distribution Totals</i>	0.34103	0.461366	0.760135	0.593571	0.224071	1.197252
<i>Euphausia spp.</i>	0	0	0	0	0	0
<i>Stylocherion spp.</i>	0	0	0	0	0	0
<i>Thysanapoda spp.</i>	0	0	0	0	0	0
<i>Total Abundance</i>	68.7943	3.13853	19.3238	14.593	4.45858	18.5576

Table C.7: Biomass (g/m<sup>3</sup>) by species collected on the SSV *Corwith Cramer*, 2012-2013.

	12-S	12-D	13-S	13-D
<b>Cold-Water Species</b>				
<i>Meganyctiphanes norvegica</i>	20.577513	13.744459	0.6524	0
<i>Nematoscelis megalops</i>	15.325581	20.443192	0	6.955379
<i>Thysanoessa longicaudata</i>	2.857049	0	20.5942	0.16195
<i>Thysanoessa gregaria</i>	0	0	0	0
<i>Thysanapoda acutifrons</i>	4.350076	8.498293	15.920942	6.886439
<i>Euphausia krohnii</i>	9.803173	2.400351	39.343027	3.164105
<i>Distribution Totals</i>	52.91339	45.0863	75.85817	17.16787
<b>Warm-Water Species</b>				
<i>Stylocherion maximum</i>	0	0	0	0
<i>Stylocherion longicorne</i>	0	0	0	0
<i>Stylocherion carinatum</i>	0.199125	0	0	0
<i>Stylocherion elongatum</i>	0	0	1.070482	0
<i>Stylocherion abbreviatum</i>	0	0	0	0
<i>Stylocherion affine</i>	0	0	0	0
<i>Stylocherion Suhmi</i>	0	0	0	0
<i>Euphausia mutica</i>	0	0	0	0.120372
<i>Euphausia tenera</i>	0	0	0	0
<i>Euphausia americana</i>	0	0	0	0
<i>Euphausia pseudogibba</i>	0	0	0	0
<i>Euphausia hemigibba</i>	0	0	0	0
<i>Euphausia gibboides</i>	0	0	0	0
<i>Nematoscelis microps</i>	0	0	0	0
<i>Distribution Totals</i>	0.199125	0	1.070482	0.120372
<i>Euphausia spp.</i>	0	0	0	0
<i>Stylocherion spp.</i>	0	0	0	0
<i>Thysanapoda spp.</i>	0	0	0	0
<i>Total Abundance</i>	53.1125	45.0863	76.9287	17.2882

Table C.8: Biomass (g/m<sup>3</sup>) by species collected on the R/V *Connecticut*.

	WSS-S	WSS-D	AC-S	AC-D	VC-S	VC-D	ESS-S	ESS-D
<b>Cold-Water Species</b>								
<i>Meganyctiphanes norvegica</i>	26.56169	0	23.93784	0.047027	21.64743	3.098175	3.397349	0
<i>Nematoscelis megalops</i>	13.5715	0.5808	5.856993	0.929114	94.02888	15.03049	13.83277	2.348204
<i>Thysanoessa longicaudata</i>	16.53118	0.037977	1.422552	0.657862	4.320867	9.102059	8.11356	1.234648
<i>Thysanoessa gregaria</i>	0.530335	0.00213	0.374296	0.490781	0	0.017987	2.874506	0.072761
<i>Thysanapoda acutifrons</i>	0	0	0	0	0	0	0.098506	0
<i>Euphausia krohnii</i>	4.215071	1.488289	23.62372	0.313849	1.189165	8.123851	15.75993	1.472637
<i>Distribution Totals</i>	61.40978	2.109196	55.2154	2.438632	121.1863	35.37256	44.07663	5.12825
<b>Warm-Water Species</b>								
<i>Stylocherion maximum</i>	0	0	0	0	0	0	0	0.002022
<i>Stylocherion longicorne</i>	0	0.048449	0	0	0	0	0	0
<i>Stylocherion carinatum</i>	0.227265	0.017963	0	0.016422	0	0.001444	0	0
<i>Stylocherion elongatum</i>	0	0	0	0.030264	0	0	0	0
<i>Stylocherion abbreviatum</i>	0.17901	0.017976	0.521517	0.034276	0	0	0	0
<i>Stylocherion affine</i>	0	0.000229	0	0	0	0	0	0
<i>Stylocherion Suhmi</i>	0	0.001079	0	0.003717	0	0	0	0
<i>Euphausia mutica</i>	0.216384	0.035514	4.469265	0.006238	0	0	0.528754	0.013396
<i>Euphausia tenera</i>	0	0.117693	0	0.006366	0	0	0	0
<i>Euphausia americana</i>	0	0	0	0	0	0	0	0
<i>Euphausia pseudogibba</i>	0	0	0	0	0	0	0	0
<i>Euphausia hemigibba</i>	0	0.114773	0	0.027823	0	0	0	0
<i>Euphausia gibboides</i>	0	0	0	0	0	0	0	0
<i>Nematoscelis microps</i>	0.468637	0.206697	1.021524	0.171223	0	1.682274	0.827365	0.2497
<i>Distribution Totals</i>	1.091296	0.560373	6.012307	0.296327	0	1.683718	1.356119	0.265118
<i>Euphausia spp.</i>	0	0	0	0	0	0.000565	0	0
<i>Stylocherion spp.</i>	0	0.000147	0	0	0	0.002476	0	0
<i>Thysanapoda spp.</i>	0	0.024523	0	0	0	0	0	0
<i>Total Abundance</i>	62.5011	2.69424	61.2277	2.73496	121.186	37.0593	45.4327	5.39337

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