OCS Study
BOEM 2018-035

Sperm Whale Acoustic Prey Study in the Northern Gulf of Mexico

U.S. Department of the Interior
Bureau of Ocean Energy Management
Gulf of Mexico OCS Region

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ABOUT THE COVER

Photo of two sperm whales taken during the 2012 tagging cruise (NOAA/SEFSC MMPA Permit # 779-1633).

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ABBREVIATIONS AND ACRONYMS

AWT	Aleutian wing trawl
BOEM	Bureau of Ocean Energy Management
BSS	Beaufort sea state
CTD	conductivity, temperature, depth sensor
CV	coefficient of variation
DMSO	dimethyl sulfoxide
DWH	*Deepwater Horizon*
EEZ	Economic Exclusivity Zone
FSCS	Fisheries scientific computing system
GMT	Greenwich Mean Time
Gulf	Gulf of Mexico
HSMRT	High speed midwater rope trawl
mtDNA	mitochondrial DNA
NASC	Nautical Area Scatter Coefficient
NOAA	National Oceanic and Atmospheric Administration
QA/QC	quality assurance/quality control
SEFSC	Southeast Fisheries Science Center
SI	stable isotope
SNR	Signal to Noise Ratio
SSHa	Sea surface height anomaly
SST	sea surface temperature
SWAPS	Sperm Whale Acoustic Prey Study
SWSS	Sperm Whale Seismic Study
TLE	Trophic level enrichment
XBT	expendable bathythermograph

1.0 INTRODUCTION

1.1 BACKGROUND

1.1.1 Sperm Whales in the Northern Gulf of Mexico

Sperm whales (*Physeter macrocephalus*) are protected by both the Endangered Species Act and the Marine Mammal Protection Act. They are present throughout the Gulf of Mexico (Gulf) year-round. Data collected from photo-identification studies, tag telemetry studies, analysis of acoustic behaviors (codas) and genetic studies demonstrate that the female northern Gulf population is distinct from other North Atlantic sperm whale populations (Engelhaupt et al. 2009). Sperm whales in the Gulf are 1.5–2.0 meters smaller in total length and occur in smaller groups when compared to whales in other areas (Jaquet and Gendron 2009). A study of mitochondrial DNA (mtDNA) found significant genetic differences between Gulf sperm whales and populations in the western North Atlantic, North Sea, and Mediterranean Sea. However, there was no significant differentiation in nuclear DNA, indicating that mature male sperm whales move in and out of the Gulf and breed with females there (Engelhaupt et al. 2009). Available data also indicate relatively little exchange between Gulf sperm whales and adjacent populations in the Caribbean (Gero et al. 2007).

The northern Gulf is one of the most heavily industrialized bodies of water in the world for energy exploration. There are approximately 4,000 offshore oil platforms and 25,000 miles of active oil and gas pipeline on the sea floor. The majority of these resources are concentrated on the Continental Shelf and the Continental Shelf Break west of the Mississippi River. There is extensive and ongoing exploration for additional energy resources over continental slope waters. These exploration activities typically use air-gun arrays that radiate high intensity, broad-band frequency sounds. These noise sources may result in behavioral or physiological impacts to protected marine mammals, including sperm whales. Since the 1990s, the US Department of the Interior's Bureau of Ocean Energy Management (BOEM, formerly the Minerals Management Service) has sponsored numerous studies of sperm whale abundance, spatial distribution, habitat, and response to sound sources. The most recent of these studies, before this current effort, was the Sperm Whale Seismic Study (SWSS). During SWSS, researchers conducted fieldwork between 2002 and 2005 to develop baseline information on the biology and behavior of sperm whales, characterize habitat use, and assess changes in behavior associated with exposure to sounds from seismic air-guns (Jochens et al. 2008). In April 2010, the *Deepwater Horizon* (DWH) oil spill released vast quantities of oil into oceanic, Continental Shelf, and estuarine waters of the northern Gulf. Because the wellhead was located in Mississippi Canyon, oil was released directly into habitats routinely used by sperm whales. This current study, which included sampling during the spring of 2010, provides information on habitat use and prey resources just before the DWH spill and builds on the previous work conducted during SWSS.

The current abundance estimate for the portion of the sperm whale population that lives in the northern Gulf (within the U.S. Economic Exclusivity Zone [EEZ]) is 763 animals (coefficient of variation [CV] = 0.38, Waring et al. 2014), based on a large vessel survey conducted in the summer of 2009. Historically, sperm whale abundance estimates for the northern Gulf have included 530 animals from 1991–1994, 1,349 animals from 1996–2001 (Mullin and Fulling

2004), and 1,655 animals from 2003–2004 (Mullin 2007). The variation among these estimates is likely a function of survey design, weather conditions encountered during the different surveys, and, perhaps, underlying variation in the spatial distribution of sperm whales.

A more recent analysis summarized the abundance and spatial distribution of sperm whales in the northern Gulf based on large vessel surveys conducted in the summer of 2003, spring of 2004, and summer of 2009 (SEFSC unpublished). Distance analysis methods that included covariates in the sighting detection function (Marques and Buckland 2004) were used to estimate the detection probability of sperm whales during these surveys; information on sperm whale dive-surface behavior was incorporated into these estimates to partially correct for the probability that whales were below surface (i.e., availability bias). Remotely sensed environmental predictor variables were used in a log-linear generalized additive modeling (GAM) framework to derive species-environment relationships and develop monthly prediction maps that show the expected density of sperm whales based upon environmental conditions.

Based on this analysis, the average abundance of sperm whales in the northern Gulf was 1,147 (CV = 0.18; SEFSC unpublished). The habitat model identified a bimodal distribution of sperm whales with respect to bathymetry, with high concentrations of animals along the outer edge of the shelf break, lower densities at intermediate depths, and higher densities in deep waters of the inner continental slope (Figure 1). This is consistent with previous studies that have noted a high concentration of sperm whales in the Mississippi Canyon-DeSoto Canyon region (Figure 2).

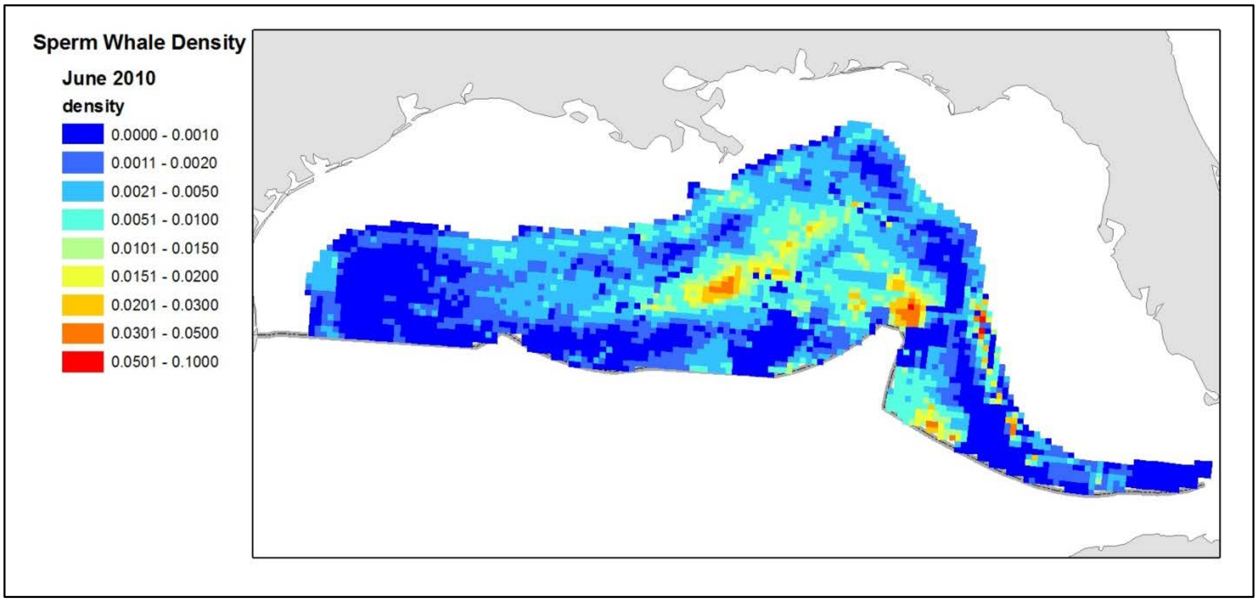

Figure 1. Predicted sperm whale density from a habitat model based on vessel data collected during 2003–2009.

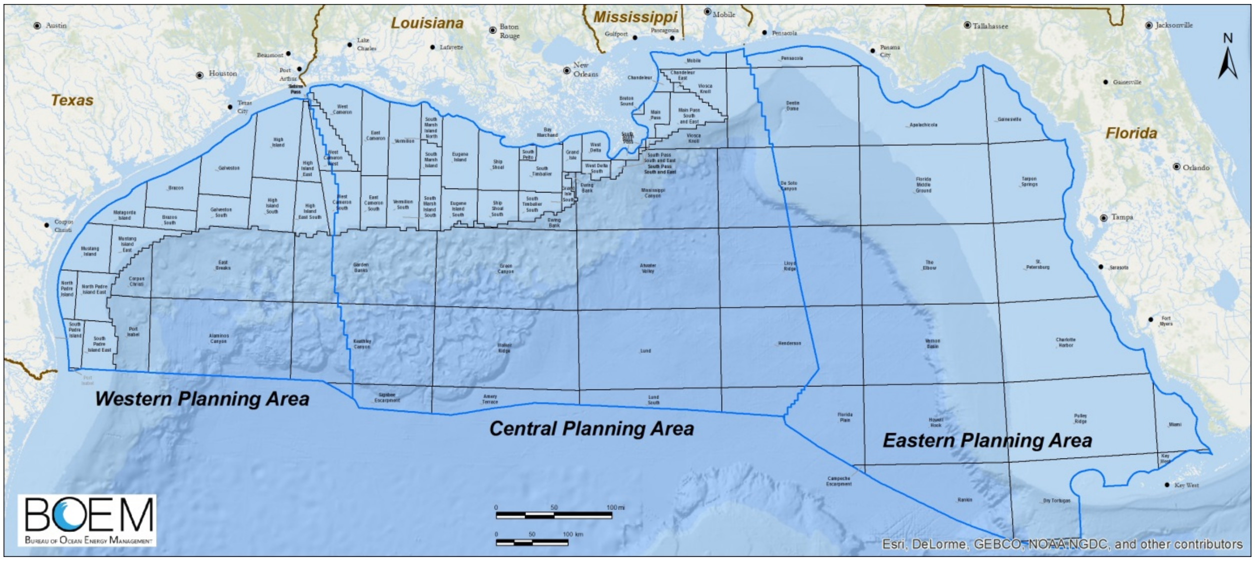

Figure 2. Mississippi Canyon and DeSoto Canyon regions

Analyses of sperm whale spatial distribution during the first two years of the SWSS cruises (2002 and 2003) and from studies done in the summers of 2000 and 2001, demonstrated a strong relationship between sperm whale occurrence and mesoscale physical features. Most notably, Loop Current eddies and cyclonic circulation along the 1000m isobath in the central northern Gulf resulted in locally elevated surface chlorophyll concentrations. Under these conditions, there were localized high densities of sperm whales (Biggs et al. 2005). Localized acoustic studies of sperm whale distribution during the SWSS studies demonstrated that areas of high sperm whale density were also related to elevated levels of back-scatter from scientific echosounders as an indicator of the biomass of prey resources at depth (Jochens et al. 2008).

Studies of sperm whale diving behavior conducted during SWSS demonstrated that the depth range between 400–600m was most consistently associated with sperm whale dives and acoustic behavior consistent with feeding. Data from scientific echosounders (70 kilohertz [kHz] and 38 kHz Simrad EK60) indicated two primary scattering layers in regions where feeding sperm whales were observed. The first consisted of vertically migrating organisms at depths between 350–550m during the day and rose near the surface at night. The second layer was more horizontally patchy, but had high acoustic backscatter levels during both day and night hours at depths greater than 500m (Jochens et al. 2008). Based on foraging dive depths, sperm whales in this region were apparently feeding near the bottom of the primary scattering layer during the daylight hours and near the top of the secondary deep scattering layer at night. The actual species composition of sperm whale prey in both scattering layers is not known, and there has been little systematic study of the deep and mid-water pelagic community of the northern Gulf.

1.1.2 Sperm Whale Diet and Squid Resources in the Northern Gulf of Mexico

The diets of sperm whales globally are presumed to be dominated by mesopelagic squid species (Clarke et al. 1993). A study of stomach contents from sperm whales in the Azores found that the modal mass of individual squid was between 400–500 g, with most taxa typically having mantle lengths between 100–300 mm (Clarke et al. 1993). A study of sperm whale diets inferred from both stranded animals and fecal collections in the northern Gulf found species composition similar to that of the Azores study; however, estimated individual prey sizes were inferred to be smaller. Gut contents from four stranded animals and fecal material collected from seven free swimming whales included squid prey from 13 species within 10 families. The diets were dominated by histioteuthid squids that were inferred (from the measured dimensions of beaks) to have a mean mantle length of 80 mm (range: 60–90 mm) and an average mass of 194 g (range: 99–303 g, Barros et al. 2003). A study of carbon and nitrogen stable isotopes (SIs) in the tissues of sperm whales also provided insight into their trophic ecology. Sperm whale skin samples collected from the Gulf of California had significantly higher ^{15}N enrichment (average $\delta^{15}N$ = 19.7‰) and ^{13}C enrichment (average $\delta^{13}C$ = -14.0‰) compared to Gulf sperm whales with average $\delta^{15}N$ = 12.2‰ and average $\delta^{13}C$ = -16.4‰ (Ruiz-Cooley et al. 2012; Ruiz-Cooley et al. 2004). These differences in isotopic ratios primarily reflected regional differences in the sources of carbon and nitrogen isotopes, but they may also indicate differences in the trophic positions of sperm whales in their respective ecosystems. Diet information from the Gulf of California indicated a predominance of the jumbo squid (*Dosidicus gigas*) with mantle lengths greater than 60 cm. In contrast, the available data from the Gulf, both in stomach contents (Barros et al. 2003) and SI studies (Ruiz-Cooley et al. 2012), suggested that feeding is predominantly on smaller squid prey.

There have been few comprehensive studies of cephalopod taxa in the Gulf. A monograph by Voss (1956) was the first review of available information that identified 42 species inhabiting the Gulf; it was based upon collections made in the 1950s. Salcedo-Vargas (1991) reviewed the available collections in light of revisions to the taxonomy and published a checklist of 71 species from 31 families. Ongoing revisions to mid-water cephalopod taxonomy complicate identification. Most recently, the taxonomy of the broader Atlantic Ocean was reviewed by Vecchione (2002) and further updated by Judkins (2009). Based on the taxonomy provided in Vecchione (2002), Judkins (2009) identified 93 species of cephalopoda occupying the broader Caribbean and Gulf. Most of these species undergo some degree of vertical migration and occur in the feeding depths of sperm whales. Of these species, many are small or have high water content, so it may be expected that sperm whale diets are restricted to more muscular taxa (e.g., Ommastrephidae, Histioteuthidae, and Carangidae) and there are likely less frequent interactions with larger taxa including *Architeuthis dux* and *Asperoteuthis acanthoderma*. However, very little is known about the distribution and relative occurrence of squid taxa within the regions where sperm whales concentrate and feed.

1.2 STUDY OBJECTIVES

The primary goal of this study was to characterize the prey field available to sperm whales in the northern Gulf and assess the spatial and vertical distribution of prey in mesopelagic waters at depths between 300–800 m. Specifically, the project goals were to:

1) Quantify the taxonomic composition of potential sperm whale prey in deep scattering layers through acquisition of scientific echosounder data and mid-water trawl sampling at fixed stations.

2) Characterize the spatial distribution of sperm whales and other marine mammals within the survey area through visual and passive acoustic monitoring

3) Identify trophic linkages between sperm whales and mesopelagic species through collection and analysis of tissue samples from sperm whales and potential prey taxa.

These study goals were accomplished using data collected during a pilot study aboard the NOAA Ship *Gordon Gunter* during summer 2009 and NOAA Ship *Pisces* January 21–March 25, 2010. During the Sperm Whale Acoustic Prey Study (SWAPS) surveys, a large-mouth, mid-water trawl was used to collect mesopelagic squids, fish, and other invertebrates at fixed stations. Visual survey data were used to quantify marine mammal spatial distribution, and scientific echosounder data was collected continuously to provide a measure of the spatial distribution of secondary production. The echosounder and trawl data were used to characterize the distribution and biomass of potential sperm whale prey in the mesopelagic community. SI analysis from trawl specimens and sperm whale biopsies were used to identify the trophic linkages between sperm whales and mesopelagic squids.

2.0 FIELD SAMPLING

2.1 SUMMER 2009 PILOT STUDY

NOAA Ship *Gordon Gunter* departed Pascagoula, Mississippi on 10 June 2009 to conduct a cetacean survey of the northern Gulf. Operations were planned for U.S. waters of the northern Gulf in depths >200 meters (m) within the U.S. EEZ, from Key West, Florida to the U.S.-Mexico border. The primary objective of this survey was to collect data to update abundance estimates for cetaceans, employing visual line-transect and passive acoustic surveys. A second objective was to conduct a pilot study to characterize sperm whale prey using fisheries acoustics equipment and a mid-water trawl. The goal of the 2009 study was to conduct test trawls to sample mid-water squids that may be sperm whale prey and to develop sampling expertise for application to a full study to be conducted during the winter of 2010.

2.1.1 Visual Survey Effort

Visual cetacean surveys were conducted between 16 June and 13 August, 2009. Standard ship-based, line-transect survey methods for cetaceans, similar to those used in the Pacific Ocean, Atlantic Ocean, and Gulf, were used (e.g., Mullin and Fulling, 2004). The survey was conducted in waters >200 m deep within the U.S. EEZ. Survey lines were stratified in relation to depth and the location of the Loop Current (Figure 3).

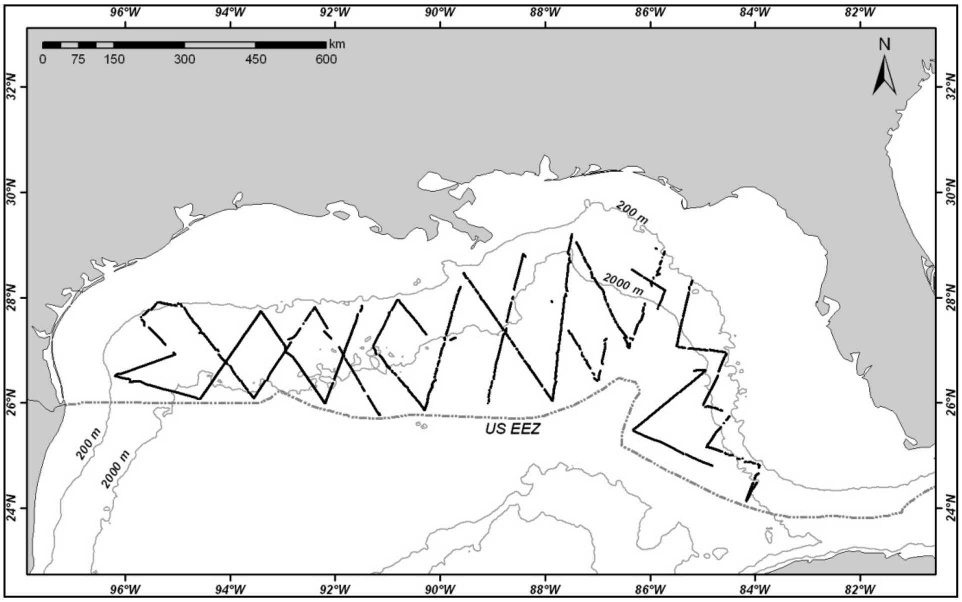

Figure 3. Tracklines surveyed during summer 2009.

A team of trained visual observers was stationed on the flying bridge (height above water = 14.7 m). The flying bridge team consisted of five to seven people rotating through three positions (left observer, data recorder, right observer) at 30 min intervals. The data recorder entered information on sightings using a data entry program interfaced with a global positioning system receiver. The left and right side observers searched to the horizon in the arc from 10° right and left of the ship's bow to the left and right beams (90°), respectively, using 25x "bigeye" binoculars. The data recorder searched using unaided eye or 7x hand-held binoculars. At least one observer experienced in ship-based, line-transect methods and identification of cetaceans was present on the flying bridge at all times.

For each cetacean sighting, time, position, bearing and reticle (a measure of radial distance) of the sighting, species, group size, behavior, bottom depth, sea surface temperature, and associated animals (e.g., seabirds, fish) were recorded. The bearing and radial distance for groups sighted without 25x binoculars and close to the ship were estimated. Survey effort data were automatically recorded every 30 seconds and included the ship's position and heading, effort status, observer positions, wind speed and direction, water depth, and temperature. Environmental conditions, which could affect the observers' ability to sight animals (e.g., Beaufort sea state [BSS], trackline glare), were updated by the data recorder every 10 min. Typically, if a sighting was within a 3.0 nautical mile (nm) strip on either side and perpendicular of the ship, the ship was diverted from the trackline to approach the group to identify species and estimate group size. Cetaceans were identified to the lowest taxonomic level possible. The group size of each cetacean group encountered was estimated independently by each of the three people on duty at the time of the sighting. Each observer recorded a best, high, and low estimate for each sighting.

Survey speed was usually18 km/hr (~10 knots) but varied with sea conditions. The effectiveness of visual line-transect survey effort is severely limited during high sea state and poor visibility conditions (e.g., fog, haze, rain). Survey effort was suspended during heavy seas (BSS > 6) and rain. Visual survey effort was conducted only during daylight hours.

2.1.2 Trawling and Sampling of Specimens

Sampling gear consisted of a 53-m (headrope length) High Speed Midwater Rope Trawl (HSMRT) and a pair of 1.8-m double-foil Suberkrub-type doors. Simrad ITI sensors were placed on the headrope and doors to monitor trawl depth and door spread. Stations were chosen adaptively and based on factors such as depth, acoustic backscatter from the EK60, mesoscale physical oceanographic features, and presence (or history of presence) of feeding sperm whales in the region. Tow duration was a maximum of 55 minutes, not including deployment and retrieval of the net.

Trawl catch data were electronically recorded at-sea with the Fishery Scientific Computing System (FSCS), version 1.6, developed by NOAA’s System Development Branch of the Office of Marine and Aviation Operations. FSCS was linked to the ship’s SCS version 4.2.3, which was used to collect metadata, including position, depth, date, time, and meteorological data. Catches were either processed in their entirety or subsampled, depending on the total catch weight. If catches exceeded 50 pounds, then a random subsample of at least 10% of the catch was taken. Catches (or subsamples) were sorted by species, enumerated and weighed. For specimens identified down to species level, length measurements were also recorded. Specimens that could not be identified to species level were frozen or preserved in 10% buffered formalin and brought back to the Pascagoula [Mississippi] Laboratory for identification. Tissue samples of selected species were collected and stored for genetic and/or SI analysis. A total of 23 midwater trawls were conducted during the survey (Figure 4). Trawl locations and times are shown in Table 1.

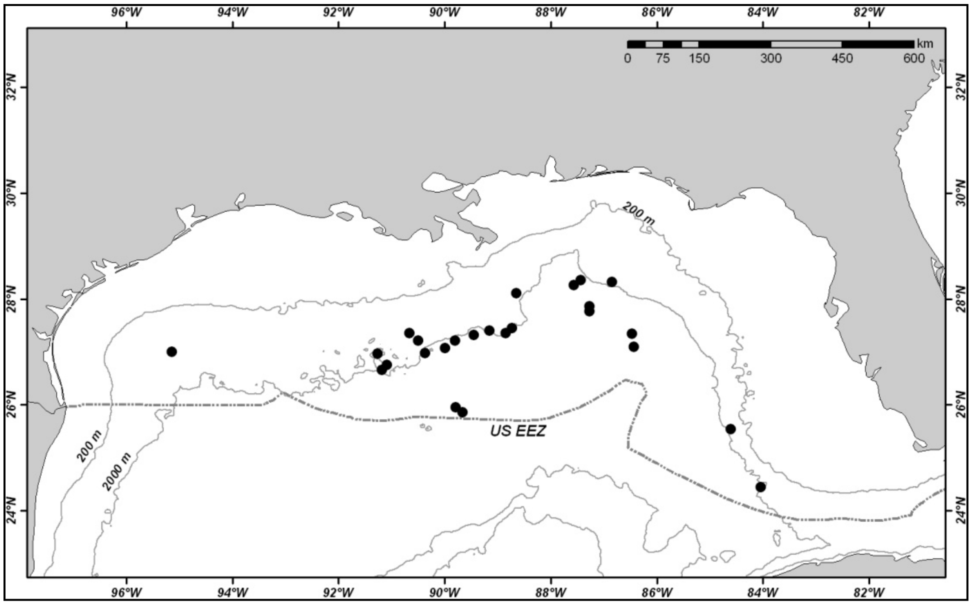

Figure 4. Midwater trawling locations during summer 2009.

Table 1. Midwater trawls conducted during summer 2009.

Times are Greenwich Mean Time (GMT).

Station ID	Start Date-Time	End Date-Time	Start Lat	Start Lon	End Lat	End Lon	Tow Speed (knots)	Tow Duration (min)	Total Catch (kg)
11	6/13/09 15:56	6/13/09 16:28	28.2630	-87.5628	28.2323	-87.5787	3.7	32.6	0.23
14	6/13/09 23:42	6/13/09 23:59	27.8723	-87.2678	27.8573	-87.2607	3.5	16.7	4.17
17	6/14/09 12:30	6/14/09 13:11	27.7695	-87.2750	27.7282	-87.2752	3.6	41.0	2.58
23	6/14/09 21:41	6/14/09 22:21	28.3577	-87.4317	28.3923	-87.4332	3.1	40.3	1.59
34	6/21/09 0:05	6/21/09 0:45	25.5488	-84.6068	25.5330	-84.6433	3.8	40.7	0.23
37	6/22/09 22:56	6/22/09 23:47	24.4540	-84.0378	24.4715	-84.0945	3.9	50.3	0.75
40	7/3/09 16:54	7/3/09 17:46	27.3517	-86.4717	27.2972	-86.4460	4.5	51.4	0.92
43	7/9/09 16:26	7/9/09 17:19	27.3612	-88.8493	27.3043	-88.8357	4.0	52.6	1.83
46	7/2/09 23:55	7/3/09 0:41	27.0998	-86.4318	27.0392	-86.4303	4.8	46.3	0.25
52	7/17/09 1:16	7/17/09 2:12	27.4523	-88.7350	27.5042	-88.7313	3.4	55.4	3.67
55	7/28/09 19:19	7/28/09 20:14	27.4110	-89.1522	27.4157	-89.0885	3.8	55.3	7.65
58	7/29/09 15:26	7/29/09 16:21	25.8650	-89.6553	25.8162	-89.6377	3.4	55.2	3.69
61	7/29/09 20:17	7/29/09 21:12	25.9597	-89.7950	26.0055	-89.7495	4.0	55.7	3.02
67	7/30/09 14:15	7/30/09 15:10	27.3547	-90.6637	27.3005	-90.6577	3.6	54.7	1.67
70	7/30/09 18:57	7/30/09 19:53	27.2142	-90.4900	27.1623	-90.5027	3.4	55.7	2.94
73	7/30/09 23:21	7/31/09 0:11	26.9838	-90.3663	26.9275	-90.3558	4.1	50.9	40.91
76	8/4/09 23:18	8/5/09 0:08	27.0028	-95.1408	27.0317	-95.1917	3.8	50.5	7.51
79	8/10/09 13:07	8/10/09 13:57	26.6655	-91.1770	26.7127	-91.1718	3.4	50.4	2.26
82	8/10/09 17:38	8/10/09 18:34	26.9712	-91.2567	26.9648	-91.3123	3.2	55.3	3.44
85	8/11/09 4:04	8/11/09 4:54	26.7552	-91.0842	26.7987	-91.0497	3.8	50.5	4.50
88	8/11/09 15:08	8/11/09 16:04	27.0757	-89.9927	27.0412	-89.9470	3.5	55.7	2.48
91	8/11/09 23:11	8/12/09 0:06	27.3207	-89.4507	27.2790	-89.3875	4.6	54.8	12.81
94	8/12/09 14:26	8/12/09 15:22	28.1192	-88.6457	28.0868	-88.5957	3.6	55.4	2.64

2.2 WINTER-SPRING 2010 SURVEY

NOAA ship *Pisces* departed Pascagoula, Mississippi, on 29 January 2010 to conduct a cetacean survey of the northern Gulf. Operations were planned for U.S. waters in depths >200 meters (m) within the U.S. EEZ, focusing on sperm whale habitats in the eastern and central Gulf. The primary objective of this survey was to characterize sperm whale prey using fisheries acoustics equipment and a mid-water trawl and to collect visual data on sperm whale distribution during the survey period. The first leg of the survey (through 10 February) experienced very poor weather conditions, which limited the capability to conduct visual surveys. Mid-water trawls were conducted in the western portion of the operational area during this leg. Trawl sampling and visual surveys were conducted in the central portion of the survey area during leg 2 from 17 February–2 March. Leg 3 (9 March–25 March) included sampling in both the eastern Gulf and in the southeastern Gulf just north of the Dry Tortugas.

Visual survey methods were the same as those described above for the summer 2009 pilot study. However, due to the difference in cruise objective, large scale systematic visual survey tracklines were not conducted. Accomplished visual surveys are shown in Figure 5.

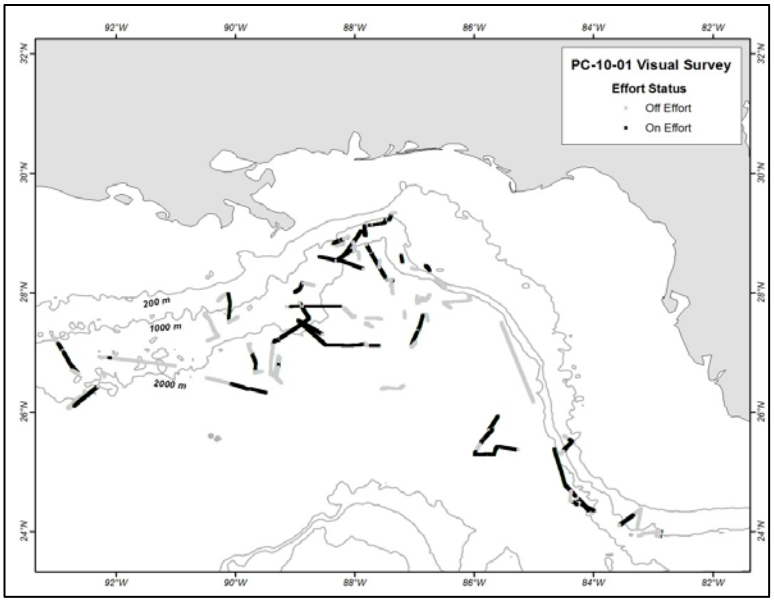

Figure 5. Visual survey effort during winter-spring 2010.

Small Boat Sampling

A 7-m rigid hull inflatable boat was launched as weather and opportunity allowed to collect sperm whale biopsy samples, scat samples, behavioral information, and photo-identification data. During small boat operations, both passive acoustic and visual monitoring were conducted to assist in the location and tracking of sperm whale groups.

Biopsy tissue samples were collected from sperm whales using modified biopsy rifles or crossbows and various dart heads from the small boat or from the ship's bow. For each biopsy sample collected, the skin layer was removed from the blubber and sectioned into subsamples for genetic and SI analysis. Genetic samples were stored in small vials of 20% dimethyl sulfoxide (DMSO) at room temperature or in a refrigerator. Samples for SIs were stored in clean vials and frozen at -20ºC. Any collected blubber was stored at -80ºC for contaminant analysis.

XBT-CTD data collection

Hydrographic profile sampling was conducted throughout the survey to characterize sub-surface water column structure that may influence the spatial distribution, biomass, and availability of sperm whale prey. Conductivity, temperature, depth sensor (CTD) profiles were conducted to depths of 1,000m in association with trawl stations, during early morning and evening each day, and in areas of high sperm whale density. Processed CTD data include salinity, temperature, and dissolved oxygen content at 1m intervals throughout the cast depth range. In addition, expendable bathythermograph (XBT) profiles were collected while underway throughout the survey. These probes recorded temperature to a maximum sampling depth of 750m.

2.2.1 Trawl Gear and Sampling

Midwater fish and squids were sampled using an Aleutian wing 30/26 trawl (AWT). This trawl was constructed with full-mesh nylon wings, and polyethylene mesh in the codend and aft section of the body. The headrope and footrope each measured 81.7m (268 ft). Mesh sizes tapered from 325.1cm (128 in) in the forward section of the net to 8.9cm (3.5 in) in the codend, where it was fitted with a single 12mm (0.5 in) codend liner. The AWT was fished with 5 m^2 Fishbuster trawl doors each weighing 1,089 kg. For AWT hauls, the vertical net opening ranged from 13 to 32m and averaged 25m. Detailed specifications for the trawl are provided in Honkalehto et al. (2002). The mid-water trawl was fished at target depths between 500m and 800m, with a total tow time at depth of two hours. Sensors attached to the trawl were monitored continuously throughout deployment to verify fishing depth, wing spread, and mouth opening. Because these sensors communicate acoustically with the vessel, there was frequent signal loss. Therefore, continuous recording depth sensors were attached to the head rope and footrope of the trawl to provide a continuous record of fishing depth and mouth opening.

The survey was designed along uniformly spaced "zig-zag" tracklines covering the northern Gulf, including waters where high densities of sperm whales were observed in previous surveys conducted by the Southeast Fisheries Science Center (SEFSC) and from reports by protected species observers stationed on seismic and other vessels. The planned stations were spaced at 50–60 km intervals in waters from the 300m isobath to the U.S. EEZ (Figure 6).

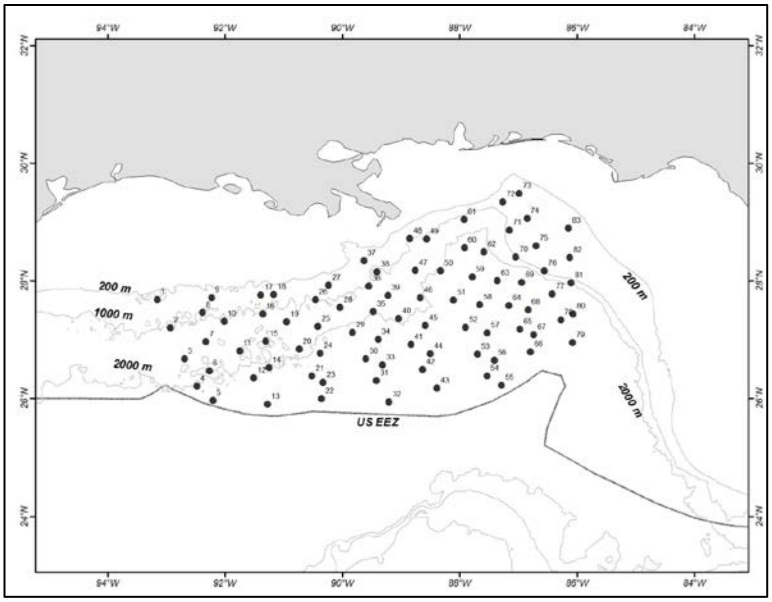

Figure 6. Locations of planned trawl stations during the winter-spring 2010.

Because weather conditions prevented the completion of all planned stations, limited numbers of stations were sampled west of the Mississippi River Delta. During a period of extended bad weather, the survey effort was modified to include a set of sampling stations in the southeastern Gulf, where there is a well documented aggregation of sperm whales that is a possible calving population. The resulting survey effort included areas of sperm whale aggregations in the western, central, and southeastern Gulf (Figure 7, Table 2).

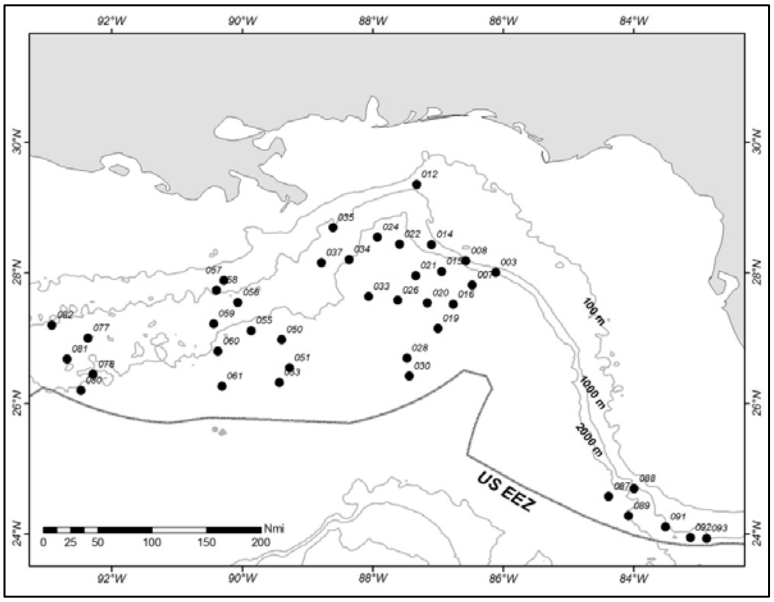

Figure 7. Midwater trawls conducted during winter-spring 2010.

Table 2. Trawl locations and depths during winter-spring 2010.

Missing fishing depths indicate tows where depth sensors failed.

Station ID	Start Date-Time	End Date-Time	Start Lat	Start Lon	End Lat	End Lon	Tow Speed (knots)	Tow Duration (min)	Total Catch (kg)	Fishing Depth (m)
003	3/10/10 11:52	3/10/10 13:52	27.9969	-86.1176	27.9031	-86.0625	3.2	119.5	3.5	650
007	3/10/10 20:28	3/10/10 22:28	27.8105	-86.4740	27.7535	-86.3998	2.7	119.9	8.4	900
008	3/9/10 21:25	3/9/10 23:27	28.1782	-86.5730	28.1089	-86.4807	3.2	122.2	10.2	750
012	2/20/10 23:26	2/21/10 1:26	29.3416	-87.3279	29.3357	-87.1837	3.8	119.7	12.8	550
014	2/21/10 17:33	2/21/10 19:33	28.4240	-87.0979	28.3902	-86.9652	3.7	119.7	9.4	720
015	2/22/10 11:53	2/22/10 13:53	28.0149	-86.9435	27.8974	-86.9586	3.6	120.1	14.9	750
016	2/23/10 12:29	2/23/10 14:29	27.5098	-86.7673	27.6123	-86.7862	3.2	119.6	10.7	980
019	2/23/10 22:44	2/24/10 0:44	27.1396	-87.0035	27.2046	-86.9433	2.6	119.9	6.3	1000
020	2/24/10 12:05	2/24/10 14:07	27.5294	-87.1618	27.6591	-87.1630	3.9	121.8	14.7	620
021	2/25/10 12:17	2/25/10 14:17	27.9509	-87.3418	28.0615	-87.3751	3.5	120.1	11.0	800
022	2/27/10 12:36	2/27/10 14:36	28.4308	-87.5884	28.5405	-87.5732	3.3	119.8	6.2	800
024	2/27/10 20:38	2/27/10 22:32	28.5393	-87.9261	28.3954	-87.5612	3.7	114.0	7.0	760
026	3/23/10 14:11	3/23/10 16:11	27.5732	-87.6180	27.5749	-87.7656	3.9	120.1	16.4	
028	3/20/10 10:46	3/20/10 12:46	26.6914	-87.4749	26.6593	-87.4865	1.4	120.1	0.7	1600
030	3/24/10 11:10	3/24/10 13:10	26.4147	-87.4409	26.3923	-87.5449	2.9	120.7	7.6	630
033	2/28/10 13:54	2/28/10 15:55	27.6306	-88.0655	27.7344	-88.1672	4.1	120.6	10.2	526
034	3/1/10 22:53	3/2/10 0:53	28.1990	-88.3615	28.1046	-88.2824	3.7	119.9	11.6	650
035	2/20/10 0:26	2/20/10 2:26	28.6852	-88.6105	28.7475	-88.4720	4.1	120.5	7.7	550
037	3/1/10 15:42	3/1/10 17:10	28.1497	-88.7859	28.1272	-88.6979	3.3	87.9	8.5	780
050	2/18/10 12:30	2/18/10 14:30	26.9688	-89.3940	27.0940	-89.3691	3.8	120.1	11.8	690
051	2/17/10 18:55	2/17/10 20:55	26.5384	-89.2750	26.6375	-89.3802	4.1	120.0	4.5	580
053	2/4/10 12:01	2/4/10 14:01	26.3092	-89.4293	26.2667	-89.2967	3.9	119.6	3.4	500
055	2/3/10 11:43	2/3/10 13:43	27.1080	-89.8634	27.1436	-89.7652	2.8	119.5	11.7	680
056	2/2/10 20:45	2/2/10 22:31	27.5348	-90.0648	27.5913	-89.9644	3.6	106.5	2.4	580
057	2/2/10 13:34	2/2/10 15:30	27.8777	-90.2788	27.9727	-90.1625	4.4	116.4	2.9	385
058	2/1/10 21:52	2/1/10 23:53	27.7298	-90.3929	27.7465	-90.3711	3.5	122.0	8.0	480
059	2/1/10 13:47	2/1/10 15:47	27.2102	-90.4382	27.2573	-90.3251	3.4	119.5	6.8	650
060	1/31/10 19:09	1/31/10 21:21	26.7923	-90.3699	26.9084	-90.3827	3.6	132.4	6.0	
061	1/31/10 3:12	1/31/10 5:12	26.2560	-90.3100	26.3625	-90.3655	3.6	120.0	4.6	

Station ID	Start Date-Time	End Date-Time	Start Lat	Start Lon	End Lat	End Lon	Tow Speed (knots)	Tow Duration (min)	Total Catch (kg)	Fishing Depth (m)
077	2/8/10 11:52	2/8/10 14:03	26.9902	-92.3600	26.9253	-92.2599	3.1	130.6	5.6	790
078	2/7/10 11:46	2/7/10 13:46	26.4406	-92.2822	26.5683	-92.2045	4.4	119.9	5.9	570
080	2/6/10 11:52	2/6/10 13:51	26.1910	-92.4707	26.3124	-92.5220	4.0	118.7	4.6	590
081	2/5/10 22:14	2/6/10 0:15	26.6717	-92.6819	26.7246	-92.7857	3.3	120.5	7.8	740
082	2/5/10 12:27	2/5/10 14:38	27.1916	-92.9135	27.2262	-93.0457	3.4	131.1	8.1	680
087	3/17/10 21:12	3/17/10 23:12	24.5681	-84.3844	24.6736	-84.3709	3.2	120.0	6.4	
088	3/12/10 23:21	3/13/10 1:21	24.6872	-83.9940	24.6304	-84.0843	3.4	119.3	53.8	800
089	3/17/10 11:58	3/17/10 13:59	24.2724	-84.0791	24.3307	-84.0002	2.8	120.6	9.4	750
091	3/15/10 0:50	3/15/10 2:50	24.1031	-83.5151	24.1326	-83.6432	3.7	119.8	7.8	640
092	3/14/10 11:45	3/14/10 13:46	23.9390	-83.1293	23.9353	-83.2336	3.0	120.2	5.9	750
093	3/13/10 16:08	3/13/10 18:08	23.9219	-82.8858	23.9480	-82.9507	2.2	120.3	2.8	830

2.2.2 Measurement of Acoustic Backscatter

The NOAA ship *Pisces* is equipped with split-beam scientific echosounders (Simrad EK60) operating at 4 frequencies: 18 kHz, 38 kHz, 120 kHz, and 200 kHz. Of these, the 18 and 38 kHz were used to measure acoustic backscatter from targets in the operational depth of the midwater trawls. The EK60 was calibrated with standard reference spheres during the survey to provide correction factors for beam sensitivity and target strength. Calibration followed standard guidelines described in the user manuals for the scientific echosounders and recommendations from the manufacturer. Briefly, a spherical standard target is suspended at a depth of approximately 15m beneath the transducer by attaching it to three reels stationed in a triangular pattern around the vessel. This allows the position of the sphere within the transducer beam to be controlled. During the calibration, the target is moved throughout the circular beam, and the resulting strength (in decibels [dB]) of the return signal from the transducer is measured. After a large number of returns are measured, a statistical model is used to correct the returns from acoustic targets for variability in the sensitivity of the receiver throughout the beam (Foote et al. 1987). The echosounder was configured to allow multi-frequency comparison of acoustic backscatter. Multi-frequency methods are particularly useful for discriminating between different types of targets (e.g., swim-bladdered vs. non swim bladdered fish) based upon relative differences in target strength at different frequencies (e.g., Jech and Michaels 2006, Benoit-Bird et al. 2009). The EK60 echosounders were active throughout the survey, and raw data were recorded to disk for post-cruise processing. The transducer settings for the EK60 are shown in Table 3.

Table 3. Transducer settings for EK60 echosounders.

Frequency	Pulse Duration	Power
18 kHz	1024 μs	2000W
38 kHz	1024 μs	2000W
120 kHz	512 μs	500W

EK60 data were processed after the cruise first by reviewing the survey trackline and identifying segments where the vessel was moving along a straight path at survey speeds. Segments where the vessel was turning, sitting idle, or moving at low speeds were identified and removed from the analysis of average acoustic backscatter to minimize the variation in noise characteristics. The data were also reviewed during this process to identify regions or times that should be excluded from the analysis due to excess noise values, sensor failure, or the presence of echoes from the bottom (i.e., “ghost bottom”). Where shallow water occurred, automated and manual bottom detection was conducted to avoid contamination of near bottom signals. Following this quality assurance/quality control (QA/QC) process, noise removal was conducted using the procedures described in DeRobertis and Higgenbottom (2007). A 3 dB signal to noise ratio (SNR) was used in this processing step. This method estimates echosounder background-noise levels and SNRs during active pinging and does not rely on the user to define which parts of the recording to use in noise estimation thereby providing an objective measure to filter and remove data with a low SNR.

2.2.3 Catch Sampling

After completion of midwater trawl tow time and recovery of the trawl, the catch was collected from the front-end webbing and cod-end. The catch was sorted to species to the extent possible with the squid taxa separated from the other catch for individual identification, genetic sampling, SI, and contaminant sampling.

2.2.2.3.1 Fish Sampling

To the extent possible, all fish taxa were identified to species. Lengths were measured for up to 50 individuals for each taxon from each tow. If a taxon could be identified only to family or genus, all individuals were preserved frozen with the exception of individuals that were sub-sampled for SI analysis. Samples were recorded on the Trawl Bulk Sample Log.

Stable Isotope Sampling

Tissue samples were collected for up to three individuals per species from each trawl for SI analyses targeting taxa of interest. If individuals could not be identified to species, then samples from five individuals were collected for SIs. The skin was pulled back from the dorsal surface with tweezers, and a sample of dorsal muscle was collected with a scalpel without sampling fin tissue or bone. The sample was stored in a plastic screwcap SI vial and frozen at -20ºC. After sampling, the individual fish was placed in a whirl-pack with sea water and an interior label and frozen after removing as much air as possible from the bag.

2.2.2.3.2 Squid Sampling

In the field, all squids were identified to the lowest taxonomic level as possible, and mantle lengths were measured for each individual (up to a maximum of 50 lengths per taxon per tow) regardless of what level they are classified to. If specimens could not be identified to species, they were preserved in formalin (or frozen for SI samples) for later identification and noted on the Trawl Bulk Sample Log.

Genetic Sampling

Genetic biopsy samples were collected from at least one individual per species for the entire cruise. Samples were taken from mantle tissue by taking one 10mm biopsy punch. If taking a sample from the mantle was not possible, then a sample was taken from a tentacle. If the squid was very small, and taking a sample might interfere with future identification, then the entire specimen was collected for genetics by placing it in a glass vial with 95% ethanol.

All genetics samples were labeled with a unique SAMPLE ID. Every squid from which a genetics sample was taken was retained as a voucher specimen or for later identification. The squid was stored in formalin (for later transfer to 50% isopropanol) and labeled with the SAMPLE ID on interior and exterior labels.

Stable Isotope Sampling

Samples of mantle tissue were collected for SI analysis from each squid taxon in each trawl. If there was a conflict between collecting a genetic sample/voucher specimen and collecting SI samples, then the genetic sampling took precedence. For each identified species/taxon, samples from up to three individuals per haul were collected. In addition, a tissue sample was collected from any "large" individuals collected (mantle length 5–15 cm). The target sample size for each squid taxa/size class was 20 SI samples for the whole cruise.

The SI samples were collected from the mantle muscle (not the fin); and two to three 10mm punch samples were collected from each sampled individual, when possible. If possible (i.e. for larger specimens), the skin on the surface layer of the mantle was peeled back to allow sampling of the muscle tissue. Vials containing tissue samples were stored frozen at -20ºC and labeled with the SAMPLE ID. Following collection of the sample, the remainder of the body was frozen at -20º C in a whirl-pack with seawater, removing as much air as possible, and labeled with interior and exterior labels showing the SAMPLE ID.

Table 4. Summary of sample storage by taxon.

Source	Storage Type	Forms
Fish Body	Whirl-pack with seawater; Frozen	Trawl Individual Sample Log
Fish Stable Isotope	Plastic screw cap vial; Frozen	Trawl Individual Sample Log
Decapod	Whirl-pack with seawater; Frozen	Trawl Bulk Sample Log
Squid Body	Formalin (OR Frozen OR Ethanol)	Trawl Individual Sample Log
Squid Stable Isotope	Plastic screw cap vial; Frozen	Trawl Sample Sheet; Trawl Individual Sample Log
Squid Genetics	Glass vial; 95% EtOH	Trawl Sample Sheet; Trawl Individual Sample Log
Fish and Squid contaminants	Ethanol-rinsed foil, then plastic bag freeze at -80C	Trawl Sample Sheet; Trawl Individual Sample Log
Squid Biotoxins	Ziplock bag frozen at -20	Trawl Sample Sheet; Trawl Individual Sample Log

3.0 OCEANOGRAPHIC ENVIRONMENT

The distribution of primary and secondary production in oceanic waters is strongly coupled to physiographic features (e.g., bathymetry, slope) and mesoscale physical features such as the presence of persistent eddies at scales of 10–100km. The circulation patterns in the Gulf are strongly influenced by the Loop Current, an eddy of high temperature water that typically extends into the southeastern Gulf flowing with clockwise circulation and exiting through the Florida Straits. The high velocity on the northern edge of the Loop Current contributes to additional mesoscale structure in the north-central Gulf including counter-clockwise eddies that tend to advect higher productivity continental shelf waters into the offshore environment. The Loop Current will occasionally "pinch off", and the resulting eddies move through the deep oceanic Gulf from east to west and influence local circulation patterns. As these circulation patterns are variable in time, and influence the distribution of sperm whales and their prey, it was important to characterize the mesoscale circulation patterns observed at the time and place of sampling during the current study.

We characterized the features of the Gulf oceanographic environment during the summer of 2009 and winter of 2010 using remotely sensed data. For time-variant features, we characterized the physical environment at monthly time scales, since this correlated to the time scale of our sampling. Data were aggregated into a common 10 x10 km grid for analysis since the resolution of each data source varied. Two bathymetric variables and six hydrographic parameters were evaluated:

<u>Bottom depth</u>: derived from ETOPO1 digital elevation model

<u>Bottom slope (degrees):</u> calculated within ARCGIS from ETOPO grid.

<u>Sea Surface Temperature (SST)</u>: Monthly composite of sea-surface temperature from the MODIS satellite platform at 4km resolution

<u>Surface Chlorophyll concentration (CHL):</u> Monthly composite of surface chlorophyll from the MODIS satellite platform at 4km resolution

<u>Sea surface height anomaly (SSHa):</u> sea surface elevation (cm) above a reference level accounting for tidal effects. Monthly average values derived from AVISO Global Altimetry products at 1/3° resolution.

<u>Geostrophic current magnitude (MAG):</u> Average surface currents (cm/s) based upon altimetry data at 1/3° resolution. Geostrophic currents are average flows driven by variation in relative pressure across the sea surface (balanced with the Coriolis force) and can be calculated from sea surface height.

<u>Along-shelf current (Uvel):</u> Current magnitude (cm/s) in an "along-shelf" direction. Calculated by rotating the east-west (U) component of geostrophic velocity to run parallel to the smoothed 200m isobath. Positive values represent flows to the right when facing the isobath. Thus, in the

central Gulf where the 200m isobath is roughly east-west, positive values represent water movement to the east.

<u>Cross-shelf current (Vvel):</u> Current magnitude (cm/s) in a “cross-shelf” direction. Calculated by rotating the north-south (V) component of geostrophic velocity to run perpendicular to the smoothed 200m isobath. Positive values represent flows from deeper water into shallow water.

3.1 BATHYMETRY

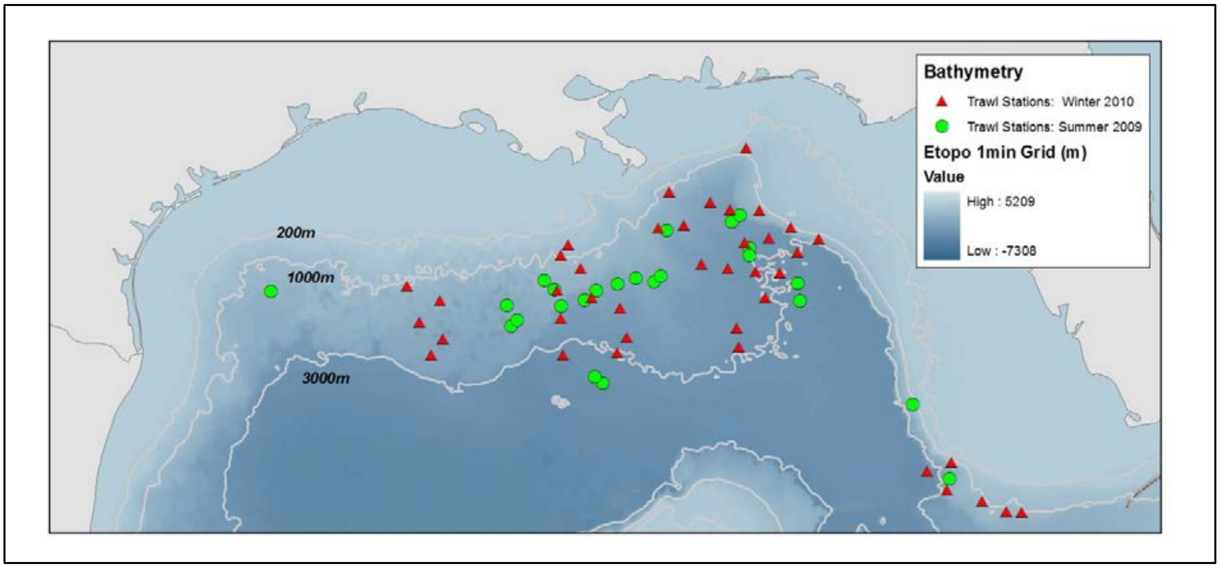

Figure 8. Bathymetry of the northern Gulf of Mexico and locations of trawl stations in summer 2009 and winter 2010.

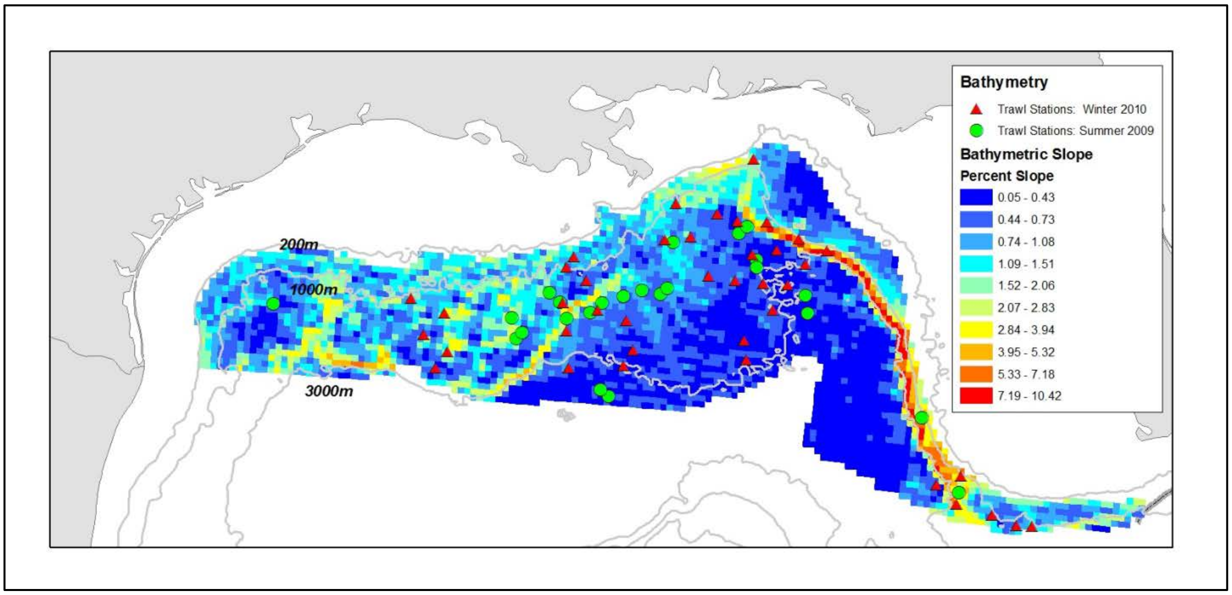

Figure 9. Bathymetric slope in the northern Gulf of Mexico and locations of trawl stations in summer 2009 and winter 2010.

Trawl sampling during both surveys was conducted over the continental slope of the north-central Gulf between the 1,000 and 3,000m isobaths, which corresponds to the primary habitat range of sperm whales. During the summer 2009 survey, sampling was concentrated along the 2,000m isobath in a region of high bathymetric slope in the deeper waters of the central Gulf. In winter 2010, sampling was conducted across a more diverse range of depths and bathymetric features including high and lower slope regions in the western Gulf, and intensive sampling in the DeSoto Canyon-Mississippi Canyon region of the central Gulf where sperm whale encounters were highest during that survey. Both surveys included trawl sampling in the southeastern Gulf just north of the Dry Tortugas, which is an area of historical occurrence of a localized aggregation of sperm whales and high bathymetric slope (Figure 8; Figure 9).

3.2 SUMMER 2009

Surface waters of the northern Gulf are characterized by nearly uniform high temperatures during summer months. During 2009, the summer surface temperature ranged between 28.2–30.2 °C with increasing and more uniform water temperatures during August than July (Figure 10). Surface chlorophyll was greatest in the northern Gulf along the shelf break in the Mississippi Canyon region, and during July a broad region of higher surface chlorophyll extended into the continental slope waters of the central Gulf (Figure 10). This region of elevated surface primary production was associated with an area of low sea surface elevation, indicating counter-clockwise circulation. This pattern weakened during August, and there was a less well defined region of low SSHa in the central Gulf and a decline in surface production (Figure 12). The position of the Loop Current, indicated by high SSHa, also appeared to shift between July and August with the Loop Current centered in the southeastern Gulf during July and then appearing to shift westward during August. This shift is reflected in the surface velocity fields with higher velocities in the southeastern Gulf in July, and then a shift westward during August with a broad distribution of high surface velocity extending east to west in the southern portion of the sampling range (Figure 13). The cross-shelf velocity field demonstrates a complex eddy structure in this region during August, with alternating flow directions (Figure 14). Trawl sampling was conducted primarily along the boundaries between these different flow regions in areas of generally low sea surface height at intermediate surface flow velocities between a broad region of lower velocity to the north and higher flows to the south. This boundary area is also associated with steep bathymetry slope, and so would be expected to be a potential area for upwelling and concentration of secondary production throughout the water column.

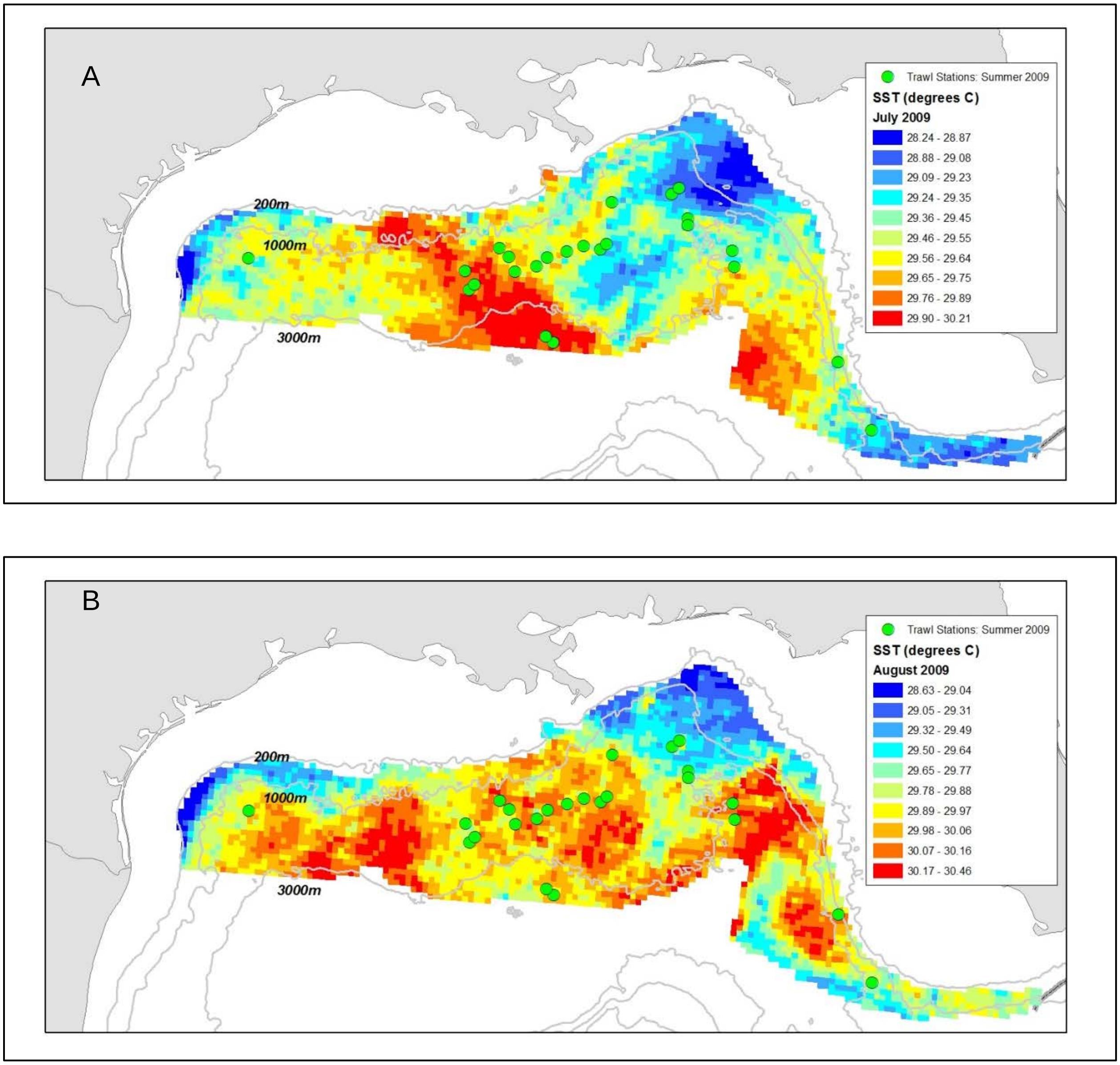

Figure 10. Sea Surface Temperature during (A) July 2009 and (B) August 2009.

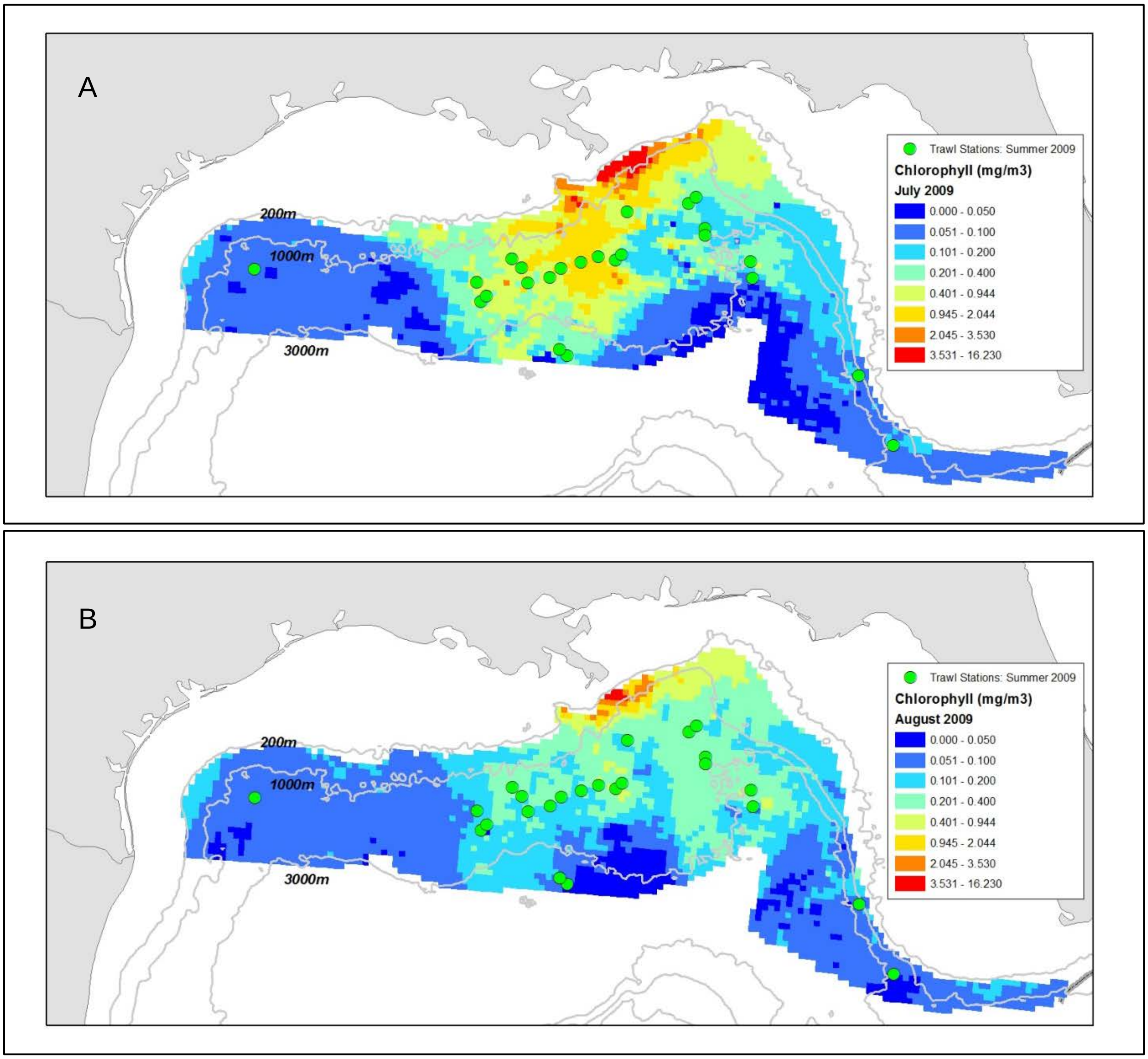

Figure 11. Surface chlorophyll during (A) July 2009 and (B) August 2009.

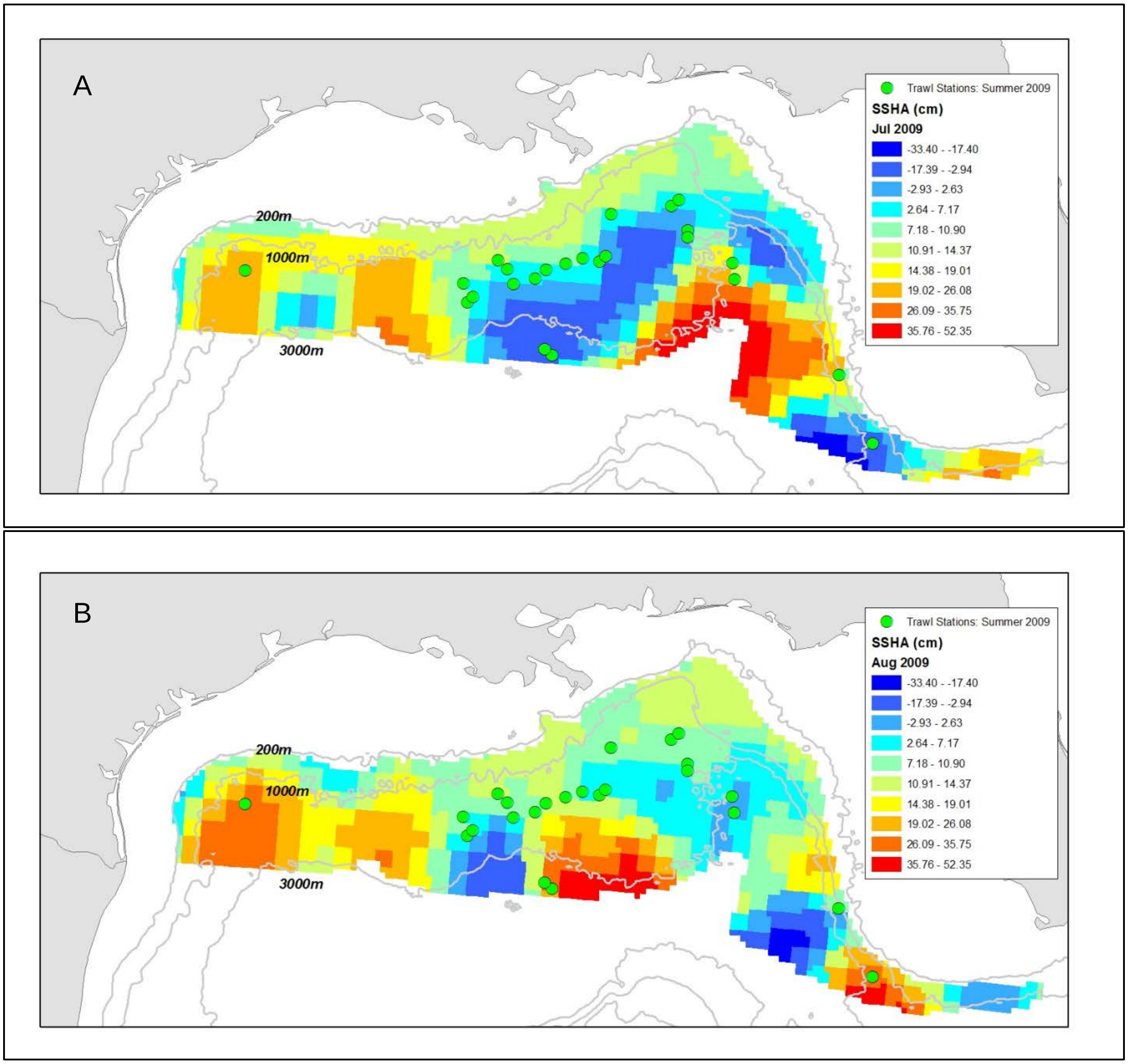

Figure 12. Sea Surface Height Anomaly during (A) July 2009 and (B) August 2009

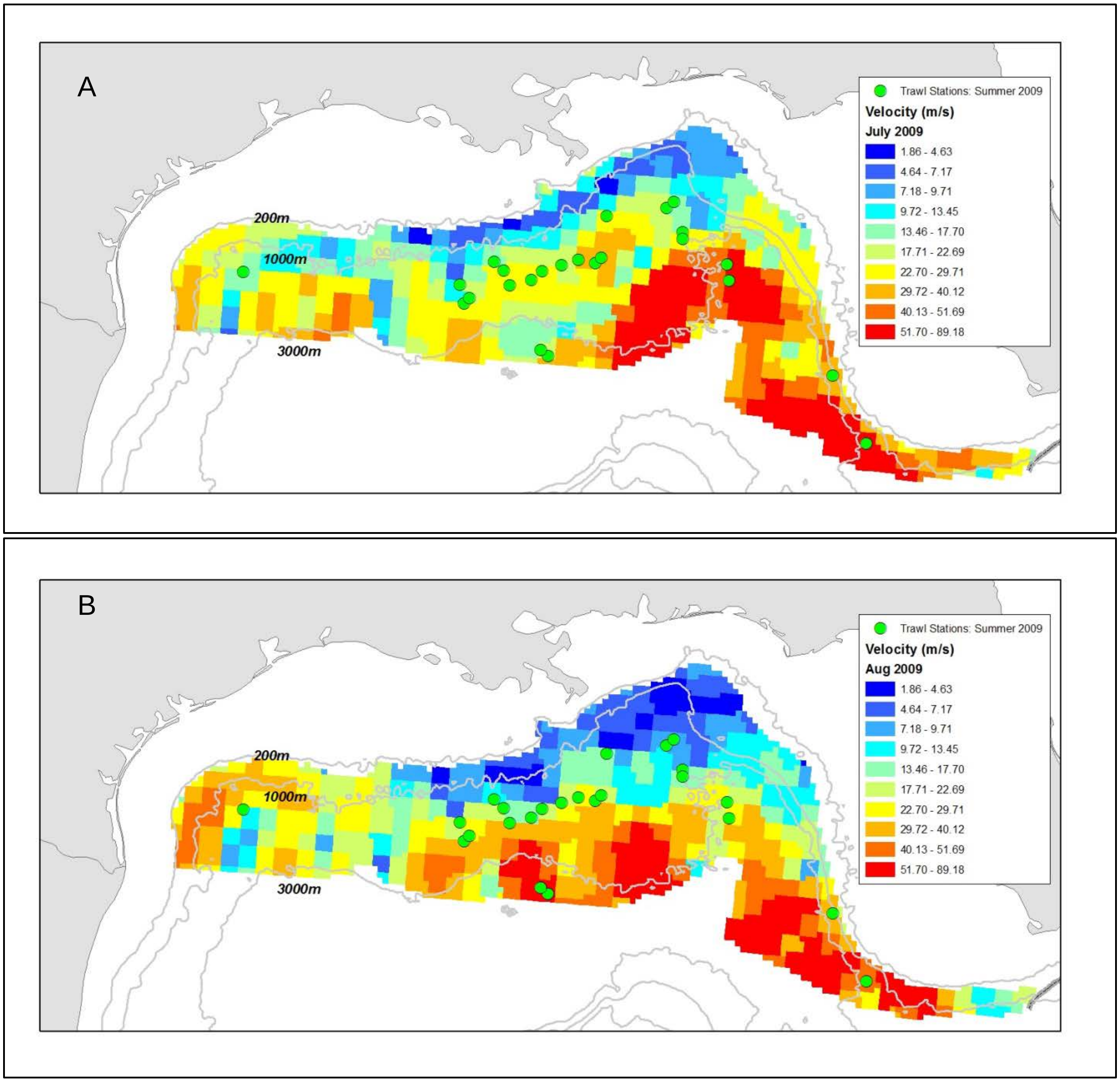

Figure 13. Geostrophic velocity during (A) July 2009 and (B) August 2009

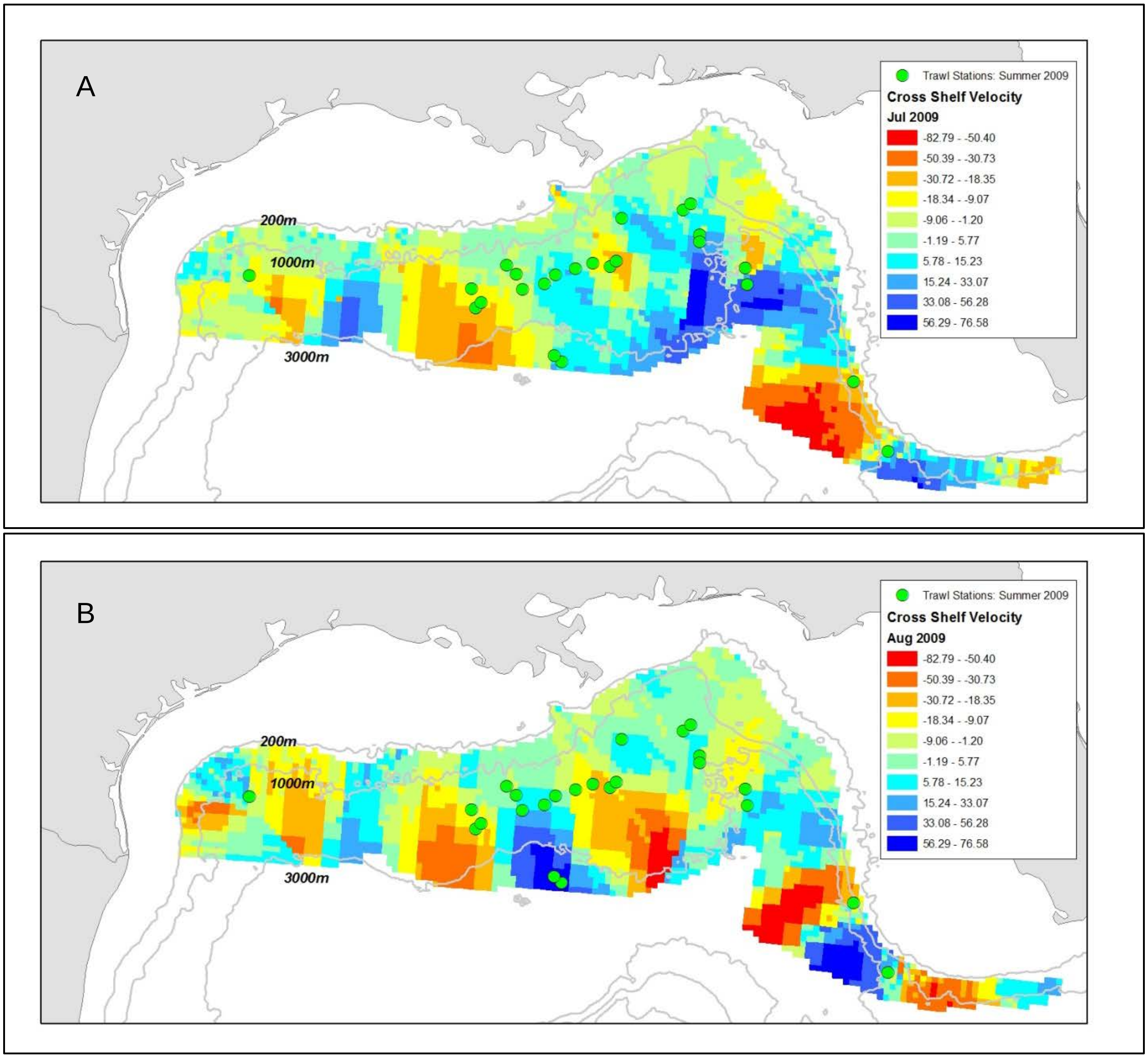

Figure 14. Cross-shelf velocity component during (A) July 2009 and (B) August 2009.

Negative values indicate off shelf flows from shallow water to deeper water.

3.3 WINTER-SPRING 2010

During the winter and spring, there was a strong north-south gradient in water temperatures. The southern portion of the region was dominated by more tropical waters, particularly in the southeastern corner of the Gulf which was dominated by warm loop current waters with temperatures above 23°C (Figure 15). Water temperatures throughout the northern portion of the region were below 20°C and did show some warming between February and March (Figure 16). Surface chlorophyll was broadly uniform and increased between February and March. The region just off the Mississippi River Delta had persistently high surface primary production, and the lowest surface chlorophyll values were associated with the warm waters of the loop current (Figure 17). The sea surface elevation indicated a high elevation region in the north-central Gulf during both February and March bounded by a region of low sea surface elevation to the south extending to the 3,000m isobath. The loop current remained well defined throughout both months dominating circulation in the southeastern Gulf, though trawl sampling occurred in a region of low elevation (counter-clockwise circulation) in the extreme southeastern Gulf (Figure 18). These circulation patterns resulted in a region of lower velocity extending east-west in the northern half of the sampling area and higher velocities to the south (Figure 18). The counter-clockwise circulation in the north-central Gulf resulted in off-shelf flows in the eastern portion just off the west Florida continental shelf (Figure 19). This region with strong off-shelf transport and gradients between velocity fields may be an area of elevated secondary productivity.

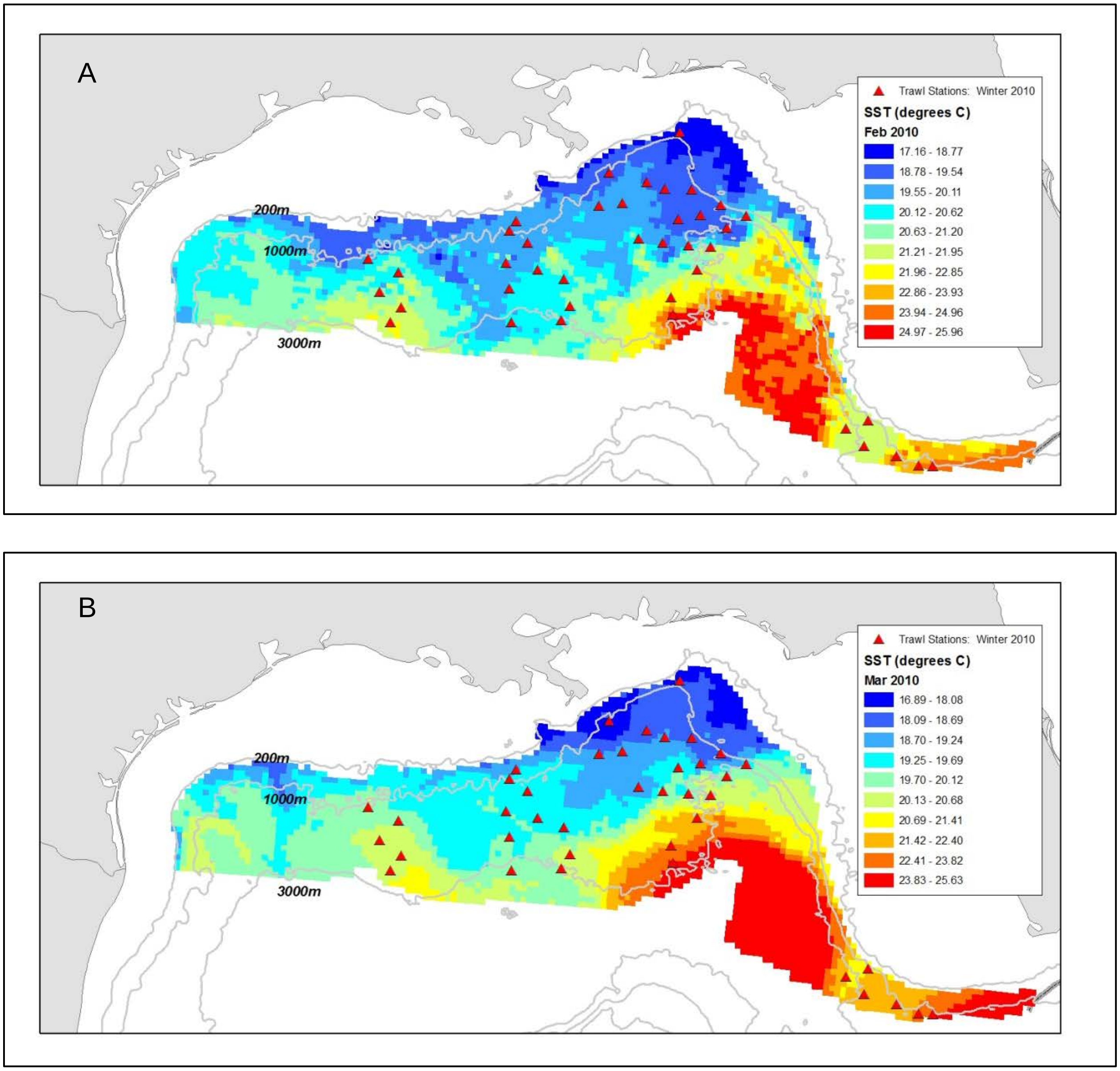

Figure 15. Sea Surface Temperature during (A) February 2010 and (B) March 2010.

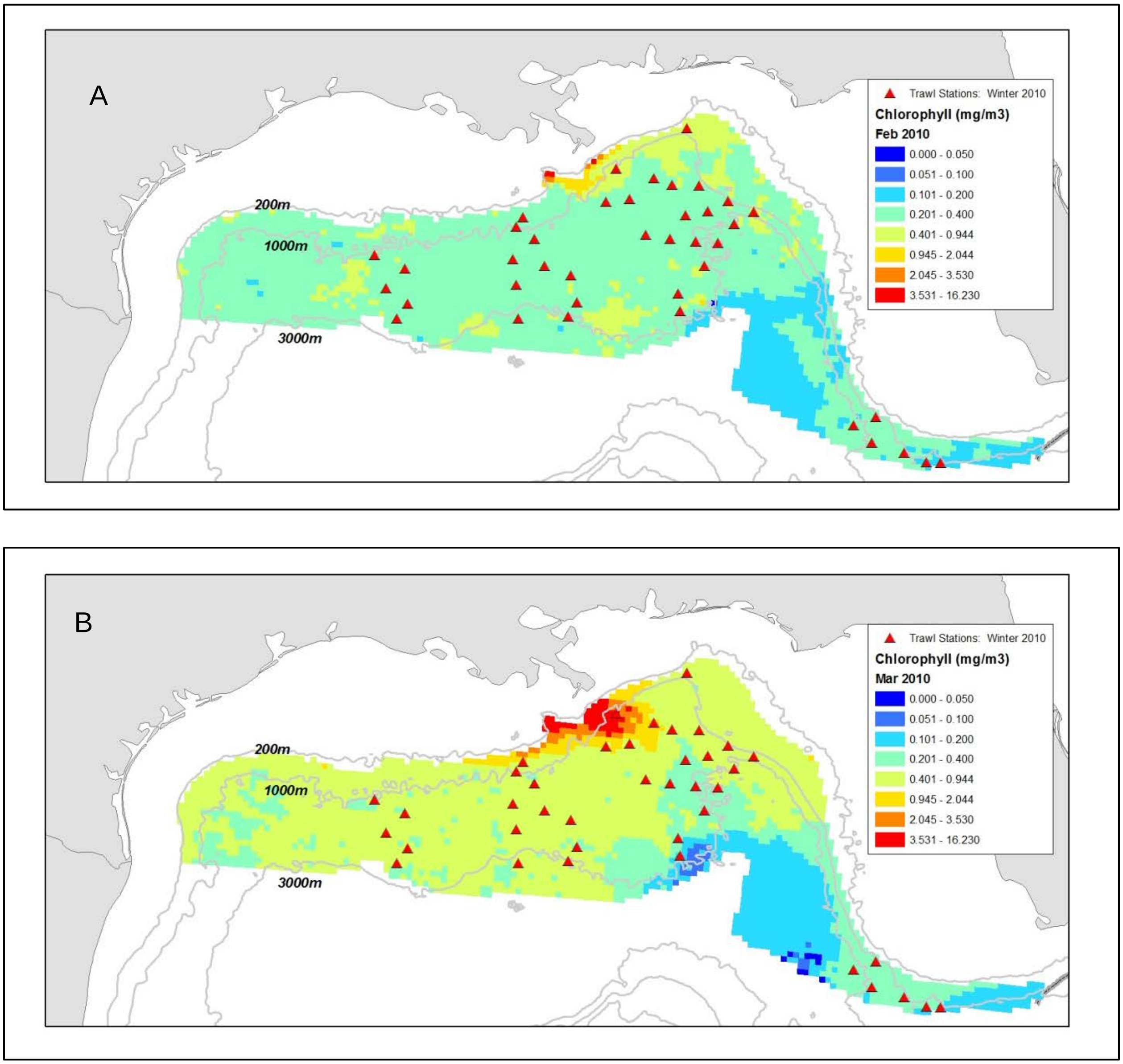

Figure 16. Surface chlorophyll during (A) February 2010 and (B) March 2010.

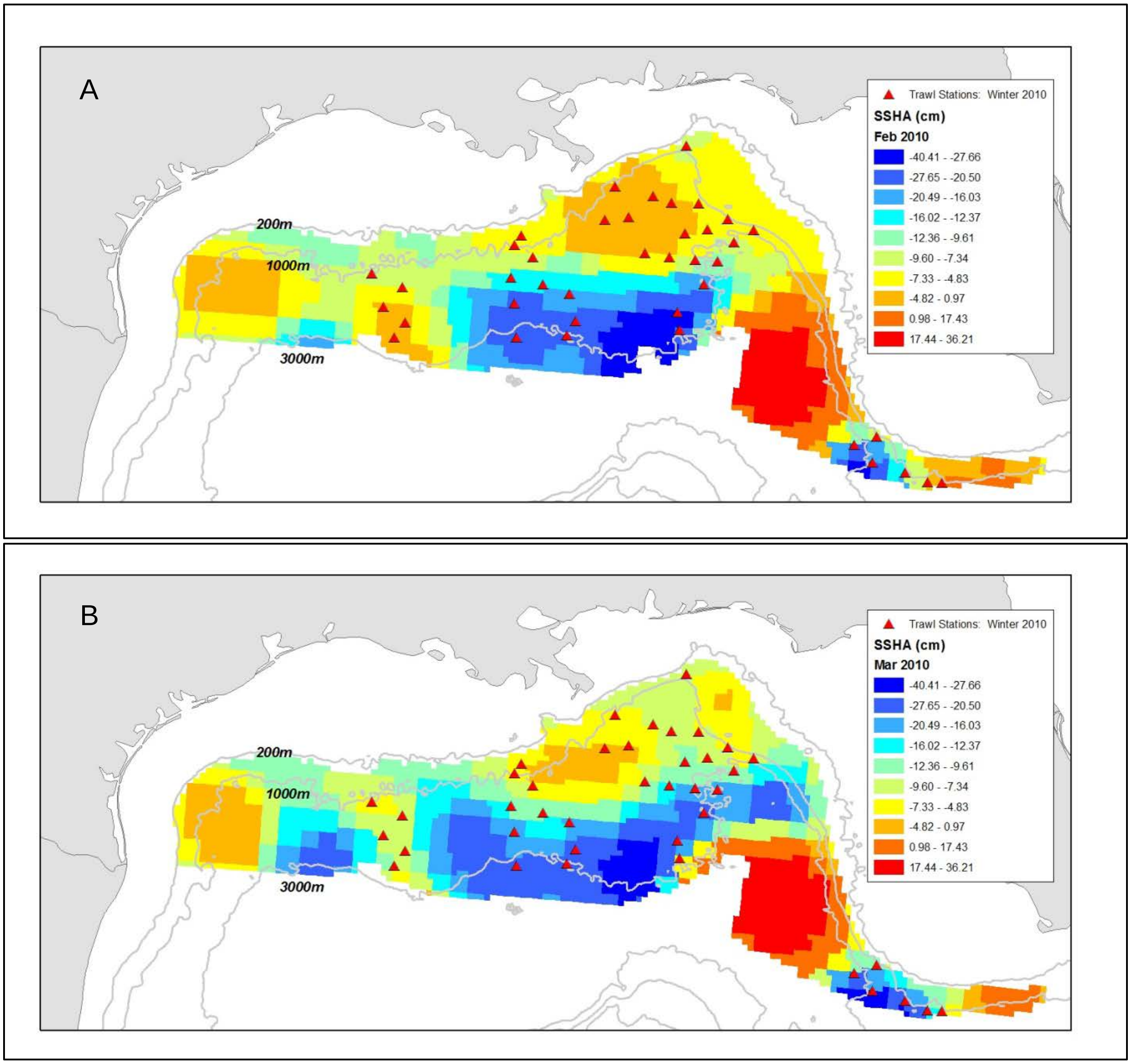

Figure 17. Sea Surface Height Anomaly during (A) February 2010 and (B) March 2010.

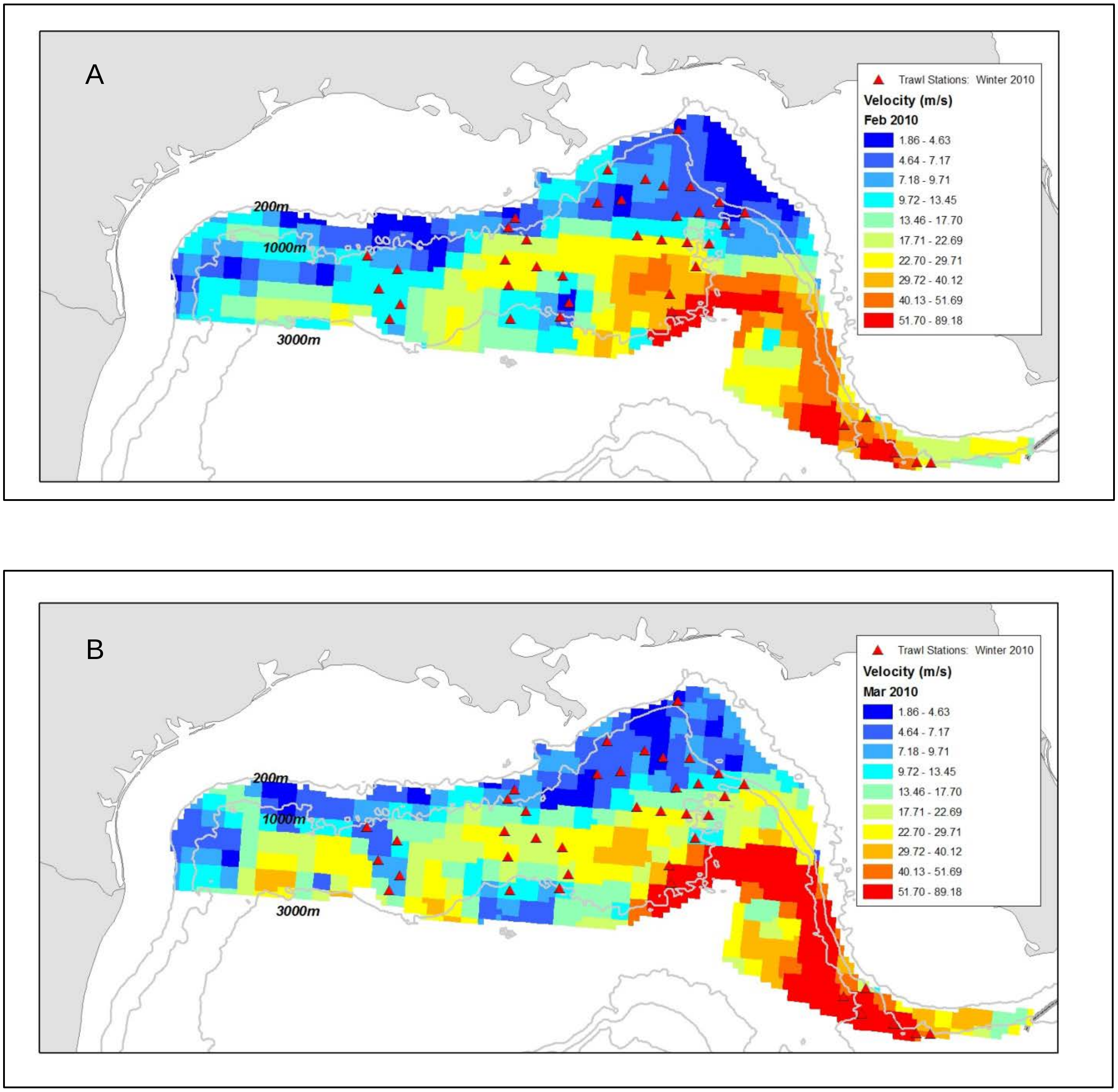

Figure 18. Geostrophic velocity during (A) February 2010 and (B) March 2010.

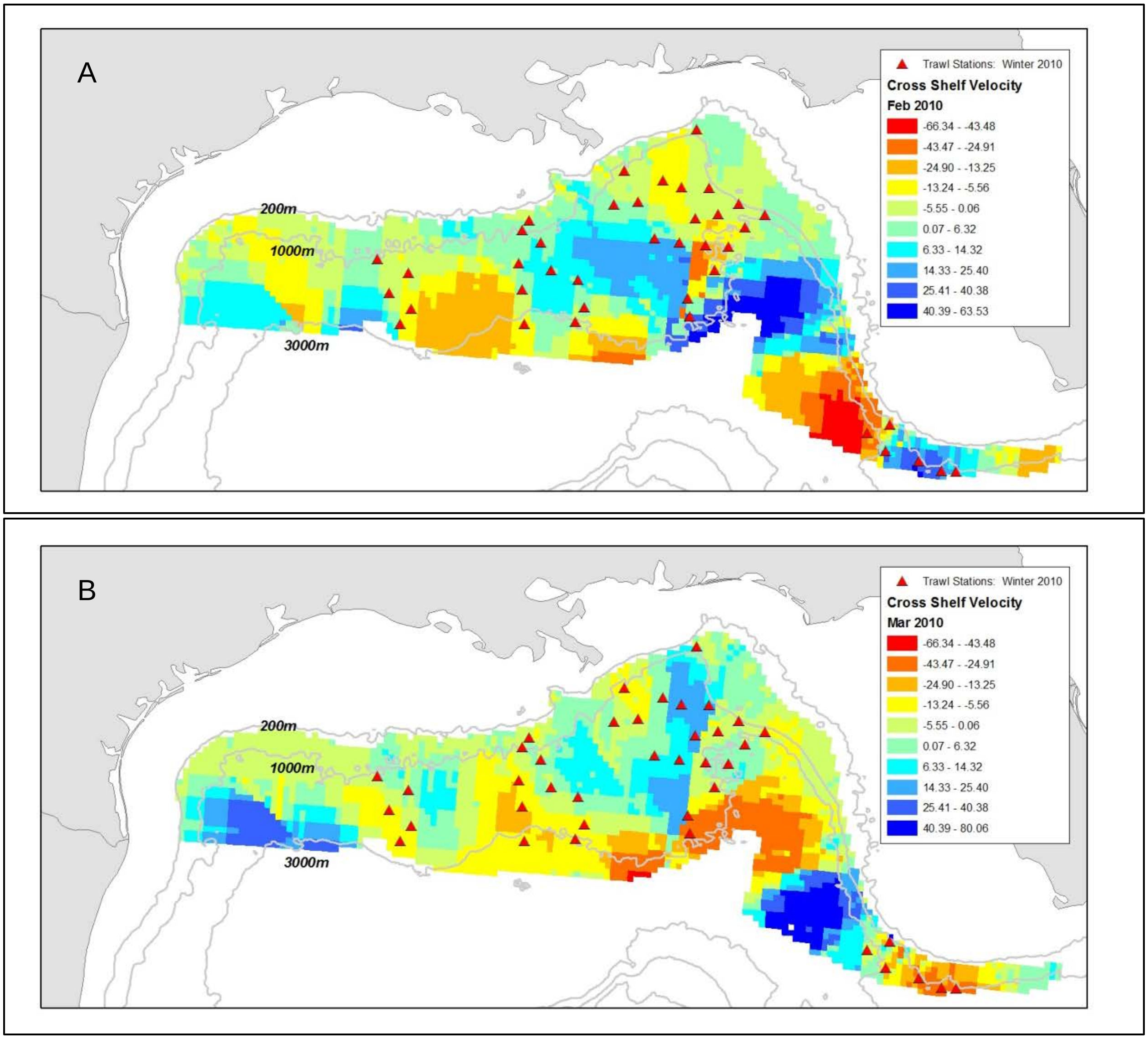

Figure 19. Cross-shelf velocity component during (A) February 2010 and (B) March 2010.

Negative values indicate off shelf flows from shallow water to deeper water.

4.0 MARINE MAMMAL OBSERVATIONS

4.1 SUMMER 2009

The summer 2009 survey was designed primarily as a visual line transect survey for marine mammals in the northern Gulf and thus covered the entire northern Gulf along systematic survey tracklines. A total of 227 marine mammal sightings were detected during the survey from at least 18 species (Table 5).

Table 5. Marine mammal sightings during the summer 2009 survey.

Species	**Leg 1**	**Leg 2**	**Leg 3**	**Total**
Bryde's whale	1	2	0	3
Sperm whale	1	31	7	39
Dwarf sperm whale	0	1	0	1
Pygmy/dwarf sperm whale	0	3	1	4
Pilot whale	0	4	3	7
Risso's dolphin	6	5	1	12
Rough-toothed dolphin	0	2	3	5
Bottlenose dolphin	9	6	6	21
Atlantic spotted dolphin	1	1	2	4
Spinner dolphin	0	3	0	3
Striped dolphin	0	2	0	2
Pantropical spotted dolphin	8	41	3	52
Clymene dolphin	2	0	0	2
Stenella sp.	3	2	0	5
False killer whale	0	0	1	1
Killer whale	0	1	0	1
Pygmy killer whale	0	1	0	1
Melon-headed whale	0	2	0	2
Melon-headed/pygmy killer whale	0	1	0	1
Cuvier's Beaked whale	1	0	0	1
unid. dolphin	11	19	4	34
unid. large whale	0	2	0	2
unid. Mesoplodont	1	1	0	2
unid. Odontocete	6	12	3	21
unid. Ziphiid	1	0	0	1
Total	**51**	**142**	**34**	**227**

The most common species observed were pantropical spotted dolphins (52 sightings), sperm whales (39 sightings), and bottlenose dolphins (21 sightings). Other observations of note include three sightings of Bryde's whales in the northeastern Gulf and one sighting of killer whales in deep waters of the central Gulf.

Sperm whales were observed primarily in deeper waters between the 2,000m isobath and the EEZ (Figure 20). Sperm whales were also observed near the shelf-break, and there was one sperm whale group sighted in the southeastern Gulf near the Dry Tortugas. Several beaked whale groups were also observed in this region of the southeastern Gulf.

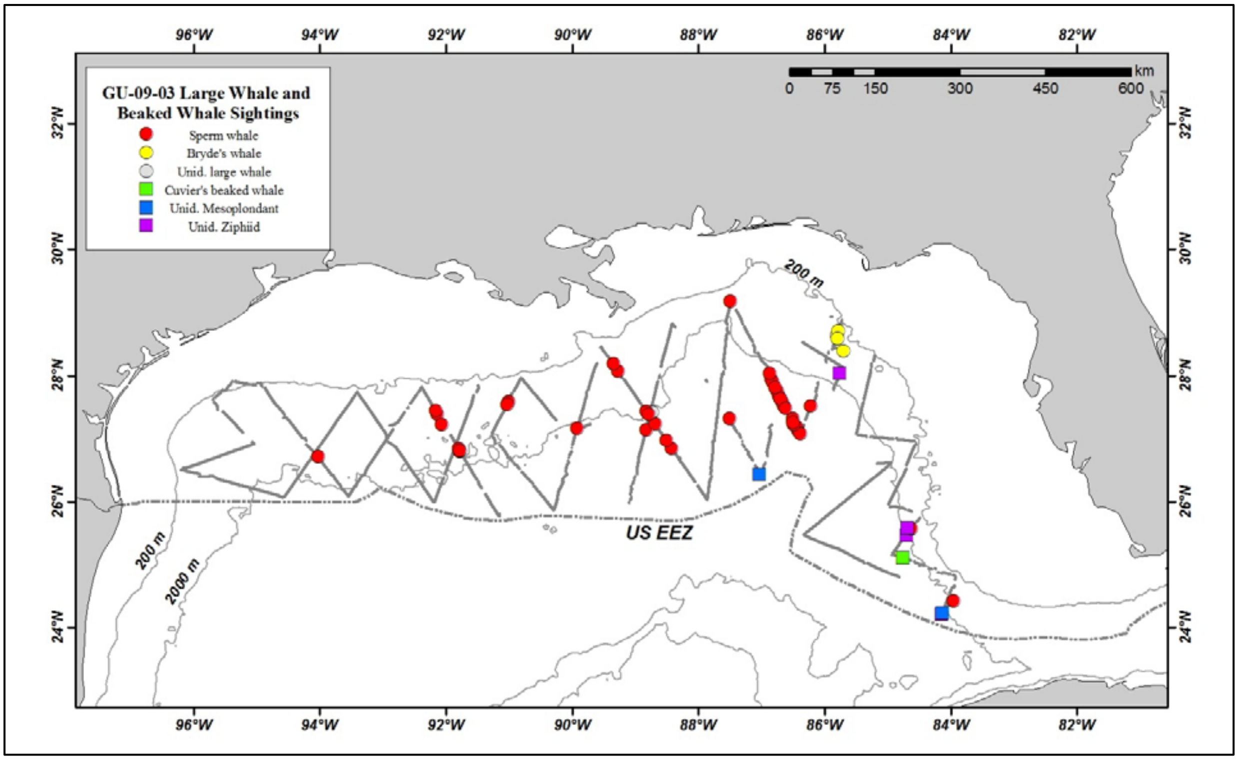

Figure 20. Large whale and beaked whale sightings during summer 2009.

Both small whales (Figure 21) and dolphins (Figure 22) were also distributed primarily in the deeper waters of the central Gulf, which was associated with the broad area of low sea surface elevation waters present during July and August (Figure 12). The western portion of the Gulf had notably few sightings of any taxa, and this may have been associated with the presence of low surface productivity, high temperature, and high sea surface elevations (Figure 12).

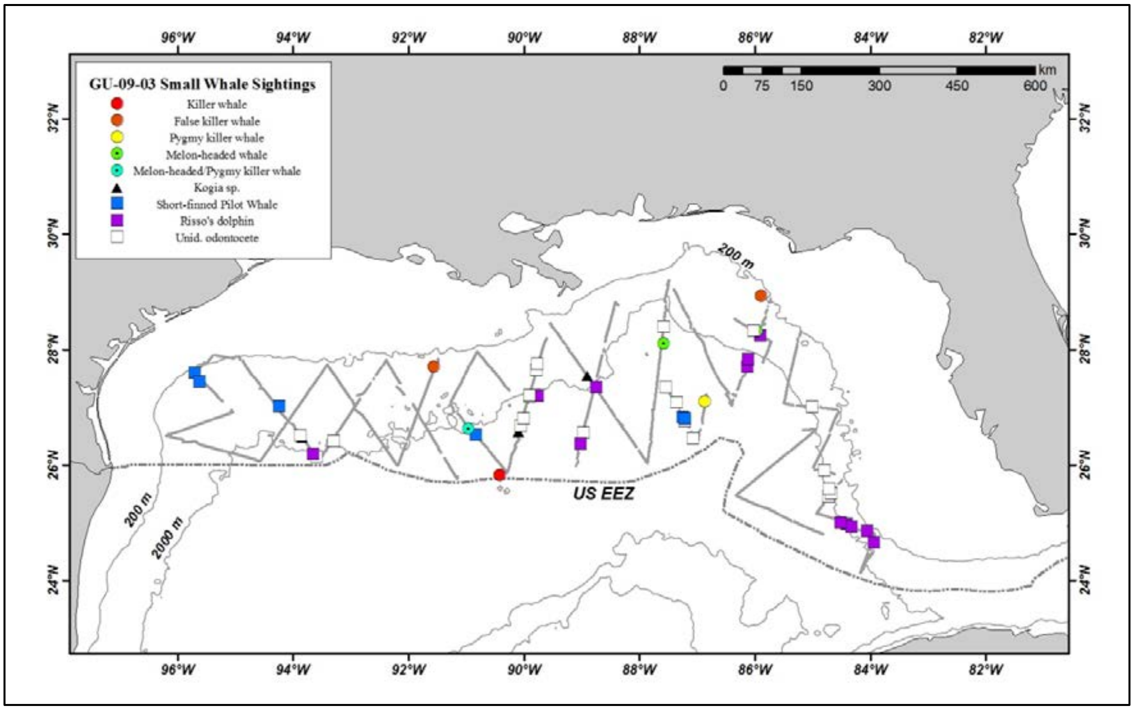

Figure 21. Small whale sightings during summer 2009

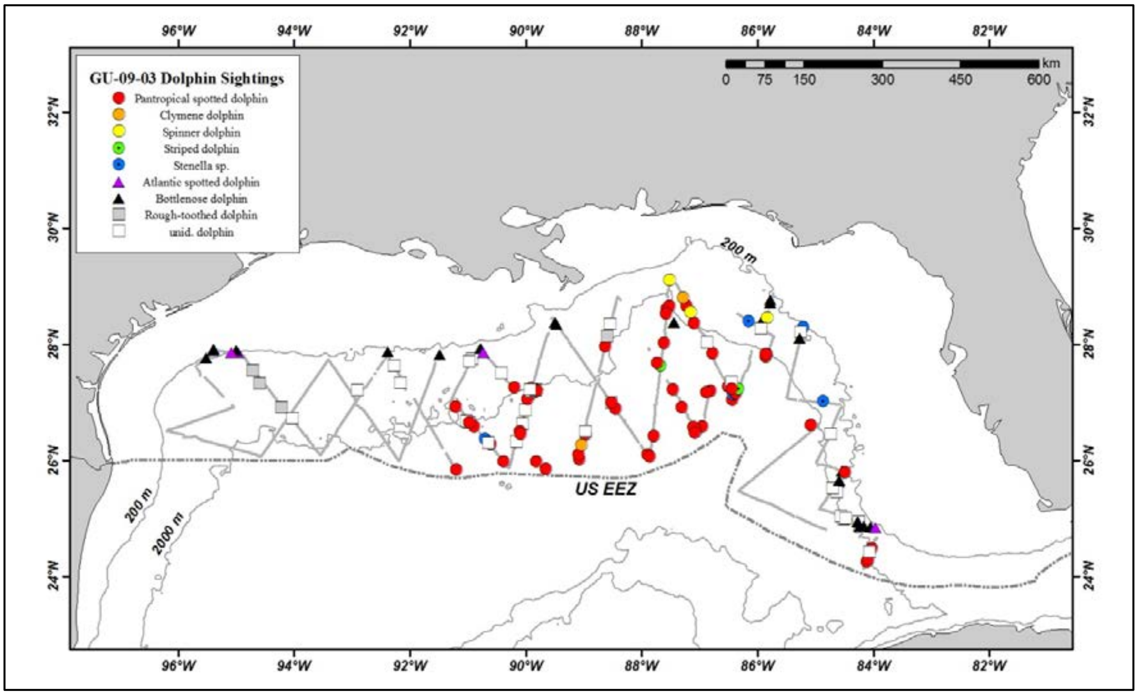

Figure 22. Dolphin sightings during summer 2009.

Sperm whale sightings occurred in two distinct habitats. First, there were consistent sightings along the 1,000m isobath in regions of weakly positive sea surface height. These occurred from the Mississippi Canyon region into the western Gulf. Second, there were strong concentrations of sperm whales in deeper waters of the central Gulf, primarily associated with the low SSHa that dominated these waters and along the boundary with the loop current (Figure 23).

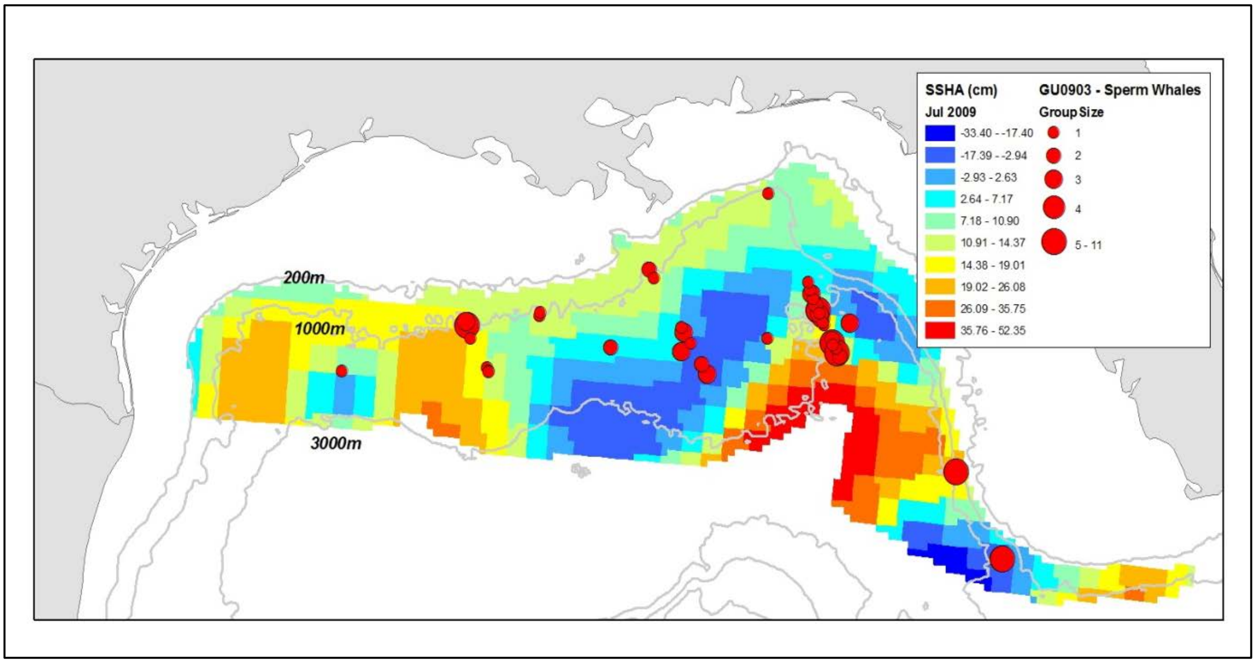

Figure 23. Sperm whale groups and SSHa during summer 2009.

4.2 WINTER-SPRING 2010

The winter-spring 2010 cruise was focused more on trawl sampling rather than a systematic survey of the Gulf for marine mammal distribution. In addition, poor weather throughout the survey, and in particular during leg 1, hampered the effectiveness of visual survey efforts. During the visual effort, there were a total of 36 marine mammal sightings including 681 animals (Table 6). Sperm whales were the most common species sighted followed by pantropical spotted dolphins.

Sperm whale sightings occurred in the north-central Gulf along the 1,000m isobath and in the region of the DeSoto Canyon. There were also several observations of sperm whales in deeper waters of the central Gulf. No sperm whales were observed in the southeastern Gulf near the Dry Tortugas (Figure 24). One group of killer whales was observed in the deeper sections of the central Gulf near the EEZ.

Dolphin sightings, particularly of spinner and Risso’s dolphins were also concentrated around the DeSoto Canyon region, while pantropical spotted dolphins were observed in deeper waters of the central Gulf (Figure 25).

Table 6. Marine mammal sightings during winter-spring 2010.

Species	Total Individuals	Total Groups
Killer whale	12	1
Melon-headed whale	83	1
Pantropical spotted dolphin	223	8
Risso's dolphin	11	2
Sperm whale	26	10
Spinner dolphin	186	4
Stenella sp.	83	3
unid. dolphin	48	6
unid. small whale	9	1
Grand Total	**681**	**36**

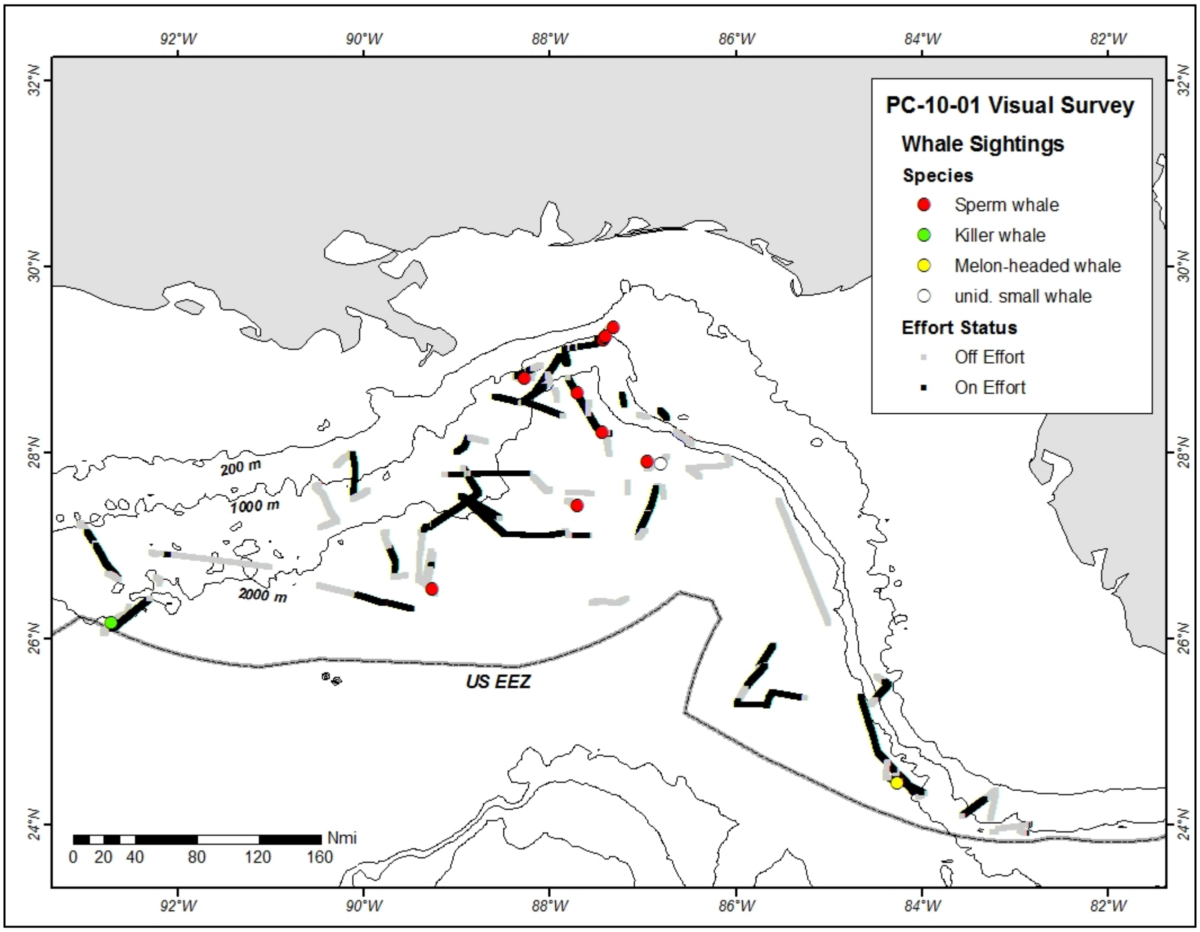

Figure 24. Whale sightings during winter-spring 2010.

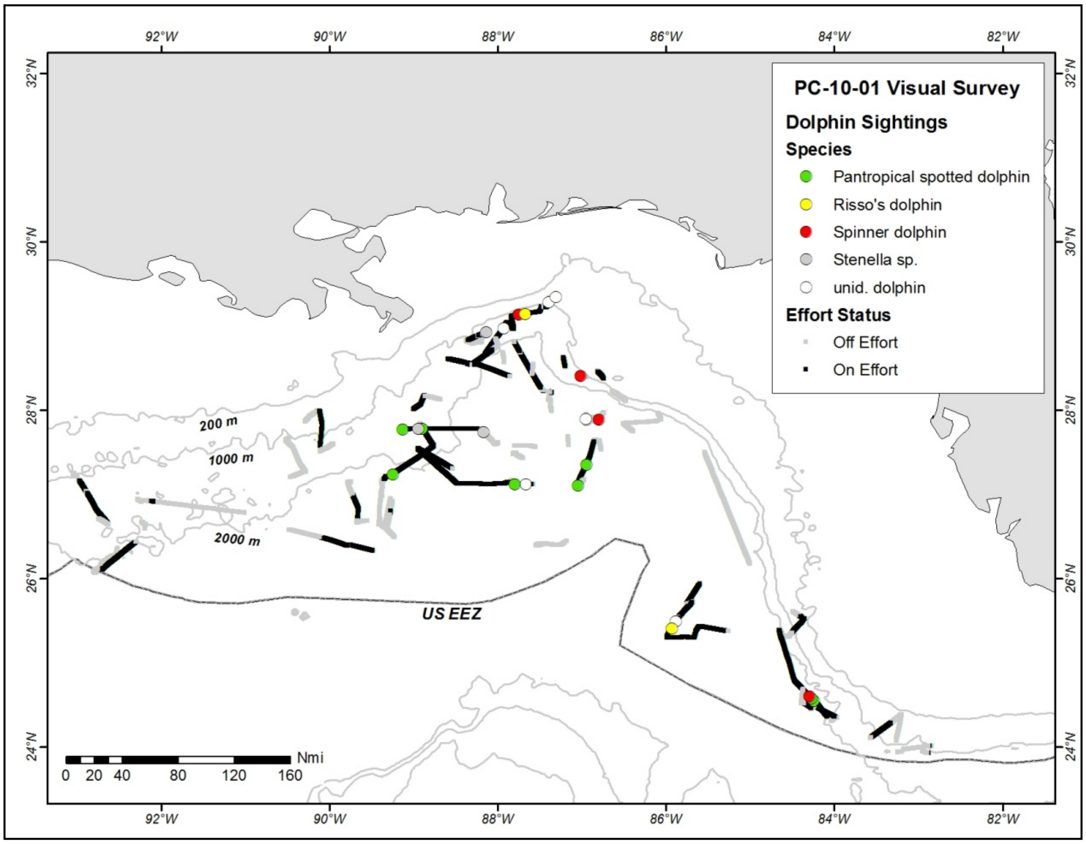

Figure 25. Dolphin sightings during winter-spring 2010.

Sperm whale groups were associated with cooler water temperatures and the region of intermediate SSHa near the DeSoto Canyon region. Sightings also occurred in association with the region of low SSHa in the southern portion of the region. The circulation near the DeSoto Canyon was dominated by off-shelf flows along the outer edge of the clockwise circulation and low surface velocities (Figure 26).

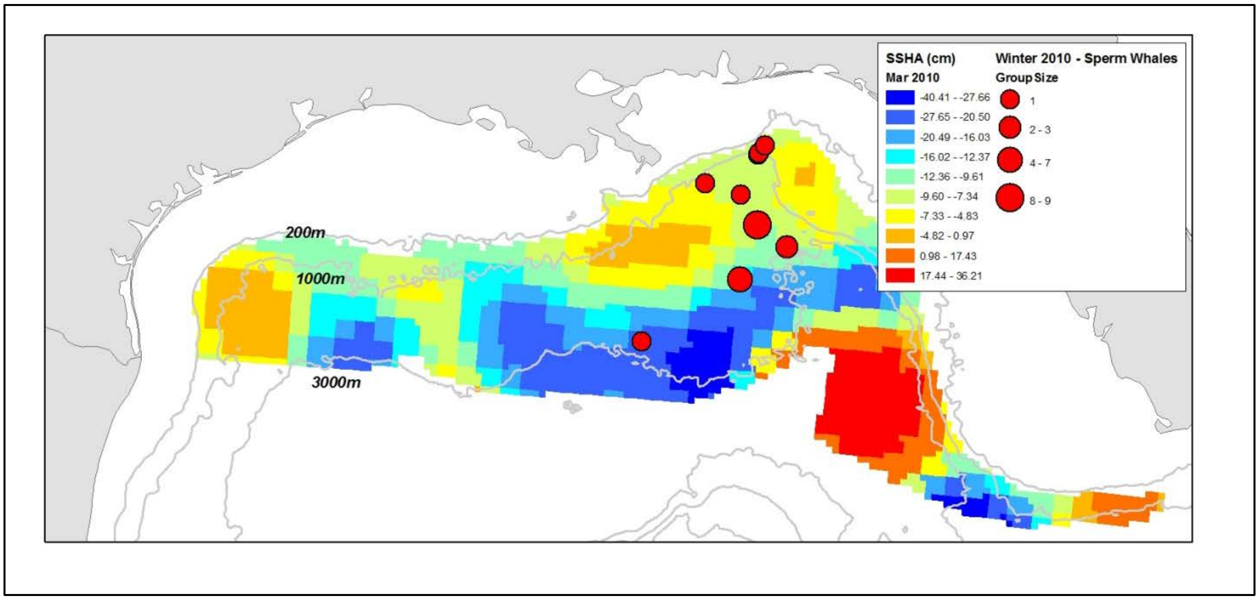

Figure 26. Sperm whale sightings and SSHa during winter-spring 2010.

5.0 SUMMARY OF SQUID CATCHES

5.1 SUMMER 2009

Twenty-three trawl stations were sampled during the 2009 pilot study. The acoustic sensors used to transmit fishing depth worked only intermittently, therefore it was not possible to fully characterize the fishing profile of each trawl. Based on the limited data received and the amount of cable deployed during the trawl, we estimate that trawl fishing depth was most likely between 400–600 m. The biomass of squid captured in each trawl was generally less than 1 kg total weight. One notable exception was the capture of a single large specimen of the giant squid, *Architeuthis dux* (Figure 27). This animal was captured on 30 July at station 73 (Figure 28) in the central Gulf along the 2,000m isobath. The *Architeuthis* had a measured mantle length of 531 cm and weighed over 40 kg. The specimen was delivered to the National Systematics Laboratory at the Smithsonian Institution for archiving (Judkins et al. 2013).

Figure 27. Giant squid (*Architeuthis dux*) collected by NOAA.

Credit: NOAA

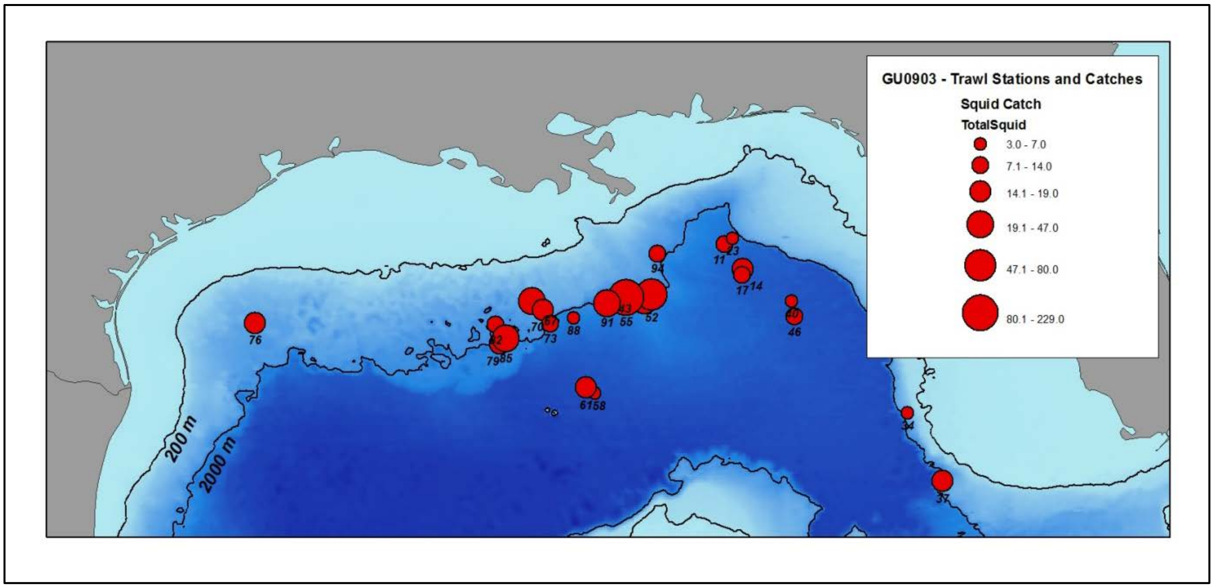

Figure 28. Numbers of squids captured in trawls during summer 2009.

Trawls are identified by station numbers.

The squid specimens were classified in the field to species to the extent possible; however, both taxonomic uncertainty and limited capability to conduct detailed examinations of specimens reduced the reliability of field identifications. Squid taxa were thus grouped into broad taxonomic categories for the current summary.

The number of individuals captured in each trawl varied widely across the survey range. Generally, stations in deep waters of the eastern, southeastern, and western Gulf contained fewer individuals compared to those stations in the central Gulf along the 2,000m isobath (Figure 28). Among the stations along the 2,000m isobath, there was a cluster of stations in the eastern portion of the sampling range with higher numbers of individuals. All of these stations were associated with the northern edge of the low SSHa feature present in the central Gulf (Figure 28). This region also corresponded to localized aggregations of sperm whales (Figure 20).

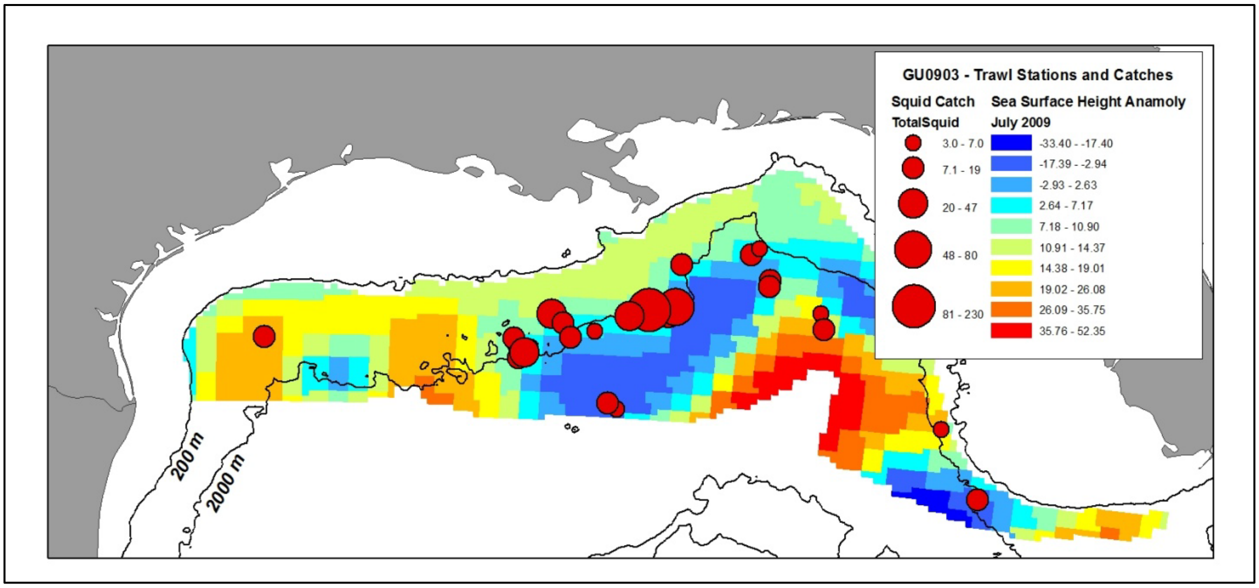

Figure 29. Squid catches and SSH anomaly during summer 2009.

At least 16 different taxa of squids were captured during the summer 2009 survey (Table 7). The most common in term of numbers and frequency of occurrence were smaller taxa such as *Abralia* spp. and *Pyroteuthis* spp. These taxa are very small, with mantle lengths less than 30 mm. Of potential prey species for sperm whales, the Histioteuthidae and Ommastrephidae squids were the most common of the larger species (Table 7).

Table 7. Squid taxa captured during summer 2009.

Taxon	Frequency of Occurrence	Number	Weight (kg)
Architeuthis sp.	1	1	43.500
Histioteuthidae	11	86	3.263
Cephalopoda	1	2	1.328
Abralia spp.	18	160	0.655
Ommastrephidae	9	341	0.463
Pyroteuthis spp.	12	108	0.240
Cranchiidae	14	42	0.218
Cranchia scabra	12	33	0.170
*Enoploteuthis*sp.	4	6	0.056
Carangidae	4	16	0.037
Onychoteuthidae	1	1	0.125
Octopodoteuthidae	1	2	0.046
Lycoteuthidae	1	1	0.005
Heteroteuthis sp.	4	6	0.011
Heliocranchia sp.	1	1	Unk
Lepidoteuthidae	1	2	Unk

There were regional differences in the spatial distribution of the common squid taxa. Among the smaller taxa, the *Abralia* spp. were more broadly distributed, occurring in trawls both in the central and eastern portion of the Gulf (Figure 30). In contrast, the *Pyroteuthis* spp. squids were captured primarily in the trawls conducted in the central portion of the Gulf (Figure 31), and the Cranchidae were more common in trawls in the eastern Gulf (Figure 32).

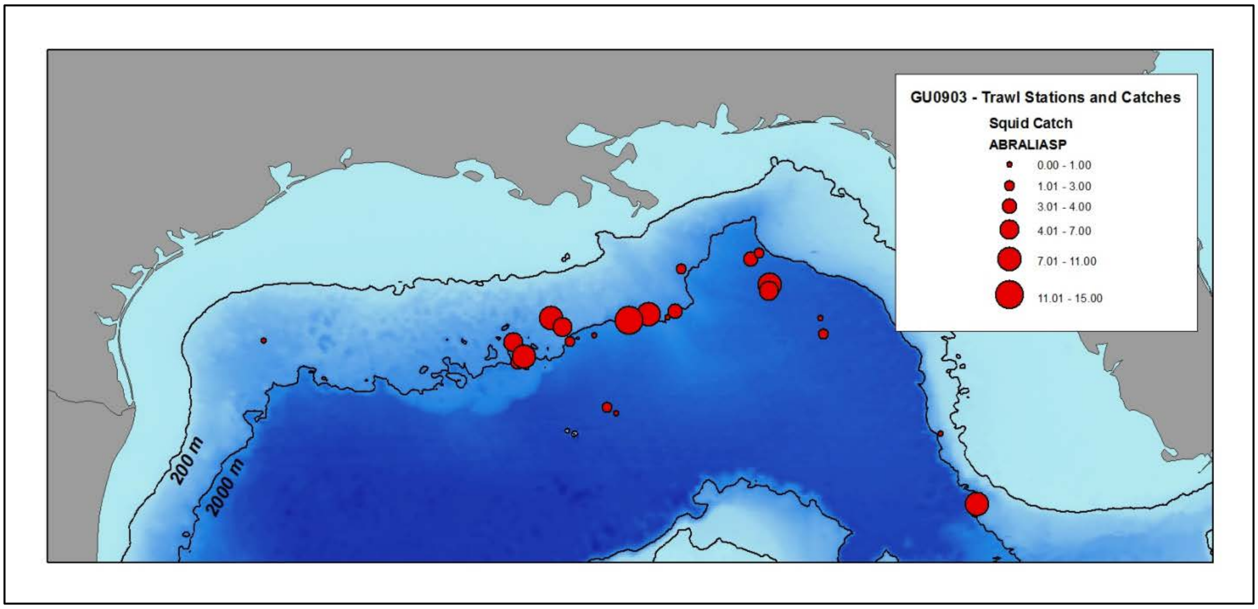

Figure 30. ***Abralia*** **spp*.* squids catch during summer 2009.**

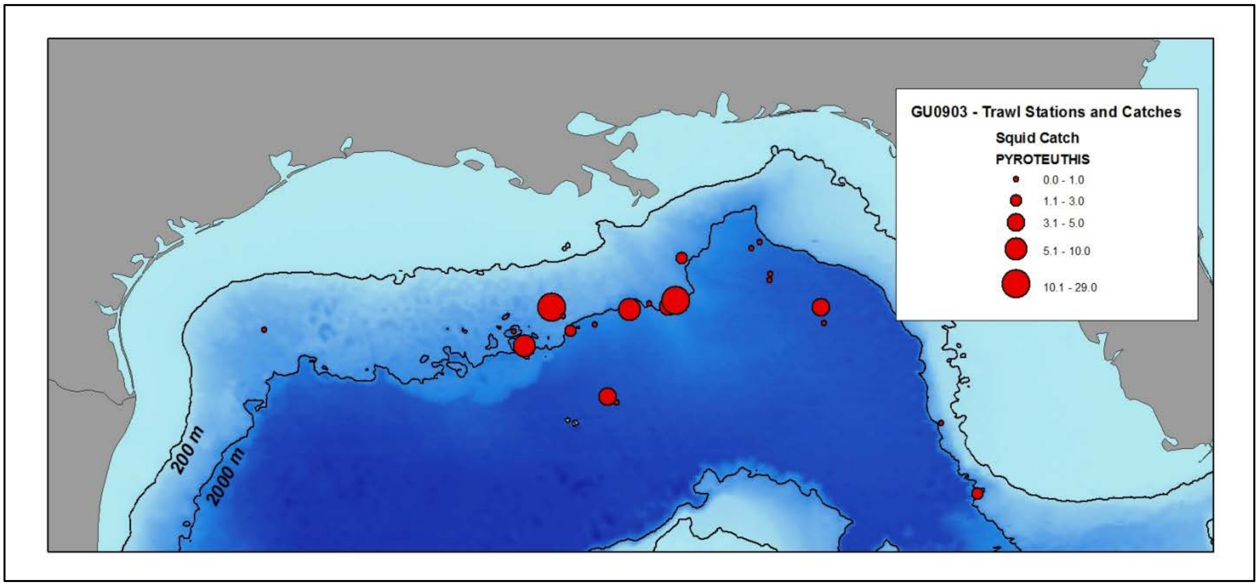

Figure 231. ***Pyroteuthis*** **spp*.* squid catch during summer 2009.**

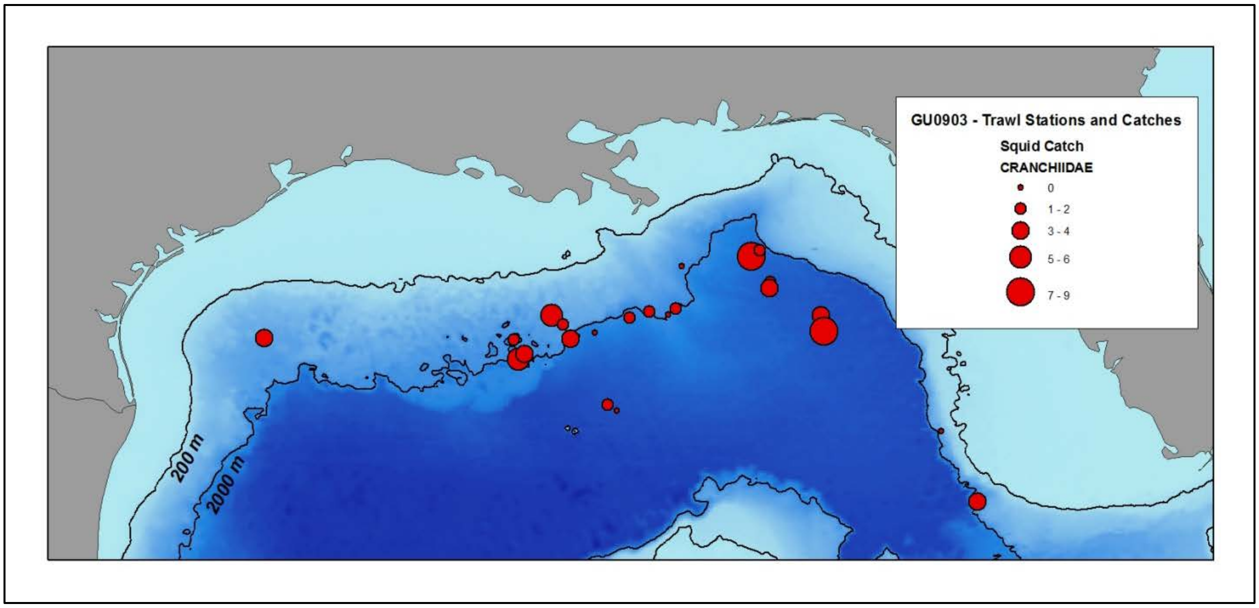

Figure 32. Cranchidae squid catch during summer 2009.

Of the larger taxa that are more likely to contribute to the sperm whale prey field, the Histioteuthidae were broadly distributed in the western and central Gulf, but were captured in higher numbers in trawls along the 2,000m isobath (Figure 33). The Ommastraphidae squids had a more restricted distribution and occurred primarily in the trawls in the central Gulf (Figure 34).

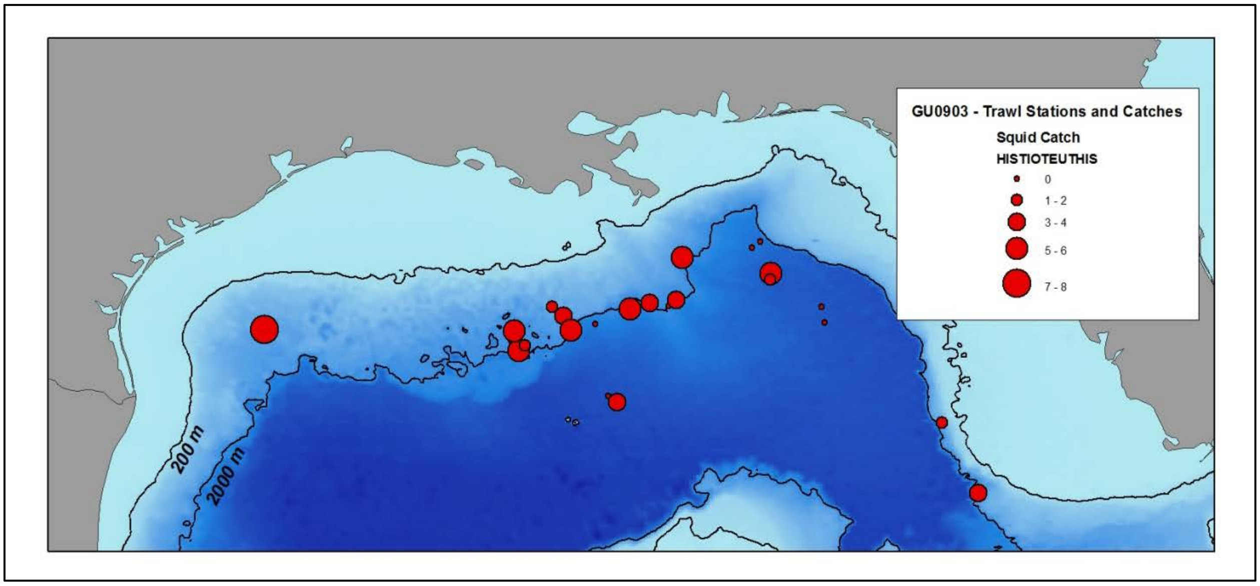

Figure 33. Histioteuthidae squid catch during summer 2009.

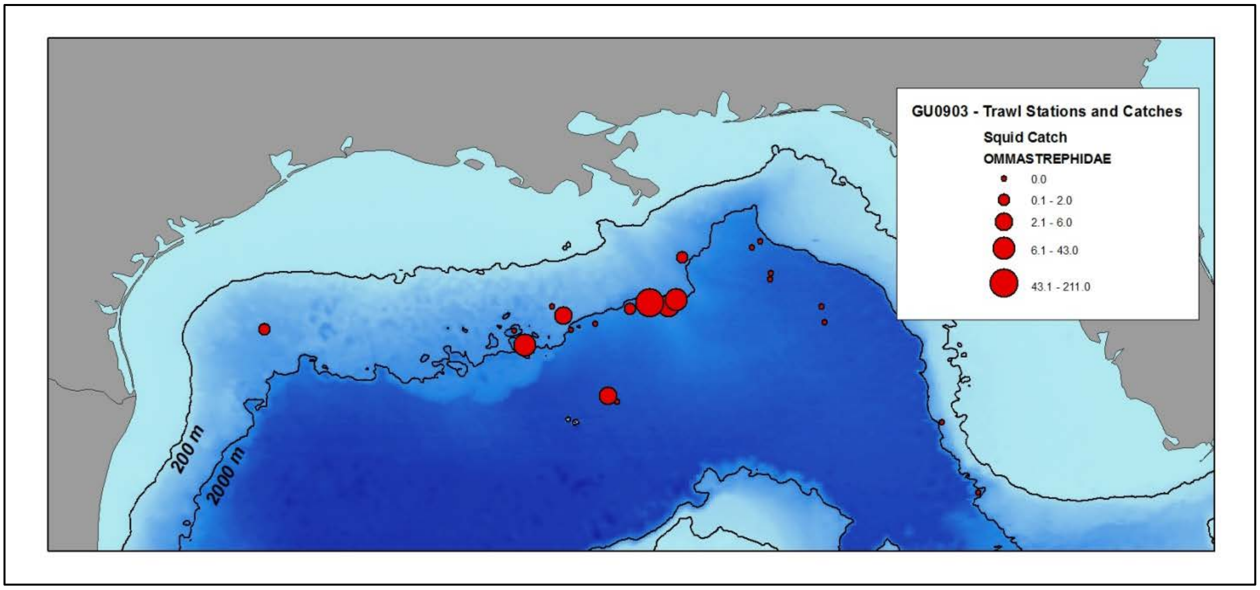

Figure 34. Ommastrephidae squid catch during summer 2009.

5.2 WINTER-SPRING 2010

The winter-spring 2010 survey included trawl sampling over a broader range of habitats than the 2009 pilot study and concentrated sampling in three general regions within the northern Gulf: western (generally west of 89º W longitude), central (covering the shelf break and slope waters between 89º W and 86º W longitude), and southeast (north of the Dry Tortugas). The limited sampling conducted in the southeastern Gulf was attempted to reflect the possible prey field of a persistent aggregation of sperm whales in this region that has been noted in previous years. However, during the current survey, no sperm whales were detected in the area. Total catch weights are shown in Figure 34. In general, catch weights were highest and most consistent in the central survey region, particularly in stations on the southeastern corner of the area south of the DeSoto Canyon. One trawl station (station 88 in the southeast region) was a clear outlier from all other samples. In this trawl, over 400 individuals of one species of squid (*Illex oxygonius*) were captured totaling 41 kg of biomass (Figure 36, Table 8). Because it is an extreme outlier, this station was excluded from summaries of average catch weights.

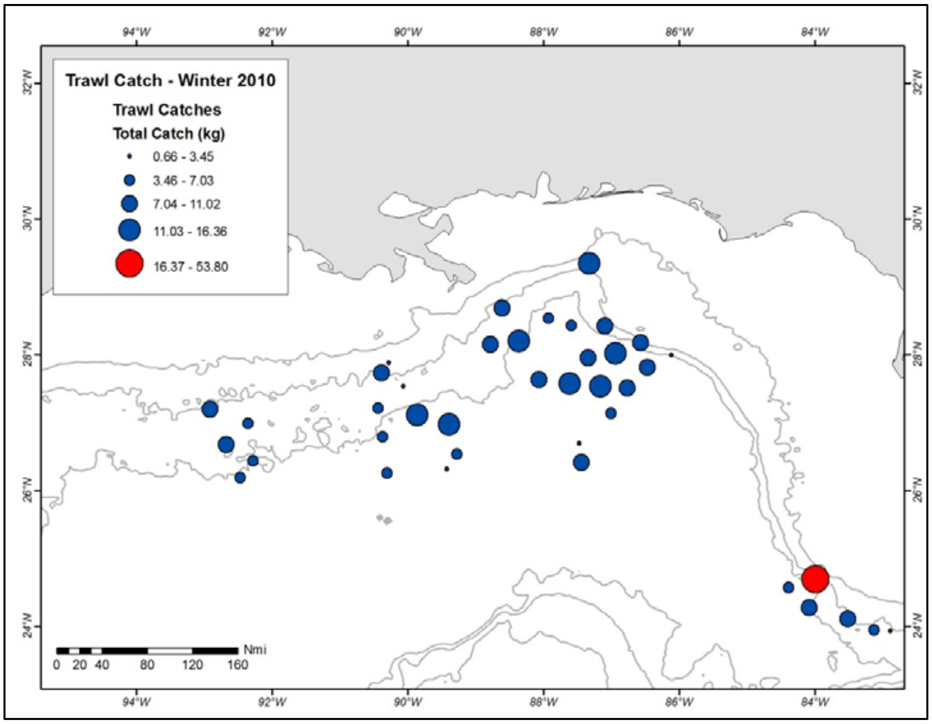

Figure 35. Total catch weights (kg) in trawls during Winter-Spring 2010.

Station 88 is highlighted in red.

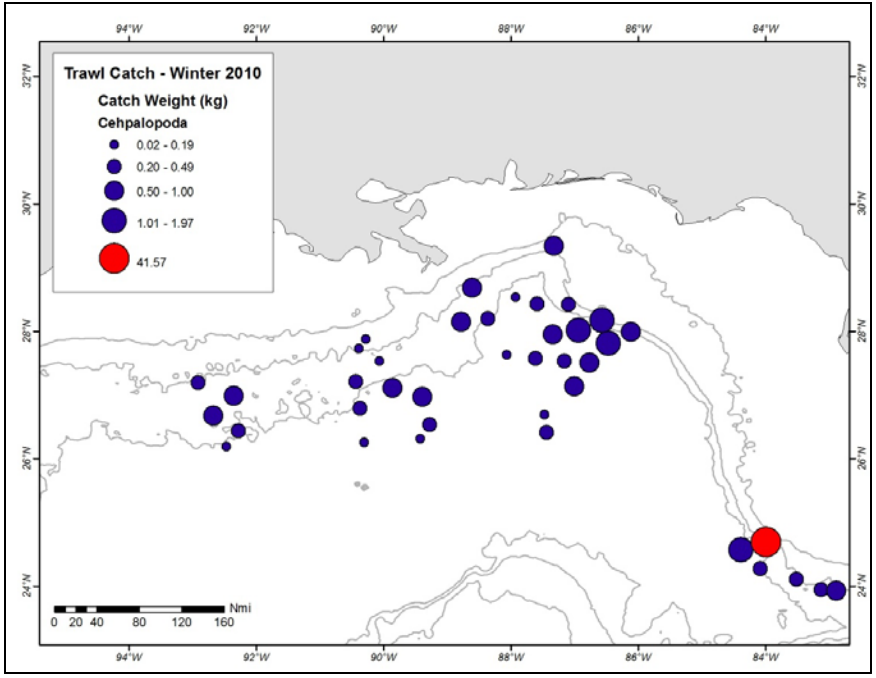

Figure 36. Total cephalopoda catch (kg) during winter-spring 2010.

Station 88 is highlighted in red.

Aside from the extremely large catch at station 88, the total catches of squid taxa were variable by region. The highest average catches of squids occurred within the central area, and a similar pattern was observed for fish taxa (Figure 37); however, the regional effect was more pronounced for cephalopoda. The southeastern portion of the central trawling area was characterized by relatively high biomass of squid taxa (Figure 36).

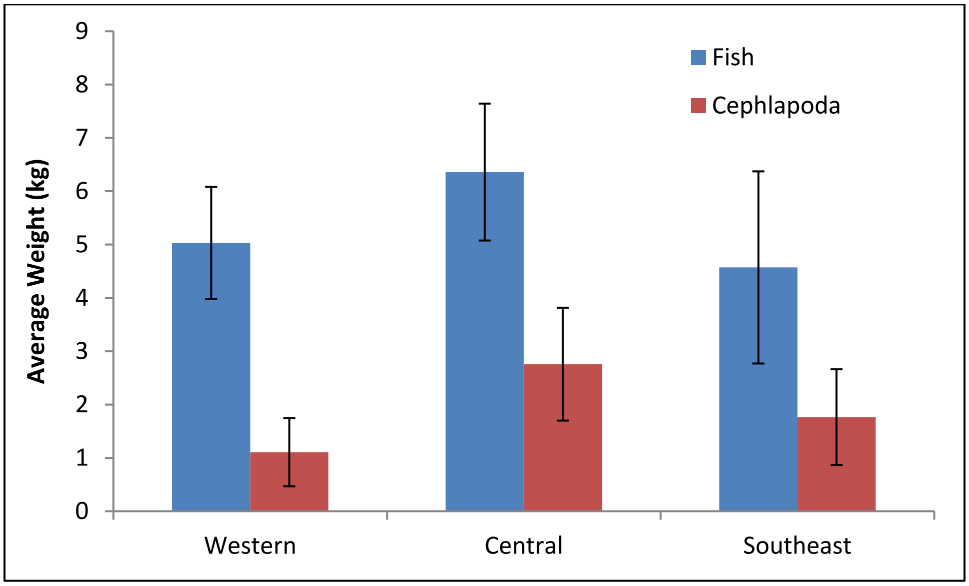

Figure 37. Average mass (kg) of fish and cephalopoda by trawling area.

Error bars indicate 95% confidence limits. Means exclude station 88 which was an outlier.

The total cephalopod catch also varied by the fishing depth of the trawl. The catch of cephalopoda was lowest in trawls fishing at depths less than 600 m, and was higher in deeper trawls (Figure 38). Though station 88 is excluded from these averages, it is notable that this station was sampled at an average depth of 800 m.

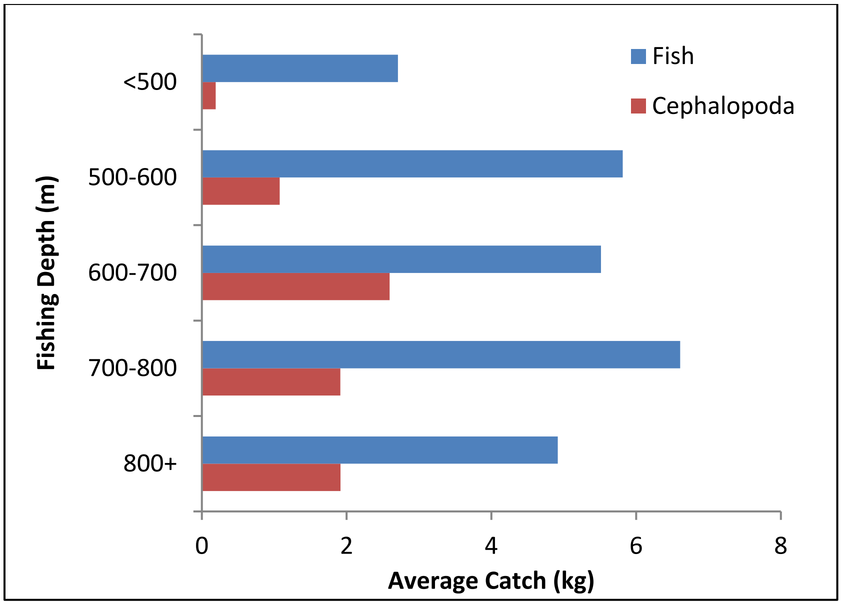

Figure 38. Average catch weight by fishing depth.

Averages exclude station 88. Fishing depth was measured by continuous recording depth sensors attached to the headrope of the trawl.

Based on field identifications, the squid taxa were summarized into 38 taxonomic categories. Some of these were aggregated at the genus or family level due to uncertainty in species level identifications conducted in the field (Table 8). As seen during the summer 2009 pilot study, there were high numbers of smaller taxa (typical mantle lengths <30mm) from the *Abralia* spp. and the Pyroteuthidae. In addition, large numbers of the genus *Leachia* (primarily *Leachia atlantica*) were captured. Though this species has a relatively long mantle length, it is not a muscular species that would be expected to be an appropriate prey item for sperm whales. The Histioteuthidae squids, which are potential sperm whale prey, are represented by several species of genus *Histioteuthis* and *Stimagteuthis arcturi*, which were collected in relatively high numbers, including some larger specimens and account for a significant amount of the squid biomass in these trawls. Other potential sperm whale prey that were relatively common include *Illex oxygonus*, *Ornithoteuthis antillarium*, *Discoteuthis* spp., and *Ommastrephes bartrmii* (Table 8, Figure 39). Other notable specimens included several *Asperoteuthis acanthoderma* individuals, including two very large specimens with mantle lengths over 70 cm.

Table 8. Squid taxa captured in trawls during winter-spring 2010.

Taxon	Total Weight (kg)	Total N
Illex oxygonius	41.50	407
Asperoteuthis acanthoderma	6.594	13
Unid. Other	6.213	341
Loligo pealeii	6.208	18
Vampyroteuthidae	4.316	80
Histioteuthis spp.	2.806	44
Chiroteuthidae	2.571	881
Other Squid	1.911	73
Stigmateuthis arcturi	1.582	58
Ornithoteuthis antillarium	1.548	172
Cranchiiae	1.357	229
Galiteuthis armata	1.055	22
Distcoteuthis sp.	0.980	14
Leachia sp.	0.777	489
Octopoteuthidae	0.718	51
Bathothauma lyromma	0.547	30
Onychoteuthidae	0.533	263
Mastigoteuthidae	0.396	22
Chiroteuthis joubini	0.382	6
Abrailia spp.	0.303	126
Pyroteuthidae	0.219	117
Leachia atlantica	0.208	106
Enoploteuthidae	0.145	62
Octopoda	0.138	19
Haliphron atlanticus	0.122	8
Abraliopsis spp.	0.120	61
Selenoteuthis scintillans	0.090	65
Bathyteuthidae	0.090	13
Onykia caribbaea	0.088	9
Pterygioteuthis spp.	0.066	89
Heteroteuthis dispar	0.042	16
Semirossia spp.	0.040	15
Ommastrephes bartramii	0.038	24
Ommastrephidae	0.034	11
Brachioteuthis sp.	0.026	4
Taonius spp.	0.018	4
Lycoteuthidae	0.012	12
Enoploteuthis leptura	0.011	1
Grand Total	83.804	3975

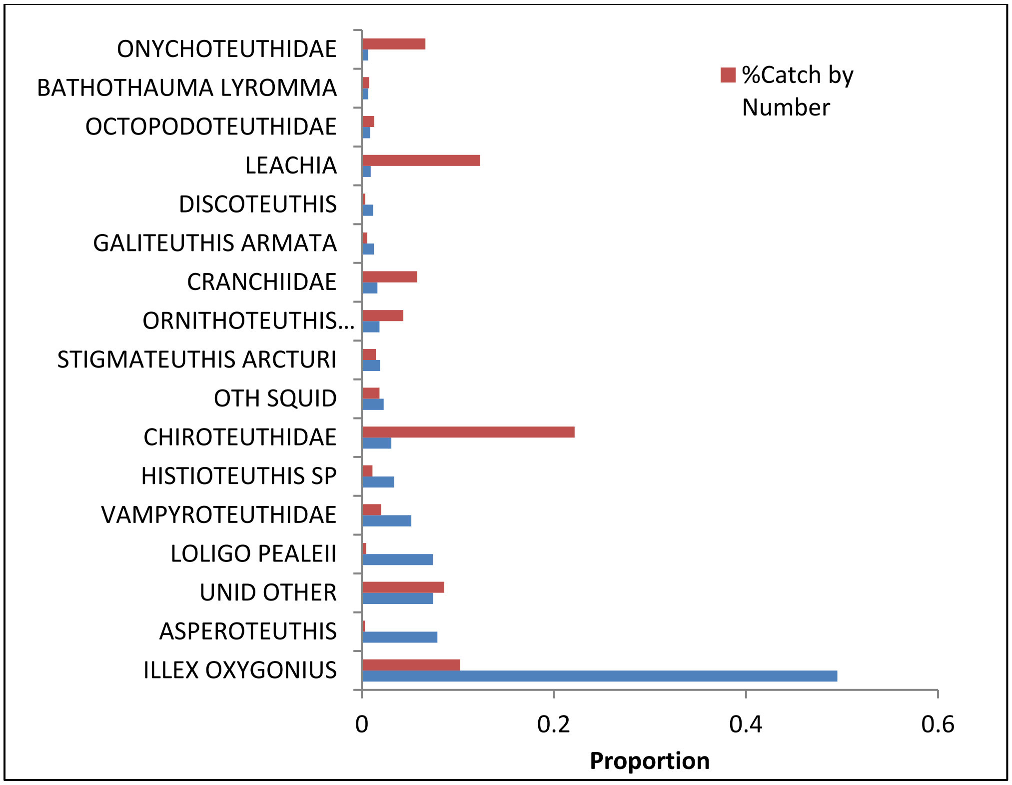

Figure 39. Proportion of total catch by number and weight by squid taxa.

Catch of *Illex oxygonius* was restricted primarily to station 88 where over 400 individuals were captured.

Maps of catches of selected taxa are shown in Figure 40–Figure 45. Catches of *Leachia* were widespread, though were more consistently high in the lower productivity waters of the western Gulf (Figure 40). The smaller *Abralia* spp. were more evenly spread across the Gulf, including catches in the southeastern Gulf (Figure 41). In contrast, the Ommastrephidae were largely concentrated in the central sampling area (Figure 42), and the relatively common *Ornithoteuthis antillarium*, while more widespread, also had the highest catches in the central Gulf and in particular in the eastern portion of that region just off the west Florida shelf (Figure 43). Another potential sperm whale prey, *Discoteuthis* spp., was also concentrated in this area (Figure 44); however, the Histioteuthids were distributed more broadly, occurring in multiple trawls in each of the sampling regions (Figure 45).

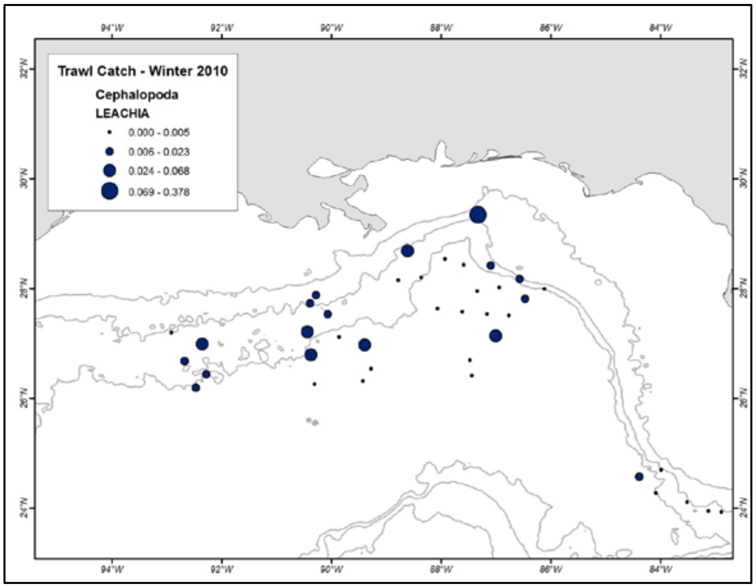

Figure40. Catch of *Leachia* spp. during winter-spring 2010.

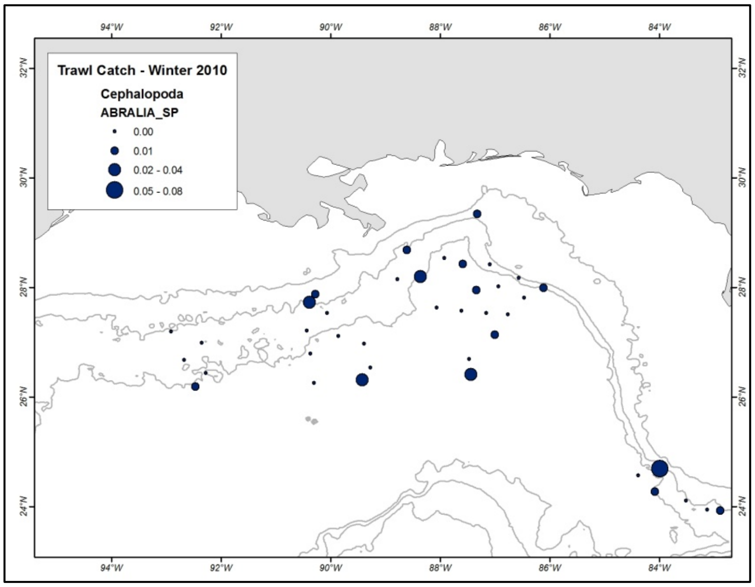

Figure 341. Catch of *Abralia* spp. during winter-spring 2010.

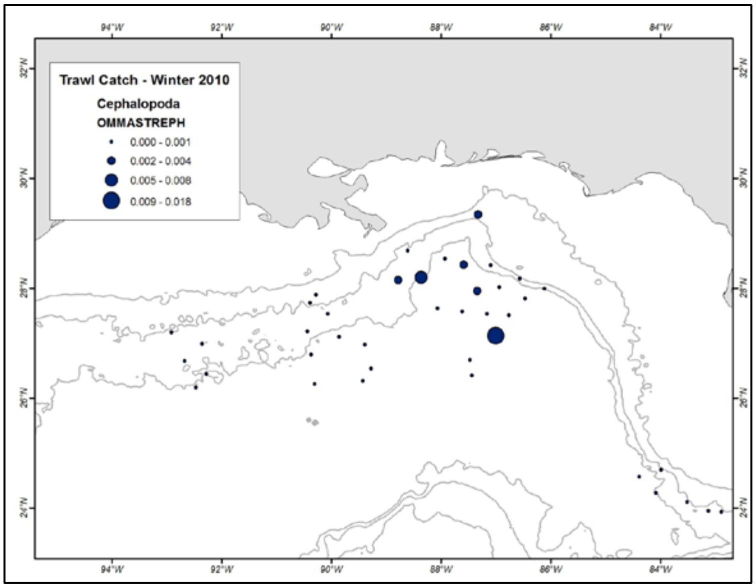

Figure 42. Catch of Ommastrephidae during winter-spring 2010.

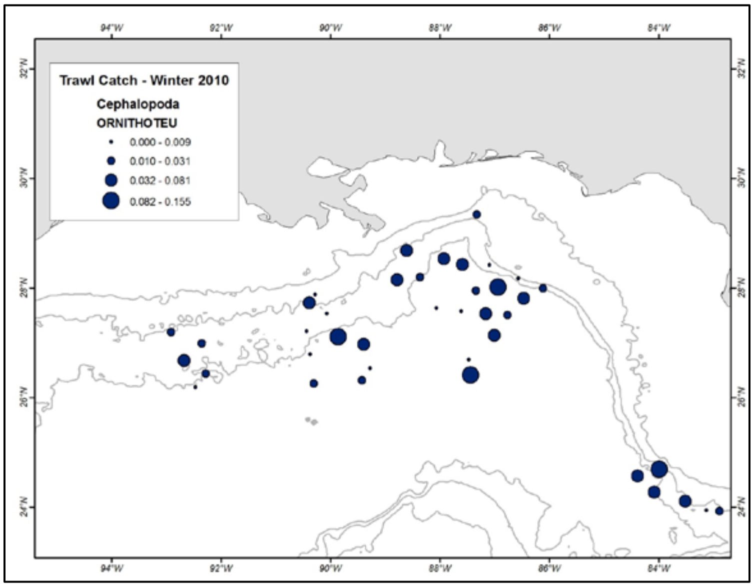

Figure 43. Catch of *Ortnithoteuthis antillarium* during winter-spring 2010.

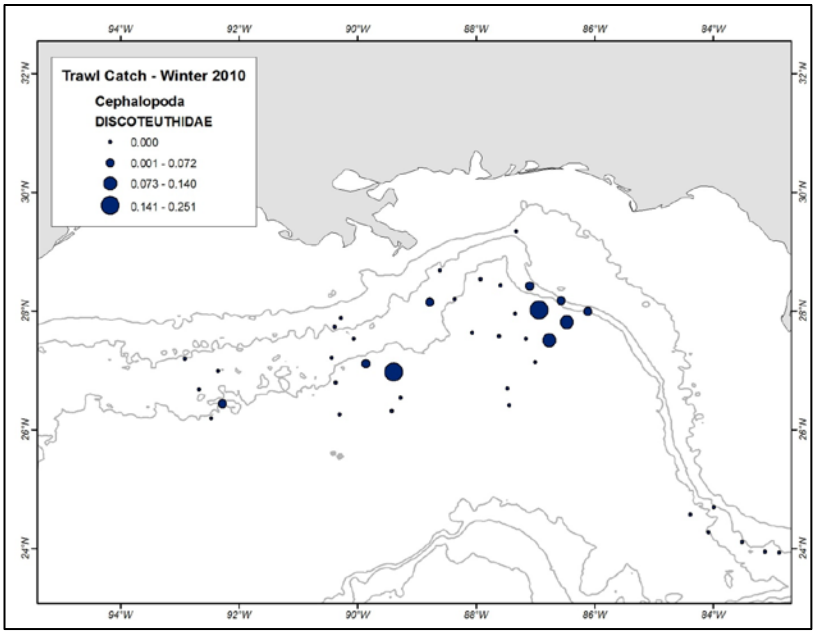

Figure 44. Catch of *Discoteuthis* spp. during winter-spring 2010.

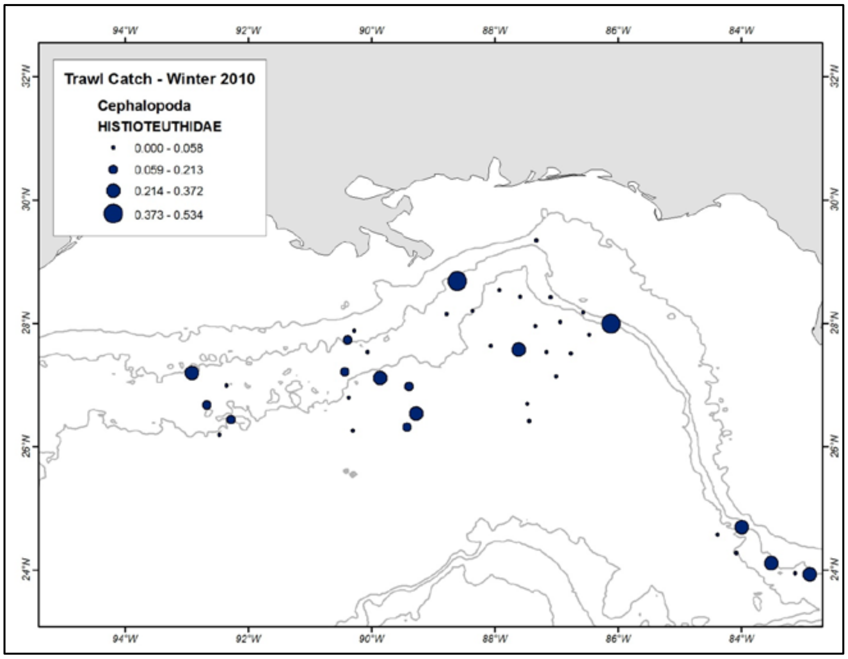

Figure 45. Catch of Histioteuthidae during winter-spring 2010.

Following field activities, all preserved specimens from both cruises were transported to the National Systematics Lab at the Smithsonian Institution for detailed taxonomic review and identification and archiving. All specimens were identified to species and verified against current taxonomic keys. The complete species list for both cruises is shown in Table 9.

Table 9. Complete species list for both the 2009 and 2010 cruises.

Decapodiformes		**TOTAL**	**AvgML (mm)**
Architeuthidae			
	*Architeuthis dux**	2	5943
Brachioteuthidae			
	Brachioteuthis sp.	6	41.2
Chiroteuthidae			
	*Asperoteuthis acanthoderma**	4	69
	*Chiroteuthis spoeli**	4	82.8
	*Chiroteuthis joubini**	7	80.1
	*Chiroteuthis veranyi**	8	62.1
	Chiroteuthis sp.*	13	44
	Grimalditeuthis bonplandi	1	90
Cranchiidae			
	*Cranchia scabra**	36	30.8
	Leachia atlantica	477	53.7
	Bathothauma lyromma	11	76.5
	Helicocranchia pfefferi	20	39.9
	*Galiteuthis armata**	6	192.8
	*Taonius pavo**	3	102.3
	Megalocranchia sp.*	3	85.5
	*Egea inermis**	3	109.6
	Teuthowenia sp.	3	79.7
	Liocranchia reinhardti	7	48.6
Cycloteuthidae			
	*Discoteuthis discus**	5	75.4
	*Discoteuthis laciniosa**	1	32
	*Cycloteuthis sirventyi**	1	78
	Cycloteuthis sp.*	3	66
Enoploteuthidae			
	Enoploteuthis leptura	6	36.8
	Enoploteuthis anapsis	13	40.7
	Enoploteuthis sp.	6	27.5
	Abralia redfieldi	39	26.2
	Abralia sp.	12	24.3
	Abralia veranyi	78	26.5
	Abraliopsis atlantica	24	28.4
	Abraliopsis hoylei pfefferi	1	15
	Abraliopsis sp.	1	13
Histioteuthidae			
	*Histioteuthis celeteria**	1	31
	*Histioteuthis corona**	12	51.3

Decapodiformes		**TOTAL**	**AvgML (mm)**
	*Histioteuthis reversa**	3	31.3
	Histioteuthis sp.*	5	41
	*Stigmatoteuthis arcturi**	25	48.2
Joubiniteuthidae			
	Joubiniteuthis portiere	1	91
Lycoteuthidae			
	Lycoteuthis diadema	1	29
	Selenoteuthis scintillans	5	30.8
Mastigoteuthidae			
	Mastigoteuthis agassizi	4	117.5
	Mastigoteuthis hjorti	5	84
Neoteuthidae			
	*Neoteuthis thielei**	3	50.7
Octopoteuthidae			
	Octopoteuthis sp.*	32	34.1
	*Taningia danae**	4	75
Ommastrephidae			
	*Illex oxygonius**	400 +	190
	*Ommastrephes bartramii**	12	120
	Ommastrephes sp.*	6	19.2
	*Ornithoteuthis antillarum**	59	45.2
	*Sthenoteuthis pteropus**	2	21
Onychoteuthidae			
	*Onychoteuthis banksii**	36	33.3
	Onykia carriboea	11	35.3
	*Moroteuthis robsoni**	1	58
Pholidotuethidae			
	*Pholidoteuthis adami**	2	91
	Pholidoteuthis sp.*	2	54.5
Pyroteuthidae			
	Pterygioteuthis giardi	63	20
	Pterygioteuthis gemmata	51	19
	Pterygioteuthis sp.	6	19.1
	Pyroteuthis margaritifera	64	29.5
Sepiolidae			
	Heteroteuthis dispar	22	18.4
Octopodiformes			
Allopsidae			
	*Haliphron atlanticus**	2	44
Bolitaenidae			
	Japetella diaphana	2	31
Vampyroteuthidae			
	*Vampyroteuthis infernalis**	11	34.2

6.0 ACOUSTIC BACKSCATTER

Scientific echosounder (Simrad EK60) data was collected throughout the Winter–Spring 2010 survey to quantify the vertical and spatial distribution of secondary productivity in mesopelagic waters. Data were collected on the 120 kHz, 38 kHz, and 18 kHz frequencies; however, the 120 kHz frequency was of limited usefulness due to shallow depth penetration (typically ~100m depth). The two frequencies have appropriate signal responses for examining the movement of micronekton and swimbladdered fish. In general, it is expected that cephalopods will provide a lower acoustic return signal because of the lack of air spaces and other acoustically reflective tissues. Therefore, the acoustic backscatter data collected during this survey likely reflect the distribution of the prey of larger cephalopods and vertically migrating fish.

A typical echosounder image observed during this survey is shown in Figure 46. Because this image includes a transition from night to day, the downward movement of the vertically migrating scattering layer is evident in both images; however, the response is much stronger in the 18 kHz frequency. The echogram is also typified by a deeper scattering layer that does not undergo vertical migration at night. In the 38 kHz image, there is a non-migrating, scattering layer at the base of the 18 kHz deep layer (approximately 400m depth, Figure 46). It is likely that these organisms in the 400–600 m depth range occur at the midwater feeding depths of sperm whales.

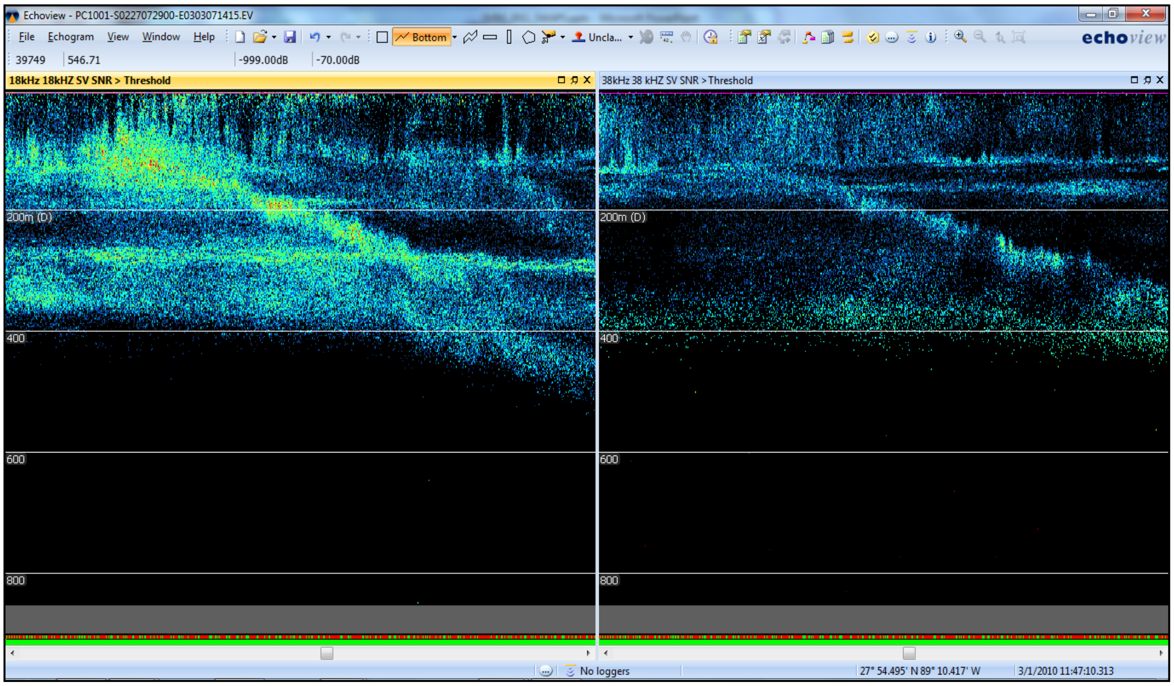

Figure 46. Typical echogram showing the 18kHz (left) and 38 kHz (right) frequencies.

The vertical migrating layer is evident, particularly in the 18 kHz echogram.

The QA/QC'd and noise filtered data (see section 2.2.2) were used to characterize the vertical and horizontal distribution of acoustic backscatter at the 18 kHz and 38 kHz frequencies. Using the echointegration tools in EchoView, the selected trackline segments were split at 5 km intervals and binned into 200m depth intervals from the surface to 1,000m. In general, the SNR at depths >600m was too low for effective integration. Therefore analysis was restricted to three depth layers: 0–200m, 200–400m, and 400–600m. The metric of average acoustic backscatter is log (NASC) where NASC is the Nautical Area Scatter Coefficient (units: m^2/nmi^2). This parameter reflects an average of the mean volume backscattering strength (Sv in dB) over the area being considered. Following the calculation of log (NASC) for each segment and depth layer, ordinary kriging was used to develop maps of backscatter over the surveyed area, separating the maps into day and night to account for the effects of vertically migrating organisms.

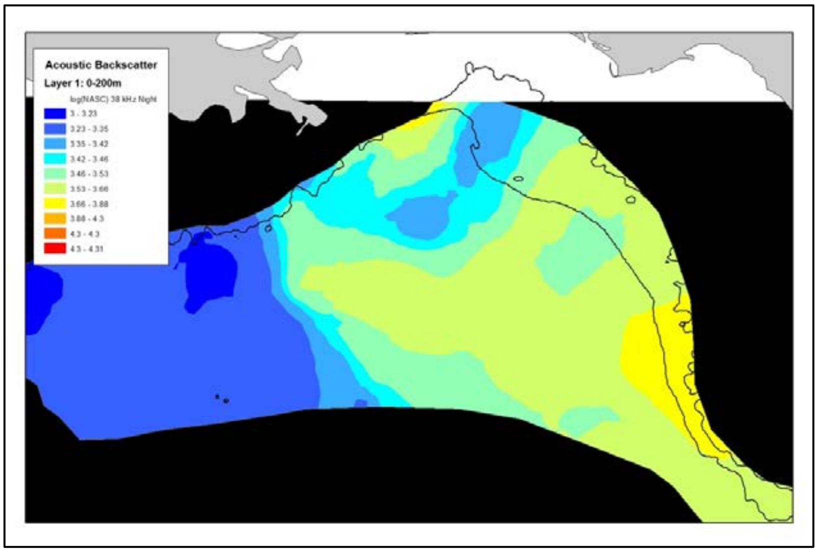

Figure 47. Night-time 38 kHZ backscatter in 0–200 m depth layer.

There was a strong east-west gradient in the acoustic backscatter data at all frequencies and layer depths (e.g., Figure 47). The lower backscatter in the western portion of the area is associated with the region of low SSHa water stretching through the southern and central portion of the survey region during winter 2010 (Figure 17). The night-time surface (0–200m) layer backscatter in the 38 kHz frequency was generally weak, associated with the relatively weak return from the vertically migrating animals at this frequency (Figure 47). The acoustic backscatter at the 18 kHz frequency was much higher, and the high backscatter region reflects a "tongue" of production stretching into the deep central area of the Gulf from the west Florida shelf (Figure 48).

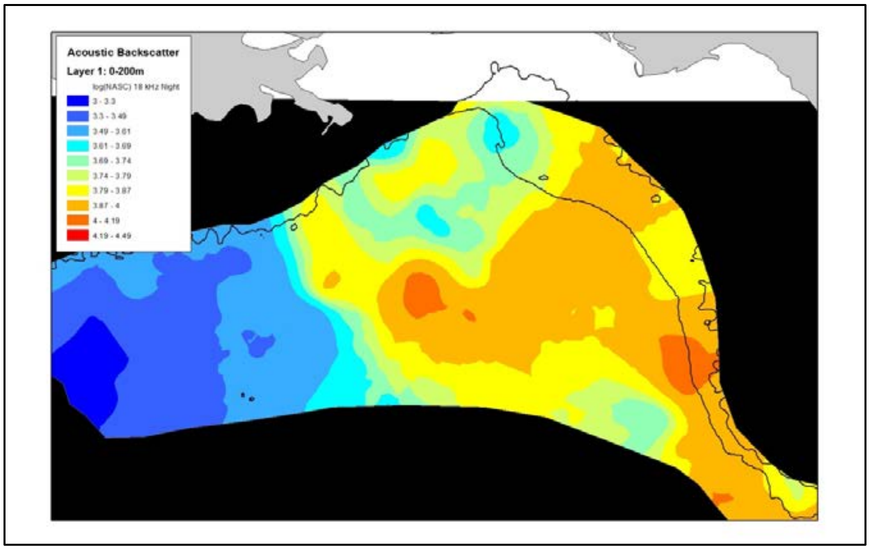

Figure 48. Night-time 18 kHz backscatter in 0–200 m depth layer.

This concentration of production is apparent in both the 38 kHz and 18 kHz surfaces, and is associated with the southern edge of the high SSHa region observed near the DeSoto Canyon (Figure 17).

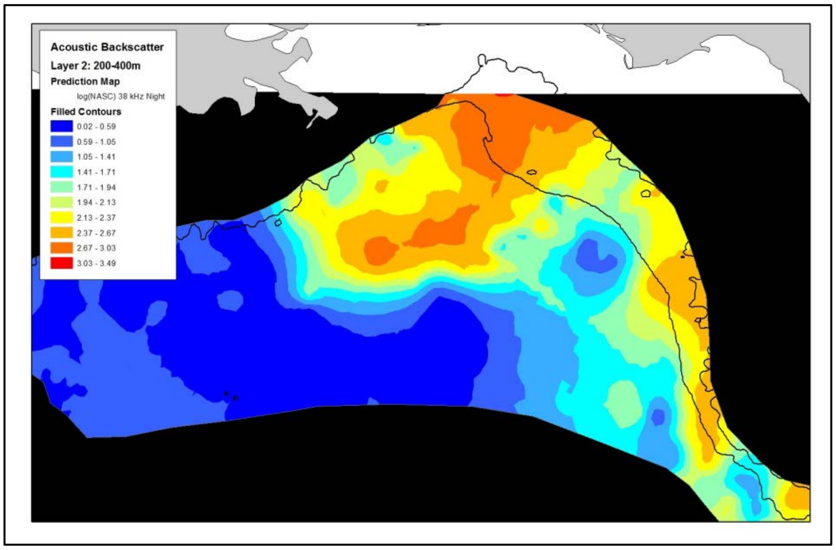

Figure 49. Night-time 38 kHz backscatter in 200–400 m depth layer.

The structure of the backscatter in the 200-400 m layer is similar to that in the shallower layer, with a tongue of higher backscatter extending out from the DeSoto Canyon region into deeper waters. However, at this deeper depth, the region of high production is shifted to the north (Figure 49).

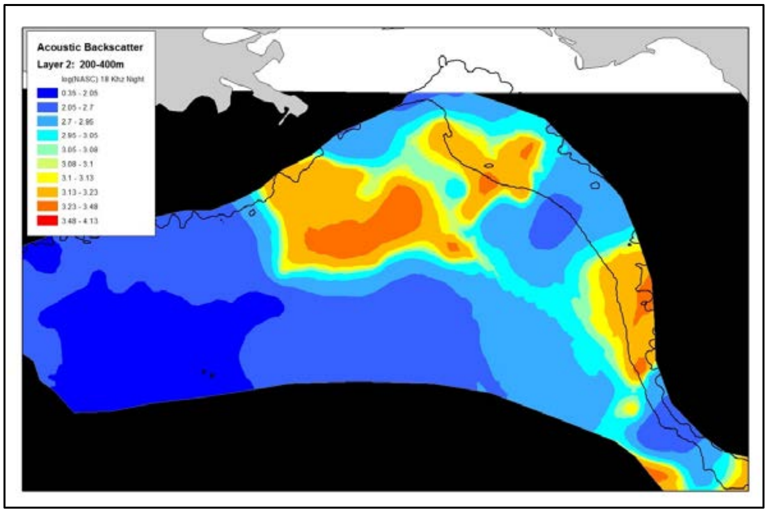

Figure 50. Night-time 18 kHz backscatter in 200–400m depth layer.

Backscatter in the 18 kHz frequency was similarly distributed in the north-central portion of the surveyed area with the highest intensity south of the Mississippi River Delta (Figure 50). The region of highest acoustic backscatter in the 38 kHz frequency was strongly correlated to the area with the greatest number and group size of sperm whale sightings (Figure 51).

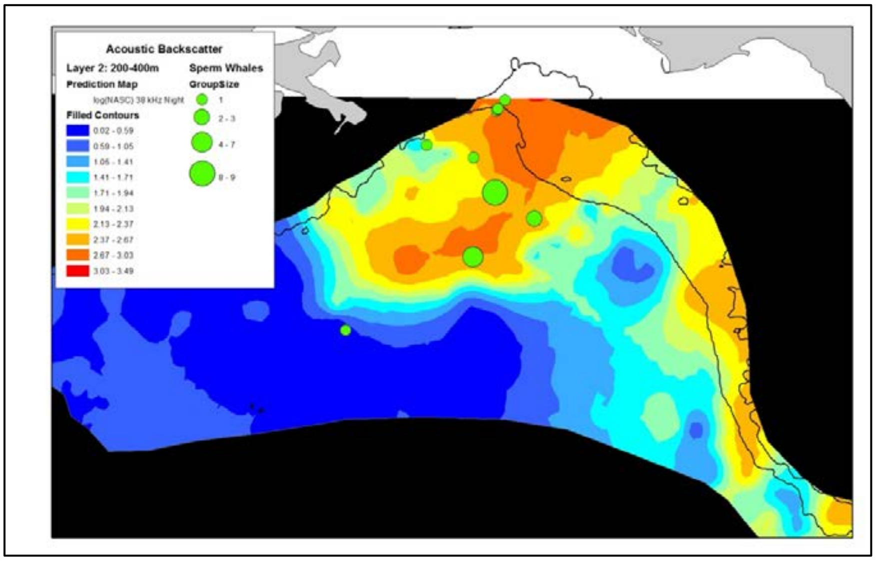

Figure 4 51. Acoustic backscatter and sperm whale groups.

This association is consistent with a close relationship between sperm whales and the advection of productivity into the deeper waters of the Gulf due to the presence of the clockwise circulation pattern associated with positive SSHa. The highest production of the vertically migrating layer is shifted to the south of the region where sperm whales were observed, again suggesting that it is the deeper scattering layer that does not vertically migrate that is the primary concentration of sperm whale prey.

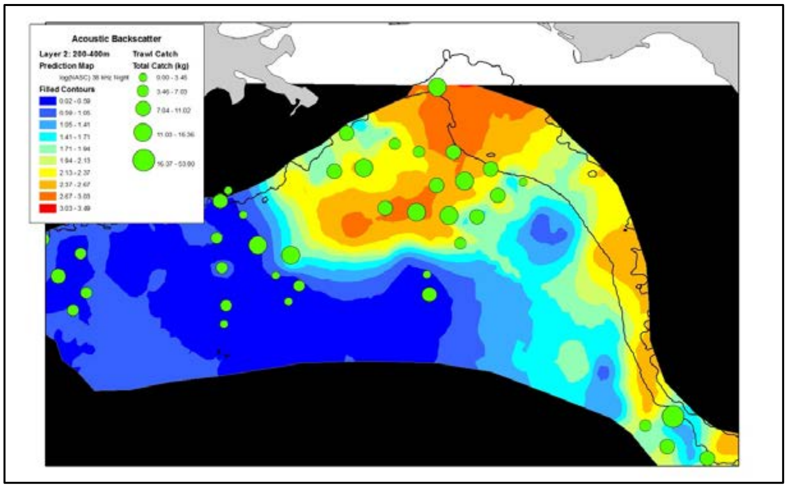

Figure 52. Acoustic backscatter and total trawl catch.

Total catch weight in the midwater trawls also reflected the distribution of acoustic backscatter with higher catch weights strongly associated with the region of high backscatter in the DeSoto Canyon region (Figure 52). In the central and western Gulf where acoustic backscatter was low, trawl catches were also lower than those observed in areas with higher backscatter.

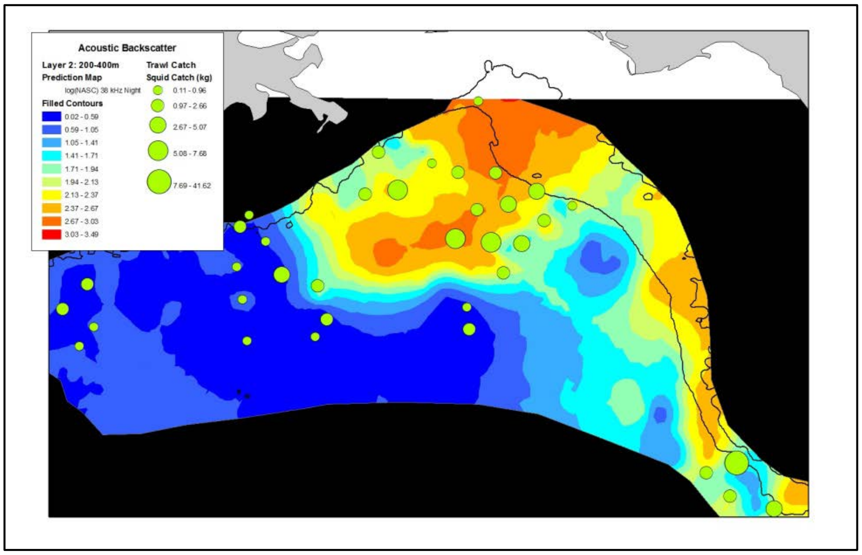

Figure 53. Acoustic backscatter and squid catch.

As with total catch, the total biomass of cephalopods captured during trawling was also associated with regions of high acoustic backscatter in the 200–400 m depth layer (Figure 53). The highest squid catches were in trawls on the southern side of the region of high mesopelagic backscatter, which is also the region where the largest groups of sperm whales were encountered. Taken together, these data demonstrate the strong coupling between physical features and the concentration of prey that support aggregations of sperm whales.

7.0 STABLE ISOTOPE ANALYSIS

SI fractionation has been used to identify trophic and food web relationships across a broad range of taxa and ecosystems (Ben-David and Flaherty 2012; Newsome et al. 2010). The primary isotopic ratio used to identify trophic level within food webs is the $^{15}N/^{14}N$ ratio as Nitrogen is fractionated during protein metabolism, and tissues become enriched in ^{15}N at higher trophic levels. However, interpretation of trophic relationships is complicated by variation in the level of enrichment in different tissue types, the variable turnover rates of different tissues, and metabolic differences between taxa. In addition, individual organisms may feed at multiple trophic levels, and hence their SI signature reflects a mixture of potential prey items that can vary both seasonally and spatially. Nitrogen enrichment per trophic level is typically in the range of 1‰–8‰ with broadly accepted averages of approximately 3‰ (Ben-David and Flaherty 2012; Hannsson et al. 1997; Deniro and Epstein 1978) or 3.4 ‰ (Post 2002). However, in several studies of marine mammals, a lower enrichment value of 1.6‰–1.7‰ has been used to compare isotopic ratios between mammal skin and the muscle tissue of potential prey. In particular, Cherel et al. (2008) used 1.7‰ as the enrichment value between elephant seal blood and prey muscle in a study of trophic relationships in the Southern Ocean, and Garcia-Tiscar (2009) identified an enrichment value of 1.6‰ between mammal skin and prey muscle in a controlled feeding study of killer whales. Ruiz-Cooley et al. (2012) found that nitrogen enrichment between sperm whales known to feed on jumbo squid (*Dosidicus gigas*) in the Gulf of California compared to the northern Gulf was more consistent, with a value of 1.6‰.

The fractionation of carbon isotopes is primarily related to differences in the photosynthetic processes between more terrestrial sources of primary production versus more marine sources of primary production. There is a degree of carbon processing during catabolic processes; however, carbon-13 enrichment is generally weakly related to trophic level. In the pelagic environment, which is the focus of this study, there is less expectation that the $^{13}C/^{12}C$ ratio will provide meaningful discrimination between dietary sources of carbon. As with nitrogen SIs, there is considerable variation in the degree of enrichment as a function of tissue types and the organisms involved. The range of enrichment levels for carbon between predator and prey is from 1‰ -5‰ in a variety of controlled feeding studies, and the widely accepted "typical" value is 1‰ (Ben-David and Flaherty 2012; Deniro and Epstein 1978). As with nitrogen ratios, Garcia-Tiscar (2009) found a 13-C enrichment of 1.6‰ for controlled feeding studies of killer whales, and Ruiz-Cooley et al. (2012) found support for using this value in sperm whales in the Gulf of California.

Ruiz-Cooley et al. (2012) provides the most direct isotopic ratio data for comparison to those observed in potential sperm whale prey taxa in the current study. The prior study included samples collected from sperm whales along the shelf-break in the North-Central Gulf from the same population which is the focus of the current study. The mean $\delta^{13}C$ was -16.4 (SD = 0.4) and mean $\delta^{15}N = 12.2$ (SD = 0.5, Ruiz-Cooley et al. 2012). These values were stable across years and did not show strong differentiation by sex or life history stage. The values observed for Gulf sperm whales were similar to those for animals from the Galapagos Islands (Marcoux et al. 2007). However, Gulf sperm whales had lower $\delta^{15}N$ levels than animals in both the Gulf of California (Ruiz-Cooley et al. 2004) and Chile (Marcoux et al. 2007). Sperm whales in the Gulf of California are known to feed predominantly on jumbo squid, which also has a high $\delta^{15}N$ value as expected from a higher trophic level predator. Therefore, these data suggest that Gulf sperm whales are feeding (on average) at a lower trophic level than those in California; however, comparison of isotopic ratios across ecosystems is complicated by the differences in the sources of primary and secondary production and ecosystem structure.

Ruiz-Cooley et al. (2012) conducted very limited sampling of mesopelagic squids and examined isotopic ratios in a few specimens of small size. They found that the animals sampled were likely smaller than the target prey of sperm whales in the Gulf. There is very little information available on the diets and trophic position of mesopelagic squid. However, there is evidence that squids move to progressively higher trophic levels as they grow larger throughout their life spans. For example, coastal squid species feed on planktonic organisms during their early life and progressed to larger fish taxa as they grew (Passarella and Hopkins, 1991; Judkins, 2009). In a study of SI ratios in cetaceans, Ostrom et al. (1993) inferred the relative trophic position of Sowerby's beaked whales in reference to that of other cetaceans. Sowerby's beaked whales along with both sperm whales and pygmy sperm whales, which primarily feed on squid, had $^{15}N/^{14}N$ ratios intermediate between piscivorous and planktivorous species and occupied one trophic level above *Illex illecebrosus* that occupied offshore waters. Interestingly, this ommastrephid squid showed a change in trophic level with both size and habitat. These findings suggested that larger squids occupy a higher trophic level than smaller squids, and that Sowerby's beaked whales were primarily feeding on smaller, offshore *Illex illecebrosus* (Ostrom et al. 1993). Likewise, Ruiz-Cooley et al. (2006) showed that larger jumbo squid fed primarily upon myctophid fishes while smaller individuals occupied a lower trophic level more consistent with predation on euphausiids. Thus, ontogenetic differences in the SI ratios of squid taxa may provide insight into the potential size and taxonomic composition of sperm whale prey.

In this study, we examined $\delta^{13}C$ and $\delta^{15}N$ ratios in 32 taxa of mesopelagic squids (Table 10) and 43 taxa of mesopelagic fish (Table 13) collected during the 2010 *Pisces* cruise. Squid taxa were grouped at the genus and/or family level both to reduce the number of categories and to increase sample sizes for analysis. SI analyses were conducted at Michigan State University and followed standard methods for sample extraction and analysis. The resulting data were analyzed to identify changes in squid isotopic ratios as a function of size and were compared to the range of SI values observed in Gulf sperm whales.

7.1 ANALYSIS OF MESOPELAGIC SQUIDS

A total of 536 individual squids was analyzed for SI values from 32 taxa. Species were combined at the family level where necessary both to maintain adequate samples sizes for comparison and due to uncertainty in identification at the species level (Table 10).

Table 10. Cephalopod taxonomic categories, sample sizes, and length ranges used in stable isotope analysis.

(ML = Mantle length in mm)

Category (Abbreviation)	Species Included	N	Avg. ML (range)
Asperoteuthis acanthoderma (Aa)	*A. acanthoderma*	13	202.2 (74-695)
Bathothauma lyromma (Bl)	*B. lyromma*	16	116.4 (58-168)
Bathyteuthis abbyssicola (Ba)	*B. abbyssicola*	10	44.3 (17-67)
Brachioteuthis sp. (Bs)	*Brachioteuthis* sp.	2	31 (19-43)
Chiroteuthis sp. (Cs)	*C. joubini, C. spoeli, C. veranyi*	24	85.3 (49-271)
Chtenopteryx sicula (Ch)	*C. sicula*	1	27 (27-27)
Cranchiidae (CrF)	*Cranchia scabra, Leachia atlantica, Heliocranchia pfefferi*	95	52.3 (16-111)
Cycloteuthidae (CyF)	*Discoteuthis discus, Cycoloteuthis* sp.	14	76.3 (12-161)
Egea inermis (Ei)	*E. inermis*	7	143.3 (99-214)
Enoploteuthidae (EnF)	*Abraliopsis morissii, Abraliopsis atlantica, Abralia veranyi, Abralia redfieldi, Enoploteuthis leptura, Enoploteuthis anapsis*	59	29.9 (13-57)
Galiteuthis armata (Ga)	*G. armata*	19	252.7 (134-438)
Haliphron atlanticus (Ha)	*H. atlanticus*	12	33.4 (14-86)
Heteroteuthis dispar (Hd)	*H. dispar*	9	18.7 (16-23)
Hisitioteuthis sp. (HiG)	*H. corona, H. reversa, H. corona berryi*	13	60.4 (11-82)
Illex oxygonius (Io)	*I. oxygonius*	7	181.3 (132-223)
Japetella diaphana (Jd)	*J. diaphana*	9	42.3 (13-105)
Joubiniteuthis portieri (Jp)	*J. portieri*	3	81.3 (74-93)
Mastigoteuthis sp. (MaG)	*M. agassizi, M. hjorti*	17	76.4 (27-143)
Neoteuthis thielei (Nt)	*N. thielei*	1	79 (79-79)
Scaeurgus unichirrus (Su)	*S. unichirrus*	1	25 (25-25)
Octopoteuthis sp. (OcG)	*O. megaptera, O. sicula*	10	44.7 (25-110)
Ommastrephes bartramii (Ob)	*O. bartramii*	15	133.1 (28-560)
Onchyoteuthidae (OnF)	*Onchyoteuthis banksii, Onykia caribbaea, Moroteuthis robsoni*	43	40.5 (17-79)
Ornithoteuthis antillarium (Oa)	*O. antillarium*	47	70.2 (16-123)
Philodoteuthis adami (Pa)	*P. adami*	1	94 (94-94)
Pyroteuthidae (PyF)	*Pyroteuthis margaritifera, Pterygioteuthis gemmata, Pteryogioteuthis giardi*	42	25.1 (13-39)
Selenoteuthis scintillans (Ss)	*S. scintillans*	10	29.2 (10-55)
Sthenoteuthis pteropus (Sp)	*S. pteropus*	1	360 (360-360)
Stigmatoteuthis acrturi (Sa)	*S. arcturi*	24	65.7 (17-154)

Category (Abbreviation)	**Species Included**	**N**	**Avg. ML (range)**
Taningia danae (Td)	*T. danae*	2	114 (104-124)
Unid. squid (Un)	Unknown	4	128.5 (64-193)
Vampyroteuthis infernalis (Vi)	*V. infernalis*	5	39 (21-57)

The squid taxa analyzed included those that have been identified as potential prey for sperm whales in the Gulf (e.g., *Histioteuthis* sp., *Stigmateuthis acrturi*, Cycloteuthidae) with mantle lengths averaging 60–80 mm. In addition, smaller squid taxa that are very likely not prey of sperm whales but rather feed at lower trophic levels were included (e.g., Eonoploteuthidae, Chiroteuthidae, and Onchyoteuthidae). Finally, several large specimens were captured including *Asperoteuthis acdanthoderma* (ML = 760mm), *Ommastrephes bartrimii* (ML = 560 mm), *Galliteuthis armata* (ML = 438mm), and *Sthenoteuthis pteropus* (ML = 360 mm). It is expected that these specimens represent the upper end of sizes of squids that are available to sperm whales with the exception of the giant squid, *Architeuthis dux*.

The average and standard deviation of δ^{13}C and δ^{15}N for each taxon (averaged across sizes) are shown in Table 11 along with the mean and 95% confidence limit of the difference from those values shown for sperm whales. Those taxa where the 95% confidence limit of the difference includes 1.6‰ for δ^{13}C or δ^{15}N are highlighted. First, it should be noted that squid taxa with δ^{15}N differences on the order of 3‰ (the "standard" trophic level difference) include very small taxa, such as the Enoploteuthidae (size range avg. 33mm [13–57]), *Haliphron atlanticus* (average size 33 mm, range 14–86 mm) and Onchyoteuthidae (average size 40.5 mm, range 17–79 mm) which are dominated by very small specimens well below the size range of expected prey for sperm whales. This supports the use of the smaller trophic level enrichment (TLE) levels for comparison of sperm whale and their prey in this study. Second, there is a high degree of overlap among many squid taxa and the expected δ^{13}C TLE level. Sixteen of the 33 taxa had δ^{13}C levels where the 95% confidence limit of the difference with sperm whales included 1.6‰. This is also to be expected because the source of carbon for most taxa included in the study should be primarily marine; and there is less expectation of enrichment across trophic levels for carbon. Finally, only three of the tested taxa had average δ^{15}N levels that were consistent with the expected TLE value of 1.6‰: *Histioteuthis* sp., *Joubinitetuthis portieri*, and *Stigmatateuthis arcturi*. In addition, *Sthenoteuthis pteropus* had a TLE value of 1.71, but this was from only one specimen. The Histioteuthid squids have previously been identified as prey of sperm whales in Gulf (Barros 2003).

However, given the expected ontogenetic shifts in diet among mesopelagic squids, the degree of trophic overlap with sperm whales may be masked by size differences. The changes in δ^{13}C and δ^{15}N as a function of size were first examined across species using a conditional scatterplot (Figure 54). This plot shows a broad range of δ^{13}C levels within a given size class, though that range tends to decrease with increasing size. At the smallest sizes, δ^{13}C ranges from approximately -19.5 to -16.5, while at the largest size classes, δ^{13}C is only rarely below -18 (Figure 54). The δ^{15}N show a pronounced change in distribution with increasing size class, with a narrow range between 8 and 10 at the smaller size classes, an upper limit of approximately 12 in intermediate size classes, and an upper limit of 14 in the largest size classes (Figure 54).

Table 11. Mean (Standard Deviation) of δ13C and δ15N by taxonomic category and the difference from mean values reported from Gulf of Mexico sperm whales.

* indicates groups where the 95% confidence limit of the difference of means includes the presumed TLE for sperm whales

Category (Abbreviation)	Avg. δ^{13}C (SD)	Avg. δ^{15}N (SD)	ΔSperm Whale ^{13}C (95% CI)	ΔSperm Whale ^{15}N (95% CI)
Asperoteuthis acanthoderma (Aa)	-17.2 (0.71)	9.5 (1.84)	0.85 (0.43 - 1.27)	2.69 (1.67 - 3.71)
Bathothauma lyromma (Bl)	-17.3 (0.27)	9.0 (1.06)	0.89 (0.69 - 1.09)	3.17 (2.62 - 3.72)
Bathyteuthis abbyssicola (Ba)	-18 (0.81)	9.9 (1.04)	1.58 (1.06 - 2.1)*	2.31 (1.64 - 2.98)
Brachioteuthis sp. (Bs)	-19 (0.77)	8.7 (0.34)	2.55 (1.48 - 3.62)*	3.54 (3.04 - 4.04)
Chiroteuthis sp. (Cs)	-17.4 (0.52)	12.3 (1.27)	1.04 (0.79 - 1.29)	-0.15 (-0.69 - 0.39)
Chtenopteryx sicula (Ch)	-17.8	9.3	1.39	2.86
Cranchiidae (CrF)	-17.7 (0.92)	8.2 (0.81)	1.31 (1.07 - 1.55)	4 (3.75 - 4.25)
Cycloteuthidae (CyF)	-17.2 (0.52)	11.2 (0.95)	0.85 (0.54 - 1.16)	1.04 (0.51 - 1.57)
Egea inermis (Ei)	-17.9 (0.59)	9.1 (0.46)	1.5 (1.04 - 1.96)*	3.13 (2.74 - 3.52)
Enoploteuthidae (EnF)	-17.8 (0.49)	9.8 (0.9)	1.38 (1.19 - 1.57)*	2.43 (2.14 - 2.72)
Galiteuthis armata (Ga)	-16.9 (0.25)	9.5 (0.7)	0.47 (0.28 - 0.66)	2.71 (2.35 - 3.07)
Haliphron atlanticus (Ha)	-18.2 (0.6)	8.4 (1.13)	1.79 (1.42 - 2.16)*	3.83 (3.17 - 4.49)
Heteroteuthis dispar (Hd)	-18.3 (0.35)	8.9 (0.67)	1.93 (1.65 - 2.21)	3.28 (2.8 - 3.76)
Hisitioteuthis sp. (HiG)	-17.6 (0.4)	10.8 (0.83)	1.24 (0.98 - 1.5)	1.37 (0.88 - 1.86)*
Illex oxygonius (Io)	-17.6 (0.35)	12.2 (0.57)	1.2 (0.9 - 1.5)	-0.04 (-0.5 - 0.42)
Japetella diaphana (Jd)	-18.4 (0.59)	6.9 (0.81)	1.95 (1.54 - 2.36)*	5.31 (4.75 - 5.87)
Joubiniteuthis portieri (Jp)	-17.6 (0.36)	10.5 (0.15)	1.18 (0.75 - 1.61)*	1.7 (1.45 - 1.95)*
Mastigoteuthis sp. (MaG)	-17.5 (0.35)	11.8 (0.62)	1.12 (0.9 - 1.34)	0.4 (0.05 - 0.75)
Neoteuthis thielei (Nt)	-17.9	9.0	1.55*	3.22
Scaeurgus unichirrus (Su)	-20.0	7.9	3.56	4.33
Octopoteuthis sp. (OcG)	-17.2 (0.57)	9.8 (1.03)	0.85 (0.47 - 1.23)	2.41 (1.74 - 3.08)
Ommastrephes bartramii (Ob)	-18.1 (0.96)	9.3 (1.34)	1.72 (1.21 - 2.23)*	2.85 (2.15 - 3.55)
Onchyoteuthidae (OnF)	-18.2 (0.59)	9.3 (1.27)	1.82 (1.59 - 2.05)*	2.92 (2.5 - 3.34)
Ornithoteuthis antillarium (Oa)	-18.2 (0.53)	9.8 (0.79)	1.75 (1.54 - 1.96)*	2.38 (2.09 - 2.67)
Philodoteuthis adami (Pa)	-17.6	12.6	1.2	-0.38
Pyroteuthidae (PyF)	-18.1 (0.49)	9.6 (0.65)	1.75 (1.54 - 1.96)*	2.61 (2.34 - 2.88)
Selenoteuthis scintillans (Ss)	-17.9 (0.9)	9.5 (0.64)	1.54 (0.96 - 2.12)*	2.68 (2.24 - 3.12)
Sthenoteuthis pteropus (Sp)	-16.7	10.5	0.33	1.71*
Stigmatoteuthis acrturi (Sa)	-18 (0.38)	11 (1.27)	1.56 (1.35 - 1.77)*	1.17 (0.63 - 1.71)*
Taningia danae (Td)	-17.1 (0.38)	11.8 (0.18)	0.73 (0.18 - 1.28)	0.36 (0.05 - 0.67)
Unid. squid (Un)	-17.7 (1.15)	11.1 (1.84)	1.34 (0.2 - 2.48)*	1.06 (-0.76 - 2.88)*
Vampyroteuthis infernalis (Vi)	-17.9 (0.72)	9.4 (0.84)	1.47 (0.82 - 2.12)*	2.77 (2.01 - 3.53)

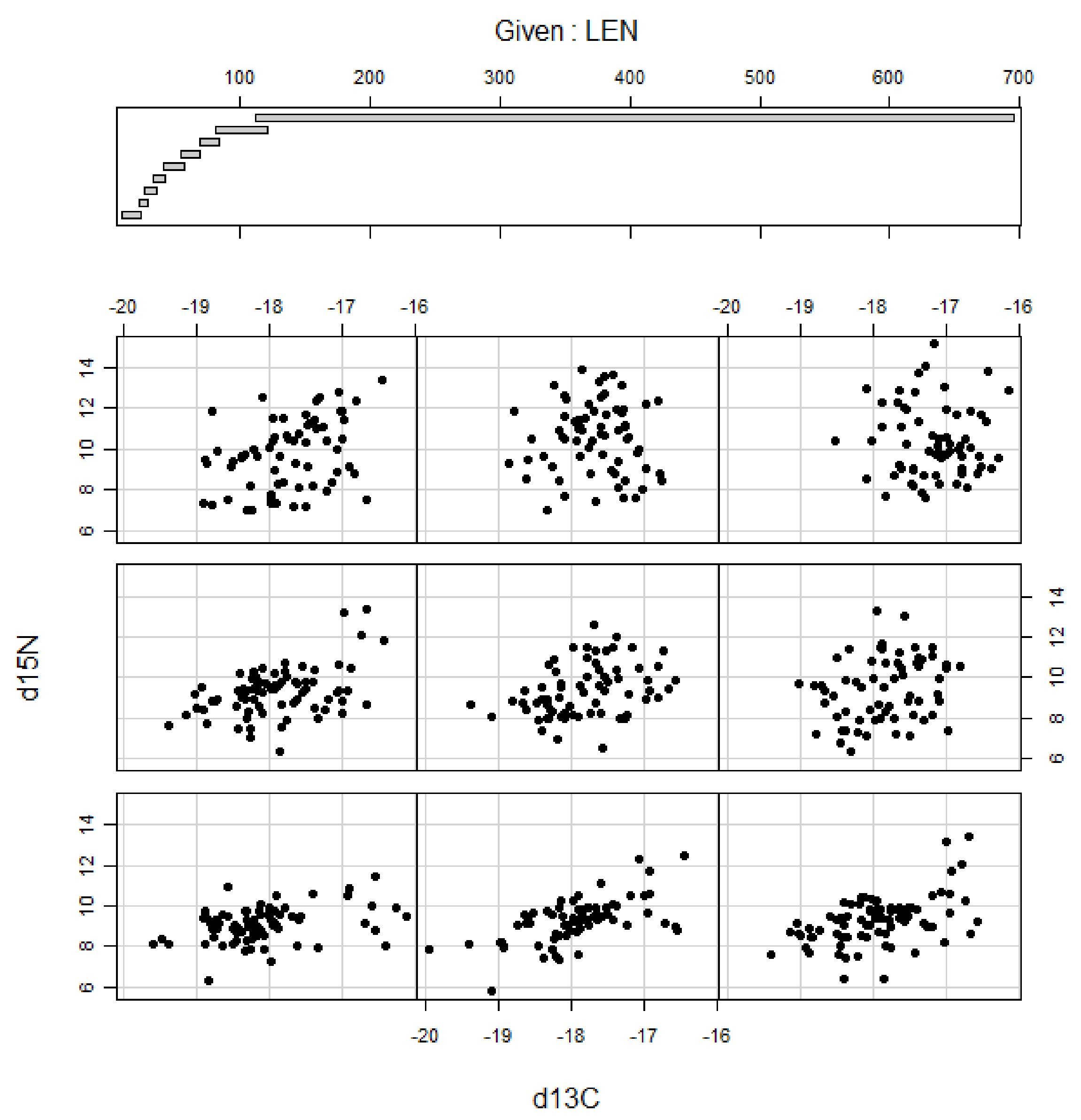

Figure 54. Conditional plot showing stable isotope profile as a function of mantle length category across all taxa of cephalopods.

This figure shows the relationships between δ13C and δ15N conditional on the size of squids across taxa. The top panel shows the division of the individual squid into nine length categories. The lower left scatterplot panel is the smallest size class while the upper right scatterplot panel is the largest size class.

Correlations between the mantle lengths of each squid taxa and $\delta^{13}C$ or $\delta^{15}N$ are shown in Table 12. There are relatively few significant correlations for $\delta^{13}C$, as would be expected from examination of the conditional scatterplot. However, multiple taxa show significant positive correlations between length and $\delta^{15}N$. These include the Histioteuthid squids (*Histioteuthis* sp., *Stigmateuthis acrturi*) along with additional robust squid species including *Ommastrephes bartramii*, *Ornithoteuthis antillarium*, and *Illex oxygonius*. Scatterplots for these correlations are shown in Figures 55-65.

Table 12. Correlations (Pearson's correlation coefficient) between mantle length (mm) and stable isotope signatures in cephalopod taxa.

Corrleations were examined only for taxa with sample sizes >7. Bold denotes significant correlations.

Taxonomic category	Correlation ($\delta^{13}C$)	p_{cor} ($\delta^{13}C$)	Correlation ($\delta^{15}N$)	p_{cor} ($\delta^{15}N$)
Asperoteuthis acanthoderma	**0.607**	**0.0277**	**0.933**	**<0.0001**
Bathothauma lyromma	0.083	0.7589	0.160	0.5532
Bathyteuthis abyssicola	**0.961**	**0.0006**	**0.877**	**0.0094**
Chiroteuthis sp	-0.004	0.9869	**0.624**	**0.0019**
Cranchiidae	-0.138	0.1852	**-0.228**	**0.0268**
Cycloteuthidae	-0.409	0.1648	**0.838**	**0.0003**
Egea inermis	0.716	0.0705	0.270	0.5580
Enoploteuthidae	0.232	0.0773	0.230	0.0795
Galiteuthis armata	0.172	0.4808	-0.027	0.9127
Haliphron atlanticus	0.006	0.9862	-0.196	0.5883
Heteroteuthis dispar	0.257	0.5040	0.525	0.1467
Histioteuthis sp	**0.665**	**0.0184**	**0.585**	**0.0458**
Illex oxygonius	-0.657	0.1085	**0.932**	**0.0022**
Japetella diaphana	0.615	0.0781	0.423	0.2567
Mastigoteuthis agassizi	-0.334	0.2237	0.243	0.3837
Octopoteuthis sp	0.088	0.8217	**0.776**	**0.0141**
Ommastrephes bartramii	**0.847**	**0.0001**	**0.882**	**<0.0001**
Onychoteuthidae	-0.046	0.7723	-0.092	0.5614
Ornithoteuthis antillarium	**0.307**	**0.0357**	**0.589**	**<0.0001**
Pyroteuthidae	**0.576**	**0.0001**	**0.366**	**0.0171**
Selenoteuthis sp.	0.067	0.8543	0.317	0.3717
Stigmateuthis arcturi	**0.651**	**0.0008**	**0.843**	**<0.0001**

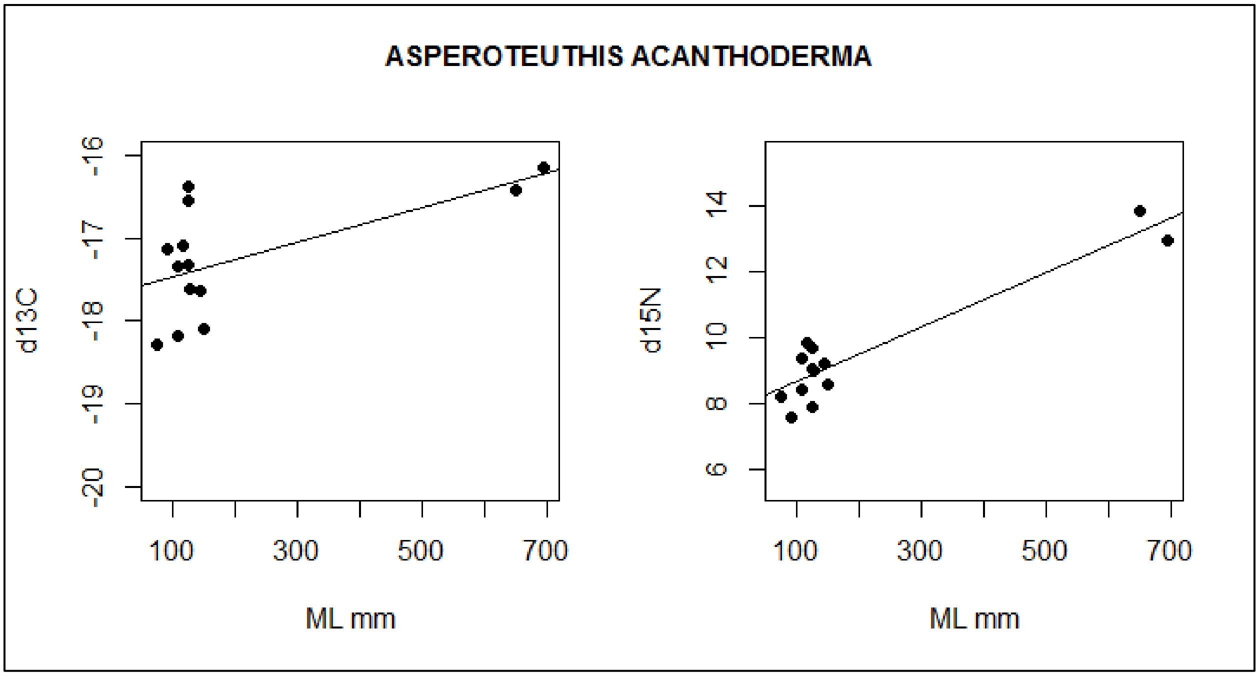

Figure 55. Scatterplots for δ^{13}C (left panel) and δ^{15}N (right panel) showing the correlation between mantle length and stable isotope signatures.

The lines indicate the linear regression line.

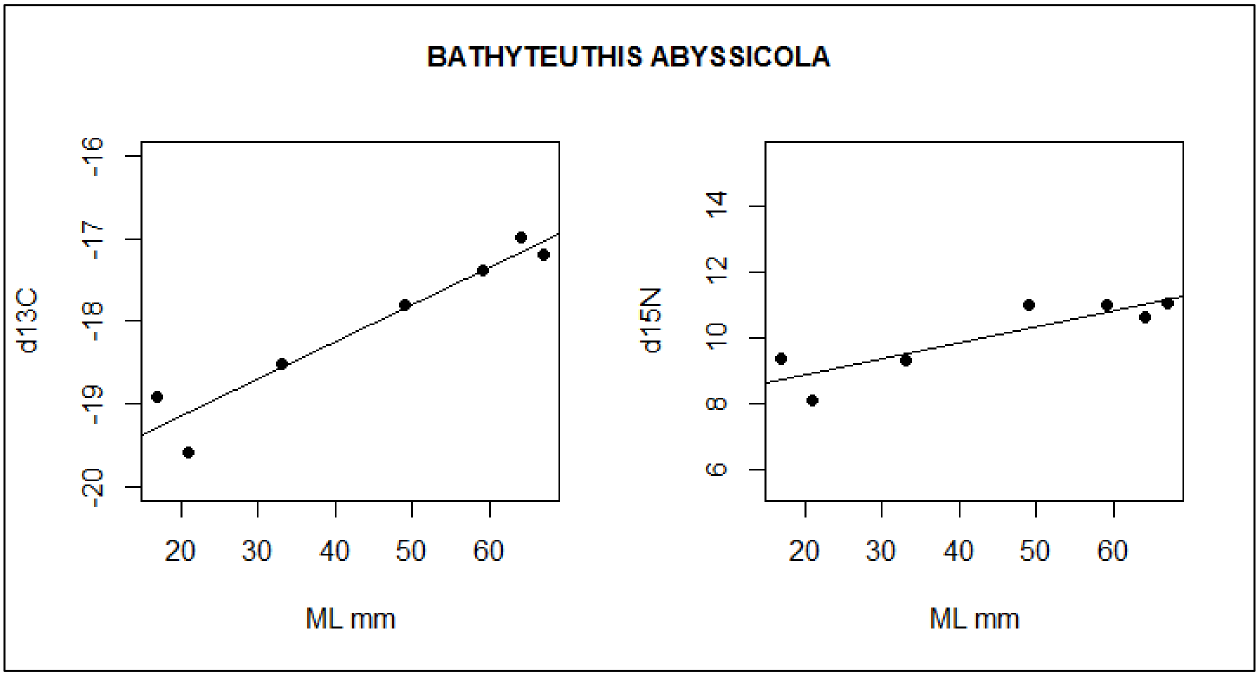

Figure 6. Scatterplots for δ^{13}C (left panel) and δ^{15}N (right panel) showing the correlation between mantle length and stable isotope signatures.

The lines indicate the linear regression line.

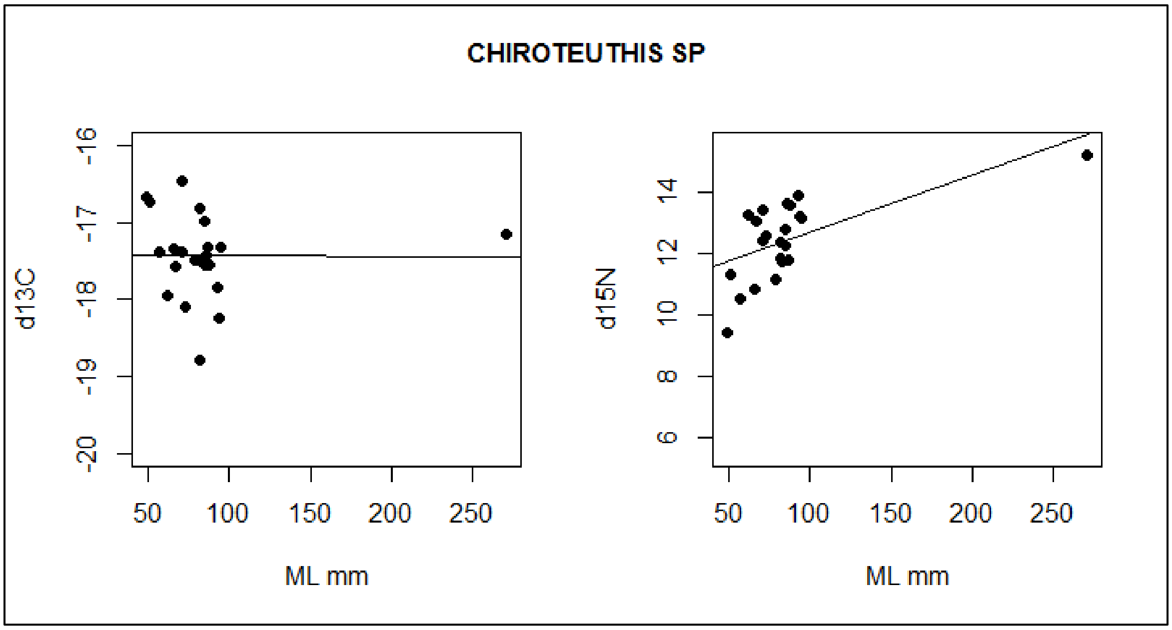

Figure 77. Scatterplots for $\delta^{13}C$ (left panel) and $\delta^{15}N$ (right panel) showing the correlation between mantle length and stable isotope signatures.

The lines indicate the linear regression line.

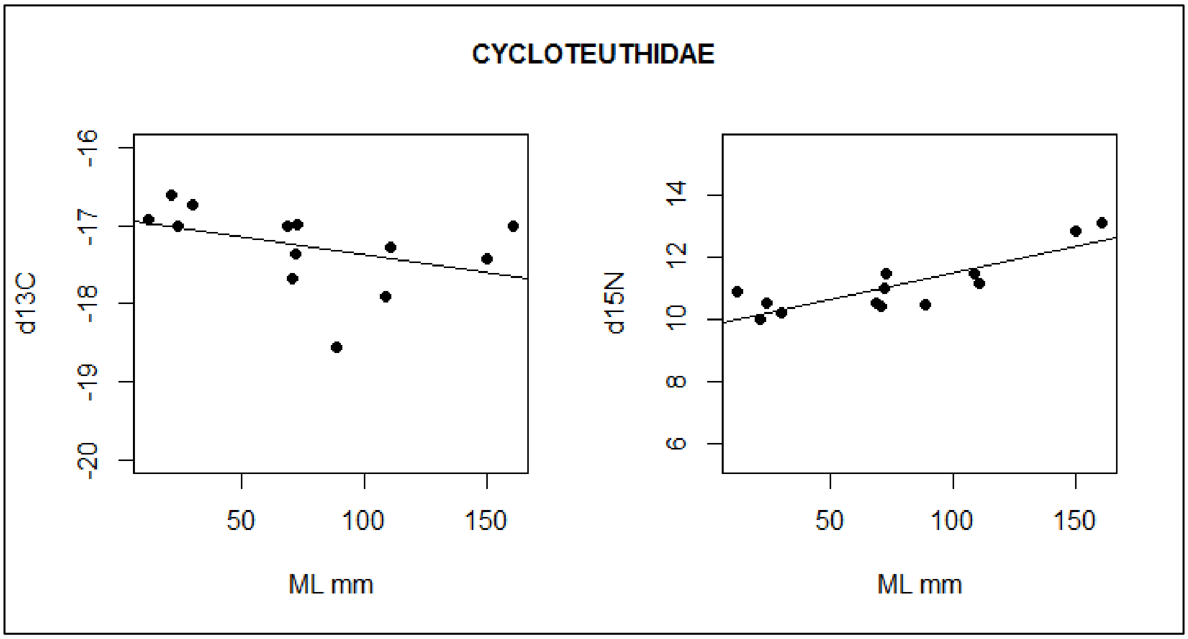

Figure 58. Scatterplots for $\delta^{13}C$ (left panel) and $\delta^{15}N$ (right panel) showing the correlation between mantle length and stable isotope signatures.

The lines indicate the linear regression line.

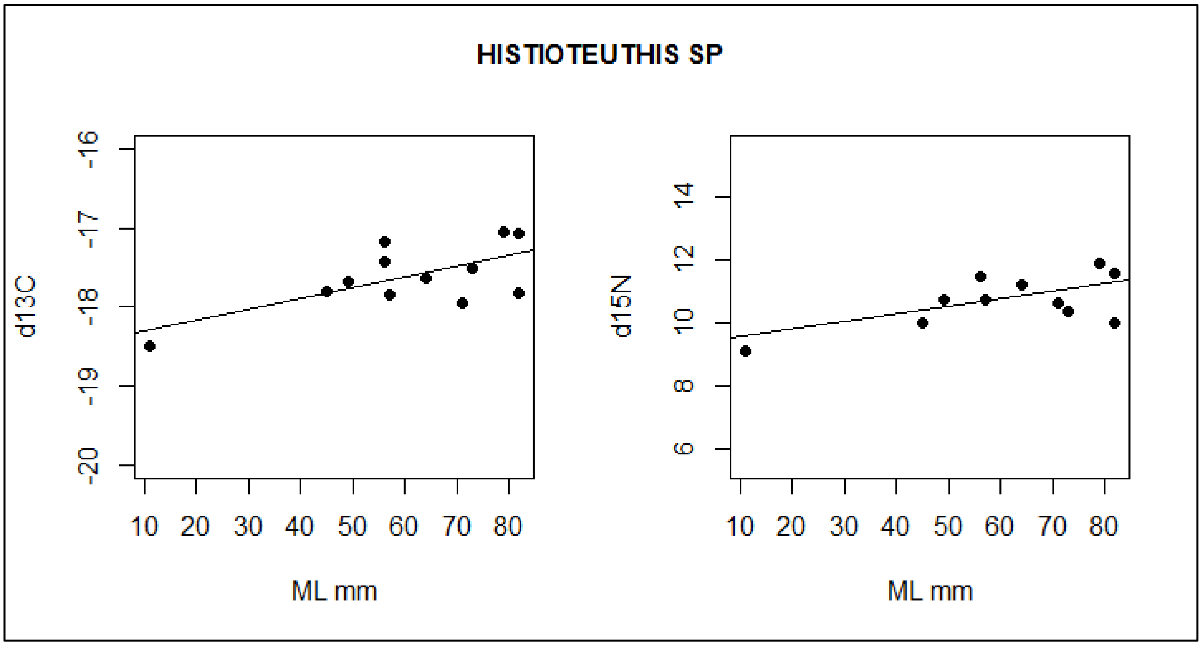

Figure 89. Scatterplots for δ^{13}C (left panel) and δ^{15}N (right panel) showing the correlation between mantle length and stable isotope signatures.

The lines indicate the linear regression line.

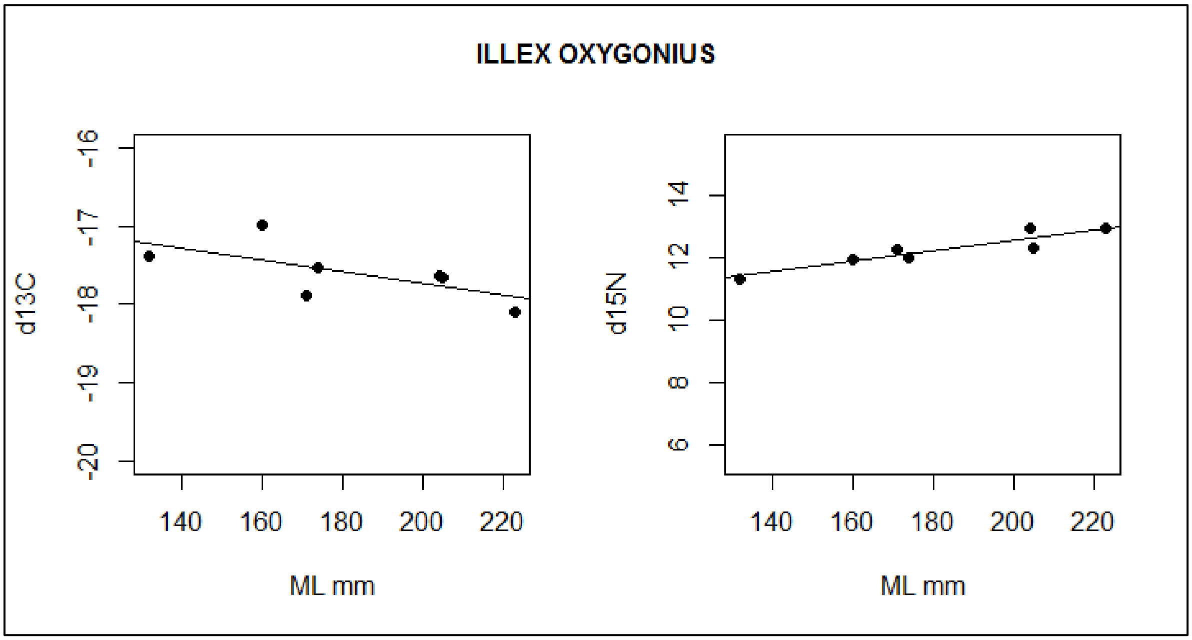

Figure 60. Scatterplots for δ^{13}C (left panel) and δ^{15}N (right panel) showing the correlation between mantle length and stable isotope signatures.

The lines indicate the linear regression line.

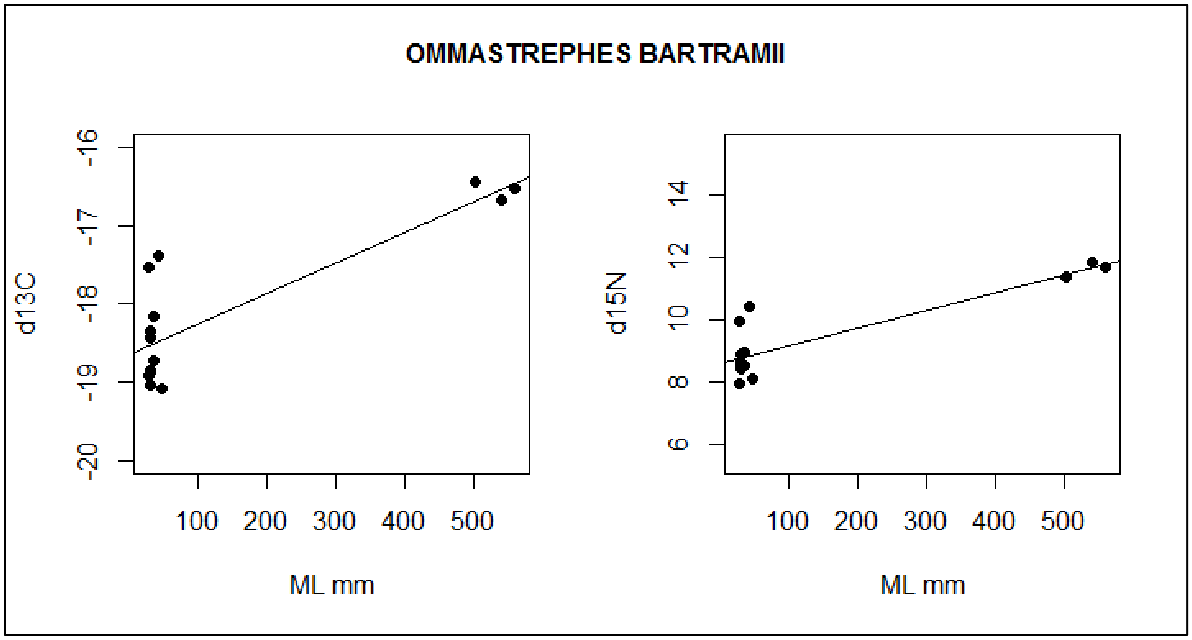

Figure 61. Scatterplots for δ^{13}C (left panel) and δ^{15}N (right panel) showing the correlation between mantle length and stable isotope signatures.

The lines indicate the linear regression line.

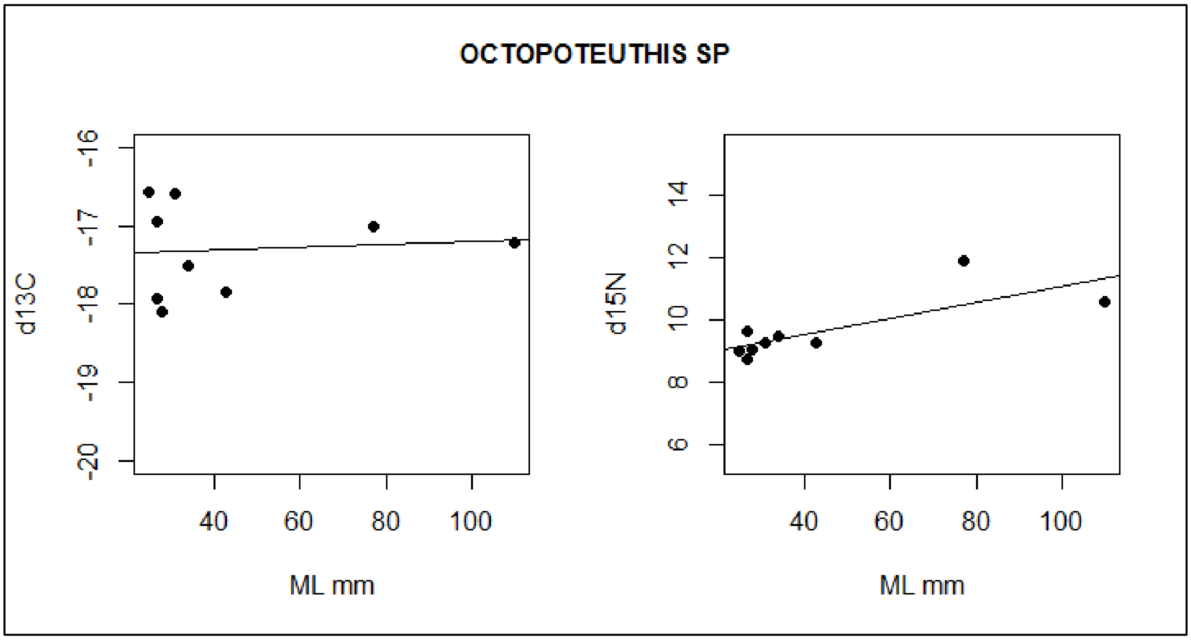

Figure 62. Scatterplots for δ^{13}C (left panel) and δ^{15}N (right panel) showing the correlation between mantle length and stable isotope signatures.

The lines indicate the linear regression line.

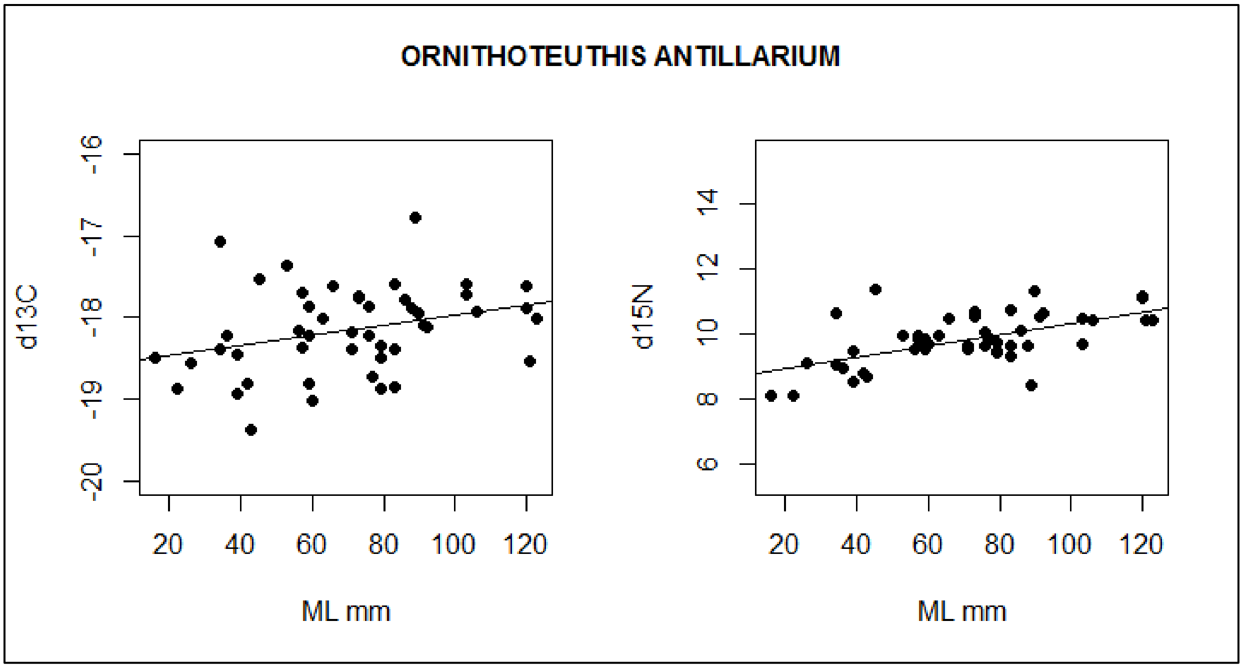

Figure 63. Scatterplots for δ^{13}C (left panel) and δ^{15}N (right panel) showing the correlation between mantle length and stable isotope signatures.

The lines indicate the linear regression line.

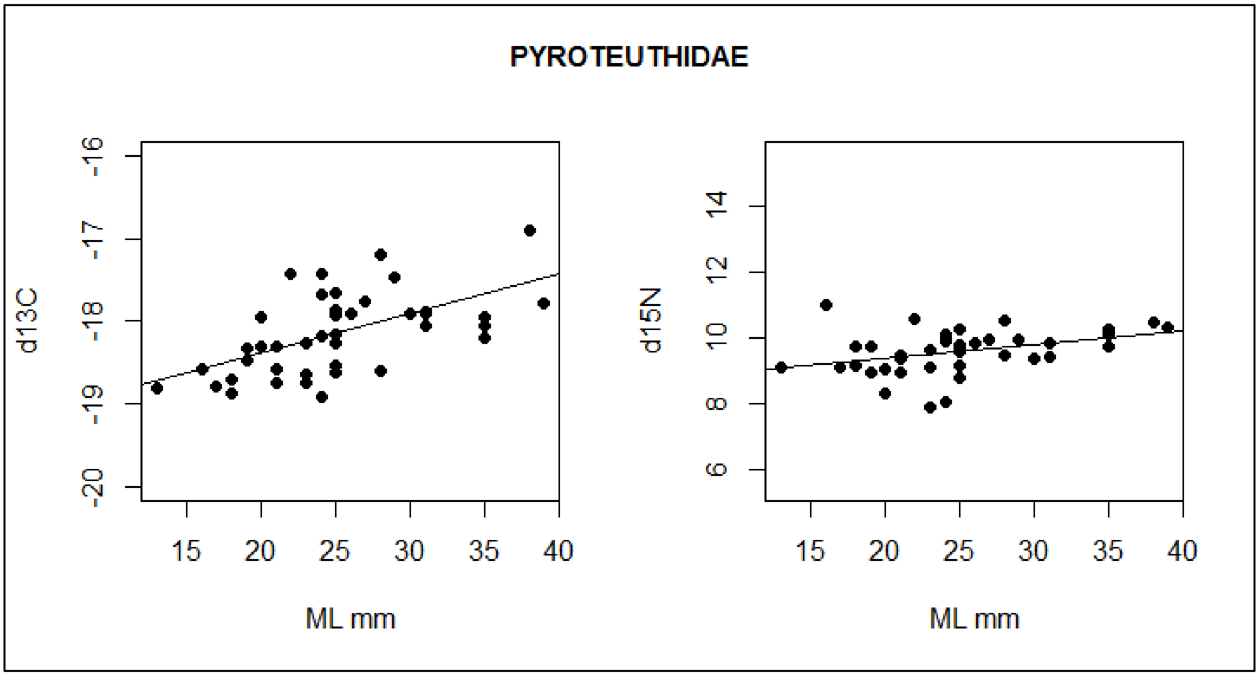

Figure 64. Scatterplots for δ^{13}C (left panel) and δ^{15}N (right panel) showing the correlation between mantle length and stable isotope signatures.

The lines indicate the linear regression line.

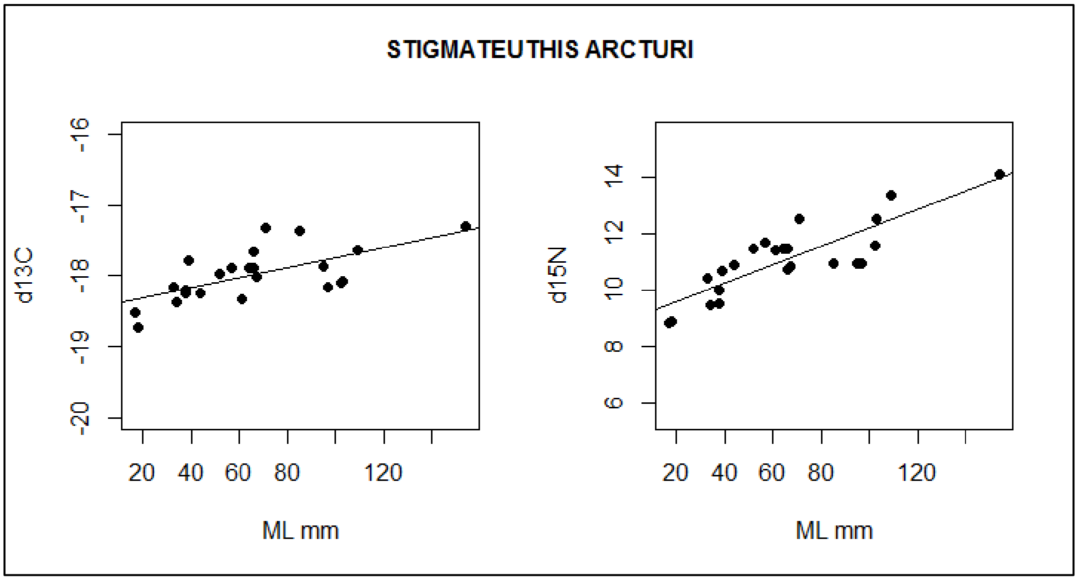

Figure 65. Scatterplots for δ^{13}C (left panel) and δ^{15}N (right panel) showing the correlation between mantle length and stable isotope signatures.

The lines indicate the linear regression line.

Scatterplots of δ^{13}C and δ^{15}N conditional on size classes indicate combinations of species and size classes of squids that have TLE levels consistent with being primary prey for sperm whales. In these figures, the grey circle indicates the range (95% confidence limits) where it is expected that sperm whale prey would fall, based on TLE levels of 1.6‰ for both carbon and nitrogen. There were no taxa with mantle lengths <31mm that fell within this range (Figure 66).

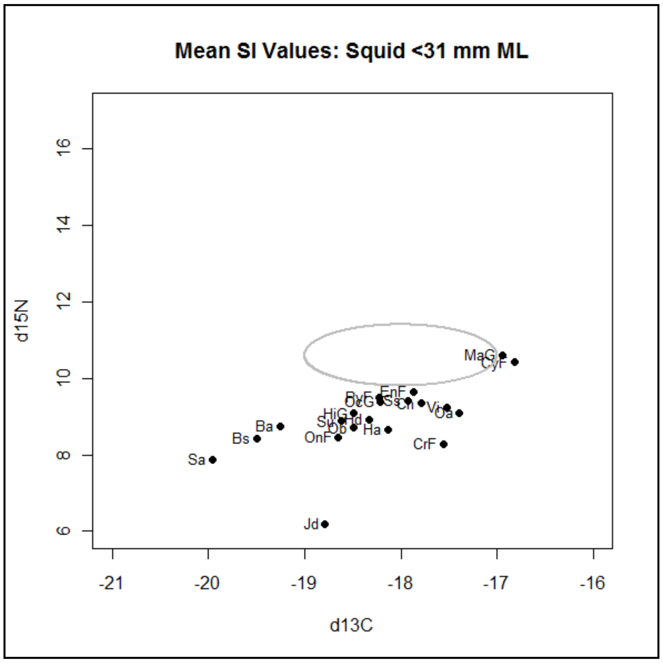

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Figure 66. Stable isotope values for squids with <31 mm mantle lengths.

In the 31–70 mm mantle length range, Histioteuthidae, Cycloteuthidae, *Bathothauma lyromma*, and *Selenoteuthis scintillans* all had TLE values consistent with being sperm whale prey (Figure 67). These same taxa were potential prey in the 70–150 mm mantle length range, in addition to Onchyoteuthide, *Octopoteuthis* sp., and *Ornithotetuthis antillarium* ,which was just outside of the range of TLE values (Figure 68).

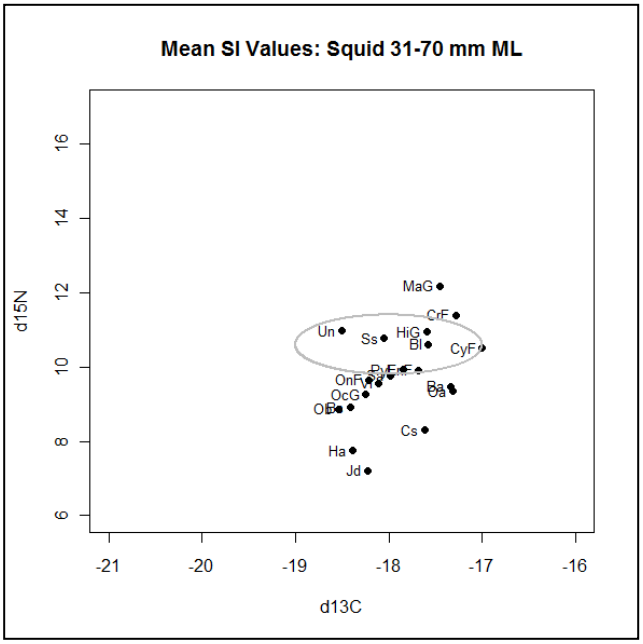

Figure 97. Stable isotope values for squids with 31-70 mm mantle lengths.

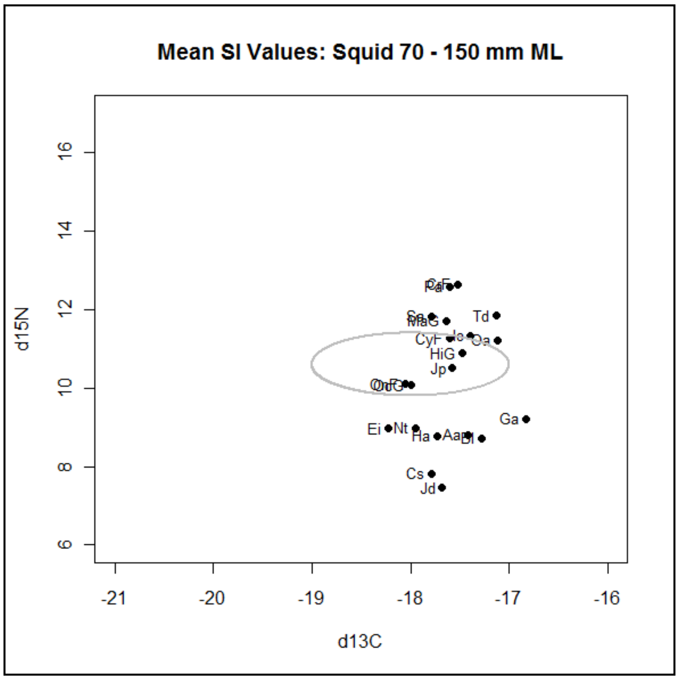

Figure 10. Stable isotope values for squids with 70–150 mm mantle lengths.

At larger size classes, only *Bathothauma lyromma* had δ^{13}C and δ^{15}N consistent with being important prey for sperm whales (Figure 69).

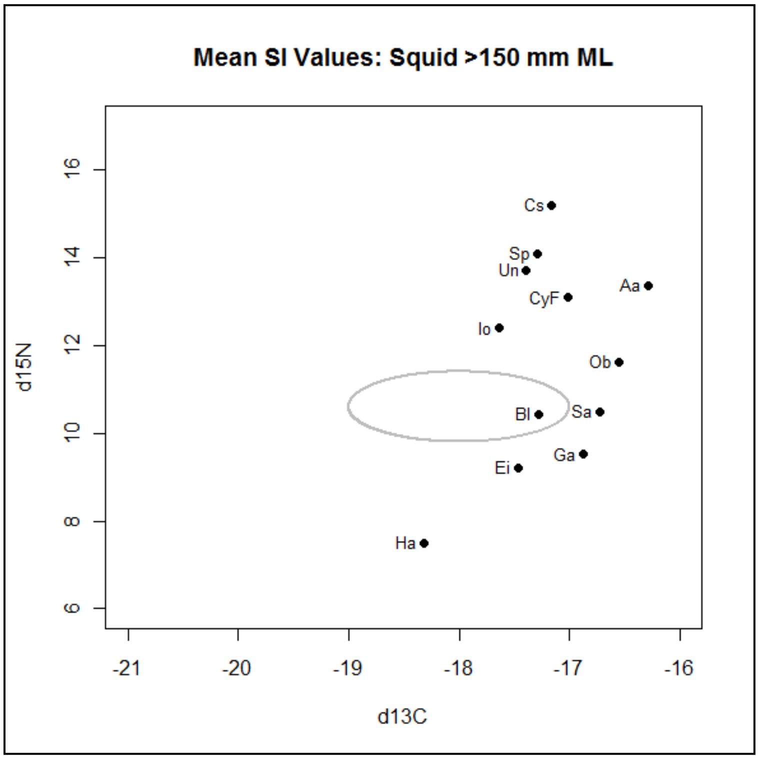

Figure 11. Stable isotope values for squids with >150 mm mantle lengths.

Overall, the SI analysis for squids demonstrates that there are ontogenic changes in SI values that are consistent with increasing trophic level over the course of their life history. SI values are consistent with the dominant prey items of sperm whales in the Gulf being squids with mantle lengths between 31–150 mm that feed on taxa at an intermediate trophic level. The SI data suggest that larger squids are feeding at a similar trophic level to sperm whales, though sperm whales hunt and capture much larger prey. It is likely that these smaller prey items are both more abundant and easier to capture, and so dominate the diets of sperm whales and their SI signature.

7.2 ANALYSIS OF MESOPELAGIC FISHES

To further describe the mesopelagic food web that supports sperm whales in the Gulf, SI analysis was also conducted on mesopelagic fish from 43 taxa, including 690 individuals (Table 13).

Table 13. Fish taxa and stable isotope signatures.

Lengths are in mm.

Taxon	**N**	**Avg. Length (Range)**	**Avg. δ^{13}C (SD)**	**Avg. δ^{15}N (SD)**
Alepisauridae	13	246 (104 - 892)	-18.4 (0.3)	9.3 (0.7)
Alepocephalidae	5	157 (103 - 188)	-18.2 (0.4)	12.1 (0.9)
Astronethinae	34	143 (83 - 297)	-17.7 (0.4)	10.2 (0.8)
Bramidae	3	143 (91 - 181)	-18.1 (0.9)	10 (1.9)
Cetomimidae	1	112	-17.3	10
Chauliodus sloani	36	215 (161 - 268)	-18.1 (0.3)	9.7 (0.4)
Chiasmodontidae	35	105 (47 - 222)	-17.8 (0.6)	9.6 (1.4)
Diceratiidae	1	52	-18.2	9.5
Evermannellidae	22	105 (81 - 128)	-17.4 (0.4)	10.1 (0.6)
Gonostoma elongatum	27	181 (109 - 235)	-18 (0.5)	10.3 (0.8)
Gonostomatidae	4	126 (79 - 165)	-18.2 (0.6)	9.6 (1.4)
Howellidae	2	64 (55 - 72)	-19 (0.3)	10.6 (1.3)
Idiacanthinae	1	61	-18.1	10.6
Malacosteus niger	21	104 (63 - 194)	-18.6 (0.5)	9.6 (0.4)
Melamphaidae	24	97 (57 - 128)	-18.2 (0.5)	11.4 (1)
Melanostimiinae	114	203 (73 - 485)	-17.9 (0.6)	10.1 (1.2)
Myctophidae	52	95 (48 - 161)	-18.3 (0.4)	10.5 (1.5)
Searsidae	8	166 (81 - 199)	-17.5 (0.7)	12.4 (1.3)
Serrivomeridae	2	488 (431 - 545)	-18.5 (0.2)	9.2 (0.6)
Sternoptychidae	88	67 (4 - 163)	-18.9 (0.4)	9.1 (0.7)
Stomias spp	30	171 (116 - 205)	-18 (0.4)	10.7 (0.7)
Trichiuridae	4	331 (87 - 832)	-17.7 (0.8)	12.2 (1.7)
Synagrops bellus	3	190 (182 - 195)	-17.6 (0.2)	12.1 (0.2)
Anoplogaster cornuta	19	108 (83 - 131)	-18.2 (0.4)	10.7 (0.9)
Barbourisia rufa	4	303 (99 - 423)	-17.7 (0.3)	11.7 (1.3)
Bathylagus sp	6	138 (122 - 154)	-18.5 (0.6)	9.9 (2)
Caristius sp	22	189 (80 - 321)	-17.6 (0.5)	11.4 (0.5)
Centrophorus granulosus	1	985	-17.7	13.5
Isistius sp	2	346 (315 - 377)	-16.7 (0.2)	11.3 (0.4)
Diretmoides parini	1	172	-18.1	11.6
Gigantura sp	20	137 (52 - 187)	-17.6 (0.6)	10.6 (1.2)
Lampanyctus sp	25	121 (88 - 153)	-18.3 (0.5)	10.3 (0.8)
Aristostomias sp	10	124 (91 - 203)	-18.7 (0.9)	9.2 (1.1)
Melanonus zugmayeri	16	155 (95 - 232)	-18.2 (0.5)	10.5 (0.7)
Nansenia groenlandica	1	113	-18.5	9.5

Taxon	N	Avg. Length (Range)	Avg. $\delta^{13}C$ (SD)	Avg. $\delta^{15}N$ (SD)
Scopelosaurus sp	1	117	-19	12.2
Opisthoproctus grimaldii	1	181	-18.8	10.2
Sudis hyalina	1	333	-18.5	12
Polymixia lowei	1	75	-18.9	9.3
Radiicephalus elongatus	5	387 (296 - 444)	-19 (0.9)	8.6 (0.5)
Scombrolabrax heterolepis	22	121 (73 - 179)	-17.8 (0.4)	8.9 (1.4)
Zu cristatus	2	288 (213 - 363)	-18.6 (0.8)	9.8 (2.1)

The fish taxa cluster into three overall regions in the $\delta^{13}C$ vs. $\delta^{15}N$ scatter plots suggesting three potential trophic levels represented in these data. (Figure 70). The highest $\delta^{15}N$ values are consistent with those observed for sperm whales; however, there may be taxonomic differences in the TLE values between marine mammals and fish, making it difficult to infer whether or not these fish species and sperm whales are feeding on prey at the same trophic level.

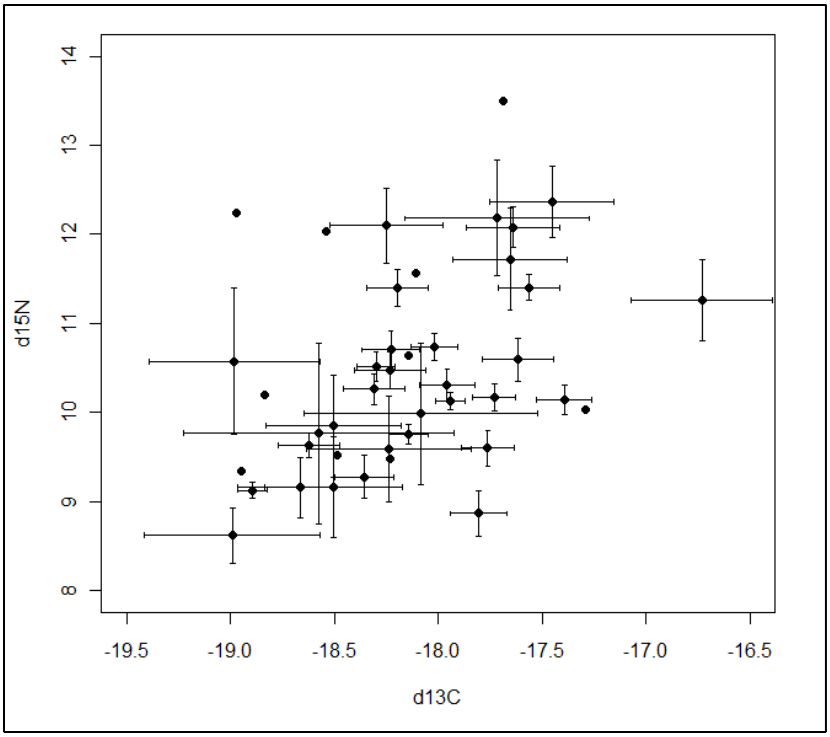

Figure 1270. Stable isotope values (mean +/- SD) for mesopelagic fish taxa.

The highest trophic level in the fish prey, with $\delta^{15}N$ values greater than 11 include, for example, Alepocephalidae (avg. length 157 mm), Melamphaidae (avg. length 97 mm), *Barbourisia rufa* (avg. length 303 mm), *Caristius sp* (avg. length 189 mm) and other taxa with body lengths exceeding 150 mm. Taxa that have the same $\delta^{15}N$ levels as potential sperm whale prey (Between 10-11) are generally smaller in average body size and include *Stomias sp.*, *Gigantura sp.*, Myctophidae, *Lampanyctus sp.*, and *Anoplogaster corunta*. The lowest trophic level includes a suite of taxa, some of which have long body lengths (e.g., *Radicephalus elongates*) though some of these have a very elongated body form and may feed primarily on planktonic or other organisms at lower trophic levels (Figure 70).

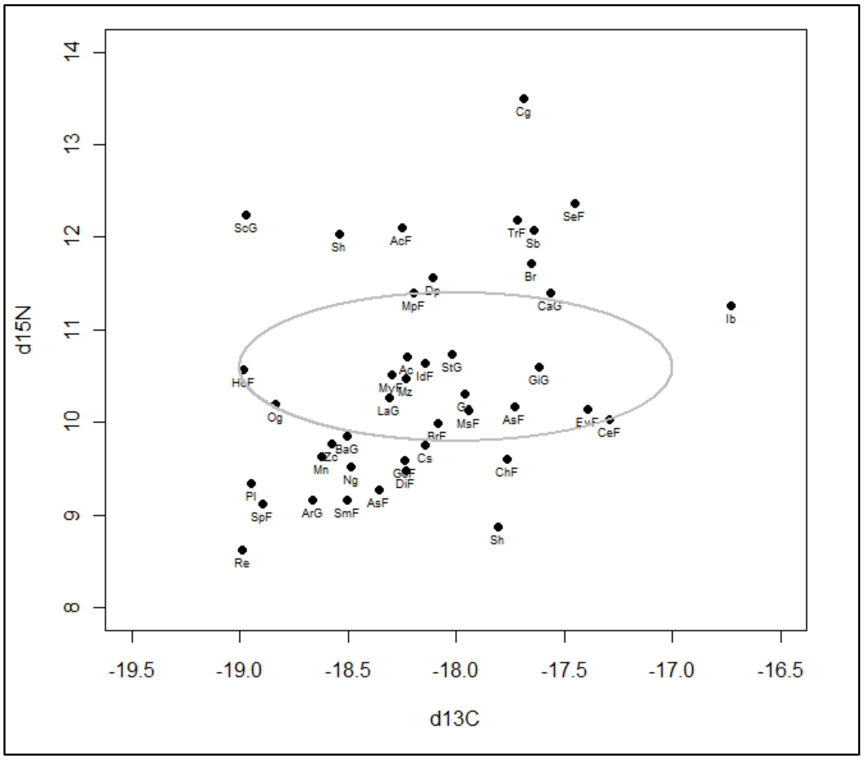

Figure 1371. Mean stable isotope values for fish taxa showing expected TLE range for sperm whale prey.

Given the SI composition of likely sperm whale prey, it is probable that they have diet compositions similar to those of fish in this intermediate trophic level and are themselves feeding on predominantly planktivorous organisms.

8.0 DISCUSSION

The spatial distribution of sperm whales in the northern Gulf is strongly associated with mesoscale circulation features that tend to enhance localized primary and secondary production in oceanic waters. This general pattern of association has been noted in previous studies. For example, Loop Current eddies and cyclonic circulation along the 1,000m isobath in the central northern Gulf resulted in off-margin flow and locally elevated surface chlorophyll concentrations. Under these conditions of elevated surface layer primary productivity, there were localized high densities of sperm whales (Biggs et al. 2005). Similarly, in previous studies of cetacean distribution in the Gulf, Davis et al. (2002) noted that deep-diving cetaceans, including sperm whales, that feed upon squids were more strongly associated with waters of steep SST gradients along the edges of cold-core eddies that serve to enhance localized productivity.

Similar processes were observed in both the summer of 2009 and the winter-spring of 2010 in the current study. During the summer of 2009, high concentrations of sperm whales were observed in association with boundaries between regions of high and low SSHa. Sperm whales in deeper waters of the central Gulf were primarily associated with low SSHa and along the boundary with the loop current (Figure 23). Sperm whales were also associated with mesoscale eddies in the winter-spring 2010 survey, though in this case the association was with cooler water temperatures and the region of intermediate SSHa near the DeSoto Canyon region where circulation was dominated by off-shelf flows along the outer edge of the clockwise circulation and low surface velocities (Figure 26). Notably, these features were not associated with elevated surface chlorophyll concentrations as an indicator of elevated production. This suggests that the primary influence of these circulation patterns is to enhance secondary productivity at a depth where sperm whales are feeding.

Catches of squids in mid-water trawls were also higher at the boundaries between mesoscale circulation eddies. In the summer 2009 pilot study, trawls were conducted in a relatively limited range of environments and were focused along the 2,000m isobath correlated to the northern edge of the low SSHa area in the central Gulf. The highest catches of squids occurred in the region where sperm whales were also concentrated and associated with a change in the orientation of the bathymetry. The high squid catch in this localized region was associated primarily with an increase in the occurrence of *Ommastrephid* squids in the trawls, which could be potential sperm whale prey. In winter 2010, squid catches were highest in the central region of the survey area where sperm whales were also more frequently observed, and the highest squid catches were associated with the off-shelf circulation region in the DeSoto Canyon area. These higher catch totals were associated with increases in the catch of *Ommastrephidae, Ornithoteuthis antillarium*, and *Discoteuthis* sp. squids, all of which have the potential to be prey of sperm whales. It is interesting to note that the *Histioteuthid* squids, which have been previously identified as a primary prey of sperm whales, were generally more broadly distributed in both the summer 2009 and winter-spring 2010 and were not strongly associated with particular oceanographic features.

Common foraging depths of sperm whales in the Gulf are in the intermediate depth ranges based upon past tagging studies. Watwood et al. (2006) used data from suction cup tags to examine feeding behaviors and found that sperm whales dove to an average depth of approximately 400m before beginning to produce “buzz” sounds associated with feeding, and that most of these feeding sounds were made during the deeper parts of their dives in the 350-600 m depth range. Jochens et al. (2008) also describe the average dive depths of sperm whales during feeding as being in the 400–700m depth range. Squid catches in the current study were also highest at these depths with the highest average catch in trawls fishing in the 600–700m depth range. The acoustic backscatter data during 2010 also suggests that enhanced production in these mesopelagic depths is associated with enhanced sperm whale feeding. The acoustic backscatter level at intermediate depths from 200–400m was strongly associated with the areas of elevated squid catches and sperm whale feeding, while the shallow waters (0–200m) were not. These data collectively suggest that oceanographic features that concentrate productivity in intermediate depths are important in concentrating prey resources for sperm whales.

The SI analysis helps to identify both the important taxa and size range of squids being consumed by sperm whales in the Gulf. It is important to note, as discussed in Ruiz-Cooley et al. (2012), that inference about trophic relationships based upon SIs is limited to some extent by the understanding of the fractionation rates of both nitrogen and carbon in various tissues and by different organisms. As in previous studies of sperm whales, the data collected in this study suggest that the “standard” TLE of ^{15}N of approximately 3‰ is not appropriate for skin samples collected from sperm whales. In the current study, prey items with δ^{15}N values of 8–9 were small squids with mantle lengths <40mm which are not appropriate prey items for sperm whales. The TLE of 1.6‰ applied by Ruiz-Cooley et al. (2012) is also appropriate for the range of δ^{15}N and δ^{13}C values seen in the most likely sperm whale prey in this study.

The ontogenic shifts in SI ratios indicating an increasing trophic level with increasing size was a common pattern across mesopelagic squid taxa collected during this study. This pattern was particularly notable in the more robust taxa that would be appropriate sperm whale prey including the Histioteuthidae, *Discoteuthis* sp., *Ommastrephes bartrami*, *Illex oxygonius*, and *Ornithoteuthis antillarium*. In general, when these species exceeded mantle lengths of 60mm, they had SI ratio values consistent with being major prey items of sperm whales. However, once squids reached mantle lengths >150mm, their SI levels were in the same range as those for sperm whales, indicating that these larger animals do not comprise the bulk of sperm whale diets. This does not indicate that sperm whales do not consume large prey. It does suggest that the bulk of their diet is made up of more common, perhaps more easily captured, prey at intermediate size ranges.

The mid-water trawl data collected during this study is one of the few broadscale datasets of this type collected in the Gulf. As such, a number of unique specimens were captured during the study. In particular, the *Architeuthis dux* captured during the summer of 2009 was the first specimen captured in the Gulf since the 1950s. The capture of multiple large *Asperoteuthis acanthoderma* specimens was unique because this species had been known from only one previous specimen in the Gulf. Collections during this study also resulted in the identification of the larval form of a globally distributed deep water ariseid shrimp, *Plesiopenaeus armatus* based upon molecular phylogenetic analyses (Bracken-Grissom et al. 2012), which is a significant finding in the field of midwater shrimp taxonomy. More recently, a review of the midwater fish collected during the study identified a specimen of the “pocket shark” *Mollisquama* sp. which is only the second specimen from this genus collected to date. The holotype, *M. parini,* was collected in the Indian Ocean; each specimen has a unique pocket gland. There were important morphological differences between the holotype and the Gulf specimen (Grace et al. 2015 and Figure 61). These examples indicate the ancillary value of midwater collections of this type as tools for improving understanding of phylogeny and the ranges of these relatively rarely examined midwater taxa.

Figure 72. Mollisquama sp., TU 203676 (142.0 mm TOT), photographs taken before preservation (A) right lateral view and (B) ventral view.

Scale bar is 10 mm in both figures.

9.0 CONCLUSIONS

- Concurrent marine mammal surveys and midwater trawl sampling demonstrated strong associations between mesoscale physical features, sperm whales, and their prey in the Gulf.

- During summer 2009, high concentrations of sperm whales occurred along boundaries between areas of high and low sea surface height in the deep waters of the central Gulf. The region of highest sperm whale density was also an area of high catches of mesopelagic squids in midwater trawls.

- During winter 2010, a region of off-shelf water flows in the north-central Gulf near the DeSoto Canyon was also associated with high sperm whale densities and high catches of potential squid prey.

- This study included one of the few large-scale sampling efforts for squids and other mesopelagic organisms. At least 61 species of cephalopods were captured during the study along with Vampyroteuthidae.

- Multiple cephalopod taxa are potential sperm whale prey including species from Histioteuthidae, Cycloteuthidae, Ommastrephidae, and Chrioteuthidae.

- The previous most-common prey item for sperm whales according to stomach content studies, Histioteuthidae, was broadly distributed and was not as strongly associated with particular oceanographic features as other taxa.

- Taxa such as Ommastrephidae, *Discoteuthis spp.*, and *Ornithoteuthis antillarium* had more patchy distributions and were concentrated in regions with higher sperm whale occurrence associated with mesoscale circulation features.

- The biomass of squids in trawl samples was highest at intermediate depths, particularly between 600–700m that correspond to primary sperm whale feeding depths.

- Acoustic backscatter data collected during the winter-spring 2010 suggest that elevated productivity in mid-layer waters (200–400m depth) was more strongly correlated with sperm whales and their prey than that in surface layers.

- SI analysis indicated an increasing trophic level with increasing size of squids across multiple taxa, and in particular within those taxa that are potential sperm whale prey. Squid taxa with mantle lengths from 31–150 mm had SI ratios that were most consistent with being sperm whale prey.

- Larger squid taxa had SI signatures similar to those of sperm whales, suggesting that they are feeding at a common trophic level. This indicates that these larger prey may be relatively rare components of sperm whale diets.

- In addition to evaluating predator-prey relationships in sperm whales, the current study included a number of unique specimens, in particular a specimen of the "pocket shark" *Mollisquama sp.*, which is only the second specimen from this genus collected to date globally (Grace et al. 2015) and a specimen of the giant squid *Architeuthis dux*.

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