# Characterizing Mid-summer Ichthyoplankton Assemblage in Gulf of Alaska: Analyzing Density and Distribution Gradients across Continental Shelf

Timothy Seung-chul Lee

## ABSTRACT

Ichthyoplankton play critical role in maintaining and characterizing complex marine ecosystems. Gulf of Alaska (GOA) encompasses one of most diverse ichthyoplankton assemblages in northern Pacific. This study assessed mid-summer distribution and density patterns of six species in larval stage across GOA's continental shelf, and assessed patterns of density gradients with three environmental variables, (temperature, salinity, attenuation). The chosen taxa are *Theragra chalcogramma*, *Hippoglossoides elassodon*, *Atheresthes stomias*, *Lepidopsetta bilineata*, *Bathyagonus alascanus*, and *Gadus macrocephalus*. I hypothesized that densities for all six taxa will be greatest in coastal waters and in parts of shelf with many islands, because these regions have greater proportion of shorelines. The study region was stratified to three shelf regions to compare ichthyoplankton densities between coastal and open waters. It was also stratified to six alongshore regions to compare densities between regions of low and high shoreline proportions. One-way ANOVA and post-hoc pairwise comparisons were used to test density significance across shelf and alongshore strata. Most species exhibited highest densities in costal shelf strata but most did not concentrate heavily in alongshore strata with islands. Linear regression and correlation tests were used to measure responses of densities against attenuation, salinity, and temperature.  Two taxa had positive relationship with temperature, four taxa had inverse relationship with salinity, and five taxa had declining densities with increasing attenuation. Further research is needed to determine which environmental factor determines ichthyoplankton assemblage variations in GOA's continental shelf.

## KEYWORDS

Ichthyoplankton, Density, Temperature, Attenuation, Salinity

## INTRODUCTION

Marine fish habitats are among the most fascinating and complex environments; interwoven with dynamic physical factors, they contain some of most biologically diverse communities (Hollowed et al. 2009). Physical factors including climate, bathymetry, salinity, current type, and nutrient transport alter organism biomasses (Doyle et al. 2009), thereby contributing to incredible biodiversity. These factors affect fishes' spatial and temporal distributions seasonally and annually (Brodeur et al. 1995). The distribution, density, and community structure of marine fish differ not only between species but also between life stages (Matarese et al. 1989). Detailed knowledge of marine fishes' early life histories is essential to understand fish recruitment; recruitment is defined as the distinct effects of physical and biological factors between different life stages (Doyle et al. 2009). Understanding early life history helps determine species-specific and life stage-specific patterns of densities and distributions based on physical environment (Brodeur et al. 1995). However, little is known about early life histories of fishes throughout marine ecosystems globally (Doyle et al. 2009).

Ichthyoplankton are fish in egg, larval, and juvenile stages (Southwest Fisheries Science Center 2007). They depend on nutrients, zooplankton, and phytoplankton for survival; ichthyoplankton concentrations differ between seasons and regions (Brodeur et al. 1995). Early life history studies determine species' distribution, spawning grounds, stock sizes, and habitat shifts through life stage progression (Matarese et al. 2003). Many ichthyoplankton in Gulf of Alaska for example, once mature, are considered ecologically vital for biomass studies and stock assessment; they are also important for bottom trawls and long-line fisheries (Mueter & Norcross 2002). Because many marine organisms are highly dependent on ichthyoplankton for survival, early life history research can characterize marine ecosystems over time (Matarese et al. 2003).

Studying the association of ichthyoplankton with with physical environmental factors is important for several reasons. Larval fish play essential role in marine ecosystems because they are staple diet for many higher trophic level organisms including large fish, mammals, and seabirds (Mueter & Norcross 2002). Ichthyoplankton ecology also helps to determine adult spawning populations (Recruitment Processes Program 2009). Marine habitats encompass dynamic range of environmental forces, and understanding the affect of these variables' early stage abundance and distribution of species help predict population and distribution patterns through time (Mundy 2005). Fisheries-Oceanography Coordinated Investigations (FOCI) conducted over three decades of ichthyoplankton study during groundfish assessment research cruises in Gulf of Alaska (Ichthyoplankton Information System 2009); past research found that larval stage densities and distributions have close correlations with marine abiotic environmental factors. A study of larval flatfish distribution found that densities of larval Arrowtooth flounder (*Atheresthes stomias*) and Pacific Halibut (*Hippoglossus stenolepis*) were greater with increasing water column heights and increasing transport pathways (Bailey & Picquelle 2002). Study of capelin showed that the larvae preferred cool and high-salinity waters (Logerwell et al. 2007). Past research has shown that Pacific cod larvae have higher concentrations in warmer waters (Hurst et al. 2009).

My objective is to analyze summer larval fish densities' association with three physical environmental variables –salinity, temperature, and attenuation (the average loss of light through water) - during mid-summer (Pacific Marine Environmental Laboratory 2007). This study is focused in Gulf of Alaska (GOA), one of the most productive and diverse marine habitats in Northern Pacific (Mundy 2005). This study analyzes six most abundant and widespread fish taxa (Walleye Pollock-*Theragra chalcogramma*, Pacific Cod-*Gadus Macrocephalus*, Flathead Sole-*Hippoglossus elassodon*, Southern Rock Sole-*Lepidopsetta bilineata*, Arrowtooth Flounder-*Atheresthes stomias*, and Gray Starsnout-*Bathyagonus alascanus*) in late larval stage across GOA's continental shelf along southern coastline of Alaskan Peninsula during summer. Royer's 1975 study of Gulf of Alaska's oceanography concludes that during summer, salty nutrient-rich water flourishes into inner shelf and coastal waters as downwelling (sinking of higher density matter) recedes, bringing higher density waters closer to surface (Royer 1975). Based on this, I hypothesize that for each taxon there will be overall higher density in inner shelf near coastline than mid or outer shelf toward open waters. I also hypothesize that for each taxon there will be positive correlation between salinity and density, positive correlation between temperature and density, and negative correlation between attenuation and density.

Some parts of continental shelf are "obstructed" by groups of small islands near southern edge of Alaskan Peninsula; therefore, the shelf strata with more islands have greater proportion of coastal waters. Since Royer's 1975 study found higher nutrient concentrations in coastal waters, for each taxon I hypothesize overall greater density in strata with greater proportion of islands (for example, if alongshore strata A has more islands than alongshore strata B, I expect to observe greater densities in alongshore strata A).

This study will be based on preserved ichthyoplankton samples collected during summer 1987 FOX (Fisheries-Oceanography Expedition) Cruise in northern GOA and physical environmental data applicable to my study area during time frame of the cruise. Most of these environmental variable data are available in EPIC database (EPIC 2006). This study endeavors to add possible explanations of ichthyoplankton density patterns and distribution phenomenon in GOA regions beyond study area during mid-summer months. It also strives to predict summer ichthyoplankton ecology of marine habitats in other parts of the globe, thus contributing to characterize overall marine ecosystems based on salinity, temperature, and attenuation.

## METHODS

**Study Area** Gulf of Alaska (GOA), a region of northern Pacific Ocean outlined by southern coastline of Alaska and coastlines of British Columbia, is one of the most productive marine habitats in Northern Pacific (Mundy 2005). This region has immense biodiversity ranging from seabirds, marine mammals, and fish, whose life history and ecology are affected by physical factors including bathymetry, current velocity, salinity, temperature, and seasonal weather shifts (Royer 1975). These environmental factors vary across GOA's continental shelf, which extends from west to east along southern coastline of Alaskan Peninsula (Matarese et al. 2003). The continental shelf is characterized by randomly assorted troughs and valleys, and two major currents, the Alaska Coastal Current running nearshore, and the Alaska Stream, which flows offshore along shelf slope (Matarese et al. 2003). GOA encompasses immense diversity of larval fish year-round (Matarese et al. 1989). Distributions and density of ichthyoplankton differ between species but all species' densities and distributions are affected by GOA's physical environmental variables; oceanic forces influence distribution of ichthyoplankton and associated nutrients can create feeding grounds for higher trophic organisms (Royer 1975). The ever-changing seasonal and annual densities and distribution of ichthyoplankton makes GOA an excellent study area of marine communities' early life history (Matarese et al. 1989).

*Systems Profile*: The subjects are six most abundant fish species (all in larval stage) occurring in GOA's continental shelf, and three environmental variables significant to the region (temperature, attenuation, and salinity). All larval fish samples were collected during summer research cruise of 1987 by research vessel *Miller Freeman*. They were then preserved in ethanol vials and stored in Plankton Sorting and Identification Center in Szczecin, Poland (Bailey et al.

2002). Fish samples arrived to Alaska Fisheries Science Center in Seattle, WA in spring 2009, mainly unidentified or incorrectly identified. Hydrographic data pertaining to the study area during mid-summer 1987 are archived in EPIC database of Pacific Marine Environmental Laboratory webpage.

**Data Collection** The specimen samples I have identified and verified were collected by RV *Miller Freeman* during mid-summer 1987 Fisheries-Oceanography Expedition cruise (4MF87), which was held from June 18-July 15. All specimens during this cruise were collected with Methot that was towed obliquely (Ichthyoplankton Cruise Database 2009). There were total of 148 stations throughout the region of the cruise. In each station, after the specimens were collected, the average density of each taxon in each station, also called catch per unit effort, was recorded in units of catch/$m^2$ (Ichthyoplankton Cruise Database 2009). After cruise was completed, specimens were stored indiscriminately in jars of ethanol, and were shipped to Ichthyoplankton Identification Center in Szcecin, Poland. After the samples were sorted in smaller vials based on taxon identification and life stages, they remained in Poland until spring 2009, when they were shipped to Alaska Fisheries Science Center (AFSC) in Seattle, WA –a subset of National Marine Fisheries Service, which is a division of National Oceanic and Atmospheric Administration- where re-identification and verification of every specimen took place. From late May to mid-June 2009 I used stereomicroscope, probe, forceps, petridish and “Laboratory Guide to Early Life History Stages of Northeast Pacific Fishes” (Matarese et al. 1989) to identify every specimen to lowest possible taxon. Identification was based on morphological features such as melanophores, pigmentation, eye diameter, standard length (from snout tip to base of caudal fin), and meristics (i.e. fin ray and vertebrate count).

After the verifications, data for every ichthyoplankton sample for 4MF87 cruise was recorded in spreadsheets organized for each 148 stations, including the number caught and catch/$m^2$ in every station for every taxon. I entered spreadsheet data into ichthyoplankton database editing software called IchPPSI. All data entered into IchPPSI are processed and archived into ichthyoplankton database called IchBASE, where cumulative density (catch/$m^2$) of each taxon is automatically calculated for entire cruise. I retrieved the .csv files applicable for each six taxon from IchBASE that belonged to every station of 4MF87 cruise. Each .csv file includes the raw number caught and density, or catch per unit effort, also known as catch/10$m^2$.

After completing re-identification and verification, in late June 2009, using ArcGIS Map I made a map of study area with all 4MF87 stations plotted. I stratified the cruise region into three continental shelf strata because it appeared to evenly divide the number of stations across continental shelf, and helped to distinguish larval fish concentrations between nearshore and offshore waters. Figure 1 shows the study region with all 148 stations of 4MF87 cruise. Figure 2 shows the continental shelf stratification of the study region; the shelf was stratified into inshore (Shelf I), midshore (Shelf II), and offshore (Shelf III). In Figure 3, I have also stratified the study region into six alongshore strata because this helps distinguish which regions have greater proportion of shorelines depending on presence of islands jutting out from southern edge of Alaskan Peninsula. Furthermore, this helps to test the third component of hypothesis, which seeks to compare densities of each taxon between regions with different proportion of coastal waters.

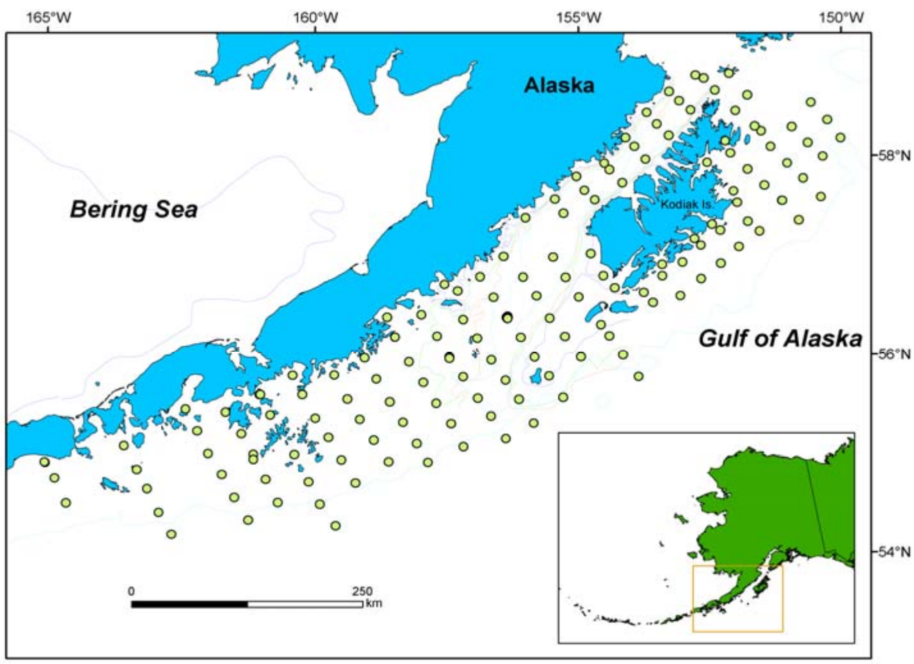


**Figure 1**: This is the study region, depicting all 148 stations of 4MF87 Cruise, which was held from June 17 - July 18, 1987. The cruise began in southwestern corner of the map and proceeded in zigzag pattern, initially directed towards southeast and then towards northwest.

**Figure 2**. **The study region is depicted with shelf stratification.** This method is to help distinguish larval fish densities between inshore and offshore waters.

**Figure 3**. **The alongshore stratification of study region**. Stratification was based on pattern of islands jutting out from southern edge of Alaskan Peninsula. For instance, B and E have greater portion of islands than anywhere else in study area. Thus, they have greatest proportions of coastal waters than other alongshore strata.

Temperature, attenuation, and salinity were obtained from NOAA's Pacific Marine Environmental Laboratory's EPIC website (www.epic.noaa.gov/epic), available to public; each station in Figure 1 has data pertaining to temperature, attenuation, and salinity recorded by CTD (conductivity-temperature-depth) probes during the time frame of 4MF87 Cruise. This is critical since it meets the objectives of comparing species' densities with three environmental variables.

**Data Analysis, Rationale for Approaches** For each six taxon, I used R software to perform one-way ANOVA to test significance of means density across shelf strata in figure 2 and alongshore strata in figure 3. Following are the null hypothesis for categorical variables, $\alpha = 0.05$:

For each taxon (shelf strata)

$H_0$: There is no difference between mean catch per 10m$^2$ (density) and shelf strata

$H_a$: There is difference between mean densities

For each taxon (alongshore strata)

$H_0$: There is no difference between mean densities between alongshore strata

$H_a$: There is difference between mean densities

All density (catch/m$^2$) values were put to logarithmic transformation because this would create more normally distributed mean densities of each taxon, which would be necessary for one-way ANOVA. For one-way ANOVA I used following formula $\text{Log}_{10}(\text{density}+0.1)+1$ for logarithmic transformation because I needed to include all zeros to test ANOVA's null hypothesis (Mendez 2010a) For all shelf and alongshore strata one-way ANOVA, I also used R to perform Post-Hoc pairwise comparison tests (Tukey's HSD) for each species to observe where the significant differences of mean densities lie between shelf or alongshore strata.

To compare relationship between species densities and three environmental variables, I tested linear regression of each three variables with each six taxon on R. All three variables are continuous and thus I wanted to test linear relationship by testing density of each species as response variable to each explanatory variable, the temperature, salinity, and attenuation (Mendez 2010b). For logarithmic conversion, I removed all zero density data for each species and used simple base-10 logarithm $\text{Log}_{10}(\text{density})$. I also performed correlation tests of each three variables with each six species to evaluate strength of relationship between explanatory and response variables (Mendez 2010b). I made scatter plots for each explanatory variable, with regression line plotted for each species. Following are null hypothesis for each six taxon in linear regression and correlation tests, with α = 0.05:

Temperature

$H_0$: There is no relationship between average taxon density and temperature.

$H_a$: There is relationship between taxon density and temperature.

Salinity

$H_0$: There is no relationship between average taxon density and salinity.

$H_a$: There is relationship between taxon density and salinity.

Attenuation

$H_0$: There is no relationship between average taxon density and attenuation.

$H_a$: There is relationship between average taxon density and attenuation.

## RESULTS

**Average densities in shelf and alongshore strata** In the analysis of species densities across continental shelf strata, most taxa had greatest densities in the inshore shelf (Shelf I). Four out of six taxa had highest average densities in Shelf I strata, except for *A. stomias* which had highest density in Shelf II strata.

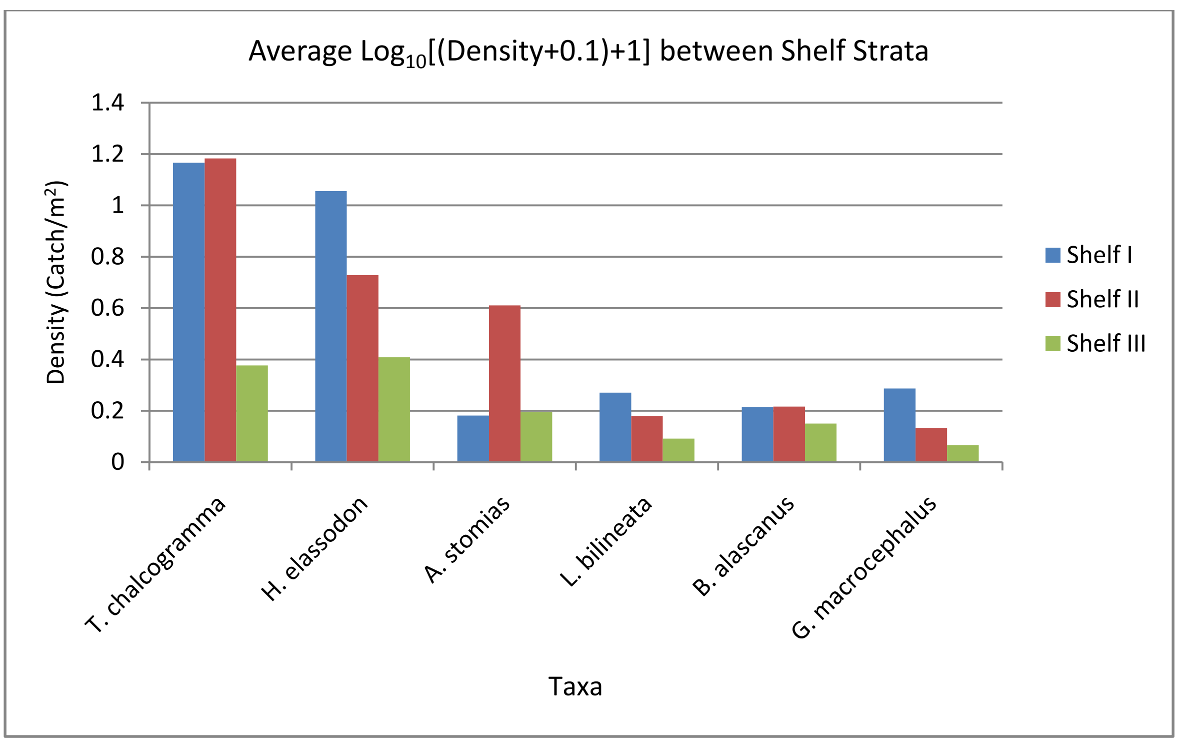


**Figure 4: Comparisons of mean Log10[(density+0.1)+1] across shelf strata**

This chart displays each species' density differences across shelf strata. Most species exhibit highest densities in Shelf I strata except *T. chalcogramma*, which has slightly higher density in Shelf II strata and *A. stomias*, which has significantly higher density in Shelf II strata.

Across the alongshore stratification, no taxon exhibited highest average densities in alongshore strata B & E (Fig 5). Instead, most species had highest densities in Strata C. For *T. chalcogramma* its highest densities are in alongshore strata B (1.61 catch/m$^2$) and C (1.94 catch/m$^2$) (Fig 5). For *H. elassodon* its highest densities are in strata C (1.26 catch/m$^2$) and D (0.95 catch/m$^2$) (Fig 5). *A. stomias* has highest densities in strata A (0.49 catch/m$^2$) and C (0.82 catch/m$^2$). For *G. macrocephalus*, the highest average densities were in strata B (0.26 catch/m$^2$) and C (0.40 catch/m$^2$). *B. alascanus* and *L. bilineata* had low densities throughout alongshore; *B. alascanus* had greatest density in strata D and *L. bilineata* had greatest densities in strata B and C (Fig 5).

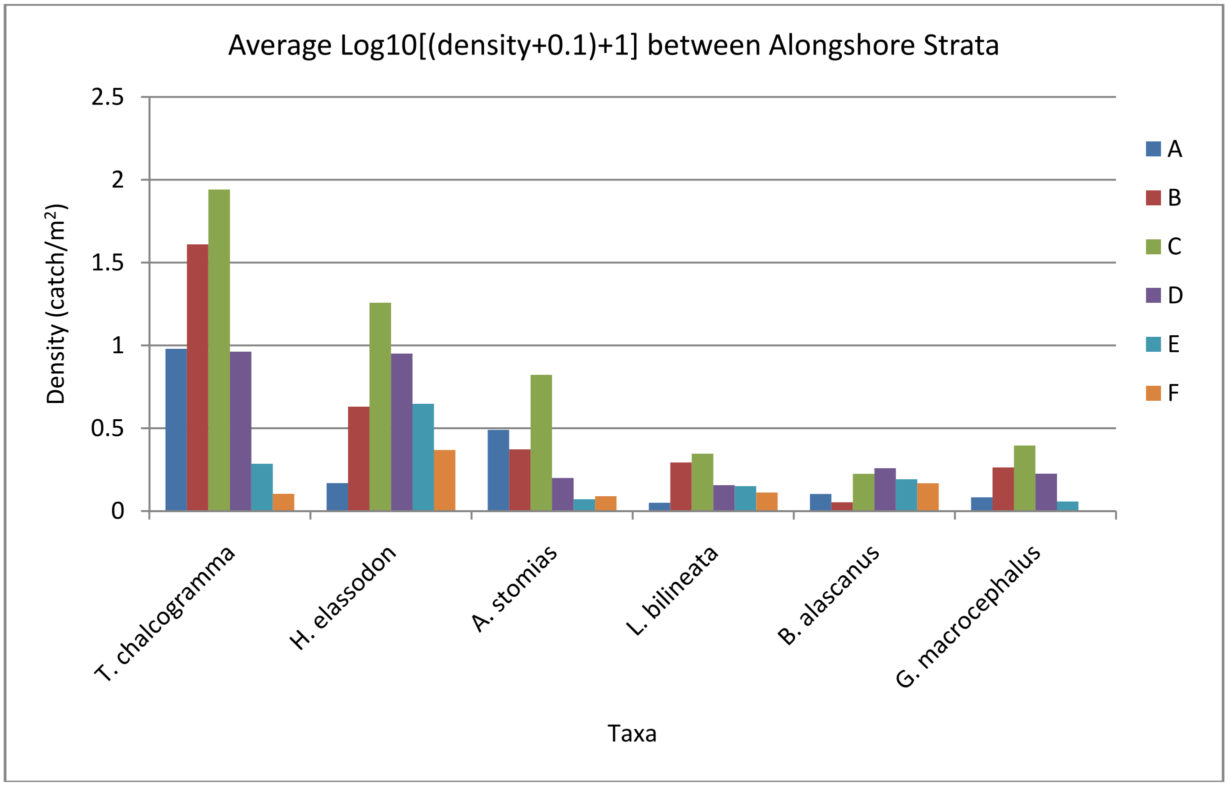


**Figure 5: Comparison of mean Log10[(density+0.1)+1] across alongshore strata**
This chart displays each species' density differences across alongshore strata. No species exhibit highest densities in strata B and E. Most species exhibit greatest density in alongshore strata C.

One-way ANOVA tests showed that for densities of all six taxa, effect of shelf stratification was statistically significant except *B. alascanus*, $F(2, 146) = 0.659$, $p=0.519$ (Table 1).

**Table 1: One-way ANOVA results across shelf strata**
This is the one-way ANOVA summary table of six species' densities across shelf strata. Results were statistically significant for all taxa except *B. alascanus* (R Development Core Team 2009).

| Species | df (Between Groups) | df (Within Groups) | F | P-value |
|---|---|---|---|---|
| *T. chalcogramma* | 2 | 146 | 13.569 | **<0.001** |
| *H. elassodon* | 2 | 146 | 15.734 | **<0.001** |
| *A. stomias* | 2 | 146 | 11.54 | **<0.001** |
| *L. bilineata* | 2 | 146 | 5.942 | **0.003** |
| *B. alascanus* | 2 | 146 | 0.659 | 0.519 |
| *G. macrocephalus* | 2 | 146 | 8.273 | **<0.001** |

The post-hoc pairwise comparison tests showed which pair of shelf strata had greatest significant differences of species densities. For *A. stomias*, there are significant differences of mean densities between Shelf 2-Shelf 1 and Shelf 3-Shelf 2 pairs (Fig 6). There are no significant differences of *B. alascanus* mean densities between shelf strata pairs (Fig 7).

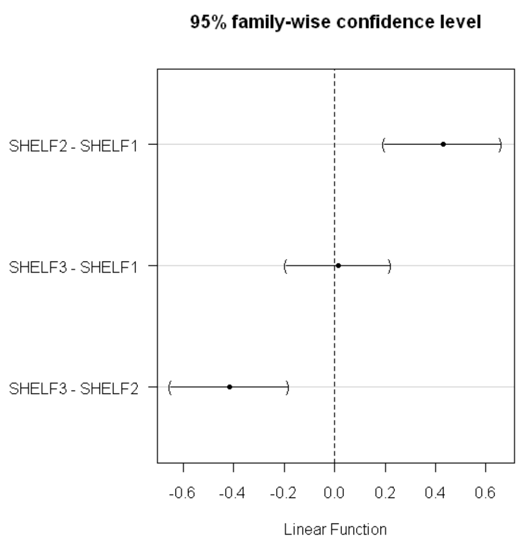


**Figure 6. Post-hoc test of *A. stomias* density comparison across shelf strata**
Significant differences of mean densities for *A. stomias* lie between Shelf 1 & 2 and Shelf 3 & 2 (R Development Core Team 2009).

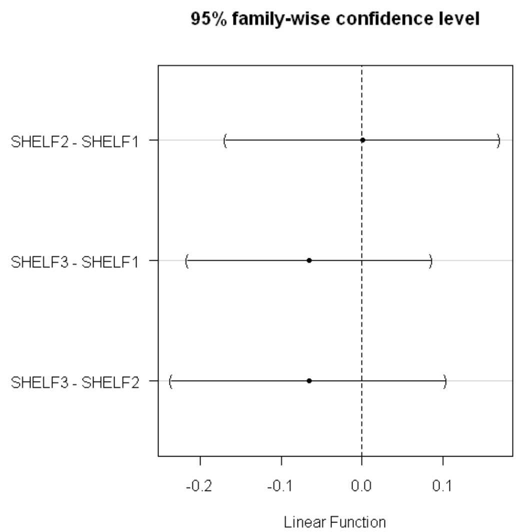


**Figure 7. Post-hoc test of *B. alascanus* density comparison across shelf strata**
There are no significant differences of mean densities for *B. alascanus* between shelf strata pairs (R Development Core Team 2009).

In other species, significant difference between average densities of shelf 3 and shelf 1 was greatest. Post-hoc pairwise comparison test for *G. macrocephalus* shows there's significant differences of mean densities between shelf 1-shelf 2 and shelf 3-shelf 1(Fig 8). For *H. elassodon* significant differences lie between shelf 2-shelf 1, shelf 3-shelf 1, and shelf 3-shelf 2 pairs (Fig 9).

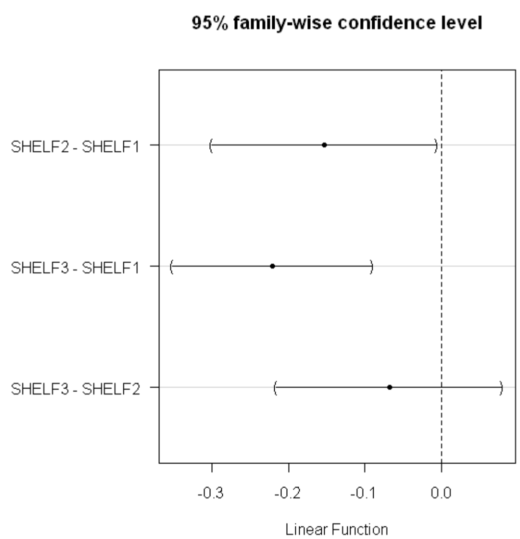


**Figure 8. Post-hoc test of *G. macrcephalus* density comparison across shelf strata**
The significant differences of mean densities lie between shelf 2-shelf 1 and shelf 3-shelf 1 pairs (R Development Core Team 2009).

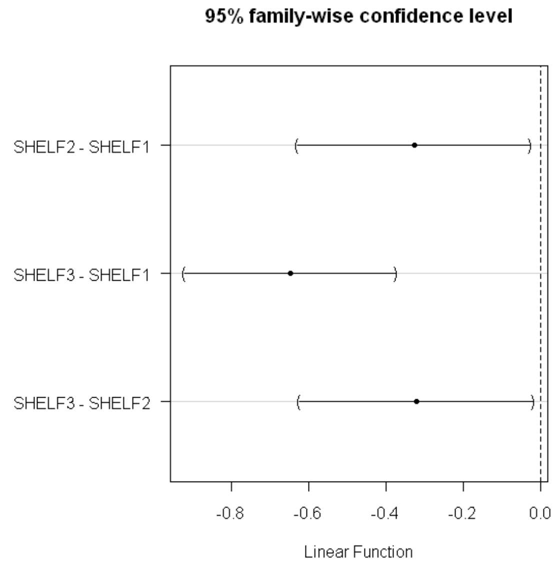


**Figure 9. Post-hoc test of *H. elassodon* density comparison across shelf strata**
The significant differences of mean densities lie between all shelf strata pairs (R Development Core Team 2009).

Post-hoc pairwise comparison test for *L. bilineata* shows that significant differences of mean densities lie only between shelf 3-shelf 1 pair (Fig 10).

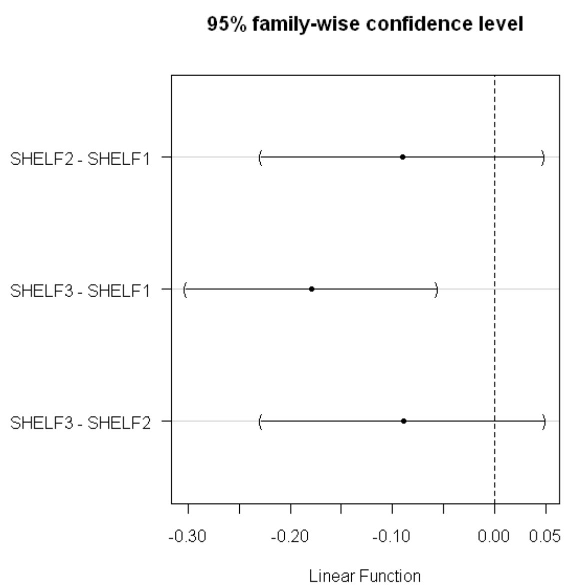


**Figure 10. Post-hoc test of *L. bilineata* density comparison across shelf strata**
The significant difference of mean density lies between shelf 3-shelf 1 pair (R Development Core Team 2009).

Post-hoc pairwise comparison test for mean densities of *T. chalcogramma* shows that significant differences of mean densities exist between all shelf strata pairs; shelf 2-shelf 1, shelf 3-shelf 1, and shelf 3-shelf 2 (Fig 11).

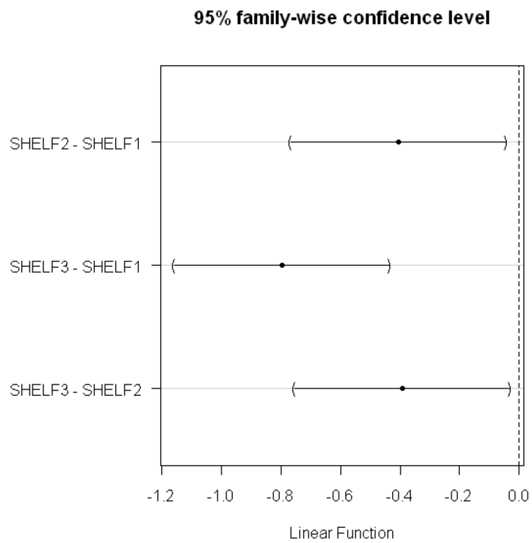


**Figure 11. Post-hoc test of *T. chalcogramma* density comparison across shelf strata**
Significant differences of mean densities lie between all shelf strata pairs (R Development Core Team 2009)

For alongshore strata, one-way ANOVA tests showed that for densities of all species, effect of alongshore stratification was statistically significant except *B. alascanus*, $F(5, 141) = 0.9645$, $p = 0.442$ (Table 2).

**Table 2. One-way ANOVA results across alongshore strata**
This is the one-way ANOVA summary table of six species' densities across alongshore strata. Results were statistically significant for all taxa except *B. alascanus* (R Development Core Team 2009).

| | df (Between Groups) | df (Within Groups) | F | P-value |
|---|---|---|---|---|
| *T. chalcogramma* | 5 | 141 | 32.314 | <**0.001** |
| *H. elassodon* | 5 | 141 | 9.097 | <**0.001** |
| *A. stomias* | 5 | 141 | 12.073 | <**0.001** |
| *L. bilineata* | 5 | 141 | 3.197 | **0.009** |
| *B. alascanus* | 5 | 141 | 0.9645 | 0.442 |
| *G. macrocephalus* | 5 | 141 | 6.586 | <**0.001** |

The post-hoc pairwise comparison test of *A. stomias* density across alongshore strata shows that any line pair not intersecting 0.0 line are significantly different groups (Mendez 2010a). In Figure 12, A & E are significantly different groups. C is significantly different from B, D, E, and F.

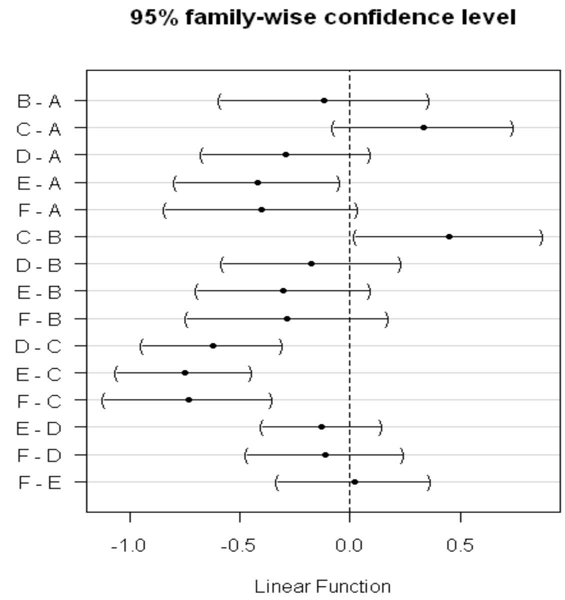


**Figure 12. Post-hoc test of *A. stomias* density comparisons**
This Tukey's HSD test shows that for *A. stomias*, densities are significantly different between A & E, and C is significantly different from all alongshore strata except A & C (R Development Core Team 2009).

Figure 13 depicts the results of Post-hoc pairwise comparison test of densities of *B. alascanus* across alongshore strata. Figure 13 indicates that all possible pair comparisons of alongshore strata are not significantly different from one another.

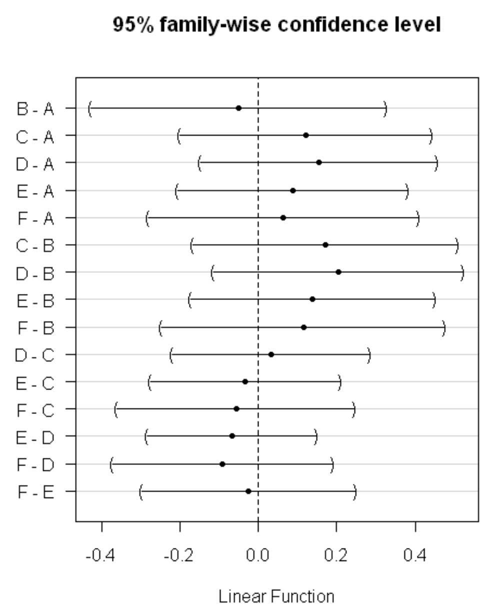


**Figure 13. Post-hoc test of *B. alascanus* density comparisons**
This Tukey's HSD test shows that for *B. alascanus*, there are no significant differences between densities of different alongshore strata pairs (R Development Core Team 2009).

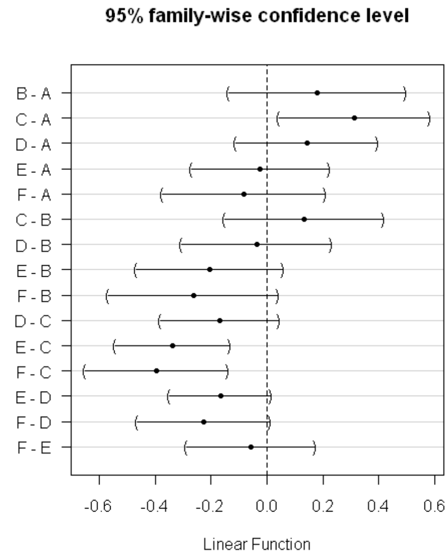


**Figure 14. Post-hoc test of *G. macrocephalus* density comparisons**
This Tukey's HSD test shows that for *G. macrocephalus*, strata C has significant difference with A, E, & F (R Development Core Team 2009).

For *G. macrocephalus*, there are few significant differences of mean densities between different alongshore strata groups except C, which is significantly different from A, E, and F (Fig 14). *H. elassodon* has significant differences with C, which is significantly different from A, B, E, & F (Fig 15). Strata A is significantly different from D, and Strata F is significantly different from D (Fig 15).

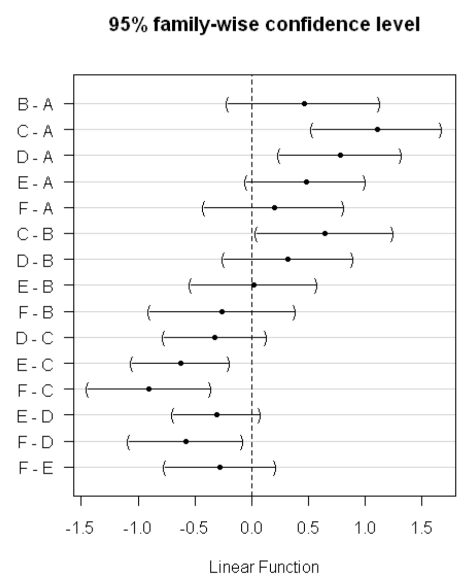


**Figure 15. Post-hoc test of *H. elassodon* density comparisons**
This Tukey's HSD test shows that for *H. elassodon* densities, strata A is significantly different from C & D. Strata B is significantly different from C, Strata C is different from E & F, and Strata D is different from F (R Development Core Team 2009).

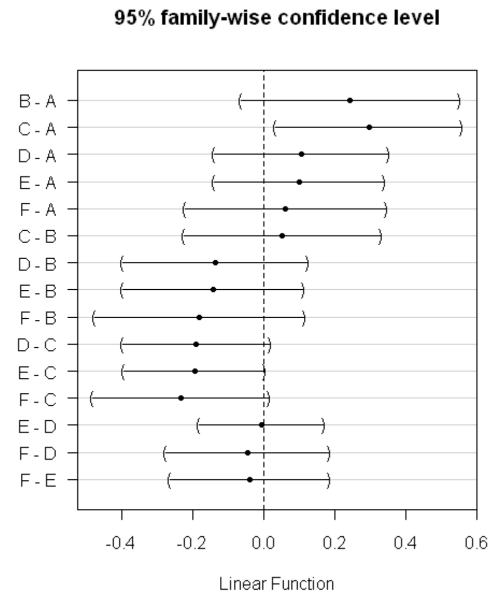


**Figure 16: Post-hoc test of *L. bilineata* density across alongshore strata**
This Tukey's HSD test shows that for *L. bilineata* mean densities, there are significant differences between only shelf strata A & C (R Development Core Team 2009).

There is no difference of mean densities for *L. bilineata* between alongshore strata pairs except between strata A & C (Fig 16). For *T. chalcogramma* significant differences of mean densities are evident between A and C, E, & F, B and D, E, & F, C & D, E, F, and D and E & F (Fig 17).

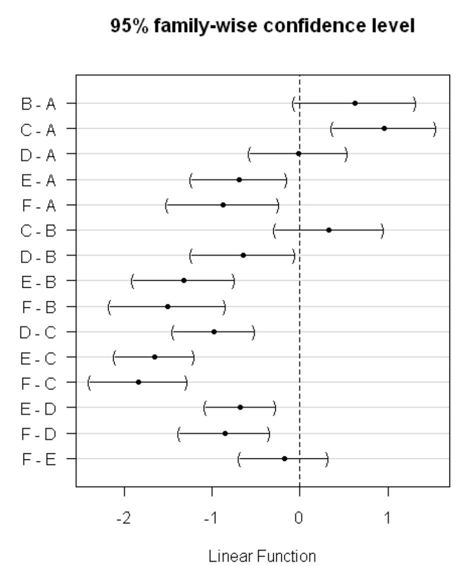


**Figure 17: Post-hoc test of *T. chalcogramma* density across alongshore strata**
This Tukey's HSD test shows that significant differences of mean densities for *T. chalcogramma* lie between A and C, E, & F. Strata B has significant differences with D, E, & F, strata C has differences with D, E, & F, and Strata D has differences with E, F (R Development Core Team 2009).

**Linear Regression Tests** The linear regression tests indicated that for all six species, none of the tests between each species' densities with each environmental variable (temperature, salinity, and attenuation) are significant, because all p-values are greater than 0.05 (Table 3). However, the relationship between *H. elassodon* densities and salinity, $R^2 = 0.044$, $F(1, 94) = 4.34$, $p = 0.04$ (Table 3) is statistically significant because p-value < 0.05. All $R^2$ are under 0.10, and thus each species' regression line of fit with each environmental variable is very poor (Table 3).

**Table 3: Linear Regression Test Results**
This summarizes the results of linear regression test between each species densities with each environmental variable (R Development Core Team 2009).

| | Attenuation | | | Salinity | | | Temperature | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Species | F | P-value | $R^2$ | F | P-value | $R^2$ | F | P-value | $R^2$ | df | df |
| A. stomias | 0.004 | 0.946 | <0.001 | 2.44 | 0.125 | 0.048 | 0.717 | 0.402 | 0.015 | 1 | 48 |
| B. alascanus | 0.39 | 0.536 | 0.01 | 0.3 | 0.587 | 0.007 | 0.106 | 0.746 | 0.003 | 1 | 39 |
| G. macrocephalus | 1.1 | 0.301 | 0.03 | 0.687 | 0.413 | 0.019 | 0.419 | 0.521 | 0.011 | 1 | 36 |
| H. elassodon | 0.9 | 0.345 | 0.009 | 4.34 | **0.04** | 0.044 | 1.71 | 0.194 | 0.018 | 1 | 94 |
| L. bilineata | 1.47 | 0.232 | 0.033 | 0.134 | 0.716 | 0.003 | 2.72 | 0.106 | 0.06 | 1 | 43 |
| T. chalcogramma | 0.67 | 0.415 | 0.008 | 9.27 | **0.003** | 0.097 | 0.124 | 0.726 | 0.001 | 1 | 86 |

**Correlation Tests** The correlation test showed which environmental variables were correlated with each species' densities, *A. stomias* density was correlated with attenuation and salinity but not temperature, $r(48) = -0.121$, $p = 0.402$ (Table 4). For *B. alascanus*, its density was correlated with salinity and temperature but not with attenuation, $r(39) = -0.099$, $p = 0.536$. *G. macrocephalus* density was correlated only with attenuation, $r(36) = 0.172$, $p = 0.301$ but not with salinity, $r(36) = -0.137$, $p = 0.413$ and temperature, $r(36) = -0.108$, $p = 0.521$ (Table 4). *H. elassodon* density was correlated with temperature but not attenuation, $r(94) = -0.097$, $p = 0.345$ and salinity, $r(94) = -0.21$, $p = 0.04$. *L. bilineata* density was not correlated with attenuation, $r(43) = -0.182$, $p = 0.232$ and salinity, $r(43) = -0.056$, $p = 0.716$. *T. chalcogramma* was correlated with attenuation and temperature but not with salinity, $r(86) = -0.312$, $p = 0.003$ (Table 4).

**Table 4: Correlation Test Results**
This table summarizes the correlation between each six taxon's densities with each physical variable (R Development Core Team 2009).

| | | Attenuation | | Salinity | | Temperature | |
|---|---|---|---|---|---|---|---|
| Species | df | P-value | Correlation | P-value | Correlation | P-value | Correlation |
| A. stomias | 48 | 0.946 | 0.01 | 0.125 | 0.22 | 0.402 | -0.121 |
| B. alascanus | 39 | 0.536 | -0.099 | 0.587 | 0.087 | 0.746 | 0.052 |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| G. macrocephalus | 36 | 0.301 | 0.172 | 0.413 | -0.137 | 0.521 | -0.108 |
| H. elassodon | 94 | 0.345 | -0.097 | 0.04 | -0.21 | 0.194 | 0.134 |
| L. bilineata | 43 | 0.232 | -0.182 | 0.716 | -0.056 | 0.106 | 0.244 |
| T. chalcogramma | 86 | 0.415 | 0.088 | 0.003 | -0.312 | 0.726 | 0.038 |

*Densities vs Temperature* The relationships with temperature differ between species. According to regression plot in Figure 18, the densities of only two species, *G. macrocephalus* and *T. chalcogramma*, have positive relationship with temperature. *B. alascanus*, *L. bilineata*, and *H. elassodon* have little to no relationship with temperature (Fig 18). Density of *A. stomias*, on the other hand, exhibit negative relationship with temperature (Fig 18).

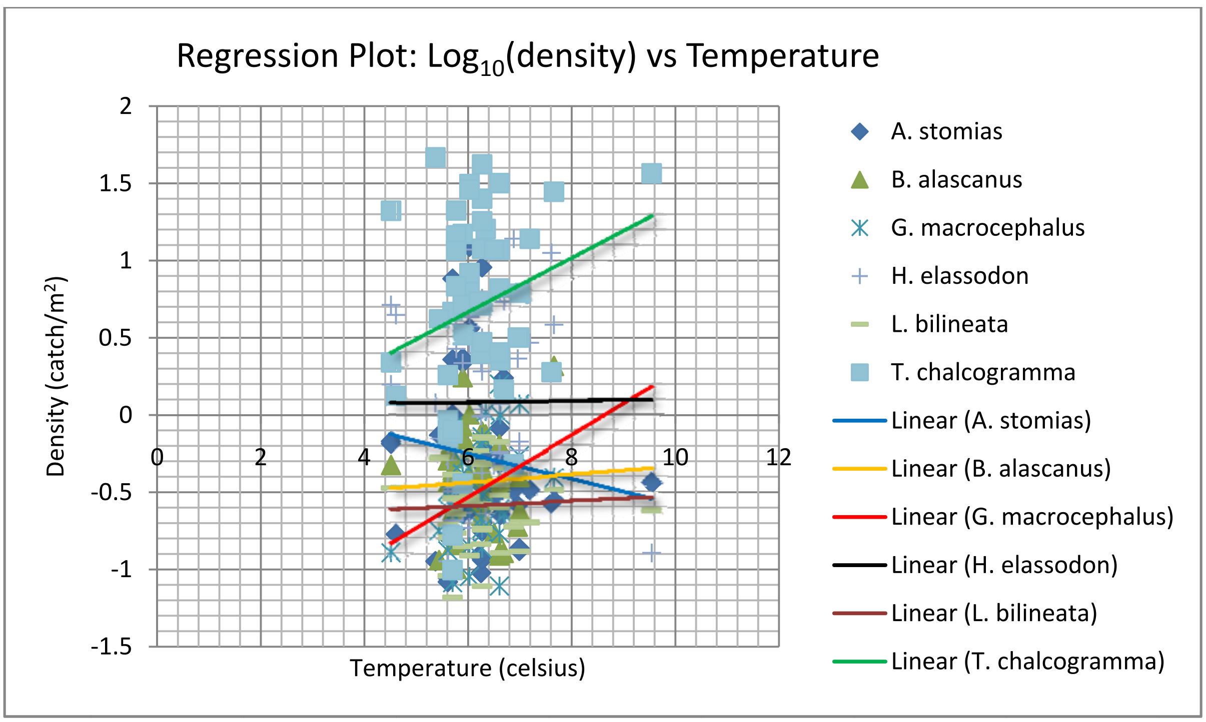


**Figure 18. Regression plot of $Log_{10}$(density) and temperature.**
Density is measured in catch/$m^2$ and temperature is measured in Celsius.

*Densities vs Salinity* For majority of species, relationship between species densities and salinity is negative. The regression line shows negative relationship for all species except *A. stomias* and *L. bilineata*. Density of *A. stomias* exhibit negative relationship whereas *L. bilineata* shows little to no relationship with salinity (Fig 19).

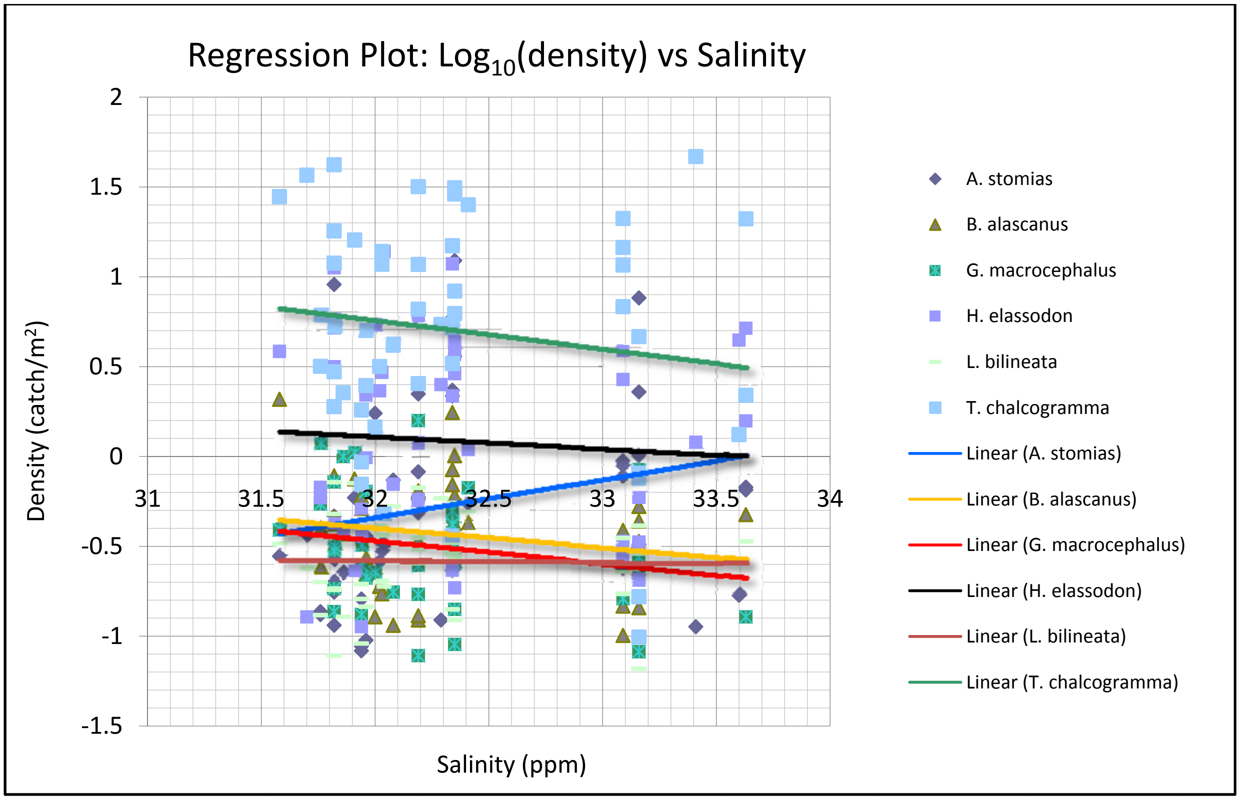


**Figure 19. Regression plot of $Log_{10}$(density) vs salinity.**
Salinity is measured in ppm (parts per million) and density is measured in catch/$m^2$.

*Densities vs Attenuation* Most species' densities exhibited negative relationship with attenuation. The densities of *T. chalcogramma*, *H. elassodon*, *G. macrocephalus*, *L. bilineata*, and *B. alascanus* are negatively sloped with increasing attenuation, whereas the density of *A. stomias* shows a nearly zero slope (Fig 20).

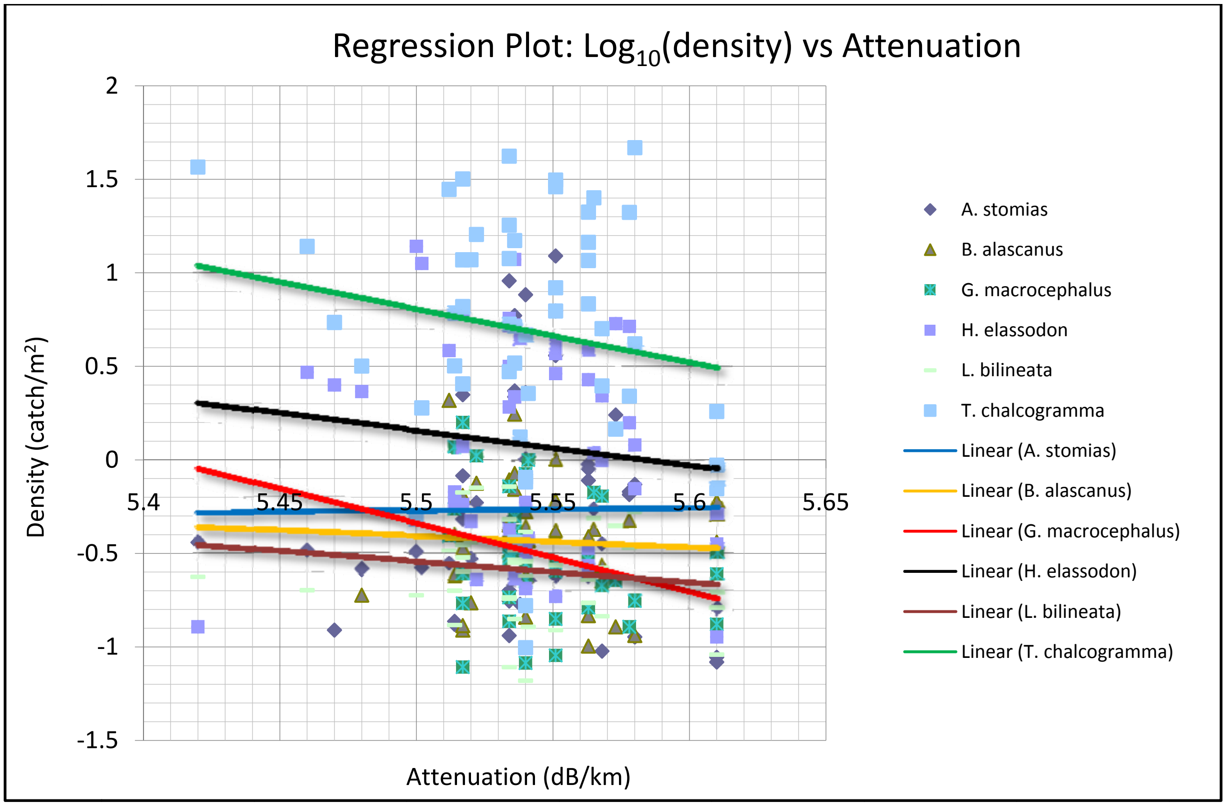


**Figure 20. Regression plot of $Log_{10}$(density) vs attenuation.**
Attenuation is measured in dB/km and density is measured in catch/$m^2$.

## DISCUSSION

Past studies have shown that ichthyoplankton have critical roles in balancing intricate marine ecosystems (Matarese et al. 2003). These studies have shown that larval fish distribution and ecology are strongly dependent on complex environmental variables circulating in oceans (Mundy 2005, Bailey & Picquelle 2002). Based on background studies and past research of ichthyoplankton ecology in coastal Gulf of Alaska (GOA), as well as the characteristics of environment supporting ichthyoplankton densities, I predicted that larval fish densities will be increasingly greater closer to coastline. The Gulf of Alaska oceanographic study carried by Royer (1975) observed increasing concentrations of high-nutrient, salty waters along the shoreline; thus, for each six taxon I expected to see greater concentrations in alongshore strata B and E where many islands are scattered. Since waters with higher concentration of nutrients are salty (Royer 1975) I expected to see positive relationship between salinity and average density for each taxon. In Gulf of Alaska, warmer temperatures have been associated with increasing concentrations of larval fish (Coyle et al. 2008) and thus, I expected that for each taxon, densities are positively related with temperature. I expected to see negative relation between attenuation and density for each taxon, since the reduction of attenuation will allow fewer phytoplankton to photosynthesize (Hernandez et al. 2009), thus reducing nutrient quality in waters. The results of this study revealed that proximity to shoreline, concentrations of salinity, temperature ranges, and attenuation variables affect mean densities of various species in larval stages. However, regardless of different proportion of shorelines, salinity, attenuation, and temperature, clear correlations between these variables and densities weren't observed for all species.

**Shelf Strata** For most species, as hypothesized, the highest densities were discovered in Shelf I, or the inshore shelf (Fig 4). This can be attributed to the upwelling mentioned in hypothesis; upwelling brings high-salinity bottom waters to inshore, and before upwelling takes full scale in beginning of summer, many ichthyoplankton are densely concentrated in these bottom depth waters (Mundy 2005). Thus, they are brought to coastal waters through upwelling effect, which brings bottom waters via shelf circulation (Gawarkiewicz & Chapman 1992). The post-hoc pairwise comparison tests do verify that among the shelf strata pairs with significantly different densities, for five out of six species the densities between Shelf I and III have greatest significant differences (Figures 6-11).

**Alongshore Strata** According to Figure 5, the greatest densities for most species were in alongshore strata C. Post-hoc pairwise comparison test results (Figures 12-17) also showed that alongshore strata C had greatest significant differences than other alongshore strata. Therefore, the proportion of shorelines didn't appear to exert significant effect on species densities; unlike the hypothesis, none of six species appeared to favor strata with many islands (strata B and E) which exhibited greater proportion of coastal waters. The lack of clear relationship between the increasing proportions of shoreline versus larval fish density could be explained by species-specific life history or ecology. Each species, in adult stage, has different preference of its spawning habitats regardless of whether it is coastal or open water (Hurst et al. 2009). One species, the *A. stomias*, was unique for this study, because, unlike other five taxa it was concentrated in mid and outer shelf (Figure 5). Bailey and Picquelle's study of *A. stomias* (2002) discovered that spawning grounds for adults lie in deeper waters. Larvae must migrate to inshore or coastal waters to nourish themselves with abundant nutrition so that they can survive to juvenile stage (Bailey & Picquelle 2002). However, these deep waters, where adult *A. stomias* migrate to lay eggs, are susceptible to various currents and horizontal transports (Stark 2008);

furthermore, the region between spawning grounds and coastal waters are filled with series of troughs and fissures (Bailey & Picquelle 2002). The region is also susceptible to dynamic weather conditions including anomalies and El Nino, which in turn, affects physical features of marine habitat (Anderson et al. 2006). Thus, *A. stomias* larvae need to overcome series of geographic and environmental barriers to reach coastal waters.

Another reason for lack of clear correlation between proportion of shorelines and fish densities can be attributed to the type of oceanic floor habitats larval fish thrive in, which this study didn't analyze. GOA habitats are diverse with sediment types, range from cobbles to sand and mud, but can be rocky and composed of bedrocks (Thedinga et al. 2008). In Gulf of Alaska, along the shoreline diverse array of habitats can be found including sand bottom, cobbles, and bedrock (Dressel & Norcross 2005). Rooper et al. (2005) found that increasing prevalence of mud reduces invertebrate population, thereby decreasing food concentration larval fish. Cobble and sand habitats appear to support highest densities of larval fish in Northern Pacific (Thedinga et al. 2008). Furthermore, the substrate types in Northern Pacific affected distribution of benthic macroinvertebrates, which are vital food source for young flatfish including *Atheresthes stomias*, *Hippoglossoides elassodon*, and *Lepidopsetta bilineata*, the three of six species central to this study (McConnaughey & Smith 2000). These studies suggest that type of habitat, regardless of proximity to coastal waters or across the same shelf or alongshore strata, could be a stronger determinant of larval fish distributions and abundances rather than proportion of shorelines.

However, the most important reason that could explain the highest densities in alongshore strata C than B or E can be attributed to a major current of GOA, Alaska Coastal Current (Mundy 2005). Alaska Coastal Current, or ACC, is a fast-moving current that moves along southern coast of Alaskan Peninsula from east to west; after passing through Shelikof strait between Kodiak Island and southern coast of Alaskan Peninsula, the current slows and circulates in vacant continental shelf (Muench et al. 1978). The Shelikof Strait is between Kodiak Island and southern edge of Alaskan Peninsula (Stabeno et al. 1995, Figure 1); according to Figure 3, Shelikof Strait is in obstructed Alongshore Strata E. The fast flow rate, which is 1 million cubic meters per second, may prevent stationary settlements of ichthyoplankton around the Kodiak Island and Shelikof Strait, therefore sending high concentrations to unobstructed alongshore strata C and D (Johnson et al. 1988).

**Temperature** In this study, relationship between temperature and density wasn't clear for most of the species; according to linear regression tests, no relationships between densities and each environmental variable was expected since all p-values are greater than 0.05 (Table 3). Furthermore, the regression plots showed little to no relationships for three species (Figure 18). The lack of clear correlation between larval fish distribution and temperature can be attributed to Gulf of Alaska's incredibly dynamic features such as currents and eddies. This may prevent the temperature from maintaining a stable state, thus, making temperature not an ideal environmental variable to consider when assessing ichthyoplankton densities and distribution across Gulf of Alaska's continental shelf. Mundy (2005) found that Alaska Coastal Current, the rapid current running along southern coastline of Alaskan Peninsula, affected distribution of warm low and high salinity waters across the Gulf of Alaska. Therefore, this affected species dependent on warm, low-salinity waters, particularly the Walleye Pollock (*Theragra chalcogramma*), but it was revealed that distribution shifted rapidly, in matter of two weeks, under influence of Alaska Coastal Current and wind patterns (Logerwell et al. 2007). This suggests that when Gulf of Alaska is under influence of dynamic characteristics ranging from vertical transport to forceful currents, temperatures are subjected to rapid change (Munk et al. 2009). However, although the results for this study shows no clear relationship between larval fish densities and temperature, one study in particular, carried out within Northern Pacific, found that young Walleye pollocks, *Theragra chalcogramma*, are widespread and abundant across the region during warm years and far less widespread and abundant during cool years (Moss et al. 2009). It can be assumed that based on studies by Moss et al. (2009) and Logerwell et al. (2007), the temperature has clear effect on species distributions but variable characteristics in Gulf of Alaskan waters makes it difficult to observe direct relationship between individual species' distribution and density versus temperature trend over scale of time.

Furthermore, the different relationships of temperature and density between each species may be due to each species' different habitat preference. Some fish species in larval stages prefer higher temperatures because their preferred prey has higher tolerance of warmer oligotrophic waters (Coyle et al. 2008). Others, like capelin, prefer cool waters, a contrast to another coexisting species, *T. chalcogramma*, which prefer warmer waters (Logerwell et al. 2007). This could explain the different relationships observed on regression lines (Figure 18) but the existing correlations for four out of six species' densities with temperature (Table 4).

**Salinity** According to Figure 19, five out of six species' densities have negative relationship with salinity, a drastic contrast to hypothesis. Past studies extensively cover the salinity and its pivotal role in determining larval fish distribution across Gulf of Alaska. A study of oceanographic variability's effects on species distribution found Walleye Pollock, *Thergra chalcogramma*, and other species inhabiting Gulf of Alaska, including Capelin, with highest concentrations in low-salinity waters (Logerwell et al. 2007). This study agrees with the results of my study, as four out of six taxa had clear, negative correlation with salinity. For the remaining two taxa, competition between two species is a possibility; Logerwell et al. (2007) has hinted possibility of interspecific competition as multiple species attempt to occupy same niches for survival. This could explain why other two taxa, the *Lepidopsetta bilineata* and *Bathyagonus alascanus* lack clear correlation with salinity, as these two species may face competition with many other species inhabiting Gulf of Alaska. However, according to Mundy (2005), Gulf of Alaska's hydrography (including salinity) is incredibly dynamic and often unpredictable, as it is subjected to change in matter of days or months. According to Mundy, predicting future hydrographic data from previous studies is inaccurate since every feature at specific time scale is unique. Perhaps the salinity was as dynamic as temperature was for this study; it may have been pure luck that clear correlations were observed.

**Attenuation** According to Figure 20, attenuation's relationship with species density was clear, since five out of six most abundant taxa had clear negative correlation with attenuation. As the loss of light increases, this affects the productivity of Gulf of Alaska's ecosystem as less phytoplankton are nourished with light to produce energy, thus affecting zooplankton community which larval fish depend so greatly on (Coyle et al. 2008). The biomass of larval fish is affected as copepod and zooplankton community shifts when productivity of phytoplankton decline (Coyle et al. 2008). Coyle et al. discovered huge declines of copepods and scyphozoans as attenuation increased in Gulf of Alaska between 1999 and 2004. Thus it is safe to conclude that attenuation is an important determining factor of ichthyoplankton distribution and density across Gulf of Alaska.

**Comparison of Environmental Variables** According to linear regression tests, for nearly all species' densities response to each environmental variable, there are no relationship, since null hypothesis was not rejected, as all p-values are greater than 0.05 (Table 3). However, the correlation test revealed that for four out of six species, there is correlation between their average densities and temperature (Table 4). But the regression lines drawn on scatter plots show that relationship with temperature differs between species (Figure 18), whereas similar relationships were observed for nearly all species in attenuation and salinity (Figures 19 & 20). Judging from the similar relationships with multiple species, it can be concluded that for these six species in larval stage, attenuation and salinity have greater influence than temperature on distribution and abundance patterns.

**Implications and Future Studies** The research design adequately addressed the hypothesis; the designs attempted to assess species density patterns across discrete variables, the shelf and alongshore strata. The research analyzed species' average densities as response variable to continuous and explanatory variables, the temperature, salinity, and attenuation. In other words, the research designs were aimed to address each component of hypothesis. Past studies have used a method called post-stratification which gave more precise and less-biased population estimates (Dressel & Norcross 2005). Perhaps this method could be a better choice to equally distribute larval densities rather than making rough stratifications through simple visualization. The Alaska Fisheries Science Center (AFSC) in Seattle, WA used statistical software called BIO-ENV to assess which environmental variable exerts biggest effect on larval fish distribution. This software, though it has limited availability outside AFSC, is an effective tool to narrow down possible choices of environmental factors to be assessed and compared with ichthyoplankton distribution. Other software, such as TWINSPAN, can assess which groups of stations exhibit highest densities of each species studied, and provide new categorical variable method.

This research and the study design runs into several major implications. First, all the samples that this research is based on were collected in summer 1987, from June 18 to July 17. Gulf of Alaska's environment and dynamics of ocean are ever-changing (Porter 2005). It is safe to assume that today's environment may be significantly different from summer 1987. Using these samples and the larval fish ecology of past may not produce an accurate or precise data to forecast the ecological trends of larval fish distribution in Gulf of Alaska years to come. In terms of life history, the habitat range and distribution of each six taxon may have changed at least to minimal degree, thus becoming an outlier (the life history could be responsible for distribution instead of physical environmental factors). Other statistical tests including Multi-way ANOVA to test significance of multiple categorical variables could help simultaneous comparison of larval fish abundances' responses to different discrete variables. Furthermore, these samples, when collected in 1987, were used with methot trawl, a tool specialized in capturing fish of juvenile sizes or greater (Ichthyoplankton Cruise Database 2009). Thus, the collected samples of larval specimen may be insufficient to study distributions and density gradients if many specimens passed through trawl meshes uncaught. Finally, rather than the samples from 1987, using the samples from more recent cruises could've provided more accurate data in relation to modern ichthyoplankton distributions and density status across GOA.

The subjects of this study were six most widespread fish species, all in larval stage, across Gulf of Alaska's continental shelf. According to results, not all of the features considered for this study (shelf and alongshore strata, salinity, temperature, attenuation) adequately describe clear relationship with densities and distribution of six taxa. From the comparisons with findings of past literature, it's clear that there are so many other environmental features to be considered better determinants of larval fish distributions. This research however, was necessary, since its results will greatly enhance understanding of ichthyoplankton ecology in Gulf of Alaska during mid-summer months. However, from this research and comparison with past literature, it is important to assume that different species exhibit different responses across different categorical (shelf, alongshore) variables and different responses to continuous (temperature, salinity) explanatory variables. Although this study tried to assess general distribution and abundance patterns of overall ichthyoplankton ecology, considering each species' different life history, focus on one taxon's density and distribution patterns is critical.

This exciting research offers brief but understandable scope of ichthyoplankton ecology for general audiences. Continuing studies can help deeper understanding of larval fish throughout the globe and determine structure of marine ecosystems on seasonal and annual basis. Studies of larval fish assemblages, in turn, may help predict the patterns of physical variables. In terms of conservation, larval fish help predict adult populations and distributions (Anderson et al. 2006). Many ichthyoplankton, once mature, are vital source for commercial fisheries. Larval fish research can provide sustainable recommendations to harvesters, which helps maintain population stocks over time. Larval fish are fundamental basis of marine ecosystem; with so many species relying on them for survival, they are a vital frame maintaining fragile food web. Continual larval fish research could help forecast and preserve marine biodiversity status in years to come.

**ACKNOWLEDGMENTS**

I thank Morgan Busby, Ann Matarese, and Debbie Blood of NOAA Alaska Fisheries Science Center for offering this fabulous research opportunity, as well their guidance and sharing their profound knowledge, experience, and insight to make this project possible. I thank Susanne McDermott for making my internship a memorable experience. I thank Matt Wilson, Kevin Bailey, Jeff Napp, Kathy Mier, Susan Picquelle, Lisa DeForest, Stacy Remple, and Kimberly Bahl of Fisheries-Oceanography Coordinated Investigations for research recommendations and additional assistance in early life history research. I thank Dave Kachel and Al Hermann of Pacific Marine Environmental Laboratory for providing up to date oceanographic data. I thank Tina Mendez, Lucy Diekmann, Gabrielle Wong-Parodi, and Kurt Spreyer for their guidance and feedbacks throughout the year to help polish my work. Lastly I thank my friends and family for their continual support.

**REFERENCES**

Anderson, J., Busby, M., Mier, K., Deliyanides, C., & Stabeno, P. (2006). Spatial and temporal patterns in summer ichthyoplankton assemblages on the eastern bering sea shelf 1996-2000. *Fisheries Oceanography, 15*(1), 80-94.

Bailey, K. M., & Picquelle, S. J. 2002. Larval distribution of offshore spawning flatfish in the gulf of alaska: Potential transport pathways and enhanced onshore transport during ENSO events. *Marine Ecology Progress Series,* ***236***, 205-217.

Brodeur, R. D., Busby, M. S., & Wilson, M. T. 1995. Summer distribution of early life stages of walleye pollock, theragra chalcogramma, and associated species in the western gulf of alaska. *Fishery Bulletin,* ***93***(4), 603-618.

Coyle, K., Pinchuk, A., Eisner, L., & Napp, J. (2008). Zooplankton species composition, abundance and biomass on the eastern bering sea shelf during summer: The potential role of water-column stability and nutrients in structuring the zooplankton community. *Deep Sea Research (Part II, Topical Studies in Oceanography), 55*(16-17), 1775-1791.

Doyle, M. J., Picquelle, S. J., Mier, K. L., Spillane, M. C., & Bond, N. A. 2009. Larval fish abundance and physical forcing in the gulf of alaska, 1981-2003. *Progress in Oceanography,* ***80***(3-4), 163-187.

Dressel, S., & Norcross, B. (2005). Using poststratification to improve abundance estimates from multispecies surveys: A study of juvenile flatfishes. *Fishery Bulletin, 103*(3), 469-488.

EPIC. NOAA Pacific Marine Environmental Laboratory 2006. Retrieved from http://www.epic.noaa.gov/epic/ on 9/27/09.

Fox, J. (2009). Rcmdr: R Commander. R package version 1.5-4. http://CRAN.R-project.org/package=Rcmdr

Garwarkiewicz, G. & Chapman, D.C. (1992). The role of stratification in the formation and maintenance of shelf-break fronts. *Journal of Physical Oceanography* 22, 753-772.

Hernandez, F. J., Hare, J. A., & Fey, D. P. (2009). Evaluating diel, ontogenetic and environmental effects on larval fish vertical distribution using generalized additive models for location, scale and shape. *Fisheries Oceanography, 18*(4), 224-236.

Hollowed, A., Wilson, C., Stabeno, P., Salo, S. 2009. Effect of ocean conditions and strong year classes of Northeast Pacific groundfish. *ICES Marine Science Symposium* ***195***, 433-444.

Hurst, T. P., Cooper, D. W., Scheingross, J. S., Seale, E. M., Laurel, B. J., & Spencer, M. L. 2009. Effects of ontogeny, temperature, and light on vertical movements of larval pacific cod (gadus macrocephalus). *Fisheries Oceanography,* ***18***(5), 301-311.

Ichthyoplankton Cruise Database 2009. Cruise Catalog Home. Retrieved 9/28/09 from http://access.afsc.noaa.gov/icc/index.cfm

Ichthyoplankton Information System. 2009. Background and Historical Review. Retrieved 9/28/09 from http://access.afsc.noaa.gov/ichthyo/history.cfm

Johnson, W.R., Royer, T.C., Luick, J.L. (1988). On the seasonal variability of the Alaska Coastal Current. *Journal of Geophysical Research* 93; 12423-37.

Logerwell, E. A., Stabeno, P. J., Wilson, C. D., & Hollowed, A. B. 2007. The effect of oceanographic variability and interspecific competition on juvenile pollock (*Theragra chalcogramma*) and capelin (*Mallotus villosus*) distributions on the Gulf of Alaska shelf. *Deep Sea Research (Part II, Topical Studies in Oceanography),* ***54***(23-26), 2849-2868.

Matarese, A.C., Kendall, A.W., Blood, D.M., & Vinter, B.M. 1989. Laboratory Guide to Early Life History Stages of Northeast Pacific Fishes. US Dept. of Commerce, NOAA Tech Rep, NMFS 80.

Matarese, A., Blood, D.M., Picquelle, S.J., Benson, J. 2003. Atlas of Abundance and Distribution Patterns of Ichthyoplankton from the Northeast Pacific Ocean and Bering Sea Ecosystems. US Dept of Commerce, NOAA Tech Rep, NMFS 1.

McConnaughey, R., & Smith, K. (2000). Associations between flatfish abundance and surficial sediments in the eastern bering sea. *Canadian Journal of Fisheries and Aquatic Sciences, 57*(12), 2410-2419.

Mendez, T. (2010a). Workshop B: Categorical Data Analysis. ES 196.

Mendez, T. (2010b). Workshop D: Continuous Data Analysis. ES 196.

Moss, J. H., Farley, E. V.,Jr, Feldmann, A. M., & Ianelli, J. N. (2009). Spatial distribution, energetic status, and food habits of eastern bering sea age-0 walleye pollock. *Transactions of the American Fisheries Society, 138*(3), 497-505.

Muench, R.D., Mofjeld, H.O., & Charnell, R.L. (1978). Oceanographic conditions in lower cook Inlet: Spring and summer 1973. *Journal of Geophysical Research*, 83, 5090-98.

Mueter, F. J., & Norcross, B. L. 2002. Spatial and temporal patterns in the demersal fish community on the shelf and upper slope regions of the gulf of alaska. *Fishery Bulletin, **100***(3), 559-581.

Mundy, P. 2005. Gulf of Alaska's Biology and Oceanography. Alaska Sea Grant Report, Fairbanks, AK.

Munk, P., Fox, C. J., Bolle, L. J., van Damme, C. J., Fossum, P., & Kraus, G. (2009). Spawning of north sea fishes linked to hydrographic features. *Fisheries Oceanography, 18*(6), 458-469.

Pacific Marine Environmental Laboratory 2007. NOAA PMEL. Retrieved from www.pmel.noaa.gov on 9/27/09.

Porter, S. (2005). Temporal and spatial distribution and abundance of flathead sole (hippoglossoides elassodon) eggs and larvae in the western gulf of alaska. *Fishery Bulletin, 103*(4), 648-658.

R Development Core Team (2009). R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. ISBN 3-900051-07-0, URL http://www.R-project.org.

Recruitment Processes Program 2009. General Overview. NOAA Alaska Fisheries Science Center. Retrieved from http://www.afsc.noaa.gov/RACE/recruitment/default_rp.php on 9/27/09.

Rooper, C., Zimmermann, M., & Spencer, P. (2005). Using ecologically based relationships to predict distribution of flathead sole hippoglossoides elassodon in the eastern bering sea. *Marine Ecology Progress Series,* 290.

Royer, T.C. 1975. Seasonal variations of waters in northeastern Gulf of Alaska. *Deep sea Research* **22**; 403-416.

Southwest Fisheries Science Center 2007. What are Ichthyoplankton? Retrieved from http://swfsc.noaa.gov/textblock.aspx?Division=FRD&id=6210&ParentMenuId=436 on 10/24/09.

Stabeno, P.J., Reed, R.K., & Schumacher, J.D. (1995). The Alaska coastal current: continuity of transport and forcing. *Journal of Geophysical Research*, **100**; 2477-2485.

Stark, J. (2008). Age- and length-at-maturity of female arrowtooth flounder (atheresthes stomias) in the gulf of alaska. *Fishery Bulletin, 106*(3), 328-333.

Thedinga, J. F., Johnson, S. W., Neff, A., & Lindeberg, M. R. (2008). Fish assemblages in shallow, nearshore habitats of the bering sea. *Transactions of the American Fisheries Society, 137*(4), 1157-1164.