

**SPATIAL AND TEMPORAL VARIABILITY OF
ZOOPLANKTON COMMUNITIES IN THE SAN JUAN
CHANNEL**

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Pelagic Ecosystem Function in the San Juan Archipelago Research Apprenticeship, Fall

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ABSTRACT

The San Juan Channel is a transitional area between marine and freshwater environments that influences the distribution, abundance and community composition of zooplankton. Zooplankton communities are highly variable seasonally and interannually due to the complexity of physical oceanography in the region. During the fall season in 2011, tidal regimes that characterize this estuarine environment appeared to spatially influence highly abundant Calanoid copepods and copepod nauplii. The results of this study suggest that tidal forcing exhibits a significant influence Calanoid copepods and copepod nauplii in the San Juan Channel, where spring flood tides influenced the Northern region and neap flood tides influenced the Southern region at depth. Spatial variation in the distribution of juvenile and adult copepods between these regions may be explained by behavioral patterns in copepod diapause, while depth variation in the Southern region may be driven by behavioral patterns in diel vertical migration. These investigations may begin to enhance our understanding of the relative life history stages of copepods as an influence on their distribution and abundance in the San Juan Channel.

INTRODUCTION

Marine food webs depend on herbivorous zooplankton as an essential route of energy transfer between the primary production of autotrophic phytoplankton and numerous pelagic heterotrophs (Aruda et al., 2011). The horizontal and vertical movements of zooplankton are strongly influenced by tides and prevailing water movement, although they are able to exhibit some limited movement that promotes their retention in suitable habitats (Nybakken, Bertness, 2005). Zooplankton are influenced strongly by oceanic and climatic variables due to their short lifecycles, and respond rapidly to changes in abiotic (e.g., temperature, salinity, advection) and biotic (e.g., nutrient availability, predation) parameters (Modéran et al, 2010). In estuarine environments that control fluxes between freshwater and marine ecosystems and influence the distribution of fauna, zooplankton community composition may be greatly affected.

Strong tidal currents and abundant plankton populations characterize the San Juan Channel of the San Juan Archipelago, which connects the Strait of Juan de Fuca in the south to the Strait of Georgia in north. The Northern region of the San Juan Channel is characterized by an estuarine signature, where waters are heavily

mixed and virtually homogeneous, and the Southern region is characterized by an oceanic signature, where water are highly stratified. In the San Juan Channel, flooding tidal currents flow from South to North and ebbing currents flow from North to South (Thomson, 1981). The San Juan Archipelago, which lies at the nexus of the Fraser River and the Pacific Ocean, is an example of a marine ecosystem at the interface between freshwater and marine environments that constitutes a transition area where complex biogeochemical processes influence fauna distribution (Modéran et al., 2010). Studies by Zamon in the San Juan Channel have shown that “...changes in copepod abundance were likely caused by advection of copepod aggregations and nutrients from near or above the pycnocline in the Strait of Juan de Fuca”, and that tidal differences in copepod abundance create predictable changes in food availability for planktivores (Zamon, 2002).

The objective of this study was to further characterize seasonal zooplankton distribution, abundance, community composition and diversity (i.e., species richness and species evenness) in the San Juan Channel between North and South stations during the fall season in 2011. This study also served to expand an existing dataset, and to utilize past data to make interannual comparisons and determine whether zooplankton assemblages in fall 2011 are unique. This study also sought to

characterize zooplankton communities by depth at the South, where shallow waters marked by estuarine outflow and deep waters marked by oceanic inflow are present. Furthermore, physical oceanographic variables (i.e., temperature, salinity, dissolved oxygen, tidal characteristics) were also investigated as potential drivers of changes in zooplankton abundance and distribution. The abundance of calcareous organisms that may be susceptible to ocean acidification were also assessed during the fall season this year.

MATERIALS AND METHODS

Study site

Zooplankton data were collected over the course of seven separate cruises that occurred on October 7th, 18th, and 24th, and on November 1st, 7th, 15th, and 19th in the San Juan Channel of the San Juan Archipelago, between the mainland of Washington State and Vancouver Island, British Columbia, Canada. These data were collected from two stations located the San Juan Cannel – the North station (48°35.00'N, 123°02.50'W), and the South station (48°25.20'N, 122°56.60'W).

Sample collection

Zooplankton samples were collected using a 70-cm diameter, 153- μ m-mesh ring net. Zooplankton samples were taken at varied depths, depending on the maximum depth at each station, where samples from the North station were towed vertically from 120m to the surface and samples from the South station were towed vertically from 80m to the surface. Samples taken at depth were approximately 10 m above the substrate. To explore the spatial patterns of zooplankton communities as they varied with depth, additional samples were taken the South station from 80 – 40 m, and from 40 m to the surface. Stratified zooplankton net tows were achieved with the use of a closing net and a weighted messenger upon reaching the desired depth. A flowmeter was attached and used to calculate the total volume of water filtered. Samples were immediately preserved in 10% buffered formalin and returned to the laboratory where zooplankton were identified by taxa and developmental stage.

Sample analysis

In the laboratory, the settling volume of each sample was calculated after a 24-hour settling period, with a metric ruler and the equation: *settling volume* (cm^3) = $\pi(4.5cm)^2 * height\ of\ settled\ sample\ (cm)$. Zooplankton samples were

strained through two stacked sieves, with mesh sizes of 1mm and 118 μ m. 1mm samples were diluted up to approximately 150 – 250ml, depending on the density of the sample, and subsampled further into 5.0ml aliquots to be inspected under the dissecting scope; 118 μ m samples were diluted up to 500ml and subsampled further into 2.2ml aliquots for inspection under a Nikon SMZ654 dissecting microscope. The organisms enumerated in each sample were classified as either holoplankton (i.e., organisms that are planktonic for their entire lifecycle) or meroplankton (i.e., organisms that are planktonic for only part of their life cycles, usually the larval stage), depending on their life histories, and were identified to the lowest possible taxonomic level. The relative subsampling volumes were taken into account by converting the number of organisms identified per taxonomic group in each subsample to a number per cubic meter, which is based on the total volume of water passing through each zooplankton net tow. This conversion was made with the equation: $volume (m^3) = \pi(0.35cm)^3 * depth\ of\ tow (m)$.

Diversity

Biological diversity was calculated using the Shannon-Wiener Diversity Index, which accounted for species richness (i.e., the number of different species per

sample) and species evenness (i.e., the relative abundance of each different species in the sample), using the equation:

$$H' = - \sum_{i=1}^S (p_i \ln p_i)$$

where S is the species richness, and p_i is the relative abundance of each species, calculated as the proportion of individuals of a given order to the total number of individuals in the sample ($\frac{n_i}{N}$, where N is the total number of all individuals). The values of the index range from 0.0 – 4.0 with higher values indicating greater species evenness and richness. Organisms were classified by the taxonomic rank of Class to normalize measurements among taxon. The diversity index value for each sampling area (i.e. North station, South station, South station between 80 – 40 m, South station between 40 – 0 m) was derived from the average values of all replicates, in which each sample dates were treated as a replicates.

Tidal variation, fall 2011

Tidal data was collected from the Nation Oceanic and Atmospheric Administration (NOAA) online (<http://tidesandcurrents.noaa.gov/>) for the Friday Harbor, WA station (9449880).

RESULTS

Season and interannual variation, 2007 - 2011

Comparisons of total zooplankton abundance from 2007 to 2011 indicated that zooplankton abundance is highly variable both seasonally and interannually (Figures 1 & 2). With respect to the total zooplankton abundance in previous years, the North station appears to have the least total abundance in 2011 and the greatest total abundance in 2007, with average seasonal densities of $3,372/\text{m}^3$ and $8,184/\text{m}^3$, respectively; the South station appears to have moderate total zooplankton abundance in 2011 and the greatest total abundance in 2007, with average seasonal densities of $6,342/\text{m}^3$ and $11,248/\text{m}^3$, respectively.

Fall transition dates were variable from 2007 to 2010, when the earliest Fall Transition was on October 15, 2009 and the latest Fall Transition was on November 1, 2008; the earliest Fall Transition date between 2007 and 2011 was likely on September 15, 2011, before sampling in the San Juan Channel began (Table 1).

Comparisons of total zooplankton abundance with respect to the timing of the Fall Transition demonstrated that the early Fall Transition in 2011 was followed by low abundance in the North ($3,372/\text{m}^3$) and moderate abundance in the South

(6,342/m³); the late Fall Transition in 2008 followed by moderately low abundance at both North and South station, with average seasonal densities of 4,507/m³ and 5,098/m³, respectively.

Abundance and composition, fall 2011

Total zooplankton abundance at North and South stations indicated a general increase over the fall season in 2011, with lower densities at the North station and greater densities at the South station (Figure 3). The greatest densities at the North station occur on October 18th and November 1st with densities of 4,653/m³ and 5,563/m³, respectively; the greatest densities at the South station occur on October 18th and November 7th with densities of 7,365/m³ and 8,264/m³, respectively. The shallow-water region between 40 – 0 m at South station experiences the highest densities on October 18th and November 1st, with densities of 6,719/m³ and 9,932/m³, respectively. The deep-water region between 80 – 40 m at South station exhibited the highest densities on October 24th and November 7th, with densities of 10,975/m³ and 11,176/m³, respectively.

Across the fall season, the total average holoplankton density at the North station was 3,745/m³ whereas the total holoplankton density at the South station

was $6,237/\text{m}^3$, accounting for 97.85% and 98.34% of the total average zooplankton density at each station, respectively (Table 2). The total average meroplankton density at the North station was $82/\text{m}^3$ whereas the total meroplankton density at the South station was $105/\text{m}^3$, accounting for 2.15% and 1.66% of the total zooplankton density at each station, respectively.

The most abundant zooplankton taxa at both North and South stations over the fall season in 2011 were Calanoid copepods, which accounted for 73% of the total average seasonal abundance and had a density of $18,263/\text{m}^3$ (Table 2). Other abundant zooplankton taxa included copepod nauplii (14.6%), Harpacticoid copepods (5.0%) and Larvaceans (4.0%), while other holoplankton taxa (1.6%) and meroplankton taxa (1.5%) were generally less abundant. Meroplankton and other holoplankton were generally less abundant at the North station than at the South station, although their relative abundance was greater at the North station. At the North station, meroplankton and other holoplankton account for 2.15% and 1.20% of the total zooplankton density, with densities of $82/\text{m}^3$ and $46/\text{m}^3$, respectively; at the South station, meroplankton and other holoplankton account for 1.66% and 1.11% of the total zooplankton density, with densities of $105/\text{m}^3$ and $71/\text{m}^3$, respectively.

Over the fall season in 2011, zooplankton abundance varied among North and South stations and among the shallow- and deep-waters at South station. At the North station, major zooplankton taxa including copepod nauplii, Harpacticoid copepods, Larvaceans and other holoplankton and meroplankton taxa exhibited the highest densities on October 18th and November 1st, which was consistent with the seasonal trend of total zooplankton abundance; Calanoid copepod abundance was generally greater than other taxa but was not consistent with this trend (Figures 3 and 4). At the South station, all major zooplankton taxa excluding the other holoplankton had the highest densities on October 24th, whereas only Calanoid copepods and copepod nauplii had similarly high densities on November 7th, which is consistent with the seasonal trend of total zooplankton abundance (Figures 3, 5.1 and 5.2).

Additional patterns in zooplankton abundance over the fall season existed between the shallow- and deep-waters of the South station. In the shallow-waters at South station between 40 – 0 m, Calanoid copepods and copepod nauplii each experienced relatively high densities on October 18th and November 1st, although other major zooplankton taxa did not exhibit patterns that were consistent with the seasonal trend in total zooplankton abundance (Figures 3, 6.1 and 6.2). In the deep-

waters at South station Calanoid copepods dominated the region of the water column between 80 – 40 m and experienced peaks in densities on October 24th and November 7th that were consistent with seasonal total zooplankton trends. Other major zooplankton taxa between 80 – 40 m did not demonstrate similar seasonal trends, although relatively high densities did occur on November 7th (Figure 3, 7.1 and 7.2).

Zooplankton composition over the fall season in 2011 varied between North and South stations and among the shallow- and deep-waters at South station, although the total abundance at each station was dominated by Calanoid copepods, copepod nauplii, Harpacticoid copepods, and Larvaceans (Tables 3.1, 3.2 and 3.3). Calanoid copepods were more dominant at the South station than at the North station and accounted for 67% and 45% of the total composition, respectively; in contrast, copepod nauplii were more dominant at the North station than at the South station and accounted for 33% and 19% of the total composition, respectively (Table 3.1). Harpacticoid copepods and Larvaceans were more dominant at the North station than at the South station; these major zooplankton taxa accounted for 9% and 10% of the total composition at North station and 5% and 6% at the South station, respectively. At both North and South stations, other holoplankton taxa

accounted for 1%, and meroplankton taxa accounted for 2%, of the total composition.

The abundance of Calanoid copepods and copepod nauplii was highly variable between North and South stations and among the shallow- and deep-waters of South station (Figures 8 and 9). The North station was characterized by lower average abundances of Calanoid copepods ($1,794/m^3$) and higher average abundances of copepod nauplii ($1,215/m^3$), whereas the South station was characterized by higher average abundances of Calanoid copepods ($4,937/m^3$) and lower average abundances of copepod nauplii ($681/m^3$) (Figure 8). The shallow-waters of the South station were characterized by lower average abundances of Calanoid copepods ($4,292/m^3$) and higher average abundances of copepod nauplii ($1,488/m^3$), whereas the deep-waters were characterized by higher average abundances of Calanoid copepods ($7,240/m^3$) and higher average abundances of copepod nauplii ($250/m^3$).

The composition of other holoplankton taxa at both North and South stations was dominated by Cyclopoid copepods and Hyperiid amphipods, where Cyclopoid copepods dominated the South station and Hyperiid amphipods dominated the North station (Table 3.2). At the South station, Cyclopoid copepods were present in

significantly higher abundances in the deep-waters between 80 – 40 m, while Hyperiid amphipods were found in significantly higher abundances in the shallow-waters between 40 – 0 m. The composition of additional holoplankton taxa did not vary significantly between North and South stations, as they were present in relatively low abundances.

The composition of meroplankton taxa did not vary significantly between North and South stations, as meroplankton in general were present in relatively low abundances (Figure 3.3). North and South stations were dominated by barnacle nauplii, gastropods and polychaetes, each of which occurred in similar relative abundances between sample areas. Polychaetes, however, were present in significantly higher abundances in the deep-waters of South station between 80 – 40 m.

Diversity, fall 2011

Values derived from Shannon-Wiener Index calculations indicated that both North and South stations were characterized by low taxa diversity and low taxa evenness (Table 4). The index values reveal that North station was more diverse than the South station, with diversity index values of 0.78 and 0.46, respectively.

The shallow- and deep-waters of South station showed similarly low taxa diversity and evenness, with diversity index values of 0.30 and 0.21, respectively.

Physical oceanographic variables, fall 2011

Results from simple linear regression analysis revealed weak correlations between average zooplankton density and physical oceanographic variables such as temperature, salinity and dissolved oxygen. Linear regressions of average temperature and zooplankton density at the North station and within the shallow- and deep-waters of South station showed no significant correlation, with R^2 -values of 0.03, 0.09 and 0.09, respectively (Figure 10). Correlation coefficients between average salinity and zooplankton density across all stations similarly indicated weak correlations, with R^2 -values of 0.02, 0.26 and 0.04, respectively (Figure 11). Dissolved oxygen and zooplankton density also exhibited weak correlations across all stations, with R^2 -values of 0.29, 0.10 and 0.32, respectively (Figure 12).

Results from simple linear regression analysis also revealed generally weak correlations between physical oceanographic variables and zooplankton diversity, but indicated slightly stronger relationships. Linear regressions of average temperature and zooplankton diversity at the North station and within the shallow-

and deep-waters of South station showed moderate correlation, with R^2 -values of 0.71, 0.62 and 0.32, respectively (Figure 13). Correlation coefficients between salinity and zooplankton diversity indicated weak correlations, with R^2 -values of 0.02, 0.08 and 0.6, respectively (Figure 14). Dissolved oxygen and zooplankton density also exhibited weak correlations at the North station at and the deep-waters at South station, with R^2 -values of 0.23 and 0.10, respectively; the shallow-waters of South station indicated a slightly stronger correlation, with an R -value of 0.48 (Figure 15).

Tidal variation, fall 2011

Seasonal variations in zooplankton abundance at North and South stations often correspond with tidal variation, although this relationship was not seen across sample areas (Table 5). The highest zooplankton densities at the North station, which occurred on October 18th, November 1st and November 15th, correspond with spring flood tides (Figure 4). In contrast, the highest densities in the deep-waters of the South station, which occurred on October 7th, October 24th and November 7th, correspond with neap flood tides (Figures 7.1 and 7.2). Similar patterns between high zooplankton density and tidal variation were not observed when the entire

water column at South station is considered, or within the shallow-waters at South station (Figures 5.1 – 6.2).

Organisms of interest, fall 2011

The percentage of copepods with significant oil storage indicated that the number of copepods in diapause in the San Juan Channel increased over the fall season in 2011, with lower percentages at the North station and higher percentages at the South station (Figure 16). The greatest occurrences of copepods in diapause were on November 15th at North and South stations, with percentages of 19.2% and 40.1%, respectively.

Calcareous organisms were observed in generally low abundances in the San Juan Channel over the fall season in 2011 (Table 3.3). Gastropods were present in similar abundances between North and South stations, where they accounted for 23% of the total meroplankton composition. Pteropods were present in lower abundances at both stations, accounting for <1% of the total meroplankton abundance.

DISCUSSION

Seasonal and interannual variation, 2007 - 2011

Results from comparisons of total zooplankton abundance from 2007 to 2011 indicated that zooplankton density was highly variable seasonally and interannually, and that the variability of zooplankton abundance experienced in the San Juan Channel during the 2011 fall season was not unique to this year (Figures 1 and 2). Seasonal zooplankton abundance appeared to be associated with the Fall Transition, the period in the season in which winds shift from being northerly to predominately southerly and cause a shift from coastal upwelling to coastal downwelling, in conjunction with shift from offshore to onshore Ekman transport (Bernard 2010). The Fall Transition may be influencing zooplankton abundance in the San Juan Archipelago, as intermediate Fall Transition dates most strongly corresponded with higher zooplankton densities (Table 1). This relationship seems to indicate a possible optimal window of Fall Transition timing during which conditions are conducive to sampling high zooplankton densities in the San Juan Archipelago. Years with earlier or later fall transitions both had lower zooplankton densities than those years in the mid October range.

The observation of significantly higher zooplankton abundances at the South station in the San Juan Channel was consistent throughout the fall season in 2011

and consistent with trends in previous years (Abernethy 2009, Kenney 2008).

Distinctly higher abundances of holoplankton at the South station may be attributed to skewing of the data due to disproportionately high Calanoid copepod abundance (Figure 5.1). Comparisons between North and South stations produce considerably different results for holoplankton abundance when Calanoid copepods were excluded from analysis of community composition. Excluding Calanoid copepods reveals that other holoplankton densities were greater at the North station in general, indicating that South station abundance was skewed by the presence of Calanoid copepods (Figures 4 – 5.2).

Throughout the fall season in 2011, differences in the abundance of meroplankton between the North and South stations of the San Juan Channel are not significant, although previous studies have found that total meroplankton abundance was generally higher at the North station (Kenney, 2008) (Table 2).

Tidal variation, fall 2011

Tidal forcing also appeared to exhibit a significant influence on zooplankton abundance in the San Juan Channel, particularly on the abundance of Calanoid copepods and copepod nauplii. At the North station, high zooplankton densities

were consistently found during spring flood tides while high densities at the deep-waters at the South experienced high zooplankton density during neap flood tides. This association of higher zooplankton densities with certain tidal phases affected only affecting the 80 – 40 m region of the water column at the South station; whether this was true for North cannot be assessed since samples of the whole water column were taken instead of stratified samples. The results of this study are contrary to those of Abernethy (2009) in which Calanoid copepods were observed in higher abundances during high exchange ebb tides. Observations by Zamon (2002) are consistent with these findings but were sampled North of the sill at Cattle Pass, much farther North of our South station. Zamon hypothesized that copepods from the Strait of Juan de Fuca were being advected into the San Juan Channel during flood tides.

Depth variation at South station, fall 2011

In highly stratified waters at the South station, the highest abundances of zooplankton were observed in deeper waters between 80 – 40 m, where colder, denser, saltier water from the Strait of Juan de Fuca is mixed into the San Juan Channel during flood tides (Table 2). Flooding tides enter the southern region of the

San Juan Channel as a laminar boundary layer, where friction occurs and reduces vertical mixing. Although less vertical mixing occurs during flood tides, moderate turbulence may still occur in the benthos and re-suspend zooplankton from the region above the boundary layer higher up into the water column. Higher abundances of Calanoid copepods observed in the deep-waters are consistent with findings by Zamon (2002), where copepods were observed in significantly higher abundances near or below the pycnocline. Samples for the current study were taken primarily above and below the pycnocline in the Southern region of the San Juan Channel where tidal mixing is minimal. This sample area was South of the sill near Cattle Pass, which creates turbulence and tidal mixing (Thomas, 2011).

It is also noteworthy that the distribution of juvenile and adult copepods was strongly associated with depth at the highly stratified waters at the South station (Tables 2 – 3.1; Figures 6.1 – 7.2). The distribution of copepod nauplii was strongly associated with the depth of the pycnocline, as results indicated that higher abundances of copepod nauplii occurred within the upper 40 m of the water column at South station. In contrast, higher abundances of Calanoid copepods were observed in the lower 80 – 40 m of the water column. One possible explanation for the difference in copepod community distribution is diel vertical migration behavior

between respective life history stages. Nauplii and other small juvenile copepods may live in surface waters with greater light intensity because they are less vulnerable to visual predators. In estuarine environments horizontal movements accomplish tidal and diel vertical migrations for earlier copepod life stages due to their limited mobility (Goncalves et al., 2011). Calanoid and Cyclopoid copepod nauplii are generally found in higher densities near the surface, while later stage copepodites stayed deeper in the water column (Titelman and Fiksen, 2004). Vertical migration patterns therefore seem to be closely related to physical parameters such as depth, which may determine the distribution of copepod communities between respective life stages.

North and South variation, fall 2011

The distribution of copepod nauplii and adult Calanoid copepods between North and South stations may not be attributed to behavioral patterns in diel vertical migration, although North-South differences may be associated with copepod diapause (Figures 8 – 9). During juvenile development, copepods undergo facultative diapause that is characterized by partial arrests in development and reductions in metabolism and respiration (Hirche, 1996). This life history strategy,

in which copepods vertically migrate to depth, enables copepods to avoid adverse seasonal conditions and high predation risk. Copepods enter a diapause stage at different times and at different intensities, as influenced by environmental conditions (Aruda et al., 2011). The differential timing of copepod diapause is likely associated with their exposure to stressors in open waters, which includes turbulence and mixing (Aruda et al., 2011). The observation that fewer copepods in diapause were present at the North station suggests that oceanic input from the Strait of Georgia that creates vigorous mixing acts as a stressor to later stage copepod larvae. In contrast, higher percentages of copepods in diapause at the South station suggest that stratified waters provide a more stable environment at depth with fewer stressors. The observations of higher percentages of copepods in diapause at the South station in this study are consistent with a previous study by Duckwall (2010), although the influence of turbulence on copepod diapause was not considered in that study.

Diversity, fall 2011

The result that both North and South stations were characterized by low taxa diversity and evenness is heavily influenced by disproportionately high abundances

of Calanoid copepods and copepod nauplii (Table 2). This same result may possibly be due to the limitations of analytical methods for calculating taxa diversity. It is possible that diversity index values would have been greater if organisms were classified by the taxonomic rank of Species rather than Class to normalize measurements across taxon. Biodiversity can be measured more accurately when organisms are classified to more specific taxonomic levels because this avoids skewing the data toward broader levels. For example, in this study, some of the most abundant zooplankton taxa, including Calanoid copepods, Harpacticoid copepods and copepod nauplii, were classified together under Maxillopoda, which is a broad and diverse class of crustaceans. Future studies that include diversity indices may benefit from identifying organisms to the most specific taxonomic level possible to ensure that measurements of biodiversity are accurate.

Physical oceanographic variables, fall 2011

Results from simple linear regression analyses suggest that average temperature, salinity and dissolved oxygen were not reliable indicators of average zooplankton abundance in the San Juan Channel during the fall season in 2011 (Figures 10 – 15). It is evident that weak correlations existed between each of these

variables because zooplankton abundance was highly variable and within a broad range of densities. In contrast, physical parameters such as temperature, salinity and dissolved oxygen were relatively stable and within a narrow range of values. Although research by suggests that temperature and salinity are important environmental factors affecting the seasonal and spatial distribution of copepods in marine environments, Calanoid copepod species found in estuarine environments are often well adapted to seasonal fluctuations in temperature and salinity and therefore have broad tolerance ranges for both parameters (Miller and Marcus, 1994; Ohs et al., 2010). It is therefore possible that that Calanoid copepods species exhibited broad tolerance ranges for temperature and salinity in the San Juan Channel during the fall season this year.

The result that weak correlations existed between zooplankton abundance and physical oceanographic variables was possibly due to the limitations of only considering average zooplankton densities. Further investigations could improve on existing work by considering additional biological implications for zooplankton associated with fluctuations in physical parameters. It is possible that biological and behavioral responses to changes in temperature and salinity differ between various holoplankton and meroplankton taxa, including changes in the rates and efficiencies

in metabolism, activity, growth and reproduction (Lougee et al., 2002), none of which were considered in this study.

Organisms of interest

Research strongly suggests that the Puget Sound estuary may have a unique status with respect to ocean acidification, as patterns in low pH and aragonite saturation are largely due to the combined affects of natural mixing, circulation and biological activity (Feely, et al. 2010). Research also strongly suggests that calcifying organisms that produce shells or skeletons with calcium carbonate minerals (e.g., calcite, aragonite) are particularly susceptible to the combined affects of ocean acidification (Feely et al., 2009). This study aims to begin monitoring the presence of calcareous organisms, although additional analyses are needed to understand trends in interannual and seasonal abundance and the potential impacts of ocean acidification.

CONCLUSIONS

Trends in total zooplankton abundance from 2007 to 2011 indicated that zooplankton density was highly variable seasonally and interannually, and that the

variability of zooplankton abundance experienced in the San Juan Channel during the 2011 fall season was not unique to this year. Significantly higher zooplankton abundances at the South station in the were consistent throughout the fall season in 2011 and consistent with trends in previous years, although distinctly higher abundances of holoplankton at the South station may be attributed to disproportionately high Calanoid copepod abundance. The percent composition of meroplankton taxa was relatively similar between North and South stations.

Tidal forcing appeared to exhibit significant influence Calanoid copepods and copepod nauplii in the San Juan Channel, where spring flood tides influenced the North station and neap flood tides influenced the South station at depth. Depth variation with respect to juvenile and adult copepods is possibly due to behavior patterns in diel vertical migration and respective life history strategies. Additional North-South differences between juvenile and adult copepods may be associated with copepod diapause, as oceanic input from the Strait of Georgia creates vigorous mixing and acts as a potential stressor that inhibits later stage copepod larvae from entering diapause.

North and South stations were characterized by low taxa diversity and evenness, likely due to disproportionately high abundances of Calanoid copepods at

both stations. Other possible reasons for low diversity and evenness may be attributed to limitations of analytical methods for calculating taxa diversity.

Average temperature, salinity and dissolved oxygen were not reliable indicators of average zooplankton abundance in the San Juan Channel during the fall season in 2011, possibly because copepods, which accounted for the majority of total zooplankton abundance, exhibited broad tolerance ranges for temperature and salinity in the San Juan Channel during the fall season this year.

Calcareous organisms occurred in low abundances in the San Juan Channel during the fall season this year, although trends in interannual and seasonal abundance and the potential impacts of ocean acidification on these organisms is not well understood.

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TABLES

Seasonal and interannual variation, 2007 – 2011

Table 1 Fall transition dates and relative total zooplankton abundance over the fall season, 2007 – 2011 (Five-point scale is based on the average abundance per year, in which higher values indicated higher average densities)

Fall Transition	Year	North Station	South Station
Sept. 15	2011	1 (3,372/m ³)	3 (6,342/m ³)
Oct. 15	2009	3 (5,657/m ³)	4 (7,506/m ³)
Oct. 17	2007	5 (8,184/m ³)	5 (11,248/m ³)
Oct. 26	2010	4 (6,145/m ³)	1 (4,096/m ³)
Nov. 1	2008	2 (4,507/m ³)	2 (5,098/m ³)

Abundance and composition, fall 2011

Table 2 Total average densities for major zooplankton taxa at North and South stations over the fall season, 2011

Organism	North station	South station	South: 40 – 0 m	South: 80 – 40 m	%
Calanoid copepod	1,794/m ³	4,937/m ³	4,292/m ³	7,240/m ³	73.3%
Copepod nauplii	1,215/m ³	681/m ³	1,488/m ³	250/m ³	14.6%
Harpacticoid copepod	322/m ³	293/m ³	242/m ³	385/m ³	5.0%
Larvaceans	368/m ³	256/m ³	235/m ³	130/m ³	4.0%
Other holoplankton	46/m ³	71/m ³	132/m ³	160/m ³	1.6%
Meroplankton	82/m ³	105/m ³	83/m ³	111/m ³	1.5%

Table 3.1 Composition of major zooplankton taxa at North and South stations over the fall season, 2011 (Values in parentheses represent raw data for the number of individuals at each station)

Organism	North station	South station	South: 40 – 0 m	South: 80 – 40 m
Calanoid copepod	45% (430,068)	67% (786,793)	69% (396,626)	87% (668,938)
Copepod nauplii	33% (312,891)	19% (229,186)	23% (130,882)	3% (23,126)
Harpacticoid copepod	9% (80,944)	5% (58,748)	<1% (2,508)	5% (35,547)
Larvaceans	10% (92,657)	6% (64,802)	4% (21,735)	2% (12,049)
Other holoplankton	1% (11,382)	1% (12,769)	2% (11,722)	2% (14,673)
Meroplankton	2% (20,934)	2% (22,984)	2% (8,312)	1% (10,374)

Table 3.2 Composition of other holoplankton taxa at North and South stations over the fall season, 2011 (Values in parentheses represent raw data for the number of individuals at each station)

Organism	North station	South station	South: 40 – 0 m	South: 80 – 40 m
Chaetognath	13% (1,436)	10% (1,237)	19% (2,282)	9% (1,372)
Cladocera	1% (166)	1% (164)	0% (0)	0% (0)
Ctenophore	<1% (3)	<1% (10)	<1% (1)	<1% (4)
Cyclopoid copepod	33% (3,771)	51% (6,523)	20% (2,283)	62% (9,138)
Gammarid amphipod	3% (303)	1% (165)	0% (0)	<1% (40)
Hyperiid amphipod	38% (4,362)	19% (2,424)	56% (6,525)	20% (2,873)
Isopod	6% (641)	8% (1,037)	4% (455)	5% (667)
Medusa	<1% (54)	1% (85)	<1% (21)	3% (429)
Ostracod	2% (200)	3% (351)	<1% (8)	<1% (1)
Pteropod	<1% (3)	0% (0)	0% (0)	<1% (1)
Siphonophore	4% (445)	6% (775)	1% (147)	1% (149)

Table 3.3 Composition of meroplankton taxa at North and South stations over the fall season, 2011 (Values in parentheses represent raw data for the number of individuals at each station)

Organism	North station	South station	South: 40 – 0 m	South: 80 – 40 m
Barnacle nauplii	29% (5,977)	23% (5,300)	32% (2,546)	28% (2,664)
Bipinnaria	2% (377)	4% (932)	4% (300)	0% (0)
Bivalve larvae	7% (1,486)	3% (653)	6% (456)	3% (300)
Brachyuran megalops	<1% (17)	<1% (39)	<1% (27)	<1% (26)
Brachyuran zoea	<1% (71)	1% (100)	<1% (26)	1% (49)
Decapods	1% (78)	1% (191)	2% (147)	1% (66)
Echinoplutues larvae	11% (2,304)	10% (2,173)	15% (1,182)	0% (0)
Gastropod	23% (4,860)	23% (5,292)	19% (1,537)	22% (2,065)
Polychaete	24% (5,050)	28% (6,411)	20% (1,655)	45% (4,275)
Shrimp zoea	<1% (4)	<1% (15)	<1% (10)	<1% (21)
Tadpole larvae	3% (705)	7% (1,650)	2% (201)	0% (0)
Trochophore	<1% (3)	0% (0)	0% (0)	0% (0)

Diversity, fall 2011

Table 4 Zooplankton diversity values (H-values) at North and South stations over the fall season, 2011 (H-values derived from Shannon-Wiener Diversity Index calculations)

Station	Oct. 7	Oct. 18	Oct. 24	Nov. 1	Nov. 7	Nov. 15	Mean (H)
North	1.41	1.00	1.15	0.40	0.43	0.29	0.78
South	0.44	0.62	1.02	0.17	0.34	0.19	0.46
40-0 m	0.43	0.30	0.44	0.36	0.25	0.04	0.30
80-40 m	0.43	0.12	0.15	0.25	0.19	0.11	0.21

Tidal variation, fall 2011

Table 5 Tidal variations across sample dates during the fall season in 2011

Station	Oct. 7	Oct. 18	Oct. 24	Nov. 1	Nov. 7	Nov. 15
North	Neap flood	Spring flood	Neap ebb	Spring flood	Neap flood	Spring flood
South	Neap flood	Spring slack	Neap flood	Spring ebb	Neap flood	Spring ebb

FIGURES

Interannual variation, 2007 – 2011

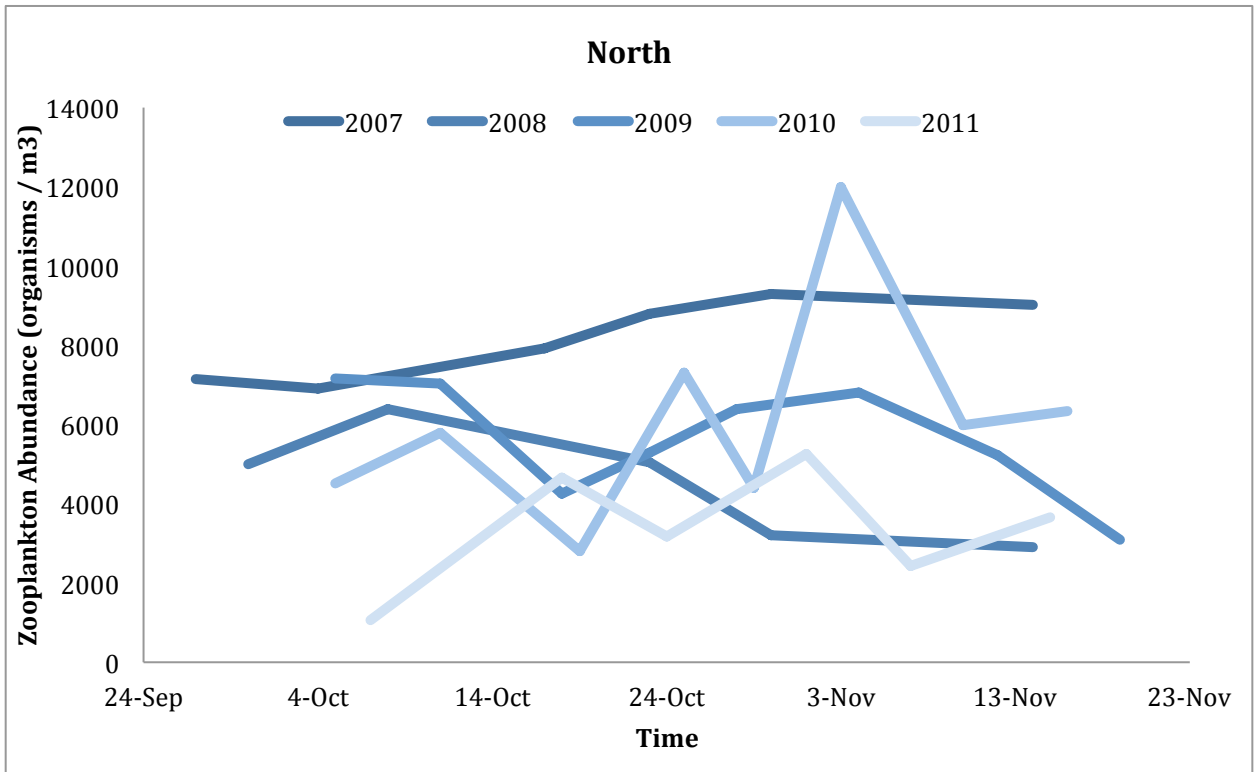


Figure 1 Total zooplankton abundance at North station over the fall season, 2007 – 2011

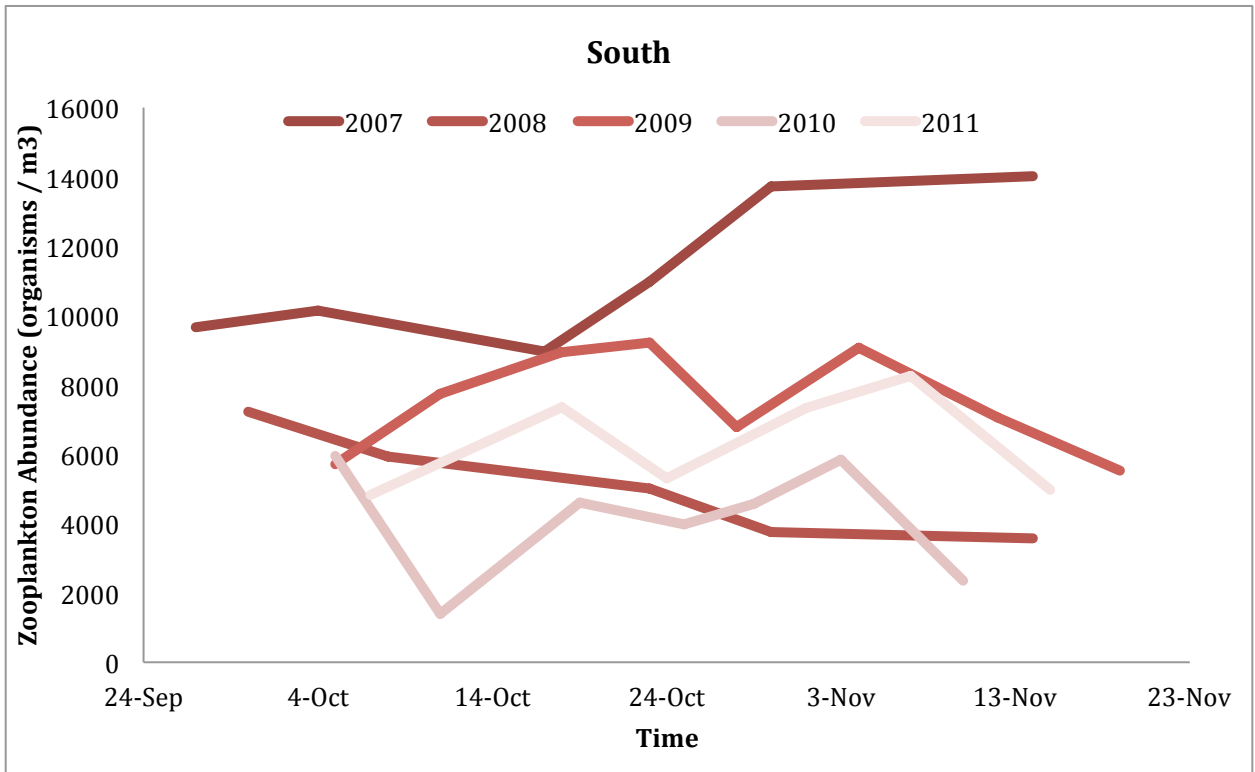


Figure 2 Total zooplankton abundance at South station over the fall season, 2007 – 2011

Abundance and composition, fall 2011

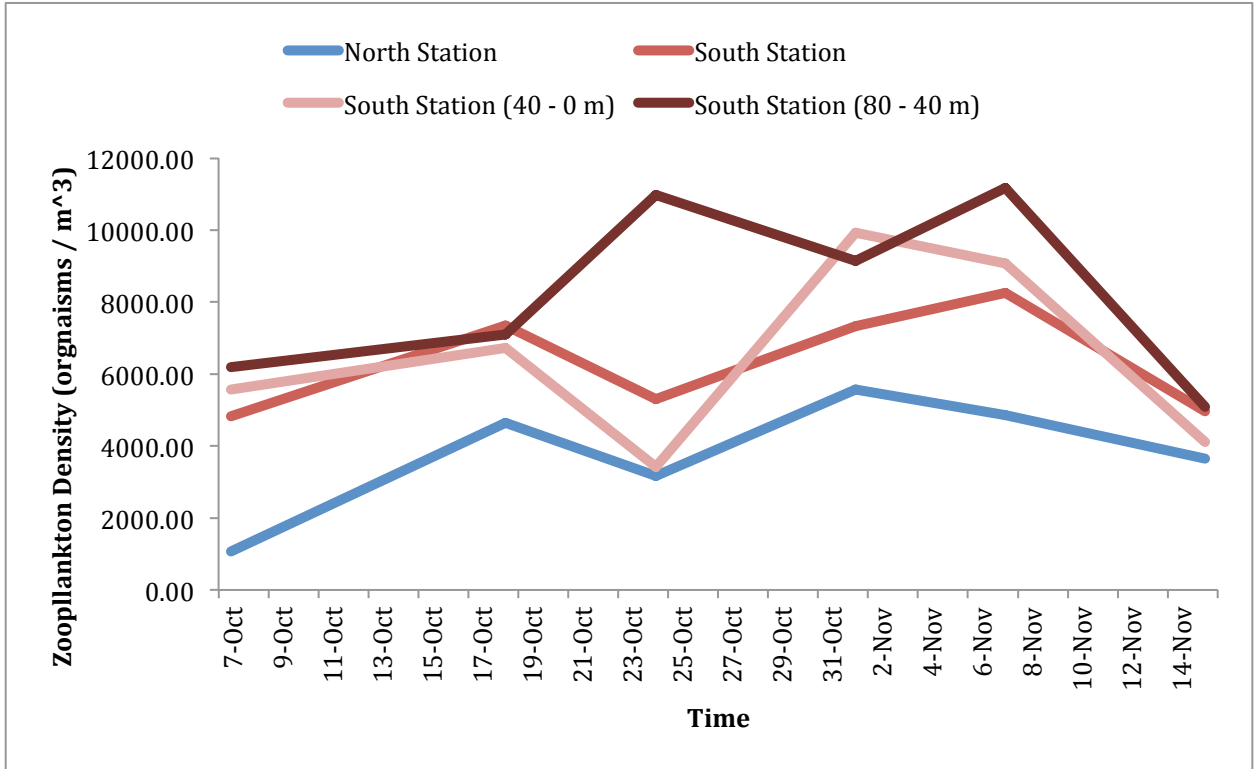


Figure 3 Total zooplankton abundance in the San Juan Channel over the fall season, 2011

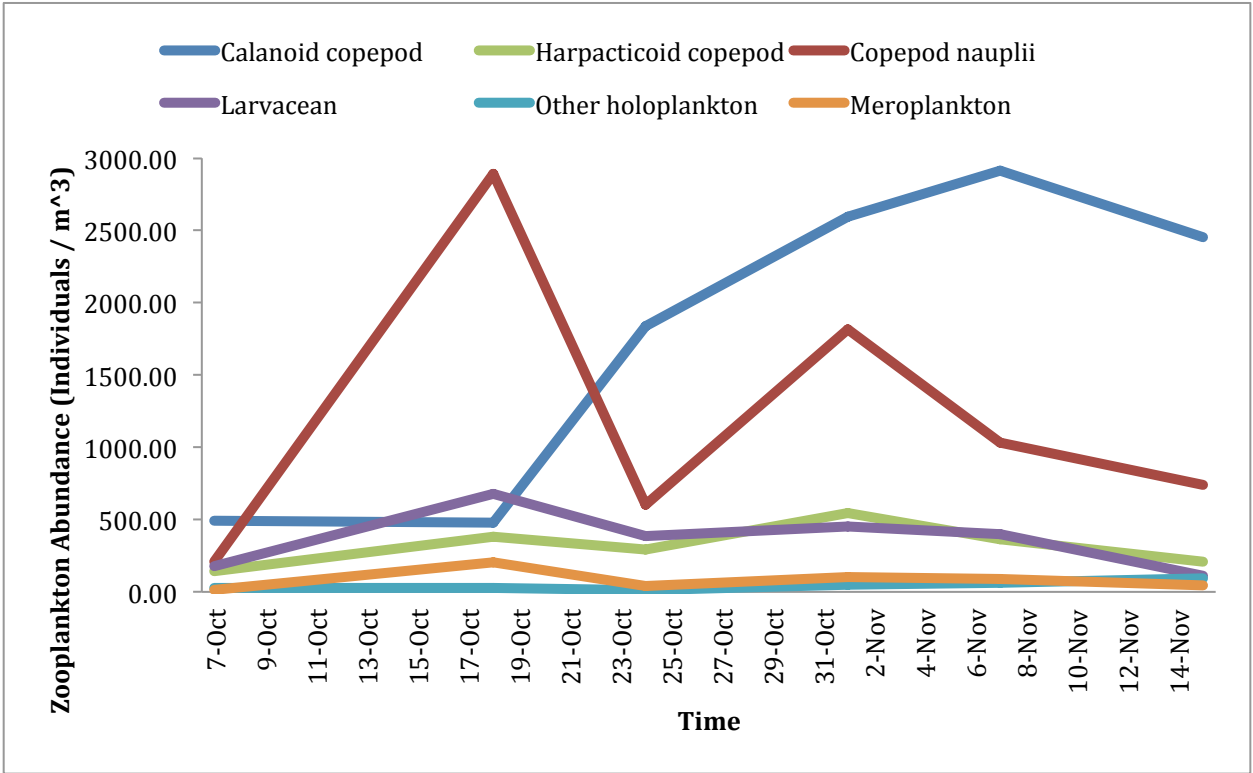


Figure 4 Abundance of major zooplankton taxa at North station over the fall season, 2011

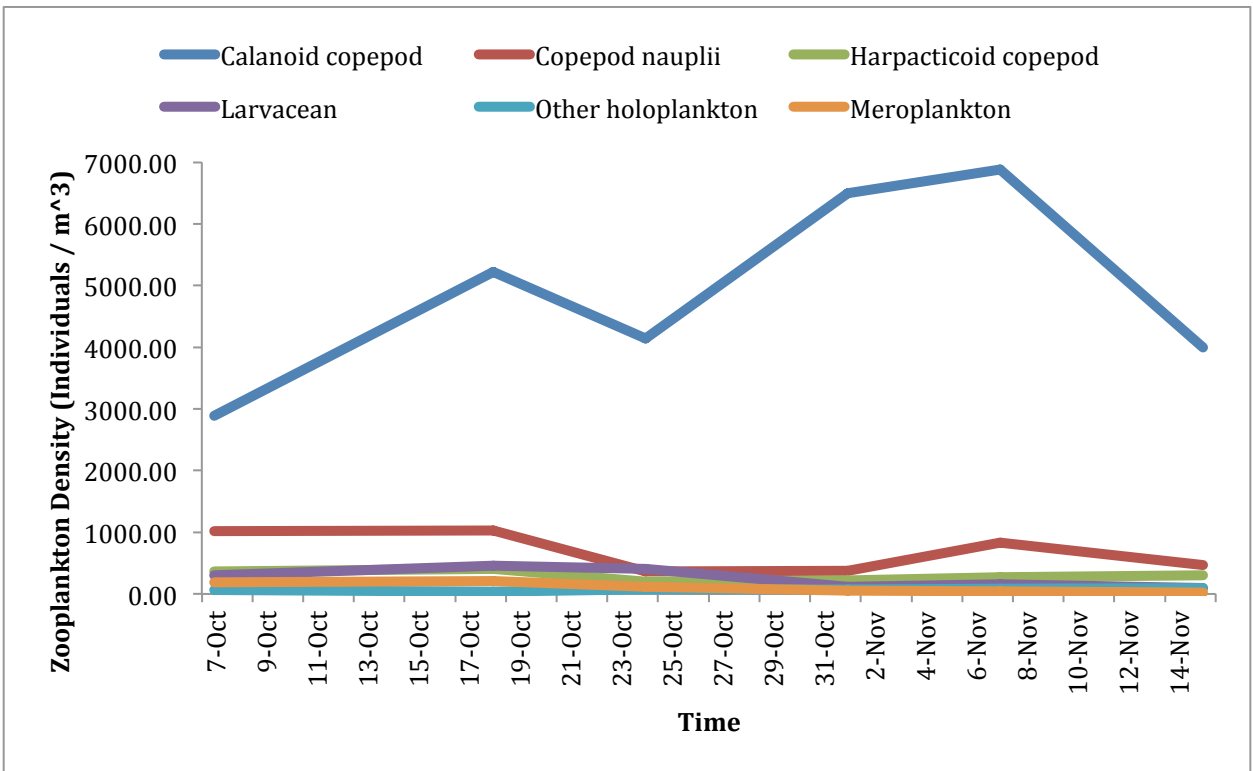


Figure 5.1 Abundance of major zooplankton taxa at South station over the fall season, 2011

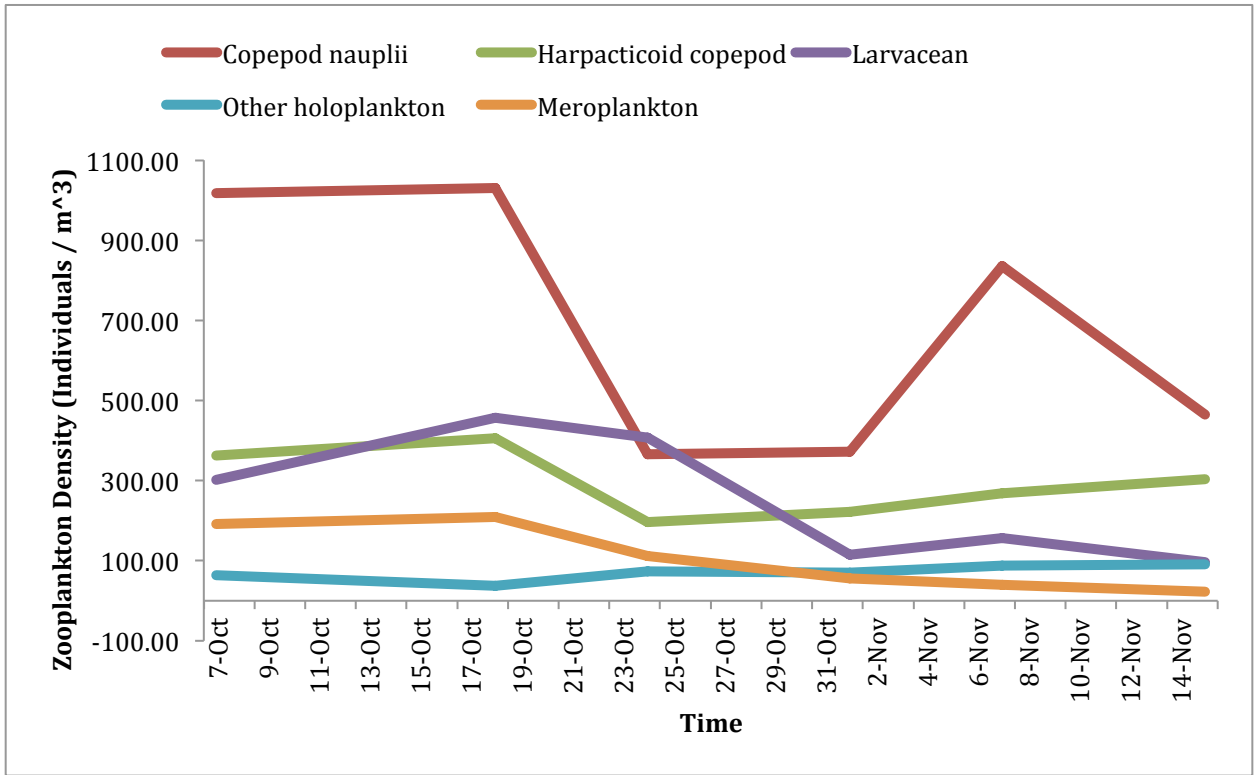


Figure 5.2 Abundance of major zooplankton at South station over the fall season, 2011 (Scale adjusted to exclude Calanoid copepods)

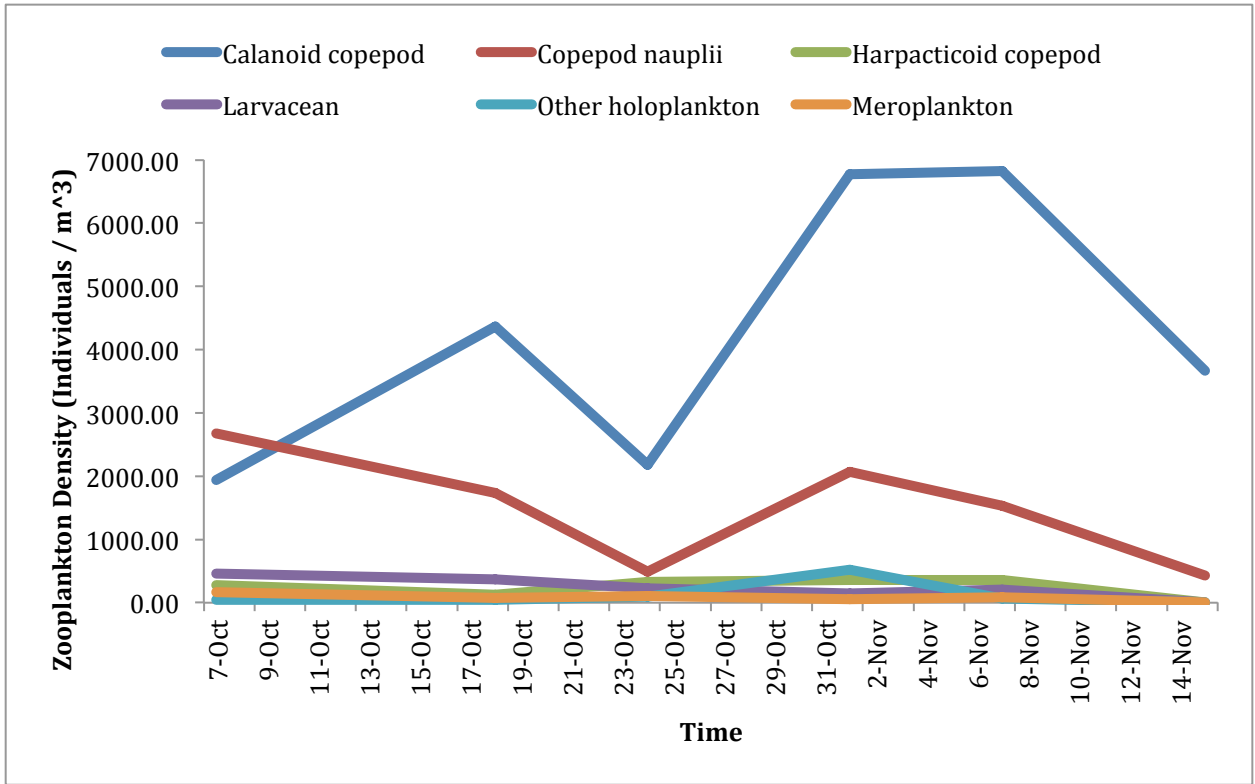


Figure 6.1 Abundance of major zooplankton taxa in the shallow waters at South station (40 - 0 m) over the fall season, 2011

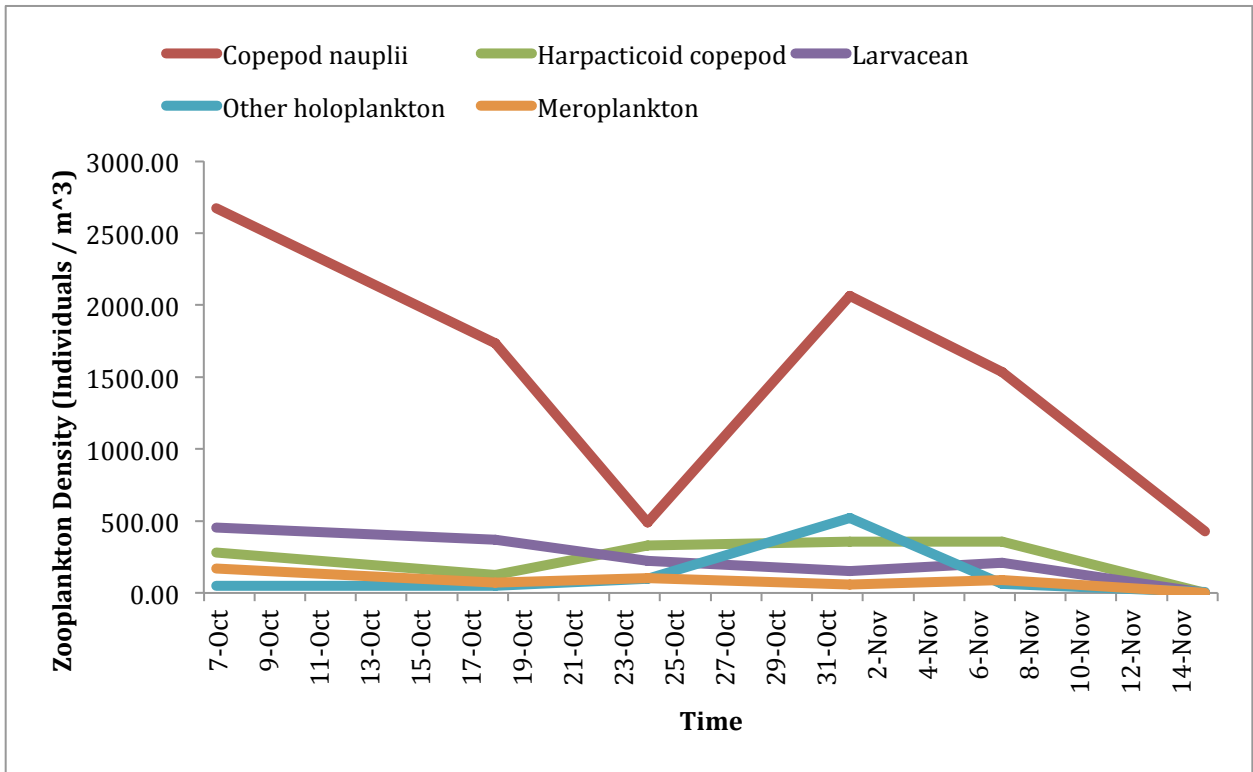


Figure 6.2 Abundance of major zooplankton taxa in the shallow waters at South station (40 – 0 m) over the fall season, 2011 (Scale adjusted to exclude Calanoid copepods)

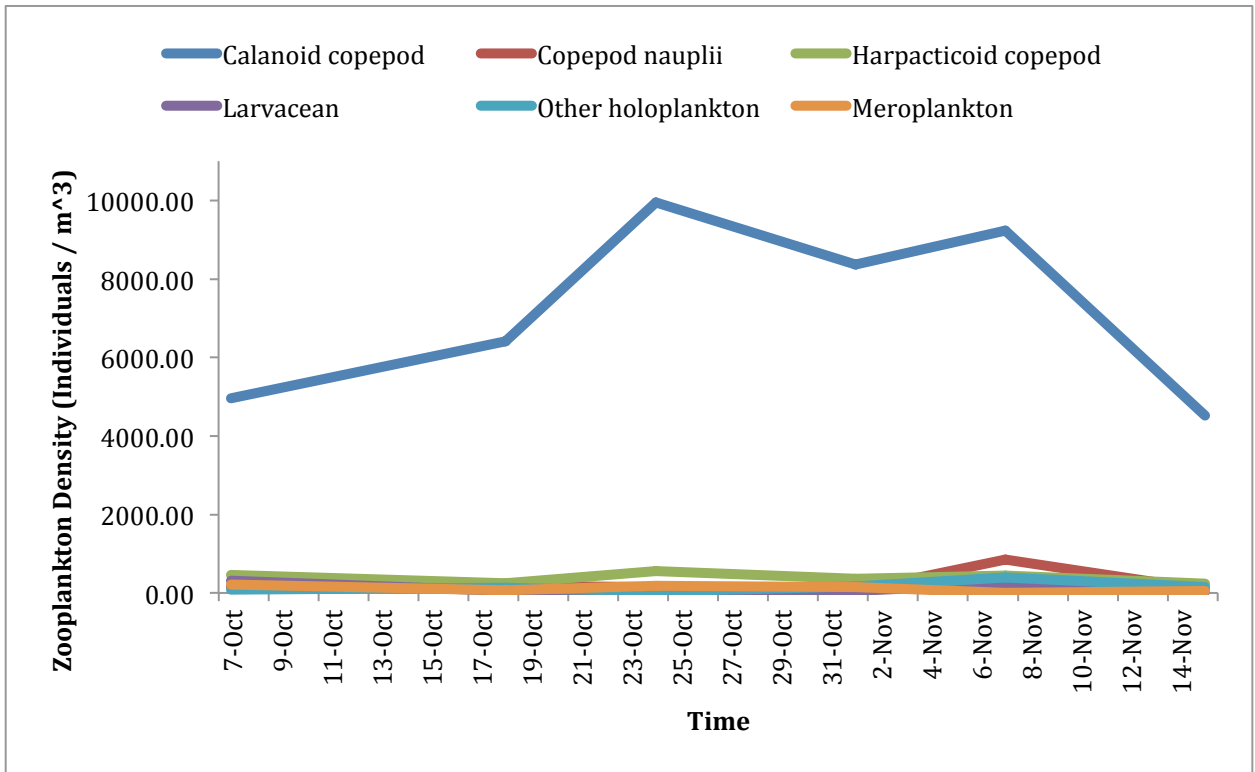


Figure 7.1 Abundance of major zooplankton taxa in the deep waters at South station (80 – 40 m) over the fall season, 2011

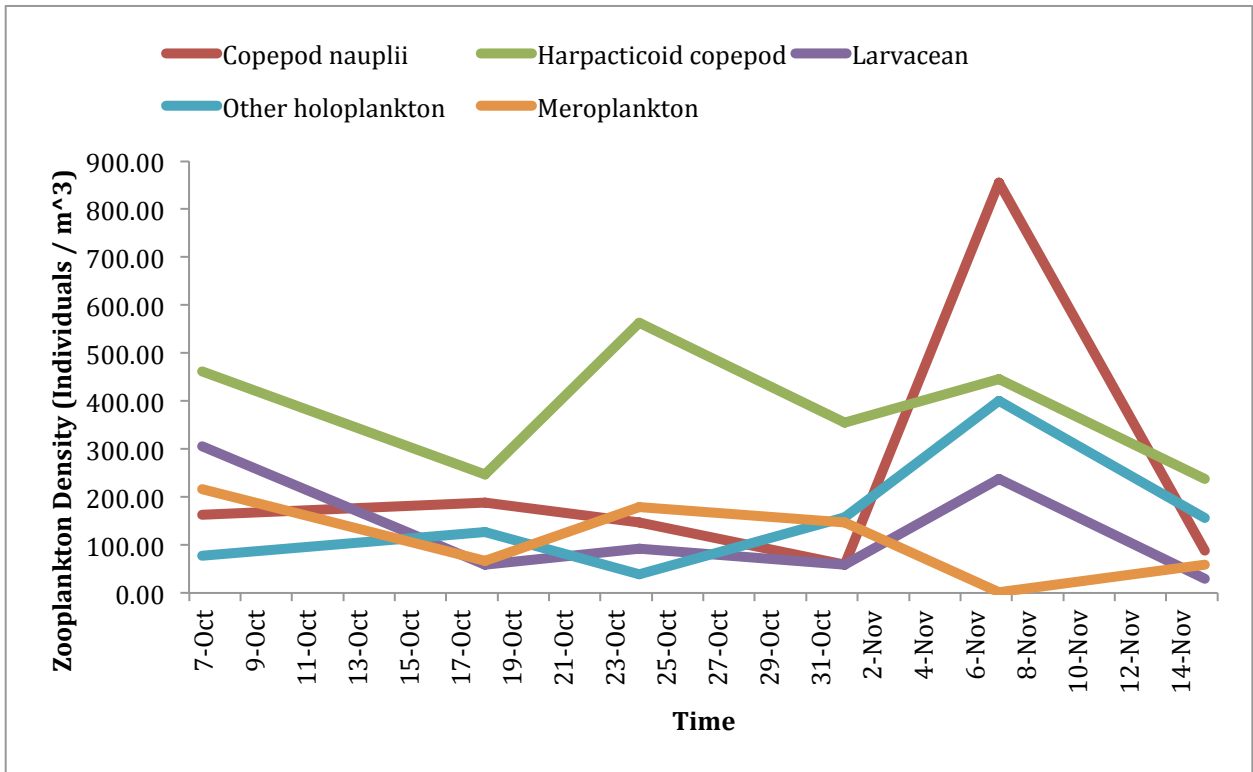


Figure 7.2 Abundance of major zooplankton taxa in the deep waters at South station (80 – 40 m) over the fall season, 2011 (Scale adjusted to exclude Calanoid copepods)

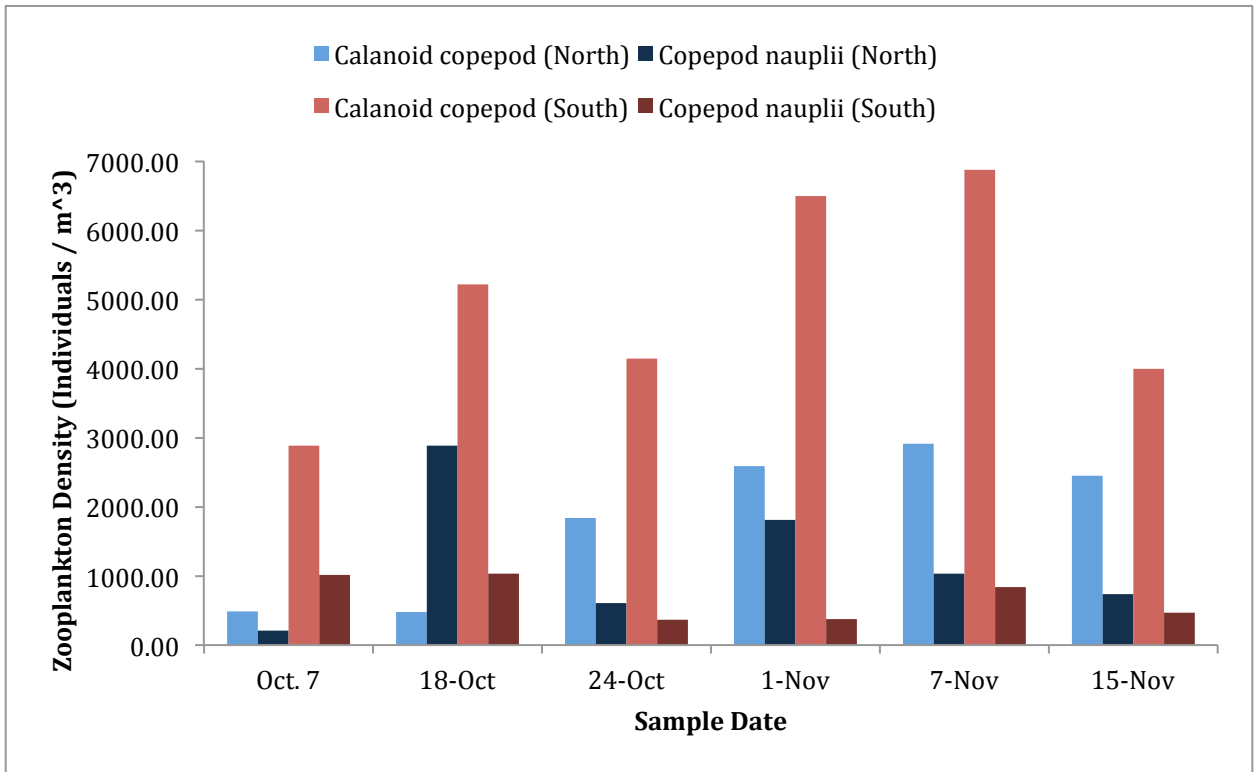


Figure 8 Abundance of Calanoid copepods and copepod nauplii at North and South stations across sample dates during fall season, 2011

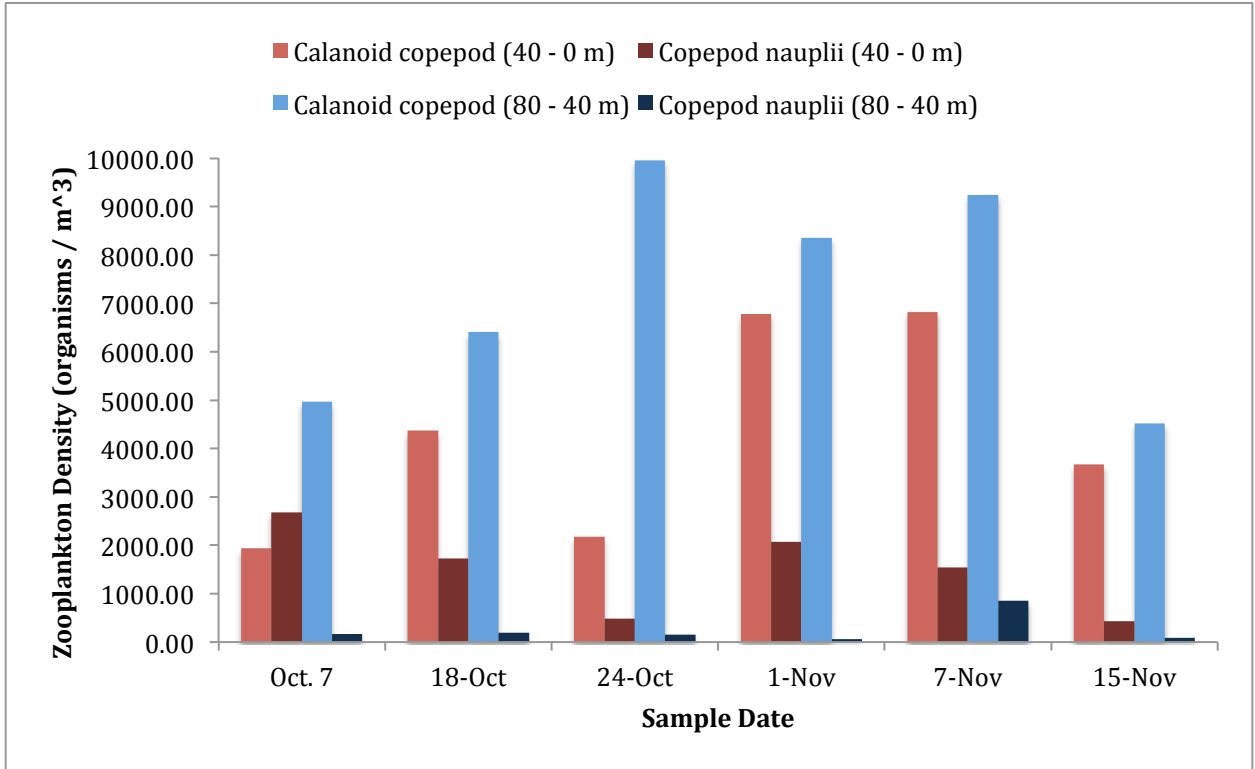


Figure 9 Abundance of Calanoid copepods and copepod nauplii at in shallow and deep waters (40 – 0 m; 80 – 40 m) at South station across sample dates during the fall season, 2011

Physical oceanographic variables, fall 2011

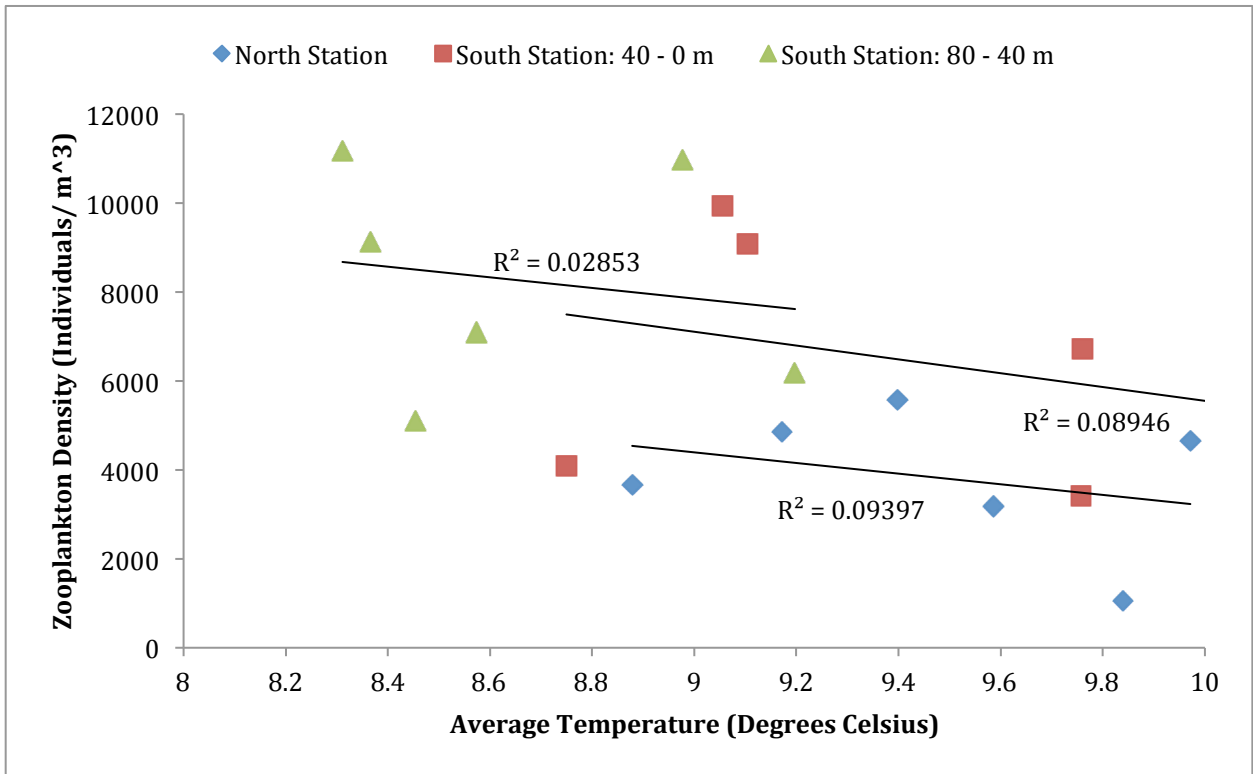


Figure 10 Simple linear regression of average temperature and zooplankton density in the San Juan Channel over the fall season, 2011

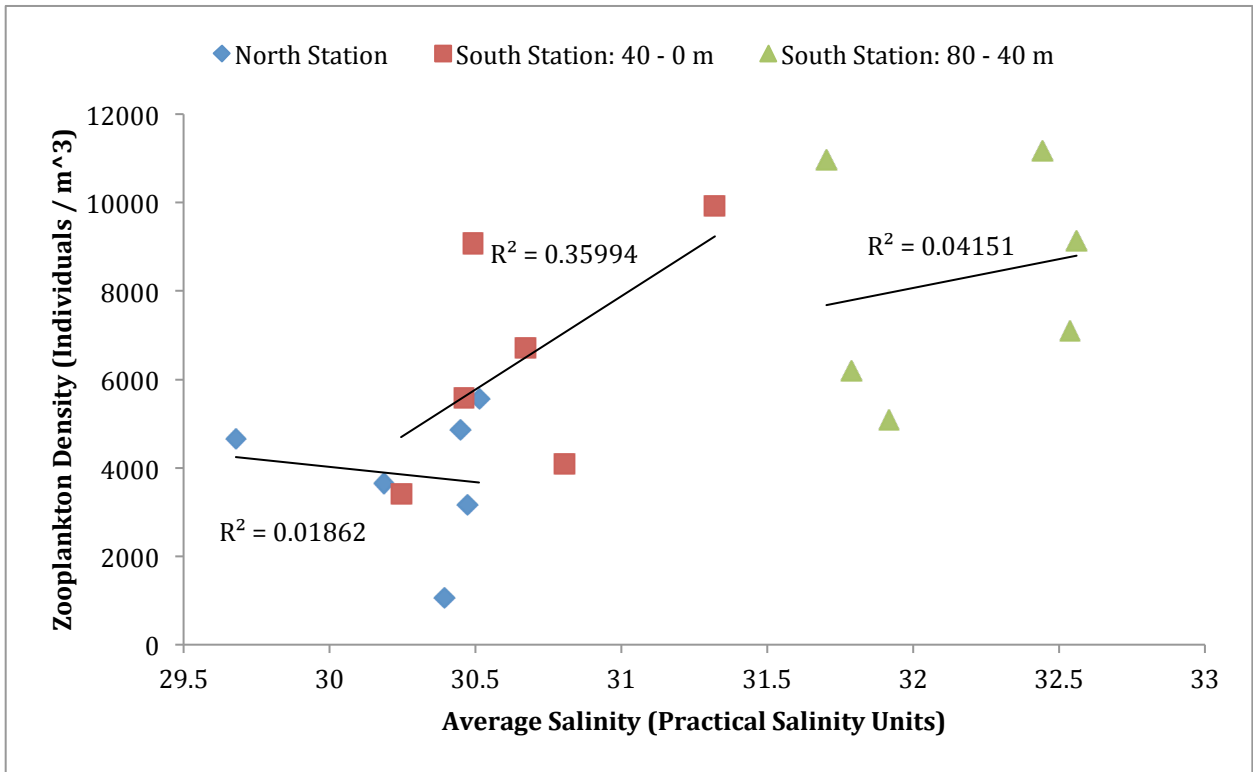


Figure 11 Simple linear regression of average salinity and zooplankton density in the San Juan Channel over the fall season, 2011

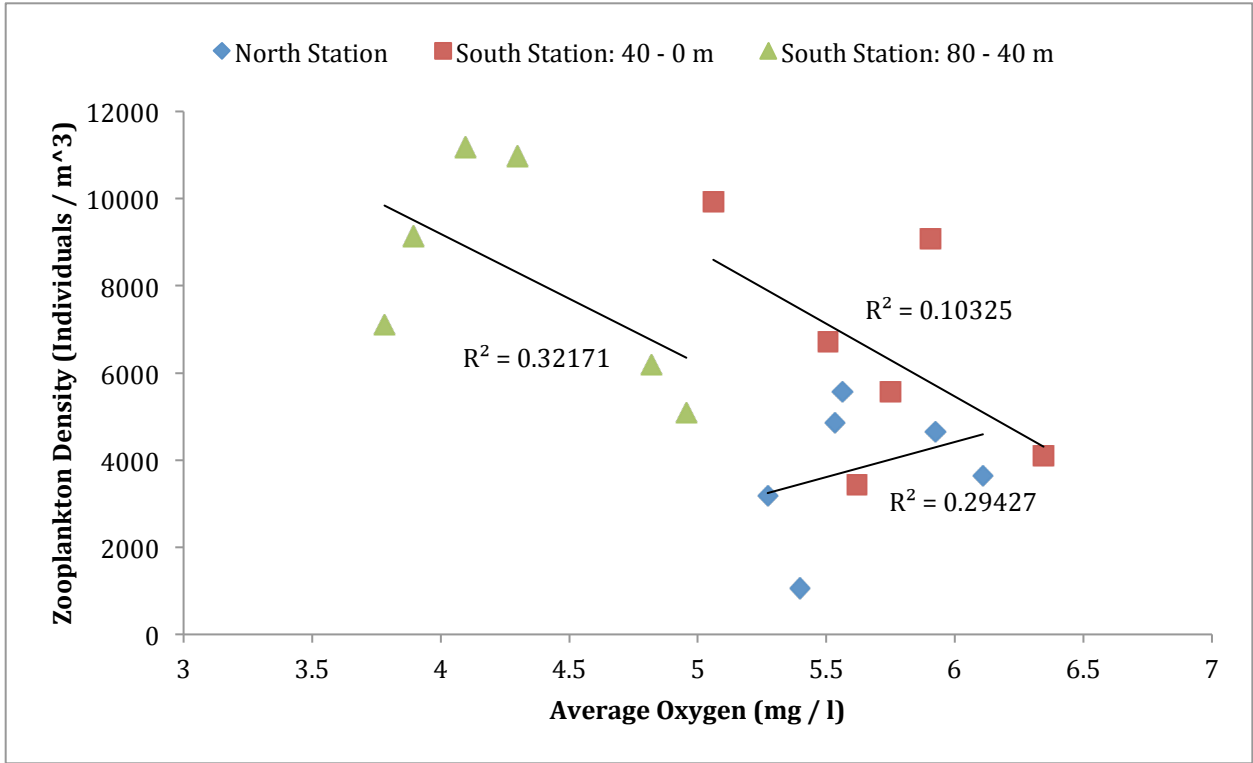


Figure 12 Simple linear regression of average dissolved oxygen and zooplankton density in the San Juan Channel over the fall season, 2011

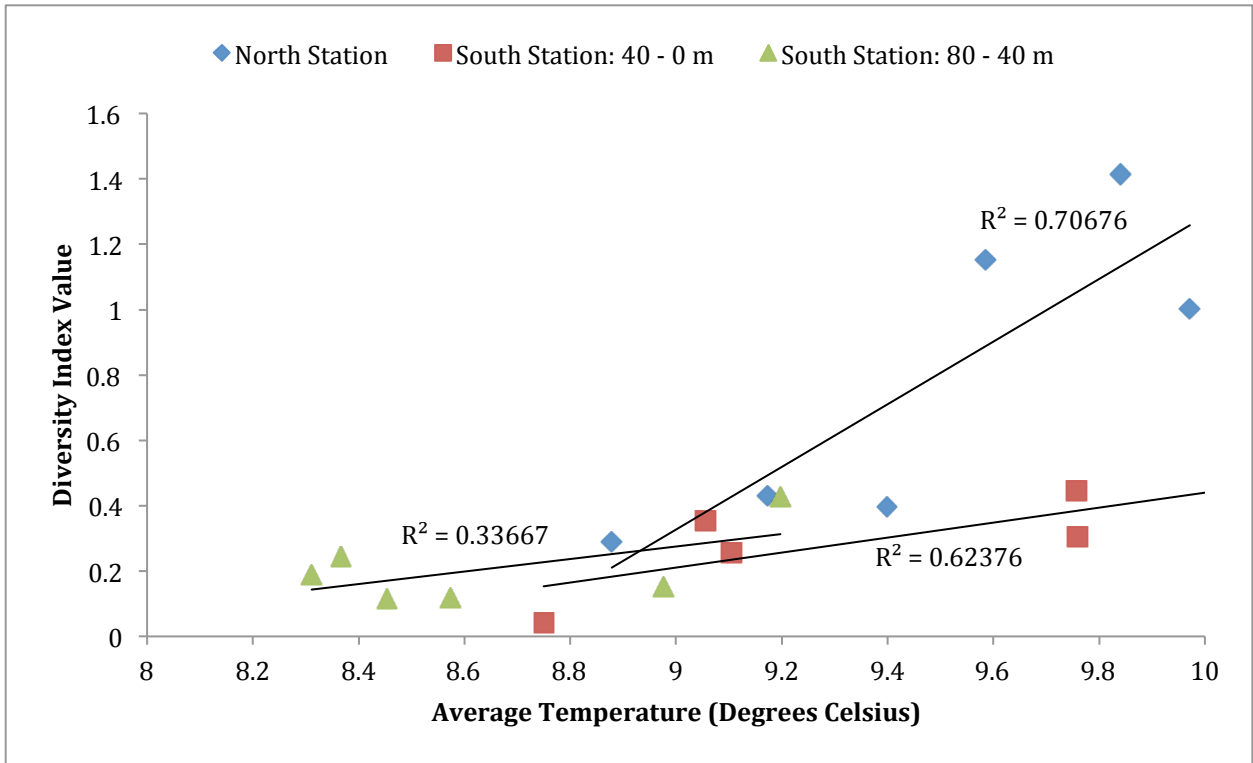


Figure 13 Simple linear regression of average temperature and zooplankton diversity in the San Juan Channel over the fall season, 2011

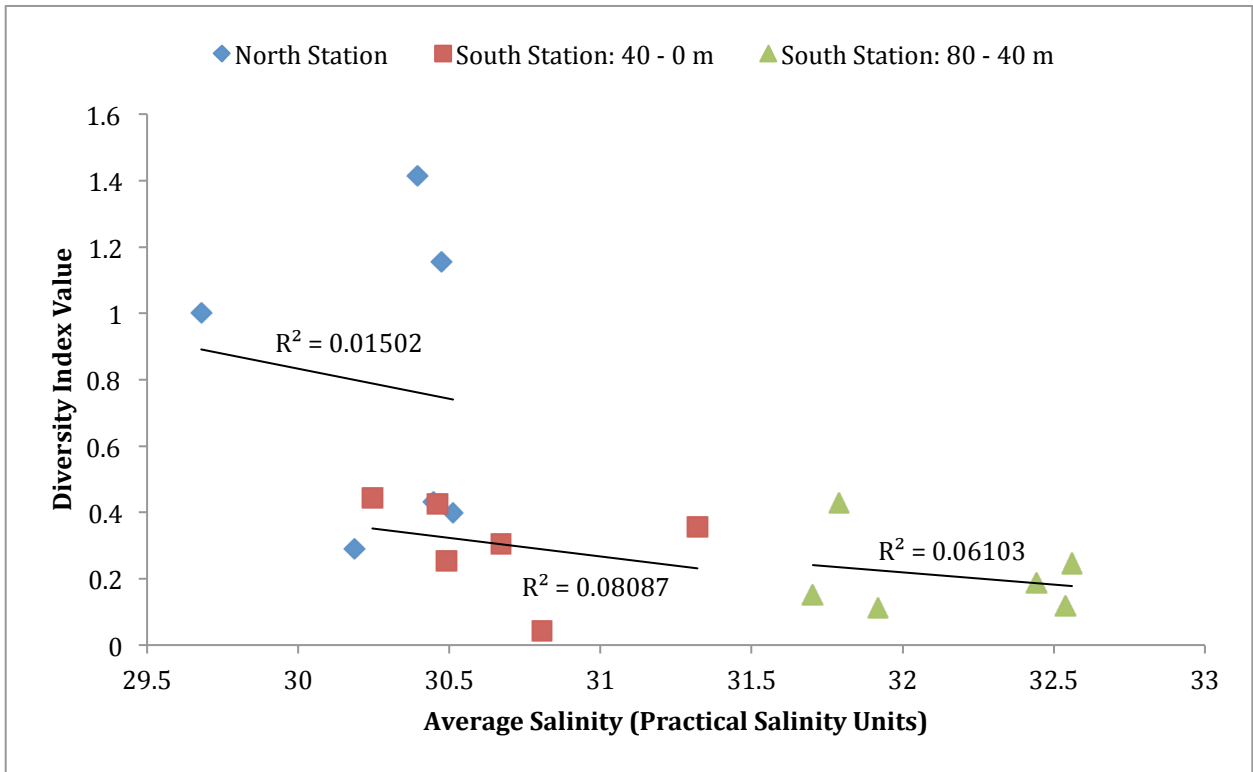


Figure 14 Simple linear regression of average salinity and zooplankton diversity in the San Juan Channel over the fall season, 2011

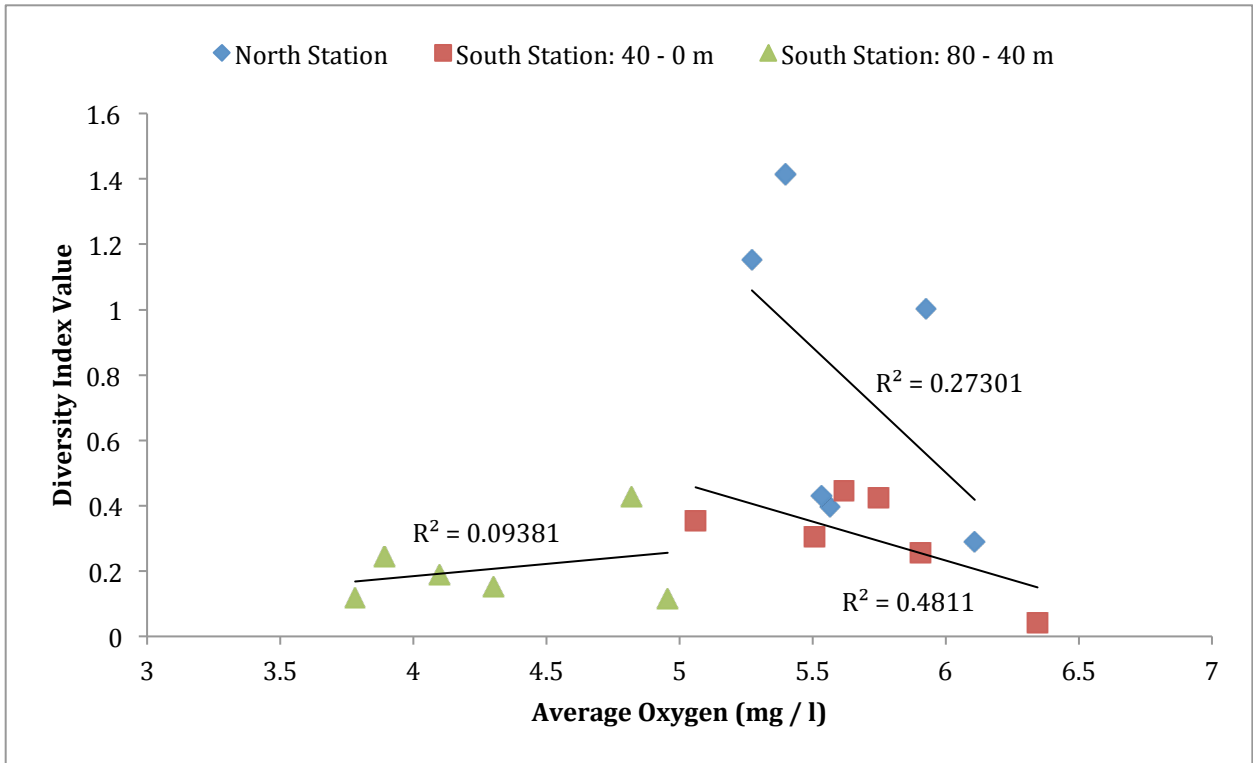


Figure 15 Simple linear regression of dissolved oxygen and zooplankton diversity in the San Juan Channel over the fall season, 2011

Organisms of interest

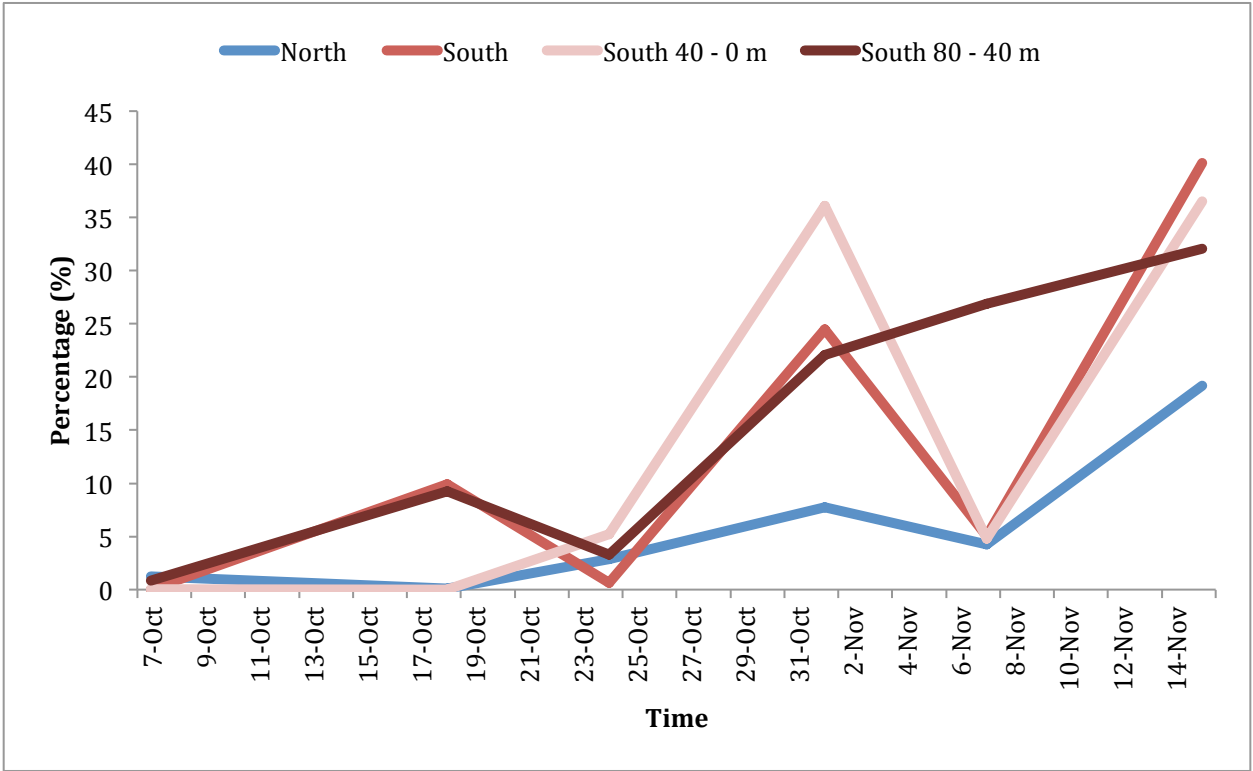


Figure 16 Percentage of copepods with in diapause in the San Juan Channel over the fall season, 2011