

# Copepod abundance and distribution in San Juan Channel, Washington: Tidal effects

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## *Abstract*

Copepods are a highly important group of organisms to local and global ecosystems and carbon cycles. By linking trophic levels and exporting production, copepods have great cumulative effect on the fate of biogenic carbon and energy. Copepod abundance across fall 2012 was measured at two stations in the San Juan archipelago, WA, a highly productive and tidally complex region. Using these data and past measurements from the University of Washington's Pelagic Ecosystem Function research apprenticeship, a pattern was shown linking higher-than-average copepod abundance with sampling that followed a flood tide. Tidal currents seem to interact with complex shallow bathymetric features near stations in the north and south end of San Juan Channel to create areas of high copepod abundance following flooding tides. These patterns suggest mechanisms influencing aggregations of animals in higher trophic levels (fish, seabirds, mammals).

## *Introduction*

Zooplankton communities play an important role in marine ecosystems, serving as a major trophic link between primary planktonic producers and secondary consumers. Copepods are the dominant zooplankton in many marine systems, and may be earth's most numerically abundant animals (Ohman and Hirche 2001). Their great numbers and ubiquity make copepods an extremely important group for marine ecosystem function, trophic interactions, and the global carbon cycle (Zamon 2000, Urban-Rich 1999). Because much of the energy and biomass from primary production passes through the copepod community to reach higher trophic levels, understanding of variations in the

copepod community is vital to tracking trophic interactions through the ecosystem (Zamon 2002).

The waters of the San Juan Archipelago are highly productive and strongly influenced by external and local forces including coastal upwelling, prevailing winds, freshwater and nutrient input from rivers, and tidal mixing (Zamon 2002, Thomson 1981). Coastal upwelling and currents are strong factors influencing productivity of marine systems (Kudela et al. 2008). The topographies of the San Juan Islands create a complex environment for understanding tidal currents and their various effects on marine organisms. The focus of this study was to gain an understanding of the effects of tidal exchange and mixing on copepod abundance and distribution in the fall season. High zooplankton densities attract schooling fish, which in turn draw larger avian and mammalian predators (Zamon 2000).

Plankton are drifters by definition. Incapable of powered swimming against currents, they are transported on wind-driven and tidal currents. In the San Juan Archipelago strong tidal currents interact with complex bathymetries and shore topographies to influence distribution and aggregations of plankton. At the southern entrance to San Juan Channel especially, flooding tidal currents meet with a narrow opening at Cattle Pass and a sharp sill and may form a high concentration of zooplankton (Zamon 2000, 2002, Abernethy PEF 2009). Copepods' diel vertical migration, as described by Dagg (1989), may also be interrupted by vertical movement of water over the Cattle Pass sill during flood tides.

The focus of this study was to investigate possible patterns relating tidal currents to differential densities and distributions of copepods between northern and southern San

Juan Channel. Understanding the effects of tidal currents on copepod densities (as a proxy for overall zooplankton abundance) will lead to greater understanding of the factors driving concentrations of animals in higher trophic levels. This study's objectives were 1) to characterize the changes in copepod populations within this fall at two sites in San Juan Channel, 2) to relate differential abundance to variation in tidal current timing and direction, and 3) to integrate data from past PEF studies of zooplankton with historical tidal data to elucidate a long-term pattern relating tidal forcing with copepod abundances.

## Materials and Methods

### *Sample Collection*

Zooplankton samples were collected on each of seven dates (September 28, October 10, 17, 23, and 30, and November 7 and 14) at two stations in San Juan Channel. The North station lies between San Juan and Orcas Islands (48°35.00' N, 123°02.50' W) and the South station lies south of Cattle Pass, in the Strait of Juan de Fuca (48°25.20' N, 122°56.60' W) (Map 1). Samples were collected by vertical tows from the University of Washington's *R/V Centennial* using a 70cm diameter, 153µm mesh net weighted at the cod end. The net was lowered to 10m above the channel bottom, as measured by a meter block attached to the boom and winch assembly aboard the ship. All tows were assumed to have sampled a cylindrical mass of water, the volume of which was calculated with the equation:

$$V = \pi(r)^2 \times l$$

where  $V$  is the tow volume in  $m^3$ ,  $r$  is the radius of the net mouth in m, and  $l$  is the length in meters of cable from the surface to the net's mouth.

Upon the net's return to the surface, the sides were rinsed with saltwater to ensure that all organisms were collected in the cod end. Each tow's sample was transferred to a jar, fixed with 30mL of buffered formalin (formaldehyde supersaturated with Borax) and stored for future analysis.

### *Zooplankton analysis*

In the lab each sample was filtered with 118 $\mu$ m mesh and rinsed with fresh water to remove formalin. The plankton were resuspended in fresh water and split to 1/2 or 1/4 dilution, depending on perceived density. Each split was diluted to 700mL for counting. Two aliquots of 5mL each were taken from each tow using a Stempel pipette and counted using a square gridded Petri dish, a Nikon SMZ645 dissecting microscope, and a series of laboratory counters. Each individual was identified to lowest taxonomic level possible for addition to the PEF database, but only data for copepods in the orders Calanoida and Cyclopoida, plus copepod nauplius larvae, are presented here.

Total densities for each taxon were calculated using the equation:

$$D = \frac{(N \times s)/(d \times a)}{V}$$

where  $D$  is the density of organisms in individuals/m<sup>3</sup> for each taxon,  $N$  is the total count of organisms in the aliquot counted,  $s$  is the volume in mL of the split sample,  $d$  is the dilution of the split as a fraction of 1,  $a$  is the volume in mL of the aliquot counted, and  $V$  is the total volume of water sampled by the tow net, as calculated above.

### *Tidal data*

Historical and present tide data were obtained from the NOAA Tides and Currents website (<http://tidesandcurrents.noaa.gov>). Tidal level was used for the Friday Harbor location (NOAA Station ID #9449880). Data were obtained for each research cruise from 2007 to 2012.

Each cruise was categorized by the complete tidal flow directly preceding the time of sampling. The two categories used were “Flood” and “Ebb” tides. Thus samples collected at the beginning stages of an ebb tide were categorized as being influenced by the preceding flood tide, and *vice versa*. Samples collected at or near a slack tide were categorized based on the flow directly prior to the time of sampling.

Average copepod abundance for each station was calculated for the fall of each year from 2007 to 2012, based on data in the Pelagic Ecosystem Function database, available online (<http://habu.apl.washington.edu/mayorga/pef/index.html>). An anomaly was then calculated for each cruise date for all years by subtracting the year’s average from the date’s density for each station. Every value with a departure of more than 250 individuals/m<sup>3</sup> from the fall’s mean was counted and categorized by tidal influence (flood or ebb).

### *Results*

Zooplankton abundances showed considerable variability over the course of fall 2012, at and between both stations. Abundance peaked during October, but these peaks fell on different dates for each station. Total zooplankton abundance reached a maximum at the South station on October 10, with a density of 11300 individuals/m<sup>3</sup>. The maximum for the North station occurred on October 17, with a density of 5203

individuals/m<sup>3</sup>. The average zooplankton abundance for the North station was 3573 individuals/m<sup>3</sup> (n=7, SD=1089), while the South station averaged 5589 individuals/m<sup>3</sup> (n=7, SD=2668). Abundances both of zooplankton and copepods were higher at the South station than at the North for each cruise date (Fig. 1).

Copepods made up a majority of individuals in all zooplankton samples at both stations during fall of 2012. Adult calanoid and cyclopoid copepods plus copepod nauplii comprised between 65 and 85% of total zooplankton abundance for all samples, averaging 72% (n=14, SD=5.93). At the North station copepod abundance by week averaged 2507 individuals/m<sup>3</sup> (n=7, SD=749). Copepod abundance averaged by week was 4176 individuals/m<sup>3</sup> at the South station (n=7, SD=2132) (Fig. 2).

Copepod abundance in the fall varied between each year from 2007 to 2012 (Fig. 3 and fig. 4). The North station had the highest copepod abundance in 2007, with an average of 3845 individuals/m<sup>3</sup>. The lowest abundance of copepods at the North station was in 2008, with an average of 1420 individuals/m<sup>3</sup>. For the South station copepod abundance averaged by week was highest for 2011, with an average of 5911 individuals/m<sup>3</sup> (n=6, SD=1529). Zooplankton abundance was lowest at the South station in 2008, with a weekly average of 1822 individuals/m<sup>3</sup> (n=5, SD=401).

Both stations exhibited considerable daily variation from each fall's mean copepod density from 2007 to 2012. The greatest departure from a season's mean was at the South station on October 10, 2012. The anomaly for this date was 4706 individuals/m<sup>3</sup> greater than the mean for 2012. The largest negative anomaly (3110 individuals/m<sup>3</sup> fewer than that year's mean) was on October 29, 2010 at the South station.

At the North station 17 measurements across all years had positive anomalies of greater than 250 individuals/m<sup>3</sup> above the year's mean. Of these samples 70.5% (n=12) occurred following flood tides while 29.5% (n=5) followed ebb tides. The North station had 15 negative anomalies more than 250 individuals/m<sup>3</sup> fewer than the year's average. Of these measurements 40% (n=6) occurred following flood tides, while 60% (n=9) followed ebb tides (Fig. 5).

The South station had 14 measurements across all years studied with positive anomalies greater than 250 individuals/m<sup>3</sup> more than the year's mean. Of these measurements 78.5% (n=11) followed flood tides, while 22.5% (n=3) followed ebb tides. Twenty measurements at the South station had negative anomalies more than 250 individuals/m<sup>3</sup> fewer than the year's average. Of these 50% each followed flood and ebb tides (n=10) (Fig 6).

### *Discussion*

Analysis of zooplankton communities within San Juan Channel exposes several interesting trends while also revealing new questions. Variation within and between years of total abundances of zooplankton and of copepods can likely be explained by a combination of food availability, hydrography, hibernation, and predation, but these relationships are beyond the scope of this study. Rather the objectives of this study were to describe the variation within the local copepod community this fall, to relate these changes to tidal effects, and to integrate past data with historical tide level data to account for some of the variation between measurements within a season.

The abundance and distribution of copepods in San Juan Channel for fall of 2012 is comparable to findings from the Pelagic Ecosystem Function (PEF) research apprenticeship for the years 2007-2011. The peak density at the South station in fall of 2012 (8883 individuals/m<sup>3</sup>) was the highest density seen in the study period. However, the overall mean abundance at the South station (4176 individuals/m<sup>3</sup>) was within the ranges seen in the PEF dataset. Abundance at the North station showed no such extremes in 2012, falling between high and low values for the study period.

Consistent differences between abundances at the two stations indicate variability in factors leading to copepod population growth or aggregation. Again, many of these factors are beyond the scope of this study, but tides have been well-documented to affect zooplankton concentrations (Zamon 2000 and 2002, Abernethy PEF 2009, Dower 2004). The finding that higher-than-average abundances are more frequent following flooding tides at both stations is indicative of tidal forcing of copepods. While Cattle Pass has been studied quite extensively due to its high current velocities and complex bathymetry (e.g. Zamon 2000), the bathymetry at the North station has been largely ignored regarding tidal forcing.

The relatively shallow bottom in Wasp Pass (Map 1) may play a similar role to the sill at Cattle Pass in forcing zooplankton near the surface on flooding tides. Incoming tides flowing over the shallow bottom around Yellow Island likely concentrate zooplankton near the North station. That positive copepod anomalies occurred at the North station twice as frequently (n=12) following flood tides than did negative anomalies (n=6) is strong indication that flooding tides bring with them higher than normal concentrations of copepods. Similarly the finding that positive anomalies

following flood tides at the North station (n=12) outnumber those following ebb tides (n=5) is further support for this hypothesis.

While the interaction between currents and bathymetry at Cattle Pass has been shown by past PEF apprentices to affect zooplankton abundances (e.g. Abernethy 2009, Dykeman 2010, Blackstone 2011), most of these studies were limited to data from just one fall. A combination of data from all years of the PEF program shows more complete trends than are visible within one season. The mechanisms of tidal forcing of copepods at the South station and Cattle Pass are not fully understood. It is clear from these data that a source of copepods exists within the Strait of Juan de Fuca. That the South station consistently has much higher abundances than the North is evidence of this.

Trends relating tidal forcing to copepod abundance at the South station are rather more difficult to elucidate. While positive anomalies following flood tides (n=11) far outnumber those following ebb tides (n=3), no such trend exists for negative anomalies (n=10 following both flood and ebb tides). It is true however that negative anomalies following ebb tides (n=10) outnumber positive anomalies following flood tides (n=3). Two separate mechanisms may be at play at the South station. Vertical forcing over the sill just north of the South station may form aggregations of copepods near the surface by interrupting their daily vertical migrations. These aggregations are likely to be most evident during the early phases of ebb tides following strong flooding currents, when the water mass containing the high density of copepods is advected back towards the sampling point.

The trends addressed here are important for understanding trophic interactions within San Juan Channel and beyond. It has been shown that complex bathymetries and topographies have strong effects on aggregations of zooplankton (Genin 2004), which in turn attract congregations of schooling fish and larger predators (Zamon 2000). Understanding the fine temporal scale variation in zooplankton abundance and density is important to predicting the feeding behavior of animals in higher trophic levels (fish, seabirds, and mammals). This has potential economic applications for commercial fishing or ecotourism.

Zooplankton are also highly important to carbon cycles (Noji 1991). In order to accurately model or predict carbon flux through an ecosystem, we must first understand each trophic level's contribution to the cycle (Noji 1999). Where complex tidal currents exist, it can be more troublesome to accurately model these systems. Dynamic and variable systems therefore require closer study to understand their contributions to the global carbon cycle.

Future research on zooplankton communities within San Juan Channel should build upon the data presented here, including the PEF database and these analyses. More extensive sampling can help clarify, support, or refute the mechanisms proposed here. Sampling on a finer temporal and spatial scale will better reveal bathymetric and tidal influences on copepod abundance, while direct measurement of currents will permit finer calculation of their effects. Together with the existing data, further sampling can lead to better understanding of this complex and unique system.

*Figures*

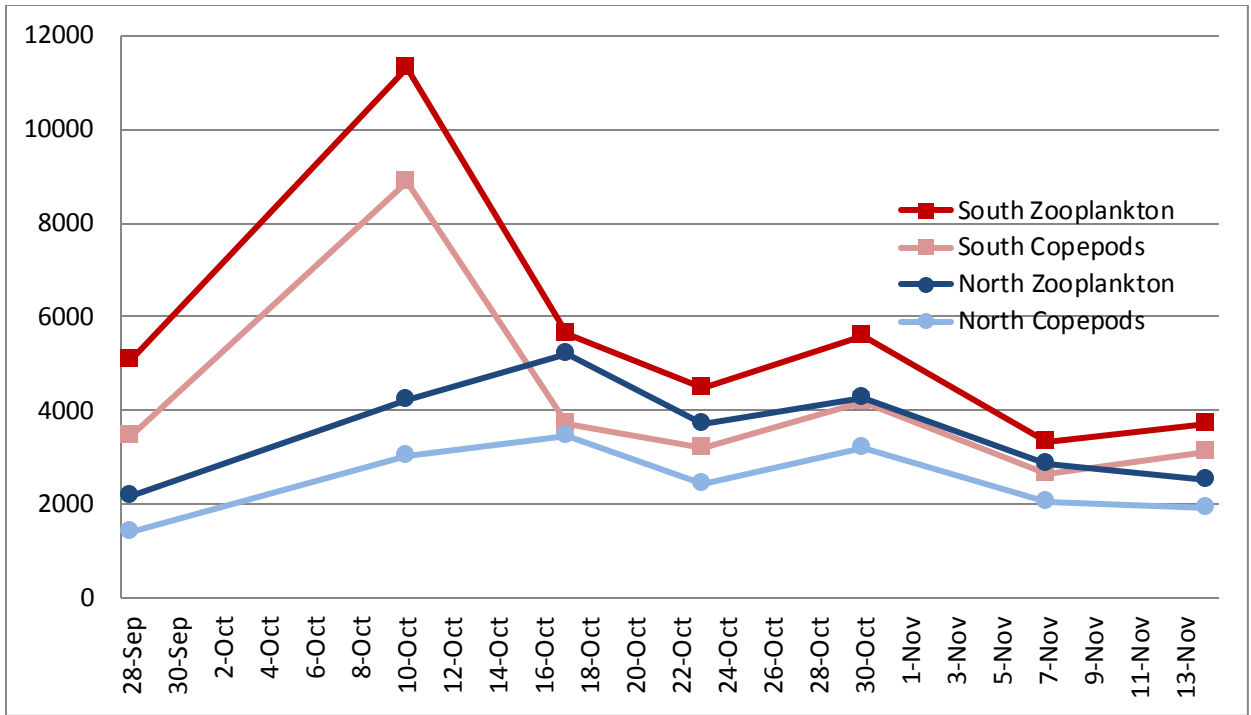


Figure 1. Zooplankton abundance (darker lines) and copepod abundance (lighter lines) for North station (blue) and South station (red) for 7 cruise dates during fall 2012. Abundances are given as individuals/m<sup>3</sup>.

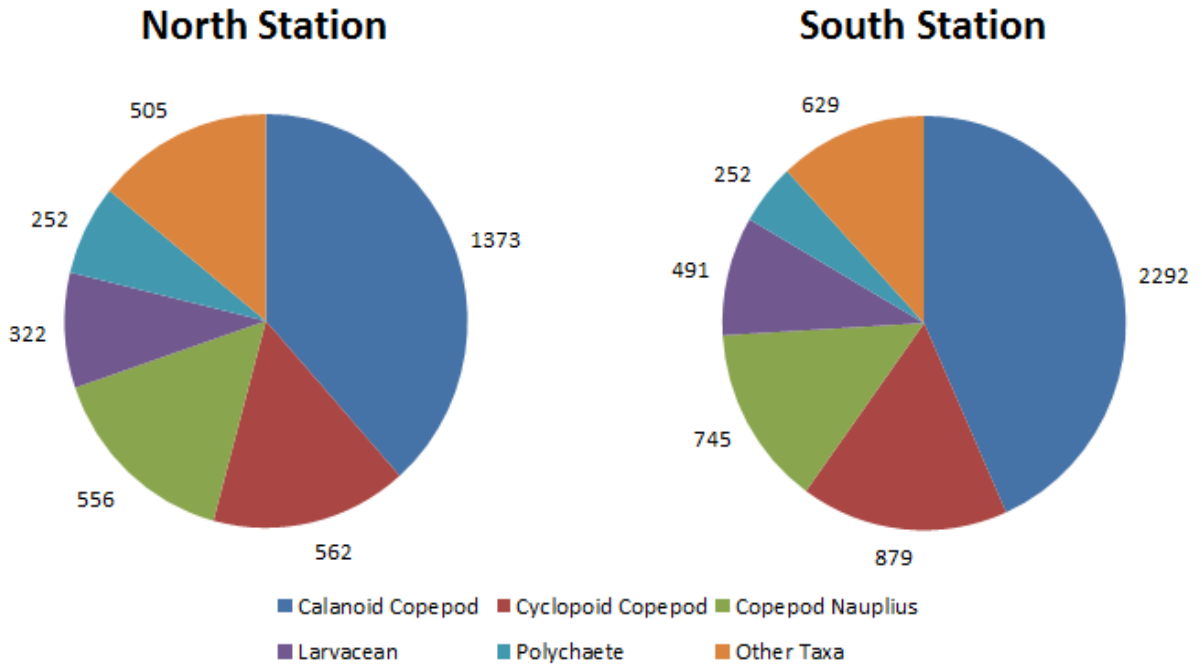


Figure 2. Mean abundance of major taxa of zooplankton for fall 2012. Abundances are given as individuals/m<sup>3</sup>.

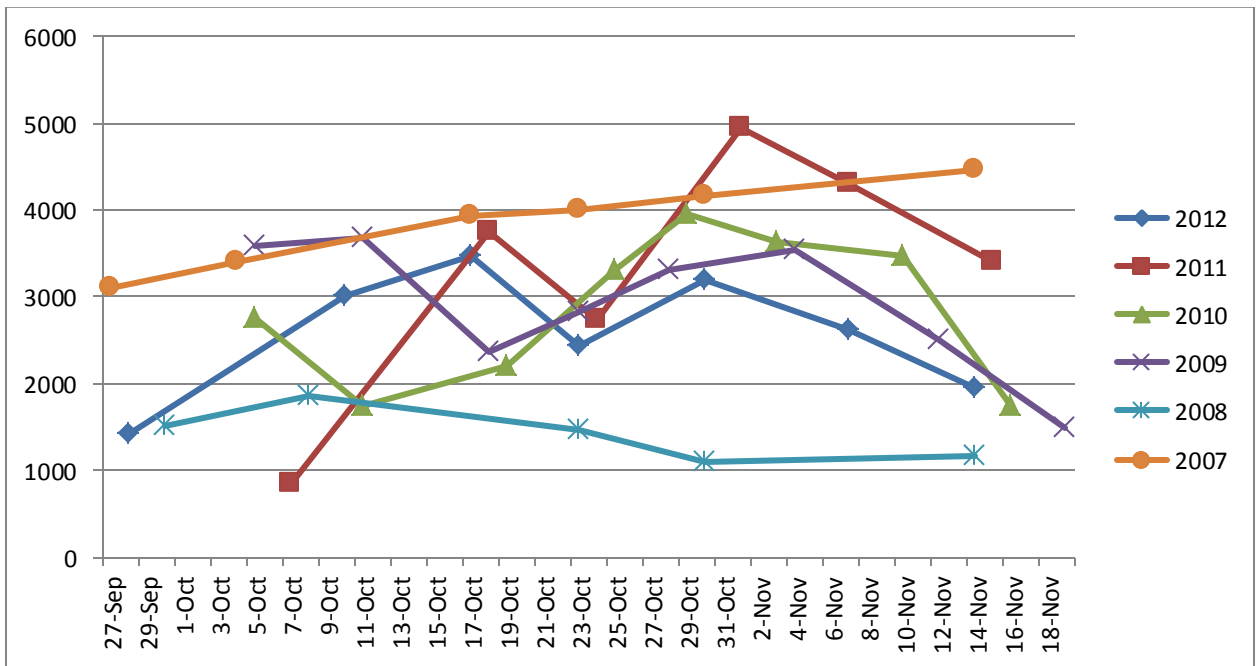


Figure 3. Copepod abundance for North station for each PEF cruise date in fall 2007-2012. Abundances are given as individuals/m<sup>3</sup>.

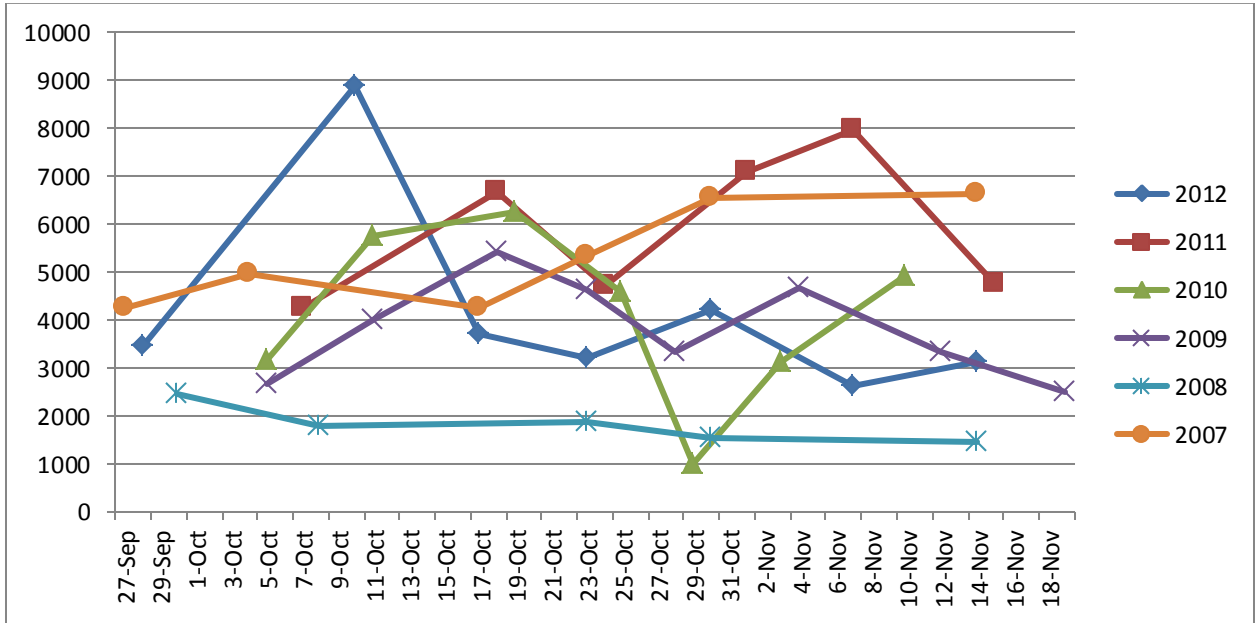


Figure 4. Copepod abundance for South station for each PEF cruise date in fall 2007-2012. Abundances are given as individuals/m<sup>3</sup>.

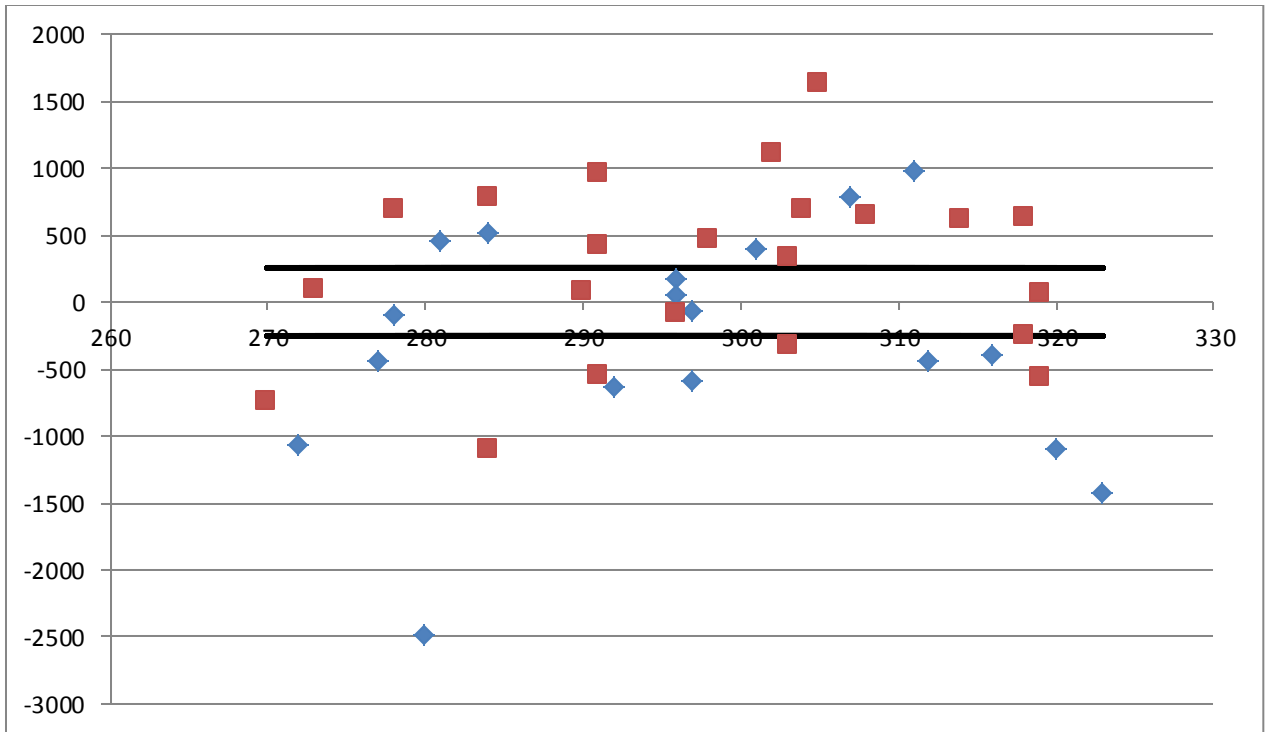


Figure 5. Copepod anomaly for North station by ordinal date for each PEF cruise date in fall 2007-2012. Anomaly is calculated as observed density minus mean density for given year. Densities are in individuals/m<sup>3</sup>. Red squares indicate measurements following flood tides. Blue diamonds indicate measurements following ebb tides. Dark black lines delineate anomalies greater than 250 individuals/m<sup>3</sup> from the mean.

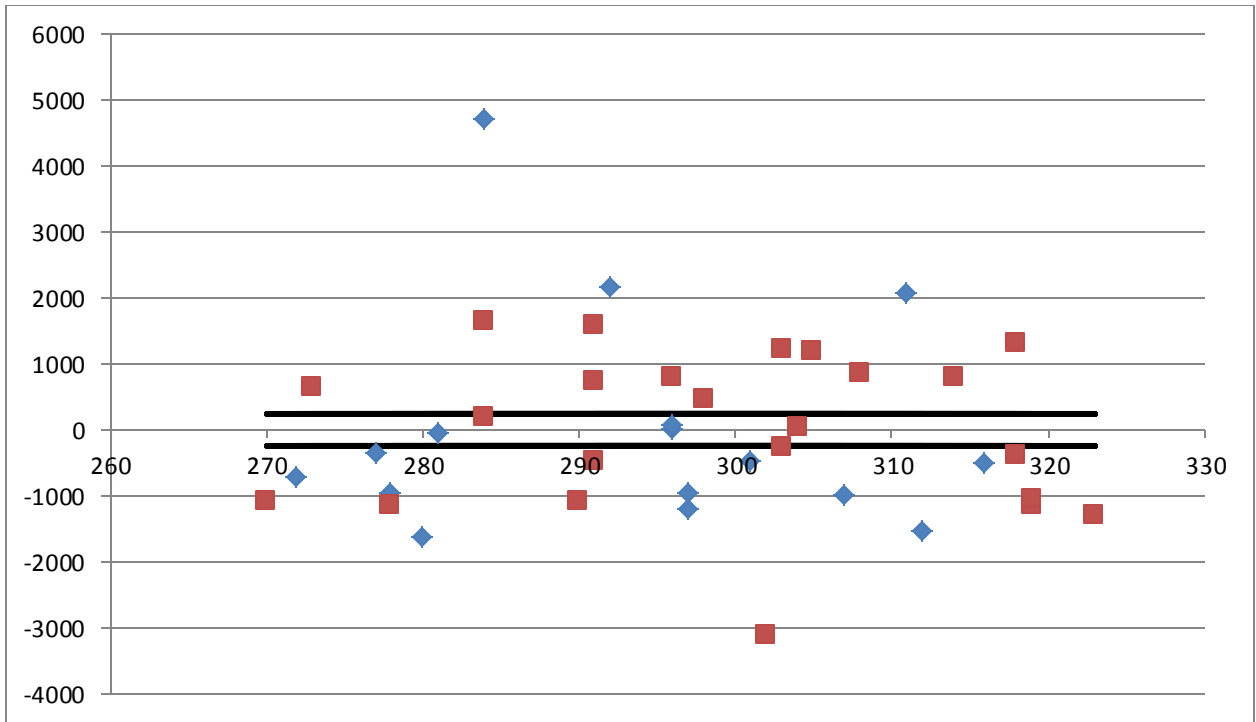
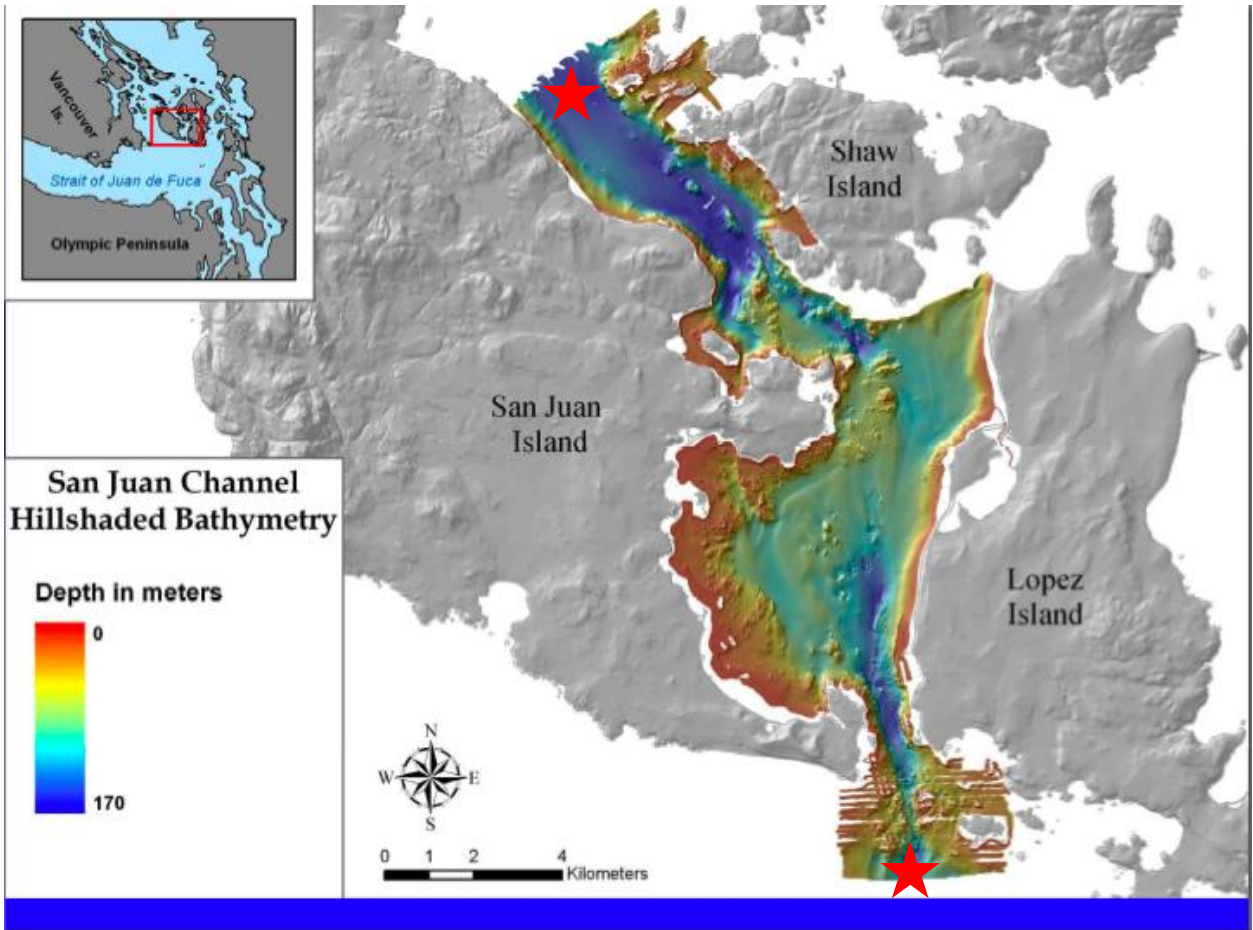


Figure 6. Copepod anomaly for South station by ordinal date for each PEF cruise date in fall 2007-2012. Anomaly is calculated as observed density minus mean density for given year. Densities are in individuals/m<sup>3</sup>. Red squares indicate measurements following flood tides. Blue diamonds indicate measurements following ebb tides. Dark black lines delineate anomalies greater than 250 individuals/m<sup>3</sup> from the mean.



Map 1. Topography and bathymetry of San Juan Channel, WA. Red stars indicate location of North and South stations. Depth range is 0 (red) to 170 meters (dark blue).

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