Characterizing Productivity of Geostrophic Eddies:

Implications for Leatherback Habitat

Nicholas Markman and Rebecca Schwartz

June 9, 2005

S-199

Characterizing Productivity of Geostrophic Eddies:

Implications for Leatherback Habitat

ABSTRACT:

Satellite tagging of leatherback turtles allowed the observation of "looping" tracks south of Hawaii along cruise track S-199. Polovina et al. (2005) correlated remotely sensed chlorophyll a data with the looping behavior of loggerhead turtles of the Kuroshio Extension Current Bifurcation Region, and concluded this observation to be the result of preferential feeing within cyclonic eddies. It was determined that the leatherback looping was observed around a similar cyclonic eddy. Additionally, it was determined that the anticyclonic counterpart was located along the cruise, just south of the cyclonic eddy.

Locating the cyclonic and anticyclonic eddy system was done using TOPEX and Jason 1 SSH imagery. Additionally, ADCP profiling allowed high resolution physical characterization of the mesoscale eddies. In situ biological sampling of the known leatherback turtle habitat reveled gelatinous densities an order of magnitude higher within the core of the cyclonic eddy versus the peripheral anticyclonic eddy. Zooplankton and fluorescence measurements mimicked this trend, bolstering the hypothesis that the cyclonic eddies, within an otherwise homogeneous body of water, are oceanic hotspots. It has been concluded that leatherbacks are exhibiting opportunistic behavior when making trans-pacific journeys, exploiting such oceanic hotspot habitat.

INTRODUCTION:

Leatherback turtles (*Dermochelys coriacea*) were placed on the endangered species list on June 2, 1970. Despite any concern or conservational efforts induced by this publicity, leatherback populations have continued to decline at alarming rates (Spotila, 2000). Recent research has begun to address basic questions necessary for designing effective conservation policy to protect such fragile populations. Improved tagging devices have allowed geographical tracking of large pelagics, which in turn has enabled identification of migration patterns and oceanic hotspots where species may gather. Moreover, these tags record basic water column information, including local sea temperature and salinity, nutrient profiles, individual dive depths, and dive times. While

the satellite tags can't provide information about the feeding habits of the turtles or the biology of the water column, the technology is still enhancing our understanding. The satellite tag data coupled with sea surface topography data from TOPEX and Jason-1 satellites creates a comprehensive picture of the physical properties of the habitat surrounding each tagged animal.

Recently, this satellite tagging has been used on loggerhead turtles in the Northern Pacific. This method has resulted in the observation of loggerhead migration and identification of apparent hotspots in the eddies and meanders of the Kuroshio Extension Current Bifurcation Region (KECBR) (Polovina et al., 2005). The authors found fluctuating levels of primary productivity dictated the movements of the turtles. Mesoscale current features create upwelling of deep nutrient-rich water, triggering primary productivity. These resulting phytoplankton blooms locally support higher trophic levels, and create vital mid-basin habitat for a threatened long-range migratory species. Only through accurately locating and characterizing areas of leatherback habitat can the next steps in protecting this species occur.

Eddy Oceanography

Studies on the Sargassa Sea (McGillicuddy and Robinson, 1998) suggest that geostrophic eddies cause nutrient mixing through the euphotic zone. Remote sensing of both sea surface topography and chlorophyll concentrations supports the hypothesis that such isolated areas can become oceanic oases through the action of mesoscale features that locally supply nutrients through the process of upwelling.

Geostrophic flow around areas of low-pressure create cyclonic eddies, which rotate counterclockwise. The low pressure induces the upwelling of cold, nutrient rich waters to the surface, regionally elevating the thermocline and enriching the water column. High-pressure areas of convergence create the opposing systems. Anticyclonic eddies circle clockwise, induce downwelling, and force thermoclines to greater depths through warm water piling (Williams, 1998). Sea surface height (SSH) can accurately map the eddy systems, with low topography characterizing divergent cyclonic eddies and high topography characterizing convergent anticyclonic eddies. Chlorophyll profiles, as a proxy for levels of primary productivity, may also be used to map these systems, because of the upwelling and subsequent phytoplankton blooms that the mesoscale features create. On a magnified scale, then, the eddy systems should theoretically show up as discrete areas of increased chlorophyll concentrations.

Leatherback Behavior

While it is generally accepted that upwelling associated with cyclonic eddies creates high levels of phytoplankton and zooplankton, little is known with regard to higher trophic levels. Polovina (2005) observed loggerheads circling what was determined to be the outer limits of eddies (Figure 1) and suggested that convergence between two eddies causes concentration of nutrients and plankton around the distal portions. The presence of primary production would then attract consumers in succession up the trophic levels eventually bringing in large pelagic feeders to forage on the periphery of the eddy. Leatherback behavior similar to that observed by Polovina was

observed through the TOPP (Tagging of Pacific Pelagics) program. These looping leatherback tracks were located just south of Hawaii along our cruise track (Figure 2).

Seminal studies by Polovina and others have begun to characterize oceanic habitat using chlorophyll as a proxy for productivity. However, few studies have sampled these regions in the Pacific. In situ biological sampling of these cyclonic and anti-cyclonic eddy systems has allowed this study to connect the physical oceanography to the biological processes that control the larger pelagics such as the leatherback. In March of 2005, two leatherbacks were observed in an eddy system along the planned S-199 cruise track. These turtles were released in Monterey Bay during September of 2004 and made a fairly direct path to the area just south of Hawaii, where they aggregated for over three months. Within this limited area, these turtles displayed circular movement patterns similar to that exhibited by loggerhead turtles in the Kuroshio Extension Current as described by Polovina et al. (2005). TOPEX and Jason-1 imagery of the areas surrounding the leatherbacks and along our cruise track just South of Hawaii showed regional topographic highs and lows corresponding to cyclonic and anti-cyclonic eddies (Figure 3).

We believe that leatherbacks are using the cyclonic eddies south of Hawaii as a food bank while making basin wide migrations. In our study, sampling of transects across the eddy system, from the cold cyclonic eddy through the intermediate waters to the warm anti-cyclonic counterpart allowed eddy characterization, which is the first step in accurately defining turtle habitat. We hypothesized that the turtles are frequenting this area as a result of increased primary productivity and the transfer of energy to higher trophic levels. As leatherbacks feed primarily on scyphozoan jellyfish, pyrosomes and

siphonophores (Davenport, 1998) we looked at the presence and distribution of gelatinous biomass across these transects, as well as characterizing the zooplankton biomass. Based on satellite tracking of turtles in eddy systems, Polovina predicts intermediate convergence waters between cyclonic and anticyclonic eddies to be the most abundant in both primary producers and larger pelagics. In our study, we have used physical and biological in situ sampling to characterize the eddy system and locate the most productive areas.

METHODS AND MATERIALS:

Detailed TOPEX and Jason-1 altimetry mapping of the water system south of Hawaii was obtained on shore and updated through images received via satellite while at sea. Images received used ten day composite averages giving approximate locations of the cylonic and anticyclonic eddy pair identified while on shore. RDI Acoustic Doppler Flow Profiler was used to pinpoint exact locations within the eddies. Three sites were used to characterize the eddy pair. One site located in the center of the cyclonic eddy, one site further toward the edge of the cyclonic eddy, and the third just over the edge into the warm, anti-cyclonic eddy (Figure 4, Table 1). Dive data obtained from a group of leatherbacks tagged in Costa Rica was used to relate water temperature to average turtle dive depth in order to determine optimal net sampling depths (Figure 5). In warmer waters, leatherbacks appear to dive strictly within the first top two hundred meters below the surface and most often to a depth of approximately 20m. Therefore we used neuston tows for surface sampling and meter nets to sample deeper portions of the eddy.

At each of the three discrete locations across the eddy system we sampled at the sea surface using a neuston tow (333μm) and at depth using a meter net (333μm). Calculating normalized biomass densities followed each net tow. Biovolumes were calculated by combining rinsed biomass with a pristine sample. Following the removal of nekton (material >2.0 cm) both rinsed and pristine biomass were sieved. Gelatinous matter was separated as were organisms of specific interest. Final biovolumes were then measured in graduated cylinders and densities determined through normalization for length towed. Separate density procedures were completed for zooplankton and jellies. Additionally 100-counts were completed to quantify diversity in each neuston tow sample. Organisms were identified to the genus level using a sample taken post volumetric measurement.

Hydrographic information was recorded using the CTD profiler with a flourometer attached for all three deployments. A rosette sampler was deployed at all three stations with water samples taken in Niskin bottles. While in Palmyra the water samples were tested for chlorophyll and nutrient (phosphate) concentrations. Chlorophyll a concentrations of the water samples were determined using immediate water filtration, followed by acetone absorption and a 12-hour wait period. Following centrifuge processing, a calibrated fluorometer measured chlorophyll a. This measurement was then compared to a normalized curve. Testing for phosphate concentrations was achieved by diazotizing the phosphate with sulphanilamide and coupling the substance with N-(1-napthyl)- ethylenediamine to form a dye that was then run through the spectrometer. Reacting the seawater sample with complex heteropoly acid results in a blue solution

when reduced. Complete details of the procedure are outline by Strickland in A Manual in Seawater Analysis (1965).

RESULTS:

Stations 7 and 9 consistently marked the high and low end members of observed data. Deepening of the thermocline, lessening of nutrients and sharp declines in biomass densities were observed as sampling moved from the cyclonic to anticyclonic eddy.

Station 7

Station 7 was in the core of the cold, cyclonic eddy and had the shallowest thermocline, beginning at 80m and continuing to 150m (Figure 6). Chlorophyll a measurements throughout the water column were also highest here, while the depth and magnitude of the peak differed only slightly from stations 8 and 9. Chlorophyll a peaked at 125m measuring 0.4 ug/l. This deep chlorophyll maximum tapered to zero at a depth of 250m (Figure 7). The fluorescence profile mimicked the chlorophyll a profile almost exactly, peaking around 125m and falling off at 250m. The fluorescence profile at station 7 peaked at 0.7 volts, notably higher in magnitude than at either of the other two stations (Figure 8). The nutricline, as indicated by phosphate concentration, began at 125m measuring 0.748um. Concentrations were variable above this depth, but below the mixed layer phosphate levels increased significantly reaching 2.291um at 175m (Figure 9).

The biological contents of both the neuston tow and meter net at station 7 displayed the highest densities of both zooplankton and gelatinous biomass. The neuston tow yielded a density of 0.010 ml/m2 zooplankton biomass and 0.019 ml/m2 gelatinous

biomass. This gelatinous density was an order of magnitude larger than that observed at either station 8 or 9 (Figure 10). Hundred count data produced the most diverse assemblage in terms of both number of different organisms and their distribution. Copepods only accounted for 26% of the observed organisms (Figure 11). Meter net sampling further bolstered the high productivity data set. The meter net was sent to a depth of 97m and collected a normalized 0.00159 ml/m3 zooplankton, slightly higher than the densities at stations 8 and 9. The calculated gelatinous density was also the highest here at .003 ml/m3 (Figure 13).

Station 8

Station 8 was located between the cold core of the cyclonic eddy and the border of the anticyclonic eddy. Its data sets, for nearly every property measured, ranged between the values yielded by stations 7 and 9. At station 8, the thermocline spanned from 100m to 150m (Figure 6). Chlorophyll a concentrations remain higher than those at station 9 through the first 100m of water, though the peak is lesser in magnitude than at stations 7 and 9. The chlorophyll a peak at station 8 measured 0.3 ug/l (Figure 7). Fluorescence measurements peaked at the same depth as station 7, but at a lesser value of 0.64 volts (Figure 8). Phosphate concentrations were variable through the mixed layer, spanning approximately the first 100m, and roughly mimicked the signature of station 7 at greater depths (Figure 9).

Zooplankton and gelatinous densities dropped in value from station 7 to station 8. A surface neuston tow yielded .008 ml/m2 zooplankton. Gelatinous density dropped from 0.019 ml/m2 to 0.0014 ml/m2 (Figure 10). The diversity observed in the biomass collected from the neuston tow was lower than that recorded for station seven, with fewer

species and 39% copepods (Figure 11). The meter net was towed at 204m and also revealed a decrease in biomass density from station 7. Zooplankton density decreased to .013 ml/m3 and gelatinous density fell to 0.0026 ml.m3 (Figure 12).

Station 9

Station 9 was located just inside the boundary of the warm anticyclonic eddy. The deepest thermocline was measured here beginning at 110m and continuing to 250m (Figure 6). Chlorophyll a measurements through the water column remained consistently lower than the signatures for both stations 7 and 8, but the maximum occurred at the exact same depth and value of station 7 (Figure 7). Fluorescence peaked at the same depth as stations 7 and 8, but was of lowest value, reaching a maximum of 0.6 volts (Figure 8). Phosphate levels were, again, variable through the first 100m and remained significantly lower than concentrations found at stations 7 and 8 for the following 400m of water (Figure 9).

Densities calculated for both zooplankton and gelatinous biomass were lowest here at station 9. Zooplankton density as measured from a surface neuston tow was 0.007 ml/m2 and gelatinous density shrank to 0.00044 ml/m2 (Figure 10). Diversity was lowest with 89% copepods (Figure 11). The meter net was towed at a depth of 125m and yielded 0.0048 ml/m3 zooplankton and 0.00095 ml/m3 gelatinous animals at depth (Figure 12).

DISCUSSION:

Trends observed throughout stations 7, 8 and 9 support the hypothesis that cyclonic eddies may serve as ocean hotspots, characterized by high levels of primary

productivity and biological activity. Station 7, located at the center of the cold core cyclonic eddy had the highest primary productivity, as inferred through fluorescence and chlorophyll a measurements. Based on these indicators there was a clear trend of diminishing productivity from the cyclonic core to the edge of the anticyclonic eddy. The high level of fluorescence and chlorophyll a recorded at station 7 is a signature of the upwelling associated with cyclonic eddies and can provide a base through which trophic succession can occur. Our data displays evidence of increased biomass in response to these high levels of primary productivity. The highest zooplankton densities both at the surface in the neuston tow and at depth in the meter net were observed at station 7. In addition, of particular significance was the drastic decline in gelatinous density from the cyclonic to anticyclonic eddy. Again, in both the surface tows and at depth, the gelatinous biomass densities decreased considerably across the eddy system stations. Biological sampling clearly matched the trend observed in primary productivity, using chlorophyll a and fluorescence as proxies. All the data serve to characterize the cold core cyclonic eddy as having increased biological activity.

While our results show clear trends between the three stations the extent of our sampling was limited by time and its allocation to competing scientific projects. Certainly more station work through our existing transect and extending the transect into the anticyclonic core would lead to more robust data sets. In addition, including station sites outside of the eddy pair would allow a control through which an oceanic baseline could be determined. Using this baseline would allow explicit characterization of the cyclonic eddy with relation to the surrounding ocean.

Inconsistent meter net deployment could have been another confounding factor in characterization of the eddy pair. Deployment of the meter nets occurred over a 100m range with intentions of targeting the migrating deep scattering layer. Time restrictions only allowed for single net deployments per station which occurred over a 24-hour period. More stations and time allotted to this project would allow consistent depth and temporal deployments.

Polovina et al. (2005) hypothesized that the intermediate waters, not the eddy core, would be most productive based solely on satellite imaging of loggerhead tracks and primary productivity. Our study, while restricted in scope, showed no indication of this distal biomass piling. Additional sampling would provide further evidence for or against our conclusion which remains in contradiction to that of Polovina.

Conservation of the leatherback has been hindered as its open ocean behavior is still largely unknown (Ferraroli et al., 2004). Adding more emphasis to the importance of defining vital turtle habitat is the fact that much of the recent decline in leatherback populations can be attributed to interaction with open ocean fisheries (Ferraroli et al., 2004). The next step that must occur for the survival of this species is developing a spatially based conservation program. Even following accurate identification of known leatherback habitat the true challenge remains in developing an effective reserve program. An effective reserve program must be able to respond to the dynamic eddy systems and constantly refine areas closed to longline and gillnet fishing, thus protecting the habitat most crucial to the survival of the leatherback during trans-oceanic migrations.

CONCLUSION:

The colder cyclonic eddy sampled along cruise track S-199 yielded higher nutrient levels, primary and secondary productivity and gelatinous densities. A clear decrease in phosphate below the mixed layer was observed through the progression of our transect. Fluorescence and chlorophyll a measurements showed a trend of decreasing primary productivity. This finding was supported by the declining gradient of higher trophic level biomass. Of most importance gelatinous density fell by an order of magnitude. The inflated biological densities found at station 7 support the idea that the looping tracks observed through satellite tagging are simply the opportunistic feeding of turtles within the cyclonic eddy.

REFERENCES

Davenport J., 1998. Sustaining Endothermy on a Diet of Cold Jelly: Energetics of the Leatherback Turtle Dermochelys Coriacea. British Herpetological Society Bulletin No. 62, p. 4-8.

Ferraroli et al., 2004. Where leatherback turtles meet fisheries. Nature, v. 429, p. 521.

McGillicuddy et. al., 1998. Influence of mesoscale eddies on new production in the Sargasso Sea. Nature, v. 394, p. 263.

Polovina et. al., 2005. The Kuroshio Extension Bifurcation Region: A pelagic hotspot for juvenile loggerhead sea turtles. [unpublished].

Spotila et al., 2000. Pacific Leatherback turtles face extinction. Nature, v. 405, p. 529-530.

Strickland, J.D.H. and T.R. Parsons, 1965. A Manual of Sea Water Analysis. Queen's Printer: Ottowa.

Tagging of Pacific Pelagics, 2005. <http://www.toppcensus.org>

Williams, Richard G. and Michael J. Follows, 1998. Eddies make ocean deserts bloom. Nature, v. 394, p. 228.

FIGURES AND TABLES

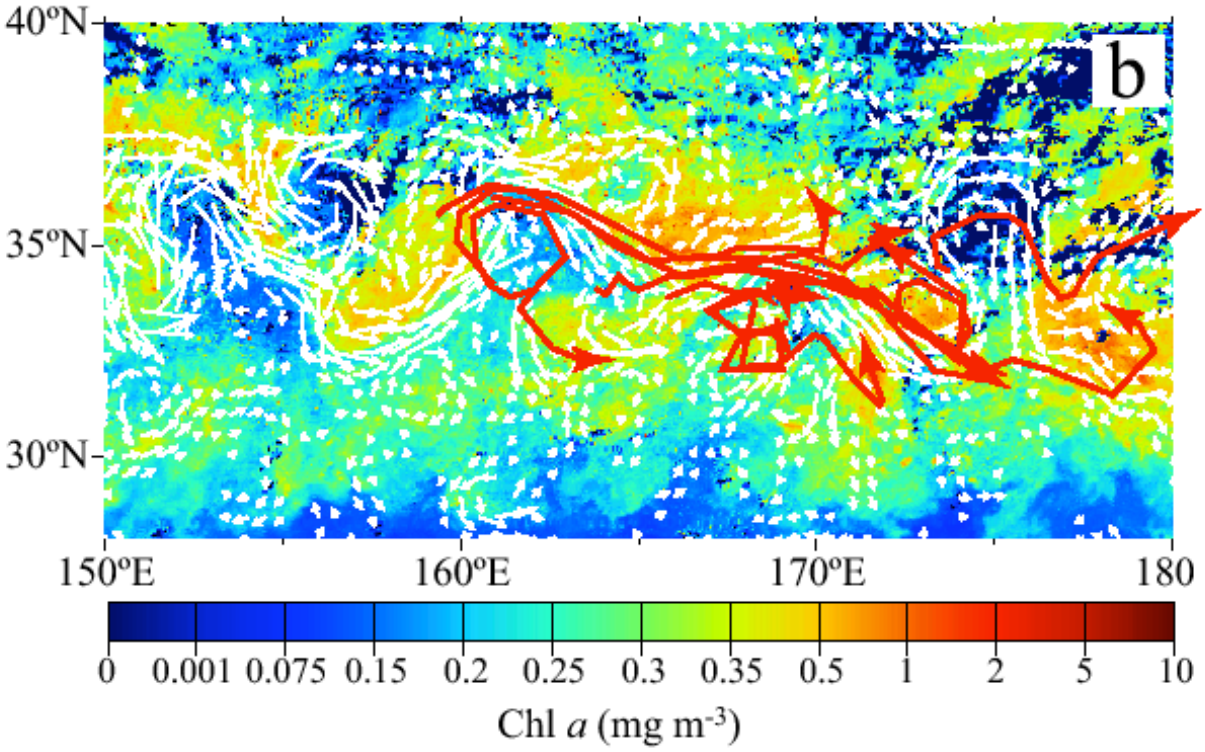

Figure 1: Loggerhead tracks in the Kuroshio Extension Current Bifurcation Region. Circling of both warm and cold cored eddies is observable (Polovina, 2005).

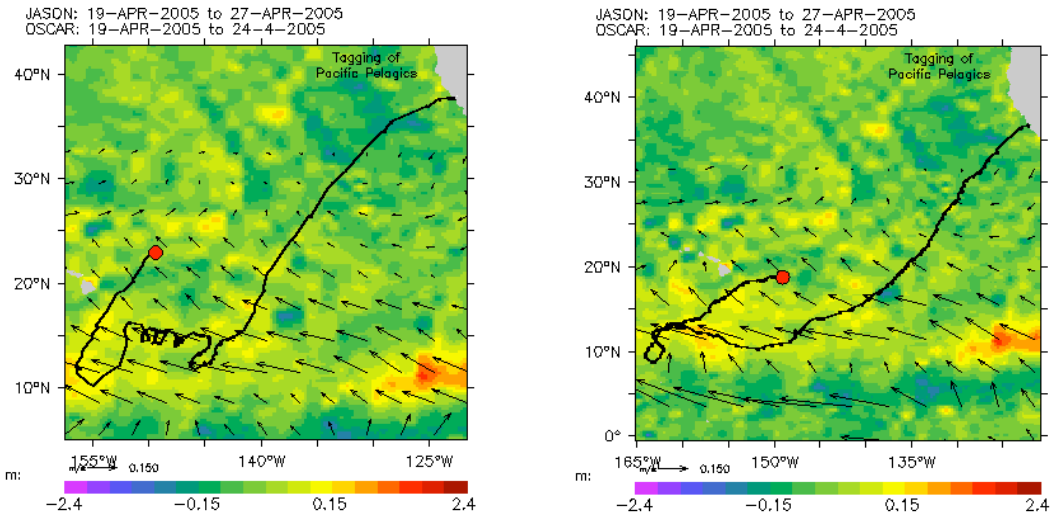

Figure 2: Tracks of two leatherbacks displaying looping behavior south of Hawaii along cruise track S-199. Figures courtesy of TOPP.

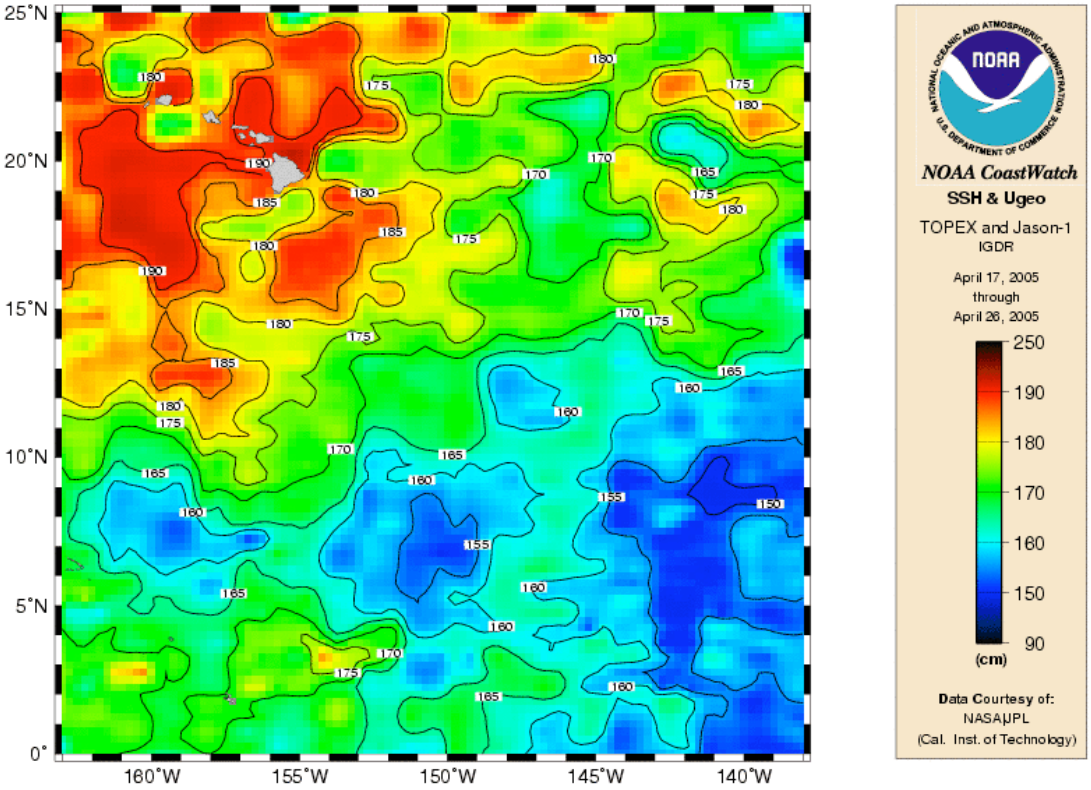

Figure 3: TOPEX imagery from April 17th through the 26th with approximate course from Hawaii to Christmas Island. Sea surface height (SSH) varies 0.5 meters from high to low along the track.

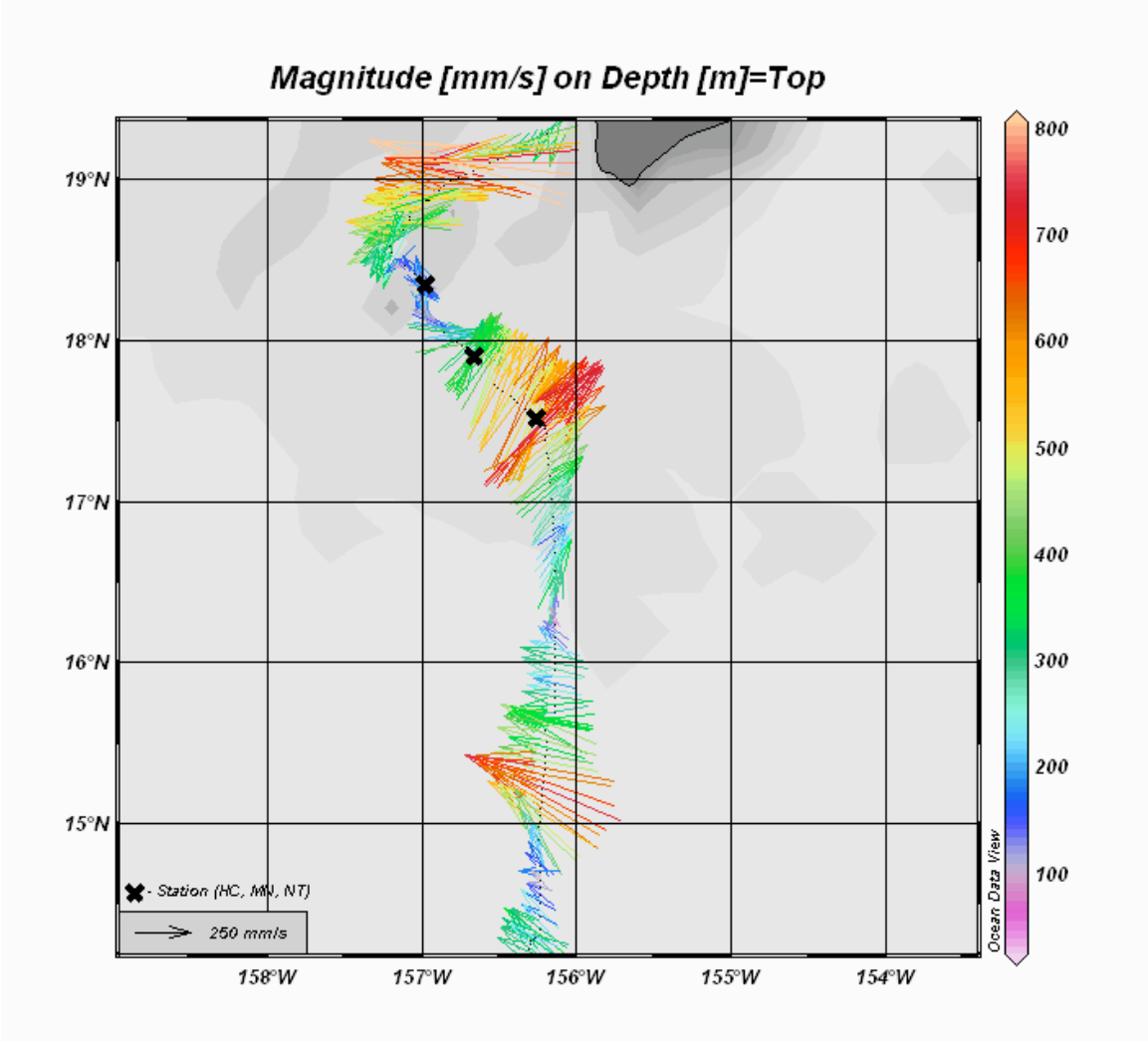

Figure 4: Current measurements taken during cruise S-199 with station locations. Exact latitudes and longitudes can be found in Table 1.

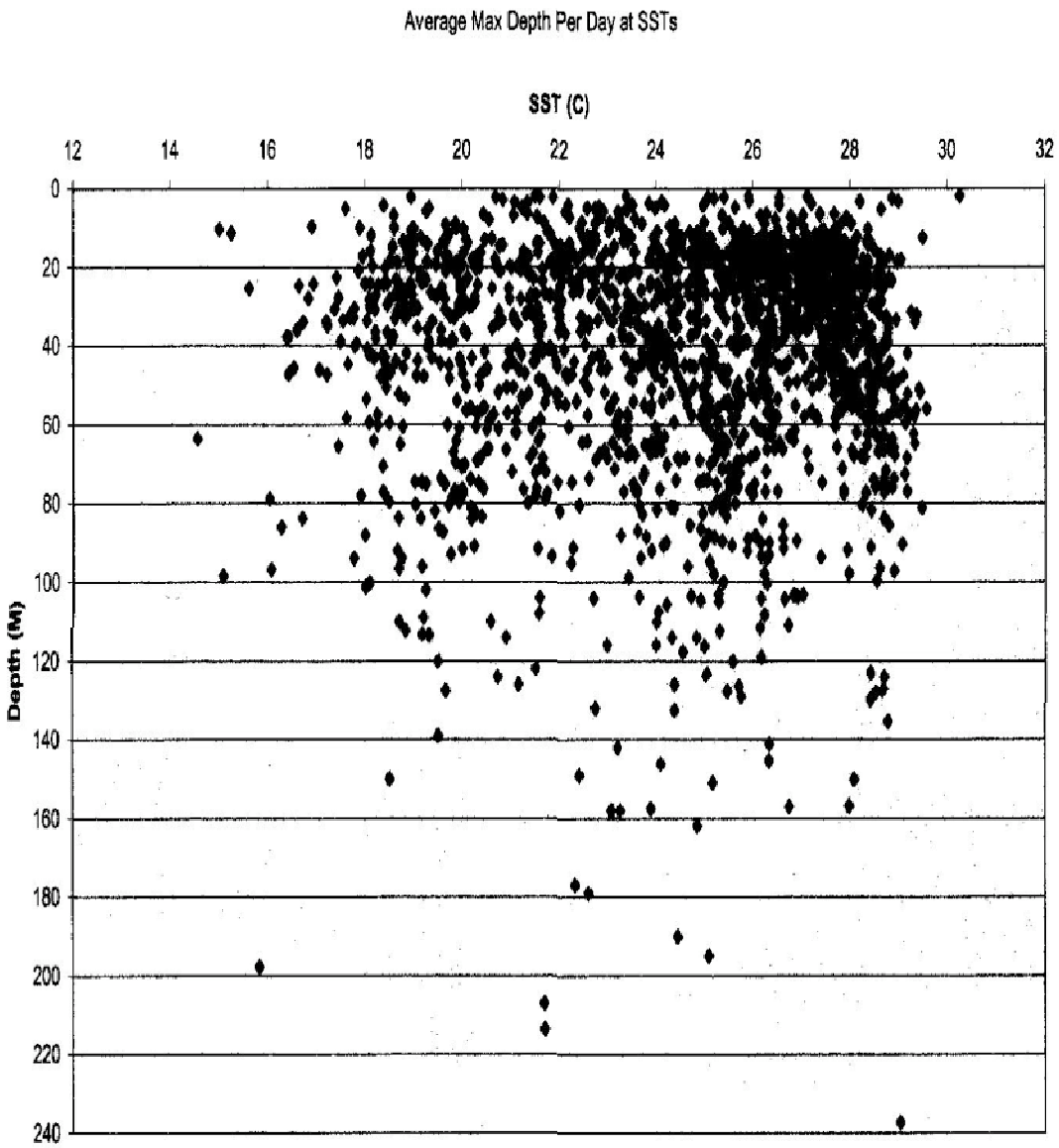

Figure 5: Dive data from a group of leatherbacks tagged in Costa Rica, relating water temperature to average turtle dive depth.

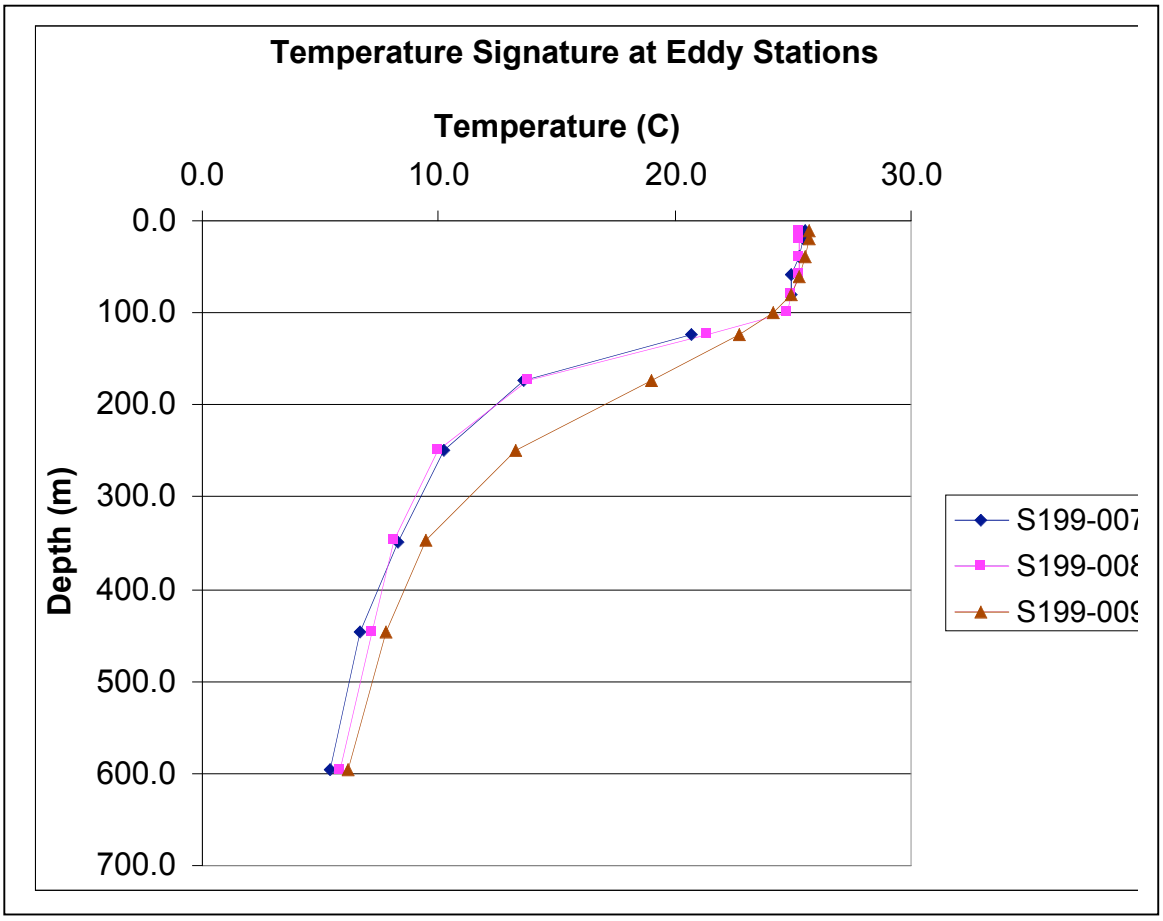

Figure 6: Temperature through the water column from the surface to 600m at stations 7, 8 and 9.

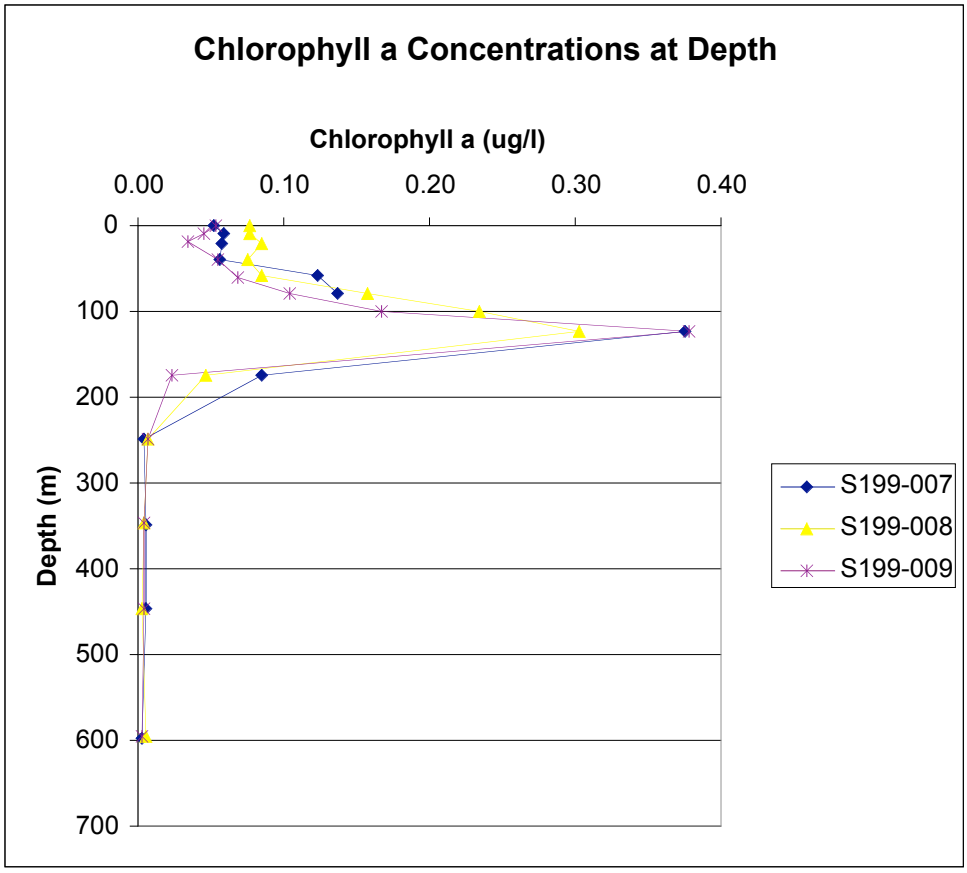

Figure 7: Chlorophyll a concentrations. All three sites peak at 125m. Stations 7 and 9 showed no difference in peak chlorophyll a concentrations.

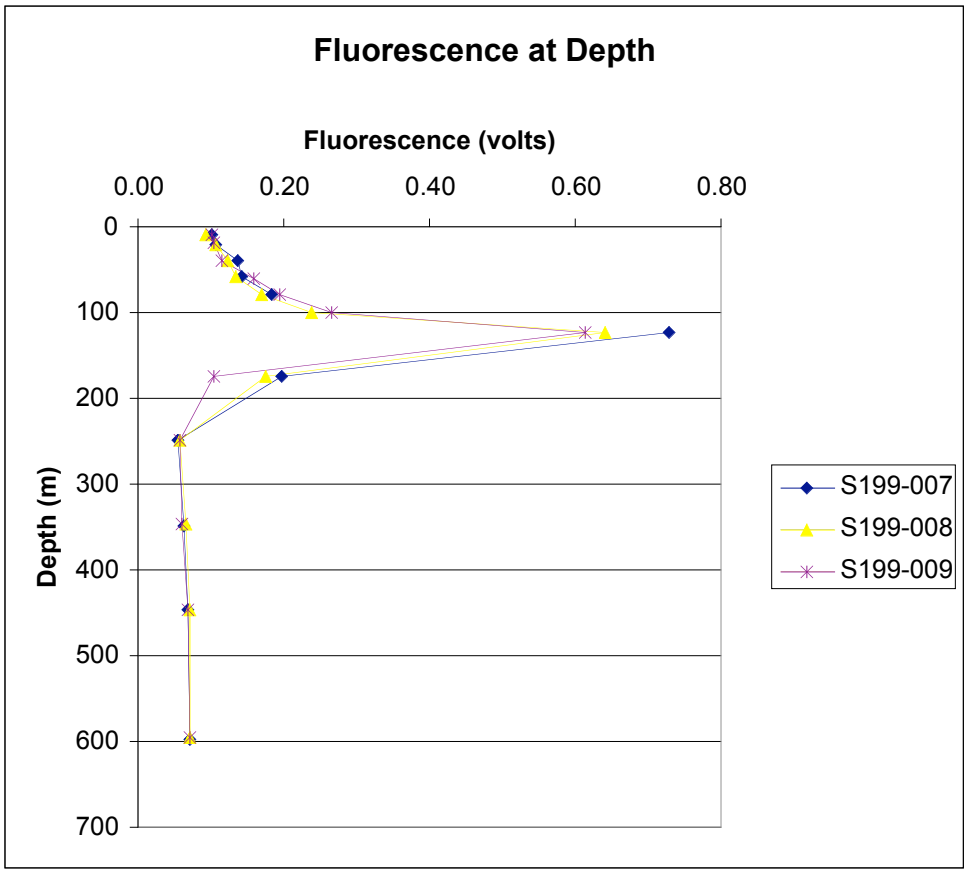

Figure 8: Fluorescence measured to 600m depth. The maximum observed at 125m corresponds with the chlorophyll a data of figure.

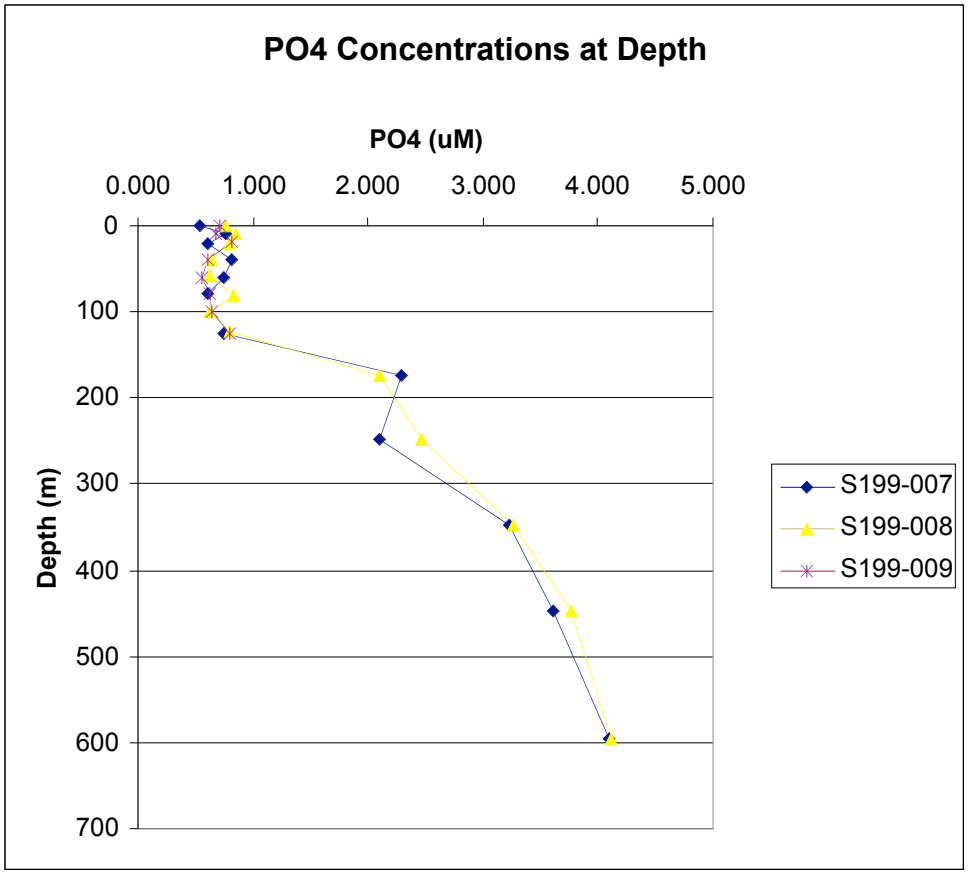

Figure 9: Phosphate concentration for stations 7 and 8 to 600m depth. Station 9 data was only collected to 125m.

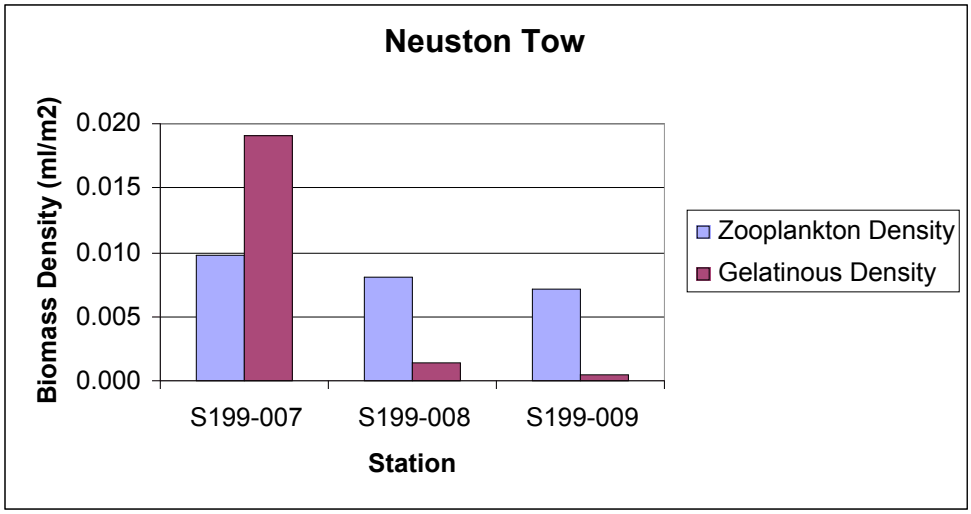

Figure 10: Zooplankton and gelatinous densities from neuston tows at stations 7, 8 and 9.

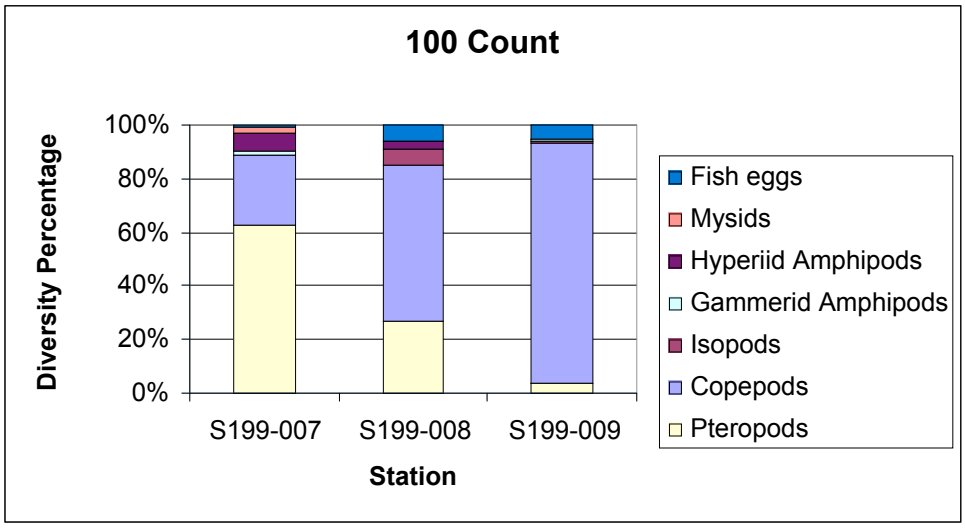

Figure 11: Hundred count data for neuston tow samples taken at stations 7, 8 and 9. Organisms were identified to the genus level.

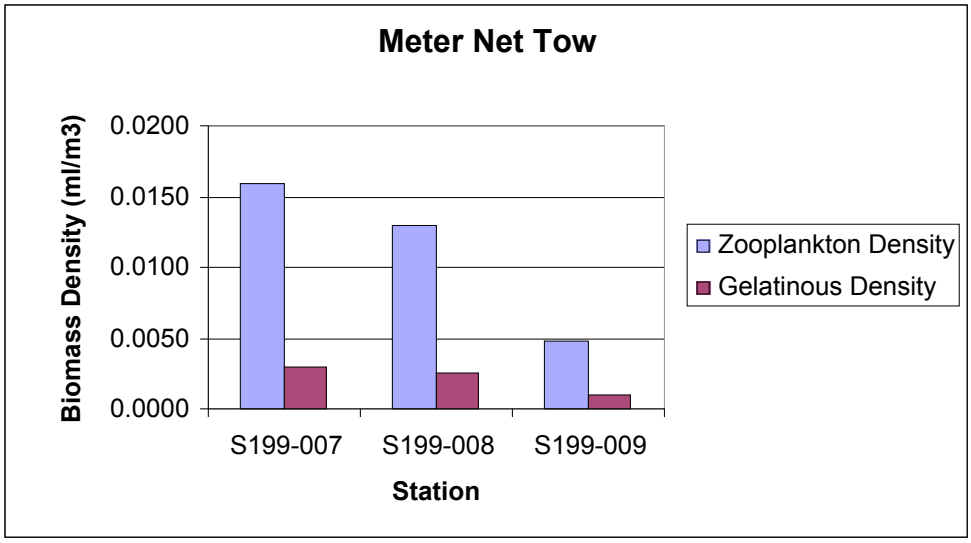

Figure 12: Zooplankton and gelatinous densities from meter net deployments at stations 7, 8 and 9.

Station	Latitude	Longitude	Log
S199-007	18˚21.6_	156˚58.6_	275.7nm
S199-008	17˚55.6_	156˚39.8_	304.0nm
S199-009	17˚30.5_	156˚14.2_	344.3nm

Table 1. Sample stations with latitude longitude and log.