Proceedings from the University of Washington
School of Oceanography Senior Thesis, Academic Year 2012-2013

Satellite based productivity models across the Kuroshio extension

Jordan McGowan[1]

[1]*University of Washington, School of Oceanography,*
Box 355351, Seattle, Washington 98195
*mcgowanj@u.washington.edu

Received June 2013

NONTECHNICAL SUMMARY

Understanding how carbon is moving around the Earth is important because CO_2 is an abundant greenhouse gas produced by human activity and has been linked to climate change. This study compares estimates made using satellite data by two different productivity models of how much organic carbon, is sinking out of the upper ocean. This is important for a few reasons; for one, if the models conflict that would not bode well for at least one of their accuracies. Finding a way to accurately estimate the movement of carbon remotely would allow for near real-time, global estimates, something that is not possible through taking samples on ships. In order to accomplish this, I have essentially drawn a line north to south across the northwest Pacific Ocean upon which I am looking at various measurements taken from space, such as chlorophyll and temperature. Using these, I make estimates of primary production, as well as an estimate of how much of that production is left over after consumers. This remaining production is what we are assuming to sink out of the upper ocean where it can be stored at depth. In addition to comparing the two models, I have made comparisons to data from water samples collected aboard a research vessel in hopes of assessing their accuracy

.ABSTRACT

As anthropogenic perturbations to the Earth's climate have continued to become more severe, it has become increasingly necessary to understand the processes that control atmospheric CO_2. One such process is the uptake and conversion of CO_2 into organic material by phytoplankton. Their excess productivity can lead to an export of carbon out of the surface ocean which can be stored in ocean sediments. In this study, I compare two satellite based productivity models, the Vertically Generalized Production Model (VGPM) and the Carbon-based Production Model (CbPM) in the Kuroshio extension region of the Pacific. The region was chosen due to its high CO_2 uptake during the winter months which has a biological component that is not currently well understood. This was accomplished via the use of net primary productivity (NPP) estimates to create a North-South transect of the northwest Pacific. Additional data for sea surface temperature and chlorophyll were also used to calculate the particle export ratio (pe-ratio) which could in turn be used to estimate net community production. I found an unusually high variance between the two model's NPP estimates. VGPM was as much as six times greater at 32° N while the opposite was true at 24° N, where CbPM estimated NPP to be more than double that of VGPM. These unusually large differences in the models estimates may be the result of the large nitrate gradient that exists are 30°N in the region.

The movement of carbon throughout the world's environments has a major impact on the Earth's climate. Due to ongoing climate change from anthropogenic sources, it is increasingly important that we understand how carbon is moving through the system. One important part of this system is the uptake and conversion of carbon dioxide into organic matter by primary producers in the world's oceans. This process helps regulate the atmospheric CO2 through the sinking and eventual burial of some fraction of the produced organic material. Biological production acts as a carbon sink, making it important that we understand its controls in order to quantify both production as well as carbon export in the ocean. One particularly intriguing method of doing this is through the use of satellite data. Satellite data has the ability to provide synoptic global data that would otherwise be unfeasible to collect. However, this ease of data with which to make estimates is moot if the estimates cannot be trusted. This study compares two satellite productivity models by determining their climatological mean across the Kuroshio extension.

This study looks at the Kuroshio extension in the North Pacific for a variety of reasons. Primarily, the region has a large annual flux of CO_2 from the atmosphere into the ocean (Fig. 1) with large seasonal variability, -6 g C m^{-2} $month^{-1}$ in February and 0.5 g C m^{-2} $month^{-1}$ in July (Takahashi et al. 2009). Additionally, the reason for this large CO_2 uptake and the role that biological activity may play are not well understood. The complex physical processes of the Kuroshio extension make this a study region of interest. The meeting of the Kuroshio and the Oyashio to form the extension leads to a large amount spatial variability in water properties across the current.

In order to determine carbon export, this study makes use of a few parameters; NPP, the pe-ratio, and net NCP. Net primary production is a measure of the amount of energy fixed as organic matter by autotrophs in excess of their biological need, that is to say, the gross production minus the resipiration of the producers. This was determined using satellite data, along with both the VGPM (Behrenfeld and Falkowski 1997) and the CbPM (Behrenfeld et al. 2005, Westberry et al. 2008). These models were chosen as they are both commonly used for satellite based productivity estimates but reach their estimates in different manners. The NPP, however, is not a measure of the export unless the system is devoid of heterotrophs, therefore we calculate the net community production. NCP is a measure of the remaining prodcution after the respiration of the entire community has been subtracted. In order to calculate this from the NPP data, we will be using the particle export ratio (pe-ratio). The pe-ratio was derived from a corellation between experimentally determined NPP and NCP as a function of temperature and chlorophyll (Dunne et al. 2007). This NCP is taken to be the carbon export, as it is the remaining organic material left to sink after the biological usage has been subtracted.

METHODS

Field

All in situ measurements were taken aboard the *R/V Melville* research cruise 1304 to be used for comparison to satellite measurements (Fig. 1). This cruise took place from February 25 – March 17, 2013 and had a cruise track from 30° N 146° E to 41° N 150° E. Chlorophyll samples were collected from the ship's underway system using 1 L dark bottles and stored until chlorophyll analysis was preformed, typically within 24 hours of sampling. Samples were taken at intervals ranging from 4 to 10 hours as required in order to obtain data for both spatial and temporal variability. This was done by filtering 200 mL of the sample water through a GF/F filter (0.7 µm pore size) using a filtration rack. Filters were then folded in half and placed into a 15 mL centrifuge tube and covered with 10 mL of 90% acetone. Samples were then run in a sonicator for seven minutes, followed by 10 minutes of rest before being well shaken and spun in a centrifuge for five minutes at 3600 rpm. Fluormetric readings of the samples were taken using a Turner TD700 fluorometer both before and after the addition of 3 drops of 10% HCL. Chlorophyll measurements were then calculated for the samples using the fluormetric method (Lorenzen 1966). These discrete measurements were then used to calibrate the ship's underway chlorophyll measurements that were taken every one minute.

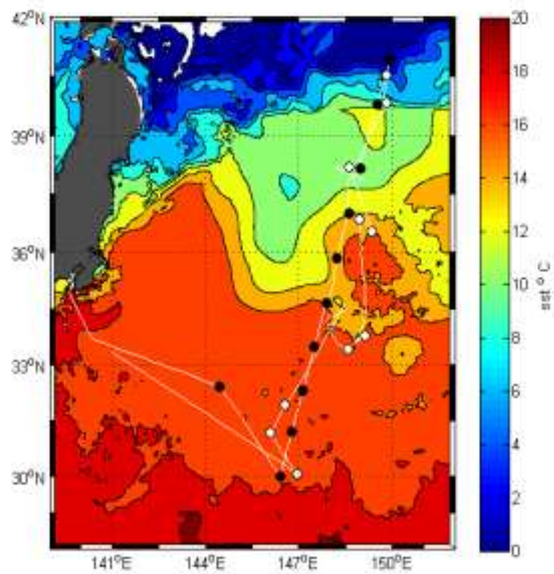

Figure 1. Map of the MV 1304 cruise track overlaid with SST. Black dots represent stations on the northern leg; white dots represent stations on the southern leg.

Analytical

In order to accomplish the goals of this study, satellite based NPP estimates for the month of February (2003-2011) were obtained courtesy of Oregon State Ocean Productivity. Estimates for two models, the Vertically Generalized Production Model (VGPM) (Behrenfeld and Falkowski 1997) and the Carbon-based Production Model (CbPM) (Behrenfeld et al. 2005, Westberry et al. 2008) were taken to compare. Both models' estimates were made using Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data averaged monthly. The VGPM's estimate was calculated using chlorophyll, sea surface PAR, daily photoperiod and the depth of the euphotic zone, with chlorophyll as the primary indicator of production. The CbPM's estimate was calculated using chlorophyll, backscatter, PAR, mixed layer depth, daily photoperiod, euphotic zone depth, and the diffuse attenuation coefficient at 490 nm, with carbon content as the primary indicator of production.

A North-South transect at 147 ° 30' E spanning from 24° N to 42° N, in order to cover both subtropical to subarctic, was created with data points every degree of latitude using Matrix Laboratory (MATLAB). This longitude was chosen because it bisects the East-West extremes of the *R/V Melville* cruise track. NPP estimates for both models were calculated along this transect for each February and then averaged to find a climatological mean. The standard deviation for each data point for calculated in order to account of the interannual variability. Additionally, intra-annual variability in NPP estimates between the two models was examined using monthly means along the North-South transect for 2011. Percent difference between the two models was calculated using the absolute value of the difference between then divided by their mean.

(1) $|(CbPM-VGPM)/((CbPM+VGPM)/2)|*100$

MODIS SST (T) and Chlorophyll (chl) measurements were taken and applied to these data points in order to calculate the particle export ratio (Dunne et al. 2007).

(2) $\text{pe-ratio} = -0.0081.*T + 0.0806.*\ln(chl) + 0.426$

$$0.04<\text{pe-ratio}<0.72$$

Once both the NPP estimates and the pe-ratios were calculated for each year, the two products were multiplied together in order to obtain an estimate of net community production (NCP).

(3) $NCP = NPP*\text{pe-ratio}$

RESULTS

There was a significant discrepancy between the NPP estimates of the two models throughout the majority of the transect (Fig. 2).

The maximum VGPM-based NPP value was 491.9 ± 45.4 mg C m^{-2} day^{-1} at 30° N and the lowest values found at the north and south extremes, 188.1 ± 32.1 and 199.8 ± 26.7 mg C m^{-2} day^{-1} respectively. The CbPM's maximum productivity was 440.6 ± 82.9 mg C m^{-2} day^{-1} at 25° N with a sharp decline to the north, dropping to 65.9 ± 31.3 mg C m^{-2} day^{-1} by 32° and remaining below 200 mg C m^{-2} day^{-1} for the remaining length of the transect. The CbPM had larger interannual variability than the VGPM for the majority of the data points. The CbPM consistently estimated higher productivity than VGPM only in waters where SST was near 21 °C, which occurred to the south of 26°-27° N in all years

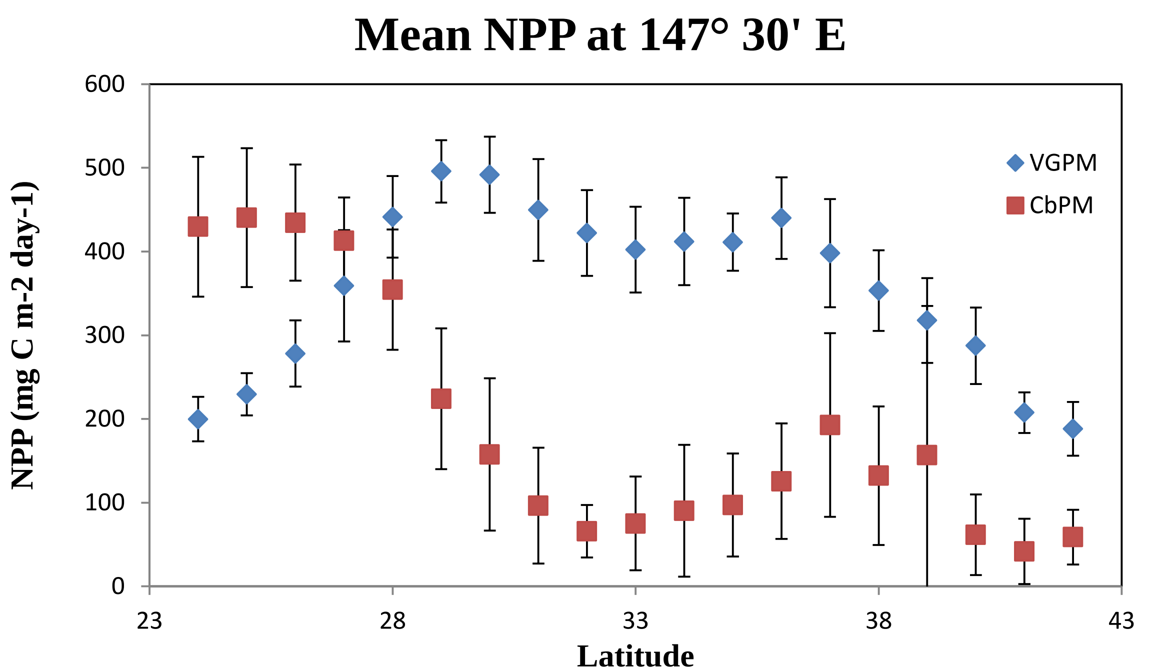

Figure 2. Climatological means of NPP for both models along the North-South transect at 147° 30' E with error bars representing standard deviation. High CbPM estimated at the southern end and low values to the north, while VGPM shows higher values in the middle.

The monthly means showed that intra-annual variability was on average largest during the months of February and March, with a percentage difference of 110% and 120% respectively (Fig. 3). The difference between the models decreases to a minimum of 45% in June and remains under 65% for the rest of the year. Maximum raw differences between the two models occurred during April with an average difference of 571 mg C m^{-2} day^{-1} across all latitudes.

Calculated pe-ratios for each year show a consistent trend of increasing values from south to north. (Fig. 4) Of acceptable values, the lowest always occurred at the southern end of the transect, varying from 25°-27° N. The absolute minimum values fall outside of the acceptable range for the pe-ratio, as it was only tested to be valid at greater than .04 by Dunne, for both 24° N and 25° N every year, and as such are to be discounted. The maximum value occurred at one of the two northernmost data points every year ranging from 0.317 to 0.339. Some additional features are a fairly constant pe-ratio from 28° N to 35° N followed by a sharp increase until 37° N and another sharp increase again at 40° N.

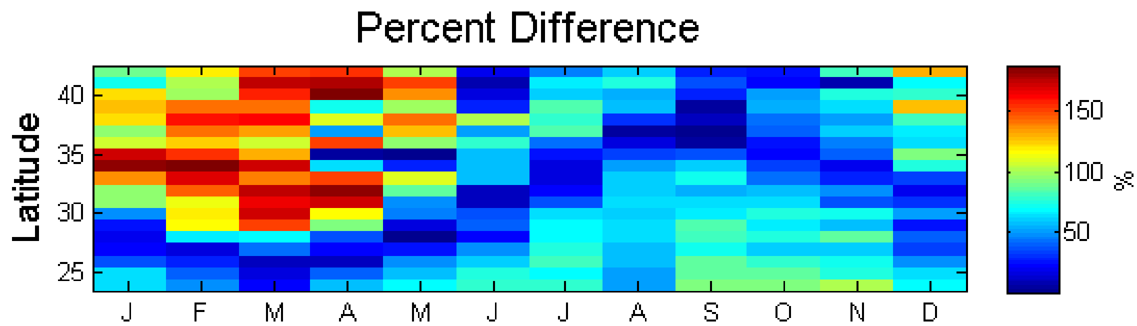

Figure 3. Percentage difference in NPP estimates between VGPM and CbPM for each month of 2011.

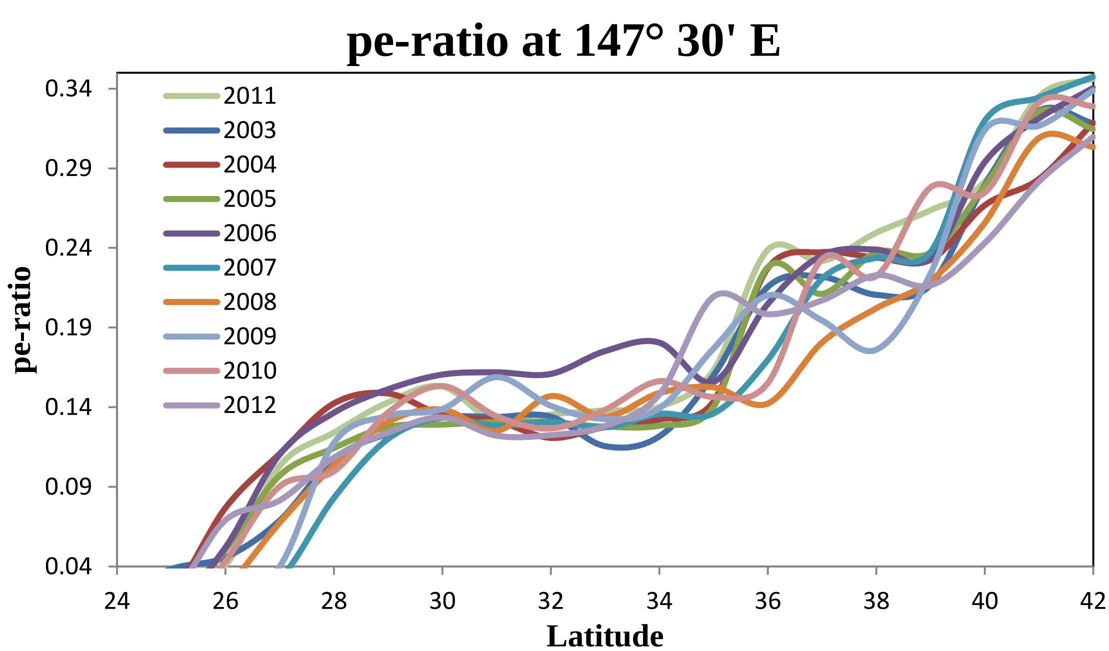

Figure 4. Yearly trends for the pe-ratio along the North-South transect at 147° 30' E showing an increase in the ratio from south to north.

NCP estimates made from the pe-ratio and NPP data show a maximum of 88.3 ± 18.8 mg C m^{-2} day^{-1} for VGPM at 36° N and 42.1 ± 24.5 mg C m^{-2} day^{-1} at 37° N for CbPM (Fig. 5). Both models predict their lowest values of NCP at the southern end of the transect, 12.7 ± 7.3 and 19.9 ± 8.7 mg C m^{-2} day^{-1} for VGPM and and CbPM respectively at 26°, discarding the points and which the pe-ratio is not valid. VGPM predicts higher values of NCP at 28° N and above, corresponding to their higher predictions of NPP. The NCP estimates mirror the trends seen in the NPP estimates, the only exception being CbPM estimates at the southern end of the transect, which decreases in its NCP prediction rather than increasing the values significantly higher than that of the VGPM.

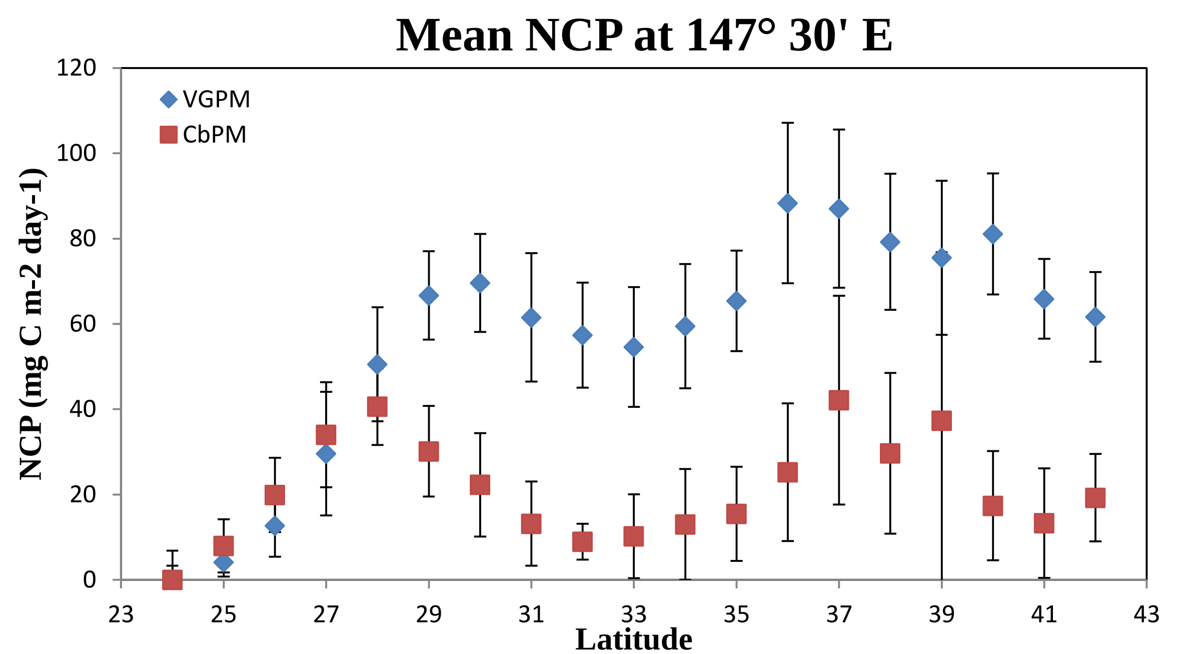

Figure 5. Climatological means for NCP along the North-South transect at 147° 30’ E with error bars representing standard deviation. VGPM estimates higher values throughout all but 2 of the viable data points at the southern end.

Calibrated in situ underway chlorophyll data for the northern transect of the cruise had a maximum value of 0.581 µg L^{-1} at 35.24° N and a minimum of 0.188 µg L^{-1} at 34.5° N (Fig. 6). Mean MODIS chlorophyll data for February and March 2013 had a maximum value of 0.450 µg L^{-1} at 40.10° N and a minimum of 0.154 µg L^{-1} at 32.36° N. Both datasets follow the same trend for most of the cruise track, chlorophyll concentrations decreasing as you move north until 34° N, followed by a spike between 34° and 36°. The only differentiation comes at the northernmost latitudes where the MODIS data sees another spike around 40° while the underway data shows a continuous increase.

DISCUSSION

There was a surprisingly large discrepancy between the two productivity models. VGPM estimates had significantly higher NPP throughout most of the northwest Pacific (Fig. 2). VGPM mean values more than 6 times that of CbPM in some places while being consistently having values at least double that of CbPM. Conversely, when you move to 27° N and further south, CbPM estimates values that double VGPM. A previous study comparing these models to in situ measurements made using oxygen found the models to vary with each other, but not to the same degree (Juranek and Quay 2012). The Juranek and Quay study (2012) study found VGPM/CbPM ratios from many latitudes in the Pacific, with ratios of 0.625, 1.33, 1.4 and 1.5. None of these are even a 100% discrepancy, let alone a 500% or more. This leads me to believe there must be something in the region strongly affecting these estimates.

One possibility is that the chlorophyll:carbon ratios of the phytoplankton in the area vary rapidly as you move into cooler water. This explanation is unlikely, however, because the chlorophyll:carbon ratio increases with temperature, which would cause the reverse of what we see in the region. This suggests that something else must be causing the difference that we see. Therefore, I suggest that the change in chlorophyll:carbon ratio could be the result of a nitrogen or phosphorous deficiency, which are known to cause a decrease in chlorophyll (Reimann et al. 1989). This seems like a likely explanation for the discrepancy due to the high nitrate concentrations in the northern Pacific with a rapid transition to low concentrations around 30° N (Horn et al. 2011). This depleted nitrate would lower the chlorophyll:carbon ratio of the phytoplankton, which would in turn lower the estimated production from VGPM relative to CbPM. This is due to the nature of the models, the CbPM varies with carbon content while VGPM varies with chlorophyll, therefore when the chlorophyll:carbon ratio is high, VGPM estimates are high while the reverse is true at low chlorophyll:carbon ratios. This is exactly what we see in the region, high CbPM and low VGPM estimates of NPP at the southern extent of the transect.

A previous study of the Kuroshio region (35-40 N, 140-160 E) during the wintertime estimating daily NCP from in situ measurements found values in a range of 24 to 168 mg C m^{-2} day^{-1} (Lockwood et al.. Comparatively, my climatological VGPM estimates ranged from 61.6 to 88.3 mg C m^{-2} day^{-1} and CbPM estimates ranged from 17.3 to 42.1 mg C m^{-2} day^{-1}. The VGPM estimates of the region all fall within the range of estimates made from in situ measurements, while only some of the CbPM meet that criteria. This suggests that VGPM may be a better suited for estimating NCP, at least in the Kuroshio region. However, neither of the two models show a range nearly as broad as that of the previous study. This could be attributed to the fact that this study only covered a single transect while the in situ data was taken from a grid. Additionally, the satellite based estimates were made using data averaged over the course of a month, which would lessen the variability seen within the region when compared to in situ data. More work would need to be done to accurately compare the satellite estimates to those made in situ.

CONCLUSIONS

Satellite based productivity models result in very different estimates of both NPP and NCP, particularly in the months of February and March. The large discrepancies between the two models suggests there is something in the region with a strong influence on the chlorophyll:carbon ratios within phytoplankton. I believe that the large gradient in surface nutrients in the region is the primary cause of this, and thus the cause of models discrepancy. All VGPM estimates made in the region fall within the range of in situ estimates made in previous studies while CbPM estimates do not. This suggests that VGPM may be a better indicator of production in the region, but more extensive work will need to be done to confirm these results.

ACKNOWLEDGEMENTS

I would like to thank everyone who helped make this project possible. Thank you to all the instructors, particularly Steve Emerson and Hilary Palevsky for their hard work in helping me develop and progress through the project throughout the past 8 months. Additionally, thanks to all of my OCEAN 445 peers for their help in reviewing and revising this paper. Finally, I would like to thank the captain and crew of the RV Melville for providing the means of data collection.

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