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Spatial, temporal and spectral scale of POC estimations for the Kuroshio Extension from satellite based observations in the wintertime

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NONTECHNICAL SUMMARY

The use of satellite based data is widely accepted throughout the scientific world. It is one of the only methods of data observation that allows for instantaneous global scale investigations of Net Primary Productivity (NPP). Measuring particulate organic carbon (POC) in the surface ocean is one way of extrapolating NPP. POC can be estimated from satellite based observations of light reflected off of the sea surface. This study investigated the accuracy of satellite based POC estimations by comparing them to measured POC concentrations from water samples. Samples were collected on a scientific cruise in the Kuroshio Extension region of the North Pacific Ocean from February- March of 2013. Due to frequent cloud cover during the cruise, data available for comparison was limited, highlighting one of the difficulties when depending upon satellite observations. When comparisons were possible I found that satellite based POC estimations significantly underrepresented measured POC values. These results suggest that data products of satellite observations cannot be used to quantitatively describe small scale processes in complex ocean regions like the Kuroshio.

ABSTRACT

Particulate organic carbon (POC) is proportional to the amount of phytoplankton in the ocean. This relationship enables net primary productivity (NPP) to be estimated via the use of remotely sensed POC estimates. The Aqua MODIS satellite is equipped with sensors that record backscatter from the surface ocean, a proxy for open ocean POC. This research investigates the applicability of a backscatter to POC relationship in a region where estimated POC has not been calibrated against in situ sampling. Water samples were collected from a transect of the Kuroshio Extension region of the North Pacific Ocean during February and March of 2013. Light measurements were also recorded in order to identify whether a relationship between optical properties and POC concentration was obvious. Of the 14 stations, only 4 were in locations where satellite imaging was possible due to cloud cover limitations. Remotely sensed estimates of POC were smaller than in situ measurements of POC at all 4 stations. The average, maximum and minimum discrepancies between in situ and remote POC estimates were 210.8 µg/L, 372.56 µg/L and 132.27 µg/L respectively. Since satellite estimates consistently underestimate POC by a factor of 4, it is reasonable to conclude that the algorithm used to convert remotely sensed backscatter into POC estimates is inconsistent and should be tailored so that it takes into account the unique characteristics of the area to which it is being applied. The Kuroshio is a region of high productivity and variability, making it an extremely difficult place to apply generic algorithms to.

INTRODUCTION

Phytoplankton productivity contributes to the carbon cycle, the biological pump and climate change. Through photosynthesis phytoplankton produce more oxygen and take up more carbon dioxide per day than all terrestrial plants combined (Falkowski 2012). Photosynthesis is an important pathway for carbon sequestration into the ocean, a process directly related to climate change. Therefore, the more that is known about phytoplankton, the better biological and chemical processes in the ocean can be understood. Historically phytoplankton biomass has been represented by chlorophyll concentrations. This estimate is simple to make based on images of ocean color, but it may not be as accurate as previously thought (Westberry et al. 2008). While chlorophyll indicates photosynthetic activity well, it does not represent the physiological state of phytoplankton, a necessary consideration when predicting total phytoplankton biomass and net primary productivity (NPP) (Behrenfeld et al. 2005). When a phytoplankton experiences changes in its physiological state its carbon to chlorophyll ratio is altered. For example, a phytoplankton experiencing a low light or nutrient environment becomes stressed and photoacclimates, reducing its amount of chlorophyll pigment (Wang et al. 2008). Therefore, something must be known about the carbon composition of the phytoplankton in order to properly predict total phytoplankton biomass. The ratio of chlorophyll to particulate organic carbon (POC) concentration in the surface ocean can then be used as a predictor of total algal productivity that is more accurate than productivity predictions based on chlorophyll alone (Westberry et al. 2010).

POC concentrations in the surface ocean depend upon the amount of phytoplankton present (Behrenfeld et al. 2005). Regions of high productivity can be assumed to be regions of high POC. This means that the physical factors that determine phytoplankton abundance also determine POC. High productivity regions are created when there is an abundance of nutrients and ample sunlight. This occurs in areas of upwelling where nutrients are introduced into the euphotic zone from depth. It also occurs when currents transport high latitude waters that are rich in nutrients into lower latitudes where there is enough sunlight to support a bloom. This is precisely the scenario at the Kuroshio. From the north there is an introduction of cold, nutrient rich water from the subarctic Oyashio and from the south flows the warmer Kuroshio out of the subtropics. When these two currents collide off the East coast of Japan they create a highly productive region known as the Kuroshio Extension. The Extension is characterized by many mesoscale eddies that effectively mix the two water masses.

Producing estimates of POC from in situ water samples is a time consuming process that must be completed in an onshore lab. The generation of an instantaneous estimate of global POC is therefore impossible via this method. The only way it can be done is by estimating POC from remote sensing of backscatter in the surface ocean (Behrenfeld et al. 2005). There is a stable relationship between suspended particle load, which is responsible for backscattering, and POC so backscattering data can be used to estimate total organic carbon with an algorithm (Westberry et al. 2010). This algorithm was provided by Behrenfeld et al. in 2005 and considers two primary contributors in the transformation of irradiance (represented by the particulate backscattering coefficient, b_{bp}) into an estimate of POC. These factors are the background amount of scattering associated with non-phytoplankton particles and the scattering of particles associated with phytoplankton. Therefore the calculation is simply subtracting the background scattering contribution from the measured particulate backscattering (b_{bp}), then scaling the result to represent phytoplankton carbon biomass. The scaling factor was determined by comparing values that captured the range of POC values found in the laboratory and choosing the value most appropriate for a wide range of growth conditions and phytoplankton species. The resultant relationship is:

$$POC = 13000*(b_{bp}-.00035) \qquad (1)$$

Estimates of backscattering (b_{bp}) gathered by satellites have been used in this formula to provide global estimates of POC (Fig.1).

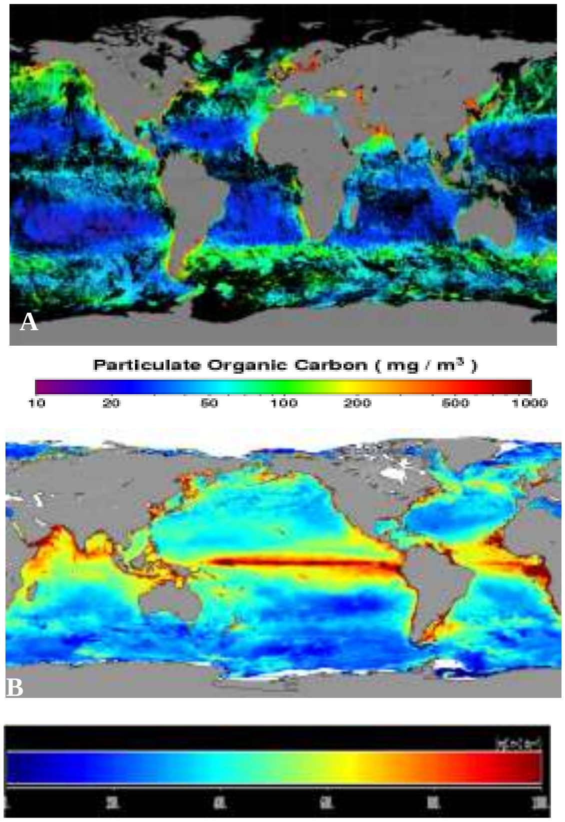

Figure 1. The average global estimation of particulate organic carbon in mg/m^3 *for March 6-13, 2013 from the MODIS sensor aboard the Aqua satellite (A) and a global carbon based productivity model (CbPM), measured in mgC m*$^{-2}$ *d*$^{-1}$ *, for February of 2011 provided by the Oregon State University Ocean Productivity website.*

Global POC estimates based on satellite observations can be used to produce global estimates of NPP via a carbon based productivity model (CbPM) provided by Westbery et al. 2008 (Fig. 2).They can also be combined with global chlorophyll estimates in a model that estimates NPP from the relationship between these properties (Fig. 2). Global models of NPP based on both chlorophyll and POC are more accurate than any before (Westberry et al. 2008). While the concept behind models based on remotely sensed data is sound, the method for estimating POC is still being refined and more information concerning the reliability of optical properties is necessary since error in POC estimates is a potential source of uncertainty in satellite based models.

Unfortunately there are many drawbacks associated with remote observations and the global products they produce. Satellite observations can be hindered by atmospheric conditions such as frequent cloud cover. This prevents the coverage of the global oceans by satellite imaging and creates spatial and temporal data gaps (Platt et al 1995). Data from regions characterized by frequent cloud cover are often averages compiled from very few real data points. Averages such as this may not capture the true state of a variable in the surface ocean due to extrapolation based on limited data points. This is why an intimate knowledge of in situ variability and local mechanisms affecting the target variable are necessary in the analysis and contemplation of satellite imaging (Platt et al. 1995). Important parameters for POC estimations include its seasonal variation, local physical forcing and the algal response to it. Sea state information is also necessary for ocean color imaging as it determines the ocean leaving radiance that is reflected and refracted from the surface ocean (Platt et al. 1995). Regardless of the drawbacks, remote sensing is the only method of global ocean observation that affords the estimation of annual primary production and long-term interannual variability within data products (Platt et al. 1995).

Fieldwork took place in the North Pacific, specifically the Kuroshio Extension. The Kuroshio is a region of high productivity, CO2 flux and sequestration that is characterized by the intersection of large scale warm and cold currents. It is also a region of complex physical properties due to the presence of recirculation gyres (Jayne et al. 2009). Due to these physical properties it is an area of extremely high carbon dioxide flux. This makes the Kuroshio one of the most important sinks of carbon in the ocean (Harada et al. 2012). High productivity in this region also contributes to relatively high POC concentrations and complex optical properties. Variations in the dynamics of the Kuroshio can greatly affect the climate of North America. Therefore the more known about this region, the better global climate can be understood. Across the Kuroshio there is tremendous north-south variation in physical properties, such as sea surface height and sea surface temperature (Fig. 2), due to the subtropical input from the south and the subarctic input from the north. The cruise track of this project was able to capture stations in both the subarctic and the subtropics. This huge gradient in physical properties influences biological productivity and POC. During this study the Kuroshio Extension region was estimated to be contained within lines of latitude 33˚ N and 35˚N based on sea surface height and sea surface temperature imaging of the region (Fig. 2). This project questions the ability of satellite based POC estimations to adequately capture in situ POC in a region of complex and highly variable physical properties.

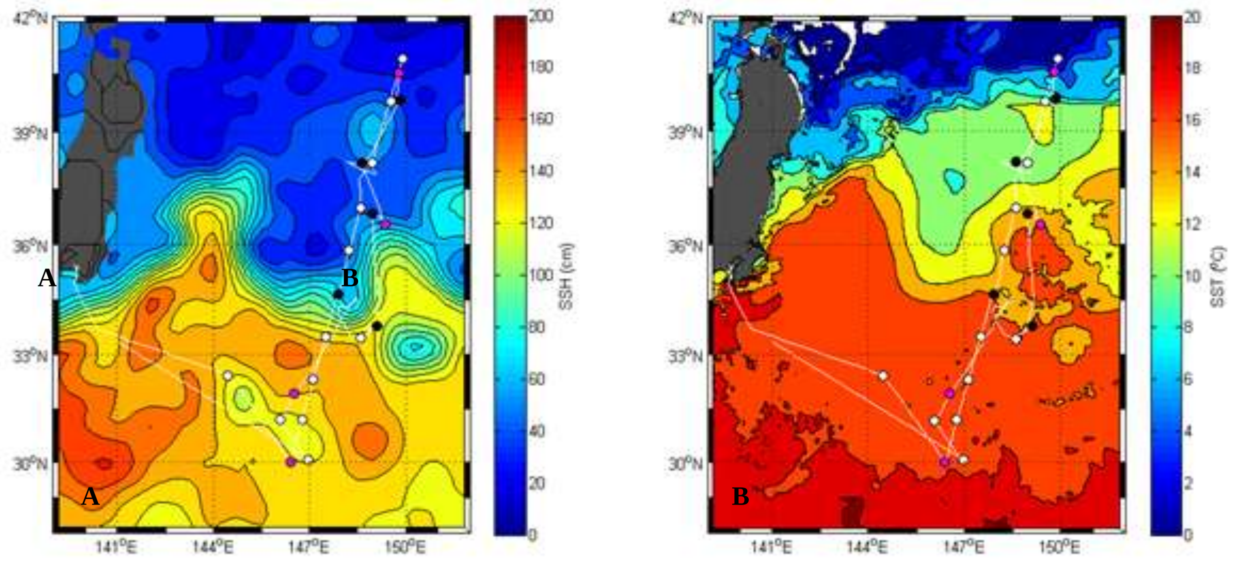

Figure 2. Variation in sea surface height from March 1-7 (A) and sea surface temperature on March 1st (B) in the Kuroshio Extension region. Sea surface temperature data provided by NASA PO.DAAC, sea surface height data provided by AVISO. Pink dots represent Stations where satellite estimates and in situ measurements of POC are available, white dots represent stations where only in situ POC measurements are available and black dots represent stations where no POC data was gathered.

METHODS

Field data was collected from the R.V. *Melville* between 24 February and 17 March 2013. The R.V. *Melville* ran two transects perpendicular to the Kuroshio Extension from the subtropics in the south to the subarctic in the north. The first transect was from 28˚ N, 145˚E to 42˚N, 150˚E (Fig.2). Along this transect the ship stopped at 11 stations to make CTD casts, collect water and gather light data. All sampling occurred in the daytime so that water leaving radiance sensors could be deployed at times that corresponded to CTD casts. Each CTD cast took about four hours and roughly 20 minutes of water leaving radiance data was collected during this time. After each cast five 2L water samples were collected from Niskin bottles containing water from varying depths for POC analysis. On the second transect the ship returned from 42˚N, 150˚E to 28˚ N, 145˚E and 10 more stations were sampled resulting in a total of 21 stations. Of these 21 stations, data was only collected from 14 stations for analysis in this paper.

Estimations of POC from satellite based observations that corresponded to sample station locations were available for Stations 3, 14, 17 and 21. The dates of pixel visibility while at the aforementioned stations were February 27th, March 5th, March 7th and March 12th respectively. Analysis was made possible by downloading .hdf images of global POC estimations from the Nasa Ocean Color website for each of these days into the SeaWiFS Data Analysis System (SeaDAS). In SeaDAS, POC estimates were extracted from each station's coordinates at the time of sampling. Examples of this extraction are displayed in Figure 3. Pixel dimensions for these images are 9km by 9km, resulting in a 81 km² single pixel area. This means that each 81km ² area of surface ocean is represented by a single POC value.

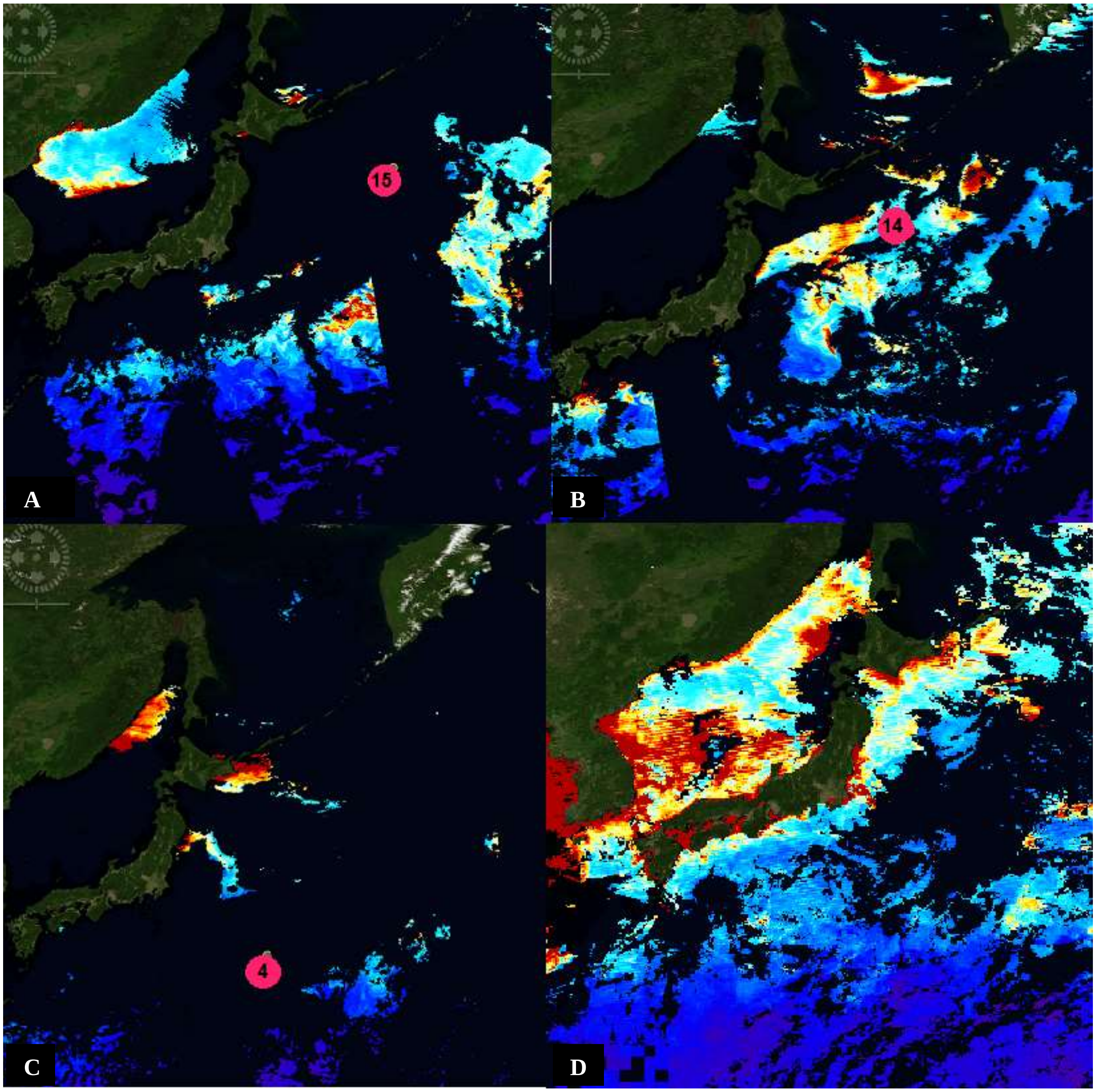

Figure 3. The extraction of POC estimates from Aqua MODIS data products using SeaDAS. Pink dots on each of the images indicate where the station was located during the time of the image. Panels (A) and (C) are examples of stations with no concurrent satellite based POC estimates, panel (B) is an example of a station with a POC estimate and panel (D) represents an average POC estimates composite image for 26 February - 6 March 2013.

In situ atmospheric conditions were collected by measuring the illuminance of 425nm light in Lux from the sky and the sea. This wavelength of light was chosen as it is blue and comparable to the wavelength that satellite sensors are measuring and using to create POC estimations. HOBO pendant temperature/light data loggers with band pass filters covering their sensors were attached to a 12 foot pole and extended over either the port or starboard side of the stern depending on which side was in full sunlight at the time of sampling. These sensors were positioned to face straight at the sky for ten minutes and then flipped over to face straight down to the sea surface for ten minutes. It is estimated that the sensors were maintained at a height of 16 feet above the sea surface. After 20 minutes of illuminance data was collected the data was extracted from the pendants into a HOBOware software program. A profile of the data series was created and the average Lux value of each data series computed via subset statistics analysis (Fig. 4). The difference between illuminance from the sky and illuminance from the sea was computed for 425nm light at each station by subtracting the average illuminance of the ocean from the average illuminance of the sky.

$$\text{Absorption} = (\text{Mean Lux of Sky}) - (\text{Mean Lux of Sea}) \tag{2}$$

Sea state at the time of each station was categorized via the Beaufort scale in order to objectively quantify the interaction of wind and waves at each station. Qualitative descriptions of the weather and sky state while on station were also recorded.

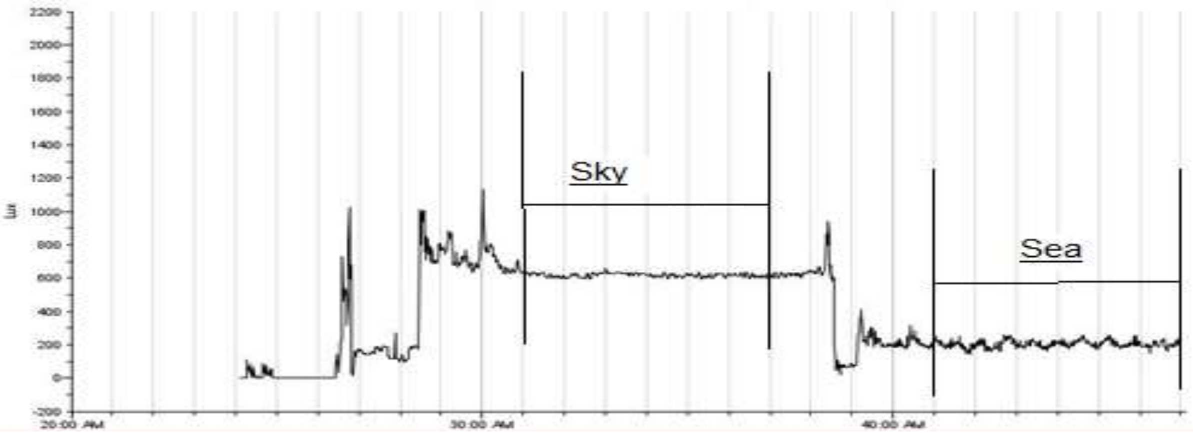

Figure 4. A time series showing illuminance in Lux of 550 nm light versus time in minutes recorded by a HOBO pendant temperature/light data logger one station. Crosshairs denoting "Sky" and "Sea" indicate time spans used to calculate average Lux values for the atmosphere and the sea surface via subset statistics. The difference between these averages was calculated in order to find the absorption of 425 nm light in the surface ocean.

Water samples were collected from CTD casts at 14 stations which are indicated in Figure 2.The samples collected at Stations 3, 14, 17 and 21 correspond to days when satellite based POC estimations were also available. Water was collected from within the top 100 meters of the water column since that is the extent to which blue light penetrates into the water column. Depth of sample collections varied per station as a reflection of varying chlorophyll profiles. One water sample was always taken at the depth of the chlorophyll maximum since there is a direct relationship between chlorophyll and POC. Two 400 milliliter replicates were filtered from each depth of sample collection since this volume provided roughly 10 times the detection limit of POC by the Carbon Hydrogen Nitrogen (CHN) analyzer. This volume was determined by calculating the amount of expected POC in the surface ocean based on the Hawaii Ocean Time-series dataset (http://hahana.soest.hawaii.edu/hot/hot-dogs/). from Station 2 and extrapolating that POC concentrations in the Kuroshio would be similar. Both locations are open ocean areas near islands in the North Pacific. Carbon clean 25mm GF/F filters were used to collect particulate samples that were then stored in a freezer onboard. Post-cruise, the dried samples and filters were taken to the University of Washington Marine Chemistry Lab and heated in an oven for twenty-four hours. The samples were then submitted to acid fuming for another twenty-four hours before being moved back into the oven for another twenty-four hour period. They were then processed by a CHN analyzer in the Krogslund Lab.

RESULTS

In situ light measurements were highly variable between stations across the Kuroshio Extension region. There was no obvious pattern detected in the amount of light absorbed in the surface ocean per station. It was expected that light absorption would be highest in region of high POC. Absorption was represented by the difference between irradiance of the sky and irradiance of the sea, as calculated in formula (2) and displayed by Figure 5. At every station the intensity of light from the sky was greater than the intensity of light from the sea, as expected. The Aqua MODIS satellite imaged the Kuroshio extension region at around 3:00 UTC every day. Stations 7, 14 and 20 were sampled within one hour of concurrent satellite imaging and should have experienced light conditions that were very similar to what the satellite experienced.

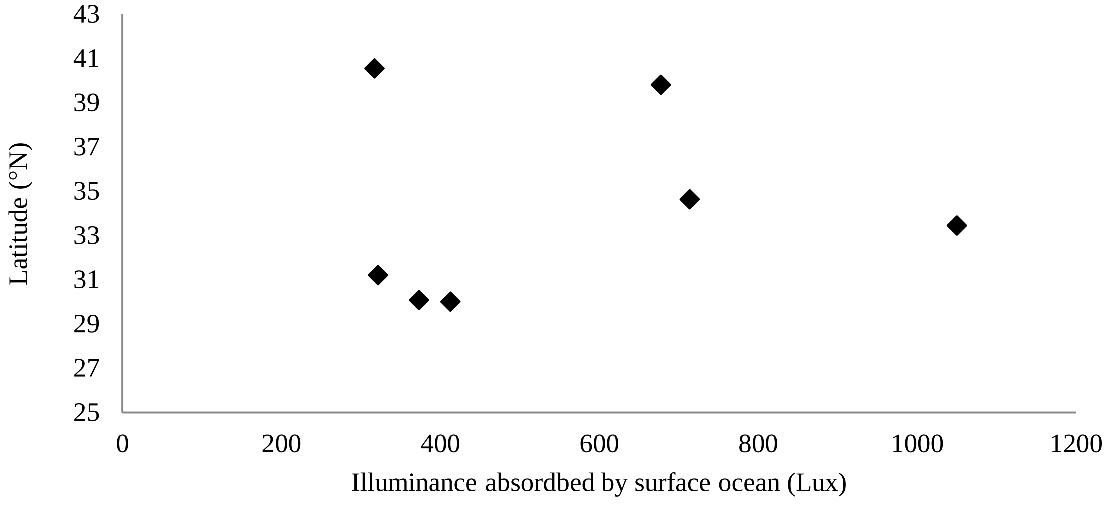

Figure 5. Absorption of 425 nm ligh,t as calculated by formula (2), in the surface ocean plotted against Latitude.

In situ POC varied visibly between stations. Depth profiles were taken starting at Station 12. Stations 3, 4, 7 and 11 only have POC measurements for the depth that corresponded to the chlorophyll maximum. This was due to a change in methodology during the cruise. The most notable depth profiles to consider are those of Stations 3, 14, 17 and 21 since they provide the POC concentrations to be compared to satellite based POC estimates (Fig. 6).

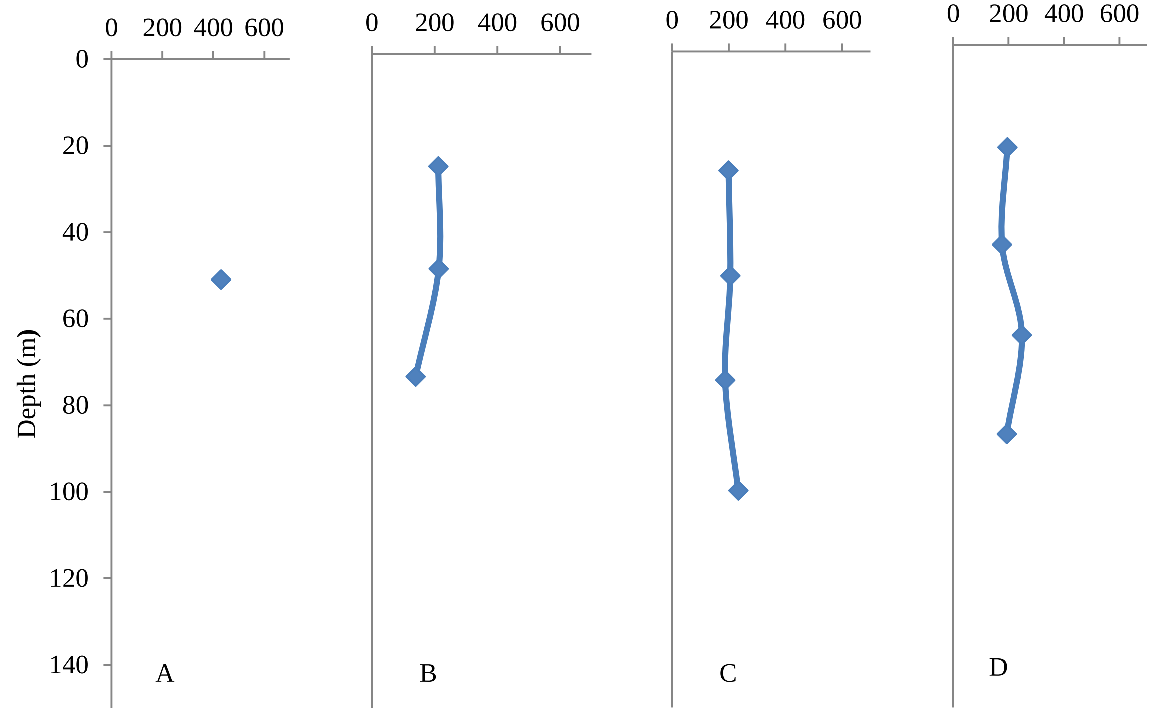

Figure 6. Depth profiles of POC concentration at Station 3 (A), Station 14 (B), Station 17(C) and Station 21 (D). These profiles were used to compute the mean POC in the photic zone at each station.

Average in situ measurements ranged from 210.59 µg/L to 429.61 µg/L for these four profiles. The maximum POC concentration calculated from a water sample was 428.82 µg/L at Station 21, the furthest south station. POC trends closely matched chlorophyll trends throughout the water column in that the maximum concentration usually occurred between 100 and 25 m, then decreased with depth. Figure 7 displays the trends in POC versus Latitude. There did not seem to be a strong linear relationship between latitude and POC. Lowest latitude stations can be categorized as subtropic and high latitude stations can be categorized as subarctic. The Kuroshio Extension is defined as between 33˚ and 35˚ north.

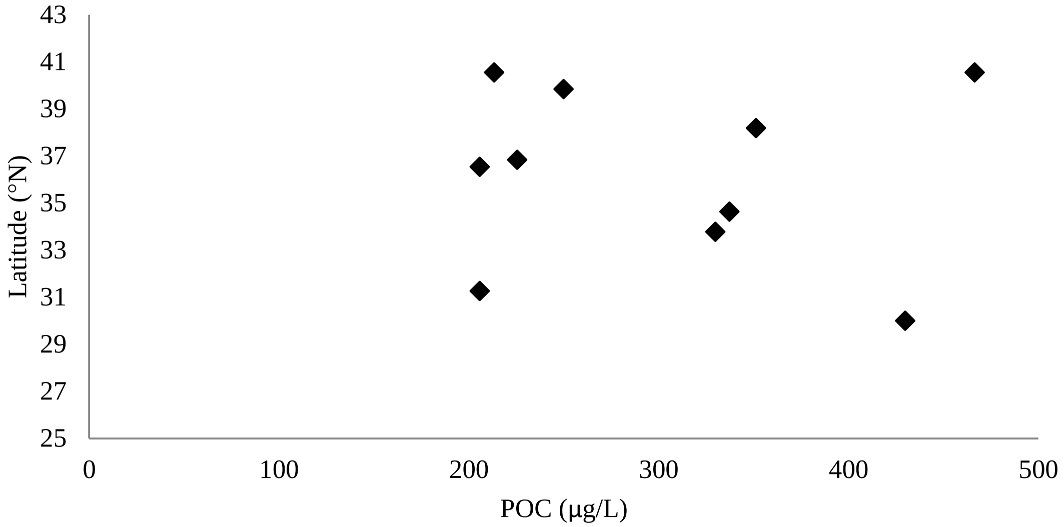

Figure 7.Variation of average POC concentrations compared to Latitude. The Kuroshio is estimated to be between 33° N and 35°.

A comparison of in situ light conditions to in situ POC concentrations does seem to display a linear correlation between absorption and POC based on an R^2 value of very close to one (Fig. 8). This trend is hard to accept due to the size of the data set. Only 2 of the 4 stations with concurrent remotely sensed estimates of POC had in situ light measurement data. This was due to variable weather and technical issues with the HOBO pendants. Light varied the most based on the time of day of sampling and POC varied the most based on sample station location. The maximum amount of light absorbed by the surface ocean was 412.7 Lux and corresponded with the maximum POC concentration of 429.61 µg/L. This trend suggests that the more light absorbed in the surface ocean, the higher the POC concentration of the water.

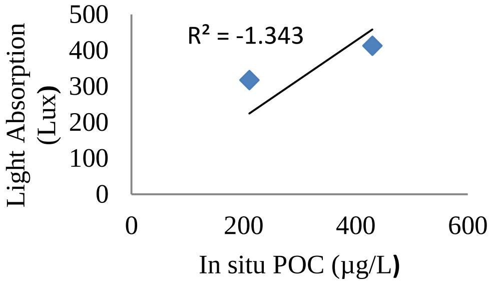

Figure 8. Absorption of 425nm light (Lux) in the surface ocean, as calculated by formula (2), versus the average POC concentration (µg/L)at Stations 3 and 14. This data is representative of the optical properties present at one point during a day when satellite observations of the surface ocean allowed for remote POC estimates to be calculated.

Satellite estimations of POC were available for four stations, 3, 14, 17 and 21. These 4 stations account for 28% of data collection events. The pixel size of the images used to make POC estimations was 9km by 9km.According to the satellite estimates of POC variation was minimal over the 14 days of data collection based on the 4 available indicator days. Estimated values of POC only ranged from 52.59 µg/L to 78.32

µg/L while average in situ measurements ranged from 210.59 µg/L to 429.61 µg/L. Satellite estimates of POC showed a change in concentration of roughly 6.43 µg/L per Station while average in situ measurements showed a change of roughly 54.755 µg/L. According to in situ data the POC max occurred at Station 21, the furthest South Station. Satellite based estimates of POC indicate that Station 14, a station in the midst of the Kuroshio experienced the highest POC concentration. According to in situ measurements Station 21 had an average POC concentration of 429.61 µg/L. Satellite based estimation Station 14 had a POC concentration of 78.32 µg/L. Satellite estimations of POC varied extensively from in situ measurements. They were closest in value to the minimum POC recorded per station, and even then these concentrations were quite different (Fig 9). The closest a POC estimate from remote observations came to matching a minimum in situ POC concentration was at Station 14, where the difference between estimate and measure was 61.24 µg/L.

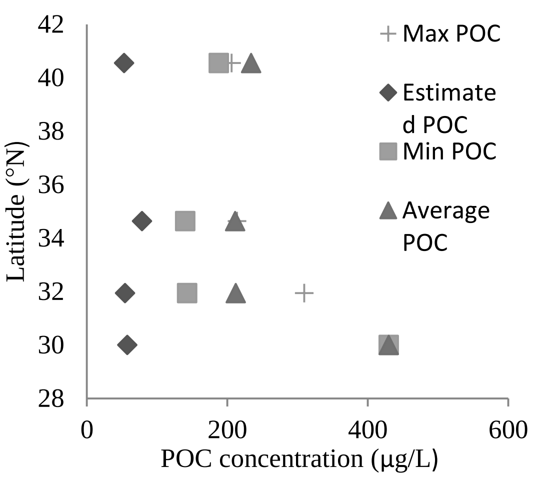

Figure 9**.** *Estimated and in situ POC concentrations plotted against Latitude.*

DISCUSSION

The first variable to be discussed is the in situ measurements of light conditions made by HOBO temperature and light pendants. The most important aspect of these measurements was the difference found between the illuminance of ambient light from the atmosphere and light reflected from the seas surface. This difference represents the amount of light that was absorbed and utilized in the surface ocean. Higher absorption of light in the surface ocean should indicate higher numbers of phytoplankton and, by association, POC. The maximum amount of light absorbed at a station where satellite estimates were available occurred at Station 14. This is concurrent with the highest satellite based POC estimate of 78.32 µg/L at Station 14. The other light measurements did not seem to display any trends that could be related to POC concentrations. Varying sea surface conditions such as waves and wind could be responsible for this lack of correlation (Fig. 10). High winds and large waves create a rough sea surface that reflects light very differently than a smooth sea surface. Backscattering gets sent in many different directions from a rough sea rather than straight back at the atmosphere from flat sea (Platt et al. 1998).

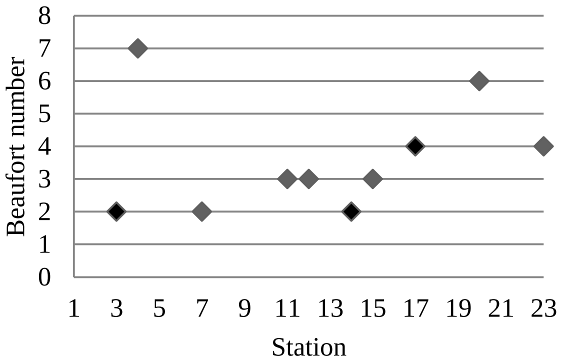

Figure 10. Sea state of each station during the time of sampling as described by the Beaufort System. The higher the number the higher the sea surface roughness based on wave and wind parameters.

Satellite based estimates of POC varied much less than in situ measurements of POC across the Kuroshio. Stations with remote POC estimates were on average 733 m apart and had a calculated average POC variance of only 16.127 µg/L per station. According to in situ measurements POC varied by 87.88 µg/L on average between stations. The satellite observations underestimate POC variance across the Kuroshio by a factor of 5 compared to what was observed in situ. In time, the stations were located 6.3 days apart on average. Based on remote estimates, POC varied by 16.127 µg/L every 6.3 days and 2.55 µg/L per day. In situ POC displayed a variance of 87.88 µg/L eveyr 6.3 days and 13.94 µg/L per day. During this time atmospheric conditions varied from high winds and rough seas to clear skies and calm seas. However, only days of clear and calm were registered by satellite sensors. This being said, estimated POC variance depended more upon spatial gradients rather than temporal change. In both time and space POC variance was greatly underestimated by satellite based estimates.

Satellite based estimates of POC greatly underestimated POC concentrations wherever there were in situ data points available for comparison. The greatest amount that POC was underestimated by was 372.56 µg/L at Station 3 and the minimum amount that POC was underestimated by was 132.27 µg/L at Station 14. These two stations are the furthest distance apart so the largest variation in POC would be expected in a region where physical properties vary dramatically with distance. Station # was in the subtropics and station # was in the subarctic. Overall there was no linear correlation tying together estimated and in situ POC (Fig. 11).

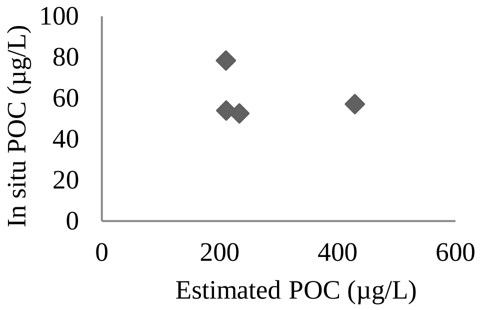

Figure 11. Measured POC from in situ water samples versus satellite based estimates of POC.

Past research comparing in situ and remote POC throughout the world's oceans have found very different results than what is presented here. The biggest difference is the scale of in situ POC measurements. In every other paper consulted POC concentrations from water samples were found to be much smaller than what was calculated in this project (Gardnera et al. 2006, Mishonov et al. 2003, Son et al. 2009, Stramska and Stramski 2005, Stramski et al, 1999) For example, in 2005 Stramski and Stramska calculated in situ POC from water samples taken along a transect of the north polar Atlantic and did not record any POC concentrations greater than 250 µg/L. In this project 250 µg/L was a middle range concentration. Differences between regional characteristics could be to blame, but this same pattern was found by Gardnera et al. in their global investigation in 2006. They calculated average POC during winter months between 1997 and 2002 and found a range of 60-100 µg/L for the Kuroshio region. The averages calculated in this project moer than doubled this range. The total range of in situ POC found was 139 µg/L to 430 µg/L, which now seems unrealistic in comparison. Gardnera et al. also created a histogram of seasonal POC data range averages for the Northern Hemisphere which concluded that less than 5% of average POC concentrations in the wintertime were greater than 120 µg/L. If this is correct the data from this project managed to capture the highest wintertime POC concentrations in the Northern Hemisphere. The disparity between the results of this paper and the results of others suggests an error in either sampling method or analysis occurred that inflated in situ POC measurements.

Finding smaller in situ POC concentrations in this research would have resulted in the discrepancy between estimates and measurements shrinking significantly, suggesting that algorithms based on remotely sensed variables are capable of reliably capturing in situ POC. This scenario would drastically alter the conclusions of this research.

CONCLUSION

In the context of the Kuroshio Extension region during February and March, satellite based estimations of POC did not accurately capture in situ POC trends or concentrations. Variation of POC across the Kuroshio was somewhat similar in trend, though not matching, and vastly different in concentration. The most important indicator of unsuccessful POC estimations is the strong underestimation of POC at all data points.

Satellites are an invaluable data source that allows the monitoring of large scale processes over long periods of time, but may not be as accurate as is expected over shorter time scales. While major trends in POC flux may be recorded accurately by satellites over periods of years, for the time scale and geographic scope of this study the results suggest that the satellite produced reliable data. This could be due to challenging atmospheric and sea state conditions at the time of this study as it was winter in the North Pacific. Frequent cloud cover was experienced for most of the study, as is represented by only 4 of 14 sample stations having concurrent satellite produced POC estimates. This limited the amount of estimations that could be calibrated against in situ data points. It also means that POC data from storm events are disregarded when computing regional averages. Storms increase mixing and can deepen the mixed layer, changing the concentration and distribution of POC throughout the water column.

To better capture in situ POC the algorithm used to produce estimates should be tailored so that it best represents the characteristics of the region it is being applied to. The algorithm currently in use was created based on parameters from a different region of the global ocean that did not take into account the specifics of the Kuroshio Extension in its development. While this algorithm may adequately estimate POC based on backscattering from the surface of the Eastern North Pacific, it does not seem to have the correct constants to be applicable to all regions of the ocean.

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