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Satellite Remote Sensing of Chlorophyll: Significance of PAR & Spatial Scale

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NONTECHNICAL SUMMARY

Satellites provide a system of large spatial and temporal data retrieval. They are orbiting the globe every minute of every day looking down at the earth. They record the reflected wavelength energy from earth which can be used in a variety of methods, including the estimation of chlorophyll. Chlorophyll is the pigment found in phytoplankton, which are in virtually every corner of the surface ocean. Satellite chlorophyll data is accordingly used to estimate phytoplankton abundance and the rate of global primary productivity. A limitation of satellite data collection is that the satellite can only record values down to where light is no longer reflected back to the surface, the 1% photosyntheically available radiation depth (0.1 PAR). This project explored the relationship between the 0.1 PAR depth and the percent difference between measured and remotely sensed chlorophyll concentration. Remotely sensed data is often unknowingly considered as true and valid. This project seeks to describe if PAR depth influences remotely sensed values.

ABSTRACT

Satellite remote sensing is used worldwide in many different sects of science. The advent of remote sensing allows a global database of daily information. The National Aeronautics and Space Administration's (NASA) Moderate Resolution imaging Spectroradiometer (MODIS) Aqua satellite is an example of a satellite currently collecting the reflected wavelength energy from the earth. The MODIS Aqua satellite records wavelength data down to the 1% photosynthetically available depth (0.1 PAR depth) of the water column, a vital component in the estimation of chlorophyll. If 0.1 PAR depth is shallow, leaving chlorophyll beneath un-recorded, there may be a under-representation of phytoplankton by the satellite. Conversely, colored suspended solids in surface waters may reflect similar wavelengths as chlorophyll creating an overestimation of total phytoplankton. This project examined the role of 0.1 PAR depth in the estimation of chlorophyll by satellites in the Eastern Tropical North Pacific (ETNP). Each station visited was assumed to be a representative sample of the 4km^2 area in order to compare it's chlorophyll with the MODIS Aqua chlorophyll. With only a limited amount of locations sampled, this project's results showed no relationship between PAR depth and the percent difference between in-situ and remotely sensed chlorophyll. This result is suggested to have occurred due to the disparity in spatial scale between the CTD and satellite values. This project affirmed that remotely sensed data is a tool that can be used to get a generalized picture of any place, but may misrepresent any spatially minute location.

Satellite remote sensing is commonly used in marine and oceanographic research as a tool to get quick estimations of chlorophyll, a proxy for phytoplankton abundance. Currently, the National Aeronautics and Space Administration's (NASA) Moderate Resolution imaging Spectroradiometer (MODIS) Aqua satellite is used in this estimation of oceanic chlorophyll. The satellite operates by collecting reflected wavelength energy daily from the earth as data; which is then converted via a chain of algorithms to chlorophyll concentration (Svab et al. 2005; Martin 2010). The MODIS Aqua satellite provides an accessible way to obtain large amounts chlorophyll data (Werdell et al 2009). Accordingly, time-series analysis of satellite data can be used as an indicator of how chlorophyll concentration changes worldwide (Brown et al. 2010; Arrigo et al. 2011).

The estimations of chlorophyll are characterized by a degree of error due to the spectral properties of the recorded water mass (Keifer 1973; Gitelson et al. 2007; Gitelson et al. 2008; Kobayashi et al. 2011; Zibordi et al. 2011). Satellite's only record the reflected wavelength energy down to the 1% photosynthetically available radiation (0.1 PAR depth). PAR is the measure of light attenuation of the water column, and will vary based on factors such as: light intensity and the concentration of total suspended solids (Svab et al. 2005; Martin 2010; Kobyashi et al. 2011).

Total suspended solids (TSS) include colored dissolved organic matter (CDOM) like biological detritus, and inorganic particulates including dust, sand, and clay (Keifer 1973; Kelbie et al. 2005; Martin 2010). Coastal regions are generally characterized by higher concentrations of TSS due to factors including terrestrial run-off and coastal upwelling. Terrestrial run-off contributes inorganic solids, and coastal upwelling promotes biological activity. Large TSS concentrations have multiple effects on the spectral properties of the water column. TSS will increase the amount of wavelength backscatter which results with the backscatter of particulates with similar spectral properties as chlorophyll; subsequently the satellite may overestimate chlorophyll concentration (Svab et al. 2005; Kobyashi et al. 2007; Zibordi et al. 2011). Additionally, TSS scattering of light will make the 0.1 PAR depth shallower (Melin et al. 2006). A shallow 0.1 PAR depth may result in a significant amount of chlorophyll which is not recorded by the satellite, creating a sub-surface chlorophyll maximum (SCM), translating into an underestimation of chlorophyll (Gitelson et al. 2007; Gitelson et al. 2008; Kobyashi et al. 2011). The objective of this project was to determine any relationship between the 0.1 PAR depth and the percent difference of in-situ and remotely sensed chlorophyll.

This project aimed to further the overall understanding of the reliability of satellite data. Investigations between satellite and in-situ chlorophyll abundance have been conducted before, revealing a relationship between percent difference of in-situ and remotely sensed chlorophyll and the number of spectral constituents (Melin et al. 2006; Gitelson et al. 2007; Kobyashi et al. 2011). This project did not delve into the exact spectral signature of the water column, but instead focused on easily measurable constituents: TSS and chlorophyll, and how they affect 0.1 PAR depth. Furthermore, this project compared remotely sensed chlorophyll values with single CTD chlorophyll integrations. Stations with high TSS and chlorophyll were expected to have a shallower 0.1 PAR depth, and that with a shallower 0.1 PAR depth there will be a greater absolute value amount of percent difference between in-situ and remotely sensed chlorophyll. This research promoted further knowledge about how PAR affects remotely sensed data and encouraged additional comprehension about the integrity of remotely sensed estimations.

METHODS

Study Area

From 19 March 2012 to 29 March 2012 aboard the University of Washington's *R/V Thomas G. Thompson* 18 distinct stations were visited throughout the Eastern Tropical North Pacific (Fig. 1). Stations ranged from 26^{o} North

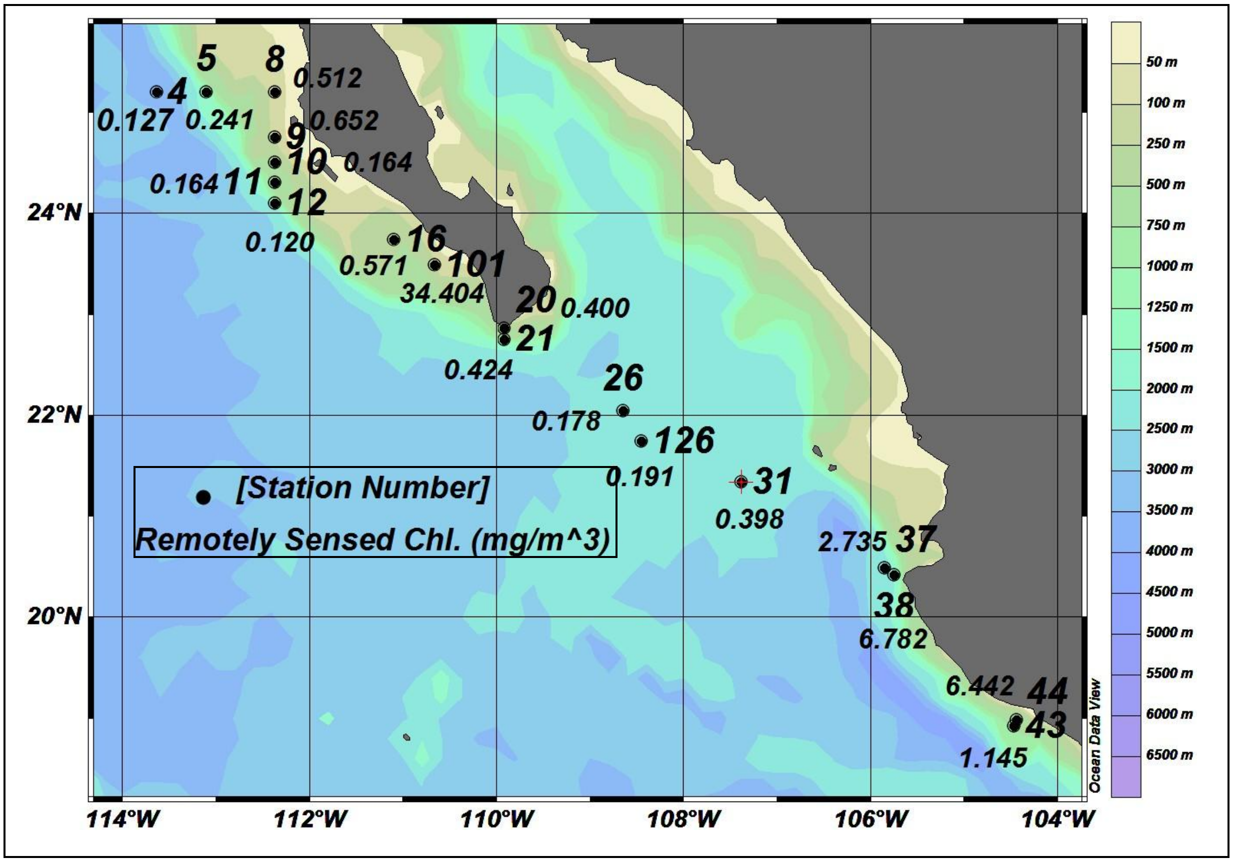

Fig. 1. Bathymetric map produced through Ocean Data View of surveyed area in Eastern Tropical North Pacific (ETNP) with station labels and corresponding MODIS Aqua post-processed chlorophyll values

116° West down to 18° North 104° West. All stations were visited during daylight hours with local time ranging between 06:30 to 18:08.

Stations were selected to represent a range of distances from shore.

Conductivity Temperature, Depth

The shipboard conductivity temperature and depth (CTD) apparatus was deployed at each station. The CTD electronics included probes measuring PAR, fluorescence and depth. The 0.1 PAR depth was determined by inserting the up-cast CTD data into Ocean Data View and locating where the PAR value approached 0.1. At nine stations (stations: 5, 9, 10, 11, 101, 126, 31, 37, 38) water samples were taken to calibrate the CTD fluorometer and to take TSS measurements. Depths of the water samples were determined based on the characteristics of the water column, making sure to get a surface and chlorophyll max sample. Stations were not sampled uniformly with depth.

Total Suspended Solids

Before departure of the cruise, 120 GF/F filters were dried and pre-weighed at the University of Washington in Kathy Krogslund's lab. 200mL of water from every depth was filtered on one of the labeled pre-weighed GF/F filter. Each water depth was sub-sampled three times. After filtration, the GF/F filter was stored at room temperature until return to the University of

Washington. The filters were dried under the same initial conditions and received a final weight using the same lab equipment and methodology. TSS values (mg) were determined by subtracting the final values from the initial weight.

Chlorophyll Concentrations

The same stations and depths for TSS water samples were used for chlorophyll sampling. 200mL from each depth was filtered on new GF/F filters. Then following the TD-700 Turner Designs Fluorometer methodology, the filters had 10mL of 90% Acetone added and were sonicated in a dark and cool environment. Next the samples were centrifuged, and then 10mL of the solution was poured into a VWR disposable culture tubes which could be inserted into the TD-700 Turner Designs Fluorometer. This bench top fluorometer produces Fo and Fa values. These were recorded and inserted into given equations to determine chlorophyll (µg/L) and phaeopigments (µg/L) which together comprise the fluorescence recorded by the CTD fluorometer. Each depth was sub-sampled the 3 times. The lab bench measurements were used to calibrate the CTD fluorometer by comparing the values and drawing a linear fit. The calibrated chlorophyll was then integrated down to where the values approached zero. The integrated values were then divided by 4000m, the spatial resolution that the MODIS Aqua post-processed data operates at.

MODIS Data

The NASA MODIS Oceancolor services database (oceancolor.gsfc.nasa.gov) was used to download single day, 4km pixel, MODIS Aqua chlorophyll concentrations. Each day's file was imported into ENVI, where it was geo-registered for exact latitude longitude values. The ENVI pixel locator tool was used to retrieve the value for the exact latitude and longitude of the station. Any station that had no value due to cloud coverage day of extraction would take its four neighbors' values (pending same condition), as well as the day before's values and the day after's (exact and four neighboring values). These three sets of up to five values each would be averaged to estimate the sample value. The difference between days at any location was only over 25% at coastal sites, which were did not experience cloud coverage during day of sampling. Percent difference was determined by subtracting the remotely sensed chlorophyll from the integrated in-situ chlorophyll, dividing that result by the in-situ value, and multiplying by one-hundred.

RESULTS

Chlorophyll

The highest integrated CTD chlorophyll values were found near the coast, stations 43 and 44 (0.750 mgm^{-3} and 0.612 mgm^{-3}). The calibrated CTD values were then compared against 0.1 PAR depths (m) (Fig. 2). As chlorophyll values increased (0.050 to 0.750 mgm^{-3}), 0.1 PAR depth (m) decreased (145m to 22m) (R^2= 0.6385).

Next, the depth of the chlorophyll max (m) at each station was compared against the stations' 0.1 PAR depth (m) (Fig. 3). As the depth of the chlorophyll max increased the depth of the 0.1 PAR also increases (R^2= 0.679). Stations found extremely close to shore had the shallowest chlorophyll max depth (stations 37, 38, 43 and 44).

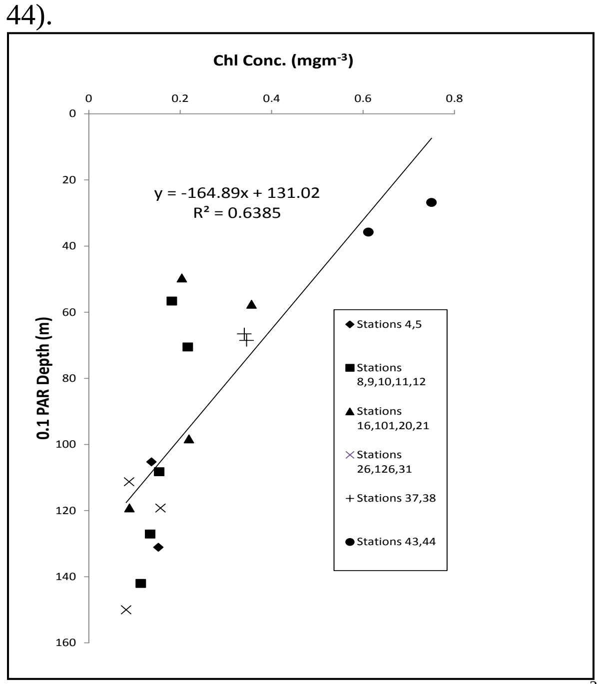

Fig. 2. Integrated in-situ chlorophyll concentration (mgm^{-3}) plotted against 0.1 PAR depth (m). A shallower 0.1 PAR depth was found with increased chlorophyll.

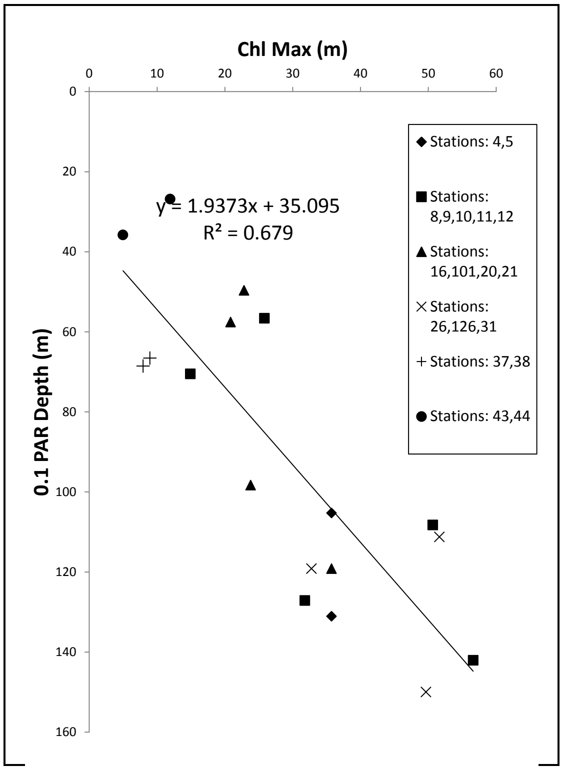

Fig. 3. 0.1 PAR depth (m) increases as the depth of chlorophyll maximum (m), determined using ODV, increases (R^2= 0.679).

Remotely Sensed Chlorophyll

NASA MODIS Ocean color website (oceancolor.gsfc.nasa.gov) chlorophyll values (mgm^{-3}) are shown on the map of stations visited (Fig. 1). The coastal stations (<500m bottom depth) exhibit a larger range of chlorophyll concentrations (0.164 mgm^{-3} – 34.404 mgm^{-3}) than the open ocean sites (0.120 mgm^{-3} – 2.735 mgm^{-3}).

These remotely sensed chlorophyll values were compared to calibrated CTD chlorophyll values (R^2= 0.0103) (Fig. 4a). Station 101 exhibited an extremely high remotely sensed chlorophyll concentration (34.404 mgm^{-3}) with a very low in-situ value (0.204 mgm^{-3}). After removal of that station, the correlation improves (R^2= 0.3274) (Fig. 4b). The coastal stations 37, 38, 43, and 44 exhibit the largest in-situ and remotely sensed chlorophyll concentrations.

The percent difference between in-situ and remotely sensed chlorophyll was determined and compared against the 0.1 PAR depths (Fig. 5). The outlier, station 101, was again pronounced in this

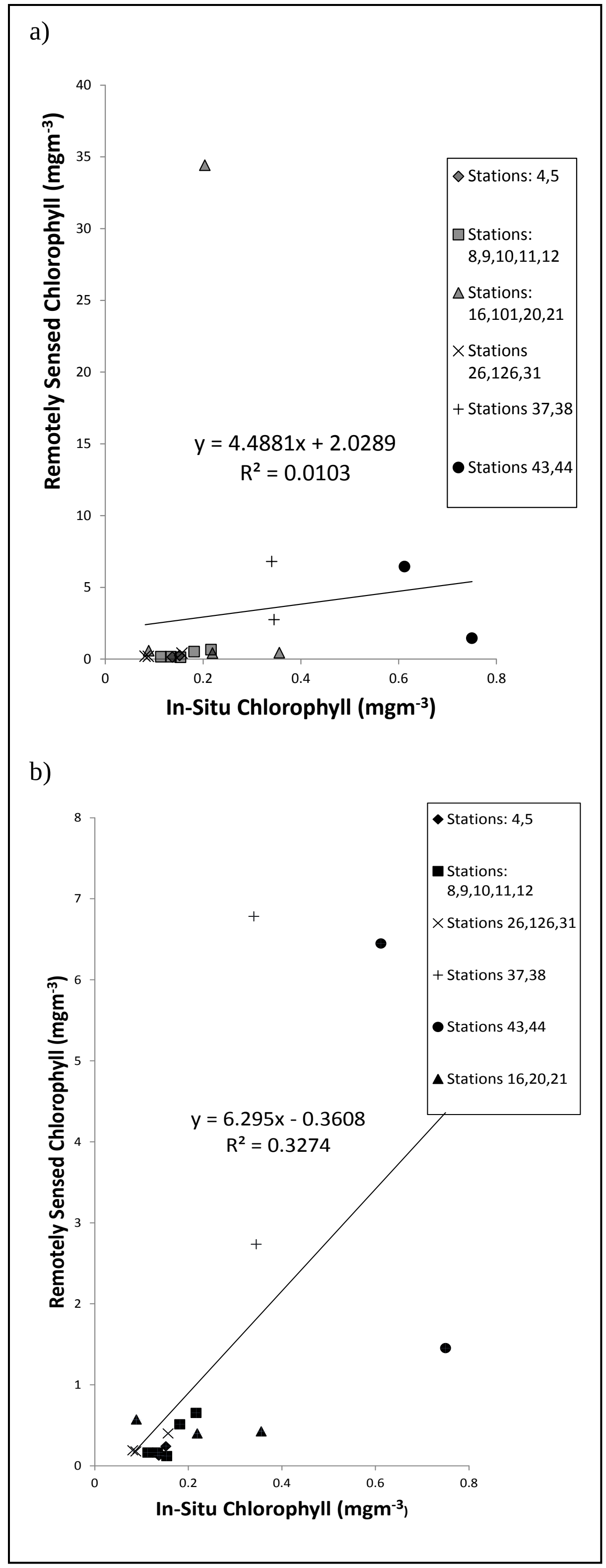

Fig. 4. Each station's in-situ and remotely sensed chlorophyll plotted (a) and the removal of outlier station 101 (b). Correlation between in-situ chlorophyll and remotely sensed chlorophyll increases with the removal of outlier station 101.

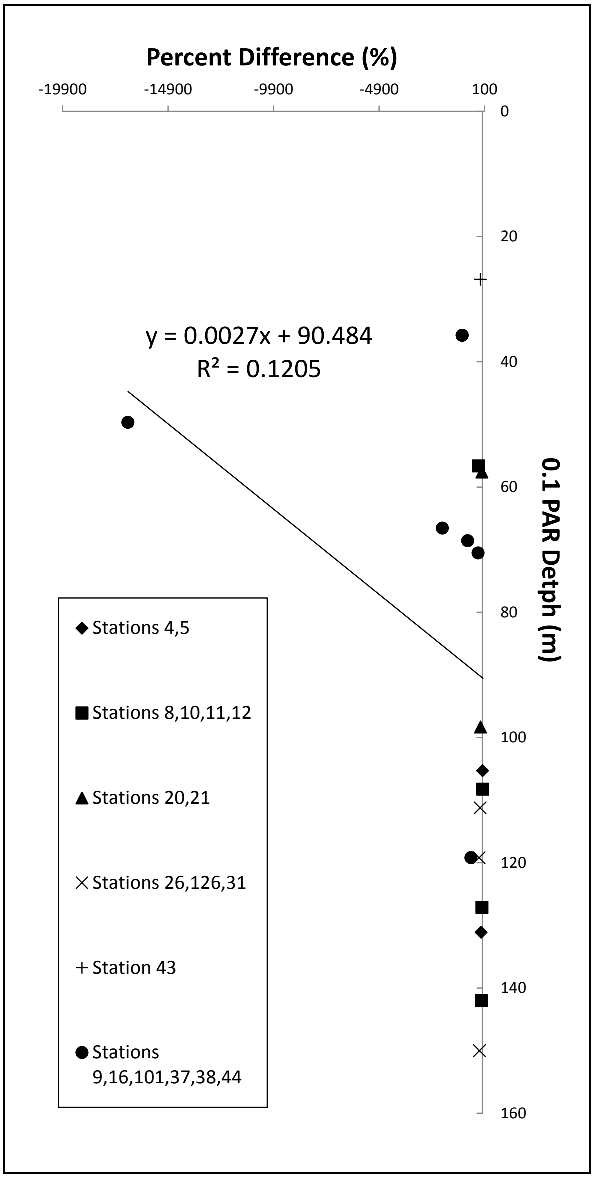

Fig. 5. Negative percent difference between in-situ and satellite chlorophyll values were seen throughout the data. Coastal stations including station 101 large percent difference construes the data.

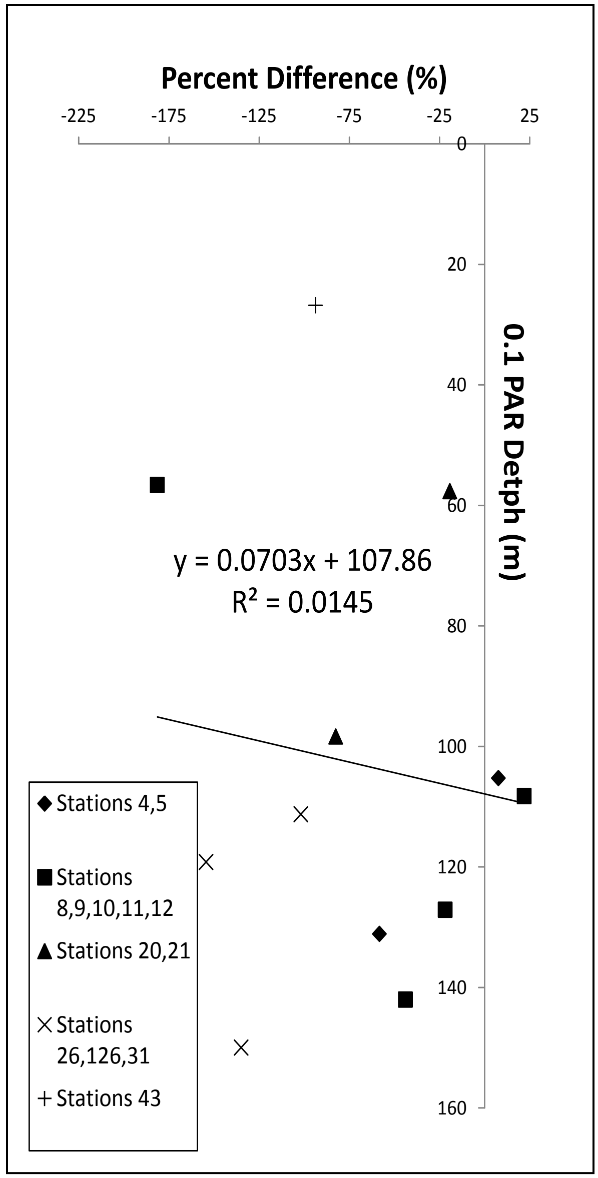

Fig. 6. Removal of coastal station outliers, zooming in on the other values, reveals that there is no significant correlation between 0.1 PAR depth and percent difference in chlorophyll.

view and removed, along with the coastal stations: 16, 37, 38 and 44. These stations dominated the results by having large negative percent differences. Once removed, the data still reveals no correlation (R^2= 0.0145) between percent difference and 0.1 PAR depth (Fig. 6).

TSS

Total suspended solid concentrations (mg) were determined for the nine stations where water was sampled. Water was sampled at different depths, requiring sample groups to be formed: stations 9, 101 and 38 had TSS integrated down to 20 meters; stations 10 and 126 down to 50m; stations 5, 11, 31, and 37 down to 100m. These depths were chosen due to the sampling method. TSS values from these stations were compared to

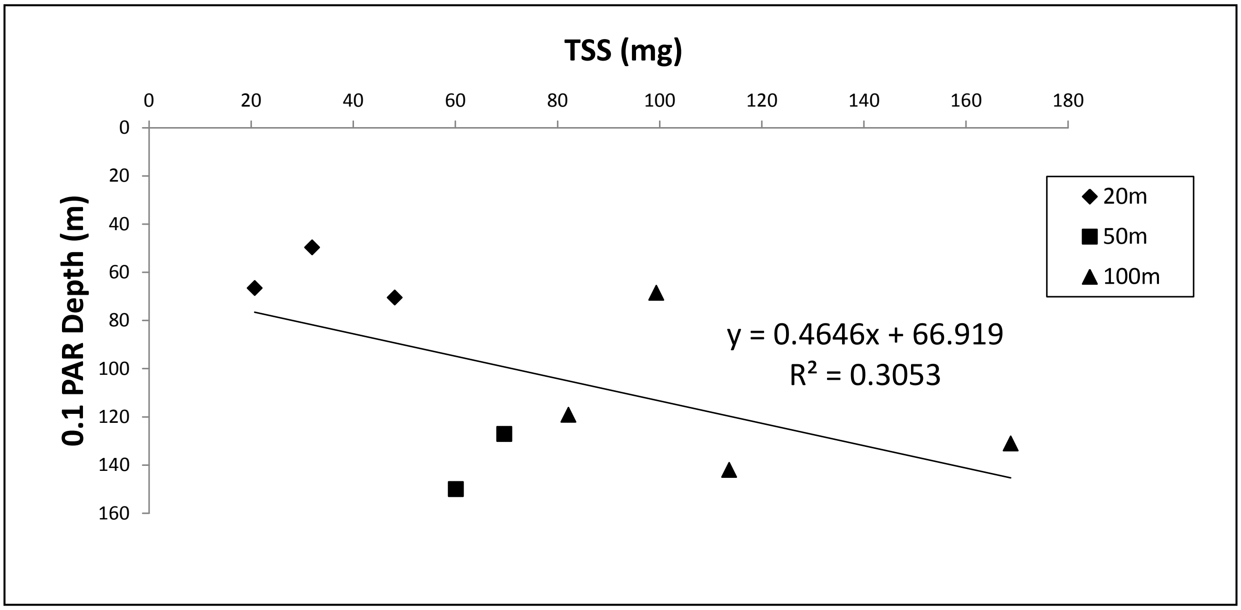

Fig 7. The correlation between 0.1 PAR depth and TSS was small (R^2= 3.053). TSS values were integrated at a range of depths (20m, 50m, 100m) due to sampling method.

the 0.1 PAR depth (Fig. 7), where 0.1 PAR depth increased as TSS increased. There was no significant correlation between TSS and 0.1 PAR depth (R^2= 0.3053). TSS was, with station 101 again removed, also found to have no correlation to the percent difference of chlorophyll (R^2= 0.0034) (Fig. 8).

More TSS was found in stations that had a larger integration range, and with more TSS there was a trivial decrease in percent difference of chlorophyll values.

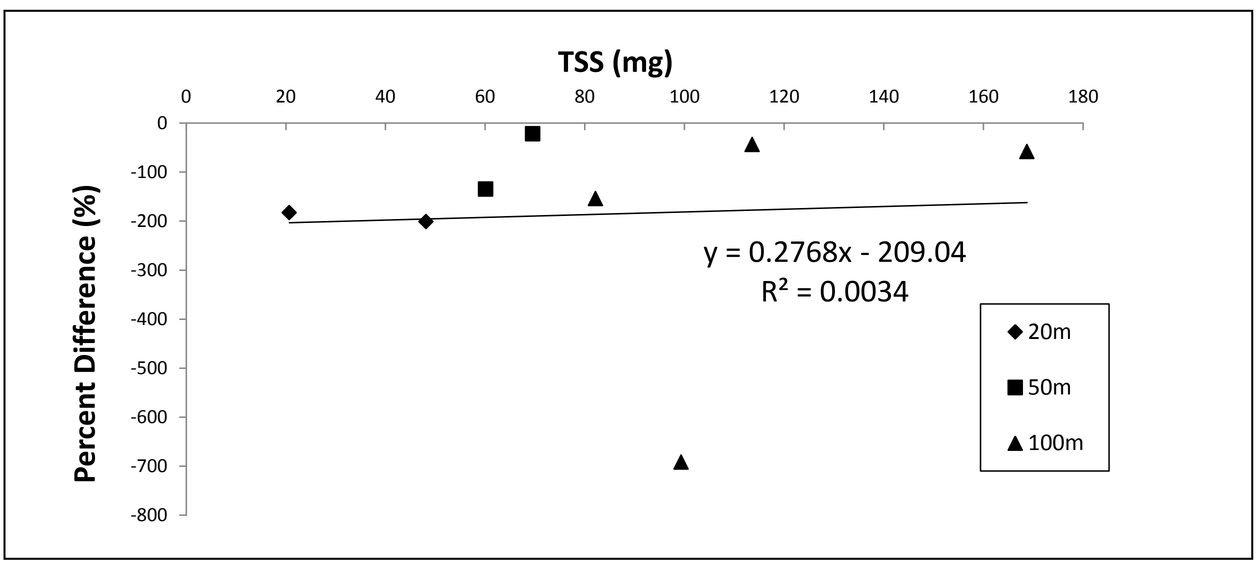

Fig. 8. Data revealed no relationship (R^2= 0.0034) between TSS and the percent difference between in-situ and satellite processed chlorophyll values. TSS samples were integrated to different depths (20m, 50m, 100m) due to sampling method.

Discussion

Stations were chosen primarily based on time of day during the cruise. The focus of the project was the role that PAR depth plays in affecting the percent difference in chlorophyll; hence every station was sampled during day-light hours. For the sake of this project, each station was assumed that time of day did not play a role in the results and that the CTD values were representative for the entire 4km area that is recorded by the MODIS Aqua satellite. This assumption was chosen mainly due to time constraints of the cruise, but also to test whether these types of comparisons are valid. Prior and likely future research has relied on remotely sensed data for estimations of concentrations in a small area (Boyce et al. 2010; Arrigo et al. 2011).

Calibrated chlorophyll values were greatest (>0.300 mgm^{-3}) at the 3 sets of coastal stations: 43 and 44, 21 and 20, and 38 and 37. The two lowest chlorophyll concentrations (<.250 mgm^{-3}) were seen at stations far from the coast (stations 26, 126 and 31; depth >2000m). Furthermore, stations 43 and 44 represented two of the shallowest chlorophyll maximums (<20m); as stations 126 and 26 had chlorophyll maximums twice as deep (>40m) (Fig. 3**)**. This trend is expected for the study area. Mid latitude waters are characterized by sufficient sunlight, with nutrients being the major limiting factor for phytoplankton growth and survival. Coastal areas are subject to increased nutrients due to terrestrial winds and runoff, as well as upwelling (Shanmugam 2010; Zibordi et al. 2011). With nutrients and sunlight, coastal phytoplankton growth can occur more than in the open ocean. The coastal increased phytoplankton combined with additional inorganic terrestrial solids will contribute to the scattering of light and will decrease the 0.1 PAR depth (Svab et al. 2005; Gitelson et al. 2007; Gitelson et al. 2008; Kobyashi et al. 2011).

This project attempted to generate an estimation of TSS at the nine stations where water samples were taken, but due to the procedure focusing more on chlorophyll the TSS values are less convincing. ‘Water’ stations had water removed at unequal intervals and frequencies, leaving some stations with only depths down to 20m sampled and others down to 100m. The results from this sampling method produced integrations of TSS that were inconclusive. Results showed that increased TSS had little effect on the 0.1 PAR depth (Fig. 7). This suggested that with more solids in the water the 0.1 PAR depth is not significantly affected (R^2= 0.3053). An explanation offered is that the stations with water samples taken only down to 20m may have a large increase in TSS just under that depth, which was un-recorded, and would decrease the 0.1 PAR depth (Svab et al. 2005; Kobyashi et al. 2011). An alternative explanation is that chlorophyll concentrations play a larger role than concentrations of TSS (R^2= 0.6385 for chlorophyll, Fig. 2) (Keifer 1973; Svab et al. 2005). A final hypothesis is that the solar intensity, which was not collected, between each station was significantly different which strongly influenced the 0.1 PAR depths. Further investigation with a more appropriate and comprehensive sampling method is needed to determine how TSS effects 0.1 PAR depth.

The majority of the remotely sensed data was greater than the CTD data (Fig.4). Coastal stations 8, 9, 20 and 21 exhibited relatively low values (0.399 mgm^{-3} to 0.650 mgm^{-3}) compared to other the other coastal stations, 37,38, 43 and 44 (1.145mgm^{-3} to 6.782mgm^{-3}); station 101 had an extreme value (34.404mgm^{-3}). One explanation for this is similar to why the remotely sensed data was almost universally higher than the integrated CTD values. MODIS Aqua post-processed data operates at a 4km spatial resolution. The spatial scale discrepancy harvests CTD values that might drastically misrepresent the pixel seen by the satellite. For coastal MODIS remotely sensed values this becomes additionally complicated due to the large chlorophyll gradient over space. Water closest to shore is commonly characterized with very high chlorophyll; and if relatively low chlorophyll water from just outside the pixel range is physically forced into the pixel (via: winds, currents, mixing, etc.) then the satellite may record the pixel as a relatively low value (Kobyashi et al. 2011). This chlorophyll gradient can be seen in stations 43 and 44 which were collected same day and were only 9km apart, but exhibited a difference in remotely sensed chlorophyll of 5.297 mgm^{-3} (Fig. 1). For stations 20 and 21 this was compounded due to the proximity of stations 26 and 126 which were further off-shore and characterized by low values (0.178 mgm^{-3} and 0.191 mgm^{-3} respectively). The data suggested stations 20 and 21 low values represented low chlorophyll water being physically driven near shore yielding a relatively low value.

Percent difference was determined between the in-situ CTD data and the remotely sensed data. The wide range of values (-16796% to 21.936%) demonstrates the complexity in this type of comparison. After excluding the extreme values, there still remains no correlation between percent difference and 0.1 PAR depths (R^2 = 0.0145). This suggests that 0.1 PAR depth and percent difference are not directly related. The only relationship found in the percent difference values was that with increased remotely sensed chlorophyll concentrations there was an increase in percent difference.

This project set out to see how percent difference of in-situ and remotely sensed chlorophyll concentrations (mgm^{-3}) compare with the 0.1 PAR depth in the Eastern Tropical North pacific. Specifically, this project intended to describe what physical constituents may affect PAR depth and thus affect the percent difference. The results from the data describe that chlorophyll is related in some degree with 0.1 PAR depth, but the data suggests no significant relationship between percent difference and 0.1 PAR depth. This project exemplifies the degree at which the spatial extent of your measurements is important in comparison with satellite data. Comparing single CTD cast data with daily satellite data proved to be a poor experimental assumption. Hence, this project illustrates the limitation of post-processed satellite data. Satellite data provides an excellent outlook into getting large spatial and temporal data, but lacks in producing small scale results. Research that plans to utilize satellite values may misrepresent their study area if this intrinsic inadequacy is not addressed. Satellite data is only appropriate when the scale of the project is similar to that which the data is produced. For this project's case, assuming one CTD would represent a $4km^2$ pixel was incorrect.

CONCLUSIONS

The creation of satellite remote sensing allows for a world-wide database of daily data. It was found in this project that to properly utilize this data, the spatial scale needs consideration. Many researchers unknowingly use satellite data believing its values valid. Though the values are not 'false', there could be extensive error if the comparison is on majorly different spatial scales. Further investigation on the role of 0.1 PAR depth effects on the percent difference between in-situ chlorophyll and satellite remotely sensed chlorophyll needs to account for spatial scale. Also, a more extensive water sampling method should be employed if the significance of TSS is to be considered.

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