Factors influencing phytoplankton and dissolved oxygen in San Juan Channel: a spatial and temporal assessment

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Abstract

The purpose of study was to investigate how physical and biological factors influence phytoplankton and dissolved oxygen spatially and temporally in San Juan Channel over fall and the annual cycle of 2011. Specific objectives were to 1) Spatially assess differences in the phytoplankton community by analyzing genera abundance over fall 2011 at North and South stations and compare spatial patterns with those found in chlorophyll, 2) temporally evaluate the correlation between chlorophyll and dissolved oxygen levels during fall 2011 at high resolution to infer whether phytoplankton, as indicated by chlorophyll, influences dissolved oxygen more than physical factors and 3) repeat the second analysis over the 2011 annual cycle. Phytoplankton genera in the San Juan Channel were consistently similar across stations and weekly cruises for fall 2011. Differences in phytoplankton genera were a result of single-species dominated periods. Phytoplankton abundance and chlorophyll concentrations were found to decrease as the season progressed to winter, consistent with previous studies. Physical factors dominated the influence on dissolved oxygen both spatially, across North and South stations, and temporally throughout the year with the exception of July. In July, biological factors appeared to be equivalent to physical factors in influencing dissolved oxygen, as a result of high summer productivity.

Introduction

It is well established that estuaries are dynamic ecosystems controlled by the circulation of water (Griffin and LeBlond 1990). Phytoplankton are essential energy sources for the majority of marine taxa in estuarine ecosystems (Begon et al. 1986). In

estuaries, phytoplankton abundance is highly variable and controlled by both physical and biological processes (Cloern and Jassby 2009). Tides, water density and winds regulate estuarine circulation and are physical drivers affecting phytoplankton distribution and abundance (Brown and Ozretich 2009; Iverson et al. 1974). These physical drivers affect not only the distribution of phytoplankton cells, but also the nutrient and light environment on which cells depend for growth.

Phytoplankton are important because they play a major biological role in the environment by contributing to 95% of marine primary production, thus forming the base of the food web (Daly and Smith 1993). Global phytoplankton concentrations have declined in the past century making them important to monitor, especially in light of climate change as they produce over 50% of atmospheric oxygen while consuming carbon dioxide (Boyce et al. 2010; Siegel and Franz, 2010). Chlorophyll pigments within phytoplankton cells are crucial to photosynthesis, and thus oxygen production. This relationship between phytoplankton and chlorophyll allows for chlorophyll to serve as a simple proxy for phytoplankton abundance. Phytoplankton, indicated by chlorophyll, are major biological factors affecting dissolved oxygen in the water column.

Dissolved oxygen is necessary for the survival of most aquatic organisms, and as previously stated; levels are influenced biologically through phytoplankton. Dissolved oxygen levels are also influenced by physical factors such as: solubility into seawater as a function of temperature and salinity; aeration of water via waves and wind and degree of mixing. Phytoplankton, chlorophyll and dissolved oxygen are thus all inter-related.

Since the pelagic ecosystem in the San Juan Archipelago is heavily driven by physical factors, previous studies from McLaughlin (2009) and Cohen (2010) have

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focused on the physical factors attributed to chlorophyll and dissolved oxygen variation across spatial and temporal scales. The San Juan Archipelago is situated south of the Strait of Georgia and north of the Strait of Juan de Fuca (Fig. 1). Waters north of Cattle Pass have a higher freshwater influence from the Fraser River and thus exhibit higher levels of mixing (Cohen 2010). In contrast, waters south of Cattle Pass show a stratified water column with a deeper oceanic layer from the Pacific Ocean (Cohen 2010). North and south stations located in upper San Juan Channel and in the northern part of the Strait of Juan de Fuca, just south of Cattle Pass, respectively have been ideal study sites to discern spatial differences in phytoplankton based on varying physical factors.

The purpose of my study was to build on previous investigations made on physical factors influencing dissolved oxygen to include biological influences, in order to better understand the relationship between phytoplankton and dissolved oxygen in San Juan Channel during fall and over the annual cycle for 2011. Specific objectives were to 1) Spatially assess differences in the phytoplankton community by analyzing genera abundance over fall 2011 at North and South stations and compare spatial patterns with those found in chlorophyll, 2) temporally evaluate the correlation between chlorophyll and dissolved oxygen levels during fall 2011 at high resolution to infer whether phytoplankton, as indicated by chlorophyll, influences dissolved oxygen more than physical factors and 3) repeat the second analysis over the 2011 annual cycle.

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Methods

Study site

This study was conducted in the San Juan Archipelago in Washington State, USA at two sites within the San Juan Channel: the North Station (48˚35.00' N 123˚02.50' W) and South Station (48˚25.20' N, 122˚56.60' W) (Fig. 1). Previous studies show spatial variation between North and South Stations (Zamon, 2002). Data were collected from North and South Stations on R/V Centennial cruises occurring in October and November of fall 2011 (Table 1).

Hydrographic measurements

At each station fluorescence (chlorophyll indicator) and dissolved oxygen versus depth measurements were acquired using a Seabird SEACAT SBE-19 conductivity-temperature-depth instrument (CTD). CTD sensor arrays were soaked at ten(10) meters for three(3) minutes and zeroed at the surface to attain consistent calibrations before each cast. The CTD was then uninterruptedly deployed to maximum cast depth, approximately 5-10m from the bottom, and fluorescence and dissolved oxygen data from downward casts were averaged into 0.5m bins. CTD sensor data were converted into Microsoft Excel spreadsheets using SBE Data Processing Software following the standard operating procedure generated by the JEMS lab (Joint Effort to Monitor the Strait of Juan de Fuca, FHL, 1999).

Water samples were collected with two liter Niskin bottles during the ascent of CTD casts at fixed depths of 0m, 10m, 20m and 50m for each site. Due to the variable depth of the water column between stations deeper water samples ranged from 80m to

125m, where one sample was always taken at the specific maximum depth cast. Water samples were then subdivided for discrete chlorophyll and dissolved oxygen analyses.

Chlorophyll and phaeopigment analysis

The measurement of chlorophyll, a pigment essential to photosynthesis, and phaeopigment, a degraded non-photosynthetic pigment from chlorophyll, is a widely used technique to predict plant biomass in seawater (Lorenzen 1986). From Niskin water samples at each depth, 0.065L of water was filtered through a 5μm Whatman glass microfiber filter coated with aqueous magnesium carbonate on a vacuum filtration rack. Each filter was placed in a plastic tube with 10 mL of 90% acetone and then frozen for a minimum of 24 hours before in vitro fluorometry. Acetone extracts were analyzed using the standard operating procedure described by Newton and Van Voorhis (2002) on a Turner 10 Analog fluorometer. Fluorescent readings were used to calculate chlorophyll and phaeopigment concentrations.

Dissolved oxygen analysis

In order to avoid any air bubbles, extra oxygen, from penetrating the sample water transfer from Niskin bottles into precisely measured 125mL Erlenmeyer flasks was done within plastic tubing and flasks were overflowed. Dissolved oxygen was then fixed with 1 mL $MnCl_2$ and 1 mL NaOH-NaI and then capped, shaken, settled for 15 minutes and shaken to ensure the reaction was complete. The addition of chemicals and procedure was according to the Carpenter modification of the Winkler titration method (Carpenter 1965, Winkler 1888). Samples were then titrated to one thousandth of a milliliter, with a sodium thiosulfate solution following the standard operating procedure for the Winkler

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titration method on a Beckman® Dosimat microburet. Titration data were used to calculate dissolved oxygen content in each sample. The Winkler oxygen data was then plotted against the CTD oxygen sensor data for each depth in order to determine a calibration equation to obtain calibrated dissolved oxygen values.

Net sampling of phytoplankton

Phytoplankton were sampled from North and South stations across seven cruise dates in Fall 2011 (Table 1). At each station plankton were collected with an 80μm mesh ring net vertically towed from a depth of 10m to the surface. However, a vertical tow from a depth of 30m to the surface would have been more ideal to capture the entire euphotic zone, where phytoplankton are found actively. To account for patchiness in phytoplankton distribution two tows per net size at each station were taken. Nets were rinsed with pressurized seawater and cod-end contents were immediately emptied and preserved in approximately 1.0 -2.0mL of 10% buffered formalin in glass jars. I will further denote a tow sample as one tow

Phytoplankton identification and characterization

A subsample of 1.0mL was taken from every tow sample and mounted onto a Sedgwick-Rafter counting slide. To obtain an accurate representation of the tow sample subsamples were triplicated, thereby obtaining six subsamples per station. The Sedgwick-Rafter counting cell slide was most ideal as it allowed one to determine particles per unit volume. When filled with liquid and enclosed with a cover glass the Sedgwick-Rafter chamber holds 1 mL of volume. The base of the Sedgwick-Rafter is etched with a grid of

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100 x 1mm squares, thereby each square holding 1μL of volume. For each subsample ten randomly selected squares on the Sedgwick-Rafter counter were examined using an Olympus BH-2 compound light microscope at 100-200X magnifications. Every phytoplankton cell encountered was counted and identified to genus.

Conversely, counting ten squares per sample on the Sedgwick-rafter chamber did not yield accurate results when measuring *Coscinodiscus* species, a large and rare diatom. So in addition to the aforementioned sampling method all *Coscinodiscus* species across the entire counting chamber per sample were counted separately.

The phytoplankton community was characterized by abundance and relative genera abundance. Relative abundance in cells/L in the water column was calculated for each genus by extrapolating how many were counted in 1.0mL of the sample to the total number counted in the plankton tow (estimate of volume obtained in cod-end), and then divided by the total volume of water filtered through the net. The volume of a cylinder was determined using the diameter of the mesh ring net with the depth of the tow in order to calculate the total filtered volume.

Statistical analyses

Linear regression analyses to designate correlations for fall and annual comparisons of DO vs. Chlorophyll and DO vs. Salinity on MS Excel 2010. Contour plots of dissolved oxygen and chlorophyll fluorescence were created on SigmaPlot, vs11. Photosynthetically active radiation data (PAR) was obtained from the FHL Weather Station to determine the fall phytoplankton bloom.

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Results

1- Spatial comparison of phytoplankton and chlorophyll for Fall 2011

1.1 Genera abundance

North-

The most abundant genus at the North station during fall 2011 varied (Fig. 2). *Ditylum* spp., a chain-forming diatom, was the dominant genus at the beginning of the season (October 4 and October 7) and gradually decreased as the season proceeded (Fig. 2). The opposite trend was observed for *Chaetoceros* spp., where there was a gradual increase from 267 cells/ L on October 4 to 15183 cells/L on November 1 (Fig. 2). Aside from micro-population decreases and increases in genera, the majority of species remained consistently variable across sampling dates with the exception of a *Coscinodiscus* spp. monoculture on November 7.

South-

Genera abundance was variable across sampling dates at South station (Fig. 3). The most abundant genus at South station was *Chaetoceros* spp., which ranged from 17 - 333 cells/L (Fig. 3). Similar to North station, *Chaetoceros* spp. also increased throughout the sampling period at South station. On the dates that *Ditylum* spp. at North station decreased, *Coscinodiscus* spp. at South station also decreased. The most abundant genera were the same for both North and South stations, with the exception of *Pseudo-nitszchia* spp., which was only found at North station (Fig. 2).

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Coscinodiscus species-

Coscinodiscus spp. abundance was higher at South stations for all cruise dates (Fig. 4). The abundance remained consistent for each station across the season, abundance at North station ranged from 1 to 7 cells/ L, and the South station ranged from 3 - 10 cells/L. No *Coscinodiscus* spp. blooms were apparent.

1.2 Phytoplankton abundance

Phytoplankton abundance was variable during Fall 2011 across sampling dates; however, there was an overall trend for decreased abundance at North and South stations as the season progressed (Fig. 5). Phytoplankton abundance was higher at North stations for all cruise dates with the exception of November 7 (Fig. 5). Abundance at the North station ranged from 4 - 4589 cells/L, while the South station had a narrower range with 13 - 167 cells/L. There was evidence of a bloom on October 18. The highest abundance was at the North station, and coincided with three consecutive days of high PAR values (Fig. 6).

1.3 Chlorophyll content

Chlorophyll comparison-

Chlorophyll fluorescence measurements from the CTD sensor (*in situ*) with extracted chlorophyll (*in vitro*) correlated strongly at North station (R^2= 0.82), but weakly at South station (R^2= 0.38) (Fig. 7). In order to evaluate the effectiveness of chlorophyll as a proxy for phytoplankton abundance, chlorophyll fluorescence and phytoplankton abundance were compared using Excel regressions. North station phytoplankton

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abundance did not show a strong correlation between in vivo and in vitro chlorophyll measurements (R^2=0.05 and R^2= 0.07, respectively) (Fig. 8). South station phytoplankton abundance also did not strongly correlate with in vivo and in vitro chlorophyll measurements (R^2= 0.04 and R^2= 0.13 respectively) (Fig. 9).

Chlorophyll concentration-

Average chlorophyll concentrations in the euphotic zone (top 30m of water column) remained generally consistent for North and South station throughout the season (Fig. 10). At North station, Chlorophyll concentrations ranged from 0.35 - 0.82 µg/L, with the exception of a large peak on October 4 (2.51 µg/L), indicative of a bloom. Evidence for a bloom on October 4 at North station did not coincide with three consecutive days of high PAR levels, but did correspond to the highest PAR level this season (Fig. 3). South station also exhibited a similar range of concentrations from 0.34 – 0.87 µg/L across all cruise dates; however, there was no evidence for a bloom.

2- Within fall 2011 comparison of dissolved oxygen, chlorophyll and salinity

2.1 Dissolved Oxygen

Dissolved oxygen levels varied between North and South stations. Dissolved oxygen remained stable within each station throughout fall 2011. Dissolved oxygen concentrations ranged from 4.5 – 7.0 mg/L at North Station, and was evenly distributed throughout the water column during our sampling period (Fig. 11). South station oxygen levels were stratified throughout the sampling period. Oxygen levels deeper than 30 m

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ranged from 3.5-5.0 mg/L. In the euphotic zone (30 m and shallower), oxygen concentrations were 5.0 – 6.5 mg/L (Fig. 12).

2.2 Chlorophyll

Chlorophyll fluorescence varied between North and South stations, but within-station variation was constant throughout the sampling period. North station chlorophyll content ranged from 1.0 - 2.0 mg/m^3 throughout the water column. The exceptions were on October 4 to October 18, when concentrations peaked from 2.5 – 4.5 mg/m^3 at 0-20m (Fig. 13). In contrast, chlorophyll content throughout the entire water column at South station had a smaller range (0.8 - 2.2 mg/m^3) but exhibited stratification at 40m with higher oxygen values in surface waters (Fig. 14).

2.3 Dissolved Oxygen versus Chlorophyll

Discrete dissolved oxygen and chlorophyll linear regressions showed strong correlations (R^2=0.59 - R^2= 0.94) for each cruise at North station (Fig. 15). South station linear regressions from discrete oxygen and chlorophyll data displayed somewhat weaker correlations (ranging from R^2= 0.042 to R^2= 0.94) across all cruise dates (Fig. 16). Sensor (CTD) dissolved oxygen and chlorophyll linear regressions also exemplified strong correlations, with high R^2 values for each cruise date at North and South stations (Fig. 17, Fig. 18). Regressions made from discrete data had stronger correlations than sensor (CTD) data (Table 2), indicating more precision in discrete measurements.

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2.4 Dissolved Oxygen versus Salinity

Linear regressions of dissolved oxygen and salinity showed strong correlations for each cruise at North and South stations (Fig. 19, Fig. 20). Salinity increased as oxygen decreased. Salinity ranged from 28- 32 PSU and 29– 33 PSU at North and South stations respectively. To determine how phytoplankton may have affected dissolved oxygen, dissolved oxygen versus salinity linear regressions were performed and compared to dissolved oxygen versus chlorophyll (proxy for phytoplankton) linear regression correlations. Dissolved oxygen versus salinity regressions yielded stronger correlations between both stations across the fall season (Table 3), indicating that perhaps physical factors are dominating over biological effects on DO.

3- Annual comparison of dissolved oxygen, chlorophyll and salinity

3.1 Dissolved oxygen

Dissolved oxygen levels varied between North and South stations as well as within each station across 2011 sampling periods.

North-

Dissolved oxygen concentrations ranged from 4.0 – 11.0 mg/L at North Station during 2011 (Fig. 21). Early in the year, dissolved oxygen levels ranged from 7.0 to 11.0 mg/L across the water column until a sharp decrease in occurred in June, which had concentrations from 4.0 – 7.0 mg/L.

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South-

South station dissolved oxygen levels remained stratified, with consistently higher ranges above 30m throughout the year (Fig. 22). Similar to North station, there was a transition in July from higher dissolved oxygen levels (6.0 – 10.0 mg/L) to lower levels at 4.0 mg/L below 30m and 6.0 mg/L above 30m.

3.2 Chlorophyll

Chlorophyll fluorescence varied on an annual time scale between North and South stations, but remained relatively constant within each station. North station chlorophyll content ranged from 2.0 - 4.0 mg/m^3 throughout the water column, except in April when concentrations ranged from to 10.0 – 14.0 mg/m^3 at 0 - 20m (Fig. 23). In contrast, chlorophyll content throughout the entire water column at South station had a smaller range, from 1.0 - 3.0 mg/m^3. Where a similar peak in April was also exhibited, concentrations above 20m reached 6.0 mg/m^3 (Fig. 24).

3.3 Dissolved oxygen versus Chlorophyll

Dissolved oxygen versus chlorophyll linear regressions yielded strongest correlations in February, April, and August at South station. Correlations at North station were strongest in July (Table 4). Regression plots for February 10, April 26, July 5, July 8, July 19 and August 9 are in Appendix A.

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3.4 Dissolved Oxygen versus Salinity

Dissolved oxygen and salinity linear regressions showed strong correlations for all cruises at North and South stations for fall 2011 (Table 5, Table 6). Salinity increased as oxygen decreased, where salinity ranged from 22- 31 PSU and 29– 33 PSU at North and South stations, respectively. Dissolved oxygen versus salinity regressions showed stronger correlations between both stations annually. Regression plots for February 10, April 26, July 5, July 8, July 19 and August 9 can be found in Appendix B.

Discussion

For fall 2011, centric and pennate diatoms comprised the majority of the phytoplankton community in San Juan Channel as has been found in previous PEF assessments (Green 2010). The most common genera during fall 2011 found at North and South stations consisted of: *Ditylum spp*., *Chaetoceros spp*., *Coscinodiscus spp*., *Skeletonema spp*., *Thalassionema spp*., and *Cerataulina spp*. *Pseudo-nitzschia spp.*, a genus of phytoplankton known to on occasion cause harmful algal blooms, was the exception and only found at North station.

Past studies found variable genera abundances across the weekly sampling dates and between stations (Runyan, 2006; Green 2010), however Runyan's data showed consistency between successive days, indicating that variation on a temporal scale occurs between two(2) and seven(7) days. Patterns in phytoplankton genera varied consistently across stations and cruise dates, but large genera dominated periods across days and weeks were observed for *Ditylum spp., Chaetoceros spp.,* and *Coscinodiscus spp*. (Fig. 2, 3). Variation in genera with time over short temporal scales may be due to differences in

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growth conditions. Different phytoplankton genera have different temperature, salinity, light and nutrients requisites optimal for growth and development (Smetacek 1985). Since known differences in water characteristics at North and South stations exist, genera patterns across spatial scales are expected and highly related to variations in water chemistry and movement.

Coscinodiscus spp. abundance yielded higher abundances at South station than North station (Fig. 4). Reasons could be attributable to tidal currents advecting oceanic waters to South station with an abundance of *Coscinodiscus* spp. (Zamon 2002). Abundance of *Coscinodiscus* spp. relative to other years is a lot lower, where other years concentrations varied between 4 and 77 cells/L. Increased understanding of water property combinations selecting for fluctuations of specific genera abundance would be needed to further understand genera succession and interannual differences. Continuation of fluctuations in *Coscinodiscus* spp., would contribute to knowledge of this important phytoplankton genera in San Juan Channel.

Overall phytoplankton abundance through the season decreased at both stations, with the exception of a peak on October 18 at North station, indicative of a fall bloom. This decreasing trend in phytoplankton abundance is also observed in chlorophyll levels throughout fall 2011 (Fig. 5). Phytoplankton abundance are limited by nutrients and light (Newton and Van Voorhis 2002). Patterns in declining phytoplankton abundance are driven by the reduction of nutrients in spring and light as the season progresses to winter (Reid et al. 1978; Newton and Van Voorhis 2002).

The peak phytoplankton abundance (Oct 18) did not coincide with the peak in fluorescence. The chlorophyll concentrations show a maximum on October 4 at North

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station (Fig. 10). Differences in these bloom dates and lack significant fluorescence versus phytopkankton abundance correlations (Fig. 7) are attributed to phytoplankton collection and variations in depth measurements throughout the water column. Phytoplankton collections were done with an 80μm mesh net size, limiting samples to larger species, thereby losing smaller sized plankton cells. However, studying chlorophyll concentrations are a common proxy for phytoplankton abundance and account for the presence of smaller cells (Lorenzen and Downs 1986). Phytoplankton abundance was only measured at surface waters from 10 to 0m, where as chlorophyll concentrations were calculated for the entire water column. Weak correlations between chlorophyll and phytoplankton abundance is not atypical and attributed to variability in phytoplankton species ability to photosynthesize at different rates and hold different concentrations of chlorophyll (Raith 2008). With the exception of the timing of the bloom, declines in phytoplankton and chlorophyll throughout the season remain consistent with recent years, and coincided with solar radiation patterns (Zohreh 2008; Morison 2009; Green 2010).

Nonetheless, both peaks coincide with high levels of solar radiation (Fig. 6). In order to form a bloom at least three days of consecutive high sunlight is required prior to the bloom (Eisner and Newton 1997). The 2011 phytoplankton bloom occurred after three sustained days of high solar radiation, where the chlorophyll maximum also occurred after extremely high levels of sunlight (Fig. 6). Past studies have consistently found greater abundances and blooms at North station, characteristically more tidally mixed (Pennington 2007). Light regimes experienced by phytoplankton also depend on the rate of mixing, an extremely prevalent factor in estuarine waters, whereby phytoplankton can undergo a light gradient from darkness to full sunlight within hours

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(MacIntyre et al., 2000). Differences in phytoplankton abundance across North and South stations have been attributed to differences in water characteristics between stations. Variability of light intensity as a result of mixing provides evidence for more phytoplankton at North station, even across similar times of solar radiation. At North station more turbulent waters prevented phytoplankton from sinking out of the euphotic zone.

Not only are phytoplankton genera changing in relation to water chemistry, but phytoplankton affect dissolved oxygen content in the water via photosynthesis and respiration. For North and South stations during fall 2011 and across the annual cycle in 2011 dissolved oxygen and chlorophyll concentrations strongly correlated at North and South stations (Table 2, Table). High levels of dissolved oxygen occurred with high levels of chlorophyll. However, dissolved oxygen and chlorophyll are non-conservative properties of ocean water, changing as a result of biological and chemical processes. In order to make inferences to whether dissolved oxygen versus chlorophyll correlations are indicative of phytoplankton influencing dissolved oxygen trends in San Juan Channel, dissolved oxygen was correlated to salinity. Salinity is a conservative tracer of seawater, and varies with physical and chemical processes. This method of comparison was simple and determined whether physical or biological factors were playing a role in dissolved oxygen content across 2011. If correlations between dissolved oxygen and chlorophyll were greater than with salinity, it was deduced that biological effects, from phytoplankton, were affecting oxygen beyond physical effects. If correlations between dissolved oxygen with chlorophyll and salinity are the same, biology and physics are both affecting oxygen and cannot be isolated from one another.

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So was dissolved oxygen physically or biologically affected during fall in San Juan Channel? Consistent with previous interannual studies, dissolved oxygen content was predominated by physical controls (Table 3) (Vivianni 2005; McLaughlin 2009; Cohen 2010). South station had especially stronger correlations between dissolved oxygen with chlorophyll and salinity. The correlation comparison suggests that although South station is not as tidally mixed as North station, physical factors with respect to dissolved oxygen are stronger.

Compared to the 2011 annual cycle, the fall season contained the lowest levels of dissolved oxygen, for both North and South stations. It might be expected that during summer, with a higher phytoplankton abundance that dissolved oxygen and chlorophyll correlations would be greater than dissolved oxygen versus salinity correlations, indicating stronger biological influence on DO. However, the rest of the annual cycle shows physical effects continued to outweigh biological effects for North and South stations, with the exception of July at North station.

During three cruises in July 2011 at North station similar correlations for dissolved oxygen with chlorophyll and salinity, indicative of both biological and physical influence on DO, were observed. Biological influence of dissolved oxygen is presumed to be a result of summer productivity, where large phytoplankton blooms occur. Research suggests that phytoplankton variations occur in response variations in fresh water flow and nutrient fluxes (Malone et al. 1988). Such that, North station is particularly influenced by freshwater input from the Fraser River (McLaughlin 2009). Productivity in summer may be related to high freshwater inputs, and should be explored in future studies.

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I propose that the large increase in phytoplankton over summer resulted from physical factors such as Fraser River input and thus nutrient addition into the system. During the spring bloom high amounts of oxygen were produced by phytoplankton, but physical processes such as temperature and freshwater input continued to weigh into this biological contribution.

Conclusion and Future Considerations

Phytoplankton genera in the San Juan Channel are consistently similar across stations and weekly cruises for Fall 2011. Differences in phytoplankton genera are a result of single-species dominated periods. Phytoplankton abundance and chlorophyll concentrations were found to decrease as the season progressed to winter, consistent with previous studies. However, I would recommend an adjustment of phytoplankton sampling methods. To better understand the phytoplankton community, I would suggest phytoplankton collections be done with a smaller mesh net size and across the entire euphotic zone, to account for any lost variation.

With regards to phytoplankton and dissolved oxygen, one can see a strong correlation across the annual cycle for 2011. Such that, physical factors dominated the influence on dissolved oxygen both spatially, across North and South stations, and temporally throughout the year with the exception of July. In July, biological factors appeared to be equivalent to physical factors in influencing dissolved oxygen. Continued sampling in spring and summer are recommended to facilitate a better understanding on how the complex relationship between dissolved oxygen and phytoplankton change by physical and biological influences.

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Tables

Table 1. Exact dates of R/V Centennial cruises conducted in October and November 2011 in San Juan Channel. Asterisk denotes cruise where only CTD casts were made, and no water or phytoplankton samples were taken.

2011 Cruise Dates
October 4
October 7
October 18
October 24
November 1
November 7
November 15
November 19*

Table 2. Average R^2 values for dissolved oxygen (DO) versus chlorophyll (Chl) correlations for Fall 2011 at North and South stations using sensor (CTD) and discrete data.

Average R^2	**DO:Chl (discrete)**	**DO:Chl (sensor)**
North	0.86	0.58
South	0.79	0.76

Table 3. Average R^2 values for dissolved oxygen (DO) versus chlorophyll (Chl) and dissolved oxygen (DO) versus salinity (Sal) correlations for Fall 2011 at North and South stations.

Average R^2	**DO:Chl**	**DO:Sal**
North	0.58	0.62
South	0.76	0.86

Table 4. Average R^2 values for dissolved oxygen (DO) versus chlorophyll (Chl) correlations for the 2011 annual cycle.

Date	**North**	**South**
February 10	0.40	0.77
April 26	0.19	0.67
July 5	0.84	0.82
July 8	0.91	0.71
July 19	0.88	0.01
August 9	0.002	0.78

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Table 5. Average R^2 values for dissolved oxygen (DO) versus chlorophyll (Chl) correlations and dissolved oxygen (DO) versus salinity (Sal) for the 2011 annual cycle at North station.

Date	DO:Chl	DO:Sal
February 10	0.40	0.57
April 26	0.19	0.99
July 5	0.84	0.99
July 8	0.91	0.89
July 19	0.88	0.95
August 9	0.002	0.44

Table 6. Average R^2 values for dissolved oxygen (DO) versus chlorophyll (Chl) correlations and dissolved oxygen (DO) versus salinity (Sal) for the 2011 annual cycle at South station.

Date	DO:Chl	DO:Sal
February 10	0.77	0.99
April 26	0.67	0.98
July 5	0.82	0.99
July 8	0.70	0.94
July 19	0.14	0.94
August 9	0.78	0.99

Figures

Figure 1. Map of San Juan Channel showing the location of North and South stations, designated by yellow circles and labelled accordingly.

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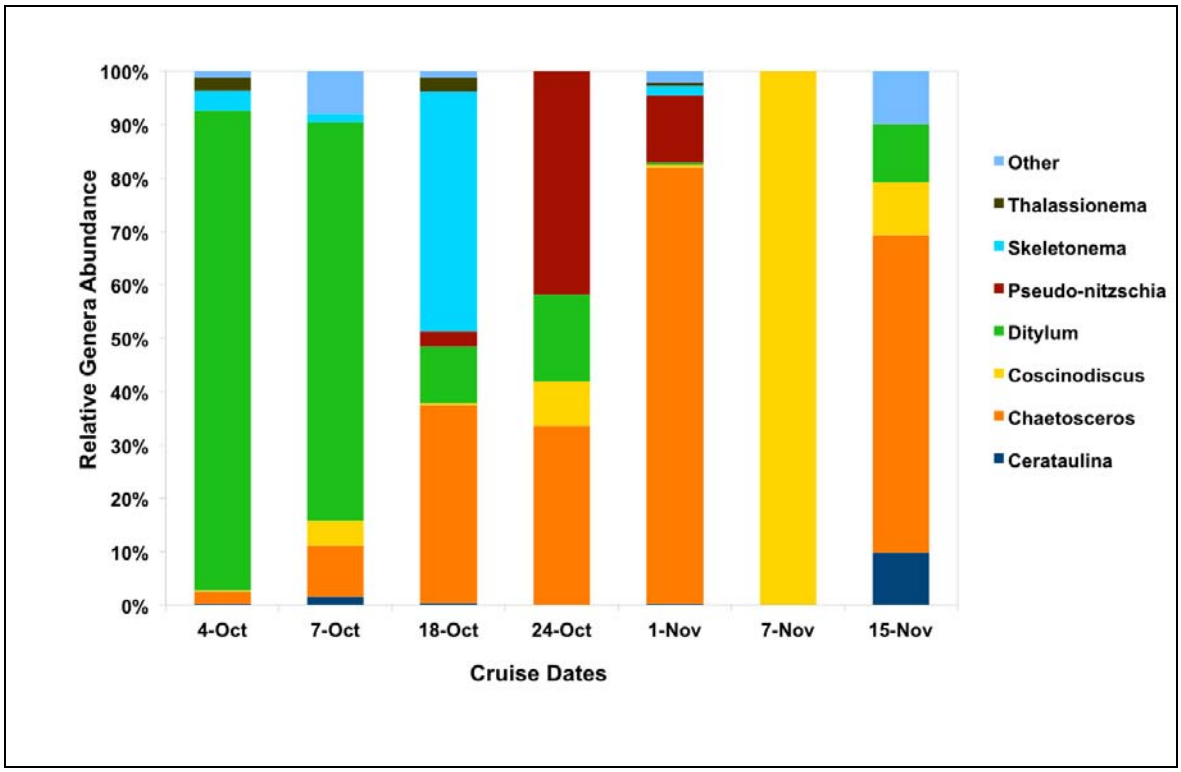

Figure 2. Phytoplankton genera relative abundance (%) for seven dates during fall 2011 at North station. Samples collected from 10m to surface in the water column.

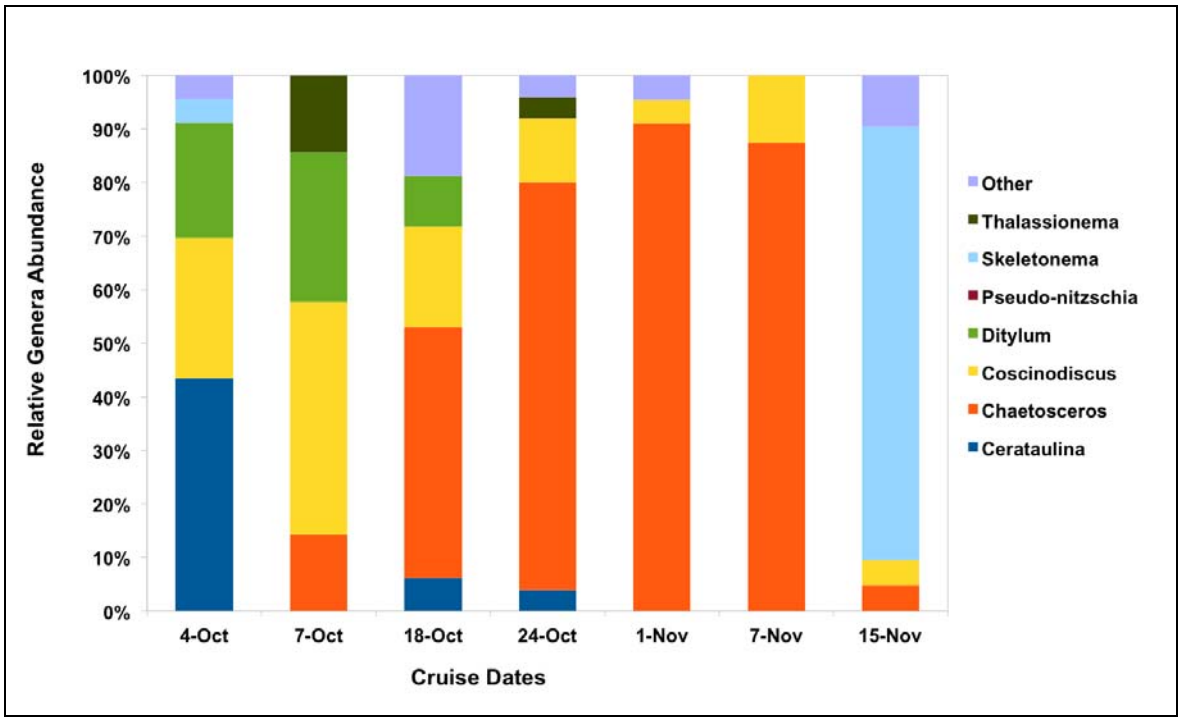

Figure 3. Phytoplankton genera relative abundance (%) for seven dates during fall 2011 at South station. Samples collected from 10m to surface in the water column.

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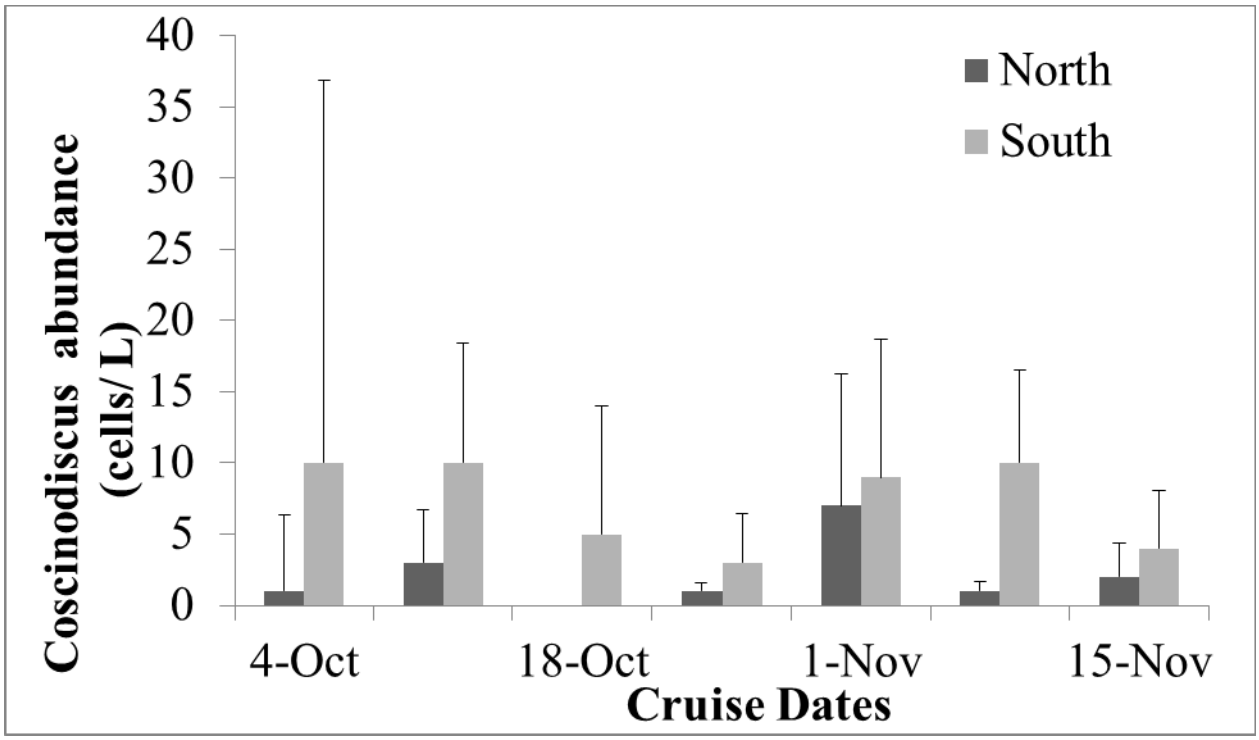

Figure 4. *Coscinodiscus* species abundance (cells/L) for seven dates during fall 2011 at North and South stations (±SE). Samples collected from 10m to surface in the water column.

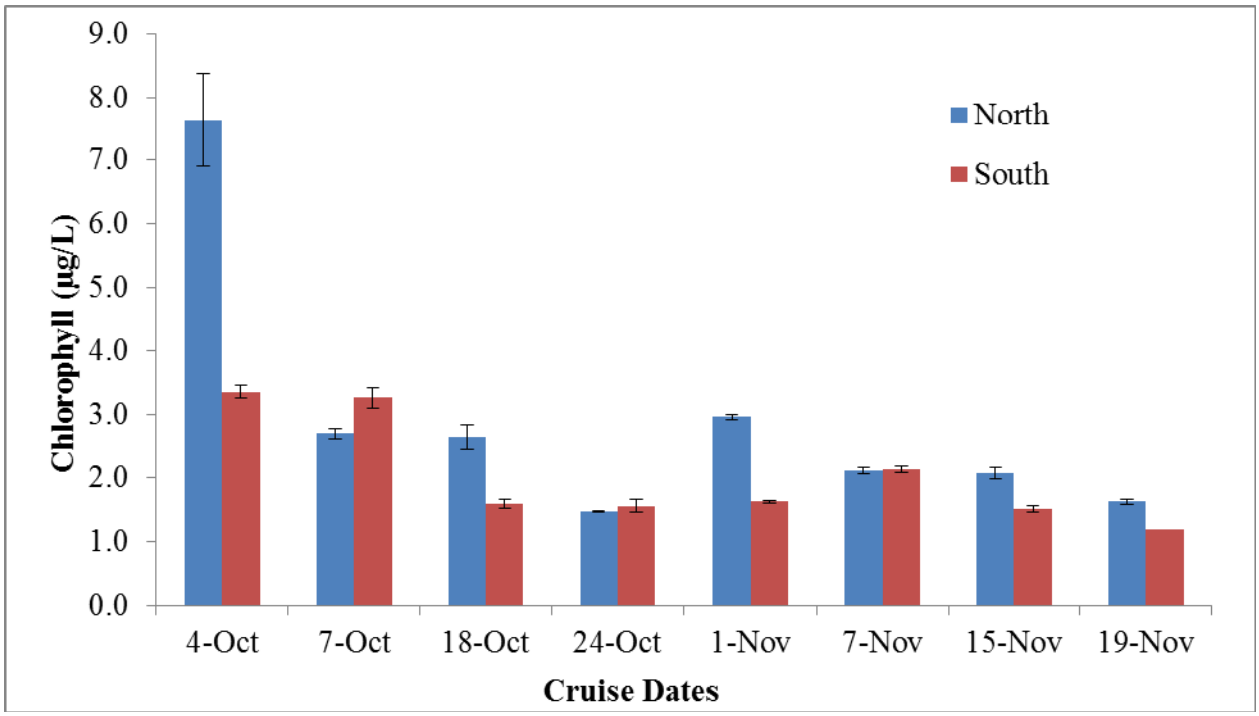

Figure 5. Phytoplankton abundance (cells/L) for seven dates during fall 2011 at North and South stations (±SE). Samples collected from 10m to surface in the water column.

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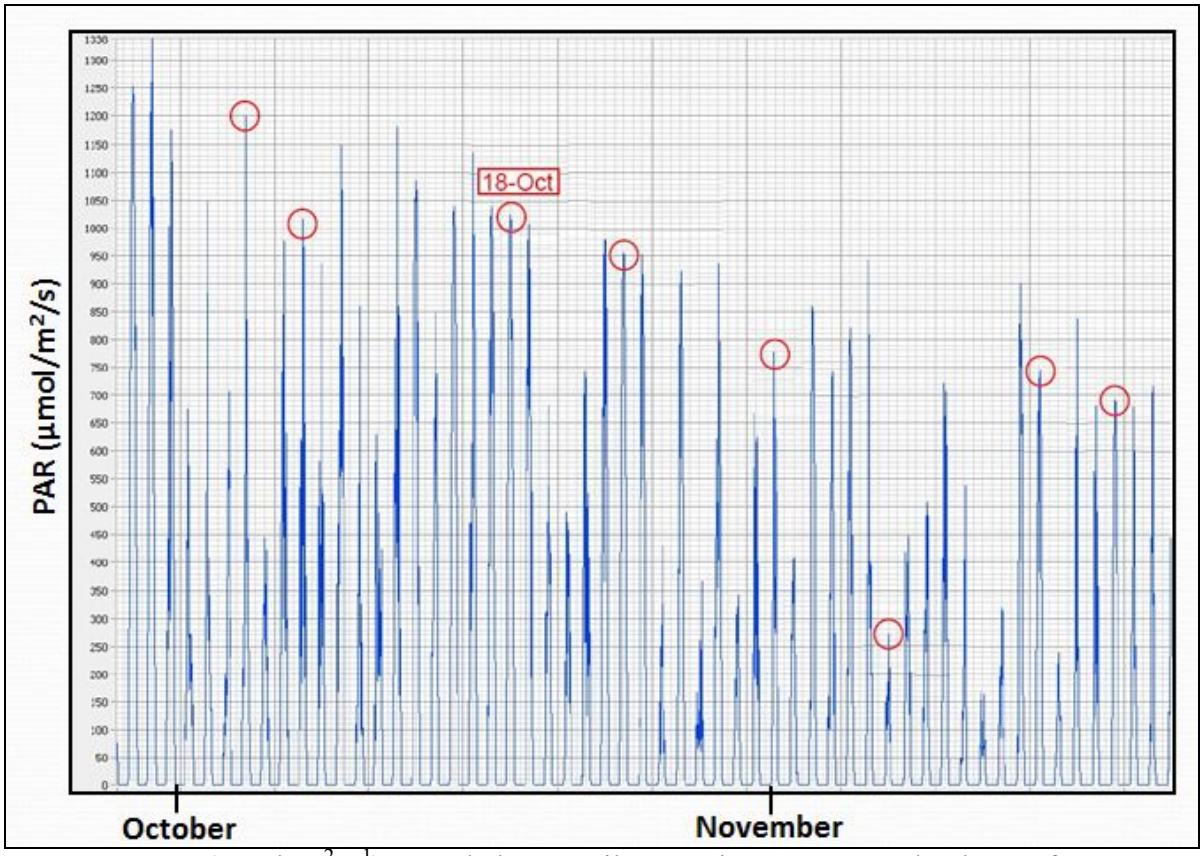

Figure 6. PAR (µmol m^{-2} s^{-1}) recorded at Cantilever Point, San Juan Island, WA from 28-September to 23-November of 2011. Red cricles indicate cruise dates. Data taken from: http://faculty.washington.edu/ecarring/weather.html, accessed 11/23/2011.

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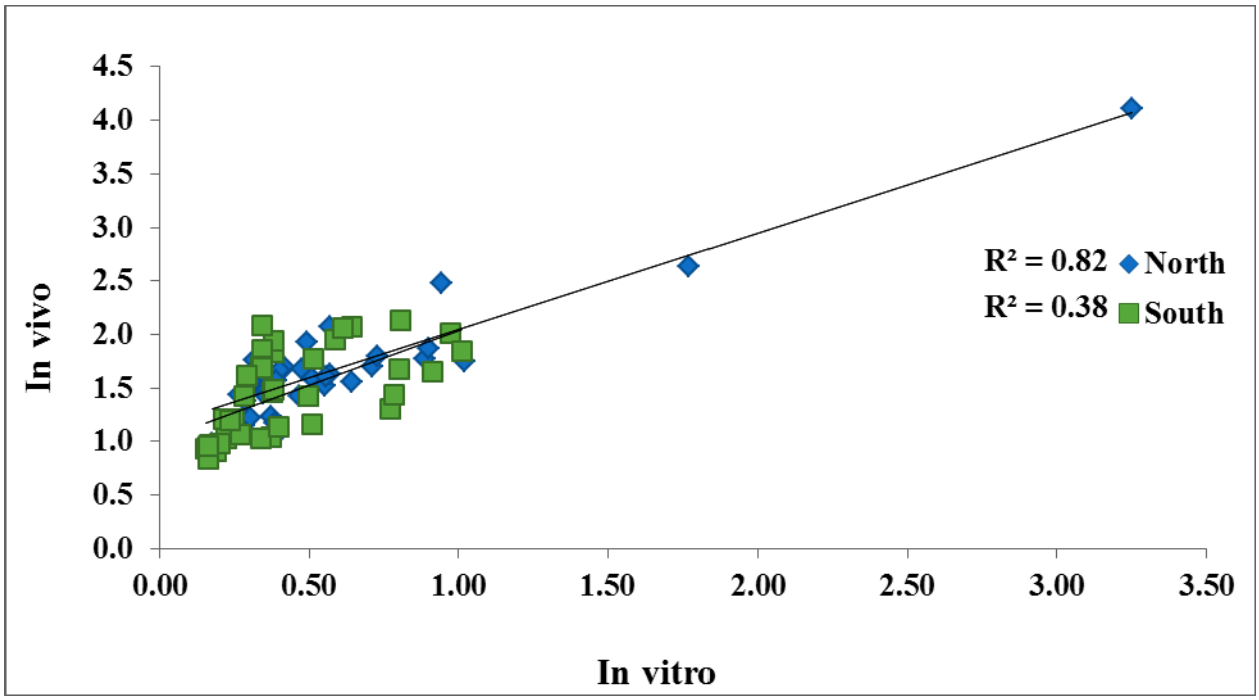

Figure 7. Correlation between *In-vivo* and *In-vitro* chlorophyll-a measurements at North and South stations for Fall 2011.

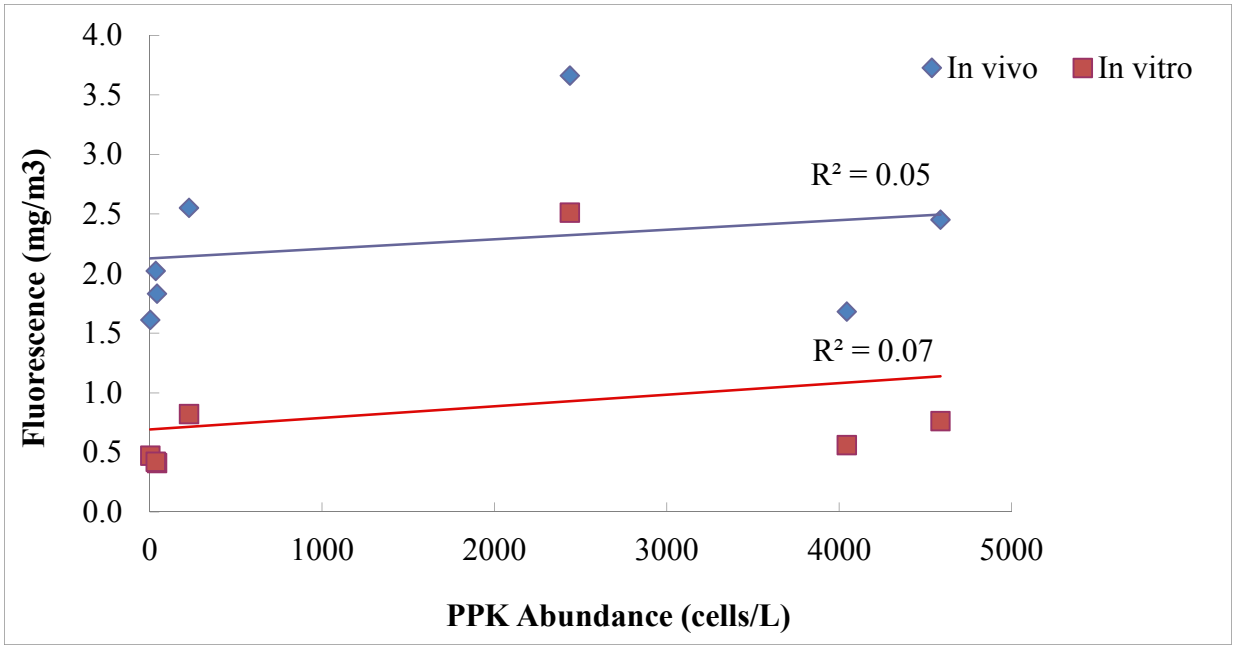

Figure 8. Correlation between chlorophyll-a, from *in-vtiro* and *in-vivo* measurements, with phytoplankton abundance showing a positive relationship at Nouth station. Chlorophyll-a measurements are from the entire water column, and phytoplankton abundance measurements are from 10m to the surface.

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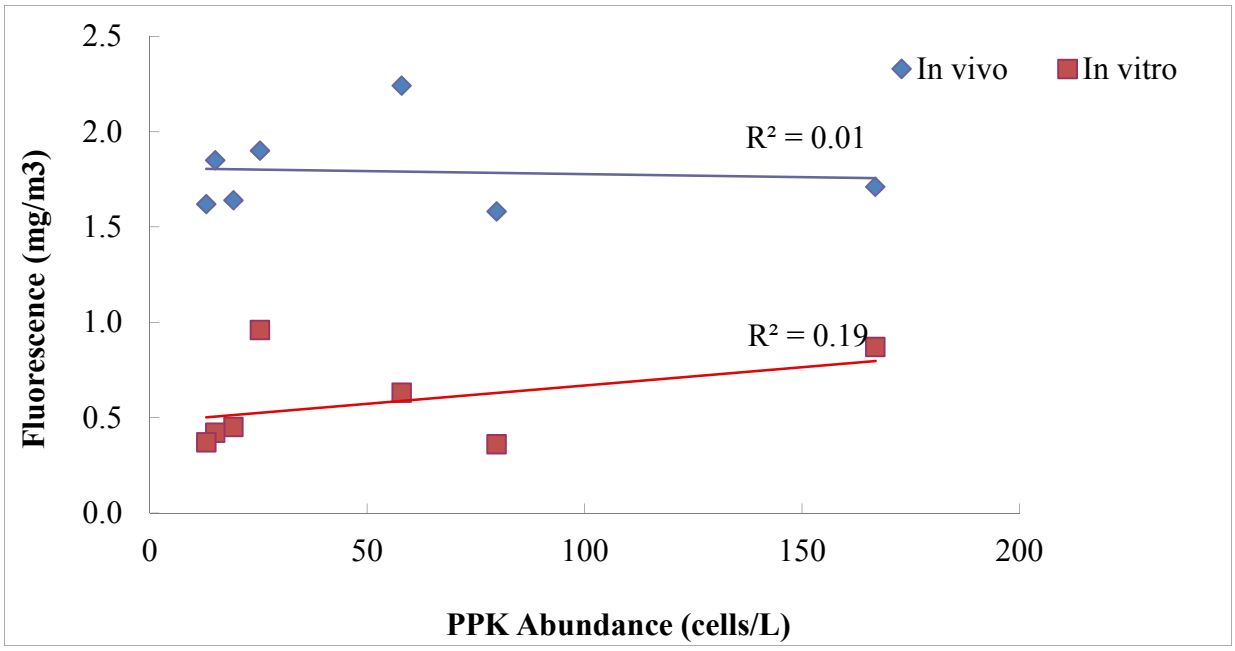

Figure 9. Correlation between chlorophyll-a, from *in-vtiro* and *in-vivo* measurements, with phytoplankton abundance showing a positive relationship at South station. Chlorophyll-a measurements are from the entire water column, and phytoplankton abundance measurements are from 10m to the surface.

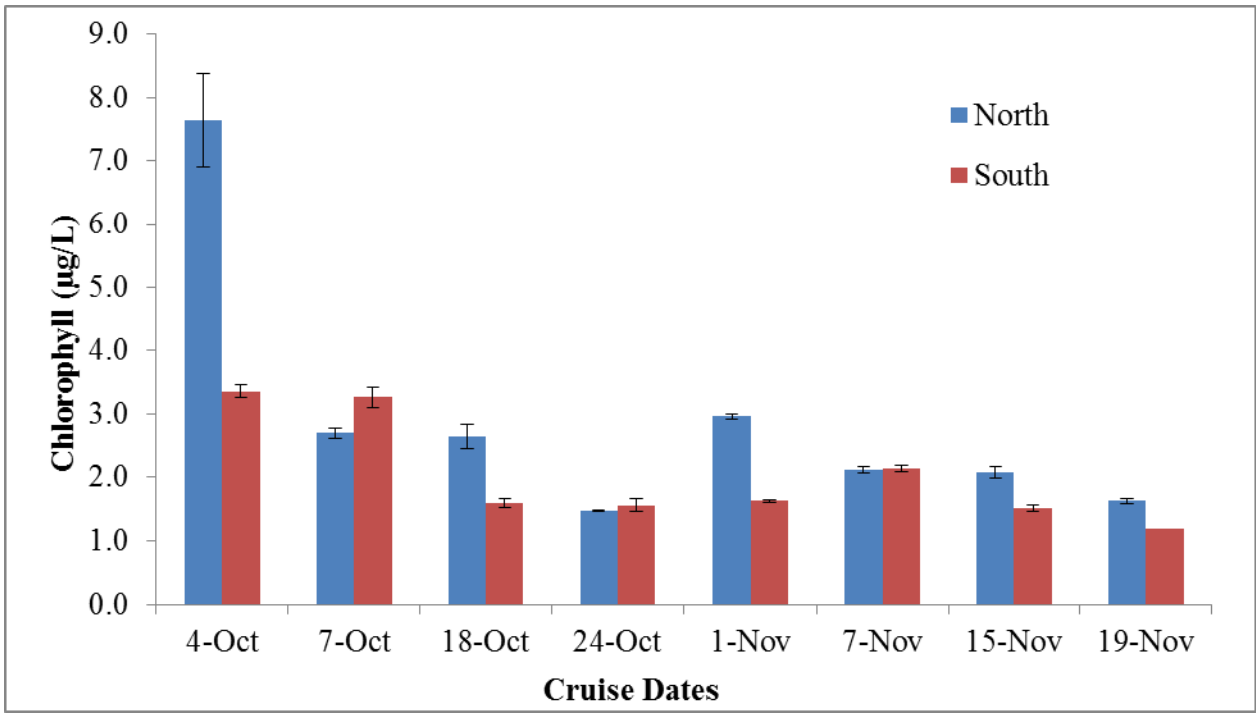

Figure 10. *In-vitro* chlorophyll-*a* concentrations (µg/L) for seven dates during fall 2011 at North and South stations (±SE)

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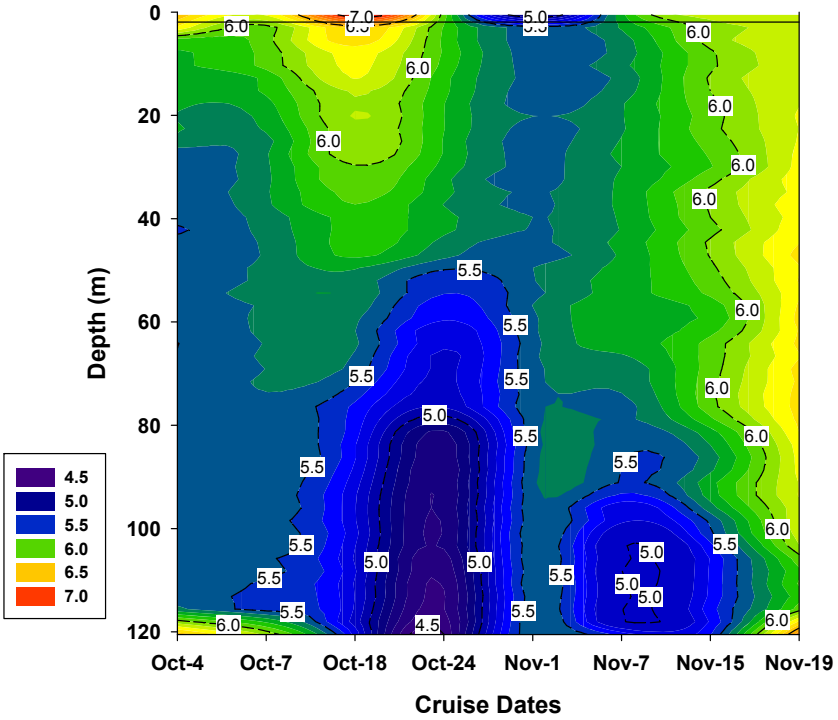

Figure 11. Contour plot of dissolved oxygen at North station by cruise date for fall 2011.

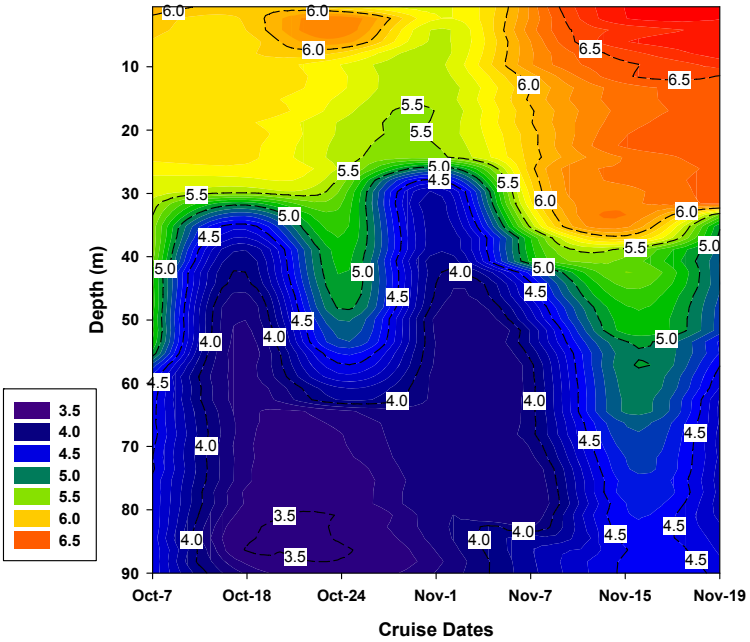

Figure 12. Contour plot of dissolved oxygen at South station by cruise date for fall 2011.

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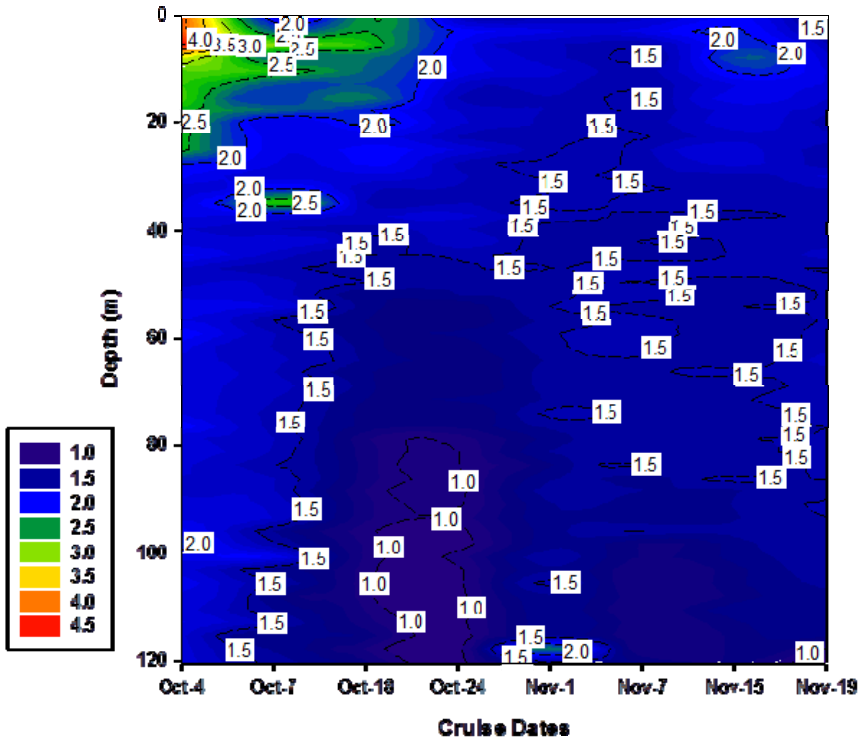

Figure 13. Contour plot of chlorophyll fluorescence at North station by cruise date for fall 2011.

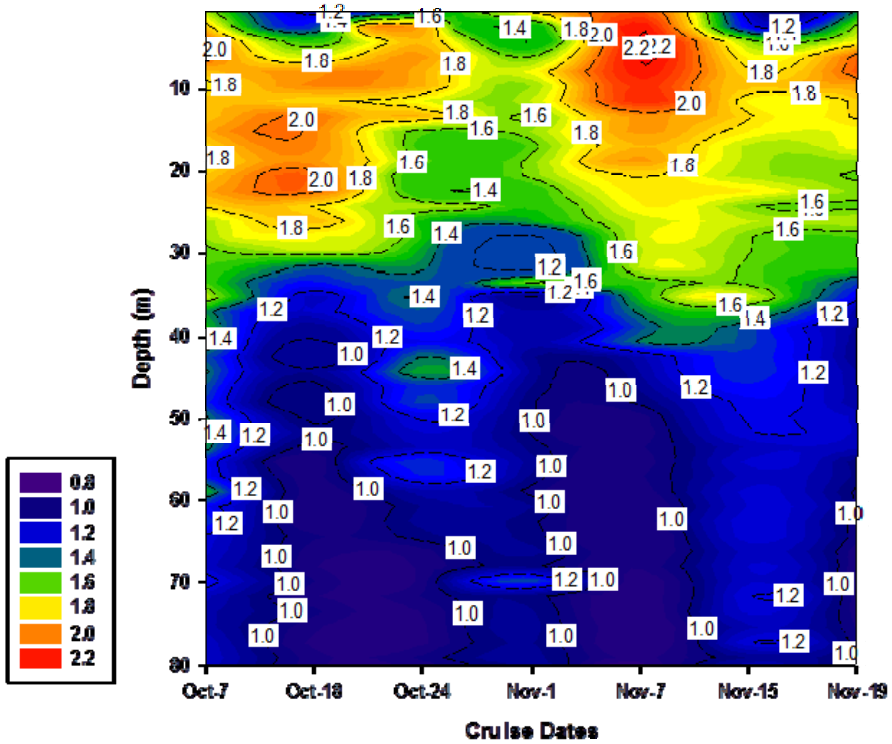

Figure 14. Contour plot of chlorophyll fluorescence at South station by cruise date for fall 2011.

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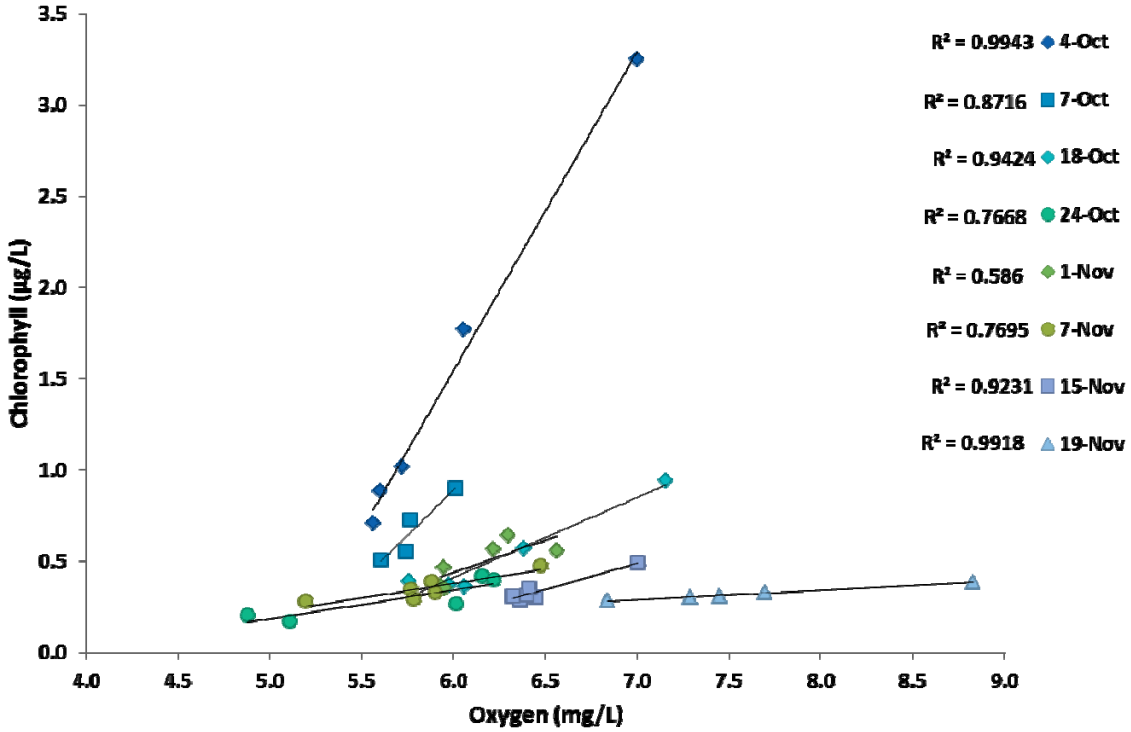

Figure 15. Correlation of dissolved oxygen (mg/L) with chlorophyll (µg/L) using discrete data for Fall 2011 at North station.

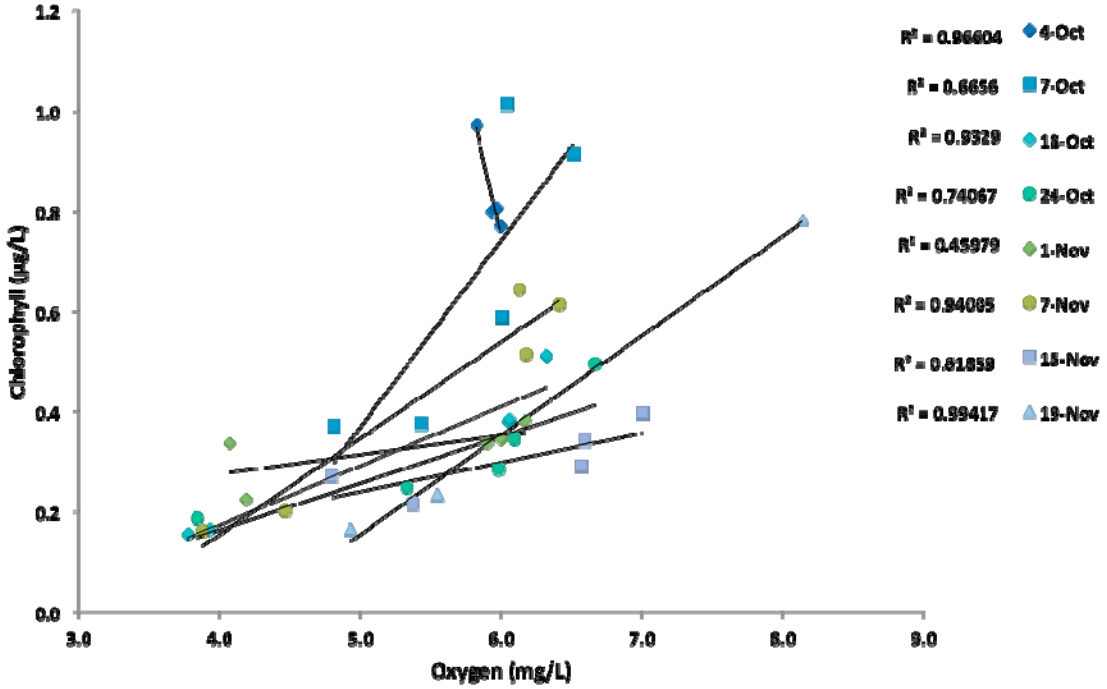

Figure 16. Correlation of dissolved oxygen (mg/L) with chlorophyll (µg/L) using discrete data for Fall 2011 at South statio

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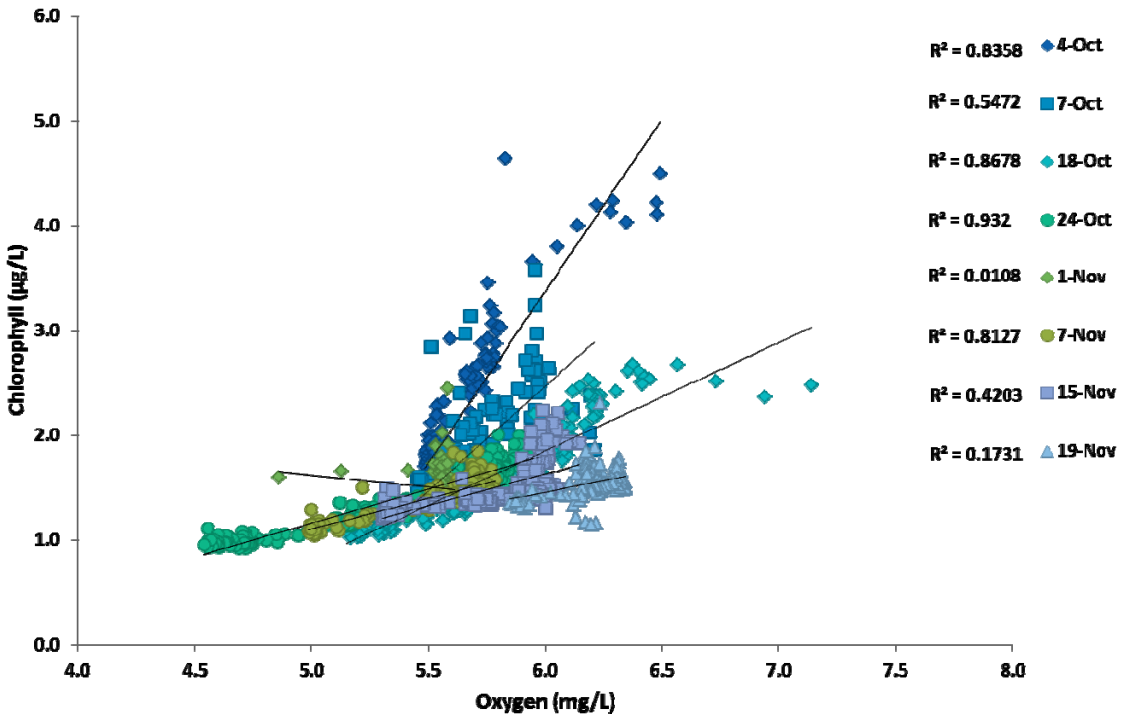

Figure 17. Correlation of dissolved oxygen (mg/L) with chlorophyll (µg/L) using discrete data for Fall 2011 at North station.

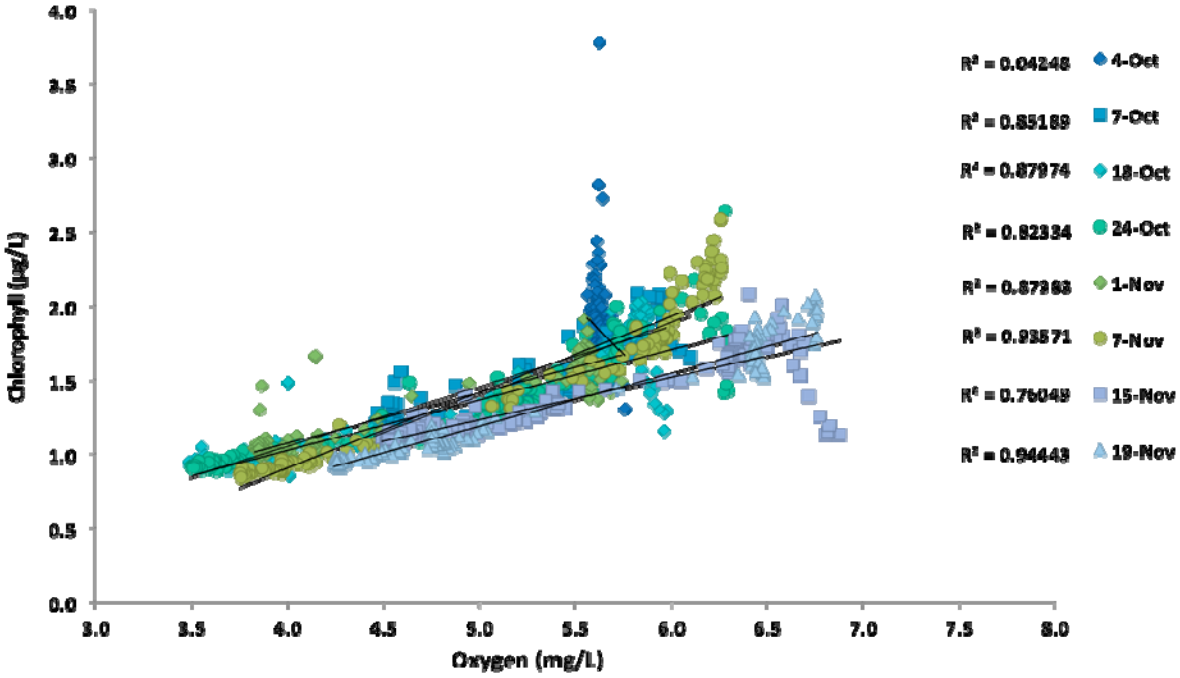

Figure 18. Correlation of dissolved oxygen (mg/L) with chlorophyll (µg/L) using sensor data for Fall 2011 at South station.

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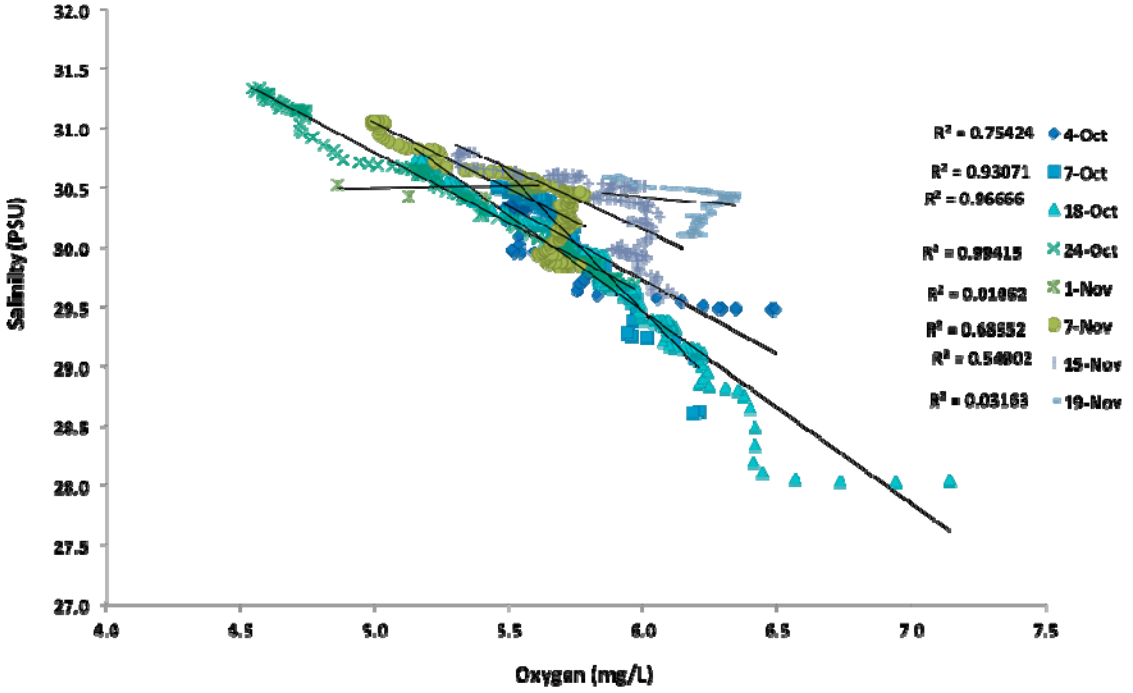

Figure 19. Correlation of dissolved oxygen (mg/L) with salinity (PSU) using discrete data for Fall 2011 at North station.

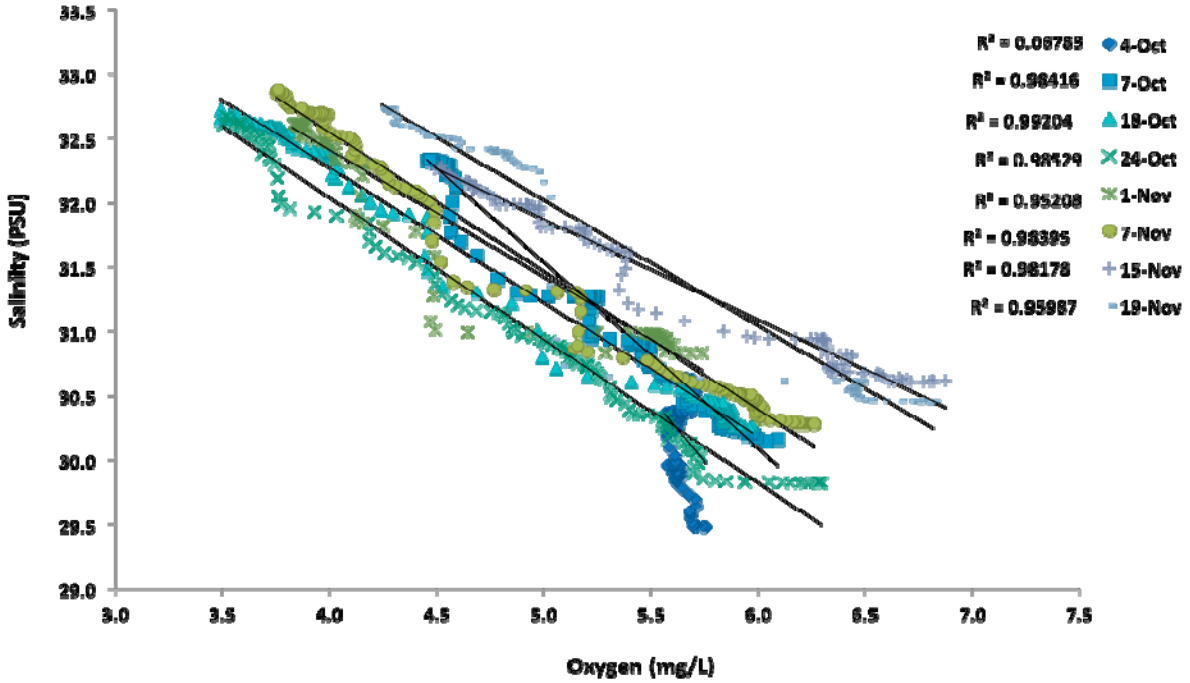

Figure 20. Correlation of dissolved oxygen (mg/L) with salinity (PSU) using sensor data for Fall 2011 at South station.

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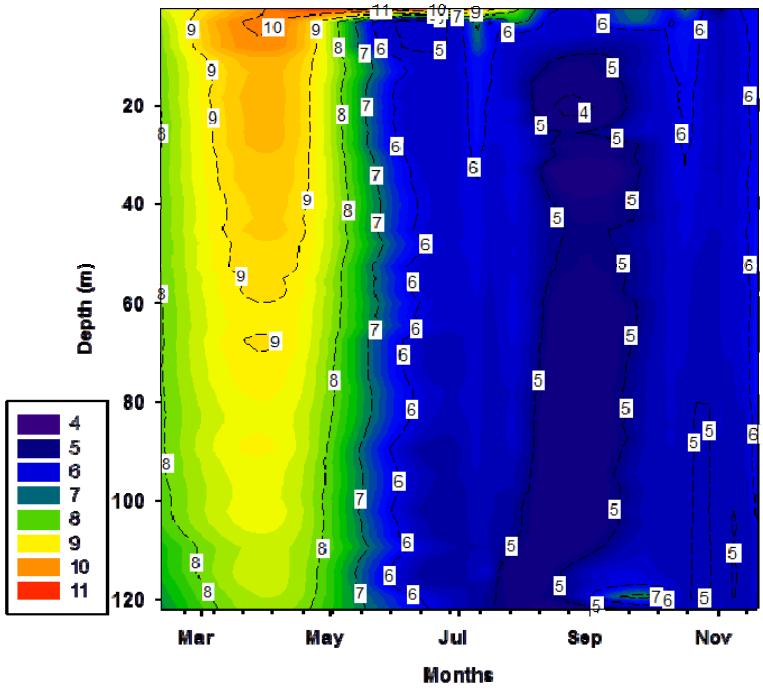

Figure 21. Contour plot of dissolved oxygen at North station over time for 2011 annual cycle.

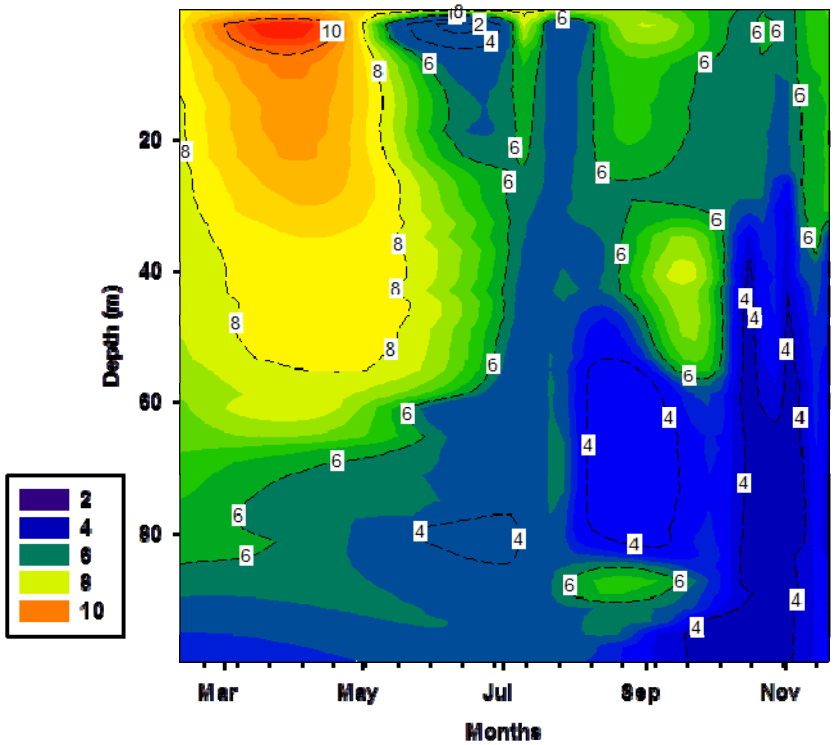

Figure 22. Contour plot of dissolved oxygen at South station over time for the 2011 annual cycle

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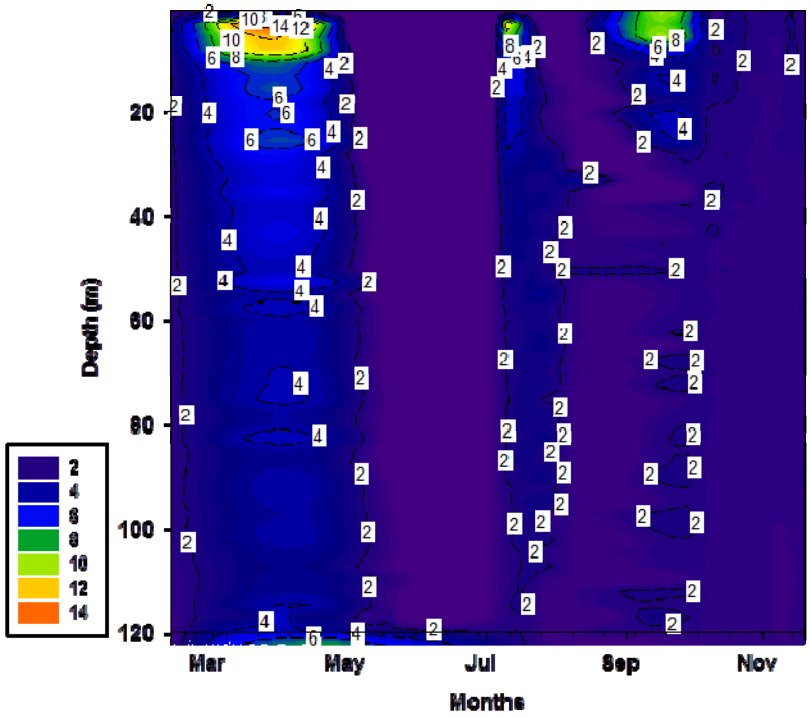

Figure 23. Contour plot of chlorophyll fluorescence at North station over time for 2011 annual cycle.

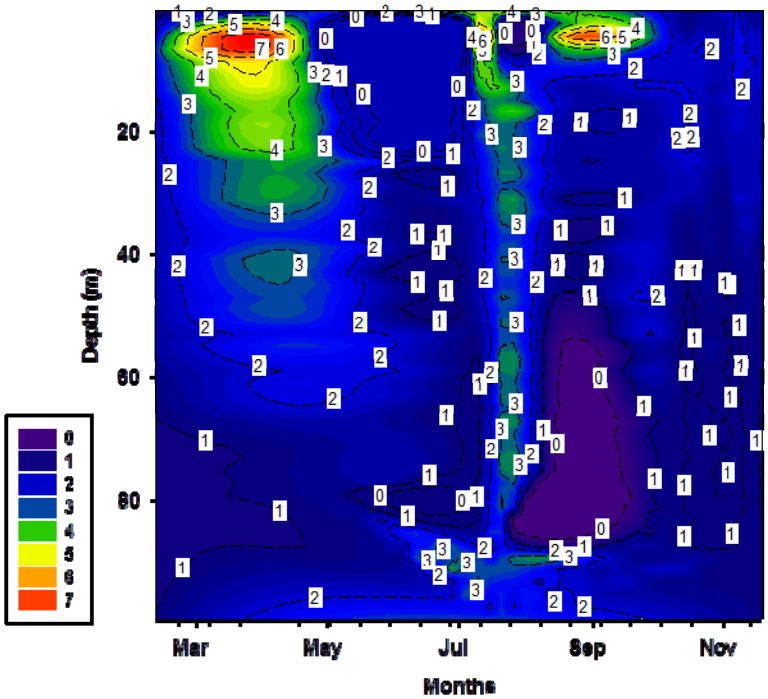

Figure 24. Contour plot of chlorophyll fluorescence at South station over time for 2011 annual cycle.

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Appendices

Appendix A

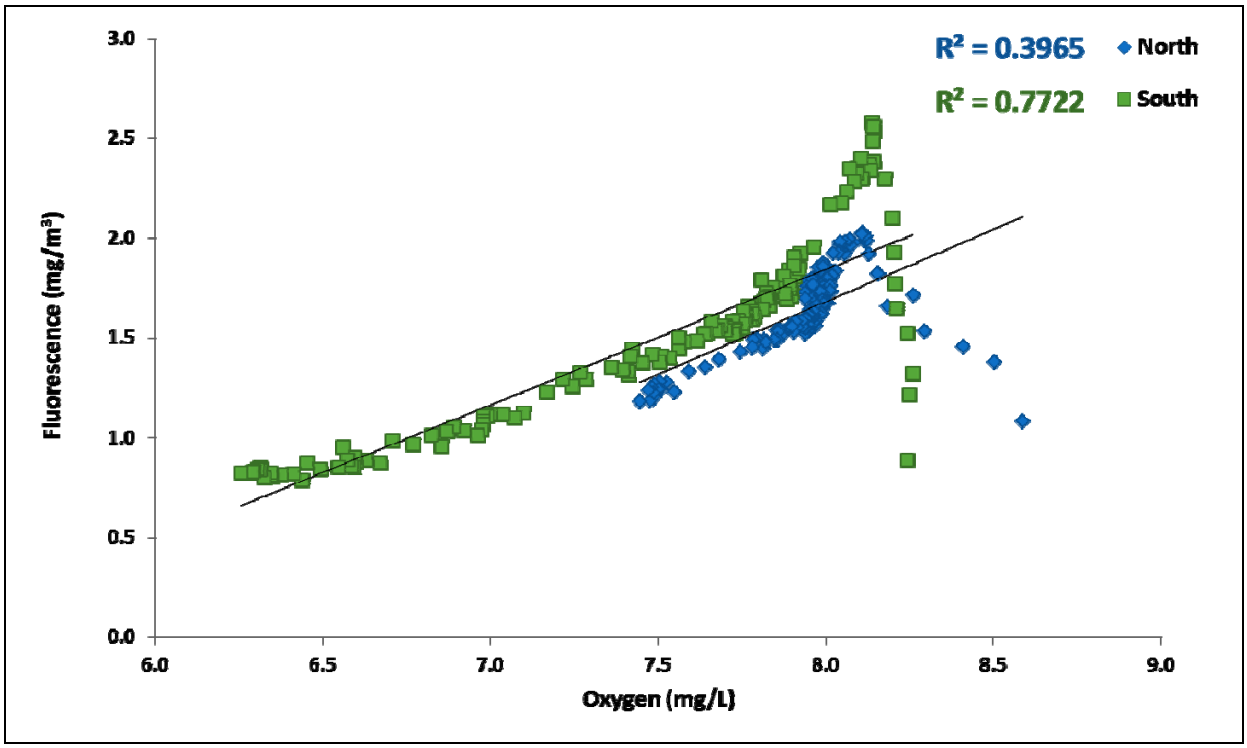

Figure A1. Correlation of dissolved oxygen (mg/L) with chlorophyll (µg/L) using discrete data for February 10 2011 at North and South stations.

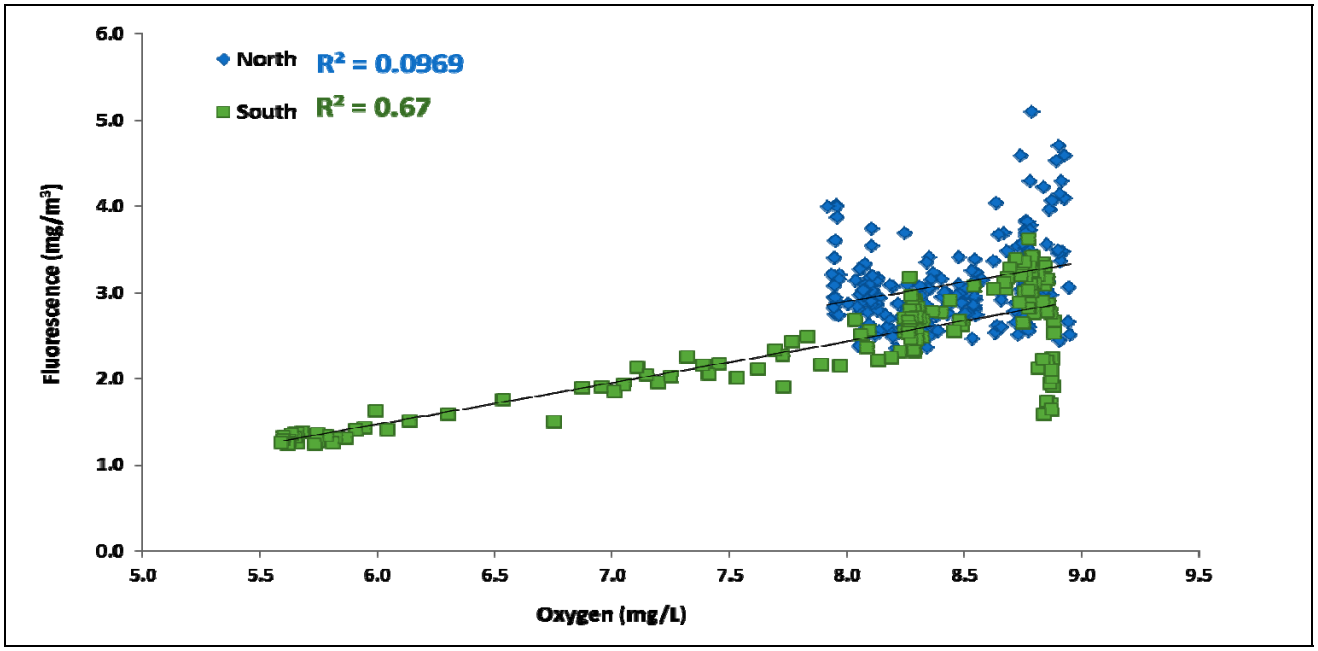

Figure A2. Correlation of dissolved oxygen (mg/L) with chlorophyll (µg/L) using discrete data for April 26 2011 at North and South stations.

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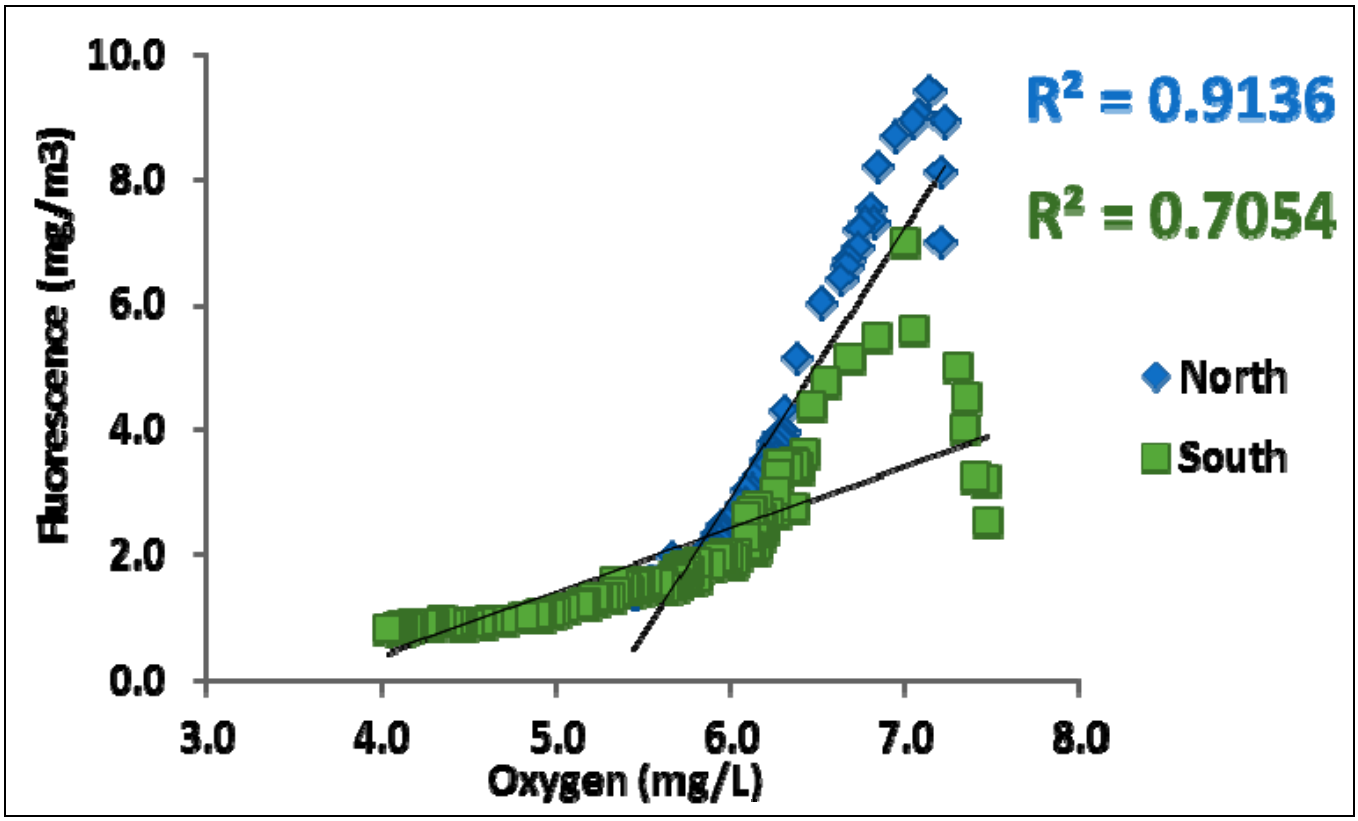

Figure A3. Correlation of dissolved oxygen (mg/L) with chlorophyll (µg/L) using discrete data for July 5 2011 at North and South stations.

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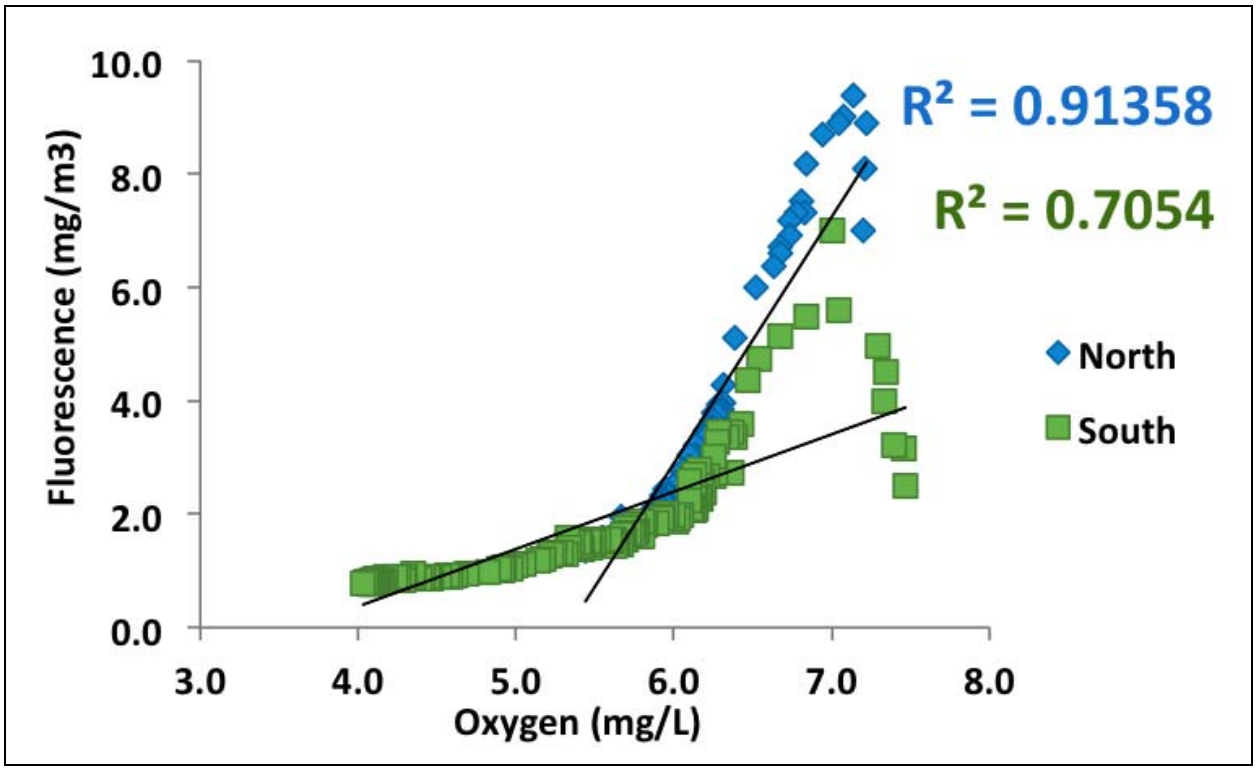

Figure A4. Correlation of dissolved oxygen (mg/L) with chlorophyll (µg/L) using discrete data for July 8 2011 at North and South stations.

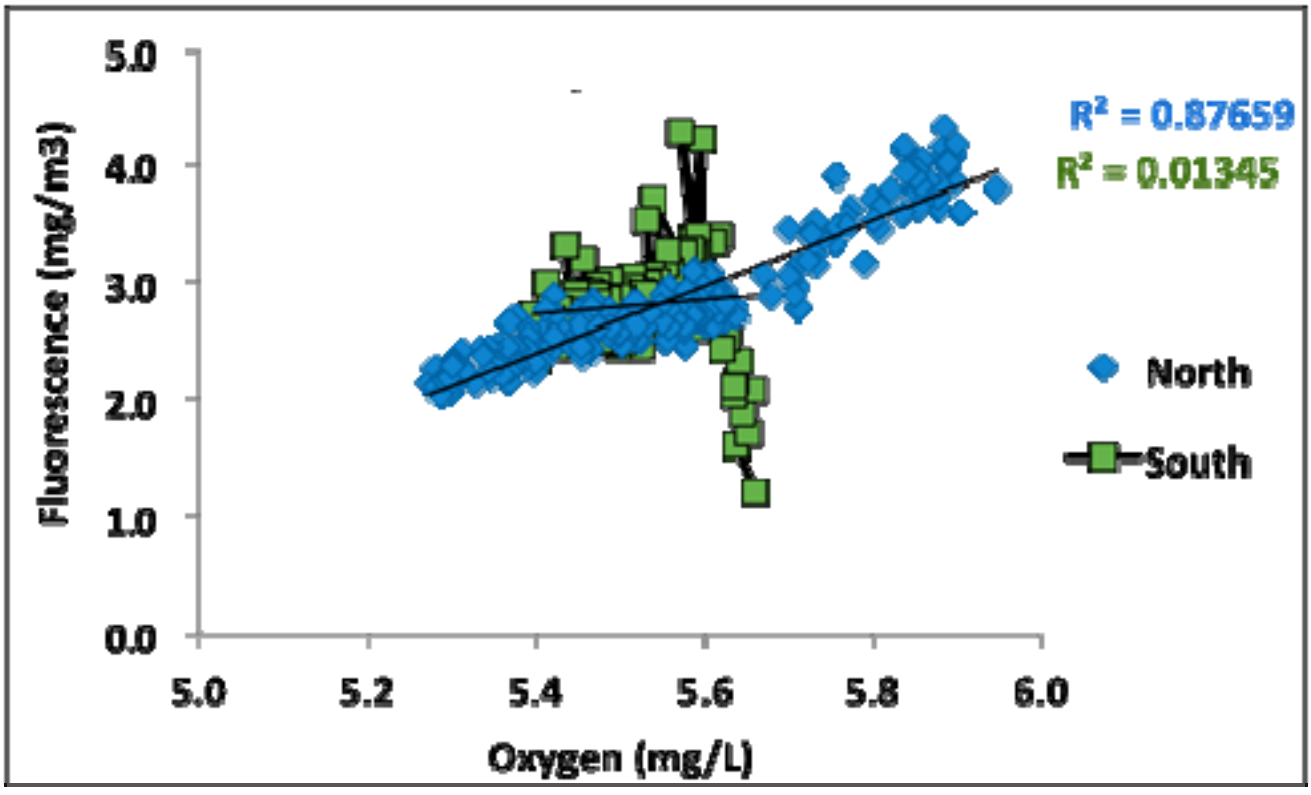

Figure A5. Correlation of dissolved oxygen (mg/L) with chlorophyll (µg/L) using discrete data for July 19 2011 at North and South stations.

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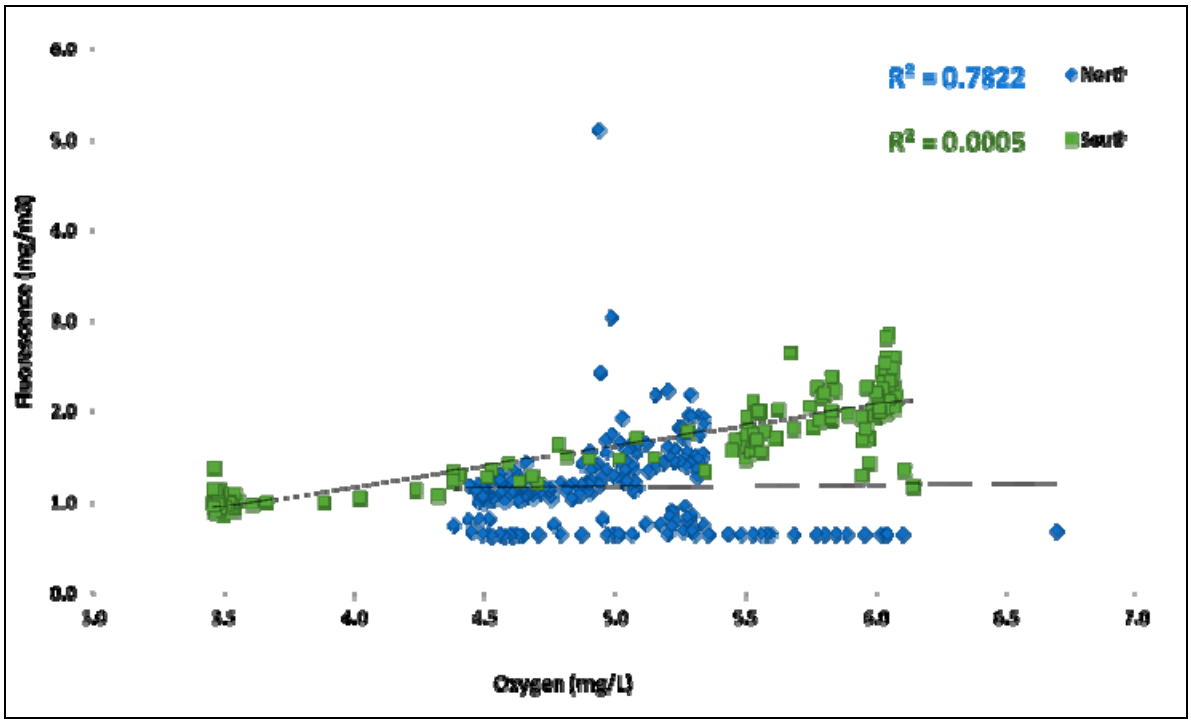

Figure A6. Correlation of dissolved oxygen (mg/L) with chlorophyll (µg/L) using discrete data for August 9 2011 at North and South stations.

Appendix B

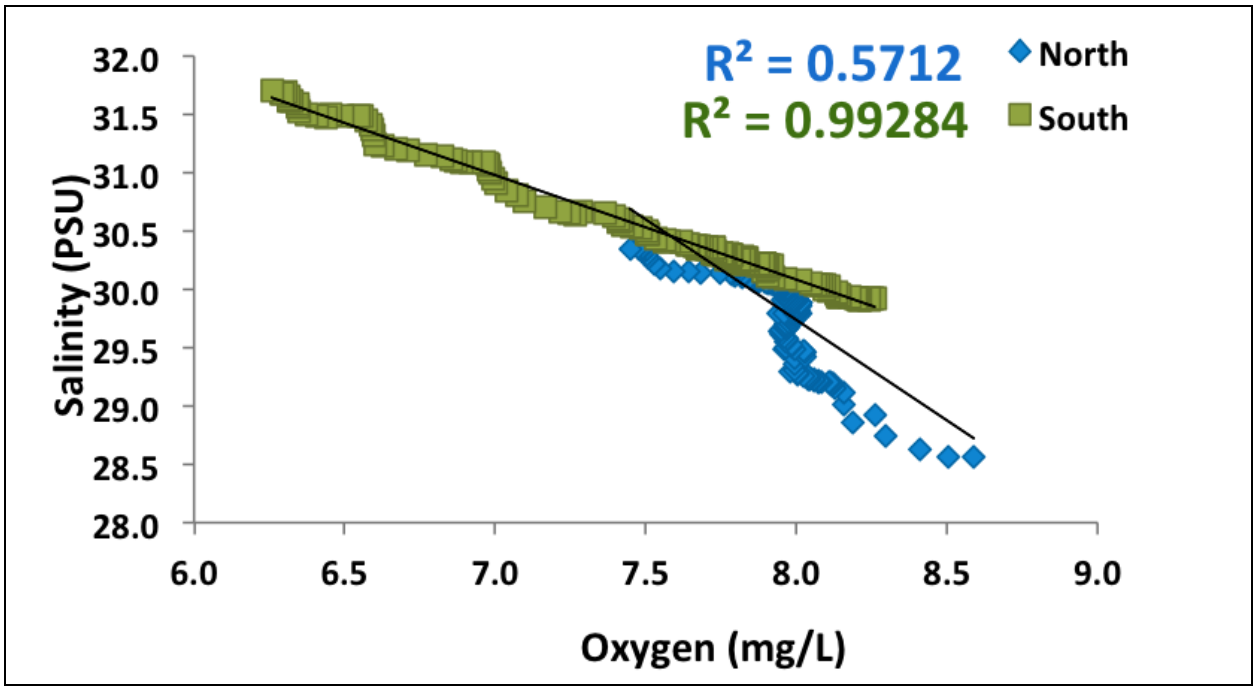

Figure B1. Correlation of dissolved oxygen (mg/L) with salinity (PSU) using discrete data for February 10 2011 at North and South stations.

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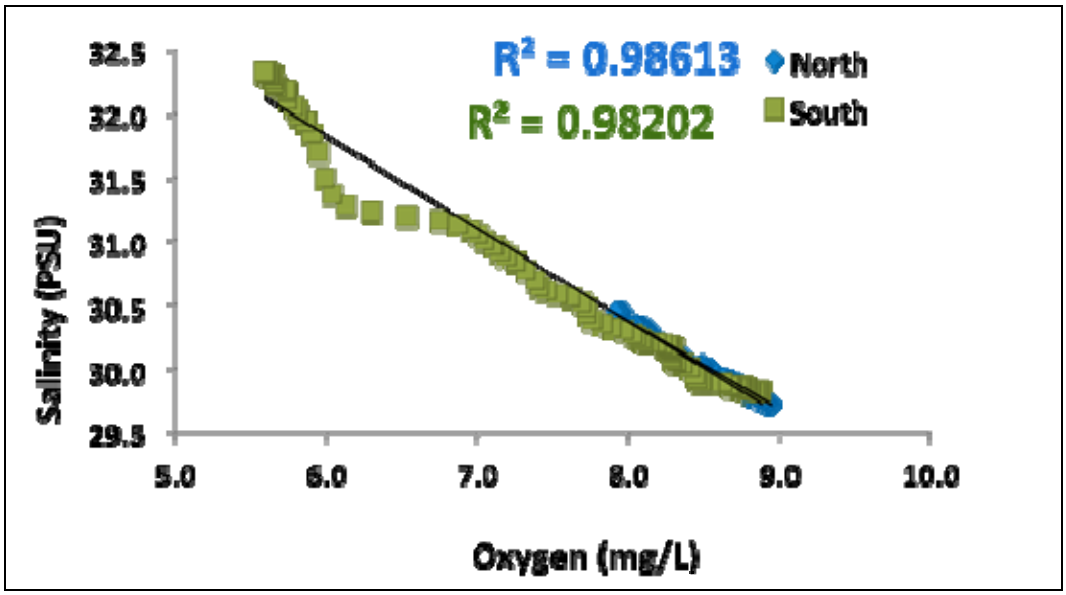

Figure B2. Correlation of dissolved oxygen (mg/L) with salinity (PSU) using discrete data for April 26 2011 at North and South stations.

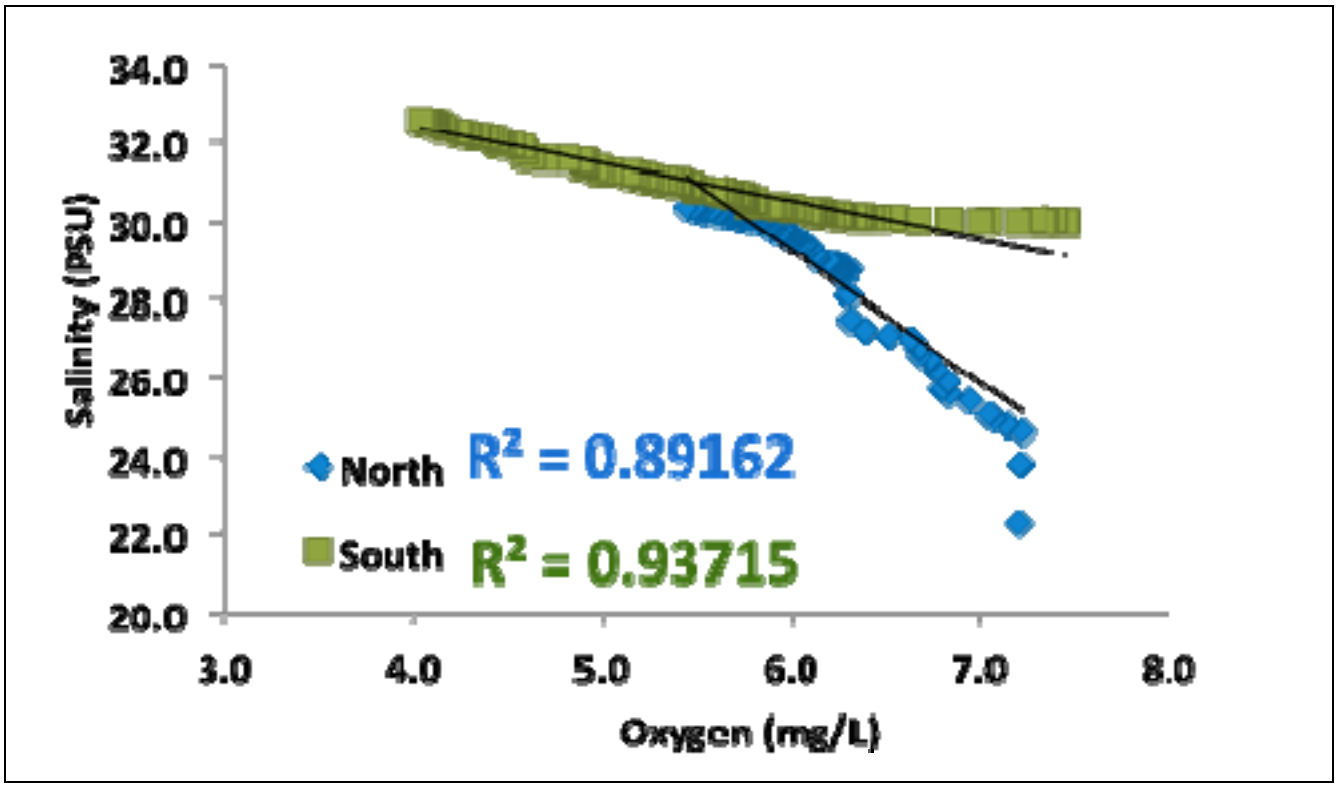

Figure B3. Correlation of dissolved oxygen (mg/L) with salinity (PSU) using discrete data for July 5 2011 at North and South stations.

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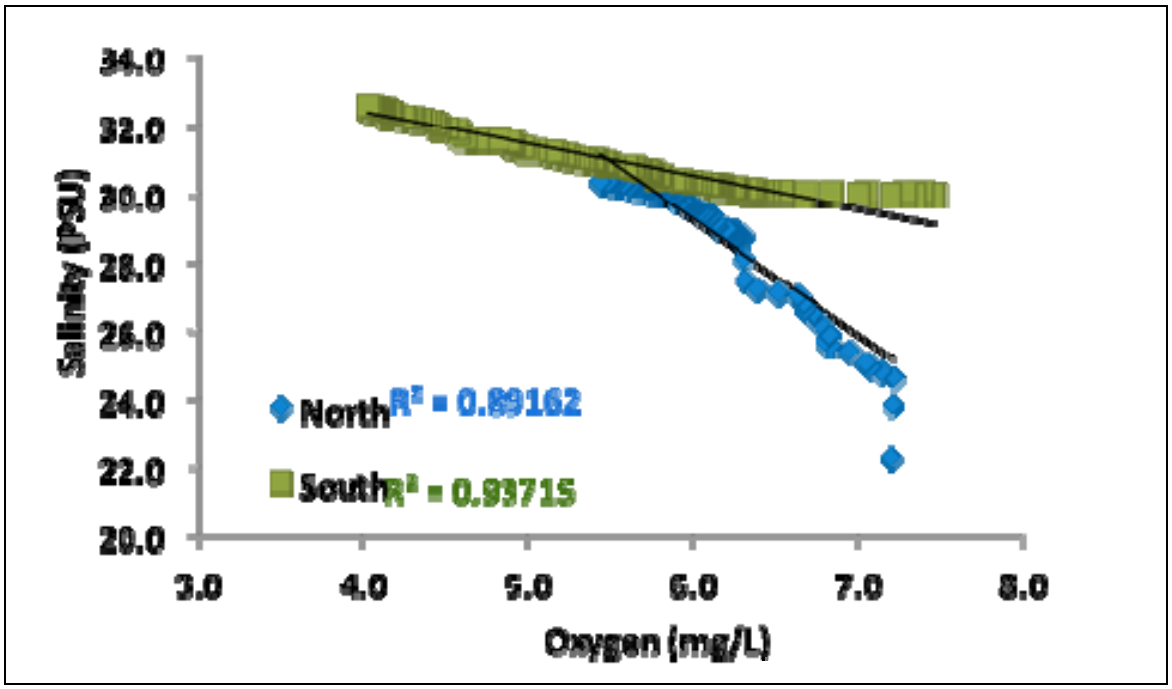

Figure B4. Correlation of dissolved oxygen (mg/L) with salinity (PSU) using discrete data for July 8 2011 at North and South stations.

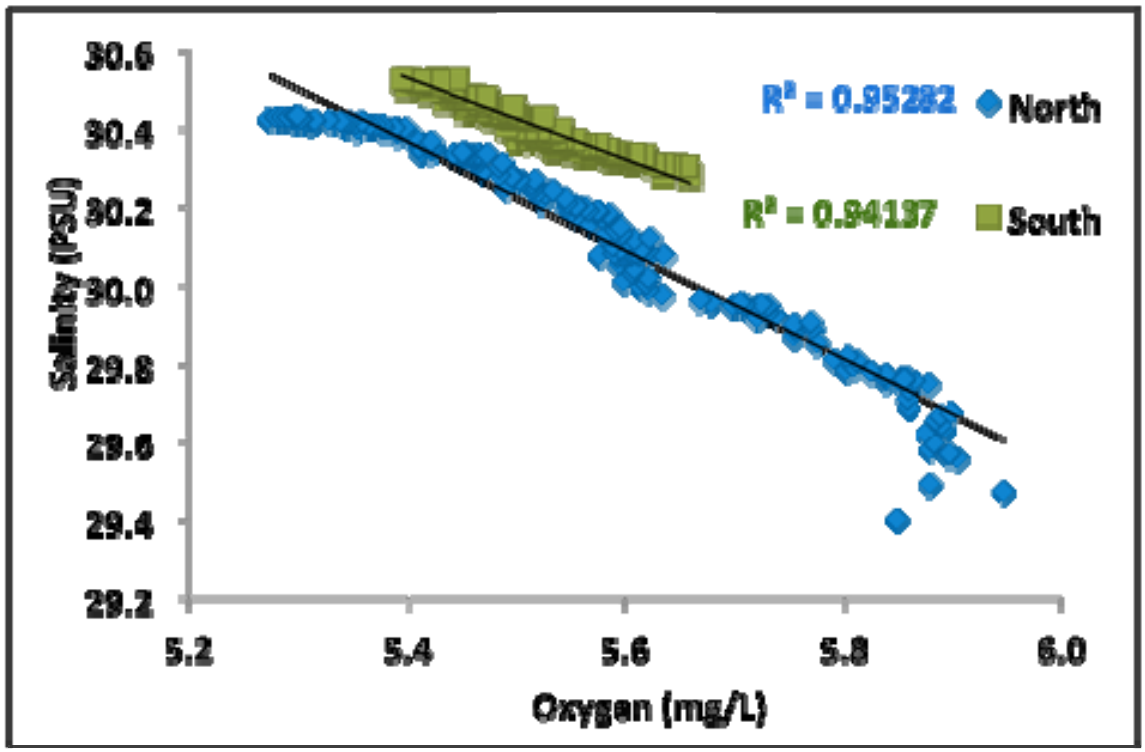

Figure B5. Correlation of dissolved oxygen (mg/L) with salinity (PSU) using discrete data for July 19 2011 at North and South stations.

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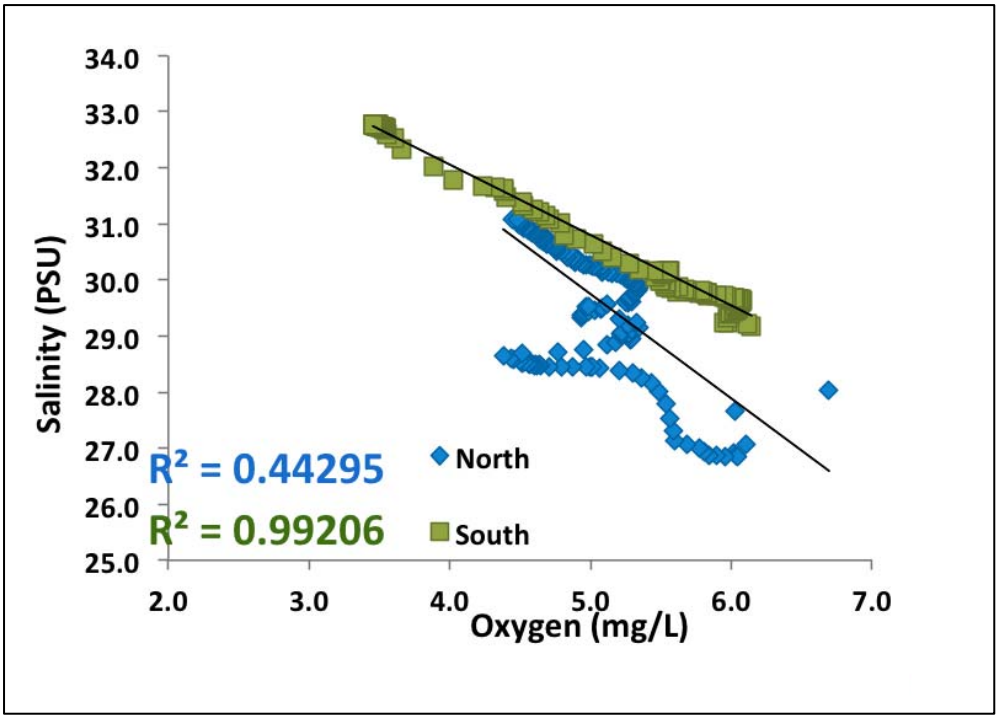

Figure B6. Correlation of dissolved oxygen (mg/L) with salinity (PSU) using discrete data for August 9 2011 at North and South stations.