

Annual and interannual patterns of physical oceanographic properties in the San Juan
Channel: effects of external drivers

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Abstract:

The San Juan Channel (SJC) lies within the Salish Sea between Washington state, USA and British Columbia, Canada. As an estuary, the physical oceanographic conditions of the SJC change constantly over small and large periods of time. It is important to understand how and why these changes occur in order to understand what influences the biota of the SJC. The purpose of this study was to determine the physical oceanographic conditions of 2013, compare them to the 10 previous years of PEF research, and to evaluate the effect of external drivers. The external drivers evaluated were the discharge of the Fraser River, the fall transition from upwelling to downwelling, El Niño Pacific Oscillation (ENSO), Pacific Decadal Oscillation (PDO), and the North Pacific Gyre Oscillation (NPGO). Weekly cruises were conducted during the fall of 2013, during which a CTD was used to measure temperature and salinity and to collect water samples for the determination of dissolved oxygen. Results revealed that the Fraser River influence on salinity was heavily affected by wind direction and strength, though the fall transition did not occur within our study period. Additionally, both ENSO and the PDO contribute to seawater temperature and the NPGO was loosely correlated with surface dissolved oxygen. The fall of 2013 was a year that clearly showed multiple sources influencing one physical oceanographic characteristic.

Introduction

The Salish Sea in northwest Washington is a tidally driven estuarine ecosystem, with freshwater influence derived mainly from Fraser river discharge from the north and oceanic influence from the south. The San Juan channel lies within the Salish Sea, with the Strait of Georgia to the north and the Haro Strait to the west (Figure 1). Annually, the San Jan Channel varies greatly in productivity, temperature, and salinity. It is affected by external drivers, such as El Niño – Southern Oscillation, the Pacific Decadal Oscillation and the North Pacific Gyre Oscillation, and the fall transition from upwelling to downwelling in addition to regional influences such as the discharge from the Fraser River to the north (Figure 2). Because this water is habitat for many organisms, it is vital

to understand its chemical and physical properties in order to better understand patterns of biology.

The Fraser River lies to the north of the San Juan Channel and discharge signals can be detected in the San Juan Channel, which they pass through to enter the Strait of Juan de Fuca (Hickey, 2012). As freshwater is added to a saline environment, salinity decreases and the water mass becomes more buoyant, remaining at the surface. Winds effect which direction surface water travels; depending on wind direction the freshwater signal may be more or less present.

The transition from summer to winter is an especially variable time in the San Juan Channel system (Figure 3). In the summer, northerly winds are dominant in the California current region. Because of Ekman transport, the net transport of water is offshore as the wind blows from the north. This creates an upwelling process to replace the surface water that has moved offshore with water at depth. In the winter, the reverse is true. Southerlies are dominant, creating conditions in which water “piles up” near the shore, causing the downwelling of surface water. (Iles, 2012; Pickett, 2003). Upwelling promotes different and opposite oceanographic conditions than downwelling, with upwelled waters typically being cold, salty, oxygen-poor and nutrient-rich relative to downwelled waters. Waters off the Washington coast are the source waters for the Salish Sea, including the San Juan Channel. PEF apprentices in the past have shown that the transition from upwelling to downwelling can be detected in the San Juan Channel (Williams, 2012).

Past PEF research has also shown that the external driver El Niño Southern Oscillation (ENSO) influences temperatures in the San Juan Channel (Williams, 2012). However, effects of the Pacific Decadal Oscillation (PDO) and the North Pacific Gyre Oscillation (NPGO) have had less analysis and less is known about their influence in the San Juan Channel. PDO is similar to ENSO in that it has warm and cold phases but while ENSO acts on an annual timescale, PDO is an interdecadal driver, taking 20-30 years to complete an oscillation (Biondi, 2001). The North Pacific Gyre Oscillation (NPGO) occurs over similar timescales as the PDO, and has been shown to influence dissolved oxygen levels in the top 0-50m of water in the Puget Sound (Puget Sound Marine Waters, 2012). Dissolved oxygen is an indicator of the extent of productivity occurring because photosynthesis adds oxygen to the environment while respiration decreases dissolved oxygen. By looking at how dissolved oxygen anomalies change over time, it is possible to see how productivity patterns may be influenced by larger-scale processes like NPGO.

The objective of my research project was to 1) characterize the physical oceanographic conditions of 2013 and 2) compare them to the past 10 years of PEF research, 3) investigate the effects of two external drivers: discharge from the Fraser River and the fall transition on salinity of 2013, 4) investigate how ENSO and PDO effect temperatures in the San Juan Channel, and 5) determine if NPGO influences the amount of dissolved oxygen in the surface layer of the San Juan Channel.

Methods

Research data was collected at two stations in the San Juan Channel aboard the R/V Centennial. The first station is north of Friday Harbor, San Juan Island located at 48° 35.00' N, 123° 02.50' W, designated as the *North station*. The *South station* is south of Cattle Pass, San Juan Island at 48° 25.20' N, 122° 56.60' W (Figure 1). Sampling during autumn of 2013 occurred on September 26, October 9, October 15, October 22, October 29, November 5th and November 13th.

Salinity, temperature, and oxygen measurements were collected using a Seabird SEACAT SBE-19 CTD, outfitted with a rosette equipped with 10 Niskin bottles. The CTD was lowered to 10m above the sea floor (downcast), raised to 50, 20, 10, and 0m from the surface at each site (upcast). Downcasts collected salinity and temperature data. Upcasts were used for collecting water samples at each depth. Water samples were taken by remotely firing two Niskin bottles at each aforementioned depth, and were used for oxygen analysis.

Real-time CTD data was sent from the device sensors to the Centennial's onboard computer, saved as a HEX file and then converted to enable analysis on Microsoft Excel (CON file type). Oxygen samples were collected in a manner that minimized the addition of atmospheric oxygen to the depth water sample and followed the sampling protocol of Codispoti (1988). Within seven days of collection, oxygen samples were titrated using the Carpenter modification of the Winkler method (Carpenter, 1965; Winkler, 1888).

Data for Fraser River discharge was obtained from Environment Canada

(http://www.wateroffice.ec.gc.ca/graph/graph_e.html?stn=08MF005), and upwelling indices

from NOAA

([http://www.pfeg.noaa.gov/products/current_products.html?loc=125W+48N&prod=Upwelling+](http://www.pfeg.noaa.gov/products/current_products.html?loc=125W+48N&prod=Upwelling+Index&Submit=Show+Plot)

[Index&Submit=Show+Plot](http://www.pfeg.noaa.gov/products/current_products.html?loc=125W+48N&prod=Upwelling+Index&Submit=Show+Plot)). NPGO analysis compared the NPGO index

(<http://www.o3d.org/nngo/>) with dissolved oxygen in (mg/l) in the top 10m of water at

the South station. For this analysis, *surface* is considered to be less than 10m depth and

depth is 10m from the bottom to 20m above the bottom. In comparing past years'

temperatures and salinities, the surface and depth at the North station and South

station for each cruise available were used.

Results

Temperature and salinity

a. North station

Temperatures at both surface and depth 20-10m cooled over the course of the study period (Figure 5). Surface temperatures ranged from roughly 11.4 to 9.2 degrees Celsius, while depth cooled from 10.4 to 9.0 degrees Celsius (Figure 4). Surface salinity increased over the study period from 28.0 PSU to 30.5 PSU, with a dip in salinity occurring on 29 October down to 28.7 PSU. Salinity at depth increased, starting at 30.9 PSU and increasing to 31.1 PSU, with a peak on 29 October (31.8 PSU) (Figure 5). Overall, this year was

warmer at the North station than previous PEF years (Table 2). Salinity was moderate this year (Table 3).

b. South station

Surface temperatures at the south station decreased over the study period from 10.6 to 9.2 degrees Celsius. Temperatures at depth also decreased over the study period from 8.7 to 8.1 degrees Celsius, with a notable increase on 22 October to 9.7 degrees (Figure 6). Salinity at the surface was variable, with the beginning and end of the study period being approximately 31.0 PSU, while the middle of the study period was markedly fresher. Salinity at depth was also varied, starting and ending at approximately 32.7 PSU, with a rise in the middle up to 33 PSU and a low point of 32.4 PSU (Figure 7). Overall temperature this year was moderate compared to the past 10 PEF years (Figure 2). Salinity was also moderate (Figure 3).

c. Fraser River discharge during 2013 (Figures 8) was predominantly lower than the 102-year mean, with an event in October where discharge increased over the mean and returned to previous levels (Figure 9).

d. The fall transition from upwelling to downwelling this year was inconclusive. During the study period, salinity at the South station did not indicate the fall transition occurred (Figure 7). The upwelling index from NOAA supports this; there is no consistent change from positive to negative upwelling values, which is characteristic of a fall transition (Figure 13).

- e. 2013 was El Niño neutral (Figure 14). Average temperatures for each PEF cruise in record demonstrate that this year's temperatures fall within a typical range for a neutral year (figure 15).
- f. The PDO was in a warm phase that ended in 2006, neutral during 2007, and in a cold phase from 2008 continuing through 2013 (Figure 16).

Oxygen

Dissolved oxygen from the surface and NPGO index values over PEF record show a weak correlation (figure 15). A Pearson correlation test conducted using the two data sets returned a value of 0.32, indicating about a third of dissolved oxygen variation is correlated with the NPGO.

Discussion

Data from PEF 2013 emphasizes that multiple factors contribute to physical oceanographic conditions in the San Juan Channel. In 2013, physical oceanographic conditions were less clearly influenced by one source, compared to past PEF research studies (refs). (?) Rather, an approach dictating multiple sources was necessary.

Annual patterns

In the North station, salinity at the surface is greatly influenced by Fraser River input. Freshwater is more buoyant than seawater, and therefore tends to remain at the surface when released into the Puget Sound estuary. This signal is seen at the North station, focused at the surface, which was approximately consistent from 9 October-22

October and 5 November-13 November. There was a marked decrease in salinity on 29 October, suggesting that the Fraser River had increased the amount of water discharged prior to this date. However, upon analysis of discharge data it was found that this was an unlikely explanation. Wind direction and magnitude provide a more accurate explanation; northeasterly winds blow the Fraser River plume toward the North station and southwesterly winds vice versa. Lack of Fraser River signal from 9 October- 22 October and 5 November – 13 November can be attributed to predominant southeasterly winds (figures 10-12). Just after the 22 October and during 29 October, northeasterly winds dominate and amplify the freshwater signal.

Because of the proximity, the yearly fall transition from upwelling to downwelling is typically seen at the South station. Because downwelling involves a piling up of freshwater at the surface that is forced downward via Ekman transport, salinity at depth would be expected to decrease after the fall transition occurs and these waters circulate into the Strait of Juan de Fuca. Additionally, during a characteristic fall transition, upwelling values clearly switch from positive (upwelling) to negative (downwelling). However, this year's fall transition was inconclusive. The lack of a characteristic fall transition signal in NOAA upwelling indices was reflected in the lack of freshwater signal at depth throughout the study period. This is uncharacteristic of past PEF study periods – all other years have been able to identify a fall transition during the study period (late September to mid November).

Interannual Patterns

El Niño-Southern Oscillation has been shown to influence temperatures in the San Juan Channel. 2013 was classified as El Niño neutral, and so temperatures were predicted to be moderate at each site. However, a mix of signals were seen; surface and depth at the North station were warmer and depth temperatures at the South station were cooler than average. These anomalies were within typical ranges of past neutral years.

The Pacific Decadal Oscillation (PDO) occurs over 20-30 year periods (CITE). PDO switched from a warm oscillation to a cool oscillation in 2007. This shift appears to contribute to the intensity of ENSO temperature anomalies in the SJC. 2009 was an El Niño year, and yet temperatures that year were lower than this year's neutral temperatures. Overall, temperatures from 2007-2013 did not exceed the last PDO warm phase in 2006 – even when it was an El Niño year (figure 14). Additionally, the La Niña in 2012 was the coolest on PEF record, while 2010 and 2011 are both colder than 2007's La Niña. This analysis of PDO also supported the overarching idea that many factors contribute to one physical oceanographic property, and there can be additive effects between different drivers. This is consistent with other studies that study the combination effects between PDO and ENSO (Lee, 2013)

When dissolved oxygen anomalies over the past 10 PEF years were compared with NPGO values, a rough pattern emerged. In general, at the times averaged NPGO anomalies were negative, dissolved oxygen anomalies were also low, and when averaged NPGO anomalies were positive, dissolved oxygen anomalies were also positive. The Pearson correlation of 32% implies that future research would benefit

from analyzing nutrient content in the water over PEF record and test correlation with NPGO values, because nutrients are closely related to productivity. Additionally, a possible bias is that the oxygen values for 2004, 2011 and 2012 were not corrected with the Carpenter-Winkler method.

In conclusion, 2013 illustrated that many factors determine the physical oceanographic conditions in the San Juan Channel. Salinity at the North station is heavily influenced by wind direction, changing the amount of freshwater from the Fraser River that the channel receives. The fall transition was inconclusive this year, not occurring characteristically during the study period. Meanwhile, temperatures were typical for an ENSO-neutral year.

The additive properties of ENSO and PDO drive temperature variation with resulting temperatures only slightly off neutral and not consistently warmer or cooler. NPGO indices and surface dissolved oxygen anomalies were found to be only loosely correlated from 2004 through 2013, and more investigation in this path of study is advised.

Using and building upon the discoveries that we have made in this study will significantly improve our understanding of the San Juan Channel as an ecosystem, and could allow for better predictions of future physical oceanographic conditions. In order to understand biological patterns in the upper trophic levels, it is important to understand how their processes are driven by physical conditions.

Acknowledgements

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Tables

Table 1 Dates of cruises

Cruise 1	September 26
Cruise 2	October 9
Cruise 3	October 15
Cruise 4	October 22
Cruise 5	October 29
Cruise 6	November 5
Cruise 7	November 13

Table 2: Fall 2013 temperatures compared to past 10 years of PEF

	North		South	
	<i>Surface</i>	<i>Depth</i>	<i>Surface</i>	<i>Depth</i>
2004	average	average	average	higher
2005	average	higher	Higher	higher
2006	higher	higher	Higher	higher
2007	colder	colder	Colder	colder
2008	colder	average	average	average
2009	warmer	warmer	average	warmer
2010	cooler	average	warmer	cooler
2011	cooler	cooler	Cooler	cooler
2012	cooler	cooler	Cooler	cooler
2013	warmer	warmer	warmer	cooler

Table 3: 2013 salinity compared to past 10 years PEF research

	North		South	
	<i>Surface</i>	<i>Depth</i>	<i>Surface</i>	<i>Depth</i>
2004	saline	saline	saline	fresher
2005	saline	fresher	saline	saline
2006	saline	saline	saline	saline
2007	saline	fresher	saline	average
2008	saline	saline	saline	saline
2009	saline	fresher	saline	average
2010	saline	average	average	saline
2011	fresher	fresher	fresher	saline
2012	fresher	average	fresher	fresher
2013	fresher	average	fresher	saline

Figures



Figure 1: Locations of North and South stations, as well as main annual influences

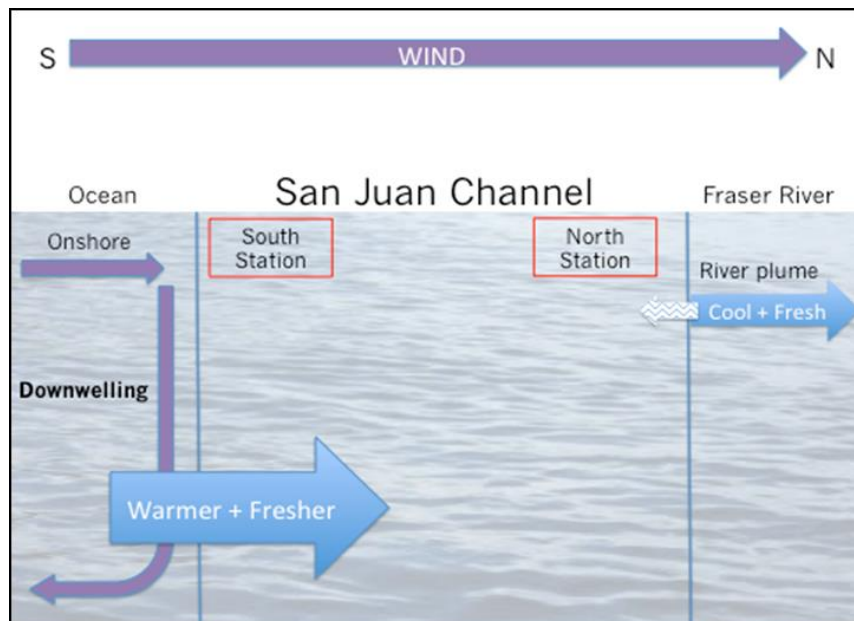


Figure 2: Representation of San Juan Channel regarding North and South station inputs

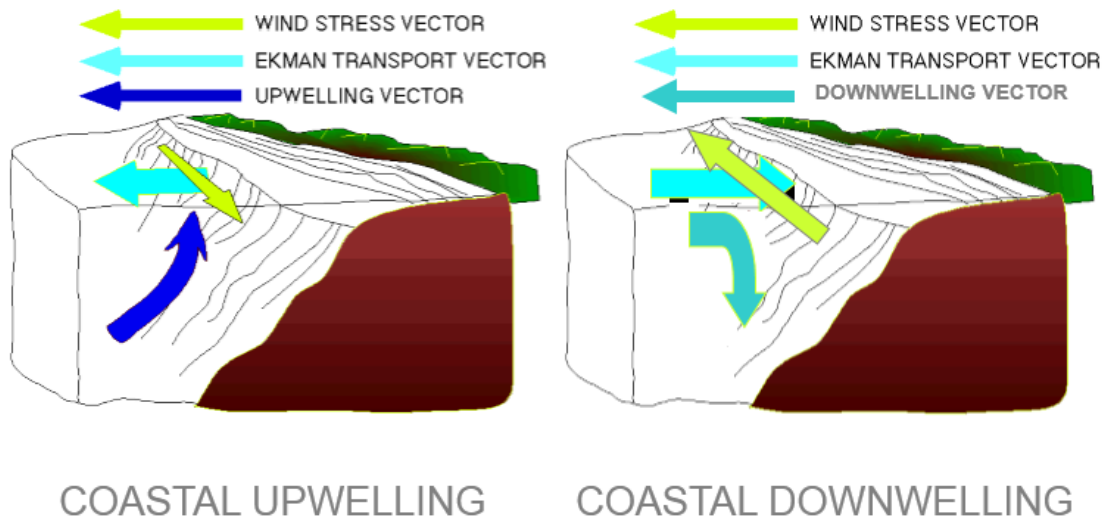


Figure 3: Upwelling and downwelling along the California Current (via NOAA PFEL)

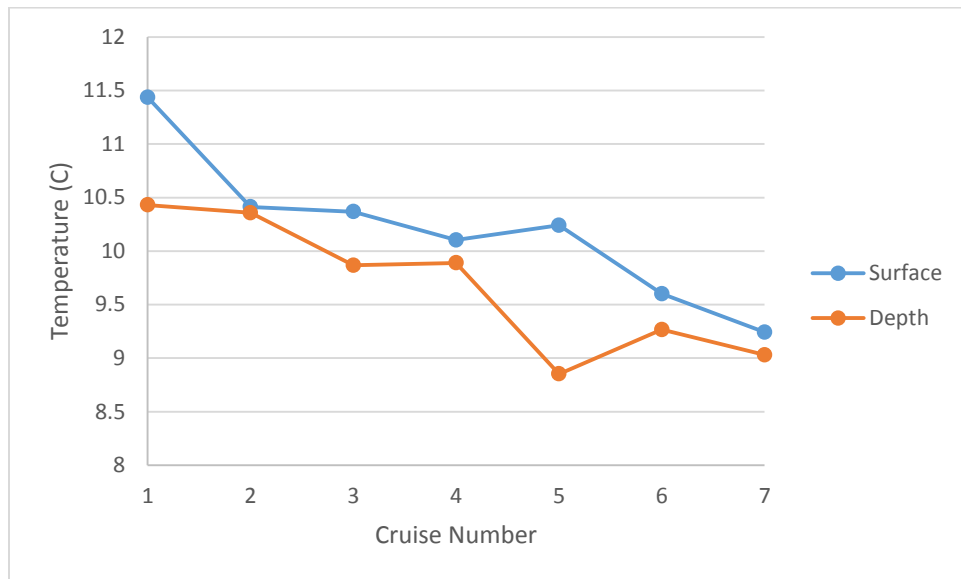


Figure 4: Average temperature at the North station

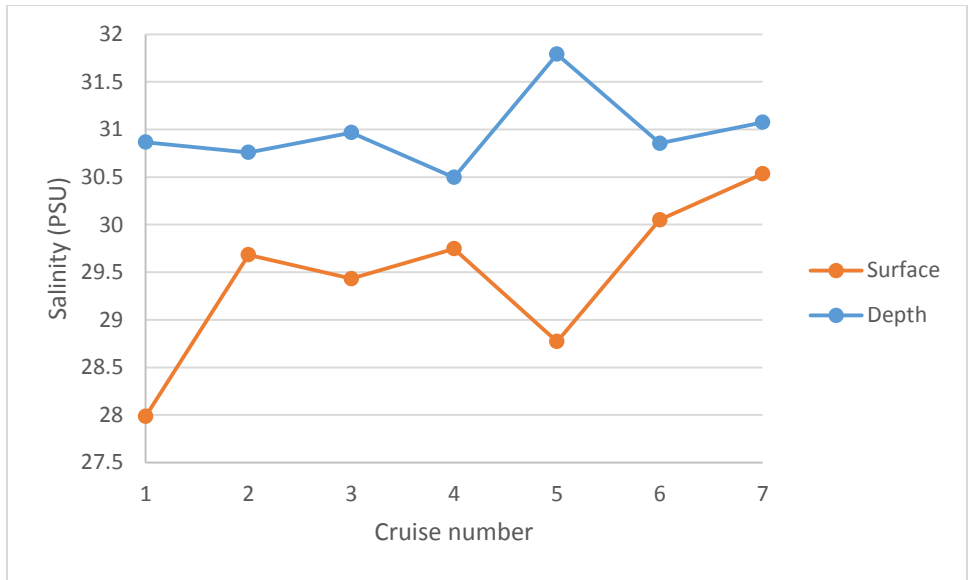


Figure 5: Average salinity at the North station

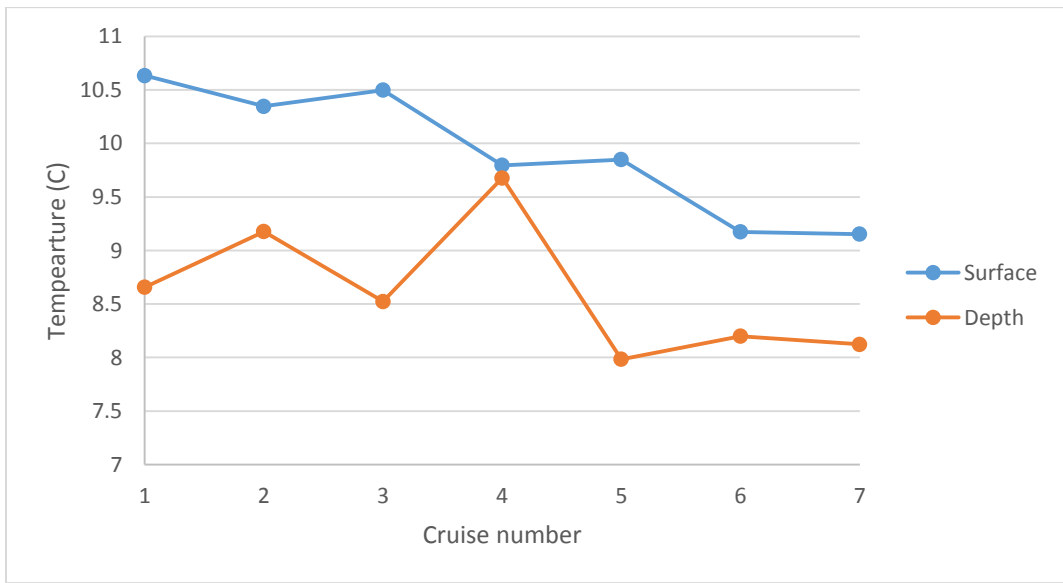


Figure 6: Average temperature at South station

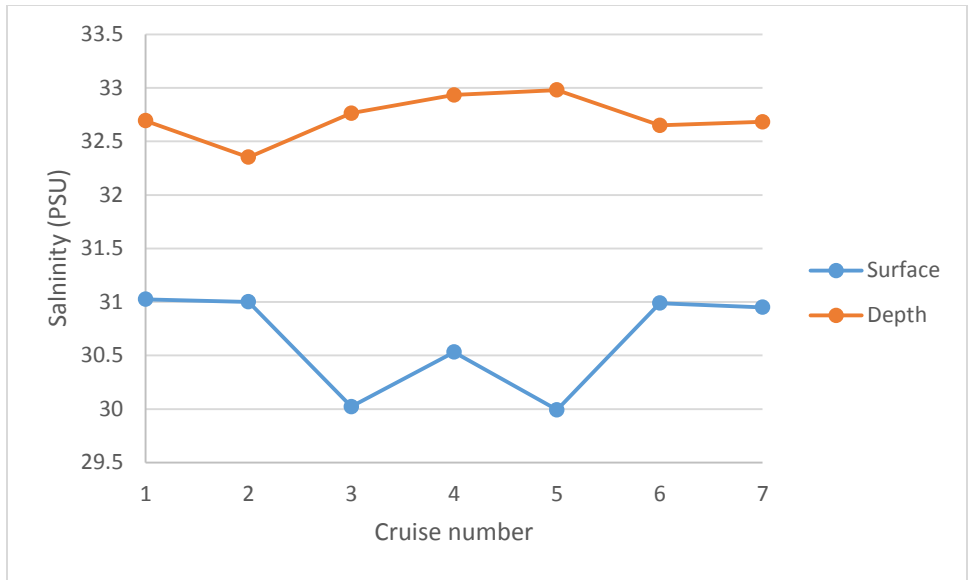


Figure 7: Average salinity at the South station

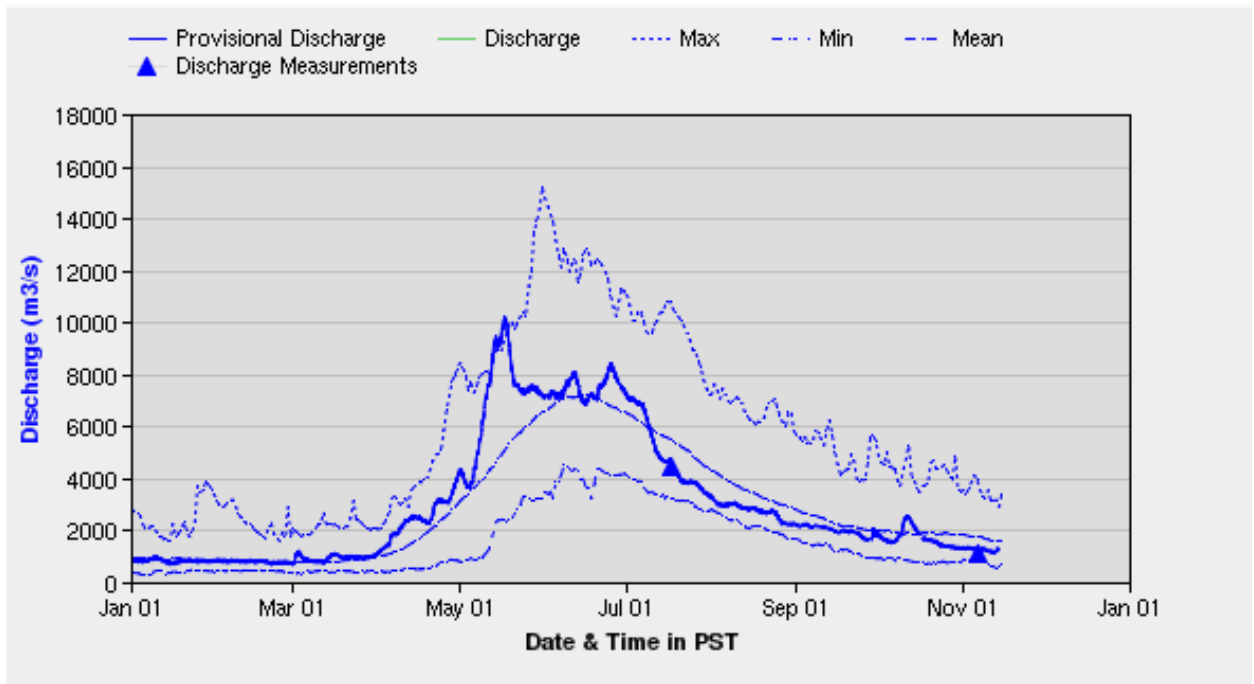


Figure 8: Fraser river discharge for the year of 2013. Record is 102 years old.

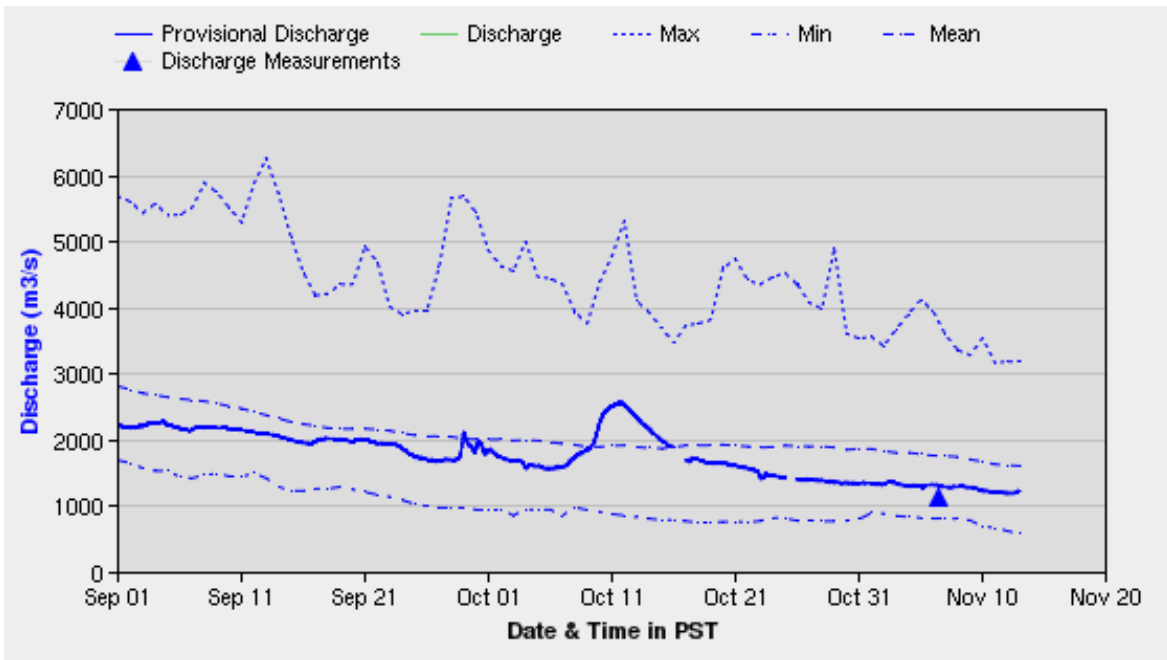


Figure 9: Fraser discharge from 3 weeks before study period to end of study period

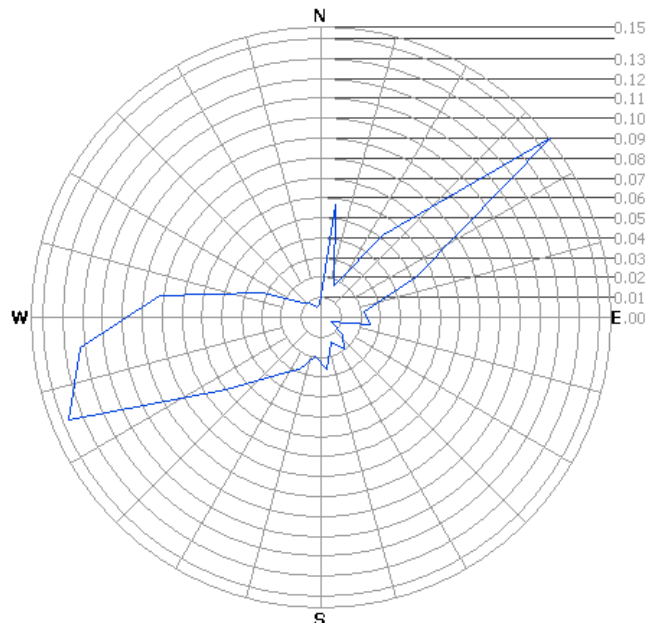


Figure 10: Wind direction and magnitude from 1-8 October 2013

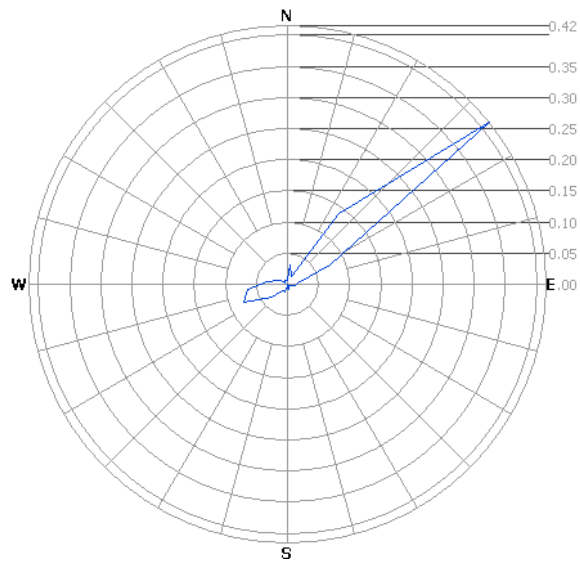


Figure 11: Wind direction and magnitude from 16-23 October 2013

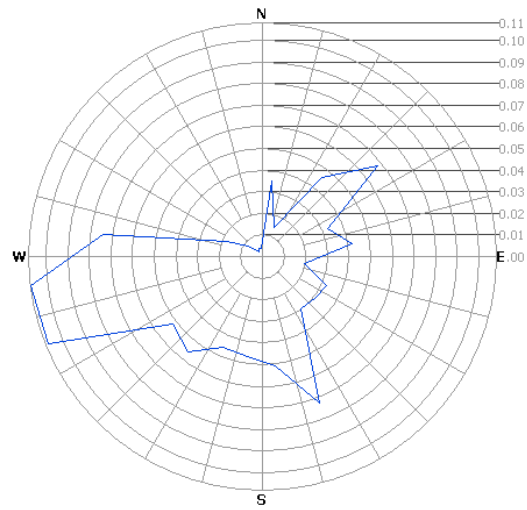


Figure 12: Wind direction and magnitude from 1-8 November 2013

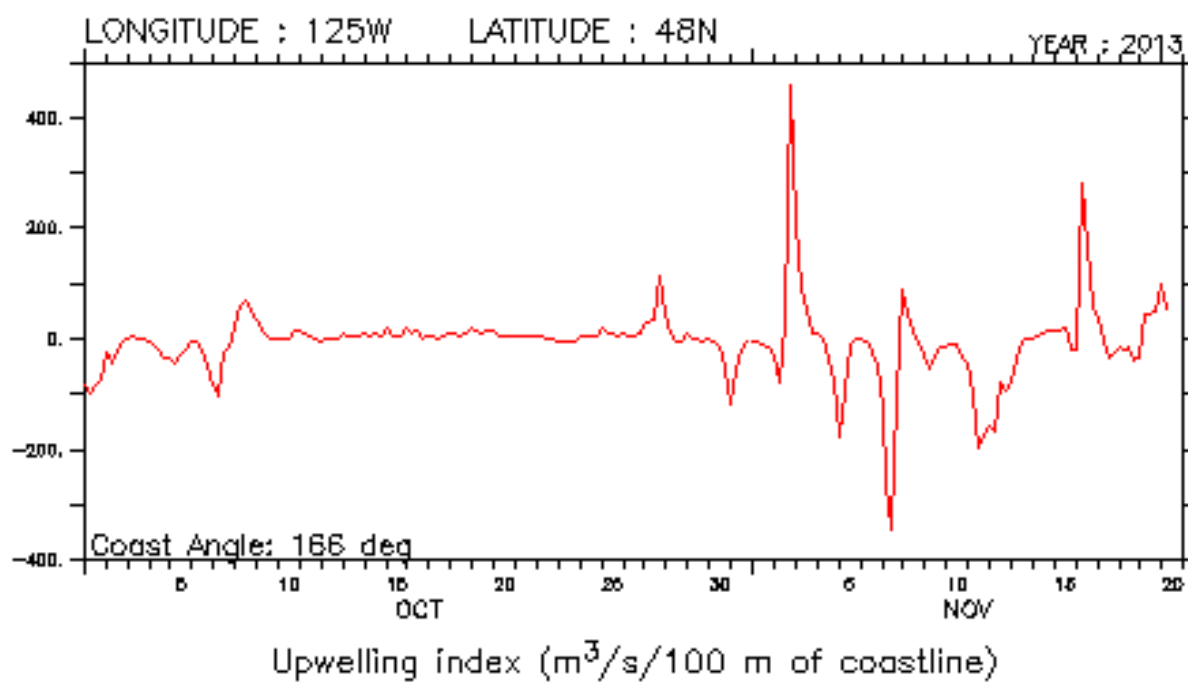


Figure 13: Upwelling index obtained from NOAA PFEL. Positive values indicate upwelling, negative values indicate downwelling

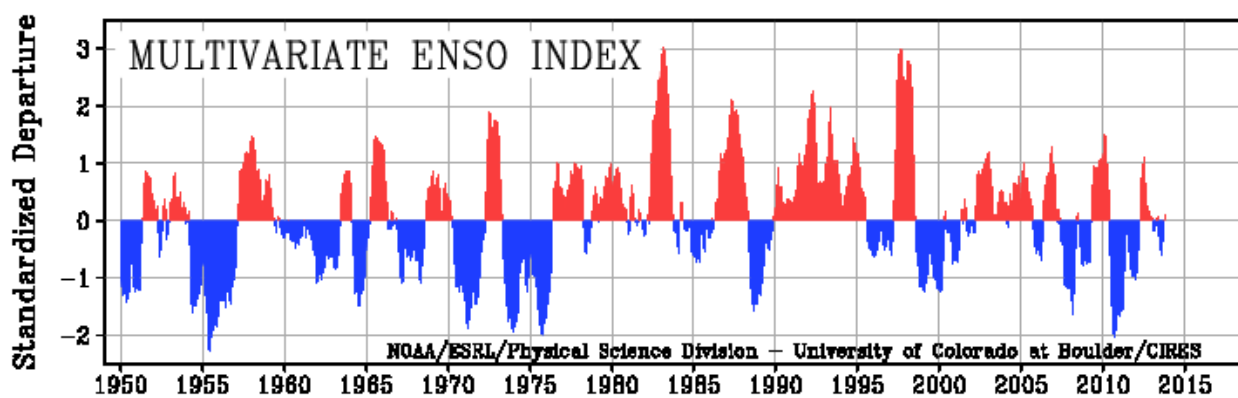


Figure 14: ENSO designation

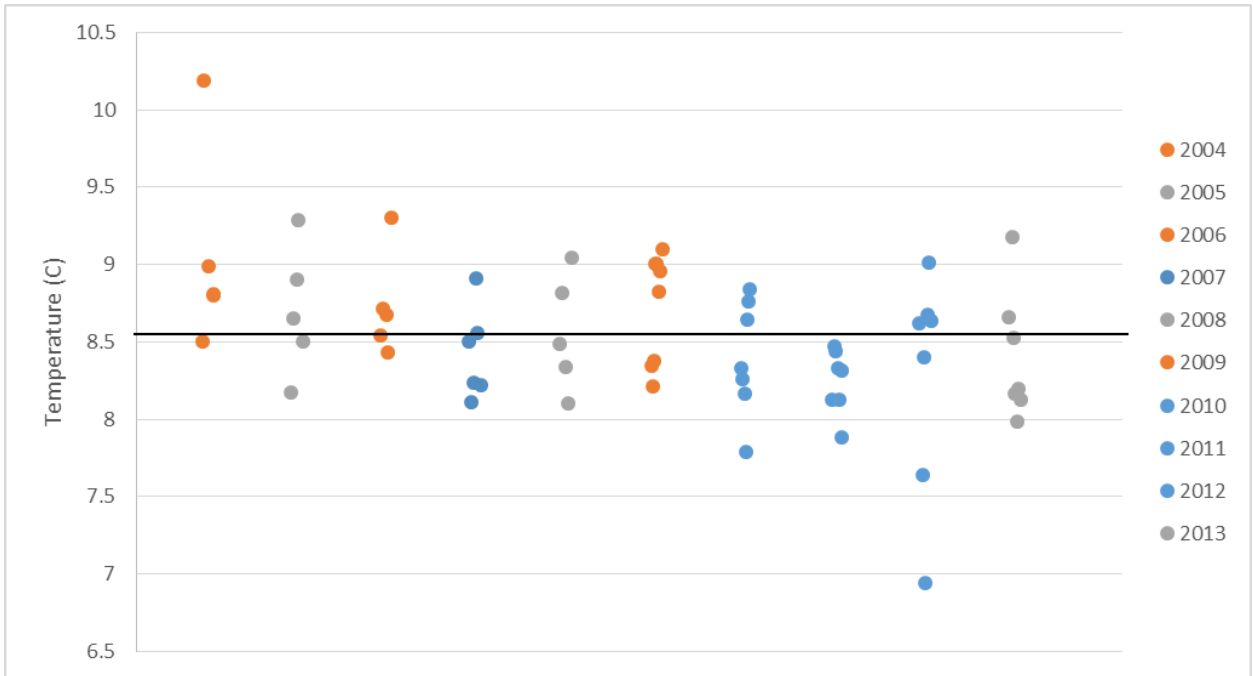


Figure 15: Average temperatures for all PEF years available. Orange dots indicate El Niño years, grey dots indicate neutral years, and blue dots indicate La Niña years

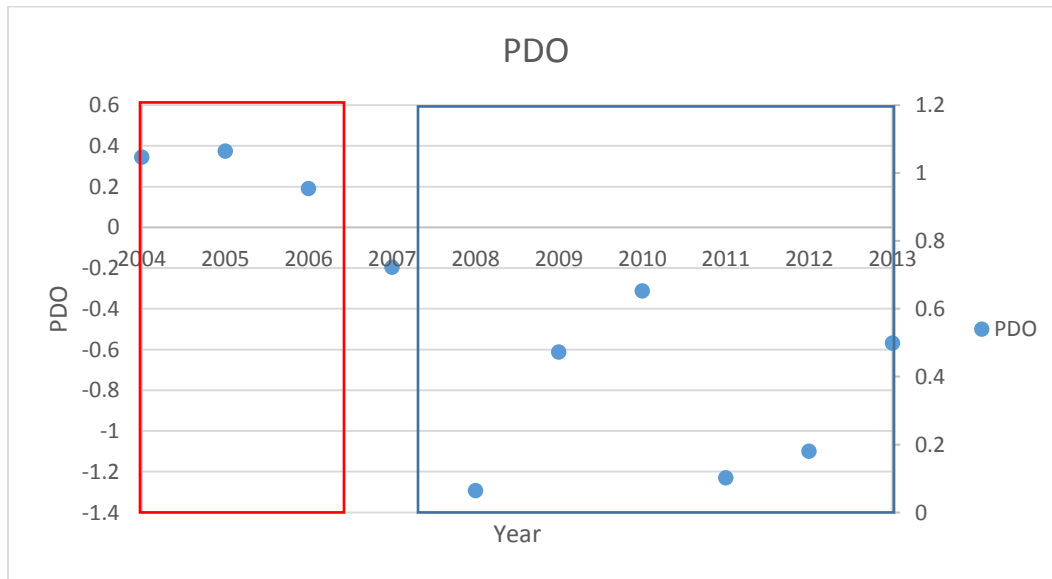


Figure 16: PDO values since 2004. Warm oscillation until 2006, neutral 2007, cold oscillation 2008-2013. 2013 average value through October

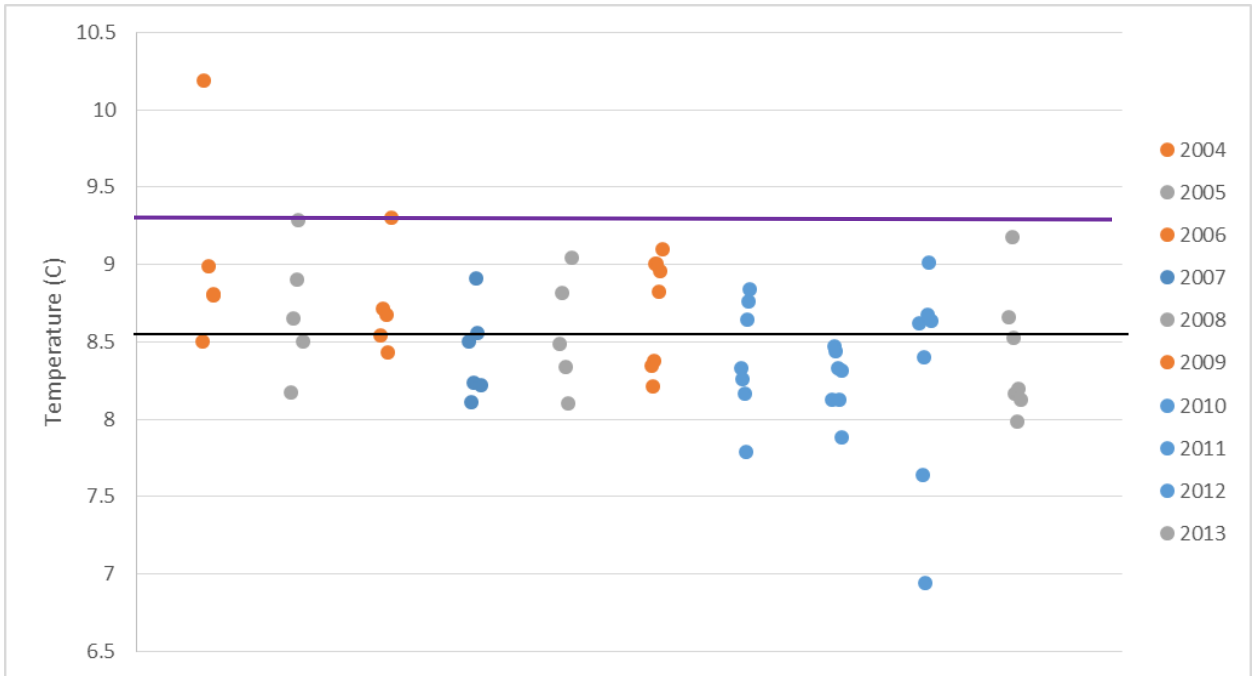


Figure 17: Pacific decadal oscillation shifts from warm to neutral/cold at 2007. Purple line indicates highest temperature reached during warm phase

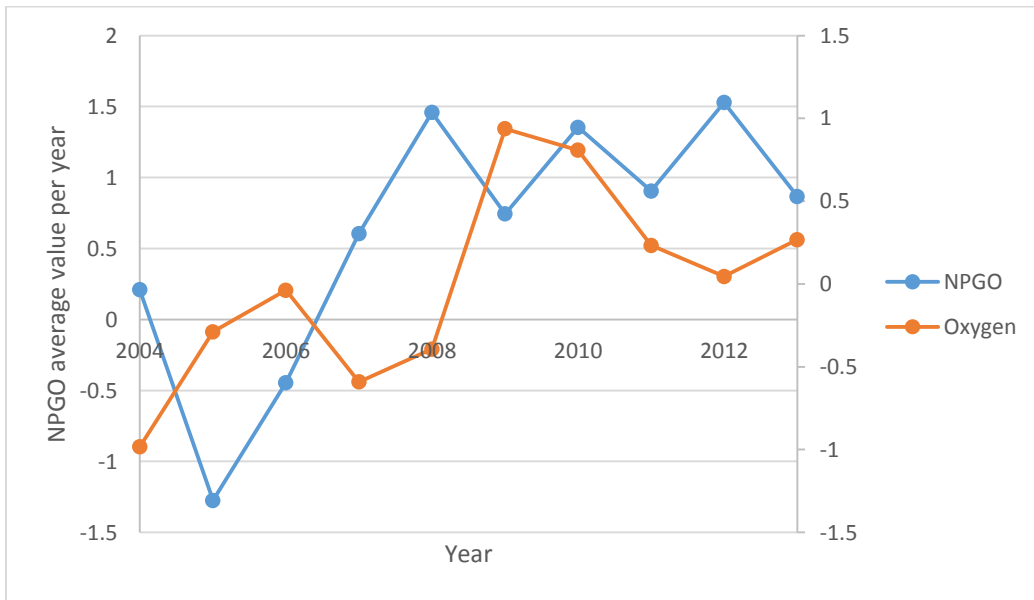


Figure 18: NPGO values and dissolved oxygen values in the top 10 m. Left hand axis is NPGO values. Right hand axis is dissolved oxygen anomaly in g/mL