Observed oxygen concentrations and a possible implication behind the Muchalat inlet subsurface oxygen maximum

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Abstract

It is expected to find the water column in Muchalat inlet to display strong stratification due to the influx of freshwater from sources like the Gold River layering on top of the denser seawater that enters from Nootka Sound and the open ocean. This stratification limits vertical mixing, denying highly oxygenated surface waters to sink below a certain depth. However, after measuring the oxygen concentrations during the 2016 Senior Thesis Cruise (TN334), a layer of relatively higher oxygen was found at a depth that was not expected of that oxygen level. Since vertical mixing through different densities is unlikely to occur, the most likely explanation for this inflow of oxygen is that it originates from a source outside of Muchalat Inlet, more specifically the open ocean. Using nutrient data as a tracer to follow the same circulation pattern as oxygen, it was inferred that the tracers could not have tracked in the hypothesized pattern because the density gradient connecting Muchalat inlet and the open ocean did not contain the same values. Therefore, the open ocean is concluded to be an unlikely source for the influx of oxygen.

Introduction

Investigating ocean properties and the basis for their current levels in a certain environment can help provide a better understanding of the ecosystem and how organisms in that area are affected. One of the most important properties is oxygen concentration as it can provide answers to complex questions about the organisms that inhabit that environment, as well as the overall health of that system. During the December 2015 Senior Thesis Cruise (TN334), oxygen concentrations in Muchalat Inlet were collected and analyzed. The results that were found showed a deviation from the previous year's conditions, leading to a possibility that an abnormality was present. This study focuses on that phenomenon and attempts to analyze the cause and mechanism behind the observed conditions.

Muchalat Inlet is one of three major fjords connected to Nootka Sound in Vancouver Island, British Columbia. Multiple rivers flow into this inlet, depositing large amounts of fresh water during the winter months. This deposition of fresh water allows for higher density water flowing in from Nootka Sound and the open ocean to be trapped below, forming a highly stratified salinity gradient. This degree of stratification makes it difficult for water to mix vertically in the water column causing other properties (e.g. oxygen concentration) to remain layered in the same position throughout the water column, with no mixing in between. A 2015 study of Muchalat Inlet showed evidence of this stagnant layering, displaying higher concentrations of oxygen near the surface, where the water is affected by atmospheric exchange and circulation, and decreases in oxygen concentration with increasing depth (Li 2015). Vancouver Island's Trevor Channel and Effingham Inlet in Barkley Sound also displayed the same pattern (Emswiler 2010). The fresh water input from sources like the Gold River near the surface and dense water from the ocean below, causes vertical mixing to become nearly impossible, keeping highly oxygenated water on top and decreasing in concentration with depth. The upper 100m of the water column contained over 150 umol/kg of oxygen while below that depth reached values under 50 umol/kg (Emswiler 2010). Due to a lack of sunlight reaching below 100m in depth in this area, photosynthesis also does not occur as frequently as it does near the surface, giving rise to the expectation that oxygen concentration will decrease with depth. Since multiple inlets and channels around Vancouver Island share this characteristic, it can be inferred that this trend is considered to be under normal conditions and can be expected to occur annually.

Although oxygen levels are predicted to consistently decrease with depth, the oxygen levels measured on TN334 displayed unusual characteristics. Oxygen levels did decrease with depth, but showed a layer of higher oxygen levels centered at 200m. This layer extended about two-thirds of the way into Muchalat inlet, forming a wedge in between the layers of lower oxygen levels (Figure 1). It is interesting to study the mechanism behind this phenomenon, as it can lead to a further understanding of the behavioral patterns of organisms based on the oxygen levels concentrated in the area in which certain organism lives in. With the expectation that oxygen levels consistently decrease with depth, we can infer that organisms relying heavily on respiration and higher oxygen concentrations will inhabit areas of the water column closer to the surface. Having an oxygenated layer at depth allows organisms to distribute themselves throughout the water column differently. Oxygen concentration also plays a key role affecting chemical properties. For example, the presence or absence of oxygen can create oxidation/reduction reactions such as the breaking of iron-phosphate bonds, varying the amount of phosphorous in the water. This effect can delay the recovery water in anoxic or dysoxic conditions and lower the overall health of the inlet (Jones 2011). By having an influx of dissolved oxygen at lower depths, the condition of the inlet can improve.

This study examines the cause and effects of an inflow of subsurface oxygen due to circulation patterns originating outside of Muchalat Inlet towards Nootka Sound and the open ocean. While vertical mixing is not expected and highly unlikely to occur in the inlet due to stratification of the water column with a freshwater layer at the surface, the most likely explanation for oxygenated water to exist at that depth is an inflow of denser seawater from Nootka Sound followed by that parcel sinking down to its appropriate depth once it enters Muchalat Inlet is the most logical explanation for oxygenated water to exist down at that depth.

Methods:

Data was collected during the University of Washington School of Oceanography Senior Thesis Research Cruise from 10-20 December 2015. Water samples were taken at multiple station throughout Nootka Sound and Muchalat Inlet using a Seabird SBE 911 plus rosette CTD and attached Niskin sampling bottles. In order to collect accurate measurements at each station, water samples were collected throughout the water column, with one sample at maximum depth (the deepest the CTD can go without hitting the seafloor), one near the surface, and a minimum of six in between at evenly spaced intervals. These water samples were transferred from the CTD's Niskin bottles to 125ml Erlenmeyer flasks and titrated immediately. The titration process was done using the Dosimat manual titrator and the Winkler method (EPA

LG501 2007). Ocean Data View (ODV) Version 4.7.6 – 64 bit (Mac OS X) was used to display the measured oxygen data observed by the CTD sensor.

While Niskin bottles were being fired off at each appropriate depth, the SBE 911 electrode on the CTD also continuously took measurements which was then recorded concurrently with each Niskin bottle filled at it's appropriate depth. The titrated measurements were used to calibrate the measurements recorded from the CTD.

These two methods of collecting oxygen concentration measurements were used in to determine which set of data was more accurate, the manually titrated water samples or the recorded sensor data. Measurements from both methods were analyzed to assure no major discrepancies existed to invalidate the results. This was done by looking at the significance of each sample measured and using statistical analysis to compare both sets of data.

In order to determine the significance of each point, the recorded value from the sensor data could not be too "extreme". Since the water sample collected inside the Niskin bottle is approximately one-meter-long, the recorded point from the sensor must be an average of that one meter equal to the Niskin bottle. Once all points have been averaged, a T-Test was used to either prove or disprove the null hypothesis that the sensor data and manually titrated samples differ significantly. All statistical analysis was done using Microsoft Excel 2015 Version 15.18.

Nutrient data was collected by taking 45-50ml water samples and filtering them through a 60ml syringe and 25mm, 0.45μm pore size Nalgene filter, and transferred to a 60ml HDPE plastic bottle. Expansion was accounted for by leaving about an inch of space at the top of each bottle. The samples were stored at -10^{o}C until they were ready to be processed at the Marine Chemistry Lab, School of Oceanography, University of Washington. Each sample of water was analyzed for nitrate (NO_3^-), nitrite(NO_3^{2-}), ammonia (NH_3), phosphate (PO_4^{3-}), and silicate ($SiOH_4^{2-}$).

Results:

Using the CTD sensor measurements, oxygen levels near the surface of Muchalat Inlet (upper 60m) ranged from 2.3ml/l to 6 ml/l. From 60m to 150m in depth, oxygen levels were lower and reached anoxic levels from 2.3 ml/l to 0.02 ml/l. From 150m to 300m in depth, oxygen levels went back up and ranged from 1 to 1.8 ml/l before dropping back down below 1ml/l past 350m depths (Figure 1). The sudden increase occurred past the first sill into the inlet and is lower near the mouth of Muchalat (left end of the figure) and increases near the head of Muchalat (right side of the figure), forming a “wedge-shaped” oxygen maximum at about 200m in depth (Figure 1).

The oxygen concentration measured using the Winkler method showed relatively different results as the CTD measurements. When compared using a scatterplot and looking at the ratio, the r^2 value that was calculated was equal to 0.4708, which showed that the sensor data and Winkler data were not comparable and contained too many outliers (Figure 2). A test of significance (T-Test) had to be done in order to provide sufficient evidence that the CTD data is accurate enough to use.

The T-Test that was performed to verify the oxygen concentrations measured by the CTD showed that the null hypothesis cannot be rejected. The null hypothesis states that the CTD data and the manually measured Winkler titration data does not differ significantly. This was not the case, and based on the values from the T-Test, there was not enough evidence to suggest that the data differed significantly (Table 1). The t Critical value produced by the table was 1.969. The t-stat value produced was 0.9575. The implications of the result give us the interval -1.969 < 0.9575 < 1.969, which means oxygen data from the CTD can be used in place of Winkler titration data in lab analysis.

The nutrient data used were from two stations: Nootka Endmember and Carbon 06. The Endmember is the closest station to the open ocean and the Carbon 06 station is just inside Muchalat Inlet. The nutrient values in the Nootka Endmember station at 168m depth are significantly lower than the values in Carbon 06 at 140m in depth (Table 2).

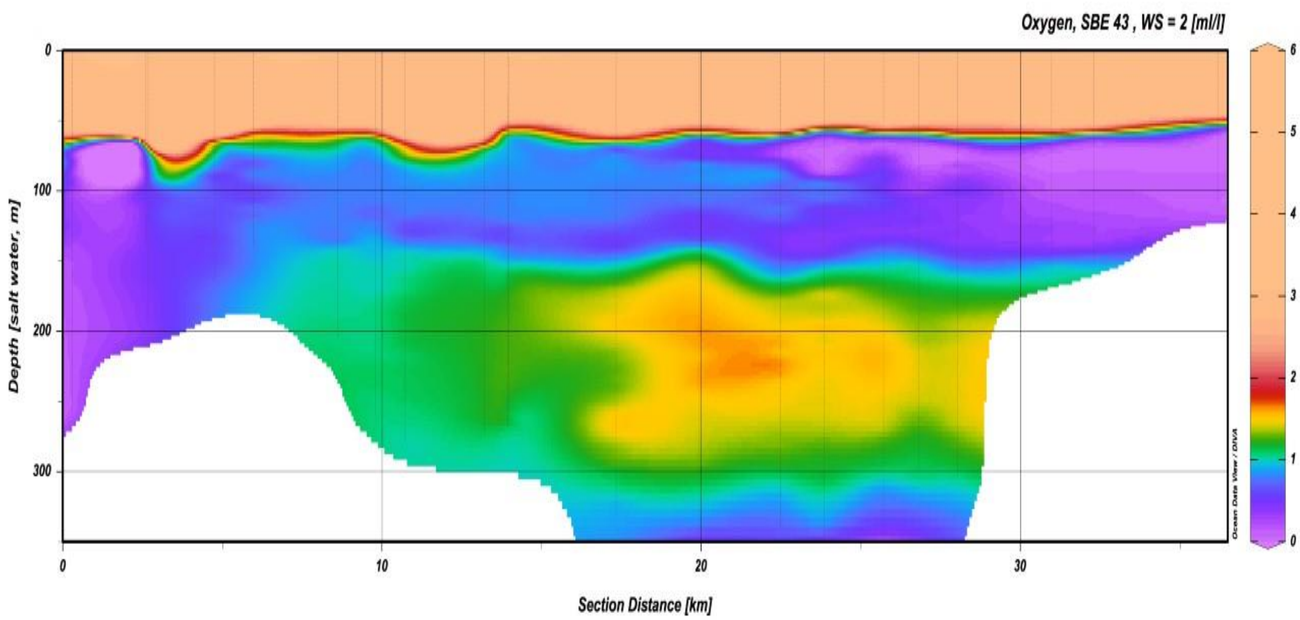

Figure 1: Cross-section of Muchalat Inlet (2015) displaying oxygen concentration (ml/l) with depth, from the mouth of the inlet (left side) to the head of Muchalat near the Gold River (right side).

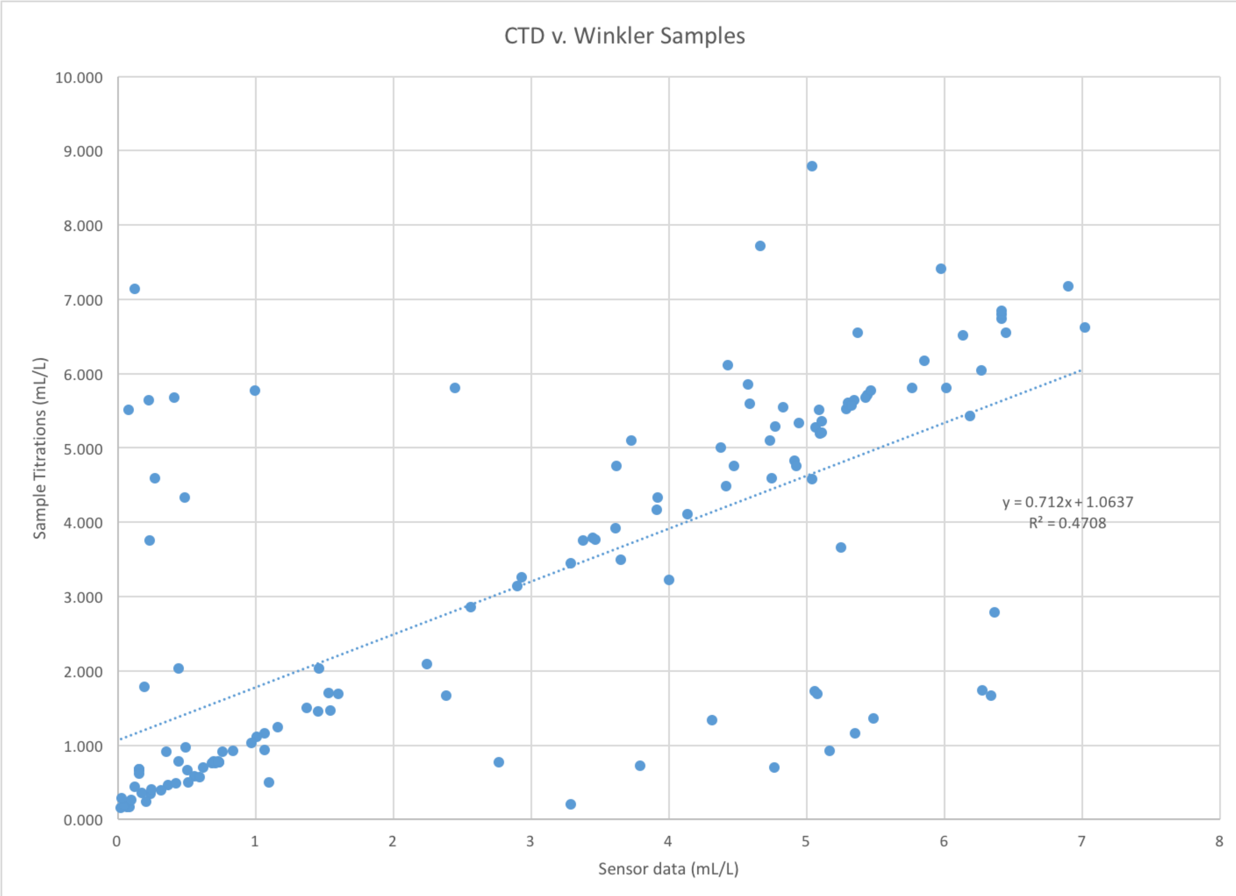

Figure 2: Scatter plot comparison of CTD sensor data (x-axis) and Winkler titration data (y-axis) in ml/l.

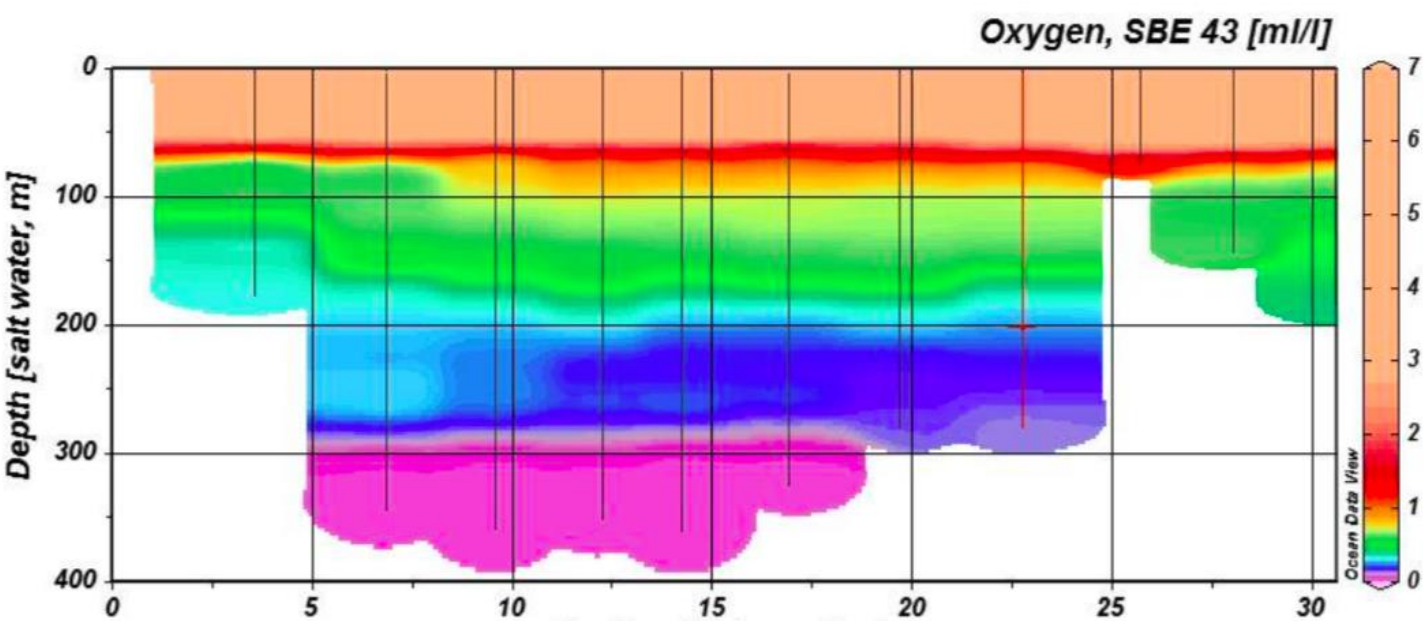

Figure 3: Cross-section of Muchalat Inlet, with the Williamson sill (and Nootka Sound) on the left end and Gold River on the right end, displaying oxygen concentration (ml/l) with depth from a previous study (Li 2015).

t-Test: Two-Sample Assuming Equal Variances		
	Variable 1	*Variable 2*
Mean	3.199438732	2.925576923
Variance	5.648124867	5.024799858
Observations	131	130
Pooled Variance	5.337665693	
Hypothesized Mean Difference	0	
df	259	
t Stat	0.96	
P(T<=t) one-tail	0.169601667	
t Critical one-tail	1.650758134	
P(T<=t) two-tail	0.339203334	
t Critical two-tail	1.97	

Table 1: T-Test values of averaged Winkler titration data (Variable 1) and CTD sensor data (Variable 2). Values used to verify significance are highlighted.

Sample ID	Depth	[PO_4]	[Si(OH)4]	[NO_3]	[NO_2]	[NH_4]
Nootka	0	0.53	3.22	2.11	0.15	0.00
Nootka	69	1.16	12.29	11.81	0.03	0.00
Nootka	168	1.85	33.47	24.40	0.02	0.00
Nootka	247	2.07	44.69	28.26	0.01	0.01
Nootka	399	2.60	66.28	35.55	0.01	0.00
Nootka	550	2.89	86.54	39.55	0.01	0.00
Nootka	1000	3.13	132.41	42.43	0.01	0.01
Nootka	1387	3.07	154.87	42.13	0.02	0.00
C06	2	0.77	32.22	7.89	0.16	0.59
C06	10	1.28	19.81	11.73	0.22	0.24
C06	30	1.49	25.82	13.39	0.15	0.00
C06	55	1.90	42.68	16.76	0.07	0.08
C06	140	3.38	81.76	26.99	0.07	0.00

Table 2: Nutrients collected in open ocean (Nootka) water and Muchalat Inlet (C06).

Station	Cast	Niskin	Ox Sens.	Bottle #	mL/L
Nootka End.	2	8	4.73	314	5.104
Nootka End.	2	1	0.762	319	0.916
Nootka End.	2	2	0.491	320	0.970
Nootka End.	2	3	0.195	321A	1.783
Nootka End.	2	4	0.734	322	0.773
Nootka End.	2	5	1.53	323	1.705
Nootka End.	2	7	3.375	313A	3.754
Nootka End.	2	6	2.898	324A	3.143
C06	31	1	0.44	467	2.034
C06	31	2	0.484	468	4.333
C06	31	8	5.037	469	4.585
C06	31	7	4.586	470	5.596

C06	31	5	4.576	471	5.856
C06	31	6	4.662	472	7.717
C06	31	4	3.787	473	0.729
C06	31	3	0.511	474	0.500
C06	31	11	6.271	479	1.737
C06	31	10	5.247	480	3.655

Table 3: Winkler Titration results (ml/L) and associated Oxygen Sensor data recorded (Ox. Sensor) from two stations, one near the open ocean (Nootka End.) and one just inside of Muchalat Inlet (C06).

Discussion

Looking at the oxygen profile through the cross section of Muchalat Inlet (Figure 1), we notice that oxygen concentration is at its highest near the surface (upper 70m) and decreases with depth. This is the type of profile that is expected from a fjord, and based on previous oxygen data in the inlet from December 2014, the oxygen concentration is predicted to continue to decrease with depth, forming anoxic layers beneath 300m (Figure 3). However, this did not occur, and instead a “wedge-shaped” oxygen layer was found from 150m to 300m. Input of oxygen from the atmosphere into the water’s surface can be a potential source for the oxygen wedge. But due to the differences in density down the water column, it is highly unlikely that vertical mixing occurred, bringing water parcels that are higher in oxygen down at depth. Instead, the source must come from outside the inlet, brought in by circulation.

In fjords and inlets that contain sills, deep water renewal occurs. This phenomenon is caused by turbulence generated by tidal flow over the sill and causes upwelling off the side of the sill, similar to upwelling on a coastline (Geyer and Cannon 1982). The Williamson sill at the mouth of Muchalat Inlet can cause this effect. Once upwelling occurs and saline, open-ocean deep water is brought higher up the water column, it can flow over the sill and pass through into the inlet before it settles back down to its appropriate depth, re-stratifying the layer. These oxic intrusions at depth occur frequently in fjords and inlets. For example, oxygenated intrusions and its effects in fjords were studied inside the Hunnbunn fjord (south-eastern Norway) in 2014. Oxygen concentration followed the same pattern as Muchalat Inlet, where water at depth displayed anoxic zones and the next year, given that subsurface water renewal occurred, displayed higher levels of oxygen before going back to an anoxic state (Pakhomova et al. 2014). If the trend continues, oxygen concentration measured later this December is expected to show a stratified layer without an oxic intrusion and higher concentrations near the surface while decreasing with depth.

Given the evidence from previous studies and eliminating direct vertical mixing, it is apparent that an oxic intrusion due to upwelling near offshore and circulation into the inlet is the most plausible cause for the measured oxygen concentration this year. But where does this water originate from? The mouth of Muchalat Inlet allows access for water to come from both the open ocean and from the other inlets connected to Nootka Sound, such as Tahsis and Tlupana Inlet. Looking at a generated table of nutrients (Table 2) collected from the open ocean station (Nootka Endmember) at 168m depth and the C06 station just inside Muchalat Inlet at 140m in depth (where the subsurface oxygen maximum starts to form), there is a significant difference in nutrient content, suggesting that the the water does not originate from the open ocean. The values in the 168m depth were used because that is the lowest depth measured where upwelling on the sill can occur and transfer water from the open ocean into the inlet. However, when the values at this depth were compared throughout the same salinity gradient through the entrance of Muchalat Inlet, there was no match in values, indicating that the water containing Muchalat Inlet's subsurface oxygen maximum does not originate explicitly from the open ocean, and must come from another source, like Tahsis or Tlupana.

Conclusion

The oxygen concentration that was measured during this year's Senior Thesis Cruise (TN334) throughout Muchalat is uncharacteristic for inlet basins. While it is expected that oxygen levels will continuously decrease with depth, a layer of water at depth was found to contain higher amounts of oxygen than what is anticipated. This subsurface oxygen wedge is hypothesized to be caused by an intrusion of dense water originating from outside Muchalat Inlet, near the open ocean. The mechanism behind this inflow of dense water is a circulation effect, caused by the turbulence of water as it flows in from the open ocean and hits the sill at the opening of Muchalat. Upwelling occurs, and the dense water that is brought up is able to move freely into the inlet. Once the layer of dense seawater flows through, it sinks beneath the freshwater that is brought into the inlet through river input, and settles at its appropriate depth, stratifying the water column of the inlet. This circulation effect of the water brings dissolved oxygen with it, along with nutrients that can be used as tracers. While these tracers provide supplementary evidence of where the water containing the subsurface oxygen maximum originates from, the nutrient values that were collected suggest that the open ocean is not the source.

While inferences can be made with the collected data, further study of oxygen concentration in Muchalat Inlet must be made in order to provide clear and concise evidence of oxic intrusions and its origins. Other factors such as chemical, biological, and thermodynamic mechanisms must be considered in the presence of oxygen levels inside the inlet, as well as a more precise investigation of the physical aspects in these types of inlets.

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