

Subsurface Oxygen Maximum Anomaly Found at Depth in Muchalat Inlet

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31MAY2016

Abstract

On the 2015 Senior Thesis Research cruise in Nootka Sound a subsurface oxygen maximum anomaly was found in Muchalat Inlet and the origin of this maximum was unknown. The oxygen maximum's source had to come from one of two possible sources: within the complex inlet system of Nootka Sound, or the ocean itself. Data was collected with CTD casts, nutrient data, $p\text{CO}_2$, DIC, and ALK data was processed and used as tracers to find the oxygen maximum's origin. Data collected was found to support both hypotheses, however some data opposed the hypotheses. Most of the data collected during this study points toward the northern region of Nootka Sound being the source of water and oxygen for the subsurface oxygen maximum in Muchalat Inlet.

Introduction

Nootka Sound is a large geological feature on the west coast of Vancouver Island, consisting of an intricate system of three complex inlets. These inlets, named Tahsis, Tlupana, and Muchalat, are also known as fjords. This class of inlet has its own set of specific characteristics that cause the body of water to behave in a specific manner. The general layout of a fjord system consists of a long, narrow channel surrounded by step walls and flat bottoms. At the mouth of these fjords a shallow sill can be found, at about 50 meters deep, and this is followed by a deep basin, of about 300 or more meters. These particular fjords each have three main sources of inflow: sea water, river runoff, and atmospheric precipitation. The flow pattern of these systems are similar to an estuarine flow where dense basin water at depth enters the system by flowing over the sill, and fresh, less dense water exits the mouth of the fjord at the surface (Figure 1). The stratification of these systems is dominated by salinity, and with a large input from rivers and precipitation this creates a thin buoyant surface layer that isolates deeper waters. These mechanisms form a strongly stratified water column that resists vertical mixing.

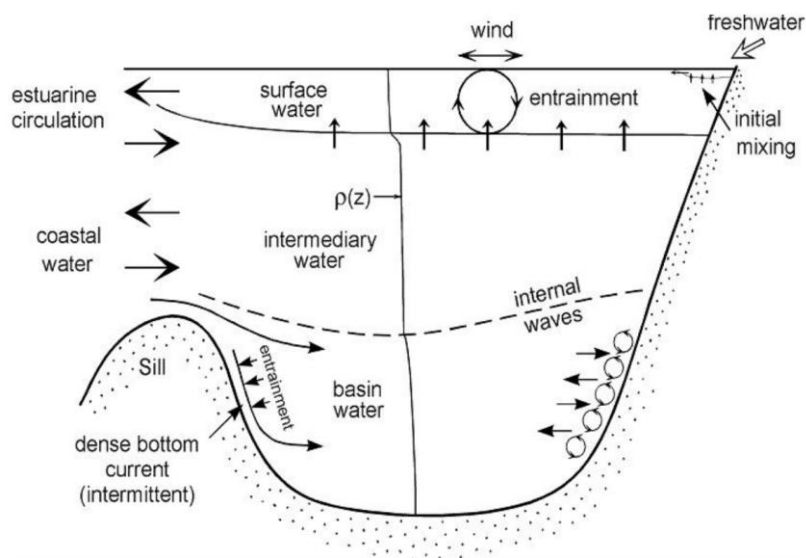


Figure 1. (http://www.ecasatoolbox.org.uk/the-toolbox/eia-species/models/copy2_of_lesv)

These fjord systems have a few mechanisms that allow oxygen to be introduced to the waters, including chemical, physical, biological and anthropogenic. With the fjords' major inflow of water being river runoff, it seems that the physical process of surface mixing would be the key factor for an exchange of gases. However, due to stratification of this surface layer, the newly oxygenated water, has a difficult time with vertical mixing, resulting in decreasing oxygen concentrations as depth increases. However, on the 2015 Senior Research Cruise in Muchalat Inlet a subsurface oxygen maximum was found. This maximum was found at depths between 150 meters and 300 meters, where oxygen levels should be anoxic or near anoxic. With near impossible vertical mixing the source of this maximum was unclear and unknown.

This newfound oxygen maximum at depth begged the question of where had or where was it coming from? The oxygen maximum's source had to come from one of two possible sources: within the complex inlet system of Nootka Sound, or the ocean itself. After further study of the oxygen maximum it was found that this feature has occurred in the past. According to G. L. Pickard's paper, "Oceanographic Characteristics of Inlets of Vancouver Island, British Columbia", the oxygen maximum is known to have occurred since (enter year here). From 1960 to present day, oxygen levels have been found to be well above anoxic levels at a depth similar to the anomaly found on the 2015 senior thesis cruise, TN334. If this maximum has become a regular occurrence, the source must be found. This anomaly has no immediate answers regarding a direct source of oxygen and the ambiguity is the soul reason for this study. This is not a natural finding to see in nature and is especially not fond of a fjord.

Methods

This study began on the University of Washington's (UW) Senior Thesis Research Cruise (TN334) to Nootka Sound, in BC, Canada. This cruise took place on the R/V Thomas G. Thompson from 11-21 December 2015. Data was collected throughout Nootka Sound, Muchalat Inlet, and Tahsis Inlet.

Temperature, salinity, and pressure data was collected from a Sea-Bird SBE 911plus CTD located aboard the R/V Thompson. One of the CTD's auxiliary ports had a SBE 43 Dissolved Oxygen Sensor to expanding the capabilities of the device to directly measure oxygen concentrations in the water column. All CTD cast locations are represented in Figure 2 by circles, squares, and triangles. The seven "Wedge" casts were selected during the cruise to allow for maximum analysis of the oxygen maximum found at depth in Muchalat Inlet. As the oxygen anomaly was found during the cruise, these cast locations were decided upon last minute while transiting through Muchalat. Exact coordinates of each cast are listed as well in Figure 3. Efforts were focused on the location of the oxygen wedge located in Muchalat Inlet, however other locations were used to cross reference the anomaly and compare other inlets. The casts outside Muchalat Inlet were selected by other students taking part in the cruise, and their data was collected from the same CTD. The CNV files from the Sea-Bird were imported into Ocean Data View version 4.7.4. allowing for further data analysis and data viewing in section plots, temperature salinity plots, and individual station views.

Nutrient data was collected to compare nutrient measurements of the water column outside of Muchalat's Williamson Sill and the water column within the oxygen maximum. These nutrients were used as tracers for this study. Comparisons of PO_4 , Si(OH)_4 , NO_3 , NO_2 , NH_4 were

used to confirm the water parcel located in the oxygen maximum originated from the outward side (western side) of the sill.

Water samples were collected via Niskin bottles attached to the CTD in a Rosette configuration. Nutrient data from station Carbon 06 was collected along the outward side of the sill at depths of 55m and 140m. Data from station Carbon 10, the location of the oxygen maximum, was taken at a depth of 350m. These waters were then collected in nutrient bottles and frozen until lab analysis could be completed (refer to Gen Hinde's analysis methods found in the Senior Thesis Methods section of the University of Washington's public research data base).

Other tracers used in this study consisted of partial pressures of CO₂ (pCO₂), dissolved inorganic carbon (DIC) and alkalinity (Alk). These tracers from the Offshore01 station and the Carbon10 station were compared against each other on the same graph. This allows for a better understand of the subsurface oxygen maximum water possibly coming from the open ocean. Water samples were collected throughout Nootka Sound at various depths by Genevieve Hinde and Daryn White. Once brought back to the University of Washington, they were processed by Genevieve and Daryn in 1-4 months after collection of the samples. Once complete, pCO₂ was calculated using DIC and alkalinity data in MatLab (refer to Gen Hinde's analysis methods found in her Senior Thesis Methods section of the University of Washington's public research data base).

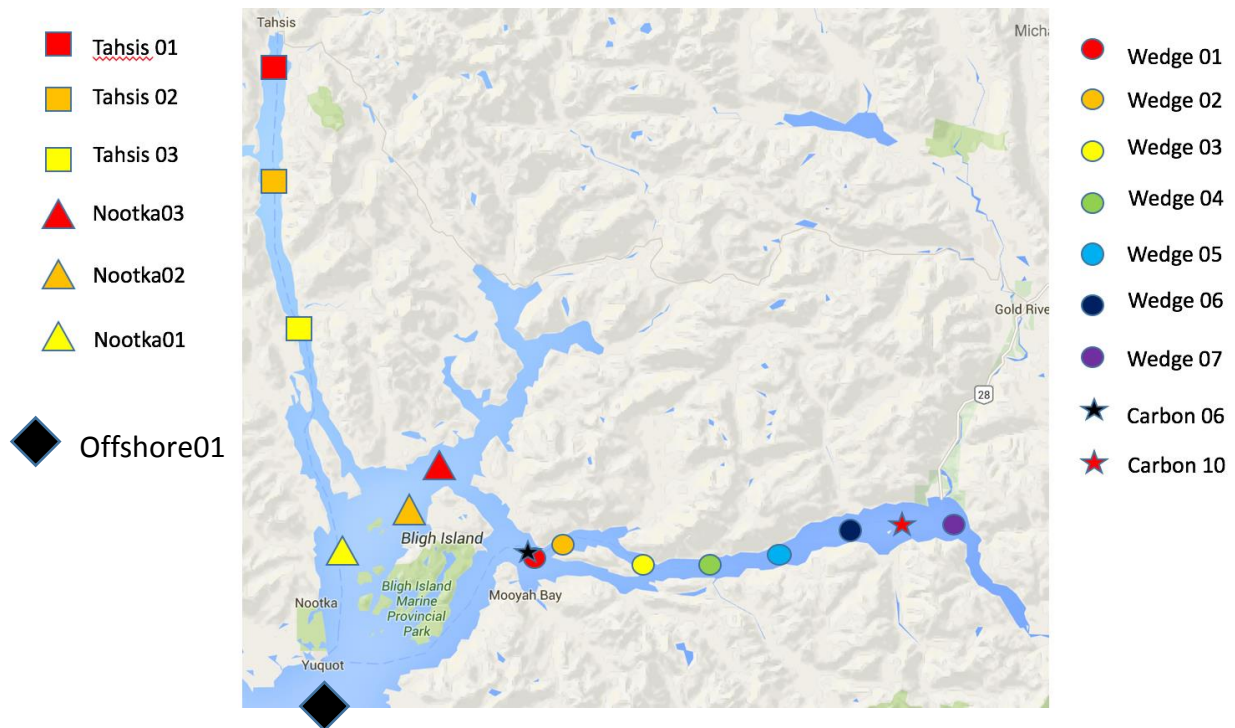


Figure 2. Map of Nootka Sound with CTD cast locations (circles, squares, triangles) and nutrient sites (stars). Colors only distinguish between individual stations.

Name	Date	Depth	Latitude	Longitude
Wedge01	18/12/2015	206.89	49 38.9634	126 26.6760
Wedge02	18/12/2015	175.23	49 39.3370	126 25.5648
Wedge03	16/12/2015	276.02	49 38.6538	126 21.4392
Wedge04	19/12/2015	289.89	49 38.6418	126 18.6606
Wedge05	19/12/2015	357.43	49 38.9430	126 15.2580
Wedge06	19/12/2015	358.43	49 39.7776	126 11.1930
Wedge07	19/12/2015	317.85	49 39.9084	126 06.7416
MitchellM01	15/12/2015	166.83	49 38.7420	126 36.3108
Purdy03	15/12/2015	158.3	49 40.1874	126 33.3966
Omoto01	15/12/2015	248.42	49 41.4384	126 32.0646
Carbon6	16/12/2015	160.23	49 38.6928	126 26.8452
Carbon10	13/12/2015	360.85	49 40.0326	126 08.5656

Figure 3. CTD cast data

Results

The subsurface oxygen maximum values are highlighted in the red box drawn on Figure 4. This plot used data from CTD casts Wedge01-07. The subsurface oxygen maximum “wedge” is shown in a cross-section view (east to west) from the opening of Muchalat Inlet to its end. The oxygen wedge is located from approximately 5-30km in Muchalat, at a depth of 250-325 meters. This wedge contains oxygen concentration values ranging from 0 ml/L of oxygen and drastically rising to approximately 2 ml/L in its center. This region is classified as the subsurface oxygen maximum in Muchalat as it begins with anoxic conditions and ends in dysoxic conditions. The oxygen concentrations are higher at the eastern end when compared to the western edge. The eastern oxygen maximum value is 1.5 ml/L, while the western edge maximum is only 1.0 ml/L.

CTD data from Tahsis Inlet was plotted in a similar fashion (Figure 5) using the same cross-section (east to west) type format. These values present data from CTD casts Tahsis01-03. The figure begins at the head of Tahsis Inlet (0km) and ends near the mouth of Tahsis as it opens to Nootka Sound (~36km). Highly oxygenated waters are found at the surface with values of approximately 6ml/L, and decrease as a function of depth to anoxic conditions around 0.25ml/L. No subsurface oxygen maximum can be found due to this decrease of oxygen with depth.

Temperature Salinity (TS) diagrams (Figure 6) were constructed using the same CTD data, plotting stations Wedge06, Nootka 03, and Offshore01. Only Wedge06 and Nootka03 show signs of a subsurface maximum. The maximum oxygen concentration value of Wedge06 is 2.0ml/L and the maximum of Nootka03 is 1.20ml/L. A TS diagram of stations Tahsis01-03 can be

found in Figure 7 using this same format, and finally, figures 8-10 represent stations Nootka01-03 respectively.

Nutrient Data was processed and depicted with nutrients PO_4 , $\text{Si}(\text{OH})_4$, NO_3 , NO_2 graphed separately (all found in Figure 11). Station Carbon06 is located outside of Muchalat Inlet just east of the sill, and Carbon10 is located directly above the subsurface oxygen maximum, found west of the sill. PO_4 , $\text{Si}(\text{OH})_4$, and NO_3 increase significantly as a function of depth, while NO_2 decreases. PO_4 increases from about $0.5 \mu\text{M}$ to $3.5 \mu\text{M}$, $\text{Si}(\text{OH})_4$ increases from about $35 \mu\text{M}$ to $82 \mu\text{M}$, and NO_3 increases from about $7 \mu\text{M}$ to $25 \mu\text{M}$. NO_2 decreases about $0.07 \mu\text{M}$ at each station.

pCO_2 , DIC, and Alk data was processed into depth profiles. Each profile consists of the Offshore01 station and the Carbon10 station. For pCO_2 (Figure 12), the Offshore01 station showed a decrease in pCO_2 with depth starting from $392.43 \mu\text{atm}$ at the surface to $1362.01 \mu\text{atm}$ at 550m. After this the pCO_2 only slightly decreased with depth to $1317.59 \mu\text{atm}$ at 1000m. Carbon10 increases quite a bit, with depth, in the first 75m from $356.89 \mu\text{atm}$ to $1975.53 \mu\text{atm}$, then it decreases to $1903.08 \mu\text{atm}$ at a depth of 350m. For DIC (Figure 13), the Offshore01 station has a steady decrease from the surface at $1992.25 \mu\text{molkg}^{-1}$ to $2379.19 \mu\text{molkg}^{-1}$ at a depth of 1000m. Again, the Carbon10 station increases rapidly in the first 75m from $792.44 \mu\text{molkg}^{-1}$ to $2269.98 \mu\text{molkg}^{-1}$, then it slightly increases to $2305.38 \mu\text{molkg}^{-1}$ at a depth of 350m. For Alk (Figure 14), the Offshore station has a slight increase from $2156.38 \mu\text{molkg}^{-1}$ at the surface to $2364.45 \mu\text{molkg}^{-1}$ at 1000m. Carbon 10 again increased turmendously in the first 75m from $798.65 \mu\text{molkg}^{-1}$ to $2222.65 \mu\text{molkg}^{-1}$, then slightly increasing to $2261.35 \mu\text{molkg}^{-1}$.

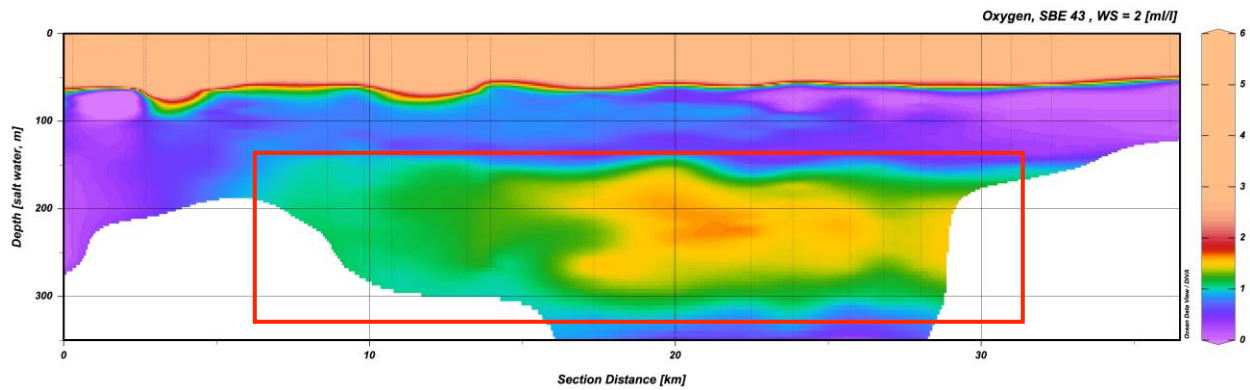


Figure 4. Muchalat Inlet, Wedge01-07. Kilometers (x-axis) from the eastward entrance of the sill, ending at the inlet's western end. Depth (y-axis) in meters increasing from the surface down. Color bar displays oxygen concentration values in ml/L. Red box highlights subsurface oxygen maximum.

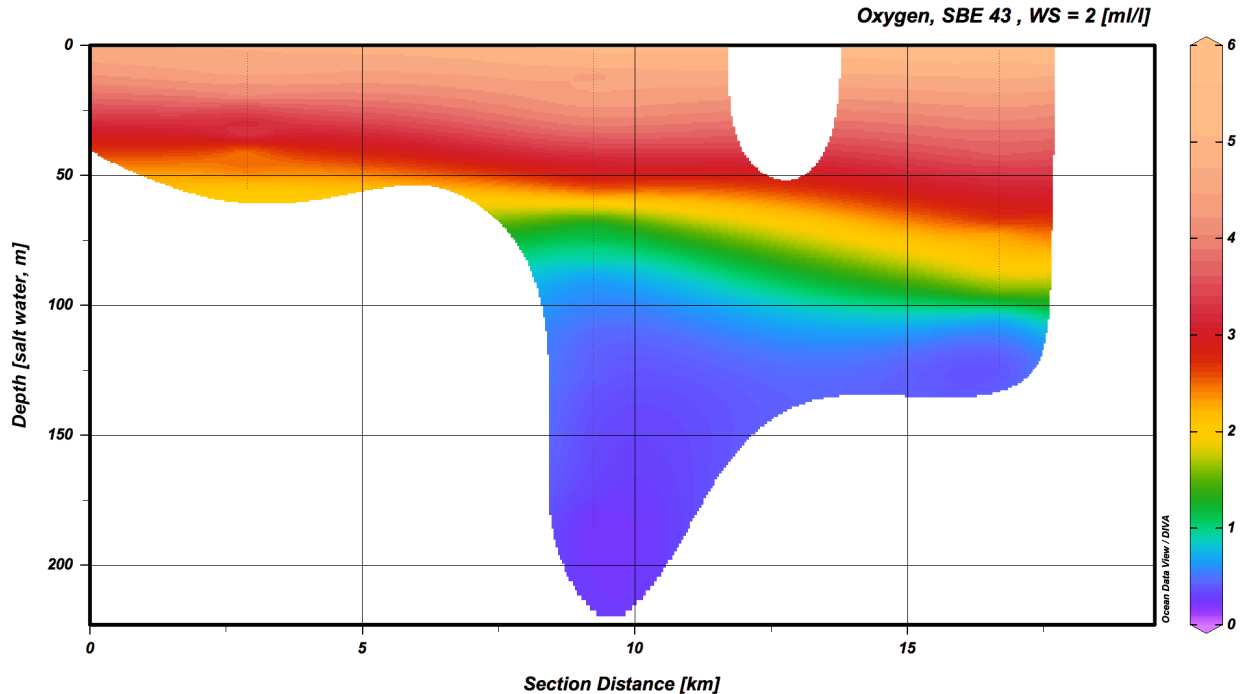


Figure 5. Tahsis Inlet, Tahsis01-03. Kilometers (x-axis) from the southern of the sill at the entrance, ending at the inlet's northern end. Depth in meters (y-axis) from the surface. Color bar displays oxygen concentration values in ml/L.

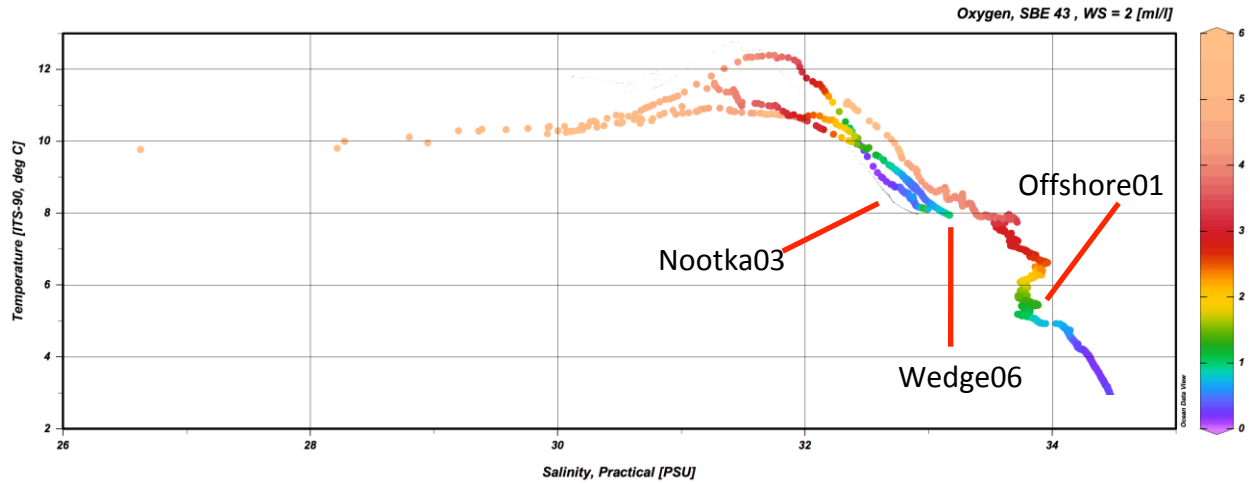


Figure 6. TS diagram of Wedge06, Nootka03, Offshore01(***)not depicted in paper yet***) . Salinity (PSU) (x-axis), temperature (deg C) (y-axis), color bar displays oxygen concentration values (ml/L). Subsurface oxygen maximums shown for Wedge06 and Nootka03.

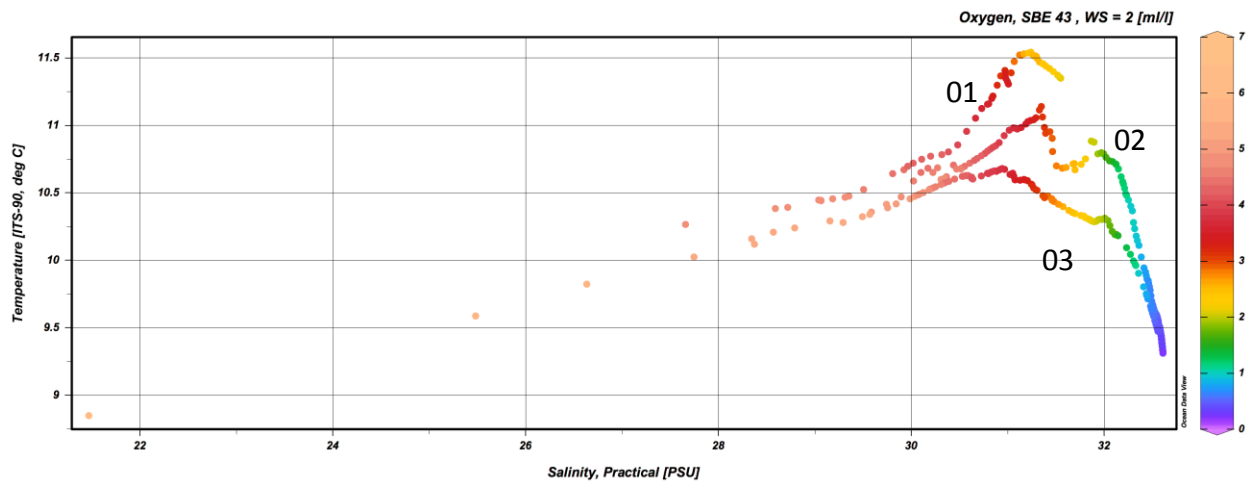


Figure 7. Tahsis Inlet, Tahsis01-03. Salinity (PSU) (x-axis), temperature (deg C) (y-axis), color bar displays oxygen concentration values (ml/L). Subsurface oxygen maximums shown for (correct the stations for Tahsis).

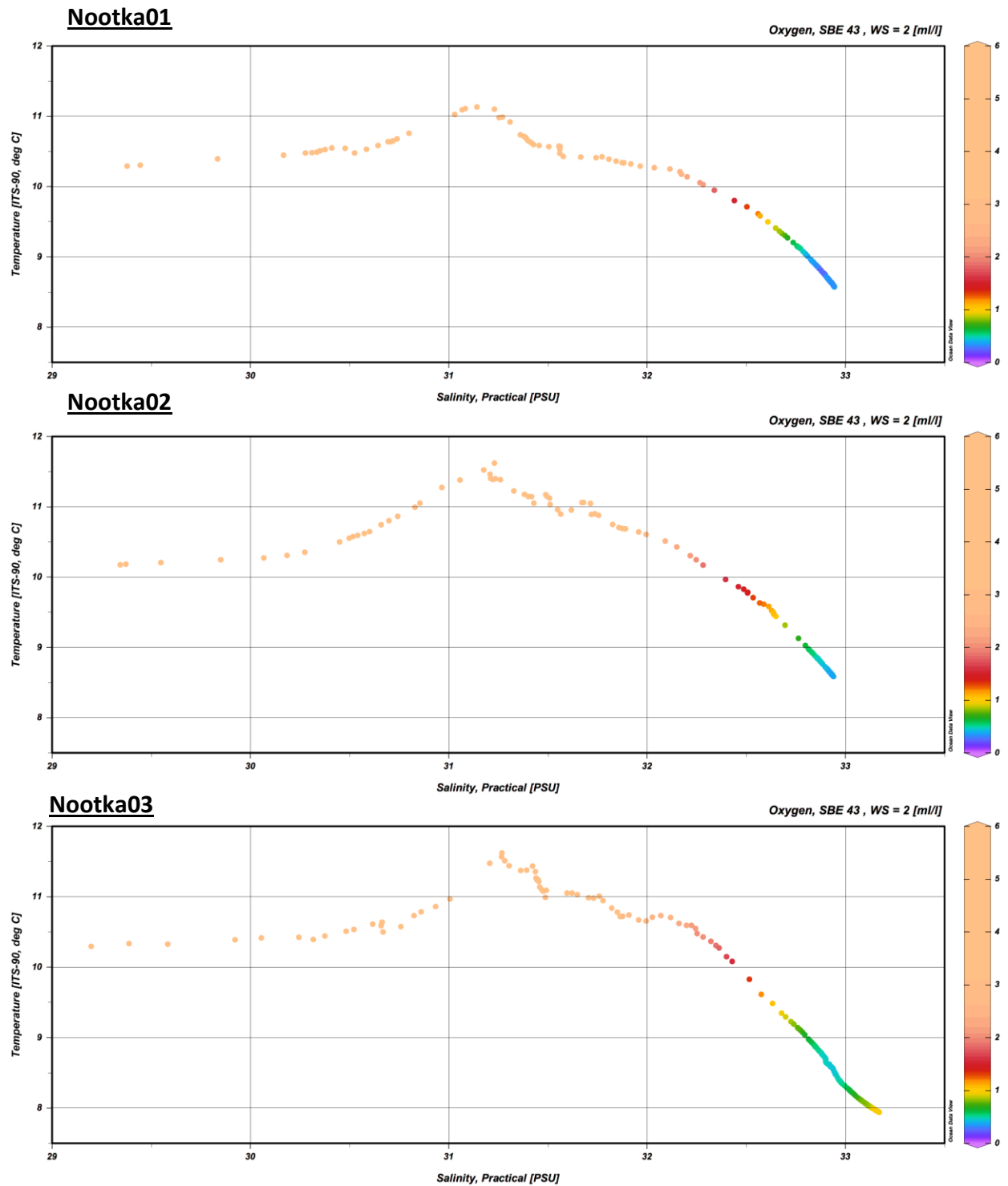


Figure 8-10. Nootka Sound, Nootka01-03 (from top to bottom). Salinity (PSU) (x-axis), temperature (deg C) (y-axis), color bar displays oxygen concentration values (ml/L). Subsurface oxygen maximums shown for (put correct stations for Nootka if this does show maximums).

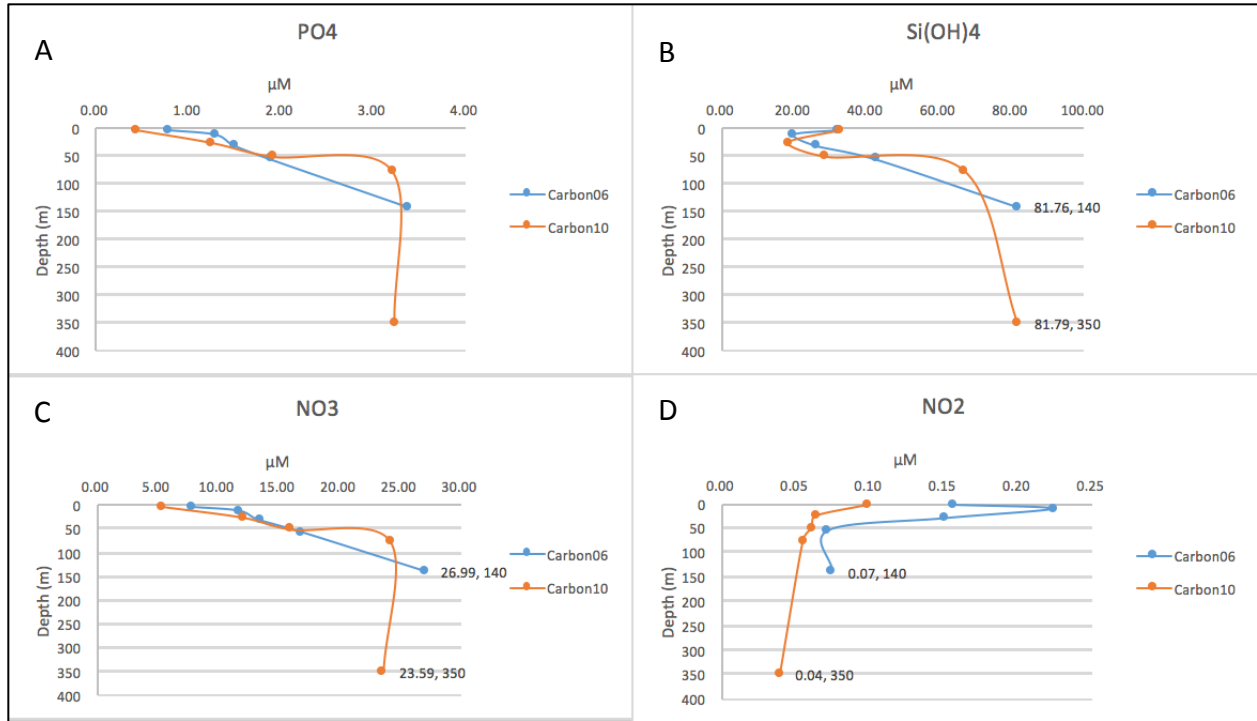


Figure 11. Nutrient Data at stations Carbon06 and Carbon10. A) PO_4 , B) Si(OH)_4 , C) NO_3 , D) NO_2 . Micromoles (x-axis) of the titled nutrient and depth (y-axis) in meters.

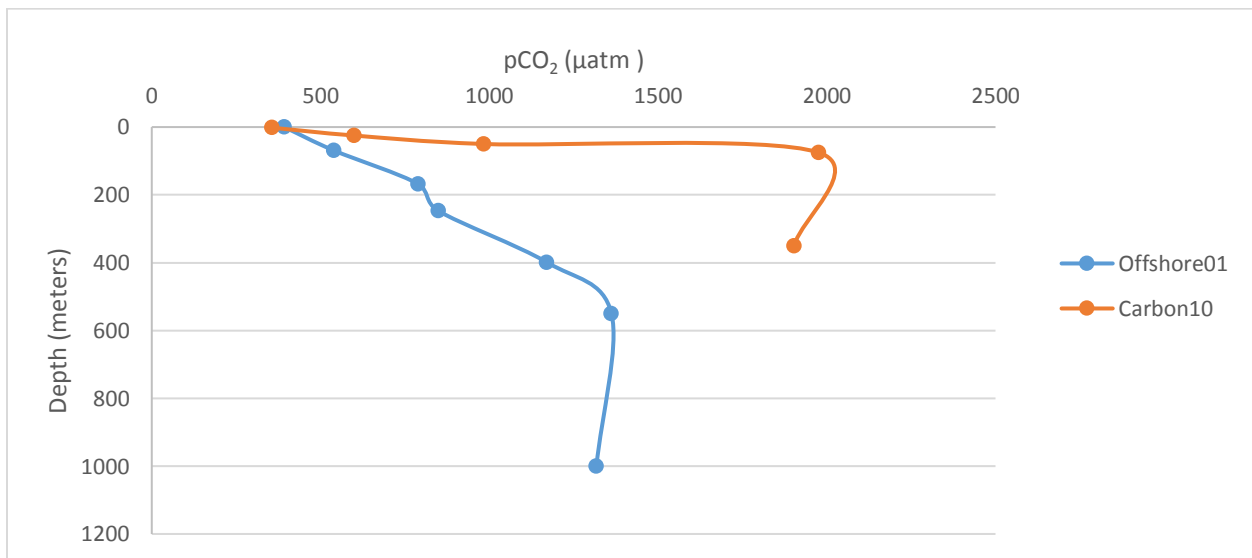


Figure 12. $p\text{CO}_2$ data at stations Offshore01 and Carbon10. $p\text{CO}_2$ (μatm) (x-axis) and depth (meters) (y-axis).

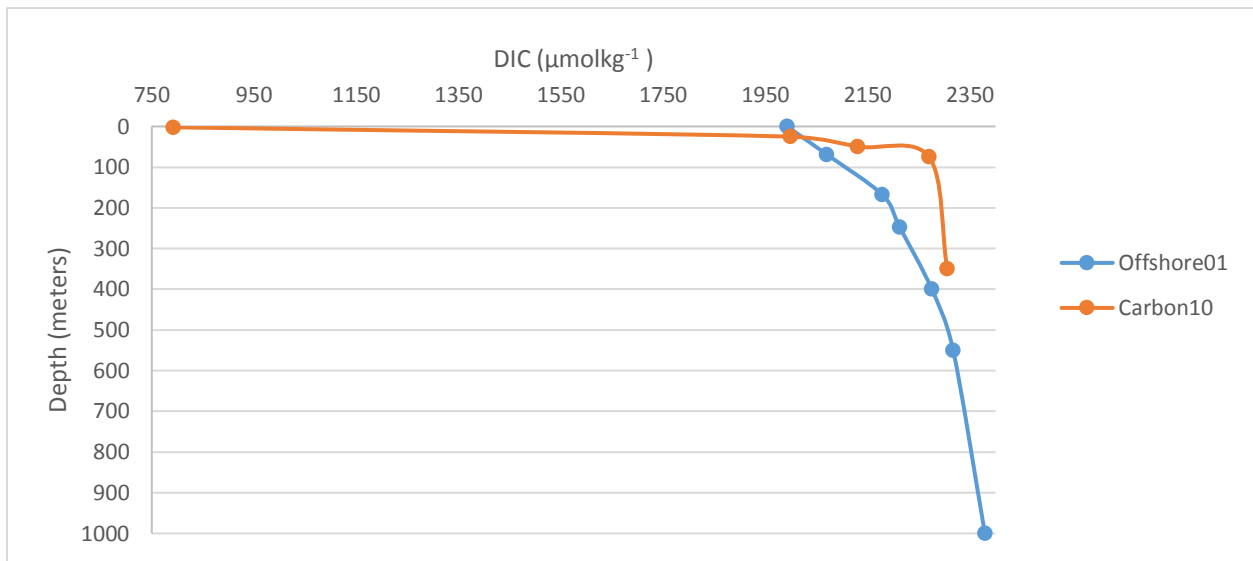


Figure 13. Dissolved inorganic carbon data at stations Offshore01 and Carbon10. DIC (μmolkg^{-1}) (x-axis) and depth (meters) (y-axis).

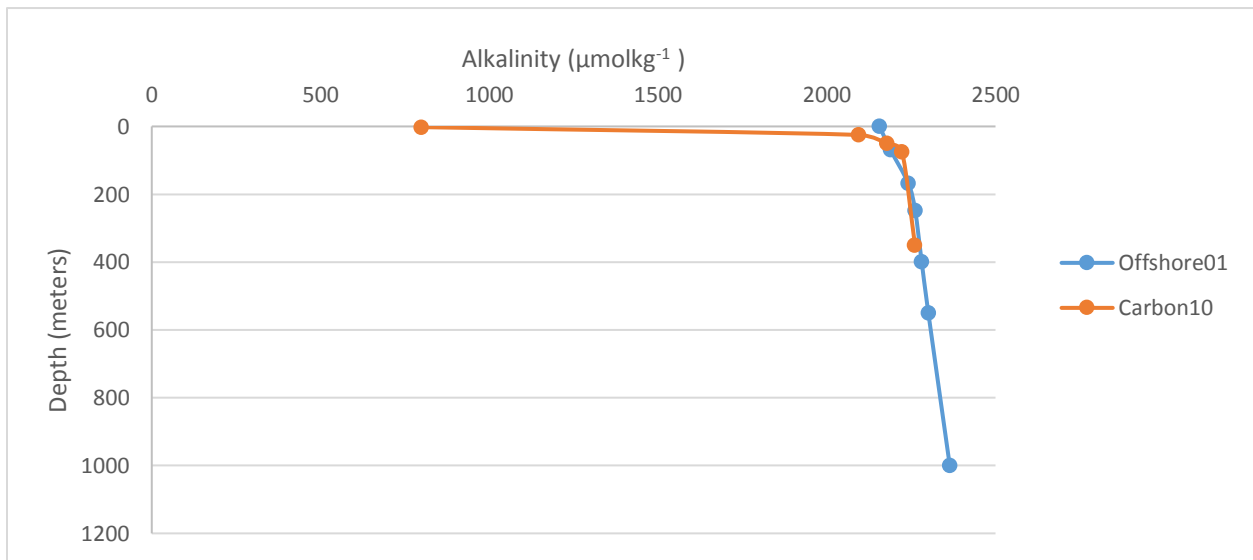


Figure 14. Alkalinity data at stations Offshore01 and Carbon10. Alk (μmolkg^{-1}) (x-axis) and depth (meters) (y-axis).

Discussion

Two hypotheses exist concerning the origin of the subsurface oxygen maximum found in Muchalat Inlet. The first is the highly oxygenated water came from the northern section of Nootka Sound, close to the mouth of Tlupana Inlet, and then traveled into Muchalat Inlet. The second, is the subsurface oxygen results from an open ocean source, entering Nootka Sound then traveling into Muchalat Inlet.

The hypothesis of the oxygen maximum originating from within Muchalat is not entertained due to the inlet being highly stratified. The major mechanism of oxygen incorporation into the water is through surface water interaction with the atmosphere and the continuous exchange of gases (Li 2015). Due to the high river input into the inlet at the head of Muchalat, a large amount of freshwater is deposited at the surface. This freshwater decreases salinity at the surface causing the density to decrease rapidly looking from depth to the surface. The highly stratified nature of this inlet greatly reduces the chances of vertical mixing of oxygen to the depth of the subsurface oxygen maximum found. As we can theorize the oxygen maximum did not originate within Muchalat inlet, it must have been transported from a source outside of the inlet.

Supporting this theory are the similar nutrient values found directly outside the inlet's mouth at station Carbon06, and those found at Carbon10. Comparing levels (μM) of PO_4 , $\text{Si}(\text{OH})_4$, NO_3 , and NO_2 at these two locations allows the nutrients to be used as a tracer within the inlet (Fig. 11). The values of PO_4 , $\text{Si}(\text{OH})_4$, and NO_3 are very similar while traveling down the water column, however NO_2 values from Carbon06 only deviate from Carbon10 at the surface. The deviation of NO_2 measurements when compared to the other nutrients is possibly due to

high ammonium concentrations or conditions with high nitrate concentrations and nitrification processes (Barnes, 1982). This deviation aside, the nutrient values as a whole are very similar at depth making it safe to assume water is entering the inlet at depth and leaving the inlet at the surface as a typical fjord circulation pattern (Fischer and List 1979). The waters of the subsurface oxygen maximum can be traced to outside of the mouth of Muchalat Inlet at depth further supporting the idea of this subsurface maximum originating outside of Muchalat Inlet.

The section view of Muchalat Inlet, in Figure 6, shows that oxygen maximum has a higher concentration of oxygen to its eastern side. Since the fjord circulation has been confirmed the hypothesis can be made that that injection of oxygenated water at depth has been halted. This can be speculated due to the lack of oxygen near the Williamson Sill or west of the oxygen maximum. This “halting” process seems to have been gradual, since the oxygen concentrations of the subsurface maximum decreases from east to west. However, the only confirmation is that the injection of oxygen has been halted during the time this data was collected.

Nootka Sound Origin

Notable subsurface oxygen maximums were found in the northern regions of Nootka Sound at stations Nootka01 and Nootka03. Nootka03 had higher concentrations of oxygen in its subsurface maximum at 1.0 ml/L around the depth of 220 meters (Fig. 10), while Nootka01 had half as much oxygen at 0.5 ml/L at 155 meters (Fig. 8). There was no subsurface maximum found at Nootka02 (Fig. 9) and this station had a steady decrease in oxygen with depth.

These subsurface maximums were not found anywhere else in the Nootka Sound region or in any of the inlets studied. Oxygen concentrations were collected from Tahsis Inlet to

compare its oxygen profile with that of Muchalat. The section view of Tahsis Inlet (Figure 5) displays oxygen concentrations (ml/L) on the Z-axis. Tahsis is depicted as a well stratified water column with highly oxygenated water at the surface with values greater than 6ml/L, and decreases in oxygen to about 0.2 ml/L at max depth. This absence of a subsurface maximum reveals the subsurface maximums at Nootka01 and Nootka03 were not influenced by Tahsis Inlet.

Comparing Nootka03, Wedge06, and Offshore01 in Temperature Salinity (TS) plots, the characteristics of temperature, salinity, oxygen and density can be examined. Nootka03 was found to have lower salinity than Wedge06, while Offshore01 has a higher salinity than Wedge06. As the salinity of Wedge06 is halfway between the other two stations' salinity values, it is theorized that the water from Nootka03 is mixing with waters from Offshore01 at Muchalat Inlet's mouth before entering Muchalat.

Offshore Origin

The second hypothesis states that if the subsurface oxygen maximum did not come from within Nootka Sound, then it would have to come from the open ocean. Figure 6 shows high concentrations of oxygen at depth at the Offshore01 station. Since the oxygen is present at depth, there is an opportunity for it to travel into Nootka Sound and ending up in Muchalat Inlet.

Looking at the TS diagram in Figure 6, similar levels of density (compared to the oxygen maximum at Wedge06) of Offshore01 have very high concentrations of oxygen, at about 5ml/L. The oxygen maximum's highest concentration is only at 2ml/L. For the oxygen from the

offshore station to match up with the oxygen maximum, it would have to decrease at a minimum of 3ml/L during its transit to Muchalat Inlet.

Using the tracers $p\text{CO}_2$, DIC, and Alk the water masses at both Offshore01 and Carbon10 can be compared to see if the open ocean might be the source of the oxygen maximum. Figure 12 shows that the concentrations of $p\text{CO}_2$ are similar in the first three stations, but at different depths. With this aside, looking at the depth in which the oxygen maximum is found at Carbon10, about 300-350m, concentrations are as high as $1975.54\mu\text{atm}$. The highest concentration from Offshore01 is only $1362.01\mu\text{atm}$, which is quite a difference. Comparing the DIC readings (Figure 13), at depths of the oxygen maximum (300-350m), shows the offshore station at about $2212.41\mu\text{atm}$ and at Carbon10 it is $2305.38\mu\text{atm}$. The DIC difference is a lot closer than that of $p\text{CO}_2$, but they are still not exact. And finally comparing the Alk concentrations in Figure 14, the data shows that both stations have similar Alk readings at the depth of the oxygen maximum (300-350m).

Comparing all these tracers $p\text{CO}_2$ was the least similar by about a $613.53\mu\text{atm}$ difference. The DIC readings were somewhat similar with a difference of $92.97\mu\text{atm}$. And finally, the Alk readings were very similar at the depth of the oxygen maximum. Only Alk showed possible confirmation that the open ocean could be a source for the oxygen maximum and the other two tracers ($p\text{CO}_2$ and Alk) possibly dismissing that confirmation.

Conclusion

This study hypothesized that the subsurface oxygen maximum found at depth in Muchalat inlet did not originate from within the inlet itself. The oxygen maximum must have traveled from either the northern section of Nootka Sound or from the the open ocean. Data collected has been found to support both hypotheses, however some data has opposed these hypotheses. For the hypothesis of a Nootka Sound origin: subsurface oxygen maximums were found in the northern regions of Nootka Sound and the TS diagram showed a great chance of mixing water masses to equal the properties of Muchalat Inlet. For the open ocean origin hypothesis: only one ($p\text{CO}_2$) out of the three tracers ($p\text{CO}_2$, DIC, and Alk) showed the open ocean being a source of the oxygen maximum, which is not good evidence to support this hypothesis. Most of the data collected during this study points toward the northern region of Nootka Sound being the source of water and oxygen for the subsurface oxygen maximum in Muchalat Inlet. However, continuous and all-year data must be collected to actively track and monitor the anomaly's path from its origin to Muchalat Inlet. Data used in this study was only collected within a two-week time period, which is two short of a time to draw a full conclusion on the origin of this oxygen maximum.

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