Patterns of apparent oxygen utilization and circulation in Barkley Sound, Vancouver Island B.C.

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Non-Technical Summary

Oxygen minimum zones are found in the open ocean and in enclosed marine environments. These are areas of low dissolved oxygen play important roles in nutrient cycling. In recent years it has been found that increased human influence has been causing them to expand in the open ocean and be of longer duration in enclosed areas. Circulation can also influence patterns of oxygen concentrations. Water impeded by shallow topography will allow for the development of low oxygen zones. Apparent oxygen utilization (AOU) is a measure of how much oxygen has been produced by photosynthesis or used by respiration. Rates of respiration and measurements of AOU can used to determine the age of water parcels. Barkley Sound is a large body of water on the west cast of Vancouver Island, and the circulation patterns are little studied. It was found that newer water is near the mouth and older water is at depth near the eastern end. The oldest water is in the deep basins of Effingham Inlet where circulation is impeded by shallow topography. Trevor Channel is also impeded by shallow topography at its mouth and the water there was found to be older than the water in Imperial Eagle.

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Abstract

Oxygen Minimum zones (OMZs) in the world's oceans and fjords have been expanding in recent years (Paulmier and Ruiz-Pino 2009; Zaikova et al. 2009). These "dead" zones can be strongly influenced by circulation patterns. Sills and shallow bathymetry can impede water flow and produce persistent anoxic conditions in enclosed marine settings. Oxygen is a useful tracer of circulation and long and short term processes that can have serious consequences for macrofauna. This is especially important in areas where aquaculture and anoxia are present simultaneously, as in Barkley Sound. Anoxic conditions on the surface and at depth can produce wide spread population decline of macrofauna. Dissolved oxygen was measured in Barkley Sound and Effingham Inlet with the use of a CTD and Winkler titrations. Newer water was found to be near the mouth of the sound with old water near the eastern end, with the oldest water in Effingham Inlet. Trevor Channel was also found to have relatively old water below 50m. Shallow sills in Trevor Channel and Effingham Inlet impede water movement and cause water movement to slow. Imperial Eagle Channel does not a have a shallow sill and water ages in that channel were only a few days old.

Introduction

Oxygen minimum zones (OMZs) are areas in the ocean and marine waters that are low in dissolved oxygen. These areas play an important role nutrient, especially nitrogen, and trace gas cycling (Paulmier and Ruis-Pino 2008). OMZs are also areas that contribute to the death of macrofauna and in the last few years have caused a lot of public concern (Zaikova et al. 2009). The biggest OMZs are found in the open ocean, but many also occur in semi-enclosed places, like estuaries and fjords, and along coasts. Increased agricultural runoff and increased seasonal temperatures have caused the expansion and the amplification of these “dead” zones (Paulmier and Ruiz-Pino 2009; Zaikova et al. 2009).

Oxygen is an important tracer as it can be quickly measured, and integrate long and short-term processes. Oxygen is generally supersaturated in coastal surface waters due to photosynthesis and depleted in the aphotic zone due to respiration (Broecker 1991). Organic matter falling from the surface will be respired and the dissolved oxygen concentration will be depleted at the depth to which the organic matter fell. Older water can also have low oxygen concentrations because it has been exposed to respiration longer.

Apparent oxygen utilization (AOU) can be used to determine the location of older water masses relative to younger water masses. The difference between the saturation concentration of oxygen and the actual concentration is the measure of the amount of oxygen gained or lost through photosynthesis or respiration, or AOU (Ito 2004; Emerson and Hedges 2008). Older water will have a larger AOU. That is to say, that parcel of water that has been out of contact with the atmosphere longer than another parcel of water. AOU is a simple measurement that can help identify areas of high respiration and photosynthesis, and circulation patterns.

Effingham Inlet, on the west coast of Vancouver Island on the eastern end of Barkley Sound, is an estuarine type fjord. Along its 17 km length, it contains two anoxic/suboxic basins. The inlet is cut by two sills: one with a depth of 40m which cuts the inlet into an inner and outer basin, while one of 60m depth separates the inlet from the sound. At the head of Effingham is a small river called the Effingham River. Its estimated maximum mean monthly discharge is 14 m^3s^{-1} (Stronach et al 1993). The steep sided walls of the fjord also some runoff to enter. Typical estuarine circulation consists of cold, salty, and relatively oxygenated water moving into an estuary at depth, with fresh water moving out at the surface (Geyer and Cannon 1982). This low flow of fresh water in Effingham Inlet produces weak circulation, and the sills prevent all but the most vigorous currents from renewing the bottom water. These conditions produce persistent anoxia in Effingham Inlet (Hay et al. 2009).

The purpose of this study is to examine the circulation patterns using AOU as a tracer of water movement. It is anticipated that newer water with a low AOU will be found near the mouth of Barkley Sound, and older water with a high AOU will be found near the eastern end. The oldest water is expected in Effingham Inlet.

Methods

Water samples for oxygen analysis were collected from March 20-23, 2010 aboard the R/V *Alta* and the R/V *Barkley Star*. Samples were collected in two locations in Barkley Sound: Trevor Channel and Effingham Inlet. CTD casts were taken in Trevor Channel, Effingham Inlet, and Imperial Eagle Channel using a SeaBird 19 and a

Beckman YSI oxygen sensor (Fig. 1). The water samples were titrated using the Winkler Method and then used to calibrate the CTD casts (Carpenter 1965). The titrated oxygen

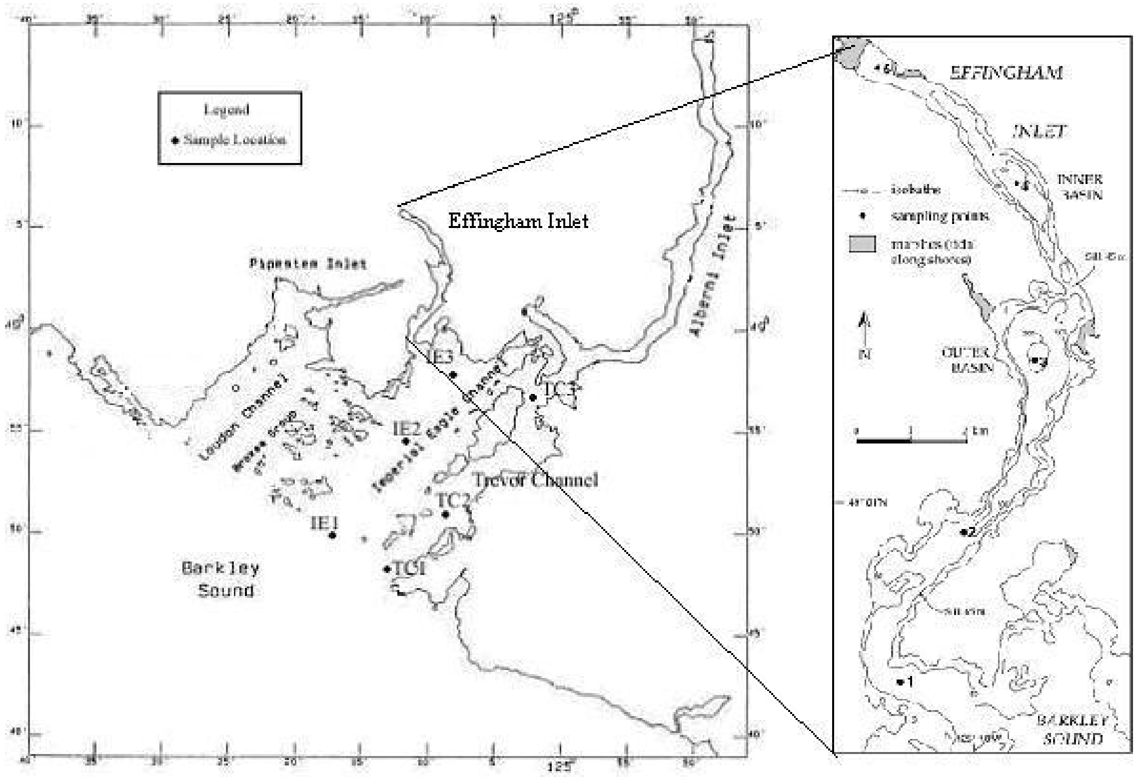

Figure 1. Map of Effingham Inlet and Barkley Sound. The map of Effingham shows the stations sampled for both the March 2010 and the February 2009 cruise. The stations overlap for both sampling years. The map of Barkley Sound shows the stations sampled in Imerial Eagle Channel and Trevor Channel. (Adapted from Hay et al. 2003, and Stronach 1993).

concentrations were plotted against the oxygen concentrations obtained from the CTD. The resulting trend line was used to calibrate the CTD oxygen concentrations (Fig. 2).

The CTD casts were processed using SBE Data Processing software. Data from September 19, 2009, collected in Effingham Inlet, was obtained from Dr. Rick Keil, and processed using the same software as the March 2010 data. The data were edited to eliminate duplicates, aligned using a 5 second lag, and binned at 4 decibar intervals. Oxygen saturation values were calculated using the Garcia and Gordon equations with a 2 second window (Garcia and Gordon 1992).

AOU was calculated by taking the difference between the concentration of oxygen if the waters were saturated and the actual measured concentration of oxygen.

$$AOU = [O_2]_{sat} – [O_2]_{measured}$$

The saturation concentration depends on the potential temperature and the salinity of the water parcel (Ito 2004). AOU was calculated for all of the data obtained in Barkley Sound during March 2009.

A respiration rate was calculated using the data from Station 3 in Effingham Inlet (EF3). The concentrations were chosen at a depth, 170.5 m, where there was no oxygen

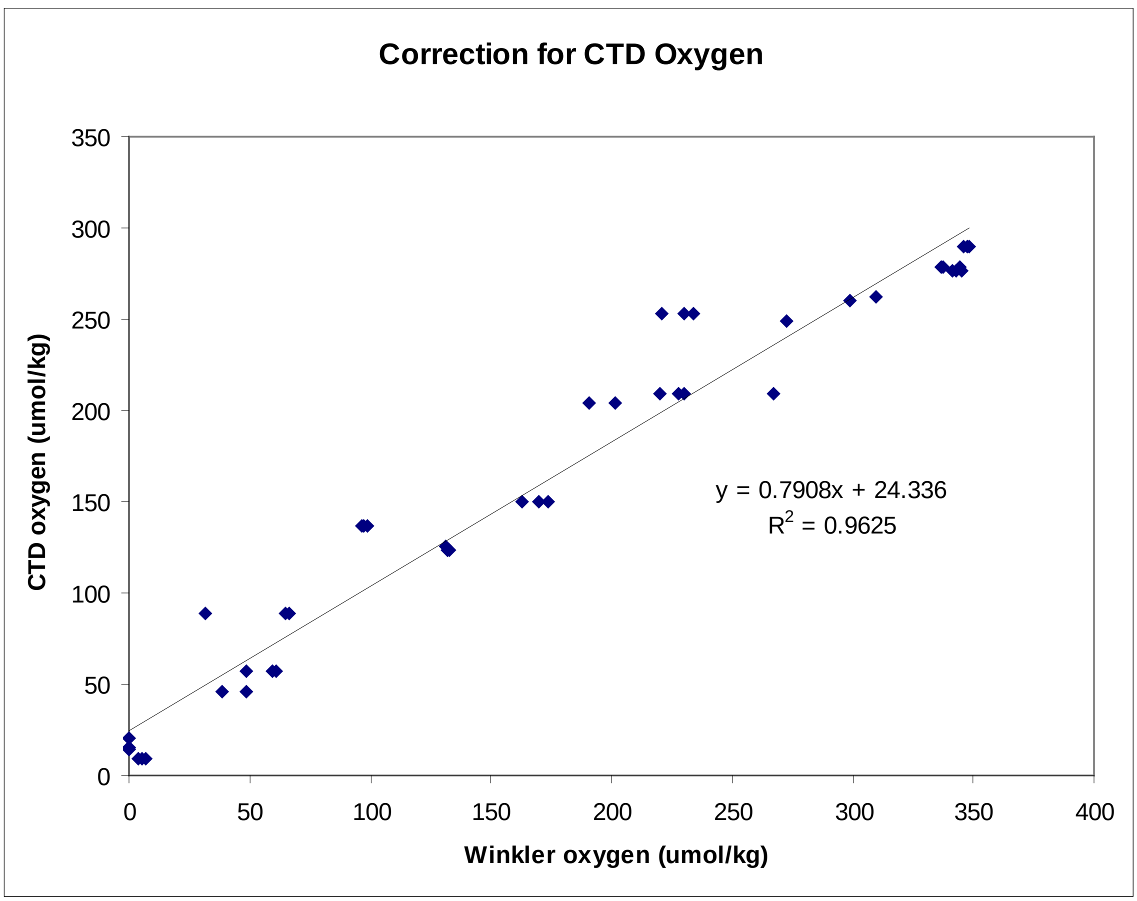

Figure 2. Calibration for CTD oxygen concentrations. The x-term is the corrected oxygen value and the y-term is the CTD value.

present in the 2010 sample and oxygen present in 2009, and where the densities were the same. The resulting concentration was divided by 183 days which was the amount of time between samples. The absolute values of the AOUs were divided by the resulting rate at all stations and depths to get time since the water entered Barkley Sound.

Results

The respiration rate calculated for Station EF3 was found to be 0.265 μmol kg^{-1} day^{-1}. The respiration rate was the difference between the September 2009 data and the March 2010 data. The oxygen values used were selected because the densities, 1025.56 kg m^{-3}, were found to be the same for both cruises at the same depth of 170.5 m.

The Imperial Eagle Channel AOU tended to be supersaturated in the surface and undersaturated at depth (Fig. 3a). The depth at which supersaturation extends is shallower the more the water moves toward the east and Effingham Inlet. At IE1, or the entrance of Barkley Sound, the water becomes undersaturated at around 62m. At IE2, or in the middle of Barkley Sound, the water becomes undersaturated at around 34m. At IE3, or the eastern end of Barkley Sound, the water becomes undersaturated at around 15m.

The AOUs tended to be higher in Effingham Inlet than in Imperial Eagle Channel (Fig. 3a). In Effingham Inlet the AOU goes undersaturated in a smaller range of depths than in Imperial Eagle, between 6 – 10m. At depth, the largest AOU is seen at Station EF4 at the bottom. The AOUs for Stations EF3 and EF4 approach the same number, about 291μmol kg^{-1}. At the depths that AOU approaches 291μmol kg^{-1}, the oxygen

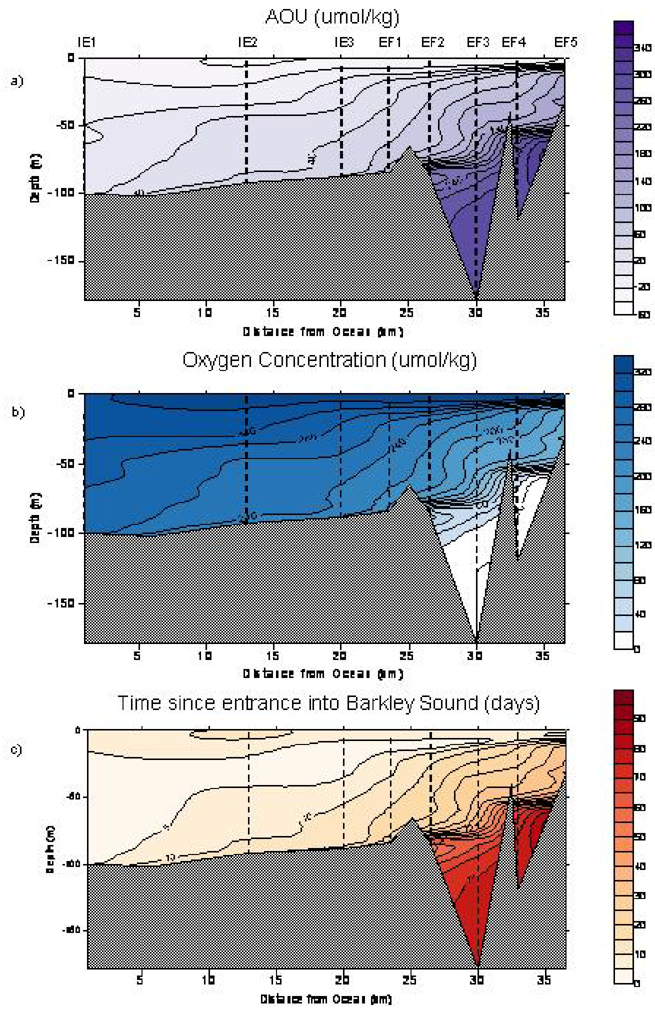

Figure 3. Trends in oxygen in Imperial Eagle Channel and Effingham Inlet. Contour plot a) shows the trend in AOU, b) is showing trends in oxygen concentration, and c) shows the trends in water ages.

concentrations approach 0 μmol kg^{-1} (Fig. 3b).

The AOU values in Imperial Eagle Channel and Effingham Inlet also correspond with the amount of time since the water entered Barkley Sound (Fig. 3c). The Station IE1, water between 0 and 5 days old is found at all depths, 0 – 100 m. That new water shallows to about 40 m at Station IE2 and IE3. At Station EF1 the new water shallows even more to 24 m and as it moves in to Effingham Inlet it is restricted to the upper 10 m of the water column. There is some new water found at the head of Effingham Inlet

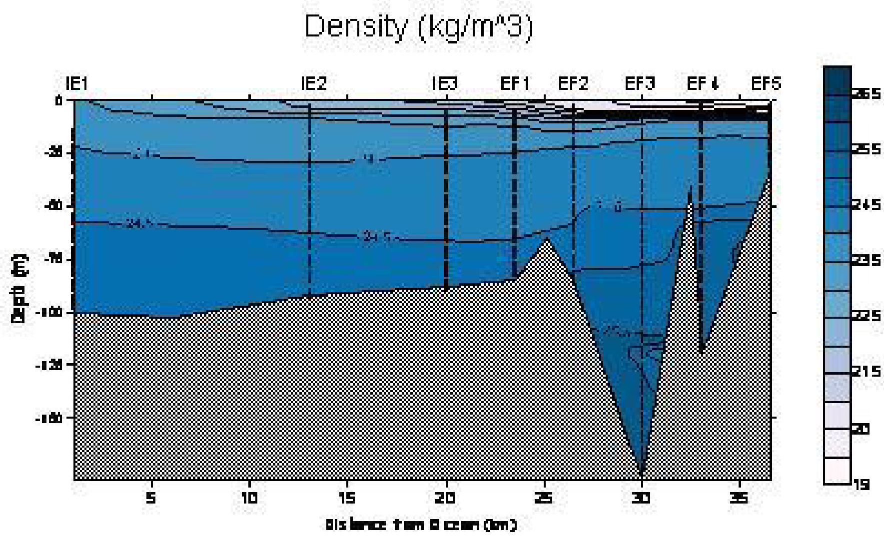

Figure 4. Density in Imperial Eagle Channel and Effingham Inlet.

where the Effingham River discharges. This is also where the inlet is the most stratified (Fig. 4). The oldest water is found in the deep basins in Effingham Inlet at Stations EF3 and EF4. The oldest water is roughly 79 days.

AOU in Trevor Channel reaches 0 µmol kg^{-1} at a shallower depth than in Imperial Eagle Channel (Fig. 5a). At Station TC1 oxygen becomes under saturated at about 24 m, and at about 20 m at Station TC2. At Station TC3 the water is not supersaturated, even at the surface. The overall oxygen concentrations in Trevor Channel are also lower than those in Imperial eagle Channel at a depth of about 50 m (Fig. 5b).

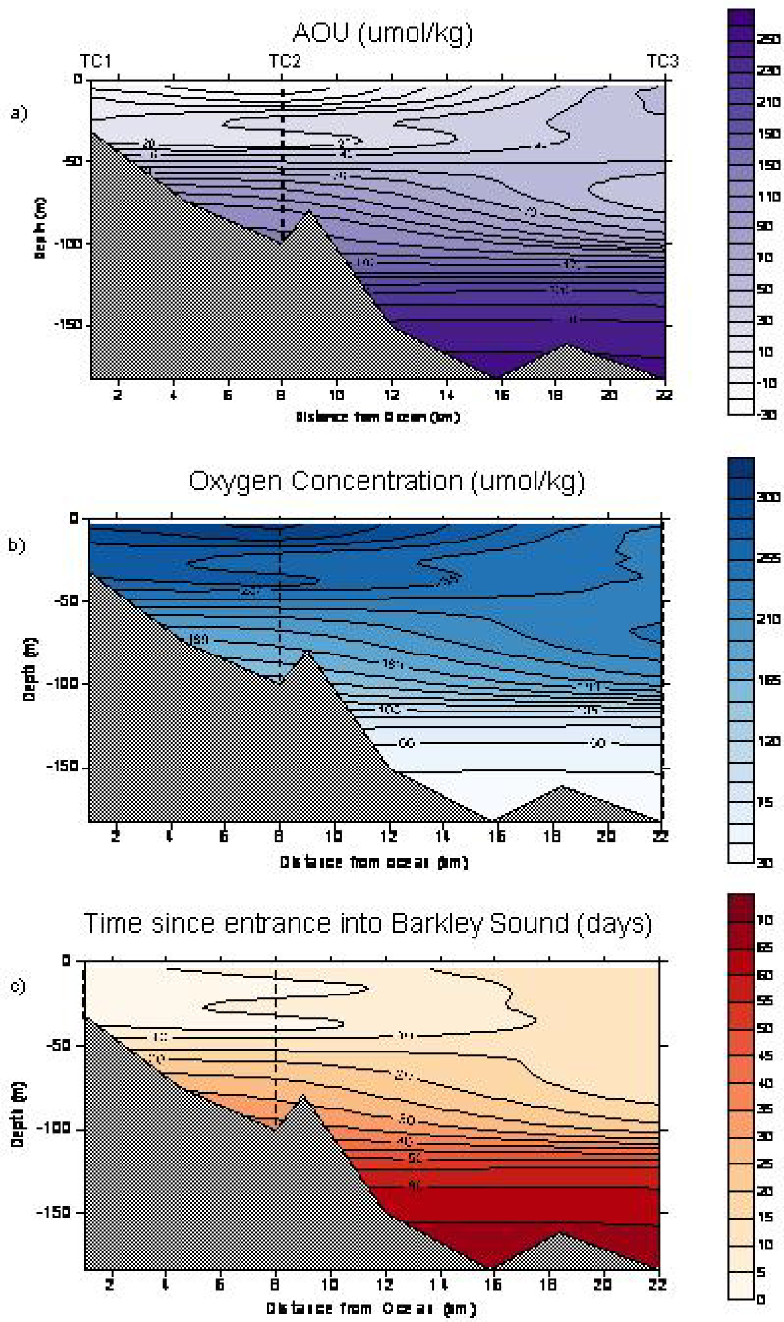

Figure 5. Trends in oxygen in Trevor Channel. Contour plot a) shows the trend in AOU, b) is showing trends in oxygen concentration, and c) shows the trends in water ages.

Trends in water ages in Trevor Channel follow those found in Imperial Eagle Channel (Fig. 5c). The newest water is found at all depths at Station TC1, 0 – 32 m. The new water, 0 – 5 days, does not penetrate as far into the sound in Trevor Channel as it does in Imperial Eagle Channel. The new water travels about 31 km from the mouth of Imperial Eagle Channel, but only travels about 11.5 km into Trevor Channel. At Station TC3 the newest water is 10 – 15 days old and extends to a depth of about 87 m. The oldest water found in Imperial eagle Channel is between 10 and 15 days old. The oldest water found under a 150 m in Trevor Channel, is about 70 days old.

Discussion

The respiration rate calculated for Effingham Inlet at 0.265 µmol kg^{-1} day^{-1} is higher than a respiration rate calculated for Saanich Inlet at 0.183 µmol kg^{-1} day^{-1} (Zaikova et al. 2009). High rates of primary productivity have been found in Saanich Inlet, which should lead to a high respiration rate (Timothy and Soon 2001). However, Saanich Inlet is annually flushed with oxygenated water in late summer while Effingham Inlet is flushed more irregularly (Anderson and Devol 1973; Zaikova et al. 2009). The longer the water in a basin stays anoxic the more the metal species in the sediments are reduced, and the higher the sediment oxygen demand (Glud 2008; Lui et al. 2009). When new oxygenated water flushes an anoxic basin the sediments will strip out some of the oxygen in the water and use it to oxidize metals. In some estuaries the sediment oxygen demand can reach 50% of the total oxygen depletion (Liu 2009). This means that in both inlets the respiration rates can be overestimated. Effingham Inlet has a higher sediment oxygen demand than Saanich Inlet and so its respiration rate, in particular, is over estimated.

An over estimated respiration rate would lead to an under estimation in the age of the water. The AOU values were divided by the respiration rate so a larger rate would give a newer water age. This means that the calculated ages of the water in Barkley

Sound and Effingham Inlet are probably a few days older than what is shown (Fig 3c and Fig. 5c). The overall pattern of water movement implied by the water ages would be unchanged though. Newer water would enter at the mouth of Barkley Sound and at the head of Effingham Inlet and the oldest water would be found in the deep basins in Effingham Inlet.

The water on the surface of the sound is shown to be a few days old in Figure 3c and 5c. This is because the absolute value of AOU was used to calculate the water ages. Water at the surface of the sound and to a lesser extent Effingham Inlet is supersaturated. This means that the AOU value is negative, and more oxygen is present than the water can theoretically hold, based on its temperature and salinity. The water age above 10 m is most likely less than 5 days old.

Another source of error in the age calculations is the fact there is no oxygen in the deep basins in Effingham Inlet. The age calculation is based on AOU which is the difference between the oxygen concentration at saturation and the measured concentration. If the measured concentration is 0 μmol kg^{-1}, then the AOU is simply the theoretical saturation value. This means that there is a maximum age that the water can reach, according to the calculation, which in this case is roughly 79 days. It’s possible that age of the water in the deep basins of Effingham Inlet is older than 79 days.

In Imperial Eagle Channel the pattern of AOU and the time since the water entered the sound is within expectation. Newer water is found towards the mouth and the older water is found towards the end, near Effingham Inlet. AOU can be used as a tracer of older water in Barkley Sound because there is a long and relatively shallow stretch of topography at the mouth where water is churned and thoroughly mixed as it enters. After the water enters the sound it becomes more stratified and respiration begins to deplete the oxygen below the mixed layer. During the March 2010 cruise, a diatom bloom was observed in the water, which would account for the supersaturation in the mixed layer.

In Effingham Inlet, the pattern of AOU and time elapsed, follows expectations of higher AOU and older water at the head of the inlet, with a few exceptions. The oxygen concentration at EF5 is lower than other stations in Effingham by about 20 μmol kg^{-1} (Fig. 3b). River discharge could have a low dissolved oxygen concentration and could displace the excess oxygen caused by the observed diatom bloom.

The pattern of water movement in Effingham Inlet is similar to that of other inlets in British Columbia, Canada. In Saanich Inlet water flowing into the basin at depth is also impede by a sill at the mouth of the inlet. Between June and August in Saanich Inlet the waters below 160m go anoxic (Zaikova et al. 2009). This implies that water is trapped within the basins of Saanich Inlet and the oldest waters are found at depth. This matches well with the observed pattern of water ages in Effingham Inlet. The deep waters of Saanich Inlet are annually flushed with waters from Haro Strait, which is unlike the waters found in Effingham Inlet (Timothy et al. 2001; Zaikova et al. 2009). This implies that the water in Effingham can reach ages older than that of Saanich Inlet.

The patterns of AOU and water ages in Trevor Channel are very different than that observed in Imperial Eagle Channel at depths lower than 50 m. A sill impedes water moving into Trevor Channel. This sill would prevent dense bottom water from flushing the basin, causing slower circulation. The oxygen at depth would be exposed to respiration processes longer than in Imperial Eagle Channel and cause low oxygen concentrations. If the water moves slowly enough it's possible that the water could become hypoxic and even anoxic.

Conclusions

The calculated respiration rate for Barkley Sound is most likely over estimated due to the inherent sedimentary oxygen demand in Effingham Inlet because of persistent anoxia. This over estimated respiration rate leads to under estimated water ages, though the pattern of circulation would be the same for corrected ages.

The pattern of circulation follows expectations. New water is found at the mouth of Barkley Sound in Imperial Eagle Channel and in Trevor Channel. Older water is found at the eastern end of the sound with the oldest water in the deep basins of Effingham Inlet. The age of the anoxic waters in Effingham is possibly older than that calculated.

Further circulation studies in Barkley Sound would benefit from a box model of the sedimentary oxygen demand. This would show how much oxygen is being used by the sediments and lessen the amount of error in the calculated respiration rate and the calculated water ages. More sampling should be done in Trevor Channel to determine the amount of time it takes for the deep water to flush out of the deep and at what time scales this flushing occurs.

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