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Circulation patterns a Circulation patterns and processes in Barkley Sound, Vancouver, BC

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NONTECHNICAL SUMMARY

Estuaries are crucial coastal ecosystems that have an immense influence on important oceanic and natural processes. The carbon pump, biological pump, and nutrient cycles are all affected by the estuary and its topographical features in question. They provide a valuable source of economic benefits for local populations through tourism and aquaculture. Barkley Sound is a fjord-like estuary located in Vancouver Island, British Columbia. It is an intricate body of water with four main basins: Imperial Eagle Channel, Effingham Inlet, Alberni Inlet, and Trevor Channel. The Sound has numerous underlying complex processes, all of which effect local biology and chemistry. The bathymetry of Barkley Sound is characterized by numerous shallow sills and narrow inlets, which restrict water flow, and deep, wide basins, which retain water over months and years at a time, decreasing the dissolved nutrient and oxygen content. This research shows the majority of net flow into and out of the Sound is through Imperial Eagle Channel, the widest and deepest basin in the Sound. This study attempts to analyze the circulation patterns within Barkley Sound and to better understand these underlying processes. Thousands of years of glacial activity have shaped Barkley Sound into a fjord with a very unique bathymetry and structure.

ABSTRACT

An in-depth study of estuarine circulation using conserved water properties has been implemented to determine the sources and rates of oxygen renewal in Barkley Sound, Vancouver, British Columbia. Conductivity, temperature, and depth profiles were taken at various stations throughout the sound to determine vertical profiles of temperature, salinity, and oxygen in each of the four main basins: Imperial Eagle Channel, Effingham Inlet, Alberni Inlet, and Trevor Channel over a seven day period from January, 27th to February 2nd. A technique called ‘characteristic diagrams’ along with the mixing proportion equation has been implemented to determine circulation patterns and processes throughout the Sound. Oxygen concentrations and the apparent oxygen utilization (AOU) were used to determine the age of the water and rates of renewal. It was found that net flow through Barkley Sound is primarily through Imperial Eagle Channel. Using oxygen as a proxy for the age of water, it was also determined exchange rates between Alberni and Effingham Inlets with Trevor and Imperial Eagle Channels are relatively low, due to their extreme isolation by the bathymetry and narrow breadth. It has been

concluded that this model will be useful in determining the underlying physical processes involved in governing the biology and chemistry of Barkley Sound.

INTRODUCTION

Scientific interest is increasingly being focused on the dynamics of coastal bodies of water such as estuaries. They are an essential environment for economic and environmental benefits which are utilized by economies around the world. With the growing need for clean energy in today's world, energy extraction via tidal energy is a largely untapped and poorly understood concept which is coming to the forefront of the physical oceanography community. Along with sustainable energy, estuaries provide direct commercial goods available for export in the form of lumber, transportation, and aquaculture. The success of our multi-billion dollar a year fishing industry is dependent on the understanding and health of coastal ecosystems such as estuaries; over 75% of fish and shellfish caught in North America spend at least a portion of their life-cycle nesting and grazing within estuarine waters (National Ocean Service Education, 2012.)

Barkley Sound is a fjord-like estuary covering an area of roughly 800 square kilometers on the west coast of Vancouver Island, British Columbia (Figure 1). It is characterized by four main basins: Imperial Eagle Channel, which is roughly 19.35 kilometers long and 7.5 kilometers wide, Trevor Channel, which is roughly 20 kilometers long and 2.4 kilometers wide, Alberni Inlet; 35 kilometers long and an average of 1.4 kilometers wide, and Effingham Inlet; 12 kilometers long and .8 kilometers wide, each having its own equally unique bathymetry. Imperial Eagle Channel and Trevor Channel are divided by the 20 kilometer long Tzaratus Island chain and are connected only via Junction Passage and Helby Passage. The exchange and mixing of oceanic and estuarine water, a process which is vital to the chemical and biological conditions of the Sound, is largely influenced by this unique bathymetry (Andrade et. al 2000). These conditions have a large influence on the resources used by local populations.

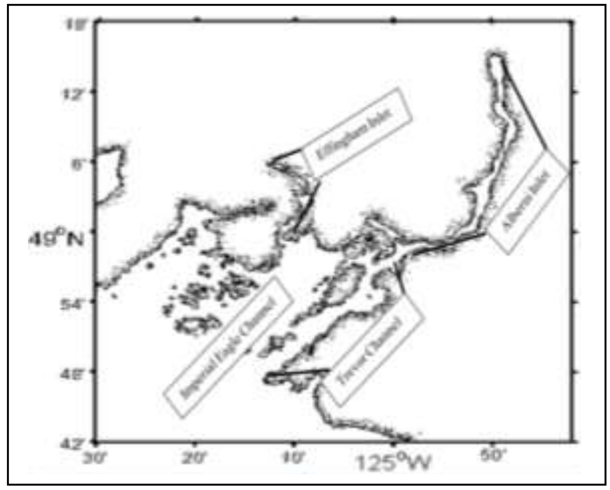


Figure 1: Labeled map of Barkley Sound showing locations of Effingham Inlet, Imperial Eagle Channel, Alberni Inlet, and Trevor Channel.

The natural resources of Barkley Sound, such as fishing, transportation, logging, and tourism and recreation have been utilized for hundreds of years (Duck et. al 2003). These resources, which continue to have an invaluable effect on the local economy today, may be drastically affected by the underlying processes which help define the conditions of Barkley Sound. To be able to fully utilize and protect resources offered by estuaries such as Barkley Sound, it is important to first understand the physical dynamics that define the Sound's biological and chemical parameters which make these resources possible. This study aims to establish and interpret the overall net flow and circulation patterns of water masses within Barkley Sound, which will then be applied to measurements of dissolved oxygen content to establish a correlation between the effects physical processes have on the chemical and biological variables within the Sound.

The flow of water within an estuary can be characterized by the combination of intertidal mixing and circulation, wind driven surface currents, and gravitational flow caused by density gradients within the water column (Hess, 1975). Salinity and temperature are considered conserved properties of water; no process exists for removing heat or salt within the water column over the time frame of this study. Using this fact, it can be assumed when water travels along stably stratified density gradients, such as in Barkley Sound, it carries the same temperature and salinity properties with it. It can then be deduced where and in what proportion the water mass came from using a technique referred to as *Characteristic Diagrams* focusing on hydrographic data to establish an overall pattern of net flow based on the collected hydrographic data (Pickard and Emery, 2007).

To determine the overall net flow of water masses within Barkley Sound, fifteen conductivity, temperature, and depth (CTD) profiles were taken Lagrangianly at various locations throughout the Sound, where vertical profiles of temperature, salinity and oxygen were measured and used to establish and circulation pattern of water masses throughout the sound. Oxygen concentrations were then correlated with these circulation patterns to establish rates and sources of renewal, vertical mixing downward or ocean water intrusion.

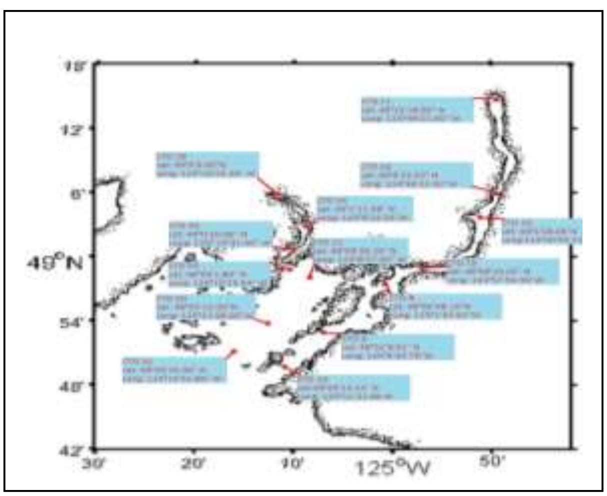


Figure 2: Labeled map of Barkley Sound showing numbers and locations of CTDs used to gather temperature and salinity profiles

METHODS

CTD casts were taken over a seven day period from January 27th to February 2nd using a SeaBird 911 Plus at a total of fourteen stations aboard the R/V Thomas G. Thompson at relatively consistent intervals throughout the main basins of Barkley Sound (Fig. 2). CTD stations were chosen based on their representation of all water types within Barkley Sound along with their ability to fully characterize all possible pathways of net circulation through the main basins of the Sound. T-S and oxygen concentration profiles were taken from the surface to the seafloor at each location, yielding full water column profiles of simultaneous oxygen concentrations and hydrographic data (Figure 3).

To deduce circulation patterns, a technique referred to as *Characteristic Diagrams* was utilized (Pickard and Emery 1990). Helland-Hansen first suggested this technique in 1916 by plotting temperature against salinity for individual oceanographic stations. The sources of the water are then determined by how close each water type is to one another. When discussing the T-S characteristic diagram, a water body whose properties are represented by a point is called a water type. Individual water types are plotted on a density contour graph showing density as a function of salinity and temperature (Fig. 3). Each point on the diagram corresponds to a specific water type's salinity and temperature and therefore a specific density.

When determining net flow for Barkley Sound, ocean water and terrestrial run-off water types are plotted on the density contour graph against the third water type in question, forming a T-S triangle. The distances between these three points are measured and a T-S ratio is determined. Under the stated conditions, the equation which governs estuarine circulation in a fjord like Barkley sound is

$$AS_1+BS_2=S_3 \qquad \text{(Eq.1)}$$

where A is the coefficient of salinity in ocean water, which is always 1 in the case of this study, B is the coefficient of salinity in terrestrial run-off water from freshwater sources such as rivers and streams, S_1 is the average salinity of ocean water, S_2 is the salinity of terrestrial run-off, taken from measurements done by Bamfield Research Center, and S_3 is the salinity of the water type being questioned. To illustrate the solution completely, it is also necessary to introduce

$$A/(A+B) \qquad \text{(Eq. 2)}$$

$$B/(A+B) \qquad \text{(Eq. 3)}$$

where $A/(A+B)$ is the fraction water in the sample that is derived from the ocean and $B/(A+B)$is the fraction of water in the sample S_3 that is derived from terrestrial freshwater sources.

A net flow is then established; if the difference between the fraction of ocean water and the fraction of terrestrial run-off is greater than the previous water type tested, net flow is towards the coast. If the difference is smaller, net flow is towards the ocean shelf.

Once a net circulation pattern was established, oxygen concentrations measured simultaneously using a SeaBird 43 oxygen sensor mounted on the SeaBird 911 Plus CTD were used to calculate the apparent oxygen utilization rate (AOU), giving us the "age" of the water type. Oxygen concentrations were compared to hydrographic data to determine sources of renewal.

RESULTS

T-S plots taken from CTD casts at all 14 stations (Figure 3) showed a maximum salinity of 33 PSU and a minimum value of 17.5 PSU. A maximum temperature of 10.15 ° c and a minimum of 7 ° c were observed. Due to the relatively much larger changes in salinity when compared with temperature, it can be inferred salinity was the primary factor in determining density changes. Due to this fact, along with variations in temperature caused by atmospheric interferences at shallow depths, salinity will be the primary tool to determine net circulation.

Barkley Sound is distinguished by a highly stratified water column, consisting of a relatively fresh surface layer, a relatively warmer, saltier intermediate layer, and a highly saline, cold deep layer. This heavily vertically stratified layer is further complicated by a strongly horizontally stratified layer due to the cold saline water at the mouth of the Sound mixing with a large rate of freshwater input from terrestrial sources. Water columns in all four basins are stratified into three distinguishable layers, showing fresh, cold water at the surface, while intermediate water columns are warmest, with a varying salinity concentration. Water masses on the seafloor show extreme cold and high salinity content (Figure 4).

Dissolved oxygen concentrations indicate extreme anoxic bottom conditions in the upper regions of both Effingham and Alberni Inlets. Effingham Inlet shows virtually zero dissolved oxygen at CTD's 27 and 28, with very little increases in oxygen concentration until CTD 35, where oxygen begins to equilibrate with Imperial Eagle Channel oxygen measurements at roughly 7mg/L. Oxygen concentrations throughout Alberni Inlet are much more sporadic, but also show anoxic conditions at locations in the upper region such as at CTD's 12 and 15, reaching concentrations as low as 1.25 mg/L. Concentrations begin to equilibrate with concentrations found in Imperial Eagle and Trevor Channels near the mouth of Alberni Inlet.

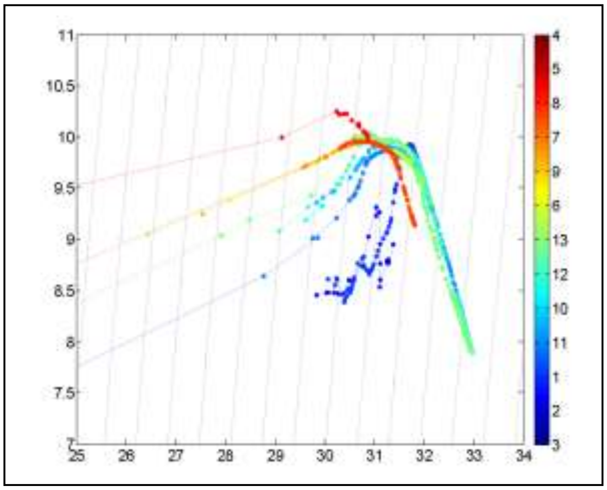


Figure 3: T-S plot depicted over density contours from Alberni Inlet through Trevor Channel

Using these salinity values, equations 1, 2, and 3 were implemented to all relevant CTD casts (Table 1) to determine a pattern of net circulation.

Channel	CTD cast	percent ocean water	percent fresh water	dissolved O2 content (mg/L)
Alberni Inlet	11	65.7	34.3	3.74
	16	68.9	31.1	4.15
	20	63.9	36.1	5.05
	18	64.1	35.9	5.42
Trevor Channel	10	73.5	26.5	8.3
	9	69.9	30.1	7.99
	8	63.8	36.2	7.26
Imperial Eagle Channel	21	67.6	32.4	7.54
	30	67.3	32.7	7.725
	32	78.2	21.8	7.68
Effingham Inlet	33	63.7	36.3	10.4
	35	62.2	37.8	10.517
	34	62.7	37.3	6.6
	28	64.5	35.5	7.34

Table 1a: Fractions of ocean water and freshwater along with oxygen concentrations in water masses at each CTD station at the surface. Oxygen concentrations represented are the averages of dissolved O_2 in upper half of water column.

Note: T-S and oxygen measurements taken in top 10% of water column were ignored to compensate for atmospheric interference (Pickard and Emery, 2007).

Channel	CTD cast	percent ocean water	percent fresh water	dissolved O2 content (mg/L)
Alberni Inlet	11	63.2	46.8	2.93
	16	55.1	44.9	3.838
	20	62.5	47.5	3.9
	18	72.3	21.7	4.8
Trevor Channel	10	95.7	4.3	7.79
	9	89.5	10.5	4.75
	8	88.4	11.6	3.98
Imperial Eagle Channel	21	90.8	9.2	7.07
	30	96.5	3.5	6.96
	32	98.5	1.5	7.21
Effingham Inlet	33	91.1	8.9	7.135
	35	91.5	8.5	6.87
	34	87.9	12.1	3.855
	28	87.5	12.5	2.099

Table 1b: Fractions of ocean water and freshwater along with oxygen concentrations in water masses at each CTD station at depth. Oxygen concentrations represented are the averages of dissolved O_2 in bottom half of water column.

DISCUSSION

A fjord-like estuary, such as Barkley Sound has numerous factors that influence its pattern of circulation. The high fraction of saline water to freshwater measured at CTD 32 indicate the majority of net inflow and outflow originates at the mouth of Imperial Eagle Channel (Fig. 4). The 111 meter depth at the mouth of Imperial Eagle Channel allows for a large tidal exchange between ocean and estuarine water compared to the relatively extremely shallow 27 meter depth of the mouth of Trevor Channel (Figure 4). This shallow depth prevents the ocean water at depth with relatively cold and salty properties from entering Barkley Sound.

There is a significant inflow of saline water to Effingham Inlet, with salinity reaching as high as 32.7 psu (Figure 3). However, low oxygen concentrations indicate an extremely long residence time and very little renewal. The extremely narrow width combined with shallow sills and deep basins prevent renewal of oxygen rich water. We see two deep basins flanked by two shallow sills. When ocean water plunges beneath the fresher estuarine water generated by terrestrial run-off and moves landward as a gravity current, saline water residing in the deeper water beyond the sill is replenished. On ebb, the saline water mass is prevented from flowing seaward by the presence of the sill, a process referred to as upstream blocking (Largier et al. 1991). In the case of Effingham Inlet, this results in long residence times with very little renewal.

Net flow at depth is then through Junction Passage towards Trevor Channel and Alberni Inlet, as indicated by the relatively larger fraction of seawater at CTD 21 when compared to CTD 8. Junction Passage serves as the primary exchange route between Imperial Eagle Channel and Trevor Channel through the Tzartus Island chain due to the high differences in water density (Figure 3) between the tops of Imperial Eagle Channel and Trevor Channel. The relatively deep and wide dimensions of Junction Passage also help it serve as a central exchange point.

We see a similar process with the exchange and estuarine water in Alberni Inlet as we did with Effingham Inlet. The larger fraction of freshwater when compared to salt water indicated very little exchange (Table 1). Inland tidal flow is restricted by a shallow sill, shown on figure 3 by CTD 16. This shallow sill combined with the extremely narrow width and long length of Alberni Inlet restricts dense, salty ocean water from entering the northern areas of the inlet. We then see patterns of net flow through Helby Passage and back out the mouth of Imperial Eagle Channel. Once again, the shallow depth of the mouth of Trevor Channel prevents a large volume of water to transfer between the estuary and the ocean.

High salinity and high oxygen content is to be inferred due to renewal from ocean water intrusion and mixing, relatively low salinity and high oxygen content is to be inferred due to vertical mixing downward from fresh water in equilibrium with the atmosphere. Anoxic zones are to be inferred due to lack of mixing and long residence times.

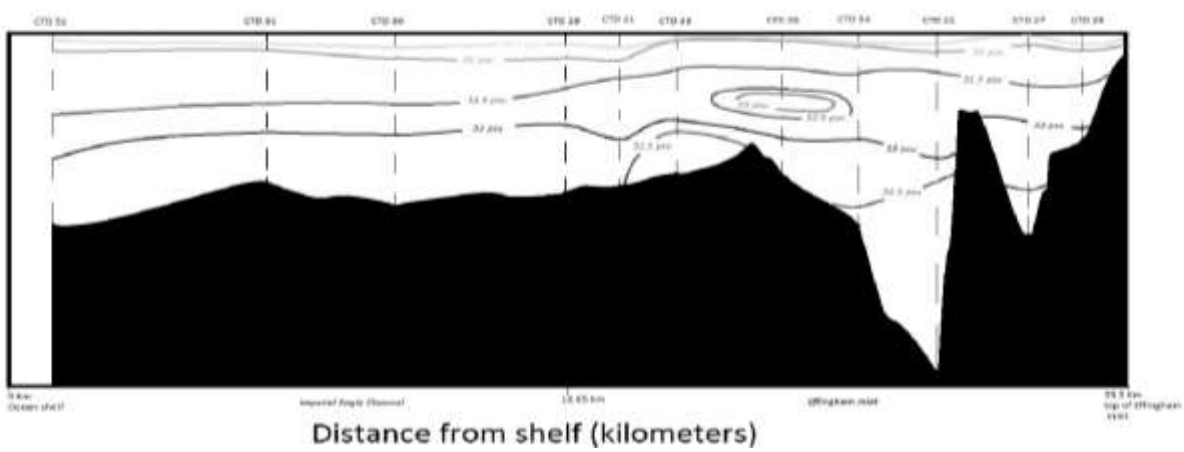


Figure 4a: Transect through Effingham Inlet to Imperial Eagle Channel depicting salinity.

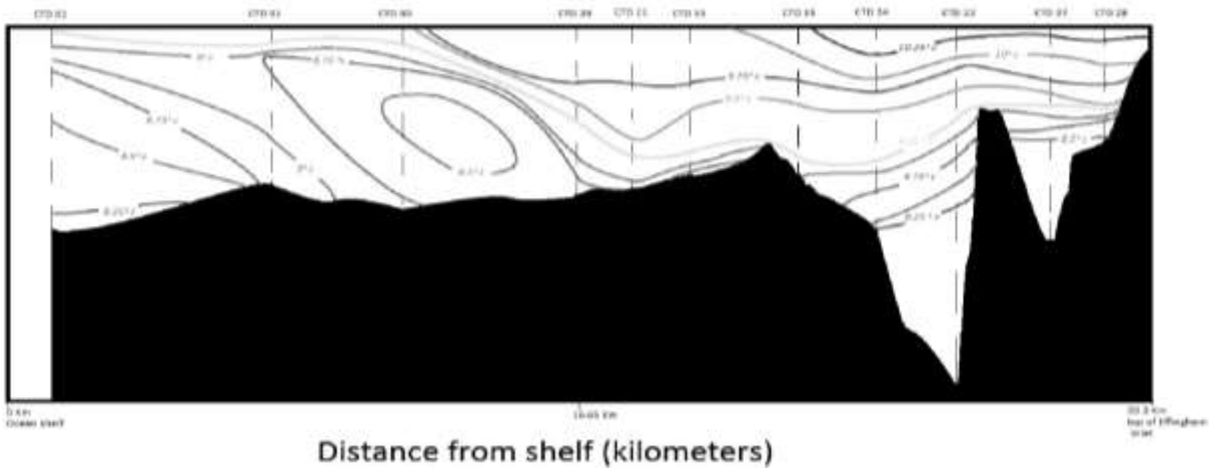


Figure 4b: Transect through Effingham Inlet to Imperial Eagle Channel depicting temperature.

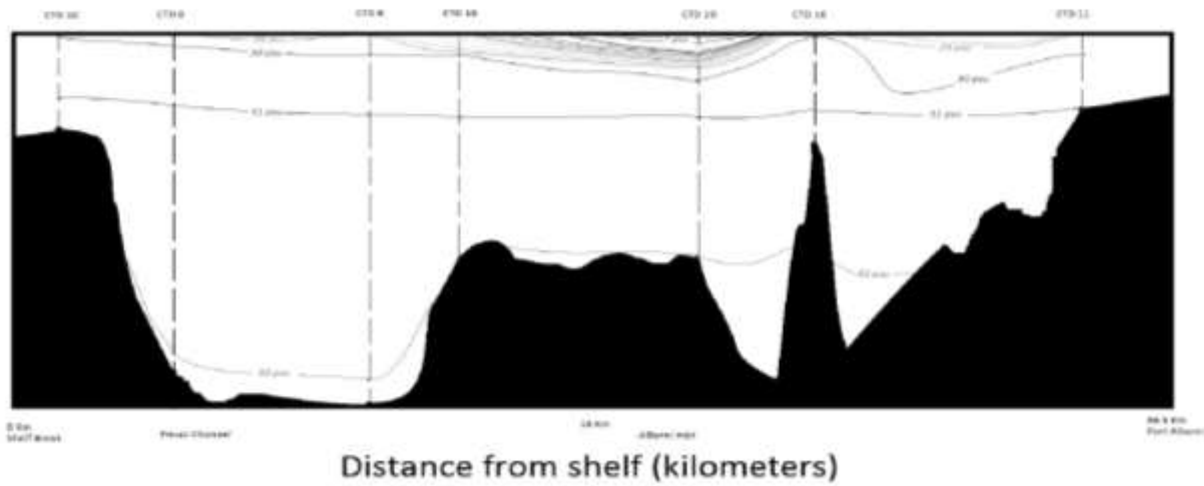
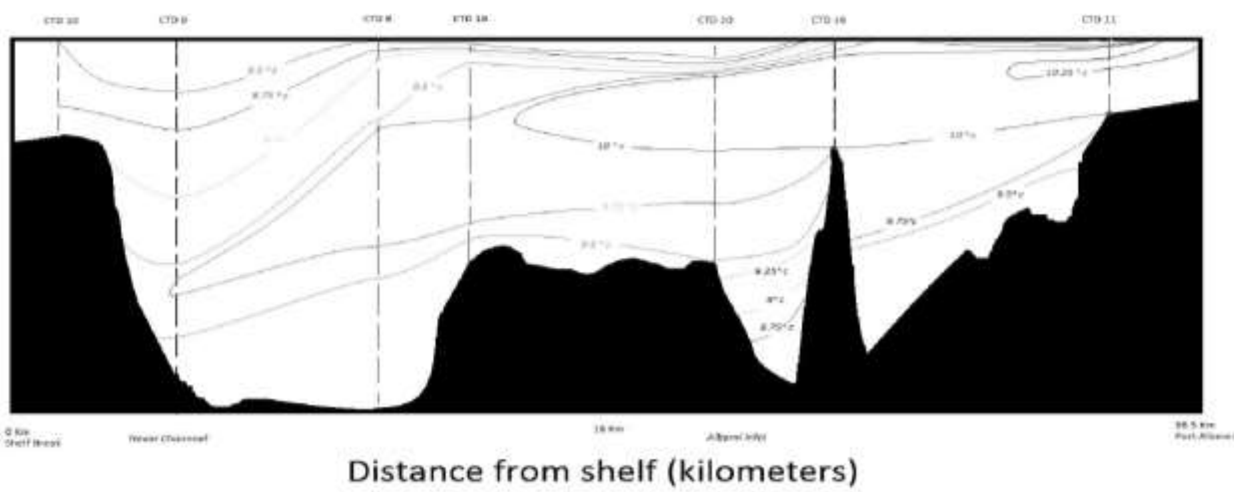


Figure 4c: Transect through Alberni Inlet to Trevor Channel depicting salinity



. Figure 4d: Transect through Alberni Inlet to Trevor Channel depicting temperature.

CONCLUSIONS

Using hydrographic data taken from CTD casts taken at various locations throughout Barkley Sound, a net flow of circulation was established.

It has been concluded that variations in bathymetry and density gradients are the primary factors influencing circulation and residence times.

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