Estuarine circulation in Barkley Sound; observed characteristics and processes

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Running Title: Circulation in Barkley Sound

Barkley Sound is located along the western coast of Vancouver Island and is complex water body with three primary channels and three significant inlets. Barkley Sound supports many local economical needs through fishing, aquaculture, and logging. These activities all put strain on the local marine ecosystem, and to better understand these dynamics it is extremely important to study the physical characteristics and circulation of the Sound. This study will help to develop an understanding of the biological community and chemical composition, and how they are correlated to the physical environment and affected by the economical impacts.

Barkley Sound is a fjord type estuary which receives freshwater input from rivers along Effingham Inlet and Alberni Inlet. As a fjord estuary the bathymetry is characterized by sills and basins, and the water column is highly stratified; made up of three principle layers. The portion of Barkley Sound being study has two Channels which connect Effingham Inlet and Alberni Inlet to the ocean; Trevor Channel and Imperial Eagle Channel. A notable characteristic differing Imperial Eagle Channel and Trevor Channel is entrance depth; at the seaward entrance to the Imperial Eagle Channel there is a depth of approximately 100 m where as at the entrance to Trevor Channel the depth is much shallower, approximately 40 m. As a result of the freshwater sources, sill and basin characteristics and locations, and tidal circulation, the Sound appears to have a focused circulation pattern which utilizes Imperial Eagle Channel as the primary exchange passage between the out flowing fresh surface water and the inflowing dense ocean water.

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Abstract

Estuarine circulation within Barkley Sound has been analyzed using hydrographic data throughout a portion of the Sound including Trevor Channel, Imperial Eagle Channel, Alberni Inlet, and Effingham Inlet. Data was collected during an approximately week long segment in March 2010. This study is aimed to develop previous circulation studies for this location and help biological studies taking place at the same time integrate their observations with the physical environment. Barkley Sound has been found to be a well stratified, three layer, fjord type estuary. Evidence for slow circulation between Trevor Channel, Alberni Inlet, and ocean waters relative to circulation between Imperial Eagle Channel, Alberni Inlet, and ocean waters indicates that Imperial Eagle channel is likely the primary exchange route for the out flowing upper layer. Freshwater exiting Effingham Inlet and Alberni Inlet is supported by evidence to likely circulate out of the Sound via Junction Passage, and then through Imperial Eagle Channel.

The deep layer water mass characteristics were observed in Barkley Sound, water which exists in the basins of the Sound. Canadian ocean observation program data was used to attempt to find when these deep waters were last renewed, the only concluding evidence is that no renewal has occurred since 15 Oct. 2009.

In March 2010 hydrographic data was collected in Barkley Sound as a part of a study to help better understand the physical properties and circulation processes within the Sound. The circulation within the Sound is an important study for three primary reasons; to contribute to and enhance previous local circulation studies, to help better understand how water properties affect marine biological species and abundances, and to determine how the circulation contributes to deep anoxic features in Effingham Inlet. Understanding the physical water properties and the mechanisms that change them will allow biological scientists to correlate their species studies to the physical environment and identify patterns of variability. Furthermore, better understanding of deep water renewal processes will lend hand to understanding the complicated processes of oxygenation and nitrification in these deep waters. One important question in this setting is how often deep water is renewed and thus the deep basins oxygenated. Few physical oceanographic studies have been conducted at this location, Doe (1952) found that fresh water from the Somass River was transported into Imperial Eagle Channel and then into Loundon Channel when studying the circulation of Loundon Channel, but further observations have been minimal.

Barkley Sound is an estuary located along the West Coast of Vancouver Island, Canada (Hansen and Rattray 1966). Barkley Sound contains three channels divided by groups of small islands; Loundon Channel, Imperial Eagle Channel, and Trevor Channel. These three channels are respectively linked to Pipestem Inlet, Effingham Inlet, and Alberni Inlet (Fig. 1). An additional important feature within the Sound is Junction Passage, a narrow link between the north end of Trevor Channel and Imperial Eagle Channel, also the point at which Trevor Channel becomes Alberni Inlet. This study specifically focuses on the circulation within the Imperial Eagle Channel, Trevor Channel, Effingham Inlet, and Alberni Inlet portion of the Sound. The inlets and channels within Barkley Sound have complex bathymetries (Table 1). As a result of the numerous deep basin and shallow sill features throughout the Sound, Barkley Sound is a fjord type estuary.

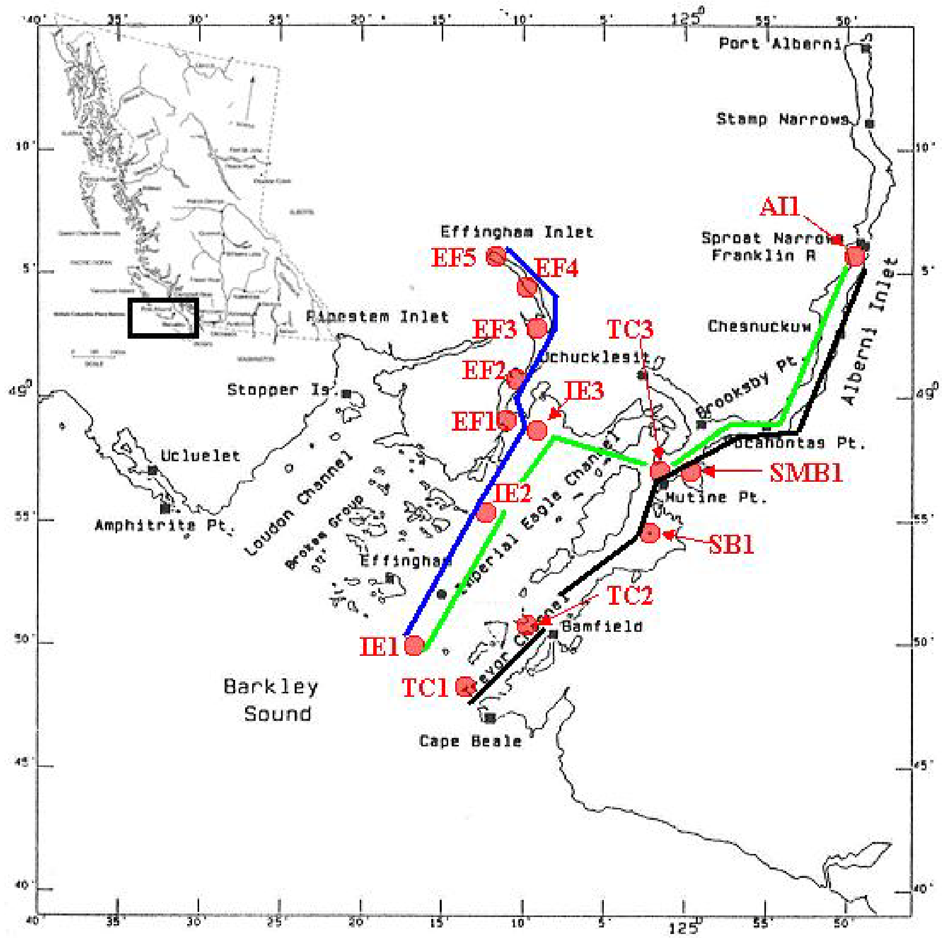

Fig. 1 Map of Barkley Sound with CTD Stations. Blue line indicates Effingham Inlet-Imperial Eagle Channel transect, green line indicates Alberni Inlet-Imperial Eagle Channel transect, and black line indicates Alberni Inlet-Trevor Channel.

Table 1 Approximate depths and number of fjord features in water bodies of Barkley Sound

Body of Water	**Entrance Depth**	**No. of Sills**	**No. of Basins**
Trevor Channel	34 m	1	2
Imperial Eagle Channel	94 m	0	0
Alberni Inlet	180 m	3	3
Effingham Inlet	90 m	3	3

In addition to the complex horizontal spatial characteristics of the Sound, as a fjord type estuary, Barkley Sound has a complex vertical structure. The vertical structure is composed of three fundamental layers; an upper, middle, and deep layer. The upper layer is a shallow, strongly stratified, brackish layer, which increases in salinity seaward and with depth. The middle layer is more homogenous than the upper layer, and has an inflow in response to the surface outflow displacement. Lastly, the deep layer is isolated at the bottom of the basins, only being displaced when denser water circulates into the Sound (Tully 1948). The intricate bathymetry as well as number of inlets and channels in the Sound are just two factors which complicate the circulation within this area. Additionally, winds, tides, and variable freshwater input combine to make the study of the Sound's circulation especially challenging (Hodgins 1978 and Farmer and Osborn 1976).

There are 17 rivers which enter Barkley Sound; their continuity as they enter the Sound is not well understood (Stronarch et. 1993 and Doe 1952). The most significant freshwater source into the Sound is the Somass River, which enters Alberni Inlet and makes up over half of the freshwater flow into the Sound. Changes in output of the Somass are observed to be linked to changes in the flow pattern in Barkley Sound (Doe 1952). Additional notable freshwater sources are the Franklin, Sarita, and Nahmint Rivers all entering Alberni Inlet, as well as the Effingham River entering Effingham Inlet (Stronarch et al. 1993). Tidal currents in Barkley Sound have northward flood and southward ebb flows, with a net flood flow moving north through Trevor Channel then west through Junction Passage (Stronarch et al. 1993).

Conductivity, temperature, and depth (CTD) profiles were collected at 14 different stations throughout Imperial Eagle Channel, Effingham Inlet, Trevor Channel, and Alberni Inlet for approximately a week long period; 20 March 2010 to 26 March 2010. These profiles have been used to observe temperature, salinity, and density gradients along these channels as well as mixing processes using temperature versus salinity plots.

The primary goal of this study will be to determine how the freshwater from Alberni and Effingham Inlets exit Barkley Sound into the Pacific Ocean. Due to the significantly shallower entrance to Trevor Channel than Imperial Eagle Channel, freshwater signals found in Loundon Channel from the Somass River, and tidal currents moving westward through Junction Passage (Doe 1952 and Stronarch et al. 1993), it can be hypothesized that circulation is inhibited within Trevor Channel. As a result there is an enhanced circulation pathway between Imperial Eagle Channel and Alberni Inlet via Junction Passage, causing the freshwater from both Effingham Inlet and Alberni Inlet to exit through Imperial Eagle Channel. This primary goal brings rise to a secondary goal of the study; to determine the time scale of deep water renewal in the Sound.

Methods

Data was collected in Barkley Sound between 20 March 2010 and 26 March 2010 aboard the M/V Alta and M/V Barkley Star. Continuous CTD profiles were taken at 14 stations throughout the Sound using a Seabird SBE-19 CTD (Table 2 and Fig. 1). Profiles at each station were made from the surface to approximately the seafloor at each location. CTD data was processed using Seabird CTD processing software, Seabird Data Processing Version 7.20b, and manually filtered. These processes resulted in one meter binned, down cast CTD data.

Table 2 CTD Station Locations

Station Name	Latitude	Longitude	Location
TC1	48˚ 48.37'	125˚ 12.94'	Trevor Channel (Entrance)
TC2	48˚ 50.82'	125˚ 09.11'	Trevor Channel (Off Bamfield)
TC3	48˚ 56.91'	125˚ 01.74'	Trevor Channel (Pill Point/Junction Passage)
SB1	48˚ 54.12'	125˚ 02.01'	Sarita Bay
SMB1	48˚ 56.66'	124˚ 59.56'	San Mateo Bay
AI1	49˚ 06.36'	124˚ 49.32'	Alberni Inlet (Franklin River)
IE1	48˚ 49.48'	125˚ 16.13'	Imperial Eagle Channel (Entrance)
IE2	48˚ 55.31'	125˚ 11.88'	Imperial Eagle Channel (Swale Rock)
IE3	48˚ 55.31'	125˚ 09.00'	Imperial Eagle Channel (Head)
EF1	48˚ 55.31'	125˚ 11.46'	Effingham Inlet (Entrance)
EF2	48˚ 55.31'	125˚ 10.27'	Effingham Inlet (Lower Basin)
EF3	48˚ 55.31'	125˚ 09.18'	Effingham Inlet (Middle Basin)
EF4	48˚ 55.31'	125˚ 09.38'	Effingham Inlet (Upper Basin)
EF5	48˚ 55.31'	125˚ 11.60'	Effingham Inlet (Head)

Objective mapping was utilized to interpolate data between stations. This method utilizes a least squares interpolation known as *Gauss-Markov smoothing*, which enables the production of a non-uniform gridded data set to be gridded and analyzed (Emery and Thomson 2001). Interpolation of data for a depth range of 6-200 m employed an x-correlation scale of 5, y-correlation scale of 15, an error energy of 0.1, and created 100 points nearest each grid point. Interpolation of data for a depth range of 0-6 m employed an x-correlation scale of 25, y-correlation scale of 3, an error energy of 0.1, and created 100 points nearest each grid point. The objective mapping program routine used was developed by G.C. Johnson.

Results

Processed CTD data was used to produce plots of along channel water properties. The along channel routes were chosen based on feasible pathways between inlets with freshwater input and channels which connect the inlets to the open ocean. Three along channel pathways were chosen; Effingham Inlet to Imperial Eagle Channel, Alberni Inlet to Imperial Eagle Channel, and Alberni Inlet to Trevor Channel (Fig. 1). Using these pathways, contour plots of along channel water properties were created, including temperature, salinity, and density. Within all water bodies the average maximum temperature difference is approximately 1.8˚C, where as the maximum salinity difference is approximately 22. Due to the significantly larger interval in salinity than temperature, density changes are determined primarily by salinity, thus salinity will be the chosen water property to observe water circulation.

Salinity along Effingham Inlet and Imperial Eagle Channel shows estuarine characteristics; surface freshwater outflow from the head of Effingham Inlet and deep ocean water inflow. The water column is highly stratified and the mixed upper layer is limited to the top 4 m. The upper layer, where water has salinity below approximately 32.5, is limited to about the upper 20 m. Water with a salinity less than 30 extends along the entire transect near the surface. Water with the greatest salinity along this route lies at the bottom of Imperial Eagle Channel, and within the basins of Effingham Inlet (Fig. 2).

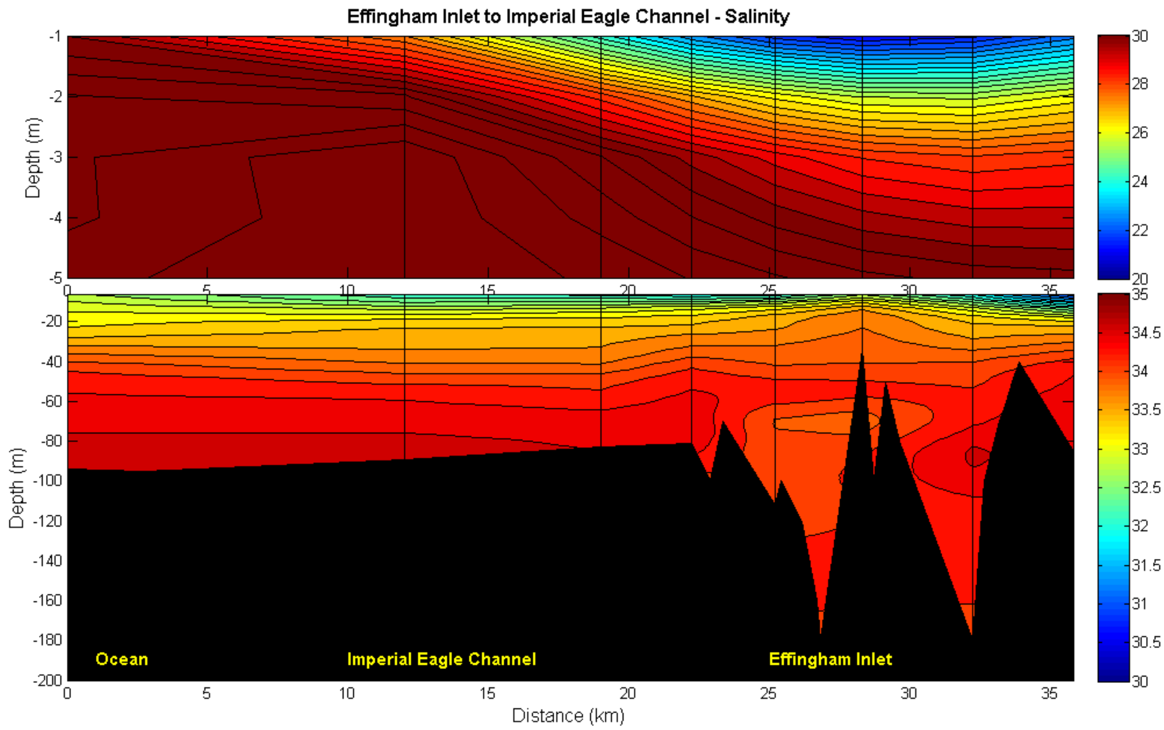

Fig. 2 Effingham Inlet–Imperial Eagle Channel salinity.

Salinity along the Alberni Inlet to Imperial Eagle Channel has estuarine characteristics and indicates a stratified water column with an upper layer confined to the top 3 m. The upper layer, where water has salinity less than approximately 32.5, is limited to about the upper 15 m. Water with a salinity less than 30 extends along the entire transect near the surface. The saltiest water lies along the bottom of Imperial Eagle Channel and in the basins of Alberni Inlet (Fig. 3).

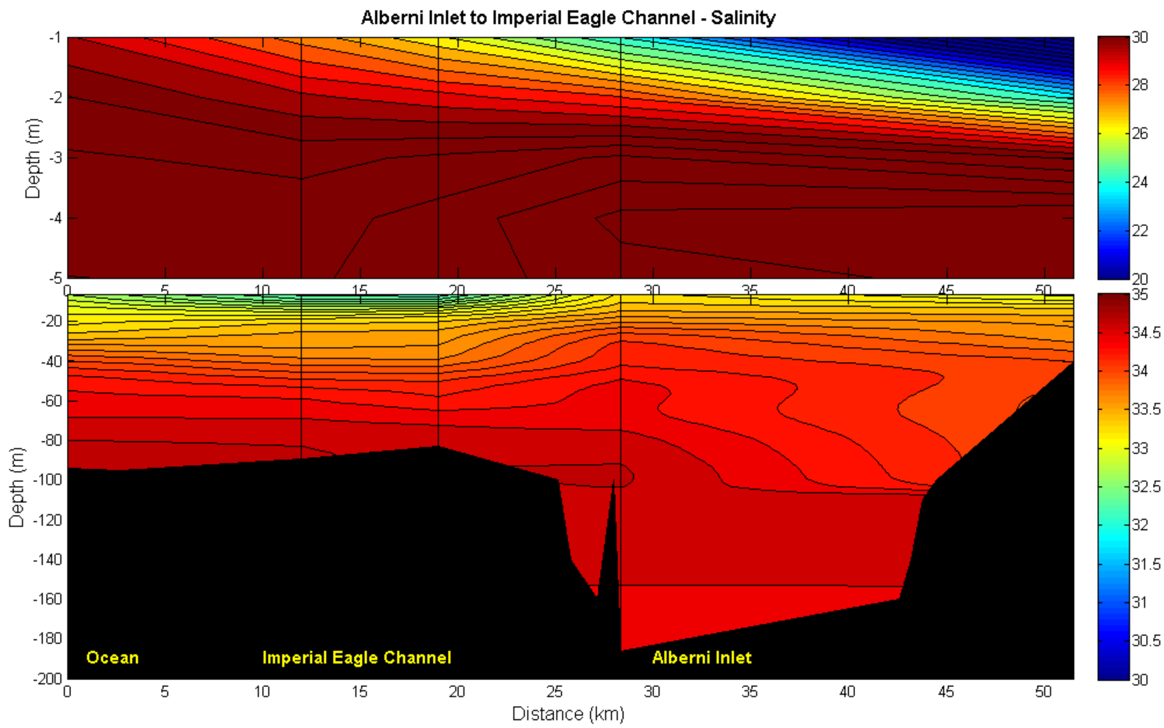

Fig. 3 Alberni Inlet–Imperial Eagle Channel salinity.

Salinity characteristics in the Alberni Inlet to Trevor Channel pathway indicate the thinnest freshwater layer of the three pathways, 2 m, in which the freshwater signal is nearly unnoticeable seaward of the Alberni Inlet-Trevor Channel transition. In general this transect appears to have a much less pronounced brackish water layer than routes which utilize Imperial Eagle Channel. Water with salinity less than 33 becomes completely unobservable below 5 m. The entrance to Trevor Channel is noted by a very shallow sill with approximate depth of 34 m. The saltiest water exists within the basins in Trevor Channel and Alberni Inlet (Fig. 4).

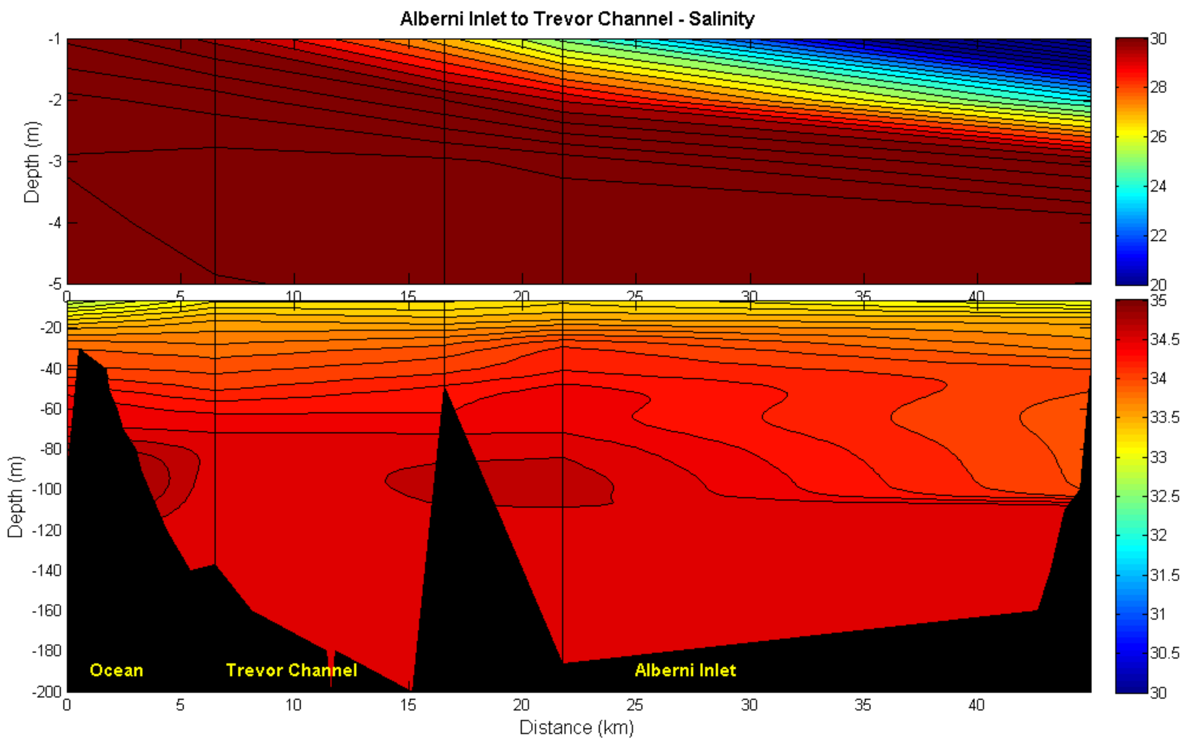

Fig. 4 Alberni Inlet–Trevor Channel salinity.

To better observe the mixing processes between fresh and saline waters, temperature versus salinity plots allow the transition of water properties across density gradients to be viewed in greater detail. Along the Effingham Inlet-Imperial Eagle Channel T,S plot, three distinct layers are identified with well stratified density. The upper layer appears to warm from about 9˚C to 9.4˚C and increases in salinity from about 30 to 35 while mixing with the middle layer. These two layers consistently mix linearly. The deep layer appears in Effingham Inlet at stations EF4 and EF2, where waters become notably cooler, 8˚C, and have a salinity of about 34. The freshest water enters this transect at EF3 and is characterized by the coldest temperatures, about 6.8˚C (Fig. 5).

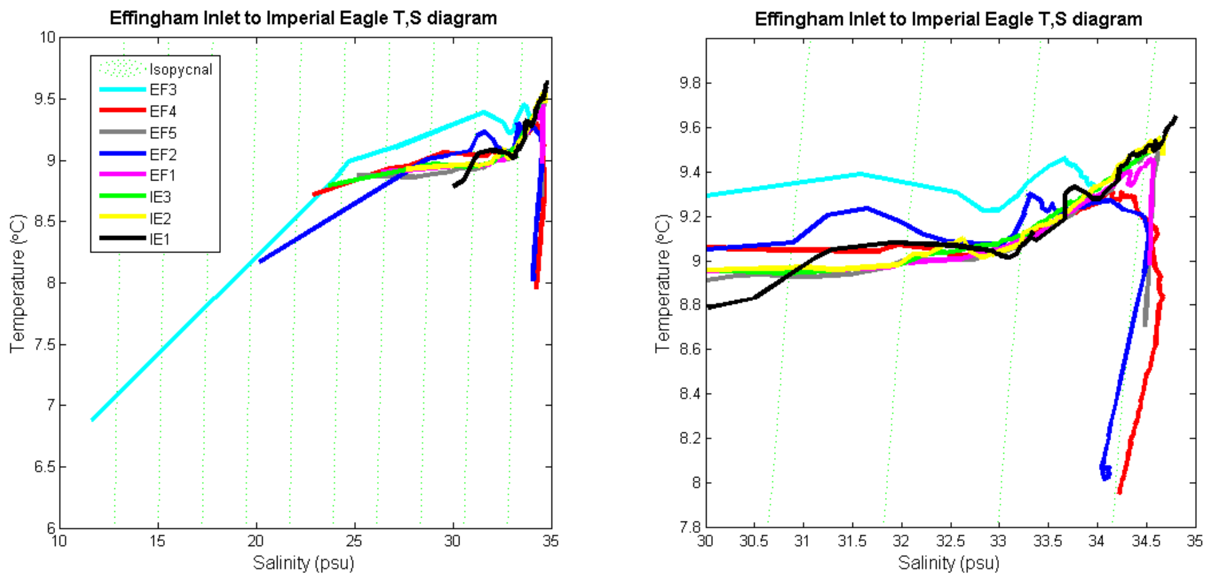

Fig. 5 Temperature versus salinity plots for stations along Effingham Inlet-Imperial Eagle transect. Panel 1 displays all measurements, panel 2 displays data with a salinity interval of 30-35.

The Alberni Inlet-Imperial Eagle transect again shows qualities of a three layer water column. While mixing with the middle layer, the upper layer warms from about 8.6˚C to 9.4˚C and increases in salinity from about 25 to 34.5. These two layers consistently mix linearly. The only station with a deep layer signal is TC3, the deep basin located at Junction Passage. The deep layer is characterized by cold, 8.4˚C, water with a salinity of 34.5. The freshest water enters the system at AI1 where the Franklin River enters Alberni Inlet, and is also the closest station to the Somass River, with a temperature of about 8.4˚C (Fig. 6).

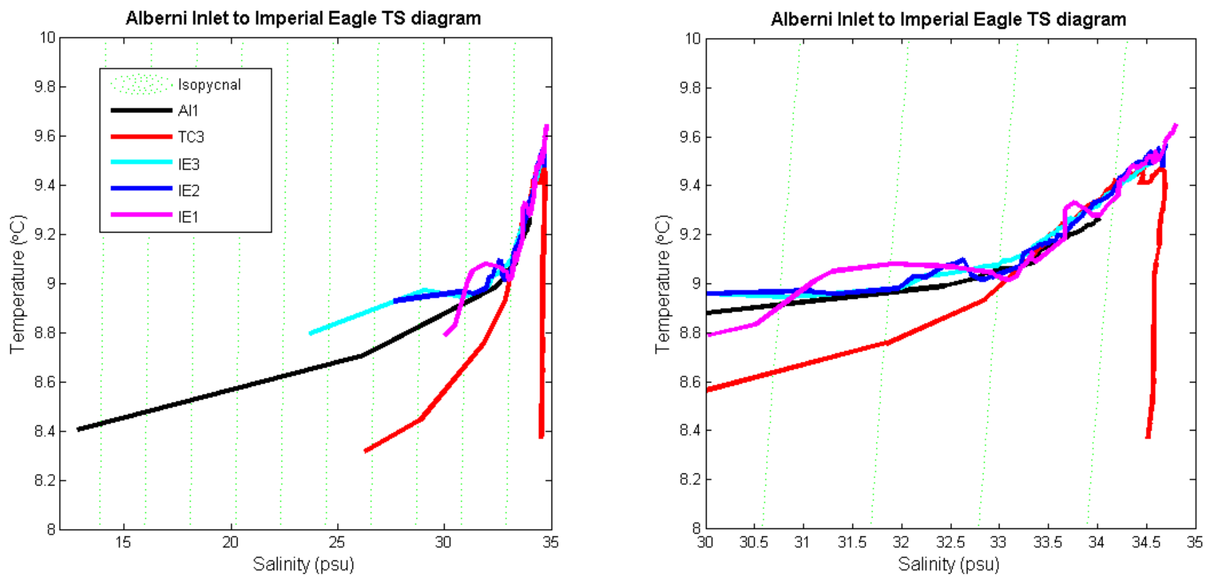

Fig. 6 Temperature versus salinity for stations along Alberni Inlet-Imperial Eagle transect. Panel 1 displays all measurements, panel 2 displays data with a salinity interval of 30-35.

The Alberni Inlet-Trevor Channel transect indicates a more complex water column. Only denser water appears to mix linearly, from about 9.1˚C to 9.4˚C and increasing in salinity from about 33.25 to 34.5, a smaller temperature and salinity range than in Imperial Eagle Channel. The upper layer only mixes linearly with the middle layer at stations AI1 and TC3; the two stations furthest from the ocean along this transect. At station TC1, TC2, and SB1, mixing processes are more complex. A zigzag structure in mixing is shown, which is evidence for there to possibly be four water masses and or slower mixing between the upper and middle layers. The upper layer at station TC1, TC2, and SB1 have greater temperatures than the upper layer water at AI1 and TC3.

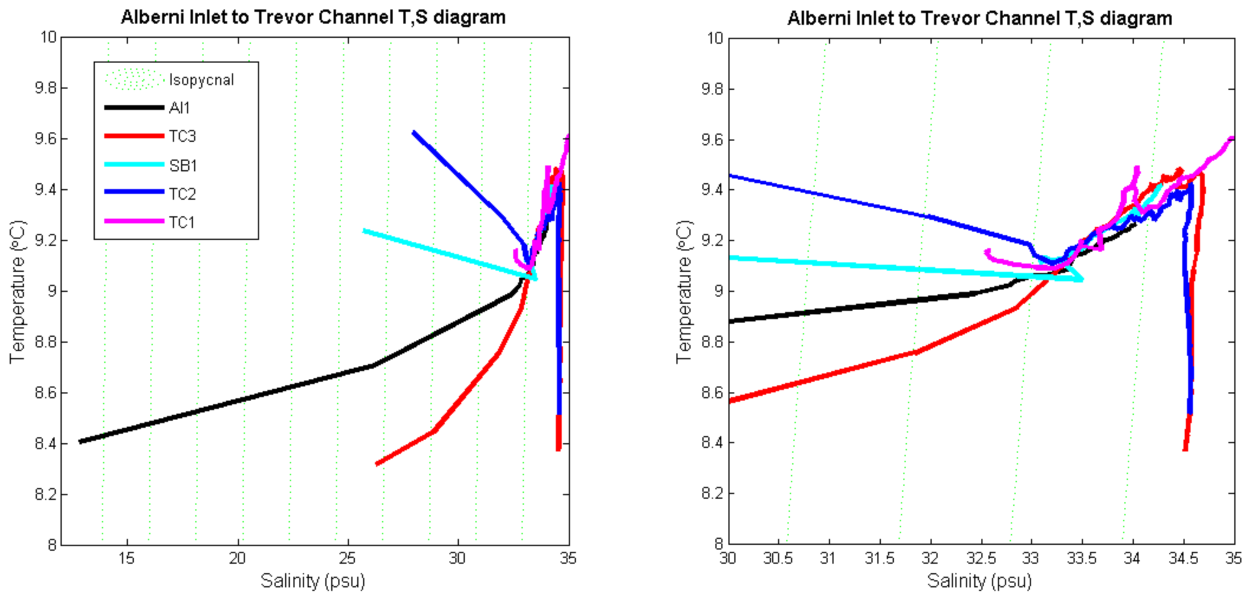

Fig. 7 Temperature versus salinity for stations along Alberni Inlet-Trevor Channel transect. Panel 1 displays all measurements, panel 2 displays data with a salinity interval of 30-35.

Discussion

Surface Circulation

Observations from this study lend well to previous observations made by Tully (1948), Doe (1952), and Stronarch et al (1993). Salinity contour plots verify that Barkley Sound is a fjord estuary (Fig. 2, 3, and 4), and T,S plots verify that the Sound has three principle layers. The three layers are distinguished by a general trend of v-shaped T,S profiles which indicate the mixing of three masses, a water mass at each end and turning point of the v-shape (Fig. 5, 6 and 7). The upper layer is confined to the top 15-20 m, the middle layer extends from the upper layer to the depth of the channel entrance, depending on which channel you are observing (Table 1). The deep layer exists below sill depths and within the basins (Fig. 2, 3, and 4 and Table 1). Barkley Sound is highly stratified, and water with density less than 30 is confined to the upper 4 m (Fig. 2, 3, and 4). The stratification is further identified in the common trend of linear mixing between surface freshwater and denser ocean water (Fig. 5, 6, and 7).

To begin to determine if the data distinguishes a particular route of freshwater flow out of the Sound, salinity contour plots must be compared between the channels. The salinity contour plot for Effingham Inlet to Imperial Eagle Channel shows a very clear freshwater signal along the entire pathway, this is very strong evidence supporting that freshwater from Effingham Inlet is exiting Barkley Sound via Imperial Eagle Channel (Fig. 2). What this plot does not indicate is whether this surface layer connection between Effingham and Imperial Eagle is solely a freshwater route from Effingham or if freshwater exiting from Alberni Inlet is additionally part of this flow.

When comparing the salinity contour plot for the Alberni Inlet to Imperial Eagle Channel route versus the Alberni Inlet to Trevor Channel route near the surface, the freshwater signal, water with salinity less than 30, extends to the ocean in Imperial Eagle whereas in Trevor it only extends to approximately 10 km inshore of the ocean (Fig. 3 and 4). This difference is evidence that surface waters in Trevor Channel mix more slowly with the ocean than surface waters in Imperial Eagle Channel and the upper layer circulation is inhibited as you move toward the ocean in Trevor Channel. An additional characteristic which contrasts Imperial Eagle Channel and Trevor Channel is the deep water, high salinity water mass which appears to be entering Imperial Eagle Channel, but is not evident in Trevor Channel (Fig. 3 and 4). Greater rates of surface outflow will be compensated by more deep water inflow, this might be the case in Imperial Eagle

Channel and could be additional evidence for faster mixing in this channel relative to Trevor Channel (Doe 1952).

Temperature versus salinity plots further indicate circulation differences between Trevor Channel and Imperial Eagle Channel. While observing the general shape of the T,S characteristics, a v-shape trend at nearly all stations is observed, whereas in Trevor Channel the mixing appears to be more variable, characterized by a zigzag pattern in the T,S space at stations TC1, SB1, and TC2 (Fig. 7). This pattern is caused by warmer surface waters, whereas at other stations surface waters tend have the coldest properties, showing that fresher surface waters do no mix linearly with the middle layer water. Additionally the densest water at station TC1 (ocean, Trevor Channel) has a greater salinity than station IE1 (ocean, Imperial Eagle Channel) by approximately 0.5. These observations can be used as further evidence that Trevor Channel mixes more slowly with the ocean than Imperial Eagle Channel.

Inhibited circulation between Trevor Channel and the ocean is evidence that freshwater outflow is more likely to circulate through Junction Passage and into the ocean via Imperial Eagle Channel than through Trevor Channel. This theory is supported by previous studies. Doe (1952) found that freshwater signals in Loundon Channel, northwest of Imperial Eagle Channel, had origins from the Somass River and Stronach et al. (1993) noted observed net tidal currents moving north through Trevor Channel and westward through Junction Passage. In addition to these observations which indicate that Junction Passage is a primary route for exiting freshwater, shallow sill depth at the entrance to Trevor Channel (34 m) likely inhibits the mixing of Trevor Channel with the ocean more so than in Imperial Eagle Channel, where no sill exists at the entrance and the depth is approximately 94 m (Stigebrandt 1981).

Observations from this study can only be used as evidence to document the circulation in Barkley Sound. To develop definitive circulation observations at these locations, CTD measurements would need to have greater horizontal spatial resolution, as well as great resolution over a larger time interval. These changes to the methods would help to find average water characteristics, whereas the measurements from this data are more likely to be influenced by particular tide cycles and variable freshwater volume input. Additionally, acoustic Doppler current profiler, drifter, and or current meter data would be essential to incorporate with this study when developing circulation observations as temperature and salinity data can only be used to infer water movement. These instruments would allow for documentation of currents and water fluxes.

Deep Layer Renewal

Deep layer renewal is a challenging study; it requires high resolution data along a large time interval leading up to the time of collected data to match water properties of the deep basins with when they last existed at the Sound’s entrance and began an inflow circulation. Temperature and salinity data for the deep basin water masses was collected for each station located at a basin in the Sound (Table 3). The Canadian government has two programs which collect long term oceanographic data, which can be used to match when water with basin properties last circulated into the Sound.

Table 3 Temperature and salinity data of deep water masses located at basin stations.

Station	Temperature	Salinity
TC2	8.52	34.56
TC3	8.37	34.52
EF2	8.07	34.15
EF4	7.95	34.21

The first is Neptune Canada, a nodal ocean observation system, which has a node at the entrance to Imperial Eagle Channel at Folger Passage with a CTD (100 m) (http://www.neptunecanada.ca/). This instrument is new and data only exists continuously between the present and 20 Oct. 2009. From the time series of temperature and salinity data it can be observed that the only time the water becomes cold enough to match even the warmest basin water mass the salinity does not match (Fig. 6 and Fig 7). For this reason we can determine that the water has not been flushed out of any the Barkley Sound basins since at least 20 Oct. 2010.

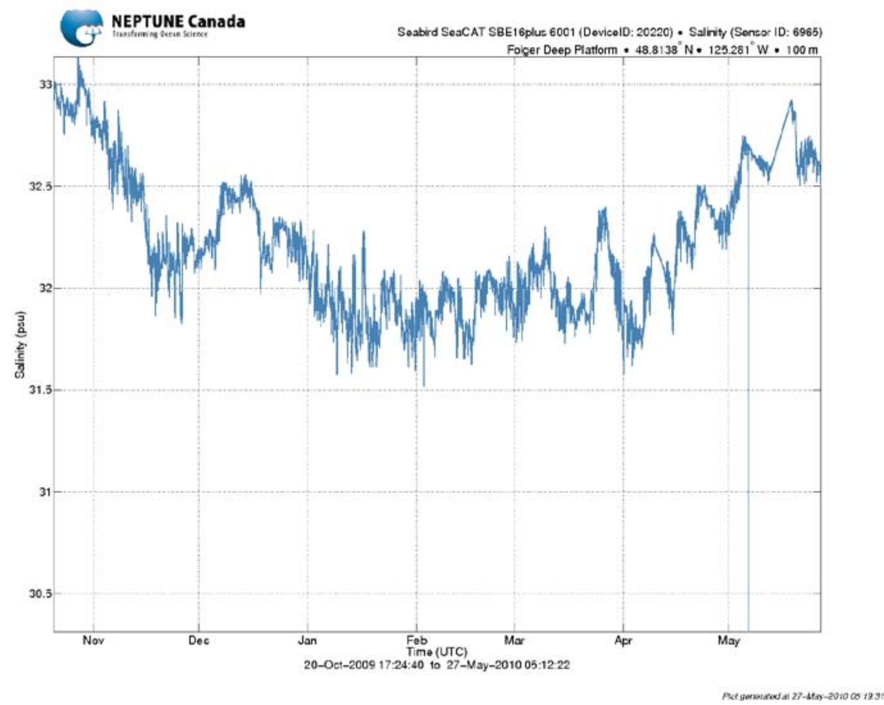

Fig. 6 Salinity time series at Folger Passage (100 m) from 15 Oct. 2009 to 27 May 2010. Figure produced by Neptune Canada.

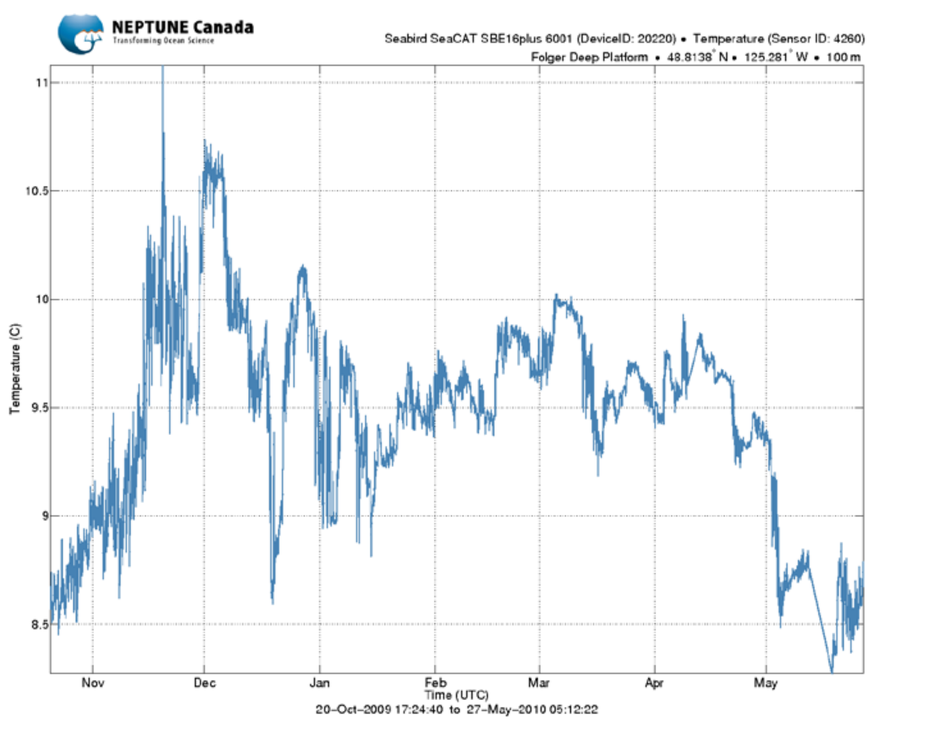

Fig. 7 Temperature time series at Folger Passage (100 m) from 15 Oct. 2009 to 27 May 2010. Figure produced by Neptune Canada.

The second program is the B.C. Lighthouse sea surface data collection, a program in which sea surface temperature and salinity data are measured daily at lighthouses in the Province (http://www.pac.dfo-mpo.gc.ca/science/oceans/data-donnees/lighthouses-phares/index-eng.htm). Amphitrite Point Lighthouse is located at the northwest corner of Barkley Sound. This data series dates back to 1934, but because it is a measurement at the surface it is very difficult to correlate this data with deep water renewal. For one temperatures will not match as the sea surface temperatures are diluted at the surface from freshwater runoff. From this data it can be determined that the last time the water was cold enough to match the deep water properties at TC2 and TC3 was 31 Dec 2009, when the water was approximately 8.2˚C. The water reached 8.0˚C on 10 Dec 2009, the first time at which the temperature was cold enough to match the basin temperature at EF2. Finally, the water reached below 7.95˚C on 30 Mar. 2009, when it was 7.4˚C, cool enough to match the temperature of water in EF4. Due to the lack of correlating temperature data and depth difference for the measurements, these data can only be used as very weak evidence for when these basins were last flushed. In the future, Neptune Canada will provide a great source for observing and correlating deep water renewal in Barkley Sound.

Conclusions

It has been determined that in March 2010, Barkley Sound was a fjord type estuary with three stratified principle layers. Low salinity waters, less than 30, are limited to the upper 5 m, and the upper layer exists from the surface to 15-20 m. There is strong evidence that Effingham Inlet waters directly exchange with the ocean through Imperial Eagle Channel. Additionally, evidence indicates that Trevor Channel mixes more slowly with Alberni Inlet and the ocean than Imperial Eagle Channel, this is shown by salinity observations, possible greater inflow at depth in Imperial Eagle Channel, and the complex mixing structure in T,S for Trevor Channel relative to Imperial Eagle Channel. This study suggests that the out flowing upper layer water from Alberni Inlet is more likely to exit the Sound via Imperial Eagle Channel than Trevor Channel. This process is a result of the slower mixing in Trevor Channel, which is likely caused by the sill at the entrance to Trevor Channel and tidal processes which utilize Junction Passage and enhance surface flow between Alberni Inlet and Imperial Eagle Channel.

Due to the interval of data available from Neptune Canada, renewal times for deep basins in Barkley Sound are still unknown but there is evidence that no flushing event has occurred in these basins since at least 14 Oct. 2009.

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