Proceedings from the University of Washington
School of Oceanography Senior Thesis, Academic Year 2012-2013

Detecting a shallow surface layer in Barkley Sound from Lagrangian drifter trajectories

Aaron K. Anderson[1]

[1]*University of Washington, School of Oceanography,*
Box 355351, Seattle, Washington 98195
[*]*akander@u.washington.edu*

Received June 2013

NONTECHNICAL SUMMARY

Fresh surface layers exist on the surface of fjords. In these areas, lighter freshwater from rivers flows over top of denser seawater from the ocean. A fresh surface layer creates stratification, which affects the distributions of biological organisms. It also greatly influences deep-water renewal in fjords since it resists vertical mixing. Low rates of vertical mixing in fjords can cause hypoxic and anoxic conditions at deeper depths. These conditions can kill fish and support bacterial communities that do not use oxygen for respiration. Studying shallower fresh layers can be challenging since their properties can change rapidly over only a few meters. Traditional water column profiling techniques may not adequate to define the existence of these layers. Drifters outfitted with GPS can be used to track water movements at varying depths. Comparing the movements of surface and subsurface water can indicate stability and layer individuality.

ABSTRACT

The existence of a fresh shallow surface layer in Barkley Sound was tested for by measuring the stability of water between the surface and 10 m of depth. Four Lagrangian drifters equipped with Global Positioning System receivers (GPS) were deployed at the surface and below the pycnocline to track the movement of water. 13 CTD casts were used to locate the pycnocline, calculate the Brunt–Väisälä frequency (N^2), and give estimates of the salinity in the upper 5 m. The pycnocline was located between 2 and 3 m of depth and had $\langle N^2 \rangle$ of 0.1 s^{-2}. At 2 m of depth the surface salinity at Sproat Narrows in Alberni Inlet was 24 psu, increasing to 30 psu in the larger channels. There were no observable trends in salinity at 3 m, and by 5 m the salinity was approximately 30 psu throughout most of the fjord. The water between the surface and below the pycnocline was found to be stable to shear instability in all areas sampled. Stability was determined by calculating Richardson numbers using average vertical shear. The average vertical shear was typically greater than 0.001 s^{-2} producing an average Richardson number (Ri) of 1000. For the largest vertical shear measured, 0.02 s^{-1}, the Ri was calculated to be 111.

Barkley Sound is a fjord type estuary located on the west side of Vancouver Island, opening to the Pacific Ocean. The region is generally shallow in depth and has three main channels and numerous inlets (Figure 1). The ordering of the channels from west to east is Loudoun, Imperial Eagle, and Trevor. Terrain consisting of groups of broken islands separates the channels from each other. The islands between Loudoun Channel and Imperial Eagle Channel are numerous and predominantly small, whereas only a few large ones separate Imperial Eagle Channel from Trevor Channel.

Trevor Channel, typically over 150 m deep, is the main connection to Alberni Inlet. Alberni is the largest inlet in the fjord, 37 km long

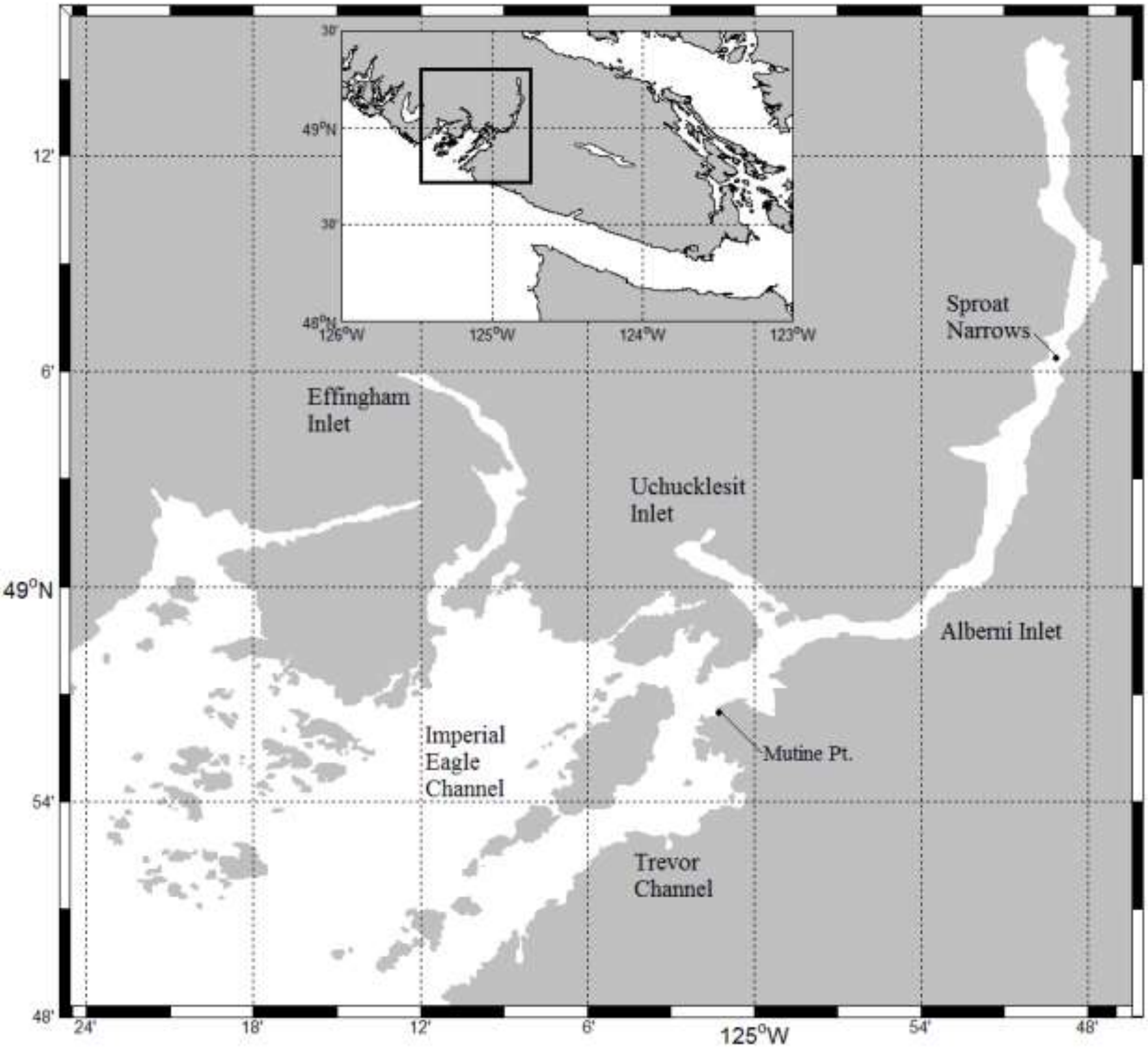

Figure 1. Map showing the location of Barkley Sound and places in the fjord referenced in this paper.

and typically 1000 m wide. Depths vary from about 300 m in the inlets central region to approximately 40 m at sills located in Stamp and Sproat Narrows (Stronach et al. 1993). Effingham and Uchucklesit are two other larger inlets located in the fjord. Effingham Inlet connects to Barkley Sound at the northwestern corner of Imperial Eagle Channel. The narrow inlet, 17 km long with an average width of 1 km, is characterized by the presence of two suboxic to anoxic basins (Patterson et al. 2000). An inner sill with a depth of 40 m separates the inner and outer basins, with depths of 125 m and 205 m. Accompanying anoxic conditions in the upper basin is the presence of methane producing and consuming bactria (Turner 2013). Uchucklesit Inlet is a small understudied branch of Alberni Inlet with a 50 m entrance sill and average depth of 60 m.

The largest freshwater source flowing into the fjord is the Somass River, which enters at the head of Alberni Inlet. This river accounts for 50% of the freshwater input, and additional rivers mostly feeding into the three major inlets supply the rest (Stonach et al. 1993). Three principal layers make up the oceanographic structure of Alberni Inlet. The upper zone is mixed fresh and seawater, and becomes increasingly more saline from the head of inlets to the mouth. Below the upper layer is a middle zone (~3 to 9 m) whose salinity is does not vary much along the length of the inlet. Lastly, below the middle layer is a very dense deep zone that is not easily renewed (Tully 1948).

Studying the physical oceanography of fjords is important for and fisheries and oxygen renewal (Stronach et al. 1993). The physical properties of seawater have been found to influence in the distribution of zooplankton in Barkley Sound (Hamlin 2013). These smaller organisms are food for commercial fish species that live nearby, or in the fjord. Physical properties of the water column can also regulate vertical mixing (Inall and Gillibrand 2010), which is necessary for renewal events to occur. Past variations in global climate have been hypothesized to effect bottom-water renewal in areas such as Effingham Inlet (Dallimore et al. 2005, Hay et al. 2009). Climate model forecasts by Pike et al. (2009), predicting decreased summer precipitation in coastal British Columbia (B.C.), could also affect renewals by decreasing estuarine circulation.

The upper layer in Alberni Inlet is believed to be very thin (< 3 m), and is observable in conductivity, temperature, and depth (CTD) profiles from the head of the inlet to the top of Trevor Channel (Tully 1948, Stronach et al. 1993). Inclinations to the favored flow path this surface layer takes to the ocean have been made (Linden 2010). When salinity induced stratification has been detected in CTD data in Puget Sound, pycnoclines are deeper (4 to 6 m) (Moore et al. 2008). However, resolving rapid gradients in very shallow surface layers can be difficult without a properly configured CTD (Stronach et al. 1993).

Turbulent mixing across the stratification is generally suppressed when the Richardson number (Ri) is large (Turner 1973). However, velocity shear is likely to overcome the tendency of a stratified fluid to remain stratified when Ri < 0.25 (Thorpe 2005). Lagrangian floats equipped with Global Positioning System receivers (GPS) may be better at identifying shallower layers in fjords since they can estimate the above parameters. Surface and subsurface floats will be used to study the upper surface layer in Barkley Sound. The water column of this fjord has a fresh shallow stable layer present on its surface. This layer is shown by observed stable shear flow between the surface and near surface waters.

METHODS

16 trajectories and 13 CTD casts were collected during a cruise on *R/V* Thomas G. Thompson from 27 January 2013 to 2 February 2013 to test for the layer. Four trajectories were taken in Trevor Channel, Alberni Inlet, Uchucklesit Inlet, and Effingham Inlet (Figure 2). CTD casts were taken in Trevor Channel (3), Imperial Eagle Channel (1), and Alberni Inlet (9). The trajectories were used to calculate vertical shear between surface flows, and flows just below the pycnocline. This calculation gives indication of differential horizontal movement of water. CTD casts and the ship's underway monitoring systems (UWD) were used to determine the water column salinity profile in the upper 5 m.

Two Davis drifters measured the velocity of the surface layer and two Holey Sock drifters were used to track the water movement below the pycnocline. Garmin Astro 220® with DC-30® dog collars were used on surface floats to record latitude and longitude positions every 30 s. The Holey Socks were outfitted with Garmin eTrex10® units to record their latitude and longitude position every 40 s. All CTD measurements were made with a SeaBird 911 plus. All drifters deployed were made in accordance with the standards of the World Ocean Circulation Experiment (WOCE). To participate in this experiment all drifters must be current to wind driven at a ratio of 40 to 1. Using this standard in the experiment will ensure that ocean currents would mostly influence drifter movement. The depth of the Holey Sock drifters was set to 10 m to make certain they were below the pycnocline. Connecting the submerged portion to a surface float with 5 m tether accomplished this. The added line made the overall drifter length 15 m, and positioned the center of the sock at 10 m. A CTD cast verified the pycnoline depth before these floats were deployed.

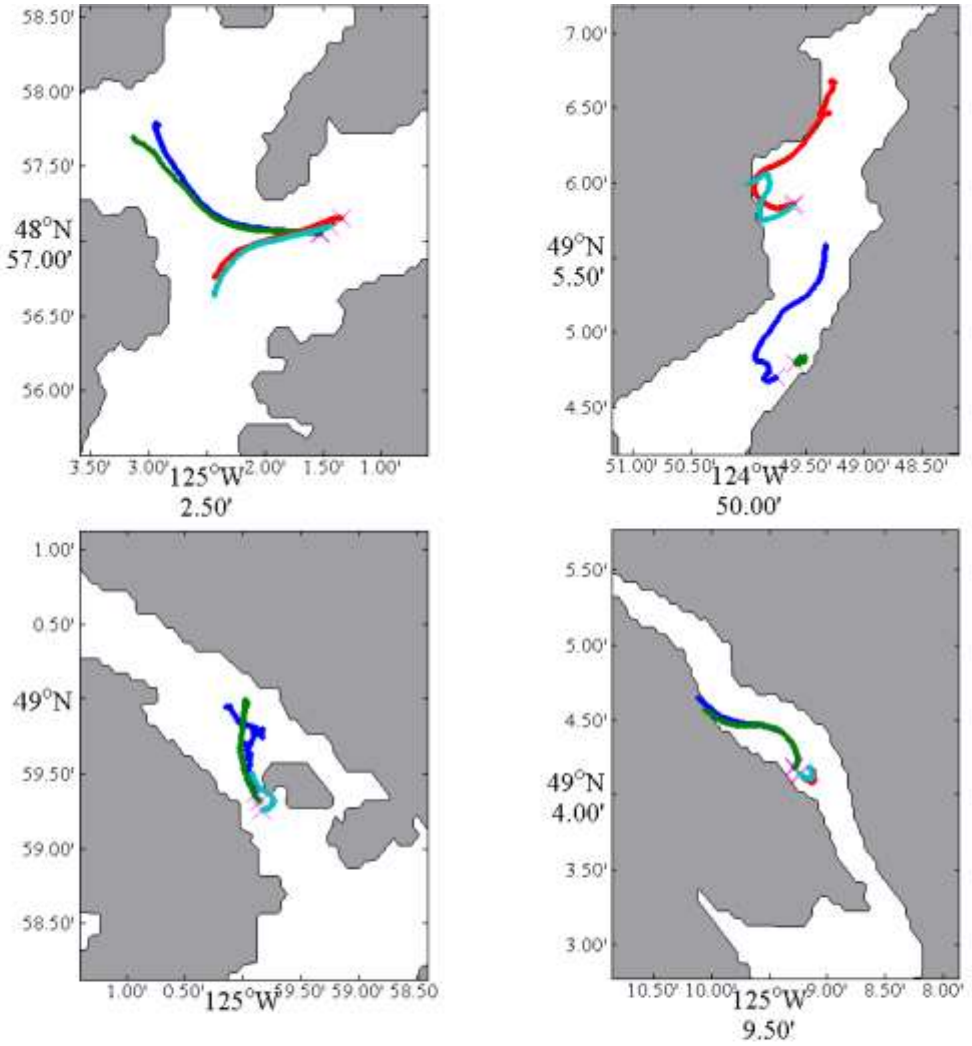

Figure 2. 16 drifter trajectories taken in Barkley Sound from 27 January 2013 to 2 February 2013. Trevor Channel (top left), Alberni Inlet (top right), Uchucklesit Inlet (bottom left), and Effingham Inlet (bottom right). Surface drifter one (blue), Surface drifter two (green), Subsurface drifter three (cyan), Subsurface drifter four (red).

Only 13 of the 16 trajectories were used during data analysis. During the drifter deployment in Alberni Inlet two units failed to record pertinent shear approximating data. Drifter two appeared to be trapped in an eddy current during the entire deployment, and drifter three beached itself soon after release. Drifters three and four lost satellite signal during the Uchucklesit deployment from what is believed to be interference from aluminum foil. The signal to drifter four lost was completely lost for the entire deployment, but drifter three regained signal. Complications occurred during the deployment of drifter three, which resulted in the submergence of the mast. A small boat was dispatched to properly right the float, and the foil was removed to check GPS functionality. This is believed to have restored the signal for the rest of the deployment. The foil had been installed because the ship operators requested all drifters have something reflective placed in their masts to increase radar visibility. This was important because of the heavy fog in the inlet. The surface drifters were unaffected by the foil. Salinity of the upper water 2 m of the water column was not well represented in the CTD data. Steep surface salinity gradients, layer disturbance from casting, and reluctance of the marine technicians operate the CTD pumps near the surface (floating contaminants can damage the instruments) are believed to be reasons for the lack of data in the upper 2 m.

This analysis ignores the horizontal dispersion of the floats when calculating vertical shear. This assumption is sound since the horizontal distance between floats is small compared to the horizontal scale of variation in Barkley Sound. Vertical shear was calculated using equation (1). Velocity was computed as the time derivative of horizontal float displacement. The stability or strength of the pycnocline is described by the buoyancy frequency (Turner 1973), and was calculated using equation (2). The bulk Richardson number (Ri), which represents buoyant suppression of turbulence to shear generation of turbulence (AMS glossary), was found using equation 3.

$$(1)\ \text{Vertical Shear} = \sqrt{\left(\frac{\Delta\bar{u}}{\Delta z}\right)^2 + \left(\frac{\Delta\bar{v}}{\Delta z}\right)^2}$$

$$(2)\ N^2 = -\frac{g}{\rho}\frac{d\rho}{dz}$$

$$(3)\ Ri = \frac{N^2}{\left(\sqrt{\left(\frac{\Delta\bar{u}}{\Delta z}\right)^2 + \left(\frac{\Delta\bar{v}}{\Delta z}\right)^2}\right)^2}$$

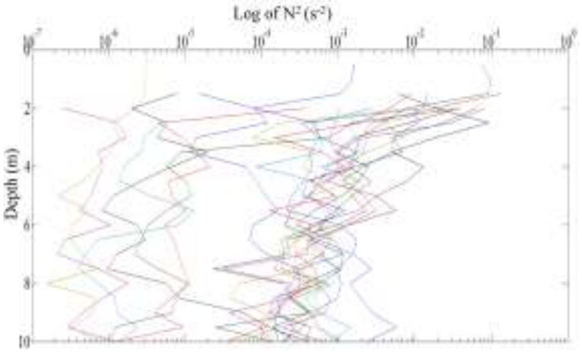

Figure 3. The value of N^2 in the upper 10 m of the water column at the 13 CTD stations.

RESULTS

The Brunt–Väisälä (N^2) frequency for Barkley Sound was used to estimate stability. N^2 changed most rapidly between 2 and 3 m of depth at most sample stations (Figure 3). Precise values of N^2 could not be determined since the CTD failed to reliably capture the top 2 m of the water column. For this reason, estimates of the Ri were made assuming the area $\langle N^2 \rangle$ value is 0.1 s^{-2}. This estimate could be lower than actual values, but using it is believed to adequate for making stability estimates in very stratified waters.

Trevor Channel

The four drifters in Trevor Channel were deployed on 27 Jan 2013 for approximately 6 hrs (Figure 4). Velocities measured by an individual float in this area were found to similar to its pair. Both surface drifters reached a maximum u velocity of -0.1 ms^{-1} at time 0.78 days (~1800 UTC) and slowed to ~0 ms^{-1} by the end of the run. Starting at u velocity of 0 ms^{-1}, both drogues accelerated to -0.05 ms^{-1} by time 0.87 days, and slowed to ~0 ms^{-1} by the end. The surface floats reached a maximum v velocity of 0.16 ms^{-1} in at time 0.87 days, with each starting and ending at ~0 ms^{-1}. The subsurface floats begin with v velocities of 0 ms^{-1} and slowly accelerated to -0.1 ms^{-1} at recovery time. The average vertical shear during this deployment was estimated to be 0.01 s^{-1} (Figure 5). The average Ri at the site was calculated to be 1000. The highest recorded vertical shear at this location occurred at time 0.87 days, and was estimated to be 0.02 s^{-1}. The instantaneous Ri measured at this time was 250.

Alberni Inlet

The four drifters in Alberni Inlet were deployed on 28 Jan 2013 for approximately 6 hrs (Figure 4). The subsurface floats were deployed earlier than the surface, but at 0.67 days all floats were in the water. At about time 0.87 days the highest positive u and v velocities for float one occurred, and the measurements were 0.12 ms^{-1} and 0.25 ms^{-1}. These were similar in magnitude to the maximum u and v velocities of 0.1 ms^{-1} and 0.3 ms^{-1} that float four measured. However, this occurred much earlier in the deployment at time 0.77 days. The average vertical shear during this deployment was estimated to be 0.01 s^{-1} (Figure 5). The average Ri at the site is calculated to be 1000. The largest vertical shear recorded was 0.029 s^{-1}, and it occurred at time 0.77 days. The Ri at this time was found to be 111.

Uchucklesit Inlet

The four drifters in Uchucklesit Inlet were deployed on 30 Jan 2013 for approximately 6 hrs (Figure 4). Vertical shear was dominated

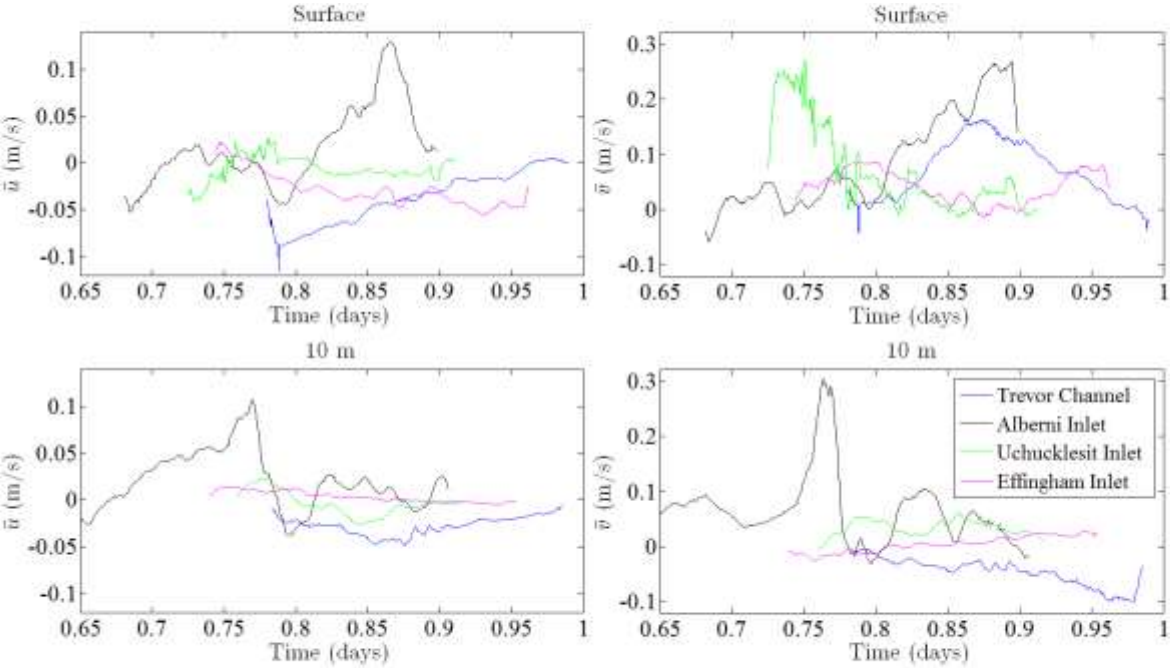

Figure 4. The average u and v velocities in the surface and subsurface (10m) waters at the sample locations. 0.65 days corresponds to 1536 UTC and time 1 days corresponds to 0000 UTC.

by the v velocity components during the first 0.5 hrs of the deployment, then transitioned to the u components after time 0.8 days. During the v dominated period the largest vertical shear occurred at time 0.77 days, and was estimated to be 0.016 s^{-1}. The highest vertical shear during the u domination was 0.0078 s^{-1}, and occurred at time 0.86 days. The average vertical shear during this deployment was estimated to be 0.005 s^{-1} (Figure 5). The average Ri at the site was calculated to be 4000. The v dominated period produced the largest overall vertical shear during the deployment. The Ri for this shear value was calculated to be 391.

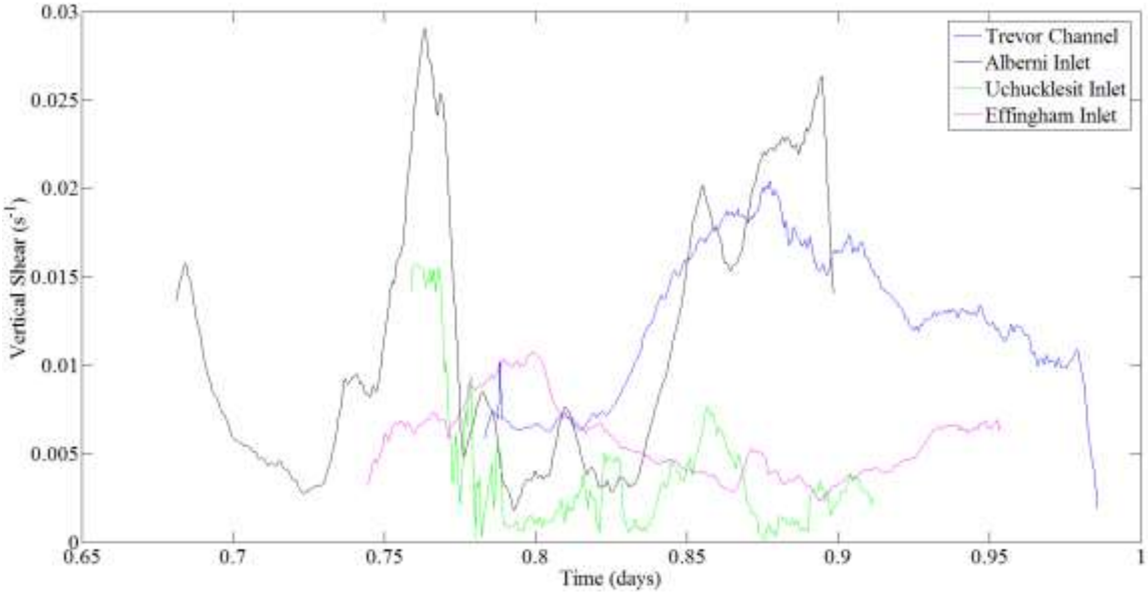

Figure 5. Vertical shears calculated at the sample locations. 0.65 days corresponds to 1536 UTC and time 1 days corresponds to 0000 UTC.

Effingham Inlet

Drifters in Effingham Inlet were deployed on 31 Jan 2013 for approximately 6 hrs (Figure 4). Velocities measured by an individual float in this area were found to similar to its pair. At time 0.75 days both surface drifters had u velocity of 0.02 ms^{-1}. After this time, both u velocities slowed and changed directions, increasing to about -0.05 ms^{-1} by recovery time. The u velocities of both drogues were slightly positive (~0.01 ms^{-1}) for the first 1.5 hrs of deployment, but remained about 0 ms^{-1} after. The v velocity component appeared to strongly influence vertical shear during this deployment. The largest v velocity differences between surface and subsurface drifters were 0.1 ms^{-1} at time 0.80 days, and 0.06 ms^{-1} at time 0.93 days. Corresponding to these times were the two largest values of vertical shear, 0.011 s^{-1} and 0.007 s^{-1} (Figure 5). The average vertical shear during this deployment was estimated to be 0.005 s^{-1}. The average Ri at the site was calculated to be 4000. The vertical shear at time 0.80 days was the highest measured, and the corresponding Ri was estimated to be 826.

Surface Salinity

The salinity at 1, 2, 3, and 5 meters was analyzed so comparisons between areas could be made (Figure 6). Salinity in Alberni Inlet at 2 m is freshest near Sproat Narrows and increased by 3.5 psu to its entrance. The salinity sampled in the middle of Trevor Channel was 2 psu higher than in upper Imperial Eagle Channel. The lowest salinity at 3 m was observed the water just south of Sproat Narrows. Salinity was approximately 29 to 30 psu at all the other locations sampled at this depth. The salinity sampled at 5 m of depth was not consistent throughout Alberni Inlet. In this area, salinity varied from 26 to 31 psu from south of Sproat Narrows to the inlet entrance. The salinity at this depth in Junction Passage was approximately the same as it was in Trevor Channel.

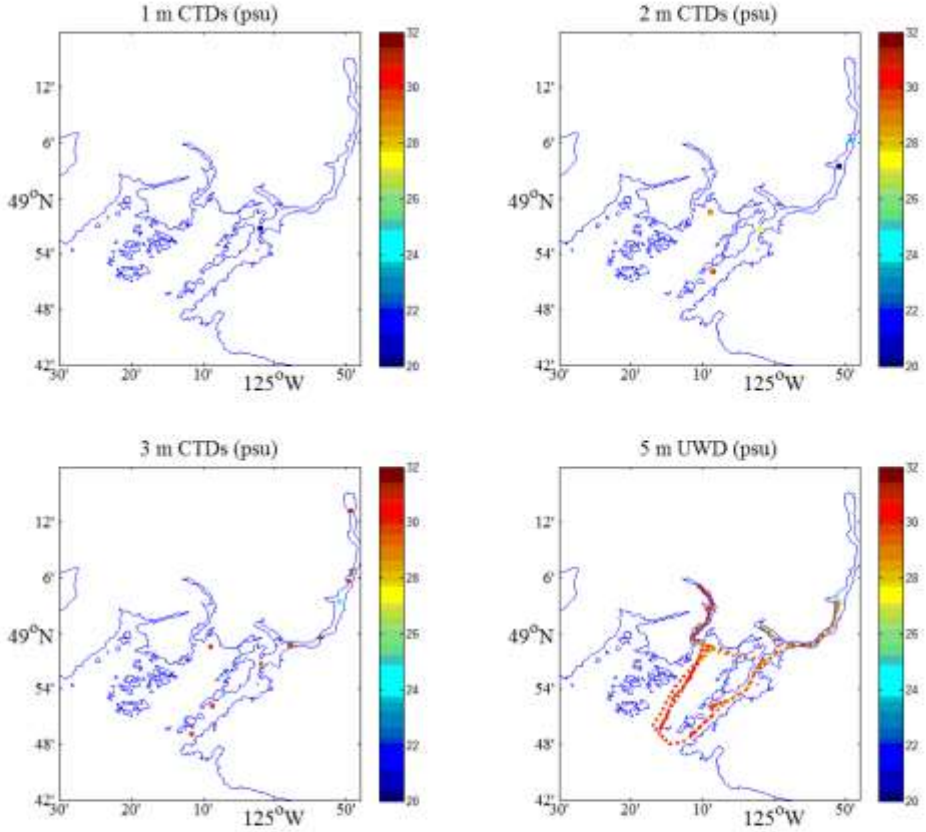

Figure 6. Salinity from CTD and underway monitoring data (UWD) recorded at 1 m, 2 m, 3 m, and 5 m.

DISCUSSION

Evidence for a stable shallow surface layer

There is evidence of a shallow fresher surface layer in Barkley Sound. The rapid decrease in the N^2 between 2 and 3 meters at most CTD stations indicates a very shallow pycnocline. Density gradients have been known to be boundaries between layers in the ocean and fjords (Thorpe 2005). A layer of brackish water is observable in the upper 3 m of the water column in CTD data. This finding is consistent with observations of others that have studied the upper water column in this area. CTD data taken by the Institute of Ocean Science in May 1988 showed a brackish layer above 2.5 m from the top of Alberni Inlet to Mutine Point (Stronach et al. 1993). During March 2010, a thin freshwater layer was present at 2 m in salinity transects from Alberni Inlet to Trevor Channel and Effingham Inlet to Imperial Eagle Channel (Linden 2010).

In addition, there is a noticeable transition to more uniform and higher salinity water at 5 m in all areas sampled. Tidal inflows and outflows are believed to be restricted to the middle layer in this fjord, beginning below 3 m in Alberni Inlet (Tully 1948). With the tide presumably entering below this depth, the subsurface floats would be directly acted on be this forcing. The vertical shear observed between the surface and subsurface at all the deployment sites is likely the result of this.

The average Ri being considerably greater than 0.25 in all deployments areas is strong evidence for the long term presence of fresh surface layer. Shallow finger inlets and areas influenced by large freshwater inflows often have strong vertical stratification (Moore et al. 2008). These types of topography were dominant features in every location where deployments took place. Stratification, primarily driven by vertical salinity gradients in Puget Sound, is strong in south Hood Canal (Moore et al. 2008). Hood Canal is similar to the deployment sites since most are long and narrow channels, with freshwater inputs. Previous research conducted in Hood Canal found it to be continuously stratified during the year, with typical N values of 0.09 s^{-1} (Moore et al. 2008). The typical value of N in Barkley Sound was found to be three times as large, and the average and minimum Ri values indicate vertical shear does not produce enough turbulence to overcome stratification.

Topographic influences on surface layer stability

The lowest Ri observed during a deployment in which all four floats were functioning properly was in upper Trevor Channel. This value was 70% less than the lowest value measured in upper Effingham Inlet, the other area where all floats functioned properly. One reason for this large difference is closer proximity of Trevor Channel to the open ocean. The brackish surface layer is not discernible in salinity profiles below Mutine Point (Tully 1948, Stronach et al. 1993, Linden 2010). Below this geographic location, the mixed layer deepens and turbulence generated by surface waves is large enough begin overcoming stratification.

Another possibility is the freshwater leaving Alberni Inlet may preferentially exit Barkley Sound via Imperial Eagle Channel. The vertical shear observed in Trevor Channel during an ebb tide suggests this. During this deployment, surface drifters moved toward Junction Passage while the subsurface floats drifted into Trevor Channel. Freshwater exit preference has been previously suggested from analysis of surface salinity trends. The transition to higher more uniform salinity was pronounced at Alberni Inlet-Trevor Channel transition when compared to the Alberni Inlet-Imperial Eagle Channel transition, which was more brackish (Linden 2010). However, these trends could not be verified in this study due to lack of surface salinity data in Junction Passage and the Alberni Inlet-Trevor Channel transition.

Shallow bathymetry has been observed to affect vertical shear in Barkley Sound. Stratification in Puget Sound, a nearby fjord, is significantly influenced by mixing over sills (Moore et al. 2008). The vertical shear profiles of Uchucklesit Inlet, and Alberni Inlet were found to be very similar. This is likely do to the short proximity between to the areas. All drifters deployed in Alberni Inlet were close to the shallow sill at Sproat Narrows. Shears from water accelerating through the sill is the likely the cause of lower Ri values. The constant eddying of one of surface drifters is possible visual evidence supporting this belief. The drifters deployed in Uchucklesit were also near the inlet's entrance sill. However, the Ri estimates for this area were four times as large as those in Sprout Narrows. The sill at Sproat Narrows being 10 m shallower could be the reason for differences in stability.

Implications of a shallow fresh surface layer

Precipitation changes anticipated from climate change could alter the distribution of the upper surface layer. Climate models have predicted rainfall in coastal B.C. will decrease 13% during summer by mid-century (Pike et al. 2009). Since rivers are not fed by glaciers in Barkley Sound, freshwater discharge rates will likely track precipitation changes. Tidal intrusions into Alberni Harbor are controlled by river discharge rate. River inflow changes alter the isotactic balance between freshwater and the intruding tide, shifting the seaward boundary location (Tully 1948). Boundary shifts could alter the distribution of zooplankton observed in Alberni Inlet and Trevor Channel, which are influenced by salinity (Hamlin 2013).

The stable surface layer could be impeding oxygen renewal in this fjord since the surface and subsurface layers are not mixing. The outflow from a fjord is not entirely fresh, but includes some saltier water mixed up from deeper depths. In order to conserve the volume of water in a fjord (during an entire tidal cycle), saline water must be drawn in to replace what was mixed up (Inall and Gillibrand 2010). The extremely high Ri observed at the drifter deployment sites indicates weak mixing between the surface and deeper layers. Weak estuarine circulation coupled with weak tidal currents favor the development of suboxic–anoxic conditions at the bottom of the fjord (Patterson et al. 2000). Sections of Effingham Inlet are known to become anoxic over the course of a year. Upwelled offshore waters that have mixed with the bottom waters off the Vancouver Island Coastal Current, penetrates into Effingham Inlet in mid-to-late summer and reaches the innermost portions of the inlet by late fall (Hay et al. 2009). If this inflow is sufficiently dense relative to the deep waters in the basins, bottom water renewal will occur. Lower summer precipitation as result of climate change could decrease the freshwater supply to the surface layer, reducing its stability. One of the principal environmental conditions suggested to facilitate bottom water renewal in fjords along the west coast of Vancouver Island is an increased stability of the upper water column (Dallimore et al. 2005). Reduced estuarine circulation could result from this, and renewal to Effingham inlet could become even more infrequent. This could adjust the present steady-state between methane producing and consuming bactria observed in upper Effingham Inlet (Turner 2013). In addition, hypoxic and anoxic conditions may manifest in others areas of the fjord where they currently do not occur.

CONCLUSIONS

There is a nearly undetectable thin fresh layer at the surface of Barkley Sound, particularly in the inlets surrounded by land. This layer is stable to turbulence generated by shear flow evidenced by large Richardson numbers. Surface contaminants are likely to flow out to sea with the fresh layer without mixing into deeper waters. This thin layer provides a stable pycnocline that helps plankton remain in the photic zone

ACKNOWLEDGEMENTS

I thank the crew of the *R/V* Thomas G. Thompson and Weelander for helping me collect my data. Bravo Zulu to Byron Kilbourne and Richard Keil for their wisdom and advice that greatly aided me in finishing this project.

REFERENCES

Dallimore, A., R. E. Thomson and M. A. Bertram. 2005. Modern to late Holocene deposition in an anoxic fjord on the west coast of Canada: implications for regional oceanography,climate and paleoseismic history. Mar.Geol. **219**: 47-69.

Hamlin, N. M. 2013. Comparison distribution, abundance, and diversity of zooplankton in Trevor Channel and Alberni Inlet, Barkley Sound, Vancouver Island, Canada.

Hay, M. B., S. E. Calvert, R. Pienitz, A. Dallimore, R. E. Thomson and T. R. Baumgartner. 2009. Geochemical and diatom signatures of bottom water renewal events in Effingham Inlet, British Columbia (Canada). Mar. Geol. **262**: 50-61.

Inall, M. and P. Gillibrand. 2010. The physics of mid-latitude fjords: a review. **344**: 17-33.

Linder, R. J. 2010. Estuarine circulation in Barkley Sound; observed characteristics and processes. http://hdl.handle.net/1773/16196.

Moore, S. K., N. J. Mantua, J. A. Newton, M. Kawase, M. J. Warner and J. P. Kellogg. 2008. A descriptive analysis of temporal and spatial patterns of variability in Puget Sound oceanographic properties. Estuar. Coast. Shelf Sci. **80**: 545-554.

Patterson, R. T., J. Guilbault and R. E. Thomson. 2000. Oxygen level control on foraminiferal distribution in Effingham Inlet, Vancouver Island, British Columbia, Canada. **30**: 321-335.

Pike, R., K. Bennett, T. Redding, A. Werner, D. Spittlehouse, D. Moore, T. Murdock, J. Beckers, B. Smerdon and K. Bladon. 2010. Climate Change Effects on Watershed Processes in British Columbia, Chapter 19. **66**: 699-747.

Stronach, J., M. Ng, M. Foreman and T. Murty. 1993. Tides and currents in Barkley sound and Alberni Inlet. Mar. Geod. **16**: 1-41.

Thorpe, S. A. 2005. The turbulent ocean. Cambridge University Press.

Tully, J. P. 1948. Oceanography of Alberni Inlet and prediction of pulp mill pollution in Alberni Inlet. Ph.D. thesis. Univ. of Washington.

Turner, C. L. 2013. The fate of biologically produced methane in an anoxic fjord in British Columbia.

Turner, J. 1973. Buoyancy effects in fluids. University Press, Cambridge, UK.