A Lagrangian study of the surface circulation of a fjordic system: the effects of preceding weather conditions and local geomorphology.

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Non-Technical Summary

A combination of drifters, based on classical designs with modern twists, was used to observe the patterns of surface and near surface water circulation in Effingham Inlet, a Canadian fjord, during late March 2010. The drifters were based on a design that has been used by oceanographers for over 130 years, but utilize the modern Global Positioning System (GPS) to record their location. They also utilized a device capable of transmitting its location to a hand held unit to make recovery simple, and prevent loss of data. Patterns in circulation were observed at 1 m deep for the surface water, and at 5 m deep for the near surface water motions. Pairs consisting of one surface and one near surface drifter were deployed at sites with different local sea floor features to discover how these differences affect the circulation. The preceding weather data was collected from a weather station 25 km to the south west of the Inlet, at the Bamfield Marine Science Centre. The results show that when river flows are low, the circulation is controlled by the preceding wind conditions. The local channel depth and shape also influences the circulation patterns, acting like a funnel to increase circulation speeds in more confined areas.

Acknowledgements

Thanks goes to Miles Logsdon for providing the drifters, time and much helpful advice throughout this investigation. Thanks also to the University of Washington Oceanography, and the 444 Team, for all their help throughout this project and over the whole year. A mention should also go to the crew of the RV Barkley Star for making sure no drifter was left behind, even when trapped behind the lines of an oyster farm. Appreciation also goes to the staff of Bamfield Marine Sciences Centre, for being welcoming and providing hosts, even at such short notice.

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Abstract

Variation in the surface and near surface circulation patterns of Effingham Inlet, a fjord on the west coast of Vancouver Island, Canada, were measured using Lagrangian drifters over two days during the early spring of 2010. The track data was compared to weather data collected from a local weather station. Drifter deployment sites were north and south of a known sill to assess the influence this bathymetric feature exerts on surface circulation. The drifters were based on designs similar the Davis Drifters and the Surface Velocity Program Holey Sock drogue. These drifters were equipped with tracking GPS recorders, enabling the drifters' velocities to be calculated. Results are in agreement with previous studies that have found surface motions to be forced by the wind when fresh water terrestrial inputs were low. The deeper circulation patterns showed a slower tidal forcing. The local geomorphology also influenced the circulation. The tracks north of the sill in a shallow channel showed reduced complexity as the water was confined by the local bathymetry. The confined channel also had speeds recorded by the surface drifter of 0.6 m/s, more than twice that of the speed in a wide basin. This demonstrated the funneling effect of the local geomorphology on the water movements.

Introduction

The surface and near surface water circulation patterns of fjords are the result of a host of processes that link the terrestrial stream flow, surface winds, ocean tides and antecedent geological formation of the local bathymetry. The classic depiction of circulation within fjords is a two layer system consisting of a fresher, less dense, surface layer moving seaward over a deeper more saline layer (Hodgins, 1978, Stiegebrandt, 1980). This circulation varies from traditional estuaries as fjords are deeper due the glacial processes that carved the channels (Syvitski and Shaw, 1995). It has been shown by previous studies that the surface currents can be controlled by prevailing winds acting over the water for periods of 10 hours, if the fresh water input is low (Gade, 1963, Johannessen, 1968 and Svendsen and Thompson, 1978). Studies focusing on the deeper currents find that the circulation is generally the result of the tide (Farmer and Osborn, 1976, Hodgins, 1978).

Fjords also have bathymetric features that lead to further variation in circulation. Sills are formed by the deposition of glacial sediment (Bennett 2001). Sills have been shown to influence deep circulation by limiting the flushing of deep water on their landward side (Cannon 1975, Leonov and Kawase 2009). This study further investigates the contribution to variation in the circulation patterns by the preceding weather conditions and local geomorphology.

Lagrangian measurements from drifters were used to observe differences between the motions of the surface and near surface water. The preceding weather conditions were recorded at a weather station at Bamfield Marine Science Centre, 25 km to the southeast of study Inlet. Terrestrial fresh water inputs are from small rivers entering from the side of the channel, so precipitation acts as a good indicator of fresh water input. Deployment sites were north and south of a known sill in Effingham Inlet on the west coast of Vancouver Island, Canada (Figure 1).

Effingham Inlet connects to Barkley Sound, and then the northeast Pacific, on the west Coast of Vancouver Island, Canada. A number of sills divide this 17 km long fjord into three basins. The upper basin has been the focus of several studies, because it is regularly anoxic. This study reports on observations made on variations in surface circulation that occurs between the two upper most basins of the inlet. This is where a sill 45 m deep separates a 200 meter deep basin from a channel 100 meters deep.

There is a long history in using drifters to observe currents; the Challenger Expedition first used drifters to monitor ocean circulation over 130 years ago (Thompson, 1877). Historically drifters' positions were found by radio direction finding triangulation giving sparse data points (Davis, 1985). The use of GPS means that the location of the drifter can be determined at shorter time intervals. Improvements have been made to these initial designs, with the availability of affordable ways to log drifter position, through Global Positioning System (GPS). These modifications in design allow more accurate measurements to be made in recording spatial and temporal information, which characterize the individual tracks.

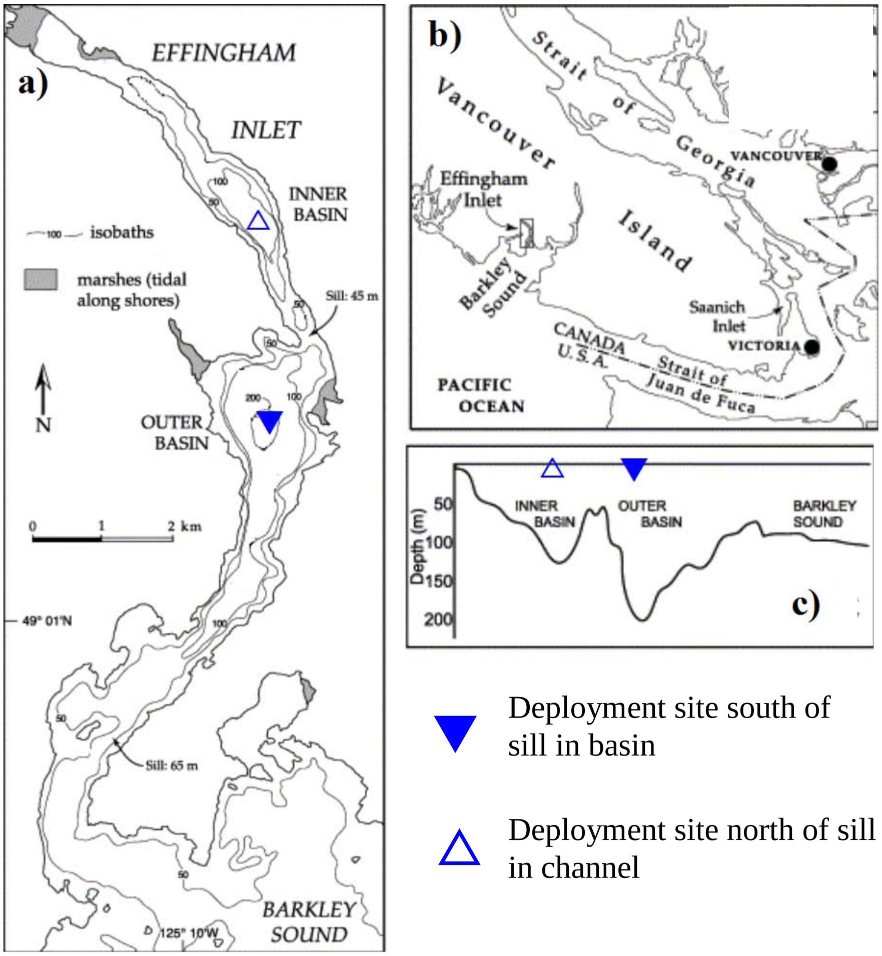

Figure 1. Location of Effingham Inlet, British Columbia Canada. Triangles depicting the drifter deployment locations. a) Effingham Inlet, with depth contours note the 45 m sill between the lower and upper basin, after Kumar and Patterson (2002). b) Geographic location of Effingham Inlet on Vancouver Island, after Kumar and Patterson (2002). c) Bathymetric Profile, showing the sill that separates the deployment sites, after Hay et al (2003).

Methods

Drifter Design

Two different drifter designs were used to record variation in the surface and near surface circulation patterns in Effingham Inlet. The circulation of the surface 1 m of water was recorded

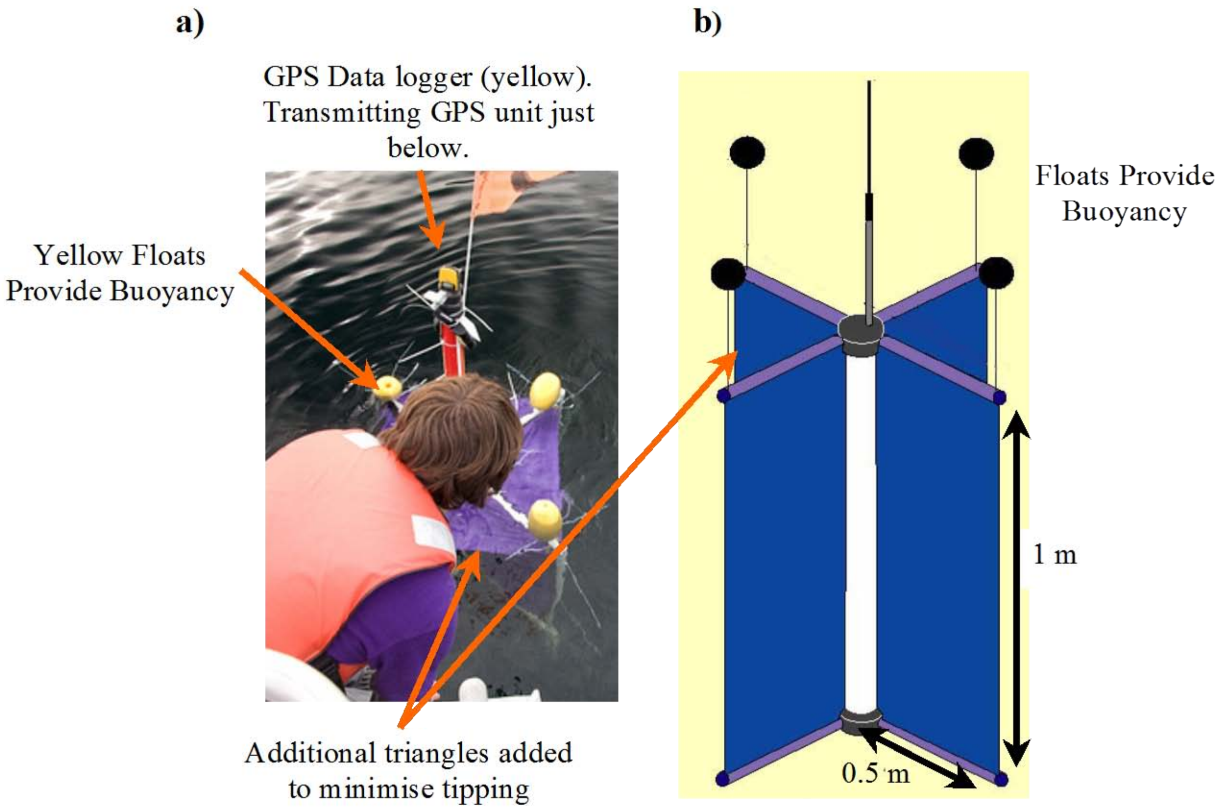

Figure 2. Surface Drifter. a) Deployment of Surface Drifter in Effingham Inlet, photograph credit to Kathy Newell. b) Schematic of a Davis Drifter, from NOAA (2006)

using a modified Davis style drifter (Figure 2). This drifter design was first proposed by Davis (1983, 1985) and was used by the US Coastal Dynamics Experiment (CODE). The design has been widely used and forms the basis for many drifter designs (Austin and Atkinson, 2004). The original design allows the drifter to follow the surface movements, without picking up movement due to wind and waves. The version used in this experiment consisted of a PVC frame; with fabric sails arranged in a cross, with buoyancy provided by four floats, one on the end of each arm. The main modification from previous designs to the frame was the inclusion of triangular sections of fabric between the top arms, to prevent the drifter from tipping.

Technological advances such as GPS have improved the ability of drifters to record more detailed information about their tracks. The surface drifter utilized two different GPS units, one to log location and the second to aid in recovery. The position data was logged by the GARMIN eTrex® H, this sensitive unit is accurate to less than 10 m (root mean square) and waterproof. The position was logged every 30 seconds, which was then downloaded using the MapSource software after drifter recovery. The second GPS system was a GARMIN Astro®, this consists of two GPS units, which can communicate their locations relative to each other using radio waves within a 8 km radius, line of sight. Obtaining the range and bearing to the drifter was instrumental in securing a fast drifter recovery, minimizing lost data.

The second type of drifter used to track water at 5 meters below the surface was a modified “Holey Sock” design (Figure 3). These types of drifters have been used in many experiments, not limited to the Surface Velocity Program (SVP) and World Ocean Circulation Experiment (Lumpkin and Pazos, 2007). The basic design is a small floating cylindrical surface unit, which houses the GPS unit and is small enough to not be significantly affected by the wind. This is tethered to a fabric tube 3 m below. The tube is 3 m long, 0.5 m in diameter, with holes with of diameter of 0.2 m, cut at regular intervals. The tube acts as a drogue and the holes act to catch the water and make sure the drogue follows the water. Work by Niller et al (1995) for the SVP calculated that in order not to be slipping through the water the drogue needs to have a drag area ratio greater than 40, and this arrangement, with a tunnel 3 m long and with a diameter of 0.5 m, has a drag area ratio of 39.7. This means it is acceptable to assume the drifter is following the water motion. This near surface drifter also used the GARMIN eTrex® H to log its position, however the transmitting GPS unit is not feasible on this design due to the smaller surface unit.

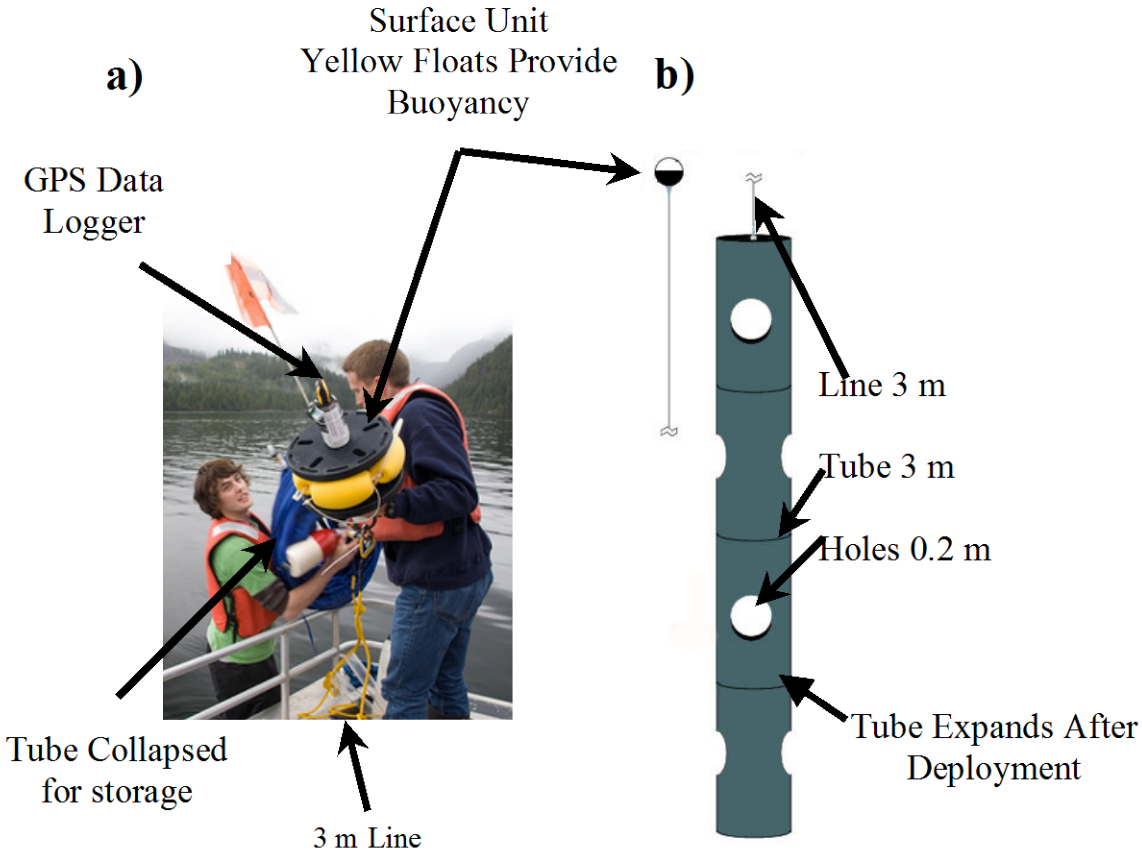

Figure 3. Near Surface Drogue. When deployed only the surface unit remains above water, and the tube extends to give the "Holey Sock". a) Labeled photograph of a drifter taken during deployment, photograph credit to Kathy Newell. Once in the water the tube sinks and extends. b) An annotated schematic of the drogue after Lumpkin and Pazos (2007).

Drifter Deployment Strategy

The investigation was carried out on the 20th and 21st of March 2010, in the Effingham Inlet. The R.V. Barkley Star from the Bamfield Marine Sciences Centre was the platform from which operations were mounted. Each day, at slightly different stages in the tidal cycle, two pairs of drifters were deployed either side of a sill 7 km from the mouth, where Effingham Inlet meets the Barkley Sound. Each pair consisted of one surface drifter and one near-surface drifter. The temporal scale for each deployment was between 4 and 6 hours.

Results

On the first day of this experiment all of the surface drifters and near surface drogues moved toward the north (Figure 4). The surface drifters traveled further than the near surface Holey Sock drogues. However the near surface drogue deployed south of the sill failed to deploy properly, failing to extend to its proper depth and as a result acted somewhat like a surface drifter.

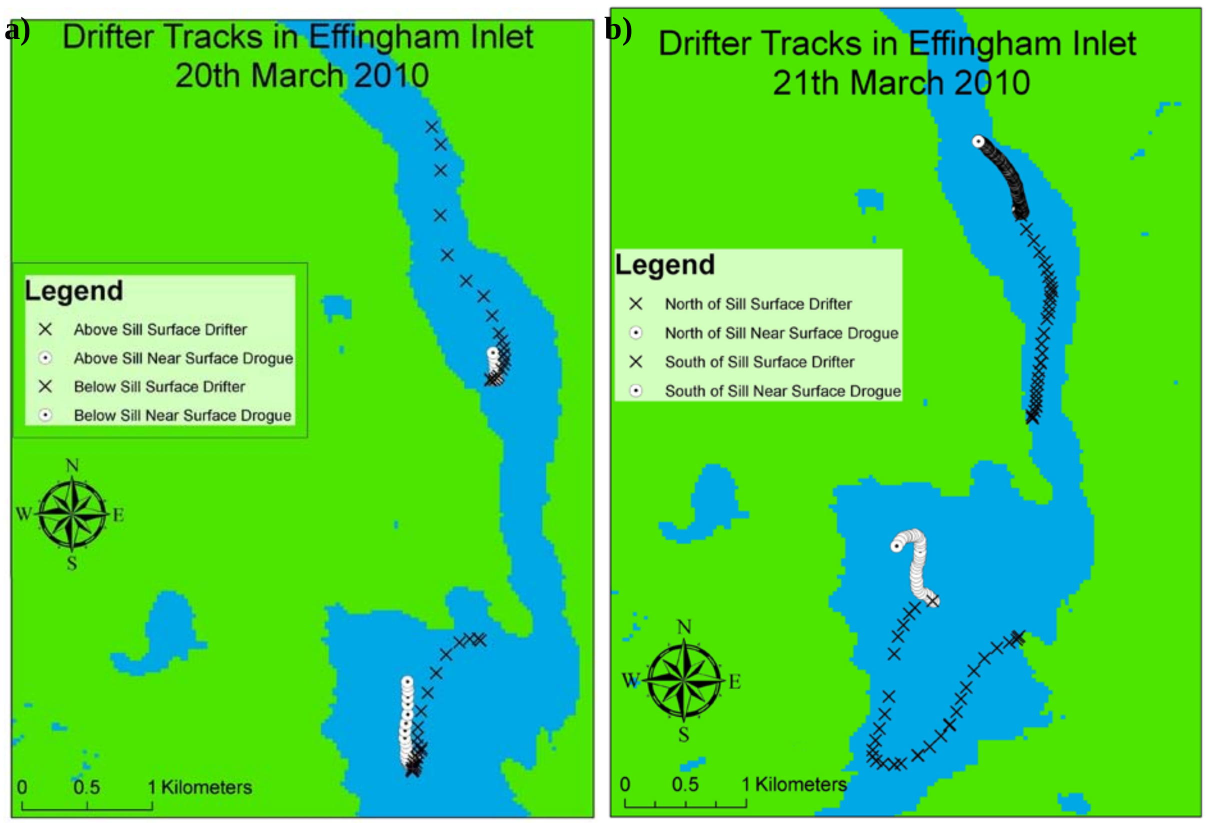

Figure 4. Map showing the paths taken by the surface drifters and near surface drogue, overlaid on an image of Effingham Inlet. a) Paths for the first deployment. b) Paths for the second deployment.

The fastest speeds were achieved by the surface drifter deployed north of the sill. This drifter reached maximum speeds of close 0.55 m/s, over twice as fast as the speeds recorded by the surface drifter deployed to the south of the sill. This maximum speed was reached in the afternoon after low speeds in the morning (figure 5a). The near surface drogue north of the sill traveled slowly for the first hour and half, with a slight increase in speed for the second half of the deployment (figure 5d). The variation in the speed around 0.03 m/s for this drogue is likely to be due to the drifter speed being close to the accuracy limit for the GPS.

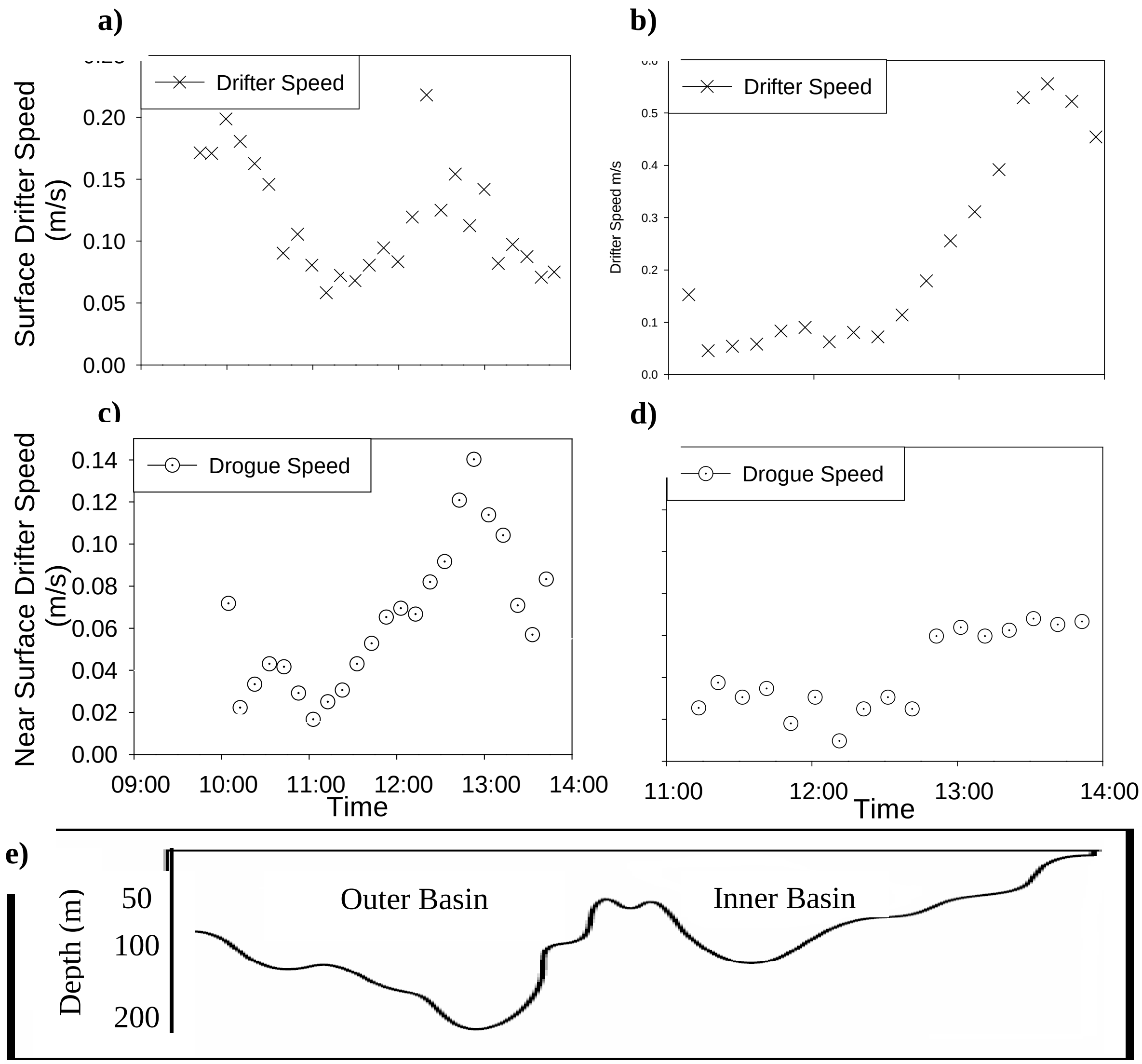

Figure 5 Drifter Speeds recorded on the 20 March 2010, speeds recorded very 30 seconds binned into 10 minute bins. The surface drifters displayed in the top line as crosses, representing their shape, and the deeper drogues shown as circles, representing the Holey Socks. a) Surface drifter speeds south of the sill in the outer basin. b) Surface drifter speeds north of the sill, in the inner basin note this moved much faster than other drifter.. c) 5 m drogue speed south of the sill, this drogue failed to sink. d) 5 m drogue speeds north the sill. e) Bathymetric profile, arranged to illustrate the differences between the deployment locations, after Hay et al (2003).

For the 3 days preceding the deployments, no precipitation was measured at the Bamfield weather station. In the nine hours before the first deployment the prevailing winds were low; less than 3 km/hour and consistently from southeast (Figure 6). During the first half of the deployment the winds remained low. In the afternoon the wind picked up to 10 km/hr and was consistently from the south. Low tide for Effingham was at 10:10 am (figure 7).

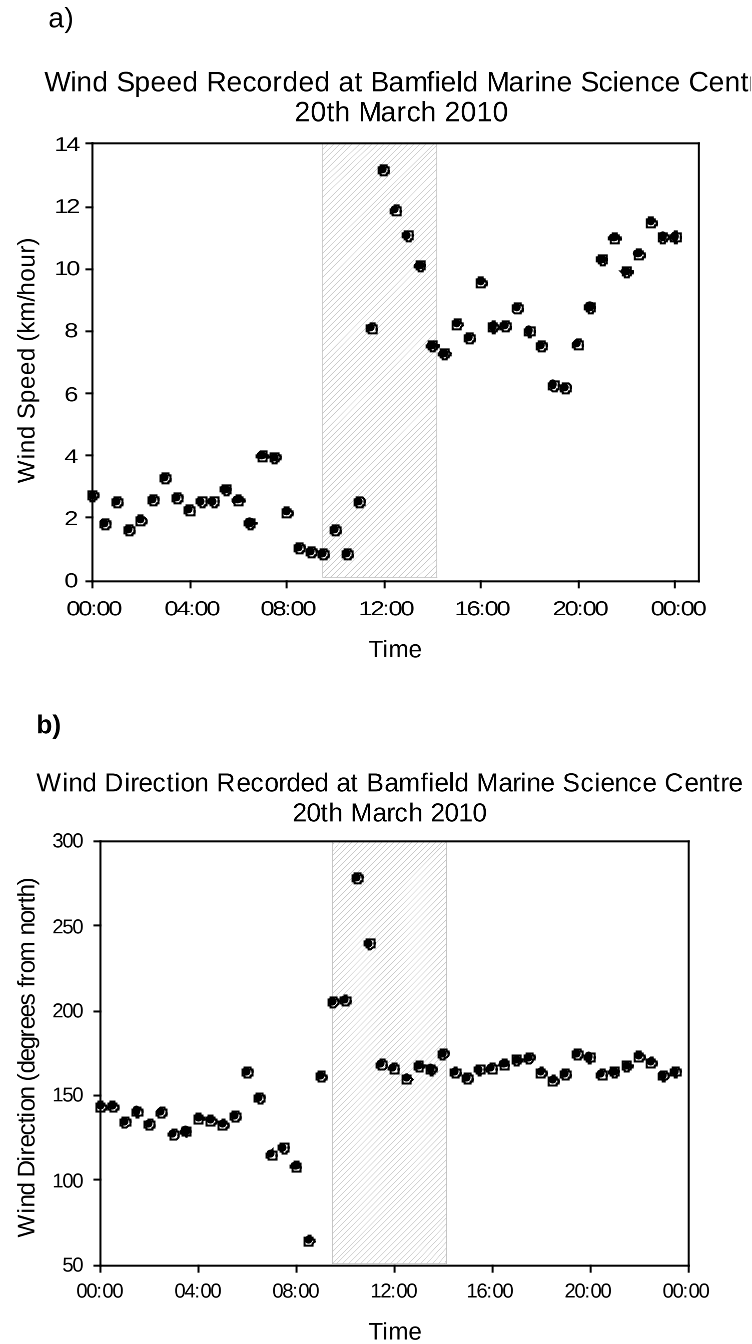

Figure 6. Wind data recorded by the Bamfield weather station on the 20th March 2010. Data recorded every minute binned into 30 min bins. a) Wind speed in km/hour. b) Wind Direction, shown in degrees from north. Grey shaded area indicates deployment times.

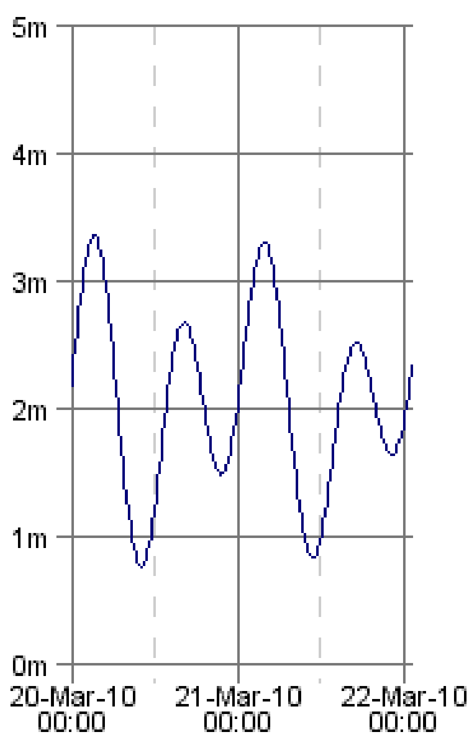

Figure 7. Tide predictions for the deployments (indicated by arrows)

On the second day the surface drifters recorded a different route (Figure 4b). Initially the two surface drifters both moved south toward the mouth of Effingham. Then mid way through the deployment the drifter in the south basin changed direction and returned north up the channel. The deeper drogues followed similar paths to the previous day; both continuously moved to the north.

The surface speeds this day showed little variation between the two locations with both surface drifters reaching average speeds of around 0.15 m/s (Figure 8a and 8b). The speeds of the surface drifters were at least twice as fast as the speed of the deeper drogues, which averaged around 0.05 m/s. The speeds of the deeper drogues varied between the two deployment locations over the duration of the investigation. The near surface drogue south the sill showed little variation in speed over the day remaining around 0.05 m/s, but the near surface drogue north of the sill showed a trend of slightly increased speeds after 11:00.

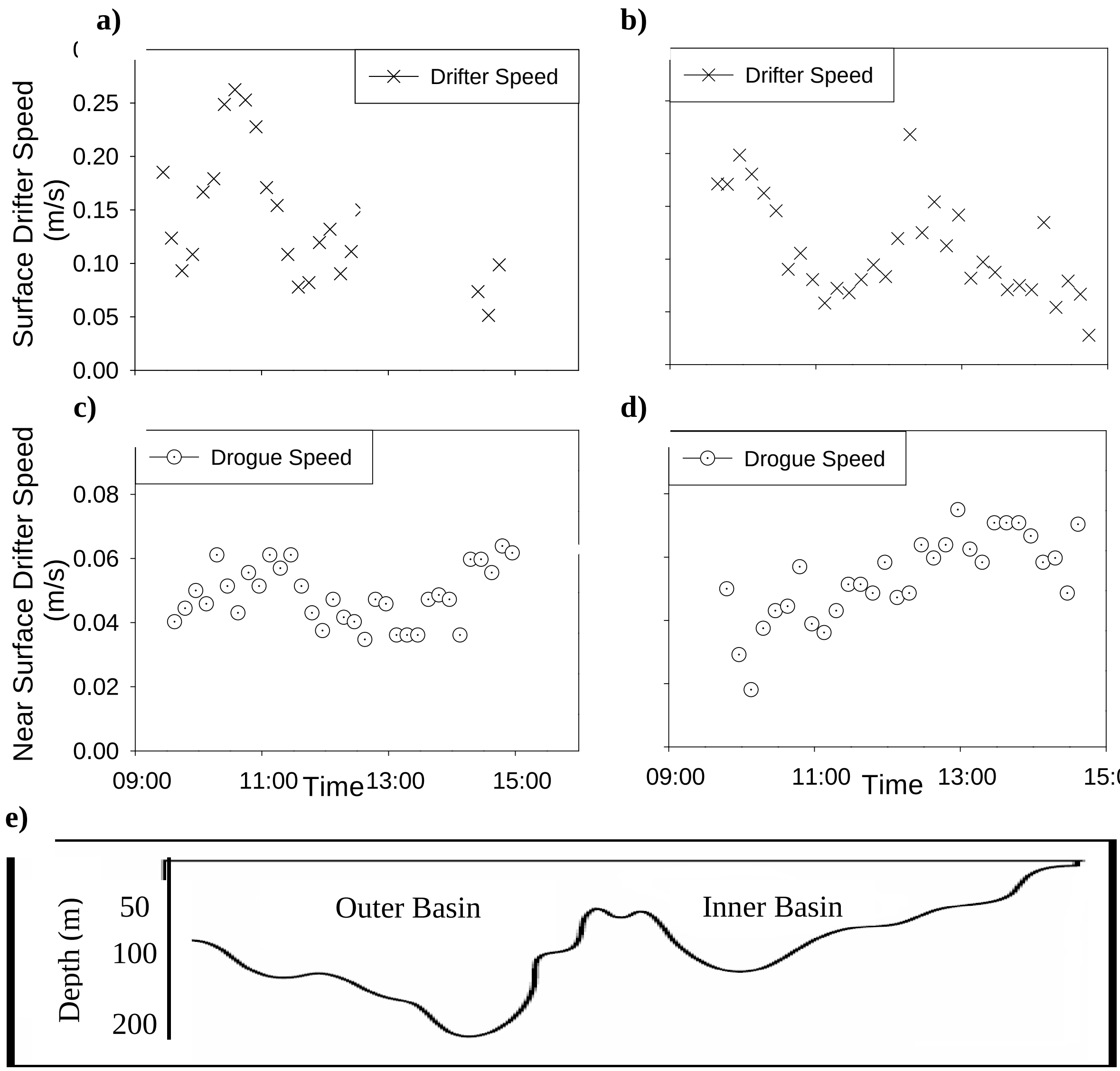

Figure 8 Drifter Speeds recorded on the 21 March 2010, speeds recorded very 30 seconds binned into 10-minute bins. The surface drifters displayed in the top line as crosses, representing their shape, and the deeper drogues shown as circles, representing the Holey Socks. a) Surface drifter speeds below the sill in the outer basin. b) Surface drifter speeds above the sill, in the inner basin. c) 5 m drogue speed below the sill, this drogue failed to sink. d) 5 m drogue speeds above the sill. e) Bathymetric profile, arranged to illustrate the differences between the deployment locations, after Hay et al (2003).

In the 16 hours prior to the second deployment, 30 mm of precipitation was measured at Bamfield. The prevailing wind was much more varied than the conditions of the previous day, its speed varied by 8 km/hour and its direction varied by 100 degrees (Figure 9). During the deployment, wind speeds were lower than the previous day, never going above 8 km/hour. The wind direction was predominantly from the south and was less variable than the preceding winds, only varying by 40 degrees. The low tide was at 11:00, then rising as the deployment progressed.

A measure of "sinuosity", or path complexity, was derived for the path of each drifter. This metric is often used to describe the shape complexity of rivers, and is calculated as the total path length by the drifter and dividing it by the Euclidean (straight line) distance traveled (Schumm, 1963). A non-complex path, or straight line, would have a value of 1, while a complex path would have a high value. The most complex tracks were south of the sill (Table 1).

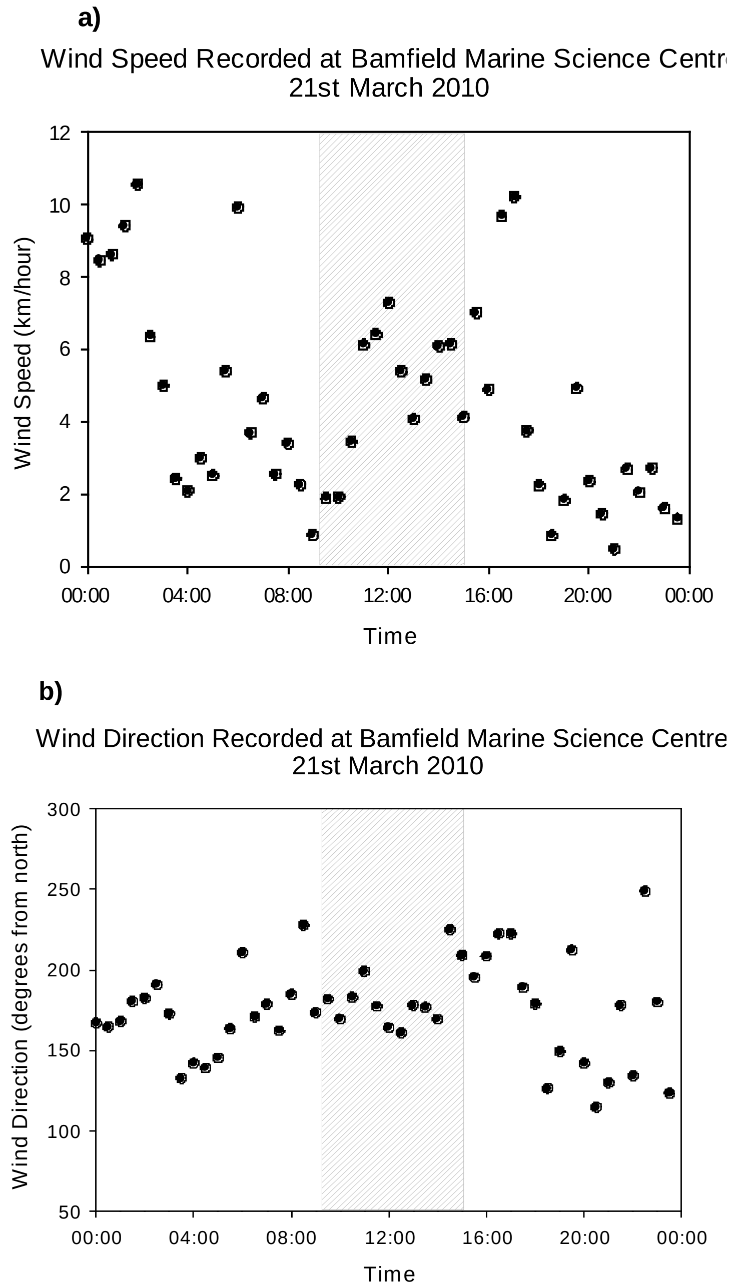

Figure 9. Wind data recorded by the Bamfield weather station on the 21st March 2010. Data recorded every minute binned into 30 min bins. a) Wind speed in km/hour. b) Wind Direction, shown in degrees from north. Grey shaded area indicates deployment times.

Table 1. Track complexity calculated by dividing path length by Euclidean length.

Date	Location	Total Path Length (m)	Euclidean Length (m)	Complexity
20 March 2010	Surface south of the sill	1580	1000	1.6
	Surface north of the sill	2205	2040	1.1
	Near surface north of the sill	250	230	1.1
21 March 2010	Surface south of the sill	2840	680	4.2
	Near surface south of the sill	750	480	1.6
	Surface north of the sill	1840	1750	1.1
	Near surface north of the sill	800	640	1.2

Discussion

The surface drifters followed different paths on each day. The tide had shifted little, so was not the driving factor in controlling the motions. Prior to the first deployment there had been no precipitation for three days, this would have lead to low terrestrial freshwater input. The prevailing wind while low was from a constant direction for the nine hours before deployment. As the river flow was low the prevailing winds were able to drive the surface motion to the north. Prior to the second deployment 30 mm of rain fell in 16 hours at Bamfield. This precipitation would increase the terrestrial inputs of fresh water. The prevailing winds were also much more variable than the previous day, and unable to set up motions in the same way they had the day before. The higher river flow was the dominant force on the surface motion on this day, driving the surface flow to the south, towards the ocean.

This finding is supported by previous studies which have demonstrated that when the fresh water inputs are low the prevailing wind is the dominant force in controlling the surface motions (Gade, 1963, Johannessen, 1968 and Svendsen and Thompson, 1978). Svendsen and Thompson (1978) conducted research on a Norwegian Fjord and concluded that the surface motion was setup by wind over a time scale of 10 hours. This is similar to the length of time the prevailing winds were constant preceding the first deployment.

The near surface drogues moved in the same direction on both deployments, so were not being controlled by the same driving force as the surface drifters. They traveled at similar speeds, with small increases over the course of each deployment. The lowest speeds were achieved at low tide, and increased as the tides flooded. A study in Alberni Inlet, a fjord 15 km away that also connects to Barkley Sound, concluded that the deeper motions were the result of the tide (Farmer and Osborn, 1976). This shows that it is likely that the 5 m drogues are experiencing a tidal forcing. This would be confirmed by a longer deployment, covering an entire tidal cycle.

The tracks in the basin south of the sill were the most complex and the tracks in the channel to the south were consistently less complex. This shows that the drifters moved in a simpler way in the channel. The basin geomorphology was wider and deep, while the channel was confined by the sill at its mouth, steep walls and narrow width. This allowed the more complex paths to be followed in the basin. The lower complexities in the channel are the result of the flow being confined by the geomorphology. The fastest surface speeds were recorded in the channel on the day when the wind was driving the flow north up Effingham Inlet. The wind was forcing a large volume of water, north from the wide bay to narrow channel. The geomorphology of the channel was then funneling this, which caused the speeds to increase. This may also offer one explanation for the observed increase in near surface speeds north of the sill seen on both deployments, when there was little variation in the basin. The tide would be focused and the speeds increased in the same way as the water being driven by the wind.

This study was limited to two consecutive days in spring. The deployments were of short duration, insufficient to completely sample an entire tidal cycle. Despite these limitations the results are in agreement with other studies focused on fjord estuaries.

Conclusions

The surface circulation patterns are influenced by many different factors. Prevailing winds, fresh water inputs and tides combine to act as the major controlling processes in the surface circulation of Effingham Inlet. There appears to be two separate systems at work to control the circulation in the upper 1 m and the deeper 5 m layer. The surface layer is predominantly influenced by the prevailing wind and fresh water input. When the fresh water input is low the winds act as the dominant forcing. The opposite then holds true when the fresh water input increases. The deeper layer is tidally forced and over this short term study showed little response to the freshwater input. This finding is in line with previous results for fjords in other areas. The local geomorphology of the basin also appears to be important in determining the circulation patterns. Tracks are less complex in channels than those in basins, where the water is confined. The geomorphology can funnel the circulation and produce more rapid speeds under certain conditions.

In the future, conducting similar experiments over a longer time scale and during different weather patterns would improve the reliability of these results. Another interesting experimental design should deploy the drifters and drogues in pairs to divergence in multiple depth layers and specifically assess the spatial and temporal scales of these divergences.

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