Performance characterization and relative dispersion of drogued drifters deployed in the fjords of Nootka Sound

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Abstract

Current velocities and dispersion were analyzed in Muchalat inlet using drifters as a Lagrangian sensor. The recorded velocity measurements were compared to two moored ADCP's that were placed in the channel of Muchalat near the base of its two sills. The classic Davis style drifter design was modified in this study and used for subsurface measurements at a depth of 30 m. Since this was the first known study to use Davis style drifters for subsurface measurements, the main objective was to characterize the performance of the drogued drifters using the moored ADCP to act as a ground truth. The surface component of the drifter incorporated the use of a handheld GPS unit to log its time and position while deployed. Four experiments were designed to evaluate the performance of the drogues with deployments on both flood and ebb tides and adjustment of the initial spacing of the drogues from 10, 25 and 50 m separation to resolve the impact of tidal forcing and across channel variability on the circulation in the channel. The commonality between all experiments was the velocity of the drogue being greater than the speed recorded by the ADCP from 0.01 m/s to 0.1 m/s. This suggests that the current was not the only mechanism forcing the drogue and other variables such as wind, stratification, GPS fix and drifter design were affecting the recorded data values. This implies that the surface area of the Davis drifter may not be large enough to accurately record subsurface measurements.

Introduction

Ocean circulation is important as it controls heat transport from the tropics to the poles, influences weather and climate, and distributes nutrients and scatters organisms. Predicting and quantifying how the ocean water moves has been an intensely researched topic for quite some time. The use of drifters to facilitate this research is one of the oldest methods for studying physical ocean circulation, and in just over the past 30 years has come a long way with the incorporation of modern technology.

The drifters offer a Lagrangian description of fluid mechanics as they follow an individual parcel of water. This differs from the Eulerian description of fluid flow which instead defines a control volume where the flow properties are described within that given volume. Lagrangian sensors allow us to track the movements of these individual parcels of water as their positions and velocities change with time.

The first documented use of drifters for scientific purposes was on the Challenger Expedition as they began to monitor ocean circulation almost 140 years ago (Thompson 1877). Drifters are commonly used for large scale circulation studies as their Lagrangian nature makes them well suited for tracing circulation pathways. With the incorporation of modern technology drifters now offer the measurement of the fine scale details of ocean dynamics such as the direction and speed of currents and eddies, to the physical characteristics such as temperature and salinity of parcels of water within the wider ocean (WHOI 2015). The U.S. Coastal Dynamics Experiment (CODE) was the first large scale modern experiment that implemented the use of drifters, predominately using the Davis drifter design (Davis 1985), and many other programs have incorporated drifter use, such as the World Ocean Circulation Experiment (WOCE).

In complex systems such as a narrow fjord with strong estuarine circulation, the use of drifter trajectories resolves the small scale variability in circulation where Eulerian current measurements can become more difficult to interpret. The influence of modern technology has reached drifter design as the Global Positioning System (GPS) has been integrated into drifter experimentation. This allows for high resolution data that is more precise than previous methods of positioning which relied on radio direction finding triangulation (Davis 1985). Through the use of GPS, circulation experiments have gone from large area and sparse data to resolving the mesoscale and sub-mesoscale variability through high frequency and accurate GPS driven locations.

The modern progression of understanding physical ocean circulation through the use of drifters gave rise to the idea of building one for this study, as they are relatively inexpensive to make. Four of the Davis drifters were built as they are the standard type of design used in CODE. Instead of measuring surface current, the setup included a surface float mounted with a GPS unit tethered to a drogue a depth of 30 m. The drogue is the subsurface component of the drifter which follows the current and the float is at the surface which records the data. Details of the drogued drifter design are further discussed later on.

The main objective of this study is to characterize the performance of these drogued drifters through field validation with the use of a moored ADCP. Field validation of this nature has been done before by Sabet and Barani who compared Eulerian data from an AADERAA recording current meter to their two GPS drifters (2011). Niller et al. also recorded the amount of tension on the drogues tether in a test tank when there were waves moving the float at the surface (1987). The use of a moored ADCP for field validation in this study provides ground truth for the recorded measurements of the drogued drifters as the ADCP is a well characterized method for measuring velocity. Through a dynamic range analysis, which is when the drogued drifters are within a predetermined distance of the moored ADCP, the numerical values of current velocities from the GPS units and ADCP are compared, and from there an assessment is made on the drogued drifters performance.

The drogued drifters were deployed in the fjords of Nootka Sound, British Columbia to see how the deep water motion was impacted by the presence of the sill. A sill is formed from the buildup of rock debris on the seafloor that is left behind from glacial moraines that paused during their retreat (Bennett 2001). Sills strongly influence the deep water circulation by limiting the flushing of the deep water on their landward side and thereby inducing stratification (Cannon 1975). By deploying the drogued drifters at 30 m, we can assess how the sill impacts deep water circulation.

There is a long history of drifter use to understand the impact that sills have on circulation patterns, for example in a long term dispersion study (Pinot 1995) deployed 22 m drifters in the Balearic basin where the drifters traveled into an eddy after passing over the sill. The impact of the sill affects the dispersion of the drogued drifters as they move through the narrow fjord channels that are found in Nootka Sound.

Methods

Drifter Design

The Davis drifter style, predominately used to measure surface currents, forms the basis for many drifter designs (Austin and Atkinson 2004), and was chosen for this study. This is different from the more traditional route of using the holey sock drogue as used in the Surface Velocity Program (SVP) and World Ocean Circulation Experiment (Lumpkin and Pazos 2007) which more commonly measures the deeper currents as (Anita et al. 2013) did on the northwest Florida shelf, setting her holey sock drogue to a depth of 34 m for the given experiment. This study is the first of its kind to use the Davis style drifters for deep water dispersion calculations, with the main focus on evaluating the performance of the Davis style drifter.

The design goal of the drifter was such that I could set the drogue to a depth of 30 m and record time and position of the drifter with a GPS unit at the surface attached to the float. In doing so the drogue had to control the movement of the surface float in the form of drag and be insignificantly effected by the processes happening at the surface in the form of slippage. The effort put into maximizing drag and reducing slippage would result in a drogue that could follow the deep water currents with maximum efficiency and reliable results.

Mechanics

The design and build of the drifter was modeled after the Davis drifters used in CODE with a few modifications. A PVC frame was chosen for this experiment as it's a lightweight and sturdy material, as well as being inexpensive allowed for multiple drogues to be built. The modifications include a series of holes drilled into the frame acting as a bypass for water so that it would sink more rapidly during deployment and not be dragged off station. Also high quality nylon spinnaker sailcloth was used for the one meter squared sail area of the drifter as this material responded to the forcing of the current without energy loss due to stretching or water absorption in the material. A 0.8 mm diameter high strength fishing line tethered the surface float to the drogued drifter at the 30 m depth resulting in minimal drag produced. The drifter was designed with a 40:1 (Beardsley et al. 2004) minimum drag ratio between the drogue and the surface buoy to optimize the drifter's water-following response and reduce slippage due to wind forcing. That is, as long as the drag of the drifter is 40 times or greater than the surface float, the data measurements are acceptable. The drag coefficient equation

$$C_D = \frac{2F_D}{pv^2A}$$

where C_D is the coefficient of drag calculated with the components $F_D$being the drag force, p is the density of the seawater, v^2 is the velocity of the seawater approaching the surface float and A is the area on the surface float in square meters was used in the calculation. A drag ratio of 640:1 was calculated between the surface float and the drogued drifter, signifying the drogue drifter setup was within the standard. Using this standard in all of the experiments ensures that the deep water currents would predominately influence drogues movement. The satisfactory drag ratio was accomplished by the dimensions of the surface float having an optimum steam-line shape to reduce drag through the water, that coupled with the tether resulted in a drogued drifter that fulfilled the given requirements.

Experimentation

The drogued drifters were deployed over the East and West Williamson sill in Muchalat inlet, Nootka Sound. Four drogued drifters were released on both flood and ebb tides, and in four experiments they dispersed over the moored ADCP and the nearest sill (Fig 1). Deployments were made from both the R/V Weelander and the R/V Thomas G. Thompson from the 13th to the 18th of December 2015. The temporal scale for each deployment was between 4 and 6 hours as recovery was constrained by available daylight. The spacing of the drogued drifters varied from one release site to the next, with 10 m spacing on the first deployment to 25 m per drogued drifter pair, and eventually to 50 m across channel spacing to gauge across sill variability and its impact on dispersion. Janzen et al. (2005) noticed how the bathymetry of a sill is not homogenous and there is great across-sill variability that was tracked with a shipboard ADCP in their experiment. The spacing of the drogued drifters was adjusted in hopes to identify the impact of the across-sill variability for Muchalat inlet in regards to dispersion. In doing so the drogued drifter's trajectory placed them within varying distances of the moored ADCP, resulting in variable overlap between drifters and ADCP measurements.

Data processing

Data was collected using a GPS unit in the surface component of the drifter that recorded time and position. The Garmin eTrex 10 was the chosen handheld GPS unit with a 25-hour battery life as well as GPS and GLONASS satellite acquiring ability for faster and more accurate positioning. Time and position were recorded every 8 to 10 seconds, with positioning accurate to 5 m. Data was initially uploaded into the Garmin BaseCamp software, with the GPX files later transferred to Matlab for analysis. The in-depth analysis of the recovered GPS data involved an evaluation of drifter velocity (speed and direction) against velocities measured by the moored ADCP.

The raw speed data was put through a number of smoothers to filter out the noise in the data including a moving average filter, outlier remover and then a third degree polynomial smoother which allowed for a cleaner interpretation of the data. The GPS data for the drogued drifters was compared to the moored ADCP in a number of ways including direct speed and velocity analysis for when the drogues were within a certain distance of the mooring to direction components of northward and eastward velocity of individual drogues as to characterize their performance is this field validation experiment.

Results

This study is comprised of four experiments which took place between 13 - 18 December, 2015. In each experiment, except the last four drogued drifters were deployed in Muchalat inlet on either a flood or an ebb tide. Only two drogued drifters were deployed for the last experiment. The tide table (Fig 2) was produced from the Canadian Governments Fisheries and Oceans department for the Gold River station, near the head of Muchalat inlet. This was used to time the release of the drogues so they would be deployed for the maximum tidal swing available in the given daylight hours.

The goal in designing the four experiments was to evaluate the channel-wide variation in current by adjusting the spacing between the drogues at deployment. In doing so, we could resolve the variability in dispersion from the impact of flowing over the sill. By having experiments on both a flood and ebb tide we are able to assess any differences between an outflowing and inflowing tide to Muchalat inlet and determine what happens on the lee side of the given sill.

The speed comparison analysis done in all four experiments is created by integrating the ADCP's average current speeds for 26 m to 34 m as the data is grouped into 4 m bins. As the drogue is pre-set to a depth of 30 m, this swath of ADCP measurements covers the depth range that the drogue is designed to follow. The speed for the ADCP is calculated from two data points whereas the drogue calculates its speed from a moving average of five data points as there is a bias in the amount of data points available during the time of the comparison. This reduces the amount of noise in the drifter data while the ADCP retains its variability. As the location of the ADCP is known, the drogues' data is used in the analysis whenever it comes within 200 m and 500 m of the position of the ADCP. The given range was chosen as a balance between amount of data available and tracking the same motion of water. Both drifter and ADCP data are standardized to UTC time where they are plotted below (Fig 1).

The most evident commonality among the four experiments was the speed of the drogues being greater than the speed recorded by the ADCP from 0.01 m/s to 0.1 m/s at any given time between all four drogues on all four experiments (Fig 3). Also, experiment one, which was deployed at the mouth of Muchalat inlet, seemed to track most closely to the ADCP velocity compared to experiments two, three and four which were deployed approximately 5 km inside the inlet.

Experiment One

On 13 December 2015 four drogued drifters were deployed off the R/V Weelander near the West Williamson sill at the mouth of Muchalat inlet on a flood tide. The first drogued drifter was released at 9:36 AM PST and the last drogued drifter was recovered at 2:17 PM PST. The average wind speed for this day recorded by the R/V Thompson was 1.1 m/s coming out of the South. As the drogues were deployed in a tight, 10 m spacing for this experiment their returned data values are similar, averaging a speed of 0.14 m/s for the duration of the deployment. When the drogues came within 200 m of the moored ADCP a speed comparison was implemented (Fig 3) displaying that all drogued drifters were reading fast by an analogous offset. The offset can be more readily identified and quantified by a one to one plot of ADCP to drogue speed (Fig 4) with an offset value of 0.046 m/s. The northward and eastward components of velocity (Fig 5) were evaluated for drogue one of this deployment to the moored ADCP's northward and eastward components of velocity. In the reference frame of the channel, eastward being along channel and northward being across channel, the ADCP showed velocity aligned across channel while the drogues show velocities 45 degrees to the right, looking upstream into the channel.

Experiment Two

On 16 December 2015 four drogued drifters were deployed off the stern of the R/V Thompson near the East Williamson sill just NE of Gore Island during an ebb tide. The first drogued drifter was released at 7:57 AM and the last drogued drifter was recovered at 1:24 PM. The average wind speed for this day 7.5 m/s out of the East, which was much greater than the first deployment. This time the drogues were released with a 25 m spacing which gave average speed values to range from 0.11 m/s to 0.18 m/s. When comparing the directional components of velocity (Fig 6) the eastward component is driving the velocity for the moored ADCP as it's showing a strong along channel motion. The drogue however, is showing velocities 90 degrees to the right looking downstream with an across channel motion. Also you'll notice that the fourth drogued drifter found an eddy as shown in its trajectory (Fig 1) where its speed reduced from 0.19 m/s before to 0.07 m/s after entering the eddy.

Experiment Three

On 17 December 2015 four drogued drifters were again deployed off the stern of the R/V Thompson with an easterly wind speed of 9.7 m/s during an ebb tide where each drogues individual station was the same as the previous experiment. This time the drogues were deployed slightly earlier at 7:33 AM to maximize their time with the tidal swing however this did mean that when they were first deployed it was still dark out for quite a while. The result of this being that the R/V Thompson could not establish visual contact with the drogued drifters, resulting in one casualty due to collision. However, on the following day this surface float and GPS unit were miraculously recovered, although the data from before the collision was not useable. The remaining three drogued drifter's speeds were compared with the moored ADCP's (Fig 7) when they were within a range of 200 m. The moored ADCP was recording an average speed of 0.11 m/s during that time period. The interesting thing about the speed recordings for drogues one and four is that as they approached the sill where the mooring was placed at the base of, their speed dropped from 0.17 m/s to 0.05 m/s as they crossed over the sill.

Experiment Four

On 18 December 2015, the last day of deployments, only two drogued drifters were released at East Williamson sill. Winds were 4.2 m/s out of the East. This was the shortest deployment of the four, with a start time of 9:13 AM and an end time at 11:58 AM. Spacing for this experiment was the widest of all four at 50 m separation in an attempt to evaluate the across channel variability. The drogues were released at the maximum tidal swing for an ebb tide that steadily decreased over the deployment. Notice the drogue's speed (Fig 8) as there is an increase seen in drogue four around 10:05 AM PST, just before it enters the eddy that drogue four also found in experiment two.

Discussion

Data from the drogued drifters deployed in Muchalat inlet revelaed interesting patterns both in their relative dispersion and in their calculated speed and velocity comparison. As this is the first known study using Davis drifters to take subsurface measurements, their ability to perform in these conditions was unknown. The main objective of this study was to characterize the performance of the drogued drifters. During all four deployments, drifters reported faster speeds through Muchalat inlet than the moored ADCP that was used as ground truth.

Study Area

The reason as to why the drogues were recording faster current speeds at 30 m depth stems from a combination of many different factors. The process that was known during the time of deployment that might bias the drifter measurements was the wind. For the deployments made on the 16^{th} and 17^{th} of December 2015 the strong 7.5 and 9.7 m/s winds proved to be troublesome as white-capping waves produced from winds greater than 6 m/s begins to alter the surface to drogue drag ratio. As (Gade 1978) found in his study that when the prevailing winds are strong and act for a period greater than 10 hours, the surface currents tend to be controlled by the force of that wind. As the wind was coming out of the East for these days during deployment, and the drogues were headed West, there is a strong likelihood that the surface float was pulling on the drogue, resulting in a faster than actual current being recorded.

There is a significant source of fresh water into the head Muchalat inlet coming from the Gold river which discharges an averaging of 133,840 liters per second in the month of December (Jackson and Cook 1997). This inflow of fresh water creates a strong layer of stratification in the water column, predominantly at the surface. As the fresh water is always an outflowing current, this fresh water outflow would have multiple impacts including the ability to influence the motion of the surface float. The fresh water layer creates a strong thin layer of stratification in the surface layer which would isolate the wind-driven flow, resulting in greater than expected velocities. This becomes most prevalent during an ebb tide when the tidal swing, fresh surface layer and prevailing winds are all compounded in the same direction.

It was noted that as the drogues approached the sill, their trajectory was adjusted northward across channel and the speed decreased significantly. As in any fjord system, like the Puget Sound where (Moore et al. 2008) found that the primary sill influences mixing and effects stratification, the sill in Muchalat inlet of Nootka Sound had a strong influence on the drogues dispersion. With the East Williamson sill located off center, closer to the southern side of the channel, the drogues deployed near the southern side of the coast in all experiments actually jumped across the channel to the northern side as they approached the sill. It appears that the drogues dispersion is affected by the bathymetry of the sill as the uneven and sloped features of the sill alters to deep water circulation. For the experiment on 17 December (Fig 7) the drogues speed decreased from 0.18 m/s to 0.06 m/s as it crossed the channel just before reaching the sill which means the presence of the sill plays a significant role in the forcing of the deep water in the region. A more quantitatively based study on the impact of sills on dispersion will need to be implemented in the future to evaluate the circulation process in Muchalat inlet.

Design

The reason that most subsurface ocean circulation experiments use the holey sock drogue design is that it has a greater surface area compared to the Davis drifter, which in turn creates more drag on the surface float and increase the efficiency of its response to deep currents at the drogue depth. The main challenge the Davis drifter must overcome is its lack of surface area. The holey sock is generally 10 m long, generating a surface area much larger than the 1 m^2 sail area of the Davis drifter. This is generally not a problem for the Davis drifter when it's used to measure current at the surface, but when deployed at 30 m the smaller surface area may be inadequate to overcome the drag generated by the surface float, especially when the float is experiencing forcing from strong wind-driven surface currents.

Mechanical

In all experiments the drogues where compared to the moored ADCP which was acting as the ground truth for the recorded measurements in this study. Aspects of the mooring configuration contributes to uncertainties in the comparison. As the mooring was not equipped with a pressure sensor, we have to assume that its anchor depth was the 120 m bottom depth recorded by the R/V Thompson. The ADCP speed and velocity comparison values came from 90 m shallower of the moored ADCP, which was assumed to be 30 m, the depth of drogues. Comparing the 30 m drogues to an ADCP depth of values shallower or deeper could alter the ground truth values by as much as 0.01 m/s. Also, it is possible that the ADCP was experiencing lean due to the force of the current which would also throw off the perceived depth range and again alter the recorded current speed values by the same amount depending on the degree of lean.

The disconnect in sampling frequency between the GPS units and the moored ADCP resulted in a large discrepancy between the amount of data points available for comparison in the dynamic range analysis. As the GPS units produced a data value every 8 to 10 seconds, there were hundreds of recorded speed and velocity measurements available to compare with the moored ADCP. The discrepancy comes from the sampling rate of the mooring which only provides a measurement every 10 minutes, as the 5 second recordings were averaged into 10 minute bins, resulting in three to five data values available during the time the drogues are within 200 and 500 m. The ADCP misses the fine scale fluctuations in current that the drogue is able to pick up do its sampling rate.

The incorporation of GPS technology makes for a low cost solution to track drifter's movements and provides a potentially valuable educational tool (Sabet and Barani 2011). This is true of the drogued drifters deployed with GPS units in Muchalat inlet, although not without its drawbacks. The fjords in Nootka Sound are narrow with tall mountains on either side that obscures the GPS signal. The downside to this is that the location fix was not always accurate, providing locations both further and closer apart then likely, resulting in false speed averages between the given positions.

Conclusion

All of the factors outlined above and more have the ability to confound the given results, providing an explanation as to why the drogued drifters were reporting faster deep water speeds compared to the moored ADCP. The use of the Davis style drifters to measure the subsurface currents may not be the most logical approach, given their low surface area, but more experimentation is needed before a significant conclusion can be drawn. Altering the design of the Davis drifter further, giving it a larger sail area, may be of interest for future studies, resolving one of the potential confounding factors. Also, if the sampling frequency of the moored ADCP is able to be increased it would provide more data values to compare the drifter's measurements in the effort to better characterize the performance of these drogued drifters. As this study focused on the design and performance of the drogued drifters, the impact of the East and West Williamson sill on the circulation was not fully studied. In future experiments the effect of the sill can be further quantified and related to how it may be altering the flow regime of the circulation at depth.

Figures

Figure 1: Google Earth overlay for two deployments in Muchalat inlet, each track is the path of an individual drifter. The first deployment of drifters on 13 December were tightly dispersed with a 10m spacing and traveled over the ADCP mooring near West Williamson sill. The second deployment of drifters on 16 December were dispersed 25m apart with a 50m spacing between the pairs and traveled over the ADCP mooring near East Williamson sill.

Times and Heights for High and Low Tides

2015-12-13 (Sunday)		
Time	Height	
PST	(m)	(ft)
02:01	3.4	11.2
07:24	1.9	6.2
13:10	3.8	12.5
20:02	0.5	1.6

2015-12-14 (Monday)		
Time	Height	
PST	(m)	(ft)
02:41	3.4	11.2
08:08	1.8	5.9
13:53	3.7	12.1
20:42	0.5	1.6

2015-12-15 (Tuesday)		
Time	Height	
PST	(m)	(ft)
03:24	3.4	11.2
08:57	1.8	5.9
14:40	3.5	11.5
21:25	0.7	2.3

2015-12-16 (Wednesday)		
Time	Height	
PST	(m)	(ft)
04:09	3.4	11.2
09:53	1.8	5.9
15:33	3.4	11.2
22:12	0.8	2.6

2015-12-17 (Thursday)		
Time	Height	
PST	(m)	(ft)
04:59	3.5	11.5
10:58	1.8	5.9
16:35	3.2	10.5
23:04	1	3.3

2015-12-18 (Friday)		
Time	Height	
PST	(m)	(ft)
05:52	3.5	11.5
12:10	1.6	5.2
17:49	3	9.8

2015-12-19 (Saturday)		
Time	Height	
PST	(m)	(ft)
00:02	1.3	4.3
06:48	3.6	11.8
13:23	1.4	4.6
19:15	2.9	9.5

Figure 2: Seven day tidal predictions for the Gold River in Muchalat inlet. Deployment one was released on a flood tide on 13 December 2015 and the rest of the deployments were released on an ebb tide of 16, 17 and 18 of December 2015.

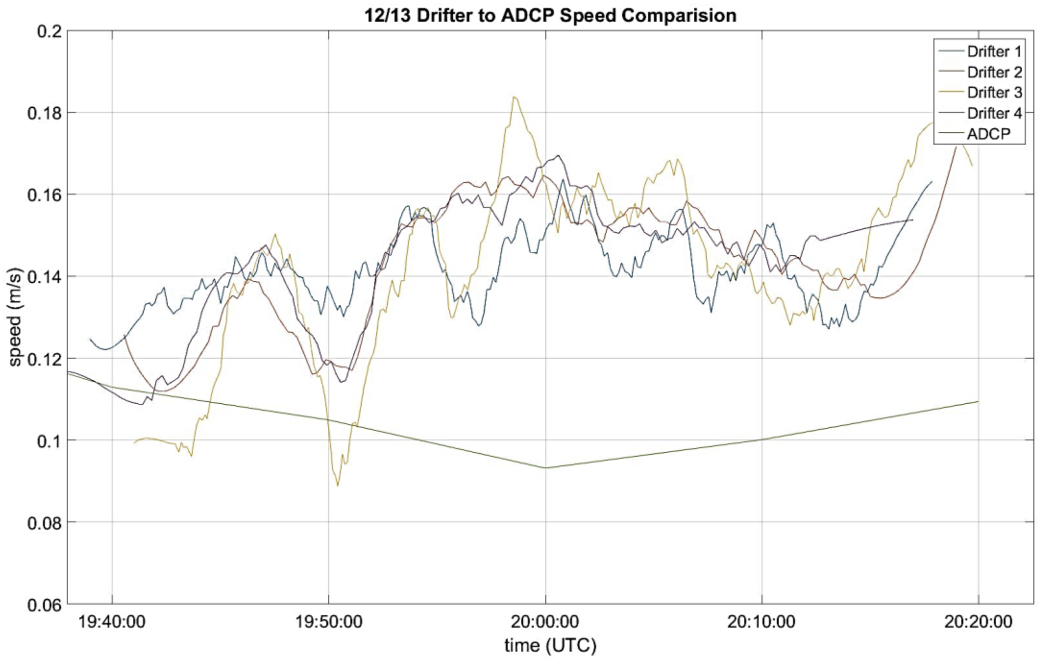

Figure 3: When the deployment on 13 December was within 200m of the western moored ADCP the drifter speed is plotted with the ADCP speed on a flood tide. The resolution of drifter speed is approximately every eight seconds whereas the resolution of the ADCP is every 10 minutes. All drifters where within the desired range for the length of this deployment.

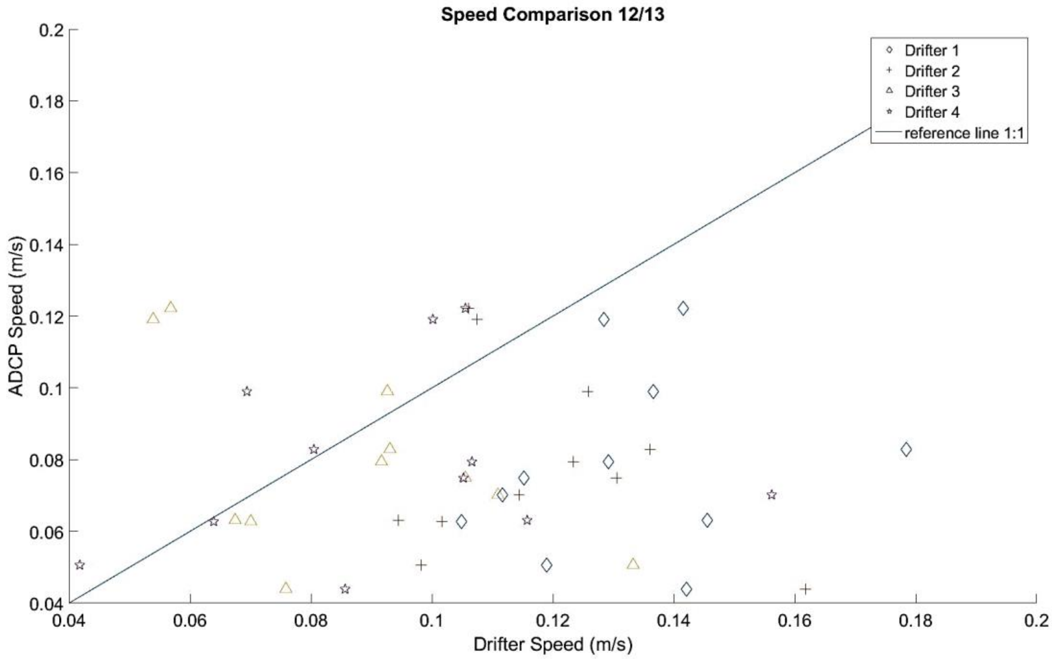

Figure 4: A 1:1 reference line is added to the plot of ADCP speed vs. drifter speed to aide with visual comparison. The drifter speed commonly falls below the 1:1 line implying a greater speed recording. A reoccurring offset of 0.046 and greater is consistent throughout the deployments with an amplitude of 0.25.

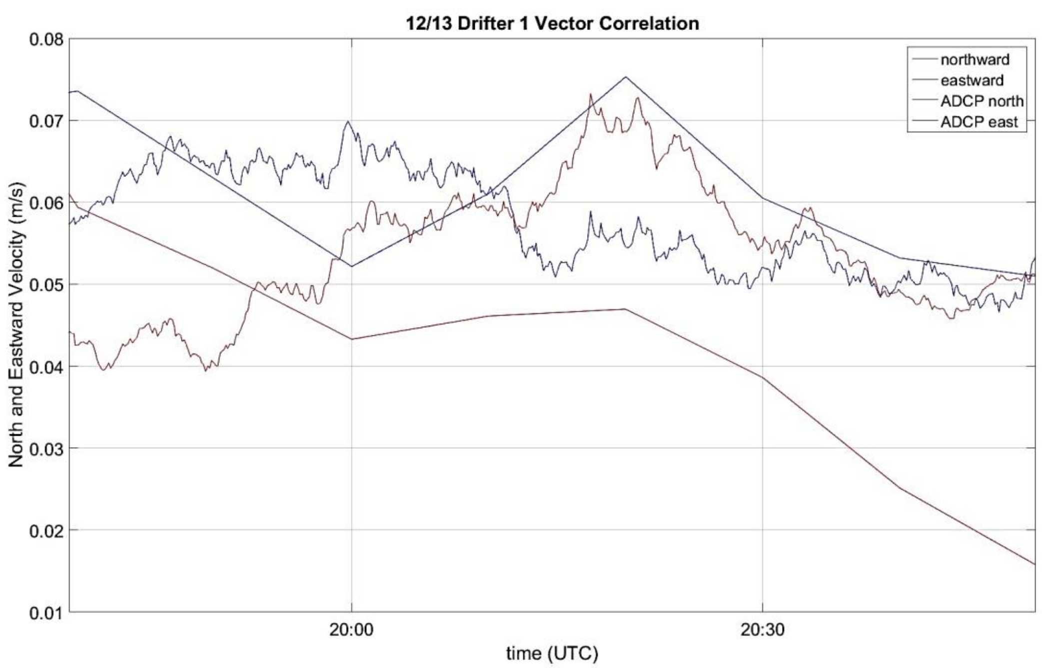

Figure 5: A northward and eastward velocity vector comparison for drifter one on the 13 December deployment. Range of ADCP data was collected when the drifter was within 500m of

the mooring. The northward and eastward velocity vectors have a tighter grouping when deployed on a flood tide.

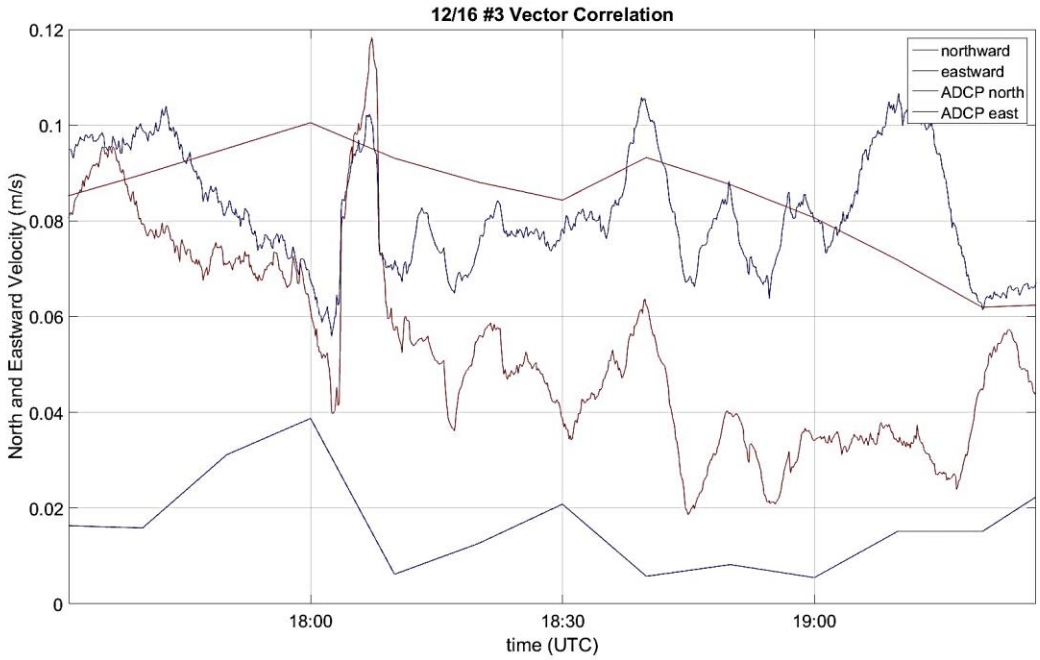

Figure 6: A northward and eastward velocity vector comparison for drifter three on the 16 December deployment. Range of ADCP data was collected when the drifter was within 500m of the mooring. There is a greater separation between the northward and eastward vectors when deployed on an ebb tide.

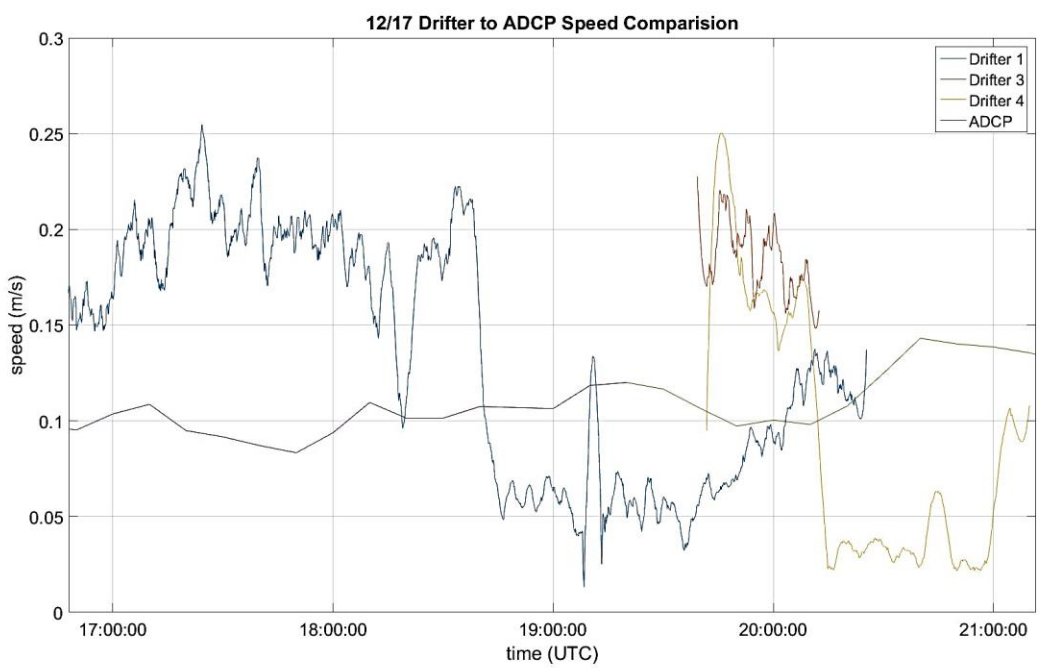

Figure 7: When the deployment on 17 December was within 200m of the western moored ADCP the drifter speed is plotted with the ADCP speed on an ebb tide. The resolution of drifter speed is approximately every eight seconds whereas the resolution of the ADCP is every 10 minutes. Some drifters were closer to the ADCP for longer depending on where they were within the channel.

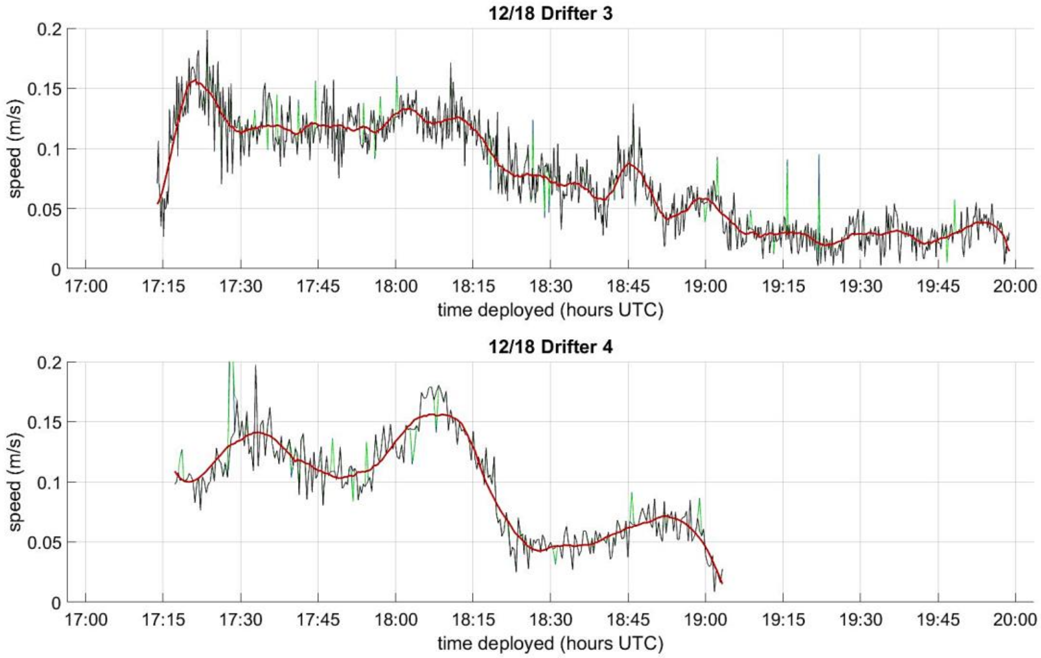

Figure 8: Speed of drifters 3 and 4 over standardized UTC time for the deployment on 18 December. Multiple smoothers applied to filter out noise in the data. The green curve is a first degree smoother, the black curve is a smoother that removes outliers and the red curve is a third degree polynomial smoother.

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