Is Dabob Bay a closed system?: water exchange in the deep western channel as a means for renewal of water in Dabob Bay, Puget Sound, Washington

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Non-Technical Summary

The goal of this study was to examine the validity of the assumption that Dabob Bay can be considered a closed system. The residence time of Hood Canal, where Dabob Bay is located, is on the order of a few months. Generally, because of its orientation relative to Hood Canal, its low freshwater input, and the sill at its entrance, it is assumed that Dabob Bay can be considered a closed system—that is, there is no significant water exchange across the sill at Dabob Bay. Dabob Bay has been a center of copepod research for several decades with no consideration of advection. One study attempted to infer the effect of advection on the abundance of copepods in Dabob Bay, however no direct measurements have been made to actually quantify the advection and its variability over the tidal cycle. This study will also further understanding of Dabob Bay and how the water exchange across the sill at Dabob Bay, Puget Sound, Washington, varies throughout the tidal cycle. Velocity was measured in sections across the sill using an acoustic Doppler current profiler (ADCP) on four cruises (3-5 March 2004, 10-12 March 2004, 22-26 March 2004, and 7-9 April 2004) on the *R/V Clifford A. Barnes*. On two of the cruises, hydrologic data was collected by a conductivity-temperature-depth (CTD) package at four locations across the sill. Water transport was examined in the western channel alone (where dense water suspected of being a source of renewal was found) as well as the entire width of the sill. The transport in the western channel was not a function of the tide but rather varied more by cruise than by tidal velocity; this transport alone gave a residence time of 1.3 years. Transport across the whole sill serves to confirm a three layer circulation model with an estimated residence time of 0.88 years. This leads to the conclusion that although Dabob Bay is not physically a closed system, it can in fact be considered a closed system for processes occurring on shorter time scales than the residence time.

Acknowledgements

I extend my gratitude to many parties who have been instrumental in making this project happen. First, for the fieldwork: thank you to Jamie Pierson, the *R/V Barnes* crew, and the Dabob Bay research team. This project would be nothing with out you. Thank you to Professor Mark Holmes for coordinating all of the details of the class and cruises so that I didn't have to worry about them. Thank you to Dave Winkel for his assistance in processing the ADCP data. And thank you most of all to Professor Eric D'Asaro and other physical oceanography option students who provided not only technical support on my project, but also provided personal support. Thank you.

This project is completed in loving memory of Noel P. Gray. May 11, 1976 – May 11, 2004.

Abstract

Dabob Bay is located in Hood Canal, Puget Sound, Washington, and is a center of biological research. Understanding the circulation of Dabob Bay is important for both physical and biological reasons. Physically, understanding the dynamics of Dabob Bay will allow for a greater understanding of the entire Hood Canal system. Biologically, the studies conducted in Dabob Bay assume that it is a closed system—that is, advection is minimal and can be ignored. This study tests that hypothesis, as well as contributes to the overall body of knowledge about and understanding of Dabob Bay. ADCP transects across the sill at the entrance to Dabob Bay measured water velocities on five cruises in the spring of 2004: 24-26 February 2004, 3-5 March 2004, 10-12 March 2004, 22-26 March 2004, and 7-9 April 2004. CTD casts collected potential temperature and potential density data on two of those cruises: 3-5 March 2004 and 7-9 April 2004. Warm (10-11˚C), dense (23.0-23.5 kg m^{-3}) water was repeatedly observed at depth at the entrance sill. In the western channel of the entrance to Dabob Bay the transport showed no significant correlation with the tides, however, an upper bound of the transport gave an estimated residence time of 1.3 years. Considering the entire channel, the data support previous three-layer models of Dabob Bay. The transport in this three-layer model gives an estimated residence time of 0.88 years. Thus, Dabob Bay can only be considered a closed system for processes acting on shorter time scales than the residence time.

Introduction

Dabob Bay is a small bay across from Misery Point (Figure 1a) in Hood Canal, Puget Sound, Washington. Dabob Bay is approximately 62 km long and 2 km wide. The sill at the entrance to Dabob Bay is at approximately 120 m water depth. The maximum depth is 193 m, whereas southern Hood Canal has a maximum depth of 180 m. The deep channel on the western edge of the entrance to Dabob Bay has a maximum depth of approximately 123 m. This small bay has been the center of biological research for many years; many influential studies on copepod population dynamics have been conducted in Dabob Bay.

While Dabob Bay has been a center of biological research, only limited studies have examined the circulation in Dabob Bay. One study (Kollmeyer 1965) looked at along channel hydrologic profiles to understand the circulation in Dabob Bay. Kollmeyer (1965) proposed a three-layer circulation regime for Dabob Bay with a strong south-wind along the channel (Figure 2). He proposed that deep, warm, very dense water flows into Dabob Bay at depth (60-120 m). Surface water flows into Dabob Bay at the surface (0-20 m). This warm surface water mixes with the very dense deep water and flows out at mid-depth (20-60 m). This research only described the along-channel regime; there was no information collected about how this profile varied across the channel. Ebbesmeyer (1973) explored the mechanism for renewal of the deep water in Dabob Bay. Ebbesmeyer thought that the deep, warm, very dense water came over the sill in an episodic manner—via discrete parcels of water he called "snarks" flowing over the sill.

It is generally assumed that the averaged advection over the tidal cycle in and out of Dabob Bay is very minimal (Welschmeyer and Lorenzen 1985). Whereas some advection probably occurs, it is thought to be over long time scales (multiple tidal cycles) in small volume scales. It is thought that the flushing time of Dabob Bay is one or two years (Ebbesmeyer et al. 1975).

The significance of circulation in Dabob Bay is two-fold: physical and biological. From the physical perspective, it is important to understand the dynamics of Dabob Bay in order to fully understand the circulation and dynamics in Hood Canal. In both Dabob Bay and Hood Canal there could be any number of processes occurring, such as seiches, internal waves, or other energy dissipating processes. It is also possible that deep-water intrusions in Hood Canal could contribute to renewal in Dabob Bay. If so, Dabob Bay affects Hood Canal because there is less oceanic deep water to renew southern Hood Canal. These, and many more questions about Dabob Bay, need to be answered in order to fully understand the dynamics of Hood Canal.

From the biological perspective, all of the studies done in Dabob Bay on plankton dynamics have been done with the understanding of the circulation as described above. Said another way, the studies assume that Dabob Bay is effectively a closed system. In the context of these biological experiments, that means that the non-mobile population (such as plankton) measured at any one location at different times is the same population. Osgood and Frost (1996) attempted to infer the influence of advection on copepod abundances. The data used by Osgood and Frost (1996) was about two decades old and was not collected for the purposes of understanding advection. Therefore, there were no direct measurements of advection, and loss terms that could not be accounted for by biological processes were attributed to advection. Most studies, however, do not even consider the affects of advection (e.g., Dagg et al. 1998; Hays et al. 2001; Welschmeyer and Loren 1985).

Before further consideration of the circulation in this region, it is instructive to examine the circulation regime in which Hood Canal and Dabob bay are located. Puget Sound, where the Hood Canal Basin is located, is considered to be an estuarine-fjord system (Cannon et al. 1984).

The understanding of estuarine fjord circulation is simple: salty, dense water flows in at depth, and warm, fresh water flows out at the surface (McAlister et al. 1959). The water column is typically highly stratified, and there is usually low tidal mixing.

The Hood Canal Basin in Puget Sound is glacially carved with several sills. The entrance to Hood Canal is in Admiralty Inlet off of the Strait of Juan de Fuca (Figure 1a). At the entrance to Hood Canal, there is a sill at Tala Point at 100 m water depth (Ebbesmeyer 1973). The broad sill extends southward to South Point where it has a water depth of 55 m (Ebbesmeyer 1973; Warner et al. 2001). There is vigorous mixing over the sill; the flow is super-critical at the sill break (M. Gregg pers. comm.). These sills restrict the flow of deep, dense oceanic water into Hood Canal.

Circulation south of the sill in Hood Canal could be simply characterized as sluggish. The residence time of Hood Canal is one to four months with an estimated transport range of 1000-3600 m^3s^{-1} (Warner et al. 2001). As is expected with estuarine-fjord circulation, the amount of freshwater input is relatively low, approximately 150 m^3s^{-1} compared to 793.5 m^3s^{-1} in the Whidbey Basin from the Snohomish, Stillaguamish, and Skagit Rivers; tidal mixing in Hood Canal is also low, which results in high stratification and sluggish circulation (Warner et al. 2001; Staubitz et al. 1997; McAlister et al. 1959).

Freshwater contribution to Dabob Bay is even smaller than to Hood Canal. The major contribution of freshwater to Dabob Bay comes from the Dosewallips River, which discharges on the average 10.7 m^3s^{-1} directly at the sill (Staubitz et al. 1997). On average, the surface values in the fall of σ_θ are less than 23 kg m^{-3}, and within 40 m of the surface σ_θ range from 23.2 to 23.4 kg m^{-3} (Kollmeyer 1965).

Based on the studies and the general information discussed above, it is not clear at this point in time if the assumption that Dabob Bay is effectively a closed system is valid. It is not likely that the many biological studies conducted in Dabob Bay would become completely invalid if the exchange was in fact larger than originally thought. It is still important, however, to test this assumption and see the extent to which it is correct.

This research study set out to answer two main questions. (1) Is the exchange a function of the derivative of tidal height (tidal current)? Water will most certainly move in and out of Dabob Bay with the tides, however, if there is some deviation from this sloshing in and out, then there are possibly some other processes bringing water into or out of Dabob Bay. (2) What is the flushing time of Dabob Bay, and where does the exchange occur? In order for exchange to occur, there must be net exchange into the bay at some depth (or region across the sill) and net exchange out of the bay at some other depth (or region across the sill). If there is indeed a region where water is filling up Dabob Bay, what is the flushing time of the bay, assuming that the exchange at that depth is the only major source of renewal?

Methods

Data collection in the field

ADCP Transects. Acoustic Doppler current profiler (ADCP) data was collected using the *R/V Clifford A. Barnes* on five cruises in the spring: 24-26 February 2004, 3-5 March 2004, 10-12 March 2004, 22-26 March 2004, and 7-9 April 2004. The ADCP data were collected at a speed of approximately 5-6 knots in a dog-leg transect across the sill (Table 1; Figure 1b), starting at either the west or east side of the channel, proceeding to the toe of the sill, and continuing to the other side of the transect. Each ADCP transect (from one side of the channel to the other) took approximately 20 to 30 minutes.

CTD Stations and Calibration. Temperature, salinity and density data were collected using the CTD package on the *R/V Barnes* on two of the five cruises mentioned above: 3-5 March 2004 and 7-9 April 2004. CTD data were collected at four different sites along the ADCP transect (Figure 1b; Table 2). The ADCP data were collected in one transect across the channel, and the CTD data were collected at each of the stations afterward.

Data analysis in the lab

CTD Data. Contoured sections of the potential temperature and potential density data collected by the CTD were used to visualize the hydrographic regime. Profiles of the CTD data were also plotted to examine more closely the hydrographic regime. A θ-σ_θ plot was created to examine the end-members and categorize the different water masses.

ADCP Data. Eric D'Asaro processed the data from the RDI format into Matlab format. Matlab was used to remove several types of "bad data." Data points with correlation values (as computed by the RDI ADCP) smaller than 180 were removed. Data points with vertical velocities (as computed by the RDI ADCP) larger than 0.5 m s^{-1} were also removed. The ADCP on the R/V Barnes has shown a "hiccup" of an echo at certain depth ranges at certain speeds (D'Asaro, E. pers. comm.). This occurred numerous transects for this study (Figure 3). These hiccups cause bad velocity values of extremely positive or negative values to form a stripe down the entire water column, even beyond the actual water depth. When one of these hiccups occurred—meaning a velocity value occurred at a point deeper than 85% of the water depth—all velocity values for that time (or position) were removed.

In order to examine the velocity values in and out of Dabob Bay to obtain an estimate of transport, it was necessary to rotate the velocity vectors so that they were situated perpendicular to and along the transect axes, instead of in the north-east situation from the ADCP. This allowed the velocity data to be used in an estimate of the actual exchange across the sill through the western channel.

Results

The CTD profiles of both potential temperature (θ) and potential density (σ_θ) at all three stations showed the presence of deep, dense, warm water—Ebbesmeyer's snarks (Figure 4)—at some depth at least once during the sampling period. While the surface values for θ and σ_θ were highly variable, there appeared to be a large mid-water column water mass that was in a small range of θ, approximately 9-9.5°C, and consistently increasing σ_θ with depth. A θ-σ_θ diagram, similar to a temperature salinity diagram, for each cruise (Figure 5) showed three major properties: (1) the surface was indeed highly variable in θ; (2) there was a large amount of water with very similar θ and σ_θ values of 9-9.5°C and 23.0-23.2 kg m^{-3} respectively; and (3) at station CTD 3 there was consistently a warm mass of water at depth that was denser than any other water across the entrance sill.

The water properties from the CTD casts identified the western channel as a region of possible deep, dense water renewal of Dabob Bay. A well-defined snark was identified at CTD 3 in both potential temperature and potential density during both cruises. The snark properties were also observed at the other stations during some of the CTD casts, however, the densest warm water occurred in the western channel. Working off of the estuarine fjord circulation model, it would make sense that dense deep water could be the main source of renewal in Dabob Bay. Thus, the velocity signature associated with the warm, dense water at CTD 3 in the western channel was examined.

An estimate of the median velocity in the western channel at the sill entrance was obtained for each of the transects by using cut-off values for latitude, longitude, and depth. For each section, the median (rotated, or perpendicular to the axis) velocity values were calculated for water below 10, 15, 25, 35, 45, 55, 65, and 75 m on the section of ADCP data between the Western Channel waypoint and the Sill Toe waypoint/CTD station.

To examine if the mean perpendicular to axis smoothed (MPAS) velocity was a function of tidal current, an estimated derivative of tidal height (tidal current) for each transect was calculated from the Lavelle model (Lavelle et al. 1988). Then, the MPAS velocity was plotted versus the tidal velocity (Figure 6). In order to see which cut-off depth would be most appropriate, the MPAS velocity was plotted versus the cut-off depth and compared among cruises (Figure 7).

To explore the possibility of the three-layer system proposed by Kollmeyer (1965), the MPAS velocity was calculated for the entire width of the channel. Then, just as the western channel MPAS velocity was examined, the entire channel MPAS velocity was examined as a function of tidal current (Figure 8) and of cut-off depth (Figure 9). The MPAS velocity is highly variable for surface (10 m) and mid-depth cut-off depths (75 m). For cut-off values of 25 m to 35 m, the flow is into Dabob Bay. From about 40 to 65 m, however, the movement is out of Dabob Bay at about 5 cm s^{-1}. Below 75 m, there is no data available. The net movement of the data available appears to be slightly out of Dabob Bay. The mid-depth flux out of Dabob Bay can be used to estimate a residence time as was done above.

Discussion

Tidal current and MPAS velocity were not correlated but appeared to have a non-zero mean (Figure 6). Thus, the median velocity for an appropriate cut-off depth could be used to calculate an estimate of the flushing or residence time of Dabob Bay. The MPAS velocity was highly variable both for surface cut-off values and deep cut-off values (Figure 7). The MPAS velocity appeared to be very consistent for mid-depth cut-off values, from 15 to 65 m. The MPAS velocity appears to diverge and only three of the cruises proceed to go more and more negative, whereas the other cruises stay clustered around 0 ± 5 cm s^{-1}. For examination let the upper bound of the velocity be the error, 5 cm s^{-1}.

Given that Dabob Bay is 63 km long, 2 km wide, and approximately 200 m deep, the total volume of Dabob Bay is approximately 2.5×10^{10} m^3. Given an influx area 200 m wide (the width of the channel) and 61 m deep (from 65 m to the bottom), the upper bound of the MPAS velocity of 5 cm s^{-1} would give a maximum flux of 610 m^3 s^{-1}. These two figures give a lower bound on the residence time of Dabob Bay of 474 days, or just under 1.3 years.

The MPAS velocity of the entire channel appeared to have a slight correlation with tidal current depending on the cut-off depth (Figure 8). In order to determine at which depths the water is flowing out of Dabob Bay and at which depths the water was moving into Dabob Bay, the relationship between cut-off depth and MPAS velocity was compared (Figure 9). The cut-off values of 10 and 75 m are probably highly variable because there were not as many data points because the ADCP looses at least the top and bottom 15% of the velocities for the water column. However, the mid-depth cut-off depths give an MPAS velocity of approximately 5 cm s^{-1}. Given a width of 1.2 km and a depth of 25 m and a velocity of 5 cm s^{-1} gives a flux of 900 m^3 s^{-1}. With an estimated volume of 2.5×10^{10} m^3, the residence time would be 321 days, or 0.88 years.

Ebbesmeyer (1973) proposed a model that fits this data in two ways. First, Ebbesmeyer (1973) proposed a three-layer vertical flow regime. Although the ADCP could not provide velocity measurements for the deep, dense water, the rest of the data fit the model. Secondly, the estimate Ebbesmeyer (1973), as well as Welschmeyer and Lorenzen (1985), gave for the residence time of Dabob Bay is also on the order of a year. The estimated residence time for the three-layer system was 0.88 years. This estimated residence time could be further revised by a finer scale and extended understanding of the velocity profiles. For example, when considering the velocity across the entire sill region, these data do not appear to give accurate information below 65 m. Thus, the estimated area of flow out of Dabob Bay (which was taken to be from 25 to 65 m) as well as the water velocities themselves could be better approximated if there were data for the deep water.

While Dabob Bay is not actually a closed system, we can assume that is for the purposes of scientific study on processes that occur over smaller time scales than the estimated residence time of 0.88 years. Given the relative consistency of the presence of the snarks in this study, it also appears that the snarks may not be discrete water parcels, as Ebbesmeyer described, but in fact a slow but consistent presence of water moving into Dabob Bay.

For further study

<u>Studying over a longer period of time.</u> The surveys for this study were done in the spring of 2004 during the months of February, March, and April. Although our study did not appear to show any relationship between the tidal current and the velocity of water into Dabob Bay in the deep western channel (or across the entire channel), it would be prudent to examine whether or not this holds true during different parts of the year. Seasonal cycles in the tides could affect the flux into Dabob Bay, and possibly even other processes, such as bottom water intrusions into Hood Canal (Higgins, E. pers. comm.).

<u>Continuous hydrographic information</u>. The exchange in and out of Dabob Bay does not appear to be governed by the tidal current, therefore there must be some other processes at work. The thermocline moves up and down on the order of tens of meters (Kellogg, J. unpubl.), which could drastically affect the water exchange across the sill at Dabob Bay.

<u>Studying with better spatial resolution.</u> Although the technology available for this study was incomparably more advanced than that available to Ebbesmeyer (1973), the ship mounted ADCP used in this study is helpful although not perfect. An array of a bottom mounted upward looking ADCP or current moorings (ideally, some combination of the two) could provide better resolution of velocities near the bottom, which the ship mounted ADCP cannot do. This could be difficult due to Navy restrictions in the area, however, if possible, it would better refine the information on the advection regime and residence time of Dabob Bay.

Conclusions

There is net transport over the tidal cycle out of Dabob Bay at mid-depth across the entire entrance to the sill. It appears that the vertical structure is as previously modeled: tri-layered. That is, the water flows in at the surface and at depth and out at mid-depth. Based on the net transport estimate out Dabob Bay, the residence time is on the order of magnitude (many months or a year) as previous estimates. While further investigation spatially and temporally is required before further conclusions can be drawn, it appears that previous assumptions that Dabob Bay is effectively a closed system are appropriate.

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Table 1. Locations of waypoints and CTD stations.

Station Name	**Latitude**	**Longitude**
W. Channel	47° 41.161’N	122° 52.633’W
Sill Toe	47° 40.669’N	122° 51.665’W
E. Channel	47° 41.072’N	122° 49.623’W
CTD 1	47° 40.938’N	122° 50.304’W
CTD 2	47° 40.803’N	122° 50.984’W
CTD 3	47° 40.985’N	122° 52.322’W

Table 2. Sampling schedule for the four data collection cruises aboard the *R/V Barnes*.

Dates	**Data Collected**	**Sampling Start Time (PST)**	**Approx. Length of Sampling (including transit time)**
25 February 2004	ADCP	1315	2.0
25 February 2004	ADCP	1654	2.0
26 February 2004	ADCP	0638	2.5
4 March 2004	ADCP, CTDs	0701	3 hours
4 March 2004	ADCP, CTDs	1549	3 hours
5 March 2004	ADCP	0609	2.5 hours
10 March 2004	ADCP	1805	1.5 hours
12 March 2004	ADCP	0605	1.5 hours
22 March 2004	ADCP	1802	1.5 hours
24 March 2004	ADCP	1440	2.0 hours
26 March 2004	ADCP	0705	1.5 hours
7 April 2004	ADCP, CTDs	1949	2.5 hours
8 April 2004	ADCP, CTDs	0901	3 hours
8 April 2004	ADCP, CTDs	1534	3 hours
9 April 2004	ADCP, CTDs	0638	2.5 hours

Figure Legends

Figure 1. (a) Map of northern Hood Canal showing the major sills and Dabob Bay (after Kollmeyer 1965). Black rectangle indicates study area shown in Figure 1b. (b) Location of waypoints for ADCP tracks and CTD casts across the sill at the entrance to Dabob Bay. Image adapted from Capn Navigation software.

Figure 2. Three-layer model proposed by Kollymeyer (1965). Water flows in at depth and at the surface, while water flows out at mid-depth. (From Kang 2003).

Figure 3. (a) Raw northward data from an ADCP transect taken 4 March 2004. Notice the large hiccups of blue (very negative) velocity values that extend down beyond the bottom. (b) Raw northward data from an ADCP transect taken 10 March 2004. Notice there are fewer hiccups in the ADCP data—only a little on the western channel side.

Figure 4. Profile of potential temperature (θ) taken at station CTD 3 on 7 April 2004 at 1949 PST. The warm portion of water below ~110 m is warm, dense water coined as a snark by Ebbesmeyer (1973).

Figure 5. θ-σ_θ diagrams for all CTD casts at all locations on (a) 3-5 March 2004 and (b) 7-9 April 2004. Notice that the CTD3 (indicated by +) have the warmest and densest water at each cast.

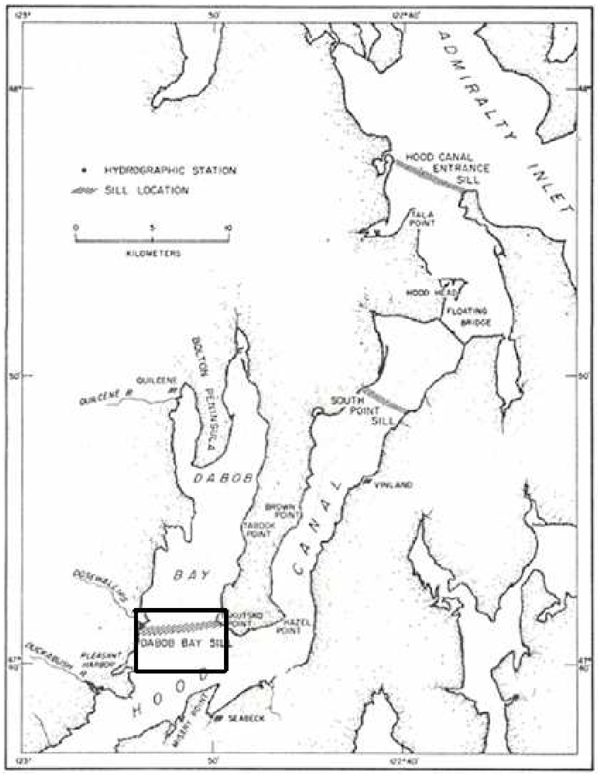
Figure 6. MPAS velocity for the western channel plotted against tidal current. Colors indicate different cut-off depths.

Figure 7. MPAS velocity for the western channel plotted against cut-off depth. Colors indicate different cruises.

Figure 8. MPAS velocity for the entire channel plotted against tidal current. Colors indicate different cut-off depths.

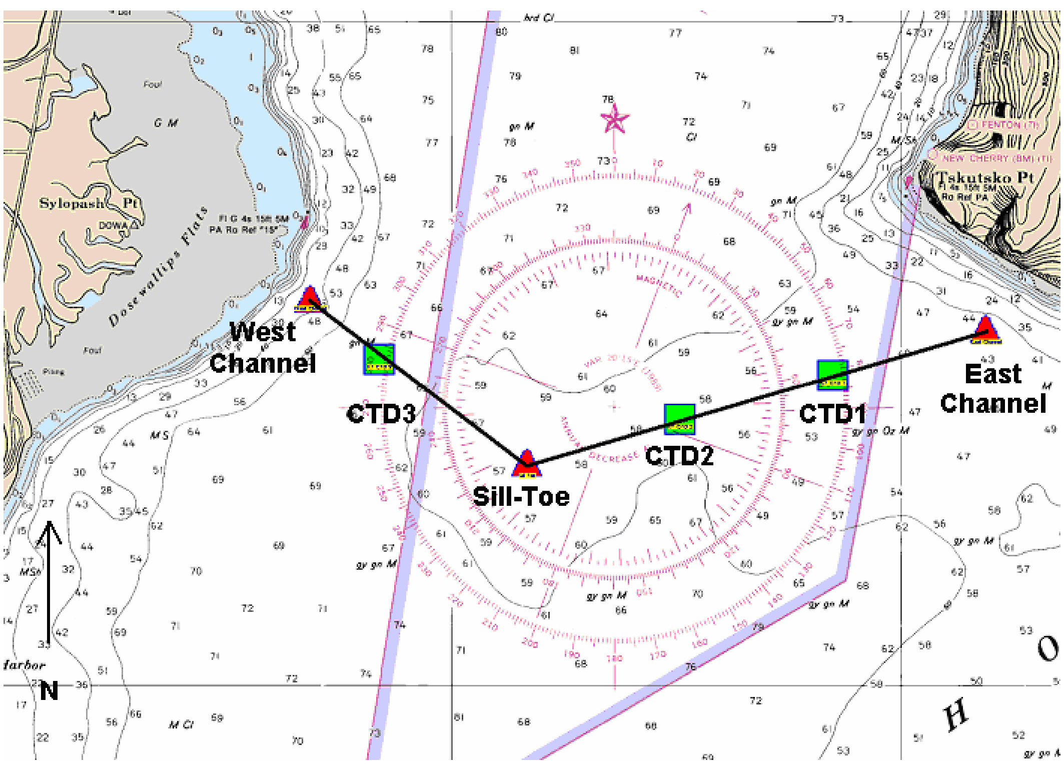
Figure 9. MPAS velocity for the entire channel plotted against cut-off depth. Colors indicate different cruises.

A

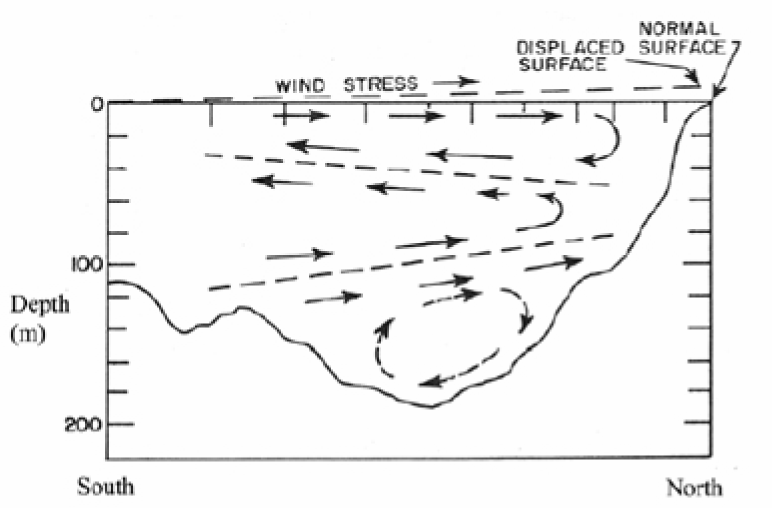


HYDROGRAPHIC STATION
SILL LOCATION
KILOMETERS
ADMIRALTY INLET
HOOD CANAL ENTRANCE SILL
TALA POINT
HOOD HEAD
FLOATING BRIDGE
BOLTON PENINSULA
QUILCENE
SOUTH POINT SILL
DABOB
BAY
CANAL
VINLAND
BROWN POINT
TABOOK POINT
HAZEL POINT
DABOB BAY SILL
HOOD
SEABECK

B



Sylopash Pt
Dosewallips Flats
Tskutsko Pt
West Channel
CTD3
Sill-Toe
CTD2
CTD1
East Channel
N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DISPLACED SURFACE
WIND STRESS
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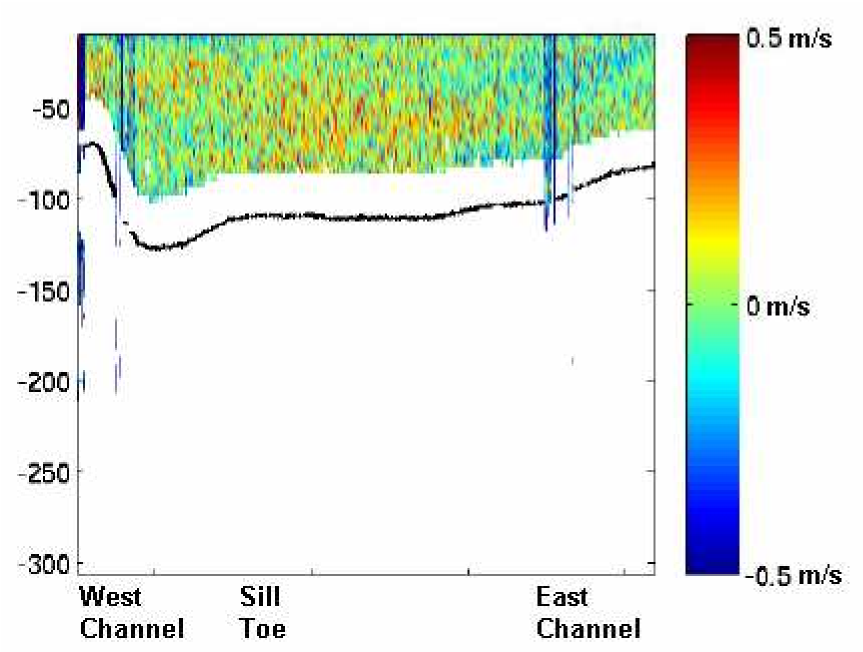
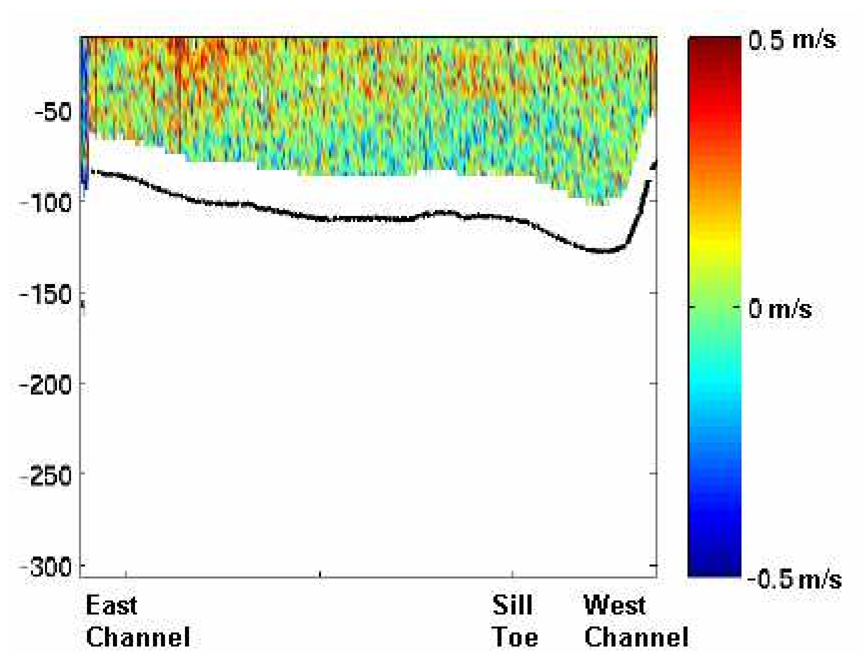
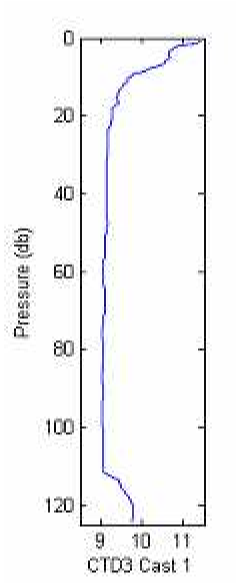
100
200
Depth (m)
South
North

A


0.5 m/s
0 m/s
-0.5 m/s
-50
-100
-150
-200
-250
-300
West
Channel
Sill
Toe
East
Channel

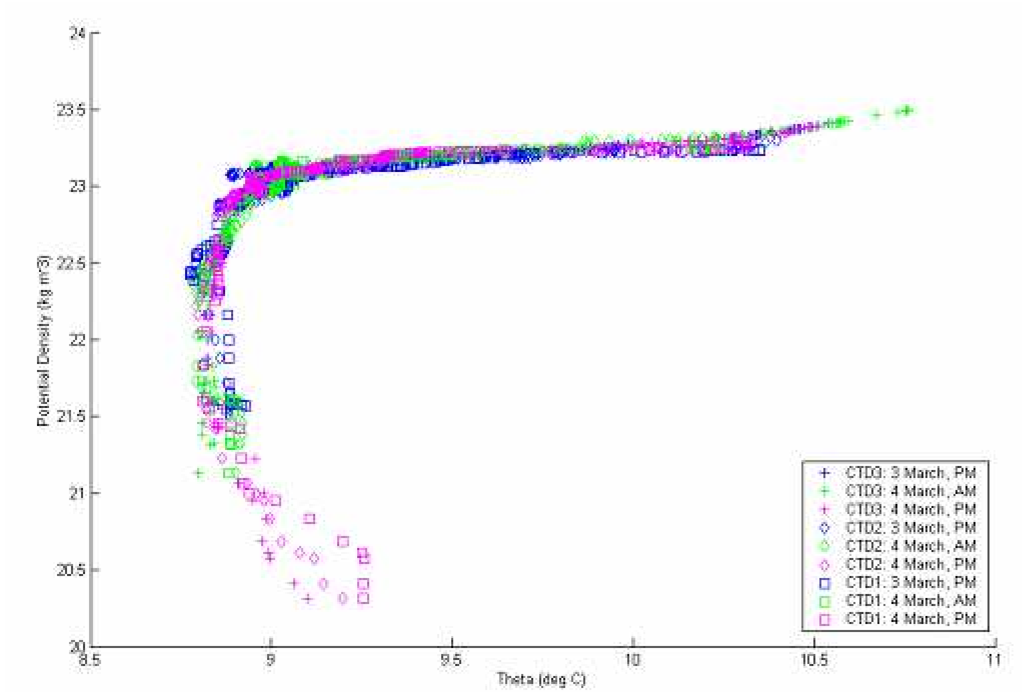
B


0.5 m/s
0 m/s
-0.5 m/s
-50
-100
-150
-200
-250
-300
East
Channel
Sill
Toe
West
Channel

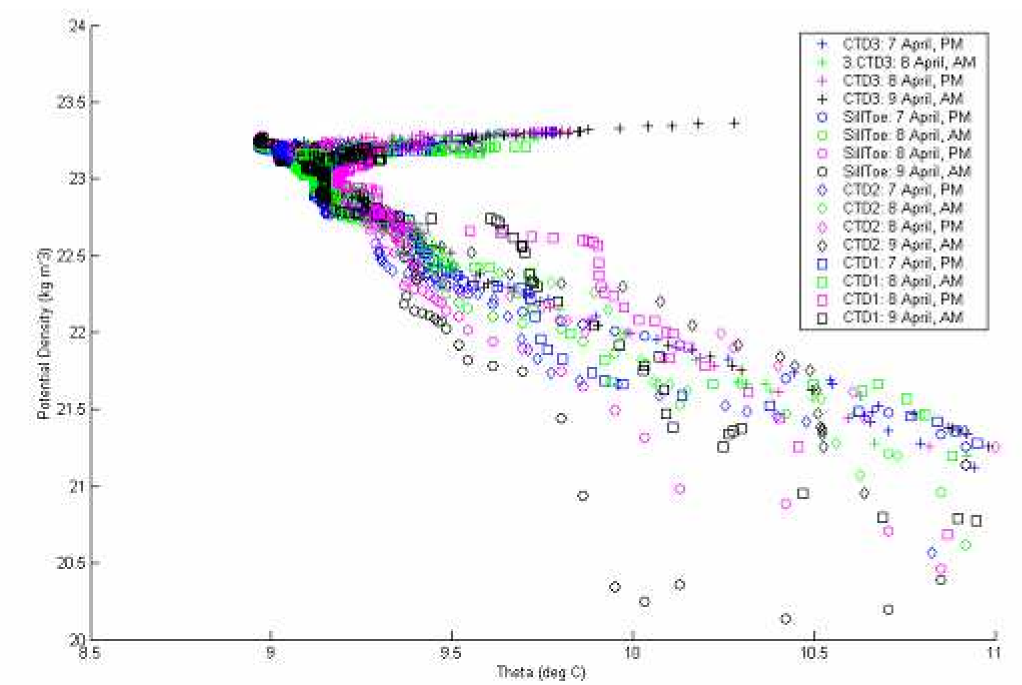


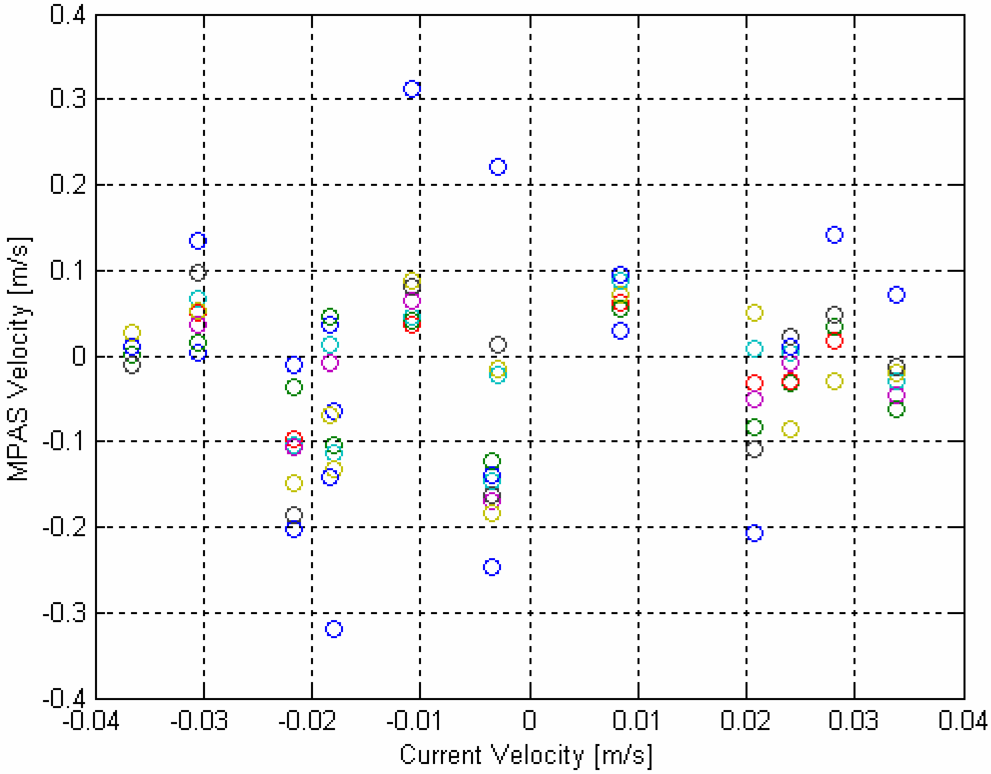
Pressure (db)
0
20
40
60
80
100
120
9
10
11
CTD3 Cast 1

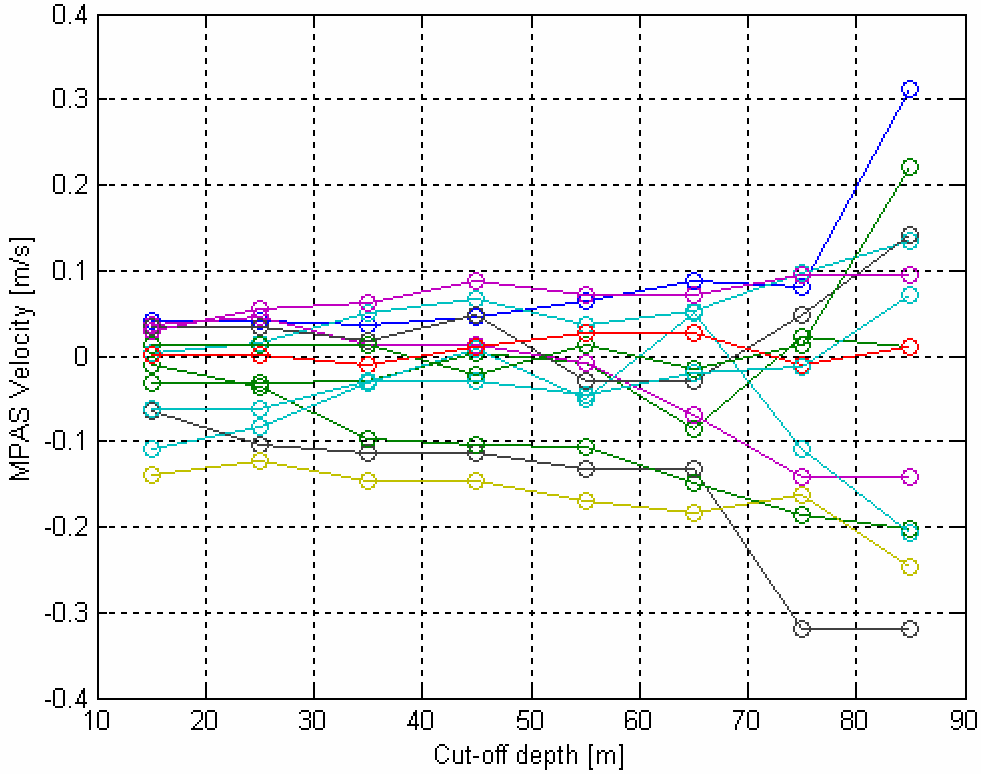
A

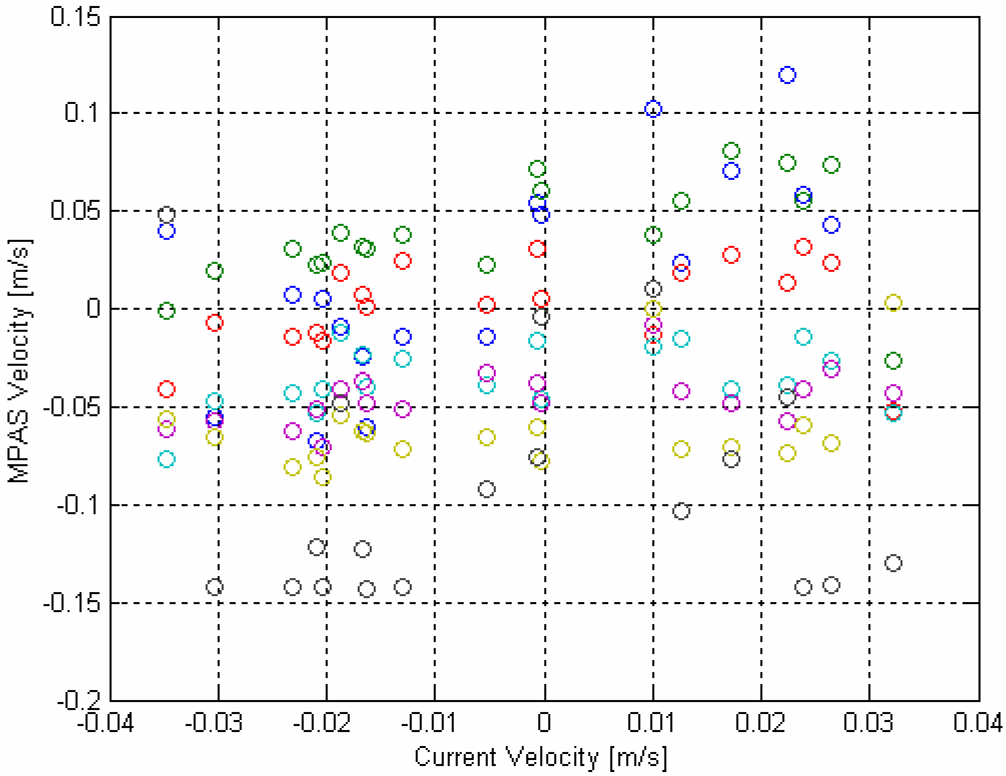

Potential Density (kg m^3)
Theta (deg C)
CTD3: 3 March, PM
CTD3: 4 March, AM
CTD3: 4 March, PM
CTD2: 3 March, PM
CTD2: 4 March, AM
CTD2: 4 March, PM
CTD1: 3 March, PM
CTD1: 4 March, AM
CTD1: 4 March, PM

B

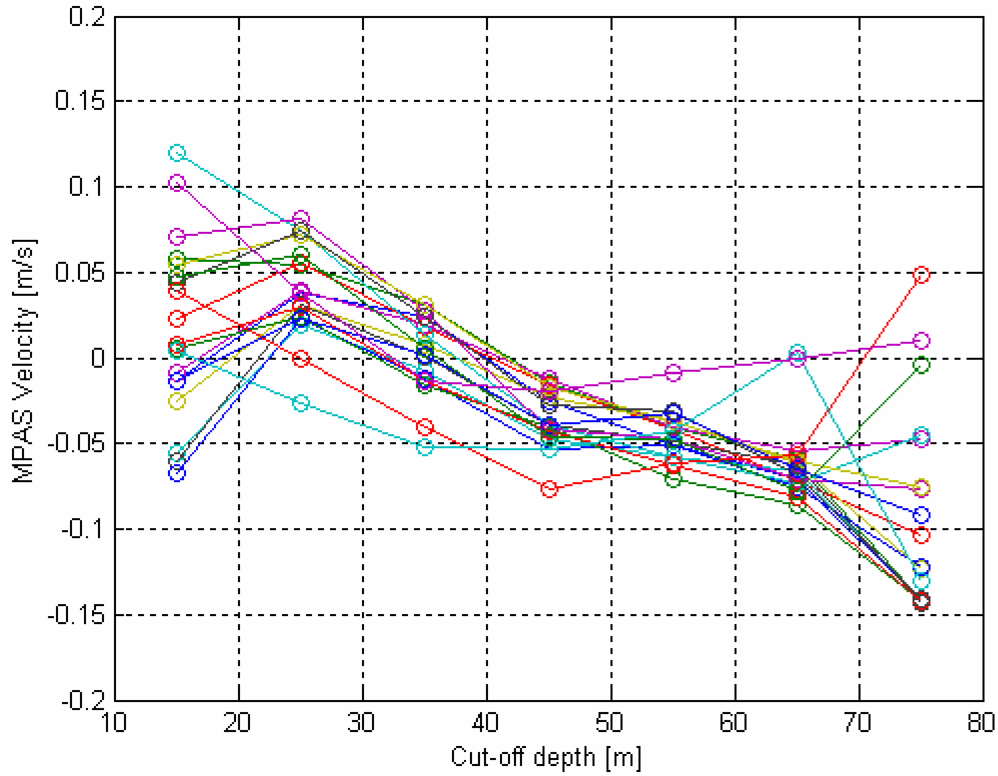

Potential Density (kg m^3)
Theta (deg C)
CTD3: 7 April, PM
3.CTD3: 8 April, AM
CTD3: 8 April, PM
CTD3: 9 April, AM
SillToe: 7 April, PM
SillToe: 8 April, AM
SillToe: 8 April, PM
SillToe: 9 April, AM
CTD2: 7 April, PM
CTD2: 8 April, AM
CTD2: 8 April, PM
CTD2: 9 April, AM
CTD1: 7 April, PM
CTD1: 8 April, AM
CTD1: 8 April, PM
CTD1: 9 April, AM


MPAS Velocity [m/s]
Current Velocity [m/s]
0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.04
-0.03
-0.02
-0.01
0
0.01
0.02
0.03
0.04


0.4
0.3
0.2
0.1
0
-0.1
-0.2
-0.3
-0.4
10
20
30
40
50
60
70
80
90
MPAS Velocity [m/s]
Cut-off depth [m]



0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
-0.04
-0.03
-0.02
-0.01
0
0.01
0.02
0.03
0.04
MPAS Velocity [m/s]
Current Velocity [m/s]


0.2
0.15
0.1
0.05
0
-0.05
-0.1
-0.15
-0.2
10
20
30
40
50
60
70
80
MPAS Velocity [m/s]
Cut-off depth [m]