Freshwater flux and mixing of a highly glaciated fjord: Glacier Bay, Alaska

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Abstract

Glacier Bay is a highly glaciated fjord in southeastern Alaska that exhibits a unique pattern of circulation due to its large amount of freshwater input from both tidewater glaciers and rivers. This freshwater input determines stratification within the water column, which also affects deepwater intrusion from the ocean. To measure this freshwater input into the bay six surface surface drifters were deployed. The tidal signal was averaged out over the course of several tidal cycles. Wind measurements were used to subtract wind forcing from drifter trajectories. Drifters were deployed in the main basin of the bay to minimize loss of equipment and maximize any freshwater output signal. Freshwater flux was then calculated using Knudsen's relation and found to be 1,865.57 m^3s^{-1} or about $\frac{1}{5}$ of previous studies for Southeast Alaska.

Introduction

A national park near the city of Juneau, Al, Glacier Bay is a unique opportunity to study freshwater input from tidewater glaciers into an estuary (Hooge and Hooge 2002). Large tides accompanied by winds from Gulf of Alaska can also present factors that affect the bay (Pickard and Stanton 1980). A large sill at the mouth of the bay provides a mechanism for estuarine type circulation (fig. 1). The freshwater flux drives a significant part of circulation within the bay, including deepwater intrusion from the ocean (Pickard and Stanton 1980). Very little is known about the magnitude of freshwater input to the bay and how it affects circulation (Hooge and Hooge 2002). This study aims to calculate the flux of freshwater entering the bay. An example of how this flux varies can be seen in difference from winter and spring circulation patterns (fig. 2). This kind of variation suggests that the magnitude of deepwater intrusion has some relation to the freshwater flux, which varies by season (fig. 3).

Many different oceanographic processes can be inferred from this study. For instance, ocean water input in an estuary can sustain phytoplankton blooms through nutrients (Banas et al. 2007), changes the gas exchange capability (Feely et al. 2007) and can even cause dead spots of hypoxic or anoxic water (Newton et al. 2006). Biologists can use general water movements to predict the location of planktonic or larval organisms.

Methods

Six Brightwater model 104a drifters were deployed from the R/V Thomas G. Thompson in a line stretching across the main basin of Glacier Bay (see table 1 and 2 for both deployment and recovery sites). Prior to each drifter deployment a CTD cast to the bottom was completed to determine the depth of the freshwater layer. Underway salinity data was taken from the ship's DAS (underway) system, whose intake is 4 meters below the surface of the water. All

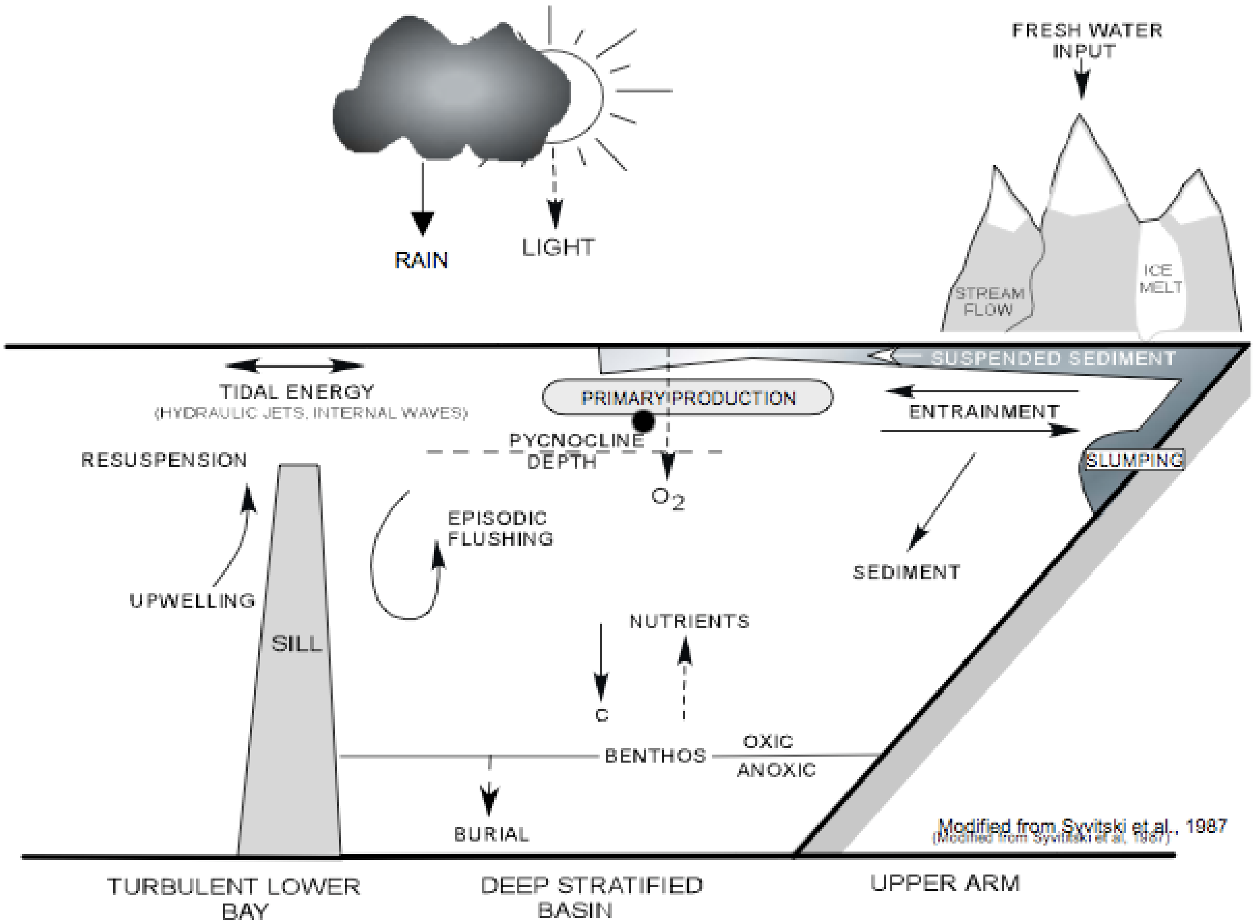

Figure 1: Conceptual model of Glacier Bay estuarine processes. From Syvitski et al. 1987 modified by Hooge and Hooge 2002.

drifters are referred to as their transmitter I.D. number.

Results

Drifting times varied according to where the drifters where headed and how fast i.e. towards the open ocean. Each recovery latitude and longitude is noted in tables 1 and 2 below with a map of drifter tracks is shown in figures 4. After an initial northerly track drifter 7900 went straight south 2 days, this was the first drifter recovered. Drifters 28471 and 8446 were deployed 4 kilometers apart and ended and were recovered within a few hundred meters of each other. Drifter 10521 moved north up the west arm. Drifter's 7906 and 8460 both initially moved north, then beached themselves closer to the deployment sites.

Salinity at the surface varied from 31.3 PSU to 29.4 within the bay itself (fig. 5). The lowest value was observed at the head of Tarr Inlet, with the highest value observed at the entrance to the bay. CTD casts (fig. 6) determined the depth of the freshwater layer to be 8 meters.

Analysis

In order to discuss drifter movement an analysis of the data must be carried out. Tidal effects can be neglected because drifter deployments lasted over several tidal cycles. Viewing the drifter trajectories we notice initially that all

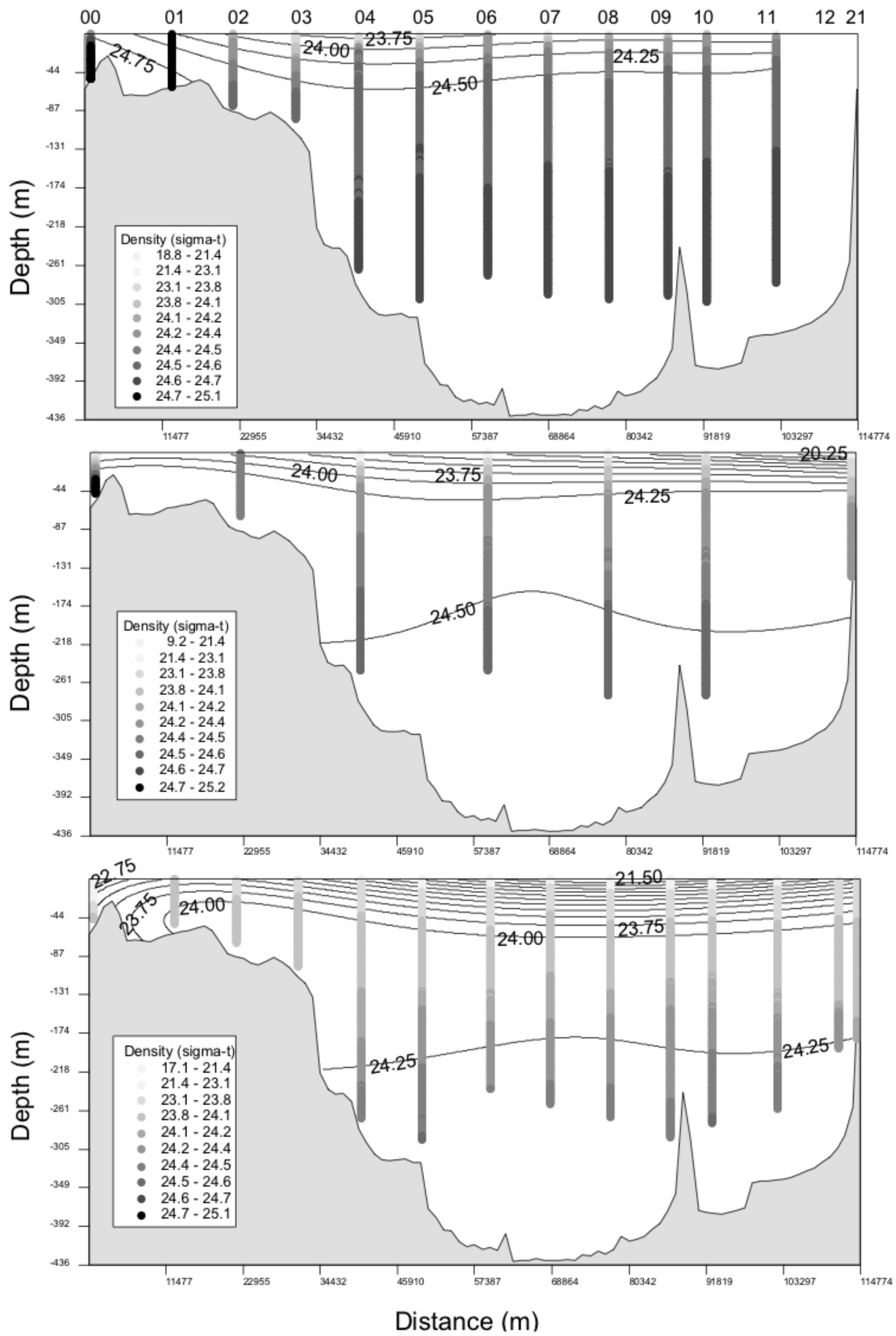

Figure 2: Density Profile from May, July, and September respectively. From stations 1-11. Note that towards the end of the summer a general freshening of the water column is observed. From Hooge and Hooge 2002.

Drifter Number	Latitude	Longitude	Time(GMT)	Date(GMT)
28471	58°40.6961'	136°17.0183'	11:25	3/19/08
10521	58°43.2090	136°15.0177'	13:26	3/19/08
8446	58°43.4462'	136°13.2987'	14:12	3/19/08
7900	58°43.8040'	136°10.9692'	14:50	3/19/08
7906	58°44.2012'	136°7.8301'	15:38	3/19/08
8460	58°44.5467'	136°5.88201'	16:32	3/19/08

Table 1: Latitudes, Longitudes, time, and date of Drifter Deployment sites.

Drifter Number	Latitude	Longitude	Time(GMT)	Date(GMT)
7900	58°31.89'	136°0.018'	20:13	3/21/08
8446	58°38.9439'	136°14.2195'	22:12	3/21/08
28471	58°39.3071'	136°14.6549'	22:17	3/21/08
8460	58°45.2985'	136°11.8785'	0:19	3/22/08
7906	58°47.0095'	136°8.7346'	1:53	3/22/08
10521	58°45.62'	136°26.91'	16:05	3/22/08

Table 2: Latitudes, Longitudes, time, and date of Drifter Recovery sites.

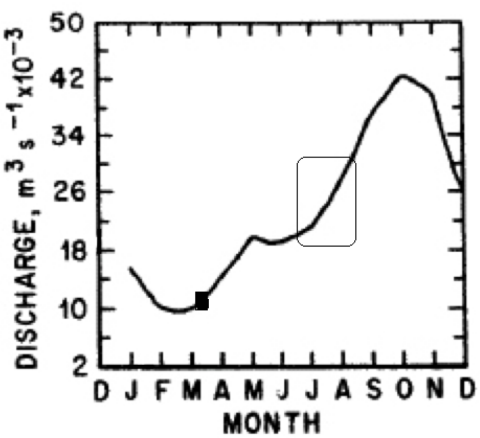

Figure 3: Seasonal freshwater discharge variation of southeast Alaska from Royer 1982.

drifters are carried north. Deployment was accompanied by a strong southerly wind, which pushed drifters and accompanying water north (figures 7–12). Consequently this factor plays a strong role in water circulation within the bay. To account for wind forcing a correlation between the drifter velocities and wind velocities was calculated. A plot of drifter U and V velocity vs. Wind U and V velocity was created for all of the drifters. By taking every drifter's velocity and correlating it with wind velocity a correlation factor can be determined (figs. 13 and 14). Multiplying this factor times the wind velocity and then subtracting the resultant from the drifter velocity yields an adjusted drifter velocity. This adjusted drifter velocity is then factored into the original trajectories for a picture of water movement without wind influences. By subtracting the distance from where the drifters were initially deployed to the adjusted end points, a rate can be calculated from the drift times. These rates are shown in the tables 3 and 4 below with an average rate calculated for all drifters moving out of the bay. Average of rates= 0.192080073 m s^{-1}.

Drifter I.D. Number	Distance Moved South(Meters)	Drift Time(Seconds)	Rate(m s^{-1})
7900	11898.4	190991	0.062298223
7906	47337.84	208440	0.227105354
8446	33582.4	201128	0.166970288
8460	39564.96	199332	0.198487749
10521	45558.64	196218	0.232183796
28471	56378.4	212400	0.265435028

Table 3: Distance that drifters moved south using adjusted using wind correlations. Rate is calculated by distance moved south/drift time.

Discussion

To calculate the freshwater flux entering the bay Knudsens relation (Knudsen 1900 and Hansen and Rattray 1966) regarding mass balance in an estuary will be used. These equations state that the volume coming into an estuary from the ocean (Q_{in}) plus the volume of rivers (Q_r) has to equal the volume leaving the estuary (Q_{out}). This equation can be written as:

$$Q_{out} = Q_{in} + Q_r$$

Knudsen's relation also states that:

$$Q_{in} = Q_r \frac{S_{out}}{\triangle S}$$

$$Q_{out} = Q_r \frac{S_{in}}{\triangle S}$$

Where (S_{out}) and (S_{in}) are salinities coming out of and into the estuary respectively. ($\triangle$S) is the change in salinity from ocean to head of estuary. Since this study only measured the velocity moving out of the bay, the second equation will be used. Rearranging this to get Q_r yields:

$$Q_r = Q_{out} \frac{\triangle S}{S_{in}}$$

Q_r is calculated from the cross section area of water moving south times velocity (Q_{out}). This area is 20,000 meters wide by 8 meters deep (fig. 6) which equals a cross sectional area of 160,000 m^2. Multiplying by 0.192080073 m s^{-1} gives us a Q_{out} of 30,732.8 m^3s^{-1}. The $\triangle S = 1.9$ part per thousand, with a S_{in} value of 31.3 parts per thousand. Combining these numbers yields a Q_r of 1,865.57 m^3s^{-1}.

This number is one order of magnitude smaller than the Royer 1982 predicted number for southeast Alaksa (fig 3). Some parts of the bay were frozen during this time, which could account for low freshwater input. Other factors of error could come from drifter deployment locations. Drifters were not located at the mouth of the bay where all sources of freshwater input had to exit. This was done to minimize equipment loss, but could account for some loss of the freshwater signal.

Conclusions

- Freshwater flux into the bay drives the surface layer to move south out of the bay.
- During March in Glacier Bay, wind forces the surface layer more than it would in the summer. This is due to weaker stratification from less freshwater runoff.
- Summer circulation patterns would be dominated by freshwater runoff and less by winds.

Acknowledgments

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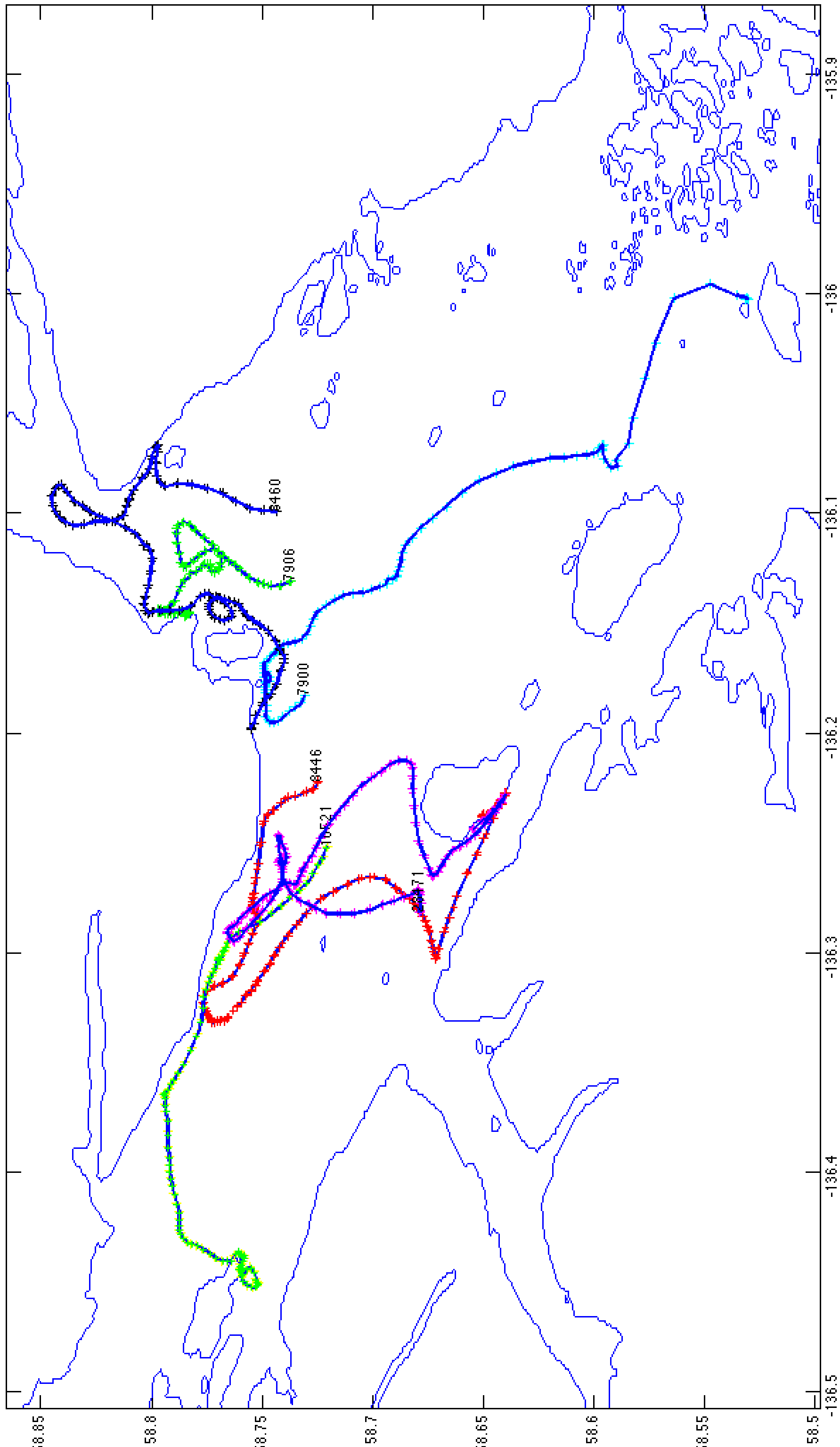

Figure 4: Map of Drifter Tracks. Each drifter is denoted by it's transmitter I.D. number and a color. Arrow Indicates North.

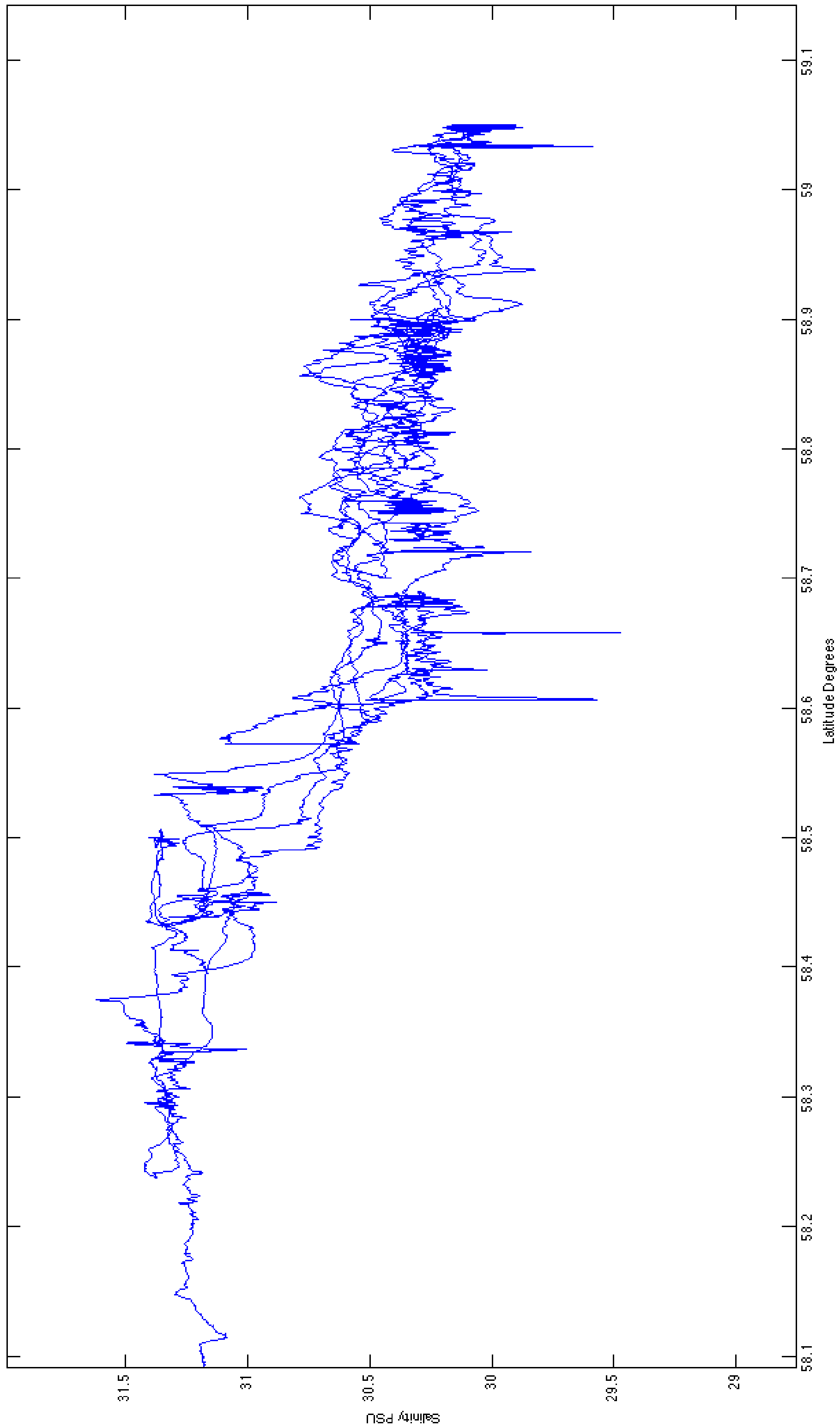

Figure 5: Figure 5: Salinity Values taken 4 meters below the surface as a function of latitude, from the ship's underway system. The salinity gradient being measured is from 58.4 degrees of latitude to 59.05 degrees latitude

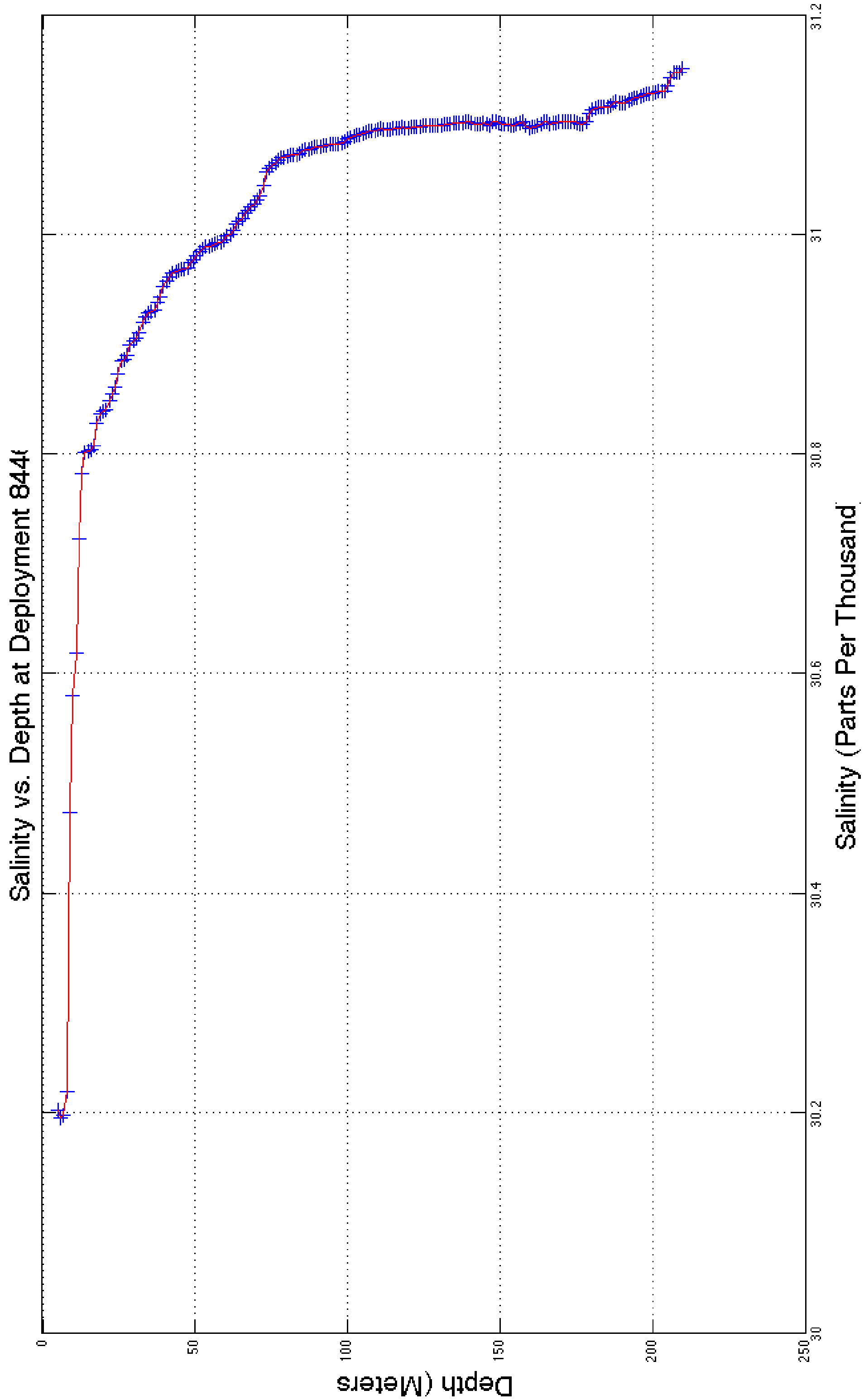

Figure 6: Plot of Salinity vs. Depth at the deployment of drifter 8446. The freshwater layer depth is 8 meters and is used later for calculating the river input.

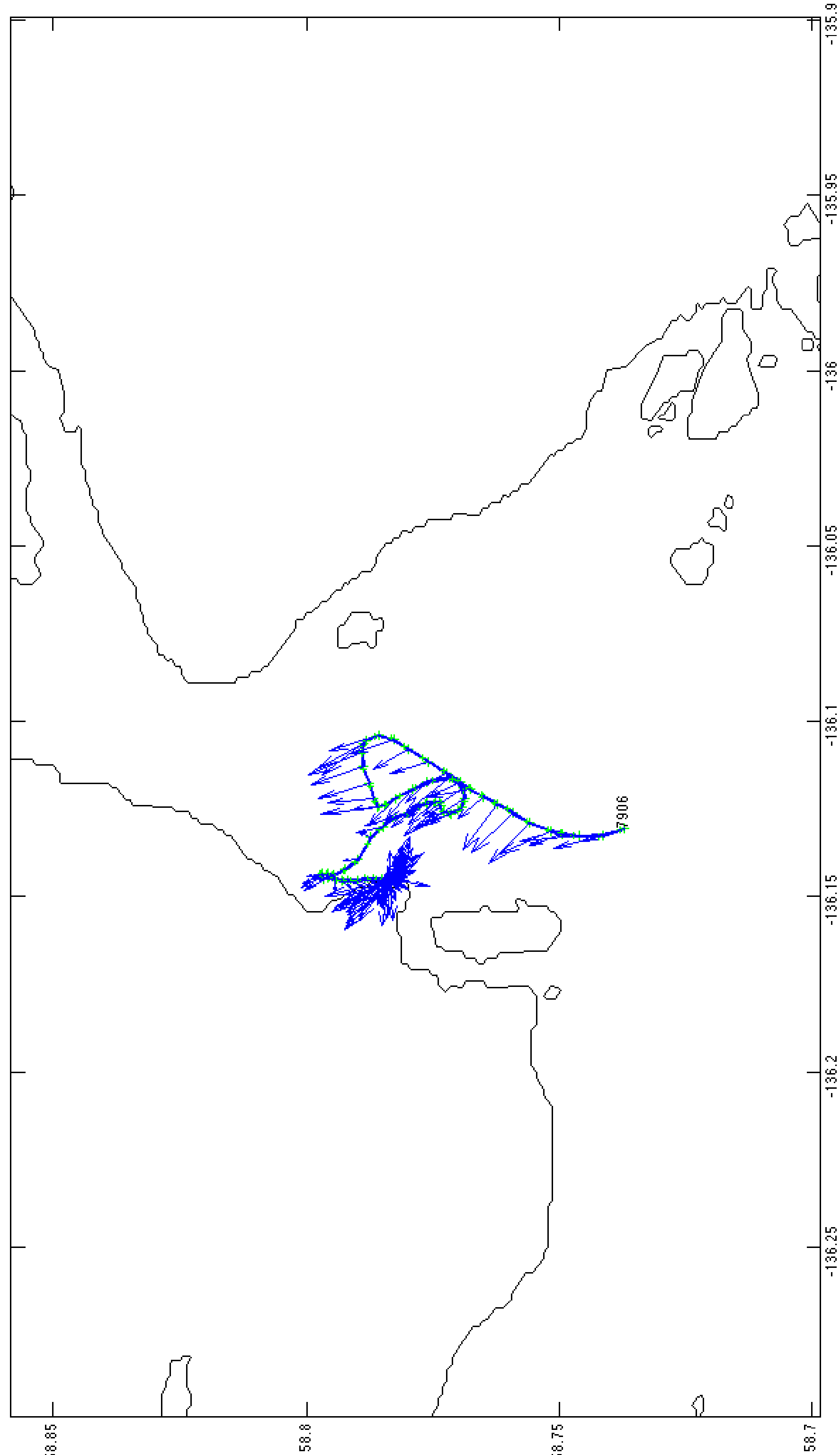

Figure 7: Quiver plot of drifter 7906. Arrows indicate which direction the wind was heading and are overlaid on top of the drifter path. Arrow Indicates North.

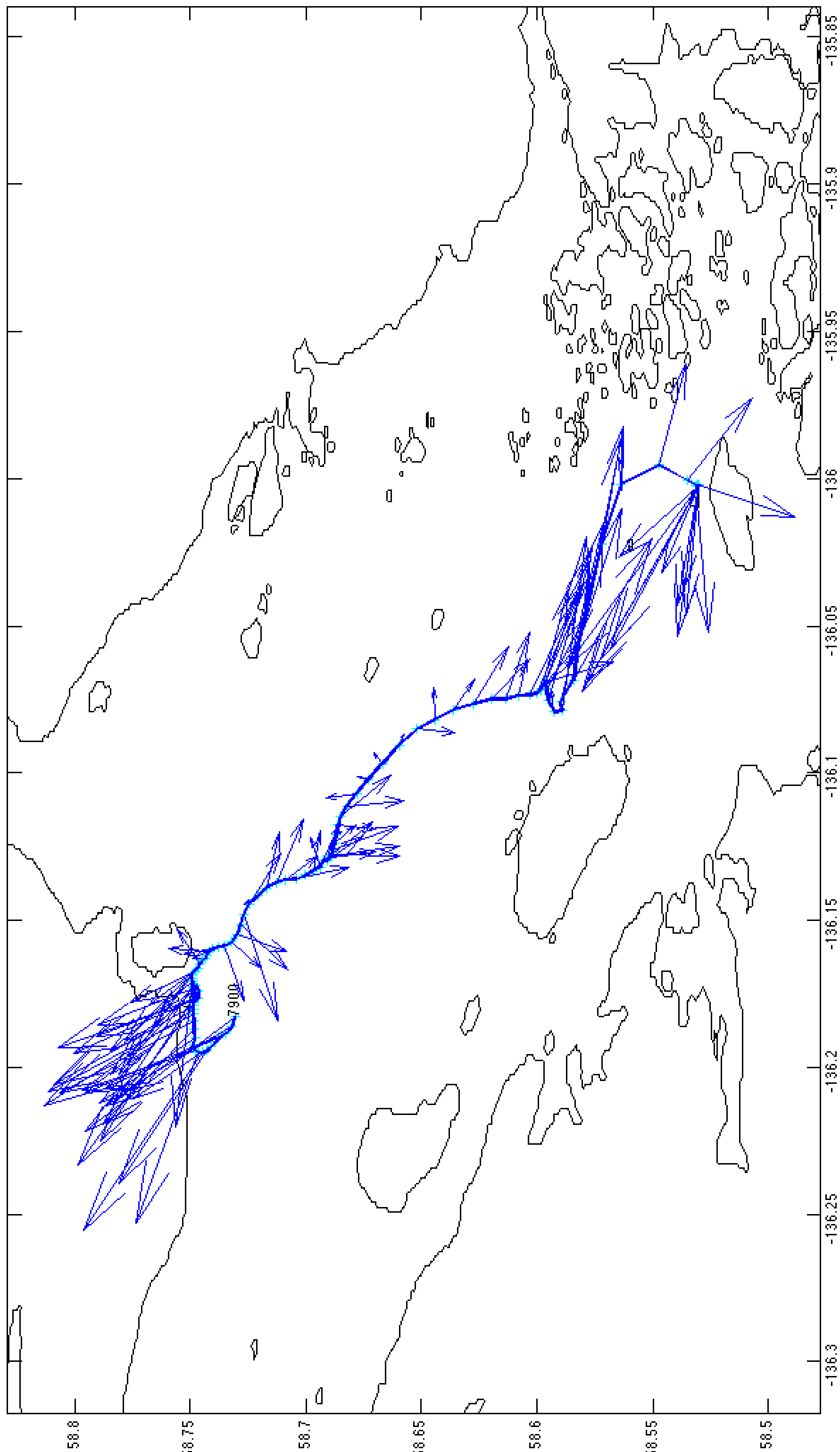

Figure 8: Quiver plot of drifter 7900. Arrows indicate which direction the wind was heading and are overlaid on top of the drifter path. Arrow Indicates North.

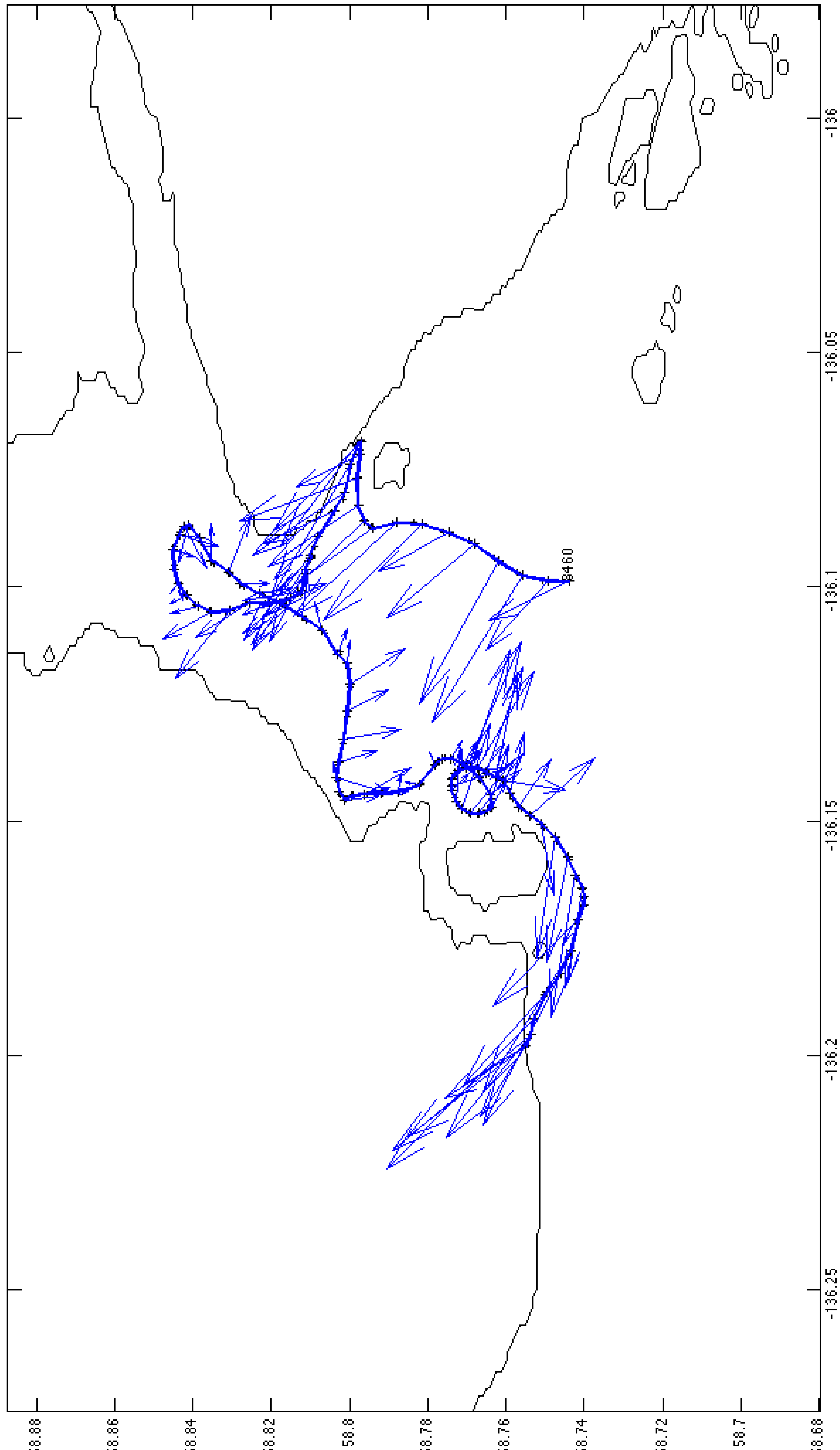

Figure 9: Quiver plot of drifter 8460. Arrows indicate which direction the wind was heading and are overlaid on top of the drifter path. Arrow Indicates North.

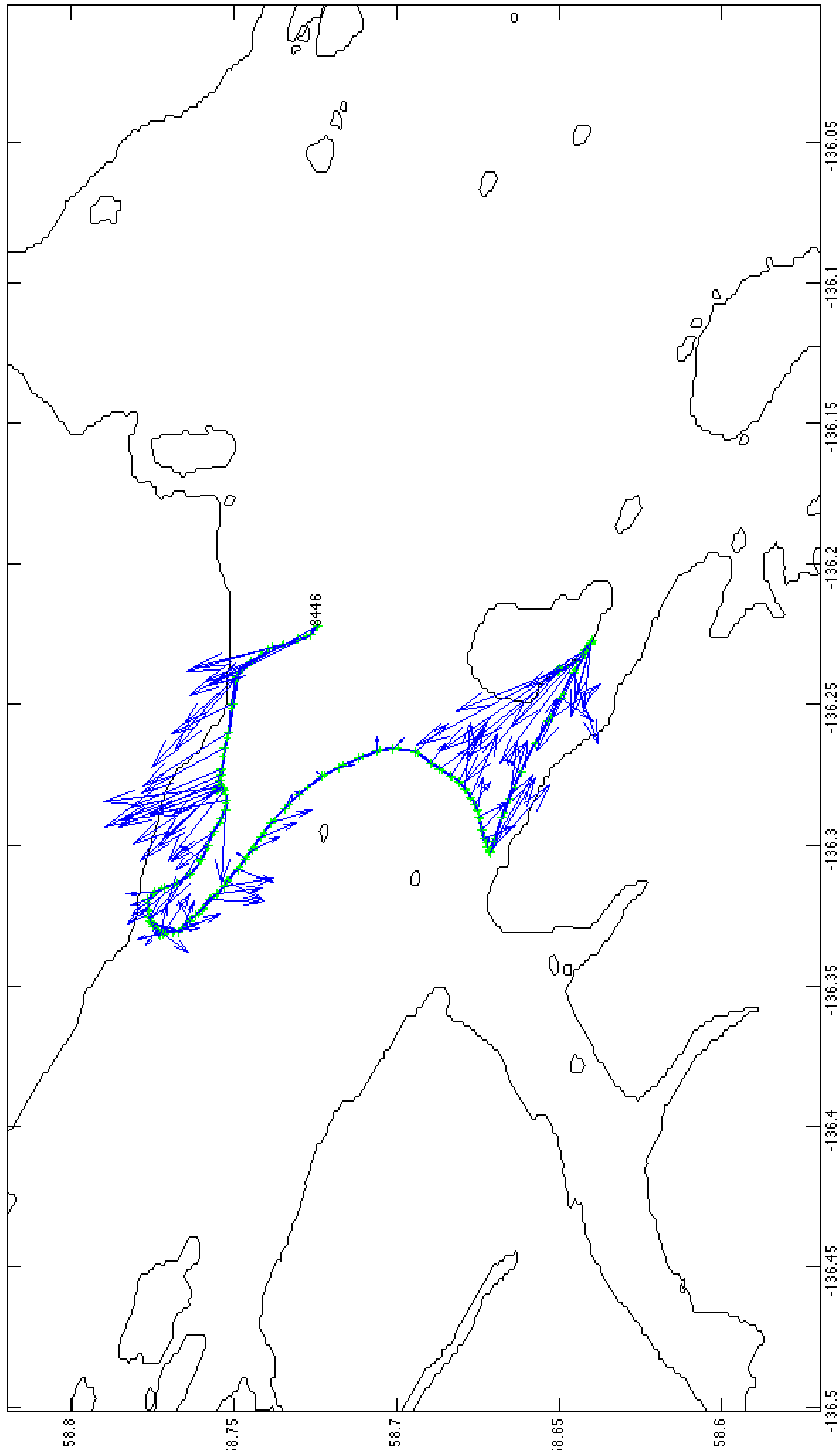

Figure 10: Figure 10: Quiver plot of drifter 8446. Arrows indicate which direction the wind was heading and are overlaid on top of the drifter path. Arrow Indicates North.

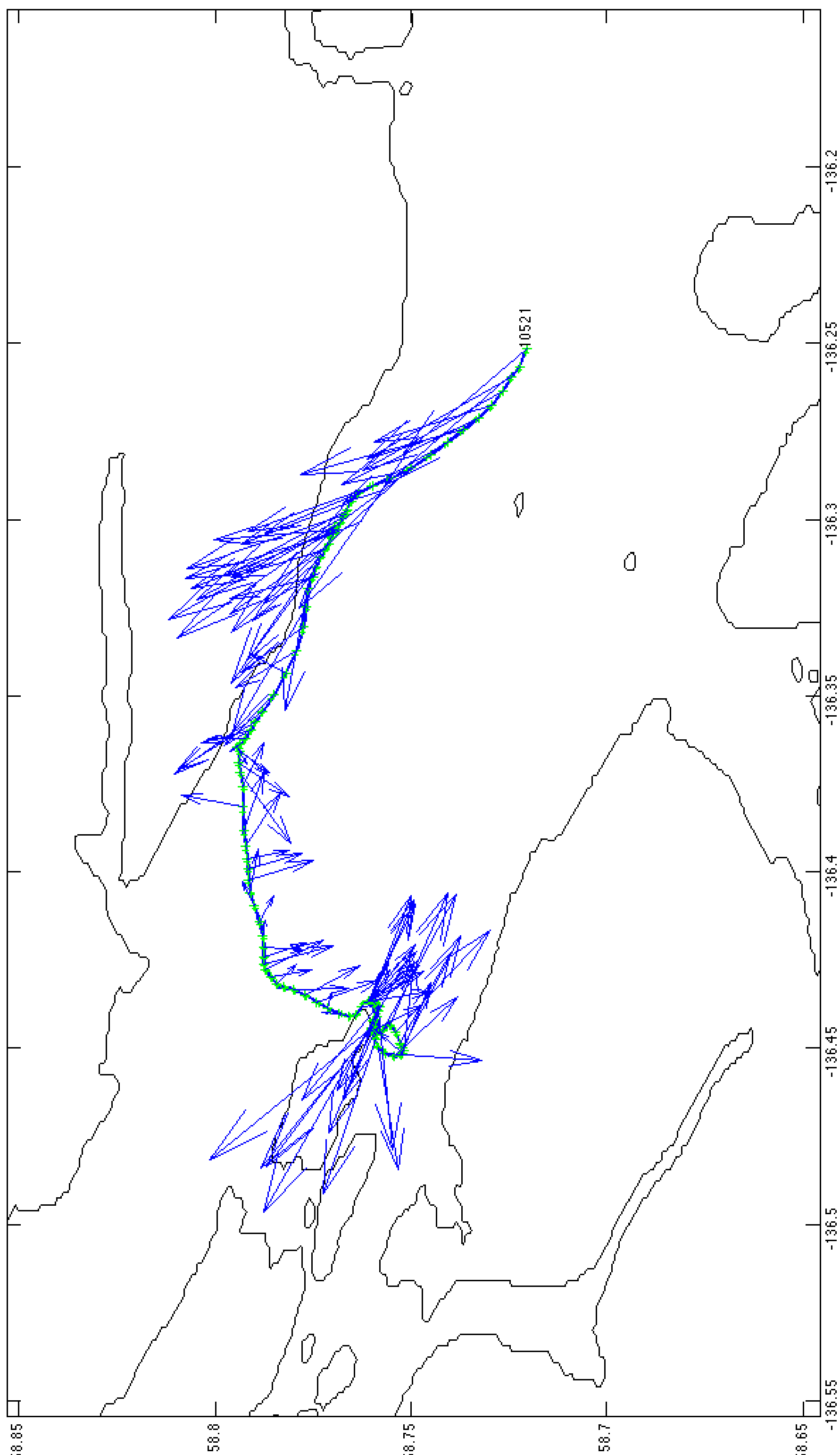

Figure 11: Quiver plot of drifter 10521. Arrows indicate which direction the wind was heading and are overlaid on top of the drifter path. Arrow Indicates North.

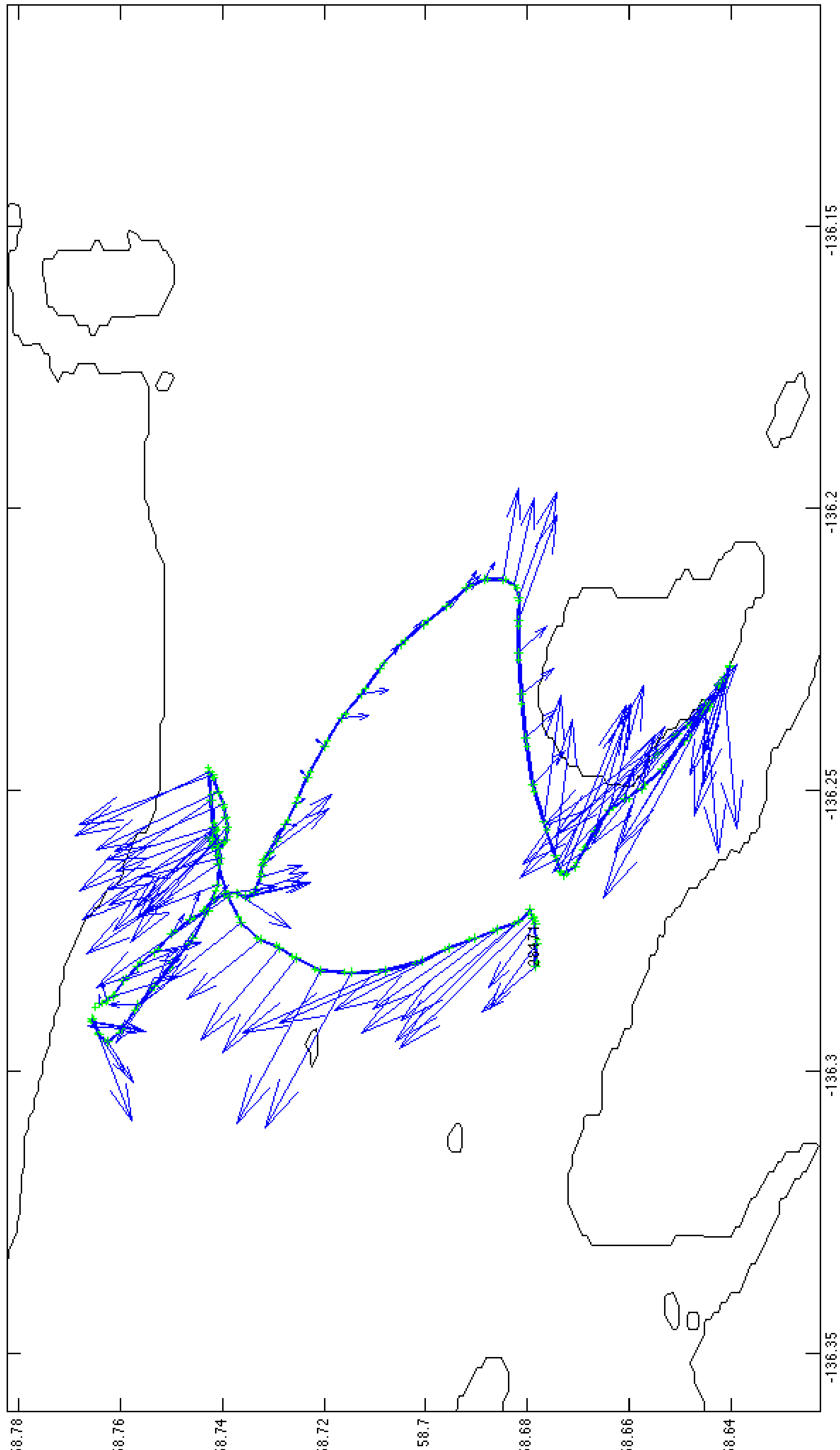

Figure 12: Quiver plot of drifter 28471. Arrows indicate which direction the wind was heading and are overlaid on top of the drifter path. Arrow Indicates North.

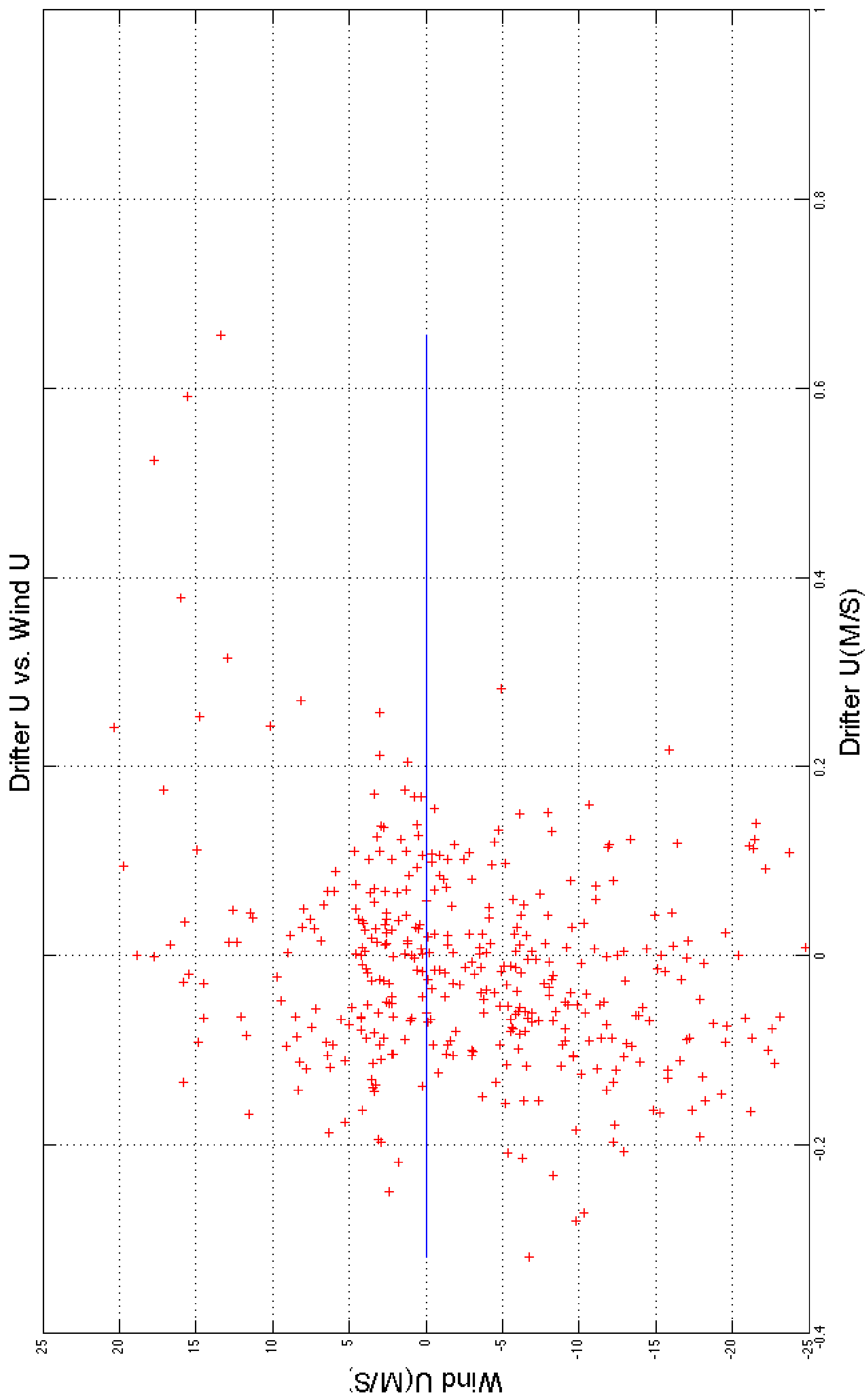

Figure 13: Plot of all drifters' U component of velocity vs all U components of wind velocity. When drifters and wind are moving both with a positive U vector the points will be positive. The trendline represents the affect the wind would have on the drifter if there was no wind. This is what is subtracted out for new trajectories.

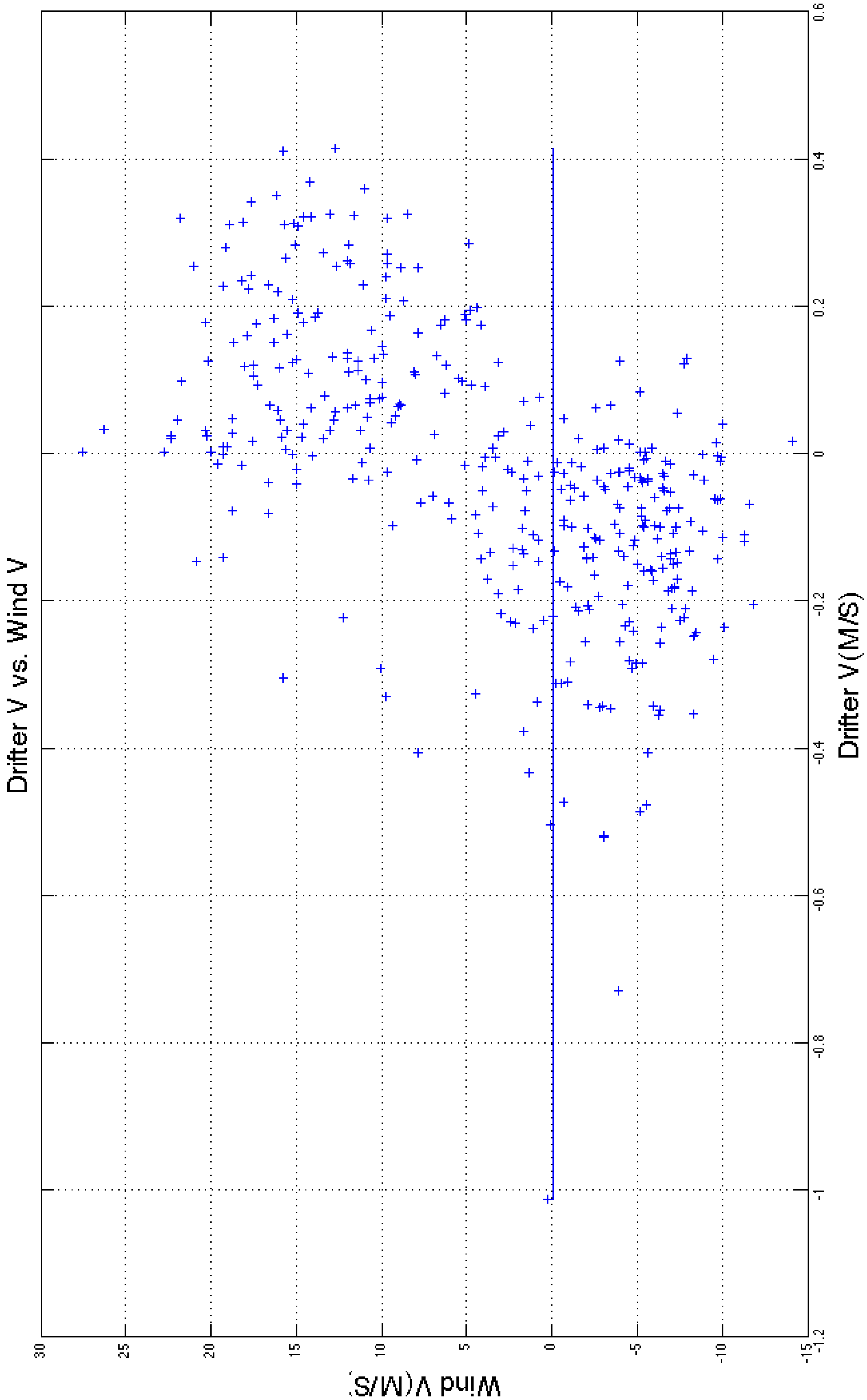

Figure 14: Plot of all drifters' V component of velocity vs all V components of wind velocity. When drifters and wind are moving both with a positive V vector the points will be positive. The trendline represents the affect the wind would have on the drifter if there was no wind. This is what is subtracted out for new trajectories.