Historical oceanographic observations in the Western Valley

Data report

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TECHNICAL REPORT

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1 Introduction

This report aims to document the historical information and data on overflow through the Western Valley (Figure 1), the northernmost deep passage across the Iceland-Faroe Ridge (IFR). The report is part of the "Western Valley Overflow" (WOW) project, which is a cooperation between the Faroe Marine Research Institute (Havstovan) and the Danish Meteorological Institute, funded by the Danish Energy Agency within the Danish Ministry of Energy, Utilities and Climate.

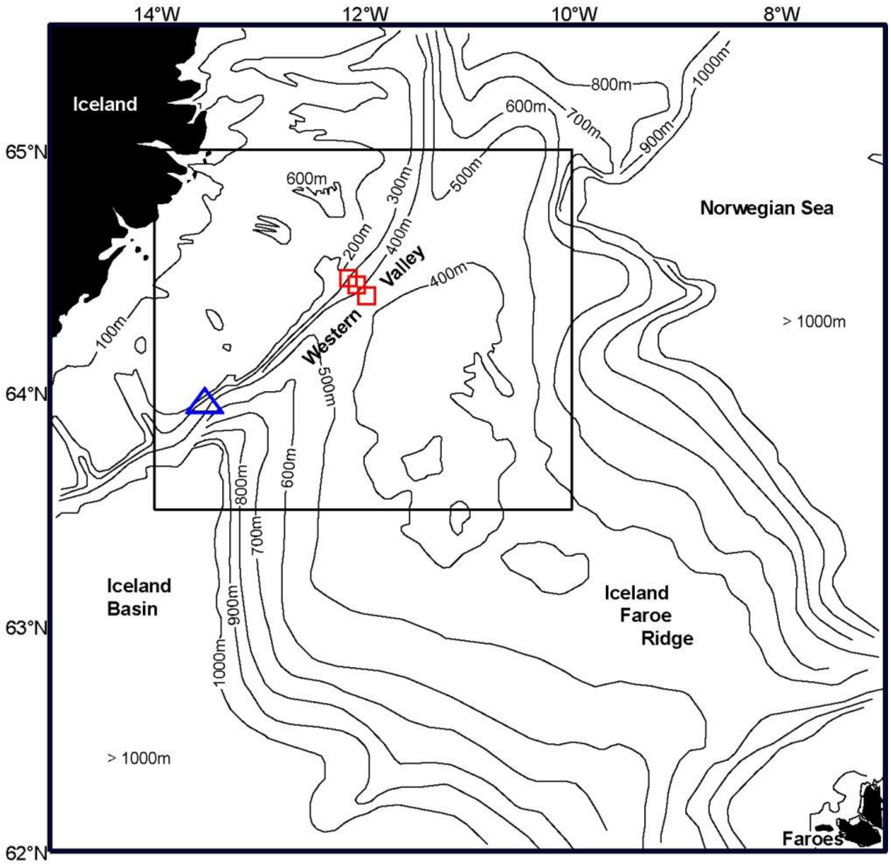

Figure 1. Topography of the Iceland-Faroe Ridge. The rectangular box shows the area around the Western Valley, from which CTD observations have been collected. Red squares indicate the three mooring sites of the WOW field experiment. The blue triangle indicates a site where Perkins et al. (1998) had a current meter mooring and where an ADCP was deployed from September 2005 to October 2007.

The report contains three chapters in addition to this introduction. Chapter 2 presents a brief historical overview of scientific research on overflow across the IFR (IFR-overflow), which started already in the late 19th century, pioneered by Danish oceanographers. Chapters 3 and 4 document our attempts to collect observational temperature and salinity data from the region, as well as an historical ADCP deployment (blue triangle in Figure 1), which are intended to supplement the results from the dedicated WOW field experiment including three moorings (red squares in Figure 1) in the Western Valley from August 2016 to May 2017, deployed in cooperation with the University of Hamburg.

2 Scientific investigations of IFR-overflow

There is a long history of research on the overflow across the IFR. Much of the early work up to the end of the 20th century was reviewed by Hansen and Østerhus (2000) in their study on the exchanges across the Greenland-Scotland Ridge (GSR). The following text is based on their review, updated with additional results from later studies using tracer observations (e.g., Fogelqvist et al., 2003), ADCP moorings (e.g., Østerhus et al., 2008), and autonomous gliders (Beaird et al., 2013).

IFR-overflow was observed more than a century ago by Danish oceanographers. Using results from the “Ingolf expedition”, Knudsen (1898) observed the overflow and suggested that it was intermittent (occurring “in jerks”) whereas Nielsen (1904) argued that it must be continuous. During the next half century, the problem seems only to have been sporadically studied until interest in it resurged in the 1950’s. Dietrich (1956) reported results of measurements from four sections across the ridge and Hermann (1959) and Steele (1959) published sections and maps of bottom temperature. All these observations showed strong evidence of overflow.

In 1960, the International Council for the Exploration of the Seas (ICES) coordinated the first overflow expedition (Overflow ‘60) in which 9 ships from 5 nations made three quasisynoptic hydrographic surveys of the Iceland-Faroe Ridge (Tait*,* 1967). In the following years, hydrographic observations were supplemented by current measurements (Steele, 1967; Meincke, 1972a), leading up to the second overflow expedition (Overflow ‘73) in August/September 1973 where thirteen research vessels carried out individual scientific programs while simultaneously contributing to the general topic of water mass exchange across the Greenland-Scotland Ridge (Meincke, 1974).

In the period 1959 – 1971, a hydrographic section west of the ridge crest was occupied by German research vessels on 14 occasions. This section was located so far west of the ridge crest that any overflow water observed would be unlikely to return eastwards over the ridge. Average properties on this section show that cold water is found all along the ridge as a 100 - 150 m thick layer with temperatures down to 3°C. Based on the comprehensive autonomous glider experiment 2006 – 2009, Beaird et al. (2013) confirmed that evidence of overflow is found at all locations on the Atlantic flank of the IFR, although highly variable.

The typical occurrence of cold water west of the ridge does not imply that the overflow occurs as a broad southwestward flowing stream all over the ridge. The water that does overflow has a velocity which is more along-slope than down-slope. This was argued already by Steele (1961) and confirmed by early current measurements (Meincke, 1972a; Koltermann *et al.,* 1976) and much more comprehensively from the autonomous glider experiment 2006 – 2009 by Beaird et al. (2013).

The water mass composition of the overflow and the origins of individual components have also been studied for a long time. In the deepest layers, Meincke (1972b) found fairly high concentrations of remotely produced deep and intermediate waters, which today would be labeled “Norwegian Sea Deep Water” and “Norwegian Sea Arctic Intermediate Water”. Over the northwestern part of the ridge, close to Iceland, Stefánsson (1962) also found high concentrations of "North Icelandic Winter Water", which according to him is homogenized in winter north of Iceland from a mixture of various source waters.

In the literature, a number of other water masses have been implicated in the formation of IFR-overflow, but even with sophisticated tracer techniques (e.g., Fogelqvist et al., 2003) it may be difficult to assess individual contributions. This is not made less confusing by the fact that water mass names have changed through the long history of research.

Although fairly pure remotely produced water masses on occasion may be identified in some regions, it seems clear that a large part of the IFR-overflow has acquired its main character in a region close to the ridge by mixing of different water masses and sinking in the frontal zone. This water is most clearly identified as a salinity minimum with salinities below 34.90 and temperatures usually around 2 - 3°C and was labeled “Modified East Icelandic Water” by Read and Pollard (1992). Some of the contributing source waters have their origin in the Arctic region but there is also a considerable contribution of Atlantic water that has entered the IFR region from the Iceland Basin (Figure 1). Based on their autonomous glider experiment, Beaird et al. (2016) made a detailed analysis of the components and processes that form the resulting overflow water and identified a seasonal variation involving winter convection, mixed layer instability and deep frontal subduction.

The volume transport of IFR-overflow was estimated already by Dietrich (1956) to be 6 Sv. He did not, however, consider the effect of geostrophy turning the flow from down-slope to along-slope and Steele (1961) reduced this value to 1.5 - 3.0 Sv. From the results of the Overflow '60 expedition, Hermann (1967) estimated 1.1 Sv.

This number, commonly rounded to 1 Sv, has remained as a canonical value in the literature (Meincke, 1983; Dickson and Brown, 1994; Hansen and Østerhus, 2000), but its observational basis is weak. Perkins et al. (1998) used a combination of moorings and hydrographic surveys to find at least 0.7 Sv of pure "Arctic Intermediate Water", but their observations only covered the northernmost part of the ridge. In their review of the overflow transport east of Iceland, Østerhus et al. (2008) discuss results from three deployments of ADCPs in trawl-proof frames on the southeastern part of the IFR. These observations show some interesting features but also demonstrate that any attempt to measure or even monitor overflow volume transport by moored instrumentation in this highly variable and heavily fished area would require immense resources.

An alternative strategy, based on the autonomous glider experiment cited by Beaird et al. (2013), gave a lower bound of 0.8 Sv for the total IFR-overflow with more than half of this occurring over the northern half of the ridge. The gliders do not, however, measure velocity directly and this result is therefore dependent on assumptions of geostrophy and frictional effects on the near-bottom flow.

Summarizing, more than a century of observations has demonstrated that overflow occurs widely distributed over the whole length of the ridge, although variable in time as well as space, but the volume transport of the overflow remains uncertain. For the southern half of the ridge, the average overflow is most likely weak. For this part of the ridge, the estimate by Beaird et al. (2013) of 0.3 Sv seems most reliable although its uncertainty appears almost as high as the value (their Figure 8).

The evidence for overflow across the northern half of the ridge seems more ambiguous. This part of the ridge is dominated by the Western Valley (Figure 1), the deepest passage across this part of the ridge with a sill depth of more than 400 m. East of Iceland, i.e. upstream of this passage, the $\sigma_\theta = 27.8$ kg m^{-3} isopycnal, which is typically used to denote the upper boundary of overflow water, is usually found shallower than 200 m and from simple hydraulic models, one would expect a strong and persistent overflow through the Western Valley (Wilkenskjeld and Quadfasel, 2005; Voet, 2010; Olsen et al., 2016).

Observational evidence for that was provided by a current meter mooring (blue triangle on Figure 1) at 639 m bottom depth close against the continental rise southeast of Iceland (Perkins et al., 1998). This mooring demonstrated a strong bottom flow with low variability at frequencies below one cycle per day. The persistence of this current has been confirmed by an ADCP moored at almost the same location for more than two years, which showed an average along-topography velocity of 50 cm s^{-1} in the core, 50 m above the bottom (Voet, 2010; Olsen et al., 2016).

A bottom current of this speed and persistence must derive from overflow and Beaird et al. (2013) have argued that this overflow must have crossed the northern half of the IFR. From their observations, Perkins et al. (1998) estimated the volume transport of this flow to be more than 1 Sv with 0.7 Sv being "pure overflow" (Arctic Intermediate Water with 0°C). In his doctoral thesis, Voet (2010) similarly estimated a volume transport of 0.5±0.3 Sv of "pure overflow" from the ADCP measurements.

Thus, there is much evidence for a fairly strong and persistent overflow across the northern half of the IFR and the Western Valley would be the most likely path for it to take, but Perkins et al. (1998) "*find no evidence for significant flow through the Western Valley*" when they considered their observations in the valley itself. In the data from their autonomous glider experiment, Beaird et al. (2013) do see periods with strong overflow, but also periods with little or no overflow, and they conclude that the variability is high.

This apparent contradiction between different sources of observational data was the main reason for initiating the WOW project and the dedicated field experiment from August 2016 to May 2017 was intended to determine how strong and how persistent overflow through the Western Valley is. In this report, we document the efforts to obtain historical observations, especially of temperature and salinity, to supplement the results from the field experiment.

3 Historical CTD data

Originally, hydrographical observations were obtained by reversing water bottles with typical vertical resolution several tens of meters at depth. To quantify volume transport of overflow, this would introduce high uncertainties and we therefore have selected only observations from CTD stations. These observations have been collected for various purposes and have variable quality. This is especially the case for salinity, which needs careful calibration to be reliable. On many fisheries research cruises, this is not of critical importance, but accurate salinity is necessary to determine density, especially at low temperatures. We have therefore only selected CTD observations where salinity has been quality controlled.

This has restricted the available data sources and we have focused on observations from three data bases: the CTD data obtained by R/V Magnus Heinason, stored at Havstovan, data from the University of Hamburg, and the NISE data base (Nilsen et al., 2008). We have selected observations from the region, termed the "WV-region", between 63.5°N and 65°N in latitude and 10°W and 14°W in longitude (rectangular box on Figure 1), in which there were 968 CTD stations (101 from Havstovan, 79 from the University of Hamburg, and 788 from the NISE database).

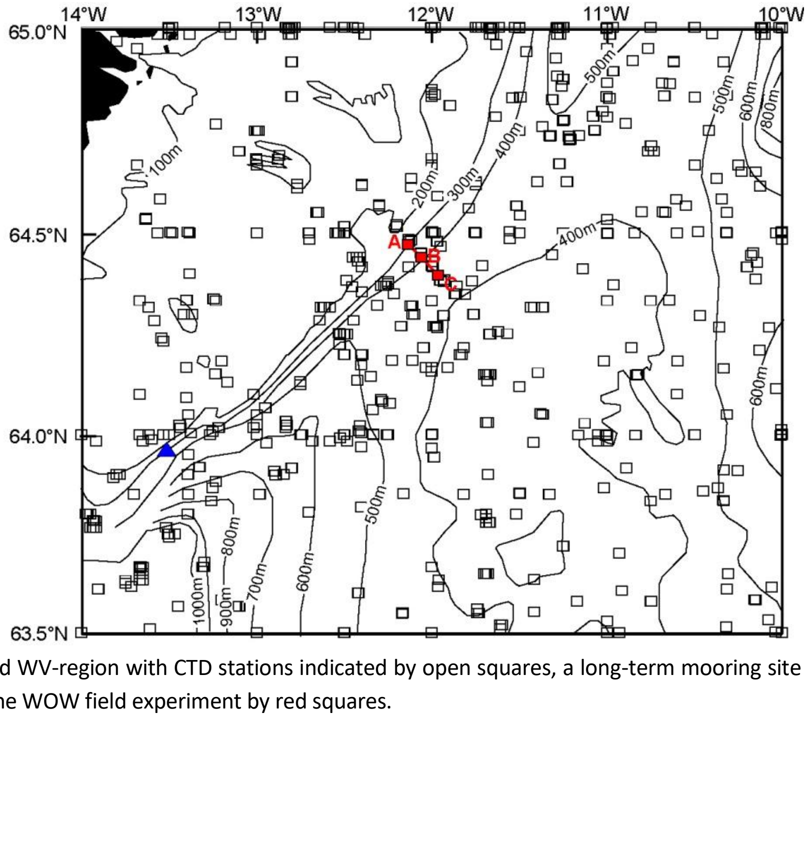

Figure 2. The selected WV-region with CTD stations indicated by open squares, a long-term mooring site by blue triangle, and mooring sites from the WOW field experiment by red squares.

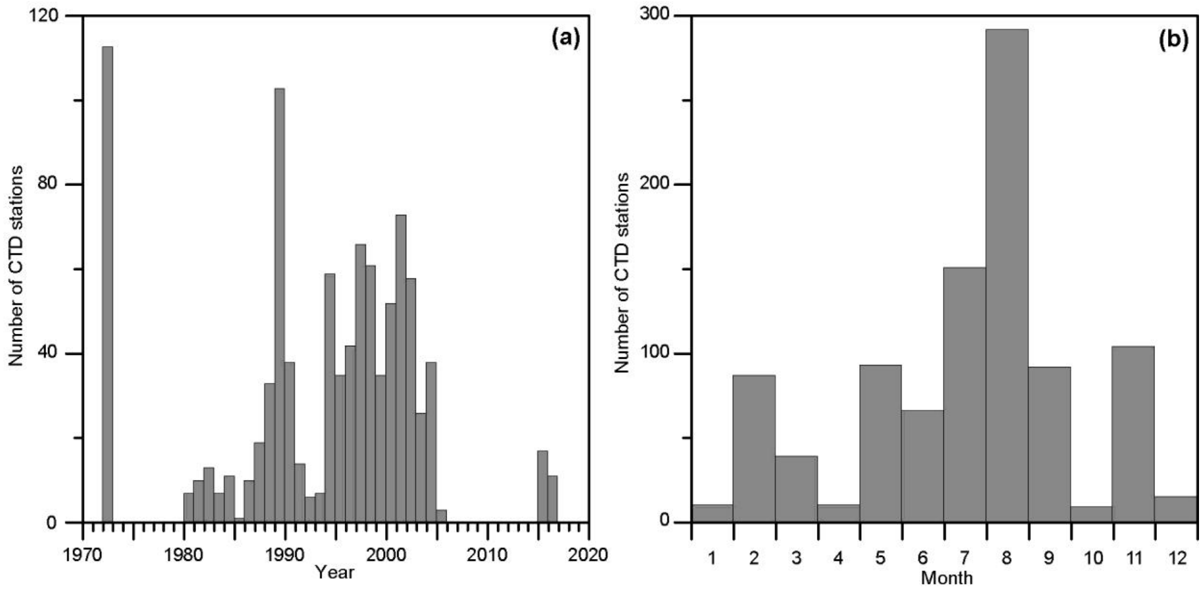

Figure 3. Number of CTD stations in selected WV-region every year (left) and every month (right).

The spatial distribution of the CTD stations in the selected WV-region is shown in Figure 2 while their temporal distribution is shown in Figure 3. In Figure 4, the temperature-salinity characteristics is shown for all CTD stations with bottom depth exceeding 200 m (778 stations).

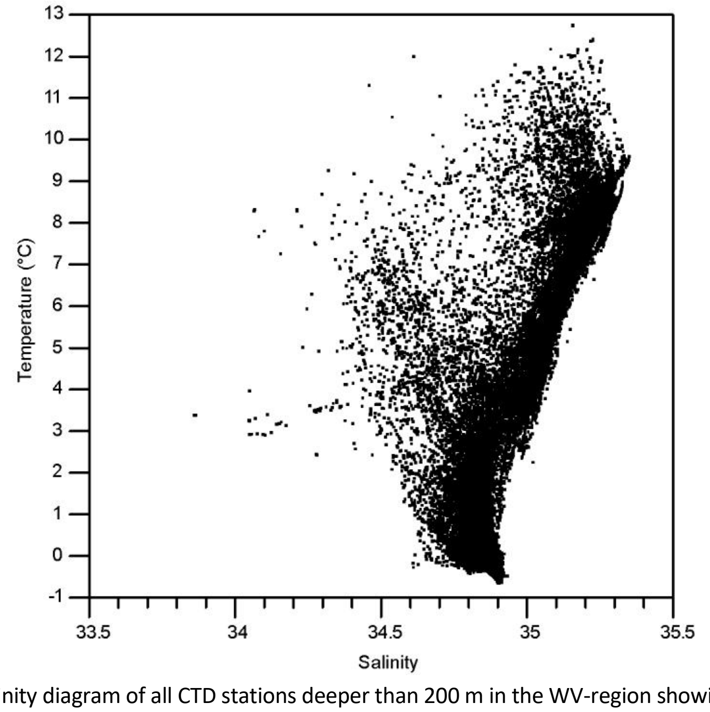

Figure 4. Temperature-salinity diagram of all CTD stations deeper than 200 m in the WV-region showing observations for every 10 m.

4 Historical ADCP data

The main focus in this report is on the historical CTD data, but we include also the data from one ADCP deployed by the University of Hamburg at the blue triangle in Figure 1 (Voet, 2010). The reason for including these observations is that this record is one of the main arguments for expecting a strong overflow through the Western Valley, as has been discussed in Chapter 2. As seen in Figure 5, the average velocity profile shows a strong bottom-intensified current with a high persistence and temperature indicating an overflow contribution. Details of this deployment are listed in Table 1.

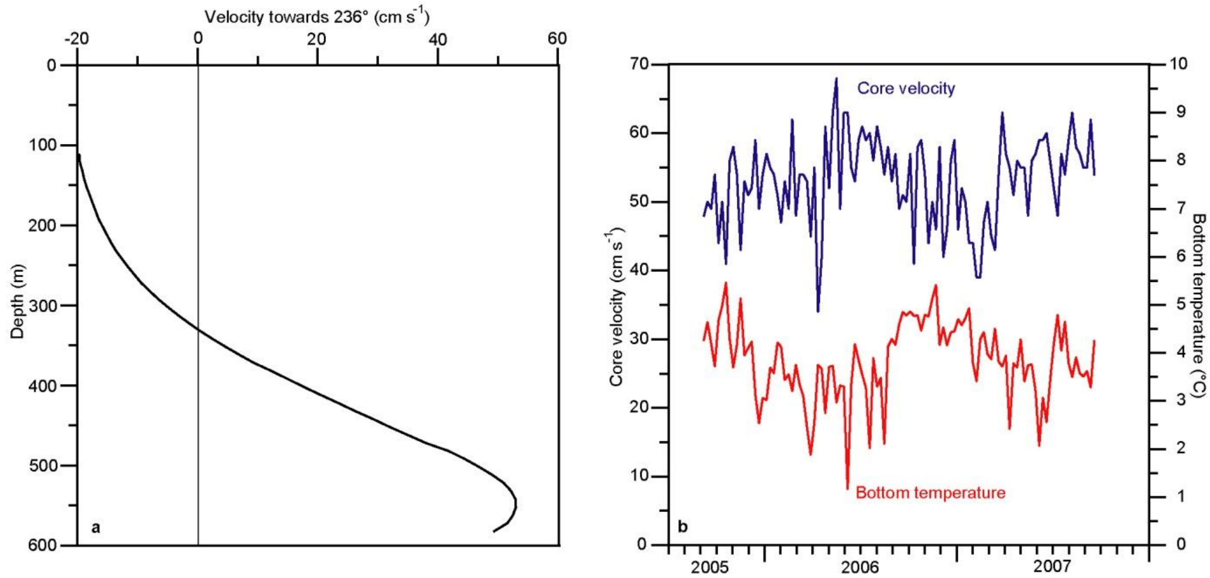

Figure 5. Results from the ADCP at blue triangle in Figure 1. Vectorially averaged velocity profile towards 236° **(a)**. Weekly averaged velocity towards 236° for bin 4, approximately 50 m above the bottom (blue) and weekly averaged bottom temperature (red) **(b)**. Figure adapted from Olsen et al. (2016).

In Figure 1, the topographical information close to the ADCP site is not very complete, but during the recovery of this ADCP by R/V Magnus Heinason, the bottom depth was logged from shortly before to after the recovery. This record demonstrates that the bottom is exceptionally steep (≈ 10%) just below the ADCP site and there is an indication of a channel.

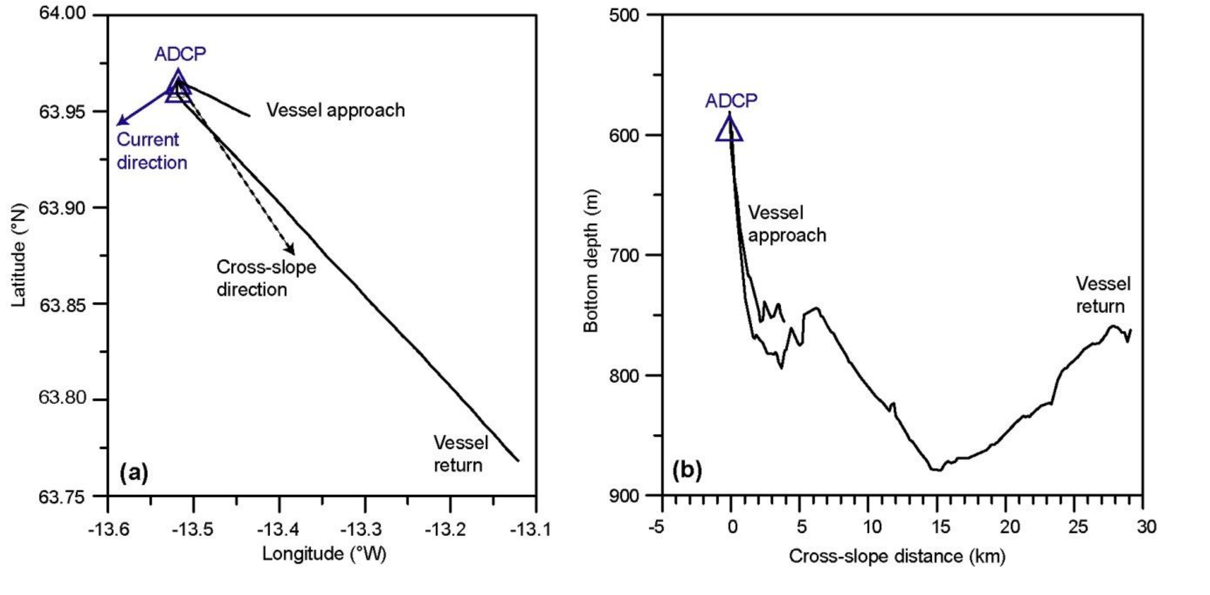

Figure 6. Bottom slope close to the ADCP mooring site as recorded by R/V Magnus Heinason on its approach towards and return from recovering the ADCP (location indicated by blue triangle) on October 4th 2007. **(a)** Map showing vessel track, main direction of the bottom current (236°), and the direction perpendicular to that, which is defined as cross-slope direction. **(b)** Bottom depth along vessel track projected onto the cross-slope direction.

Table 1. Deployment of a 75 kHz RDI ADCP (serial no.: 3368) at 63° 57.910'N, 13° 31.070'W, bottom depth: 601 m. Time of first ensemble: 2005 09 01 19 00. Time of last ensemble: 2007 10 04 08 20. Time between ensembles: 20 minutes. All directions have been corrected for magnetic deviation. For each bin, the table lists the average speed (scalar average) and the average velocity magnitude and direction formed as a vectorial average of non-flagged (Good) observations. The last column shows the number of good values in parts per thousand.

Bin no.	Depth m	Height m	Speed mm/s	Vel mm/s	Dir deg	Good ppt
1	582	19	502	494	235	1000
2	572	29	523	516	235	1000
3	562	39	532	525	236	1000
4	552	49	538	530	236	1000
5	542	59	537	529	236	1000
6	532	69	531	522	236	1000
7	522	79	519	510	236	1000
8	512	89	503	491	236	1000
9	502	99	484	469	236	1000
10	492	109	462	445	236	1000
11	482	119	438	418	237	1000
12	472	129	405	380	238	1000
13	462	139	381	350	239	1000
14	452	149	358	320	239	1000
15	442	159	339	293	240	1000
16	432	169	319	263	240	1000
17	422	179	300	235	240	1000
18	412	189	283	206	241	1000
19	402	199	269	178	241	1000
20	392	209	257	151	242	1000
21	382	219	247	124	243	1000
22	372	229	238	94	240	1000
23	362	239	235	70	242	1000
24	352	249	235	48	246	999
25	342	259	236	27	256	999
26	332	269	239	11	303	999
27	322	279	242	19	17	999
28	312	289	246	36	34	999
29	302	299	252	52	40	999
30	292	309	257	68	42	999
31	282	319	263	82	43	999
32	272	329	269	96	44	999
33	262	339	276	107	45	999
34	252	349	282	118	45	999
35	242	359	287	128	45	999
36	232	369	293	138	47	998
37	222	379	299	146	47	996
38	212	389	303	153	47	992
39	202	399	309	160	47	988
40	192	409	314	167	47	983
41	182	419	318	172	47	975
42	172	429	323	177	47	969
43	162	439	327	182	47	959
44	152	449	331	187	47	948
45	142	459	335	191	47	937
46	132	469	339	194	47	926
47	122	479	342	198	47	913
48	112	489	353	200	46	880

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