ICES Journal of
Marine Science

ICES Journal of Marine Science (2012), 69(7), 1255–1262. doi:10.1093/icesjms/fss101

Hydrography and circulation over the southern part of the Kolbeinsey Ridge

Steingrímur Jónsson[1,2]* and Héðinn Valdimarsson[1]

[1]Marine Research Institute, Skúlagata 4, 101 Reykjavík, Iceland
[2]University of Akureyri, Borgir v/Norðurslóð, 600 Akureyri, Iceland

*Corresponding author: tel: +354 4608972; fax: +354 4608998; e-mail: steing@unak.is

Jónsson, S., and Valdimarsson, H. 2012. Hydrography and circulation over the southern part of the Kolbeinsey Ridge. – ICES Journal of Marine Science, 69: 1255–1262.

Received 23 November 2011; accepted 8 April 2012; advance access publication 8 June 2012.

A study on the hydrography and circulation over the Kolbeinsey Ridge south of the Spar Fracture Zone was carried out in 2007 and 2008. A moored profiler was deployed west of the Ridge at 68°N close to the 1000-m isobath in September 2007, and measurements were obtained until October 2008. In June 2008, vessel-mounted acoustic Doppler current profiler along with conductivity, temperature, and depth measurements were made on a transect crossing the Ridge close to 68°N. The results indicate a continuous flow of Atlantic water (AW) via the North Icelandic Irminger Current northwards along the Ridge. Hence, this is an area where AW is channelled into the deep Iceland Sea. Some of the water is then recirculated westwards, whereas the remainder flows eastwards and circulates in an anticyclonic eddy that may be a semi-permanent feature of the circulation. The eddy is ~60 km in diameter, and AW accumulates there, with submerged isolines of temperature and density. The eddy was revealed in the distribution of a coccolithophorid bloom in the area in August 2008.

Keywords: Atlantic water, circulation, Iceland Sea, Kolbeinsey Ridge, water masses.

Introduction

The Kolbeinsey Ridge is a continuation of the Mid-Atlantic Ridge through the Iceland Sea, and it splits the Iceland Sea into a western and an eastern part (Figure 1). It stretches to the north from the central North Icelandic shelf and gradually deepens to the Spar Fracture Zone, which is a gap through the Ridge at 69°N that is 1500 m deep. North of the Spar Fracture Zone, the Ridge continues north to the Jan Mayen Fracture Zone at 71°N. At 68°N, the shallowest point on the Ridge is ~600 m deep. About 50 km from the Ridge on both sides at 68°30′N, there are submarine seamounts rising to 800–900 m deep, but between them and the Ridge there are channels of depth >1100 m.

The hydrography of the shelf south of the Kolbeinsey Ridge is characterized by relatively warm, saline Atlantic water (AW), which flows through Denmark Strait with the North Icelandic Irminger Current (NIIC) and along the North Icelandic shelf (Jónsson and Valdimarsson, 2012; Figure 1). North of the shelf break, cold, less-saline Arctic waters of the Iceland Sea are circulated eastwards with the East Icelandic Current (Jónsson, 2007). Partly, this water originates west of the Ridge and flows through the Spar Fracture Zone. Over the slope, at least west of the Kolbeinsey Ridge, a mainly subsurface current, the North Icelandic Jet (NIJ), carries cold deep water west to the Denmark Strait sill (Våge *et al.*, 2011; Figure 1).

The topography of the Nordic Seas has a great influence on currents, and the Kolbeinsey Ridge is a feature that might partly guide the AW into the Iceland Sea, where it can mix with the colder, fresher water of the Iceland Sea. Valdimarsson and Malmberg (1999) observed that most of the surface drifters they deployed south and west of Iceland, and that reached the area north of Iceland from the west, did not cross the Kolbeinsey Ridge but drifted north along the Ridge and then southwest with the Arctic waters from the north. They suggested that this might not be a permanent feature of the circulation, but perhaps depended on the variability of the inflow of AW to the area.

During the Iceland Sea project of 2006–2008 (Pálsson *et al.*, 2012), which set out to study the ecosystem of the Iceland Sea with special emphasis on the capelin (*Mallotus villosus*) stock in the area, the importance of the Kolbeinsey Ridge for the circulation of water masses and its potential importance to the biology of the region soon became apparent, so it was studied in greater

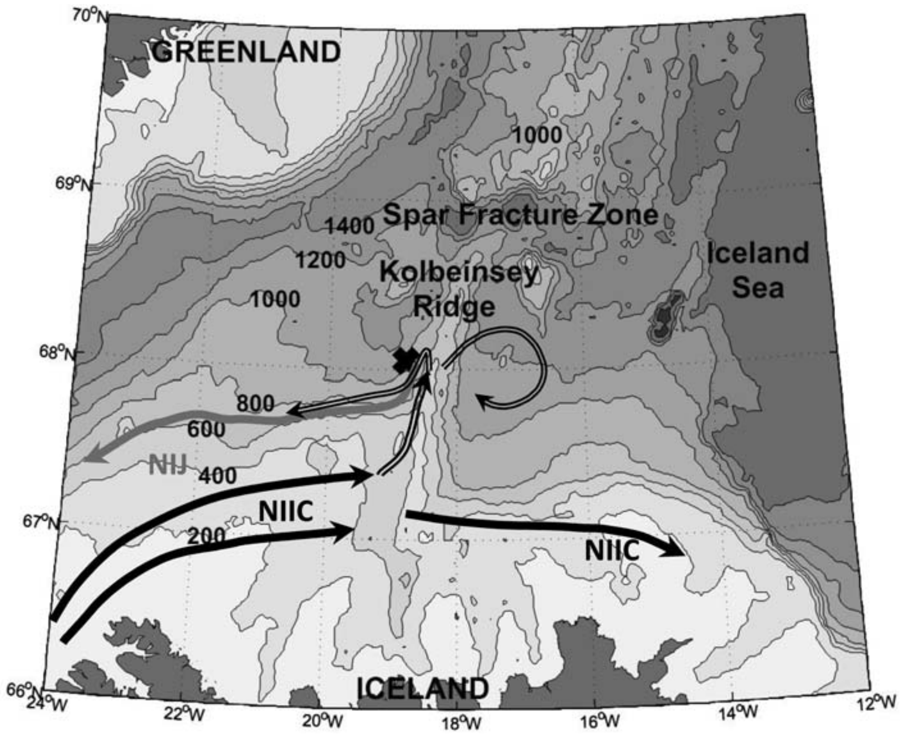

Figure 1. Map showing the study area around the Kolbeinsey Ridge. The depth contours are every 200 m, the MMP position is shown as a cross, and both the NIIC and the NIJ are shown. The suggested circulation of AW over and around the Kolbeinsey Ridge is depicted by open arrows.

detail during 2007 and 2008, using various methods. Among the questions investigated were whether and how regularly the Ridge channels AW from the NIIC into the Iceland Sea and how this influences the Iceland Sea. The dataset used is described hereafter, and it is subsequently used to outline the main features of the circulation and hydrography of the area. That information and the possible implications of the circulation for the ecology and climate of the area are discussed, and directions for further research are suggested.

Data

In September 2007, a McLane Moored Profiler (MMP), measuring temperature, salinity, and currents, was deployed at 68°02.833′N 18°47.890′W, on the western flank of the Kolbeinsey Ridge, where the bottom depth is ~1000 m (Figure 1). This is very close to the standard CTD (conductivity, temperature, depth) station, Siglunes 8, at 68°00′N 18°50′W, that has been occupied four times annually in most years since 1970 by Iceland's Marine Research Institute. In October 2008, an unsuccessful attempt at the recovery of the profiler was made, but in August 2009, it was recovered by dragging. The MMP provided good measurements from 106 to 1020 db from 1 September 2007 to 28 October 2008. It recorded profiles twice each day, rising towards the surface at midnight and returning to the seabed at 06:00. This gave 846 profiles or 423 days of data, and almost all the profiles returned data of good quality. The data have since been calibrated, and a value of each parameter has been assigned for every 2 db. The measurement uncertainties for MMPs have been estimated to be 0.004 for salinity and 0.005°C for temperature (Våge *et al.*, 2008). This was the first time that a continuous CTD profile had been obtained with a time resolution that made it possible to reveal details of seasonal variations in the hydrography of the area.

On 4 and 5 June 2008, vessel-mounted acoustic Doppler current profiler (vmADCP) sections were taken on both sides of the Ridge close to the MMP. Each section was measured four times, which took ~24 h to complete. Because of the low concentration of scattering particles in the water at that time of year, good data were obtained from the uppermost 150 m only. The current at each bin was averaged over a 5-min interval, then the data were interpolated to equidistant points along the section. An average was taken over all sections in an attempt to eliminate tidal currents. This was feasible because the four occupations of the sections took ~24 h or about two semi-diurnal tidal cycles. CTD stations were taken at seven positions along the vmADCP sections down to 600 m. In August 2008, a CTD section was taken along the 68°N latitude, crossing the Kolbeinsey Ridge. The CTD used was an SBE 911plus CTD with Carousel Water Sampler containing 12 × 5-l bottles, SBE 32.

Results

Hydrography

As the MMP only sampled up to 106 db, the surface layer is missing, and this must be kept in mind when discussing the data. The distribution of temperature, salinity, and σ_t is shown in Figure 2. A high-salinity core was observed early in the record around 200 m deep, but this then gradually deepened to ~300 m deep, and eventually disappeared when the winter mixing eroded it by February 2008. The high-salinity core then reappeared at the end of the record in October 2008. This water

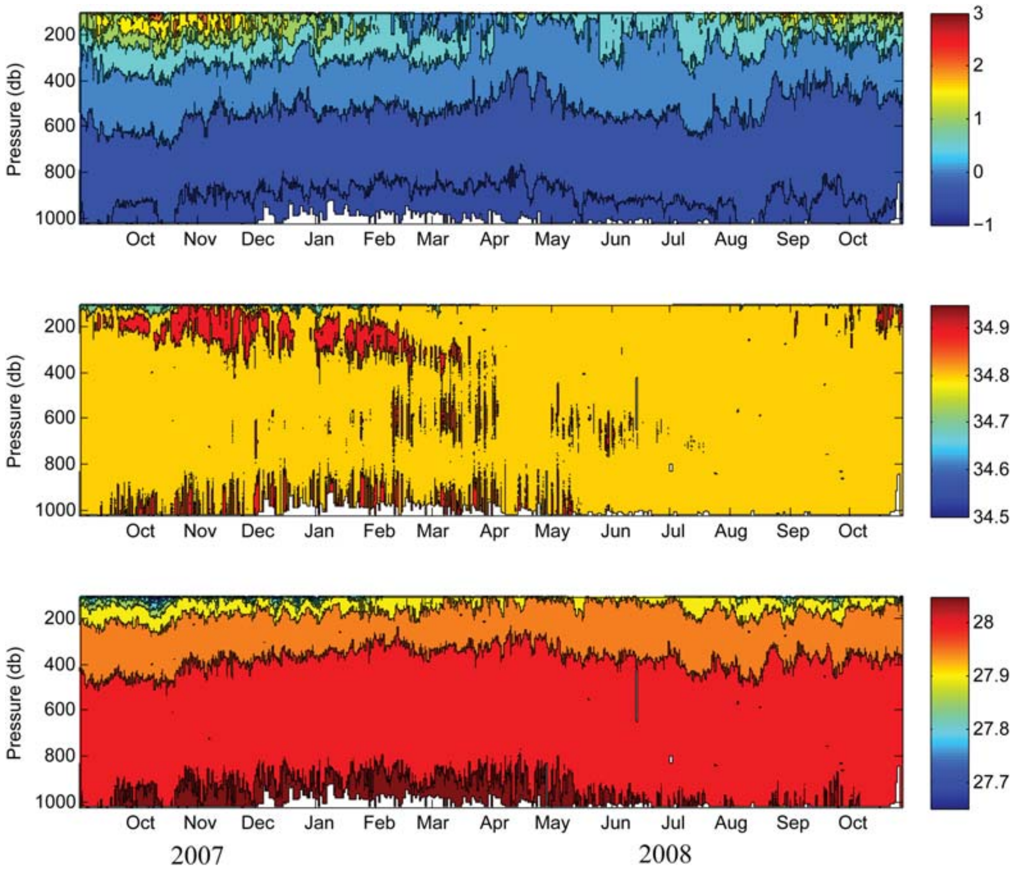

Figure 2. Temperature (upper), salinity (middle), and σ_t (lower) derived from the MMP.

was also often warmer than the surrounding waters, and the salinity was higher than the salinities associated with Arctic waters. The only possible source in the area for such saline water is the AW from the NIIC. At the upper level of the MMP data, from 100 to 150 m deep, the stratification during summer was seen mainly as lower salinity. This is in accord with the hydrographic sections that reveal that the thermal stratification is generally confined to $<$100 m (Figures 3 and 4). Below 500 m, the temperature was generally $<$0°C, and deeper still, it gradually decreased to about $-$0.6°C at the deepest level, and the salinity in that depth range was close to 34.90.

From the MMP data, unique information about seasonal variations in the hydrography of much of the water column was obtained (Figure 5). The data were divided into three periods: September 2007 to early February 2008, early February 2008 to 4 July 2008, and from then until the end of the record on 28 October 2008. The first period (red dots in Figure 5) represents the summer situation, with highest temperature and salinity. Salinity values close to 35.0 were observed occasionally, in accord with Figure 2, which shows a high salinity core between 200 and 300 m deep. The salinity also dropped as low as 34.55, which resembles Polar water from the East Greenland Current. The second period (green dots in Figure 5) corresponds to winter, when the sea surface was coldest and most saline and vertical gradients are reduced owing to mixing in the water column. Also, there was only a weak core of high salinity compared with the other two periods, because of mixing with low-salinity surface water accompanied by a cooling observed down to at least 200 m. The final period (blue dots in Figure 5) was intermittent between the other two seasons. A core of high salinity was evident at times during this final period, with salinity values well above 34.9. The salinity of the deep water was somewhat lower than during both the first two periods, indicating variability in the deep water flowing with the NIJ (Våge *et al.*, 2011). A similar range in salinity has been observed at the standard station Siglunes 8 at 68°00′N 18°50′W (Jónsson and Valdimarsson, 2004a).

The data from the MMP can be compared with the two hydrographic sections taken in June and August 2008. In August, the hydrographic section extended for more than 500 km from 25°W to 13°W along 68°N, whereas in June, two short sections were taken on each side of the Kolbeinsey Ridge along with the vmADCP measurements. The temperature, salinity, and σ_t values above 500 m along 68°N in August 2008 revealed the East Greenland Current carrying cold, low-salinity Polar water south on the westernmost part of the section (Figure 3). At the surface, summer warming had raised the temperature of this Polar water to $>$3°C. At 21°W, there was a high salinity ($>$34.9) core between 50 and 100 m, associated with relatively high temperatures. This may have been recirculated AW that became detached from the Kolbeinsey Ridge. Over and to the east of the Kolbeinsey Ridge, there was another core of AW near 100 m deep, suggesting flow along the Ridge. In that area, the isolines of temperature extended deeper, as did the density, indicative of an anticyclonic eddy. Farther east, the cold Arctic waters filled the basin over the Iceland Plateau, and there was only a thin

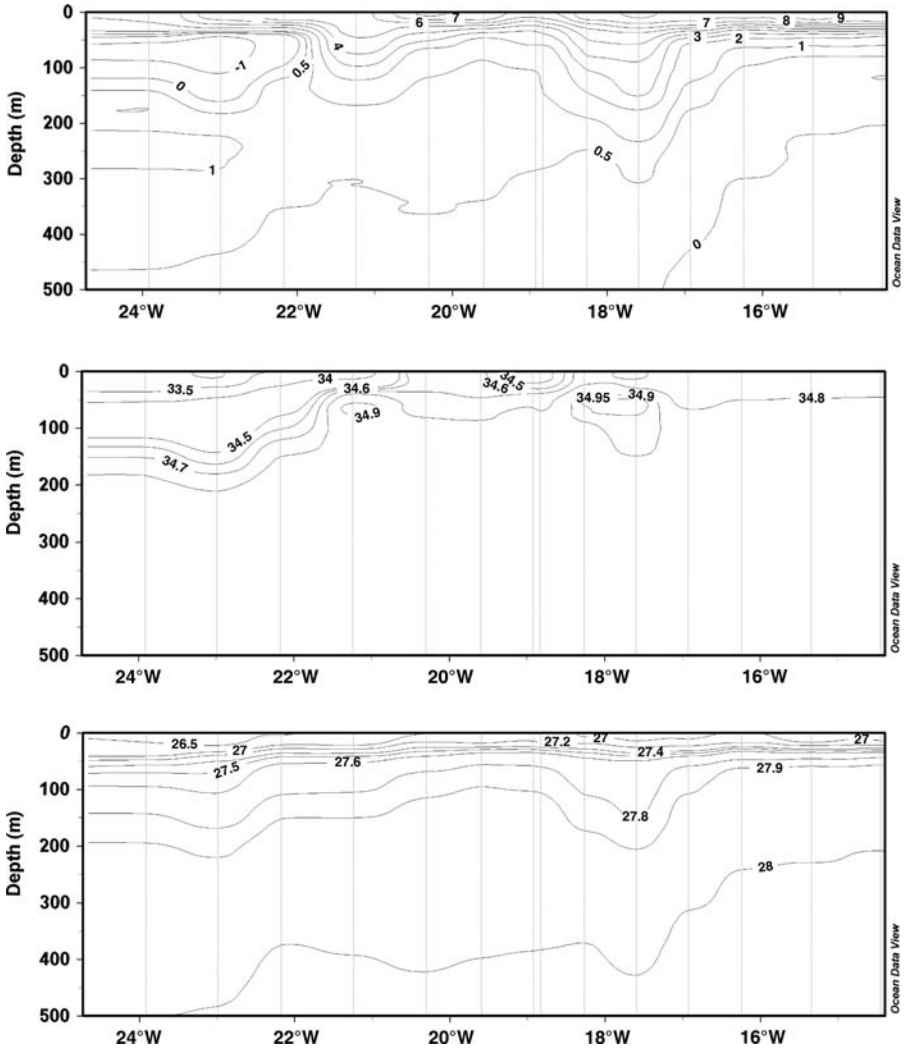

Figure 3. Temperature (upper), salinity (middle), and σ_t (lower) on the hydrographic section in August 2008 (using Ocean Data View; Schlitzer, 2008).

layer affected by the summer warming. The doming of the isotherms and isopycnals are indicative of the cyclonic circulation observed over the Iceland Plateau (Stefánsson, 1962).

The hydrographic sections from 4 to 5 June are much shorter, ~150 km, covering just a small area on each side of the Ridge (Figure 4). Over the top of the Ridge, there was a core of high salinity and relatively warm water down to ~150 m, similar to the situation in August. Again, the submergence of the isolines of temperature and density suggest anticyclonic circulation east of the Ridge, indicating that the AW that crossed the Ridge likely resided there for some time and that the waters down to ~100 m were of Atlantic origin, being warmer and more saline than surrounding waters. The AW accumulated in the gyre and was much thicker there than outside the gyre.

Circulation

The currents were measured by the MMP, and the average of the v (N–S) and u (E–W) components and their standard deviations at each depth are shown in Figure 6. The current was highly barotropic, and only at the deepest levels was there some deviation. At the bottom, the velocity turns to the left, as expected for a bottom Ekman layer in the ocean, and the speed was also slightly reduced, consistent with bottom frictional forces. The mean current was towards the south over the whole water column throughout most of the mooring duration (Figure 7). This steady southward flow is probably part of the NIJ that carries the densest part of the Denmark Strait Overflow Water (Jonsson and Valdimarsson, 2004b; Våge *et al.*, 2011). The MMP was likely situated at the western part of the NIJ, near where its strength started to decline. This is in agreement with the measurements made in June 2008 with the vmADCP that showed the MMP situated at the western edge of a south-heading current over the deeper part of the slope west of the Kolbeinsey Ridge (Figure 8). The current measured with the vmADCP averaged over seven bins, i.e. from the surface down to ~120 m, is shown in Figure 8. There was good agreement between the current measured by the MMP and the data from the vmADCP data from 4 to 5 June. They both showed speeds of roughly 0.10 m s^{-1} towards the south. This shows that the NIJ at least sometimes reaches towards the surface and is then capable of recirculating AW also in the surface layer. The same observation was made by Valdimarsson and Malmberg (1999), who observed surface

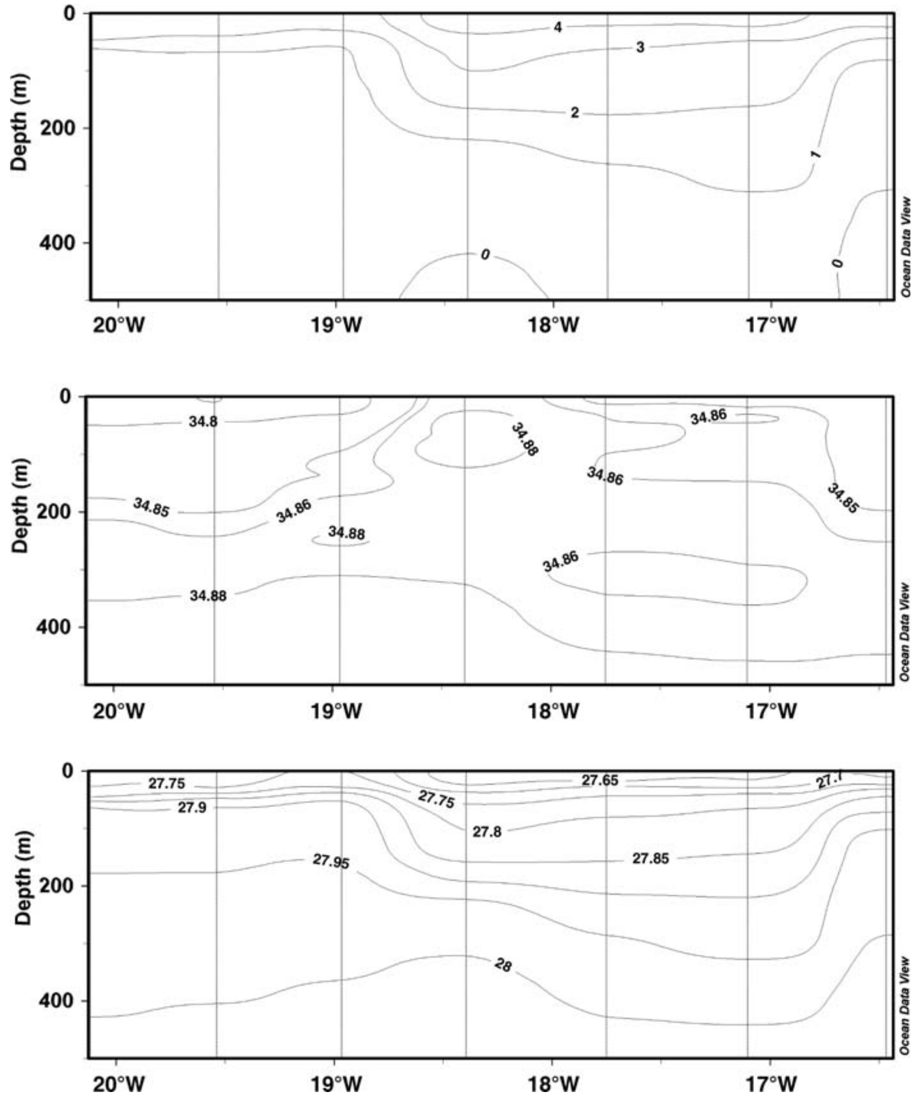

Figure 4. Temperature (upper), salinity (middle), and σ_t (lower) on the hydrographic section in June 2008 (using Ocean Data View; Schlitzer, 2008).

drifters drifting north along the Ridge and then southwest with the Arctic waters from the north. The barotropic nature of the current at the MMP from 100 m deep to the bottom, and the frequent presence of AW at the MMP down to 200–300 m (Figure 2), shows that this recirculation of AW is likely a permanent feature of the circulation. East of the NIJ and towards the crest of the Ridge, there was northward flow that in the surface layer was carrying AW along the Ridge at speeds of 0.10–0.15 m s^{-1} (Figure 8). The CTD section in June 2008 reveals a salinity maximum over the Ridge, and the geostrophic currents estimated from the density field were consistent with the current observed from the vmADCP there, i.e. northward. East of the Ridge, the vmADCP measurements showed an anticyclonic gyre of ~60 km in diameter with speeds in the range of 0.10–0.15 m s^{-1} (Figure 8). It would therefore seem that as the AW passed east of the Ridge, it was swept eastwards, presumably by the East Icelandic Current, and subsequently became entrained into the anticyclonic gyre. The seamount east of the Ridge may have helped to channel the flow southwards and create the gyre. In the gyre east of the Kolbeinsey Ridge in June, there was a pool of relatively warm water extending to 200–300 m deep, and the isolines of temperature and density are submerged, indicating the existence of an anticyclonic eddy just east of the Ridge (Figure 4), consistent with the vmADCP measurements.

In August 2008, the CTD section along 68°N also revealed the presence of an anticyclonic eddy, from the submergence of the isolines of temperature and density, and there was an accumulation of AW similar to that seen in June (Figure 3). There was a salinity maximum (>34.95) over the Ridge indicating northward flow of AW, because the only possible source for water so saline in the area is the AW of the NIIC. During the same period, a bloom of the coccolithophorid *Emiliania huxleyi* was observed in MODIS satellite images in the waters north of Iceland on 10 August (Figure 9). This bloom was studied in some detail by Guðfinnsson *et al*. (2009). Such blooming is common in AW, especially south of Iceland and also recently in the area west of Iceland, but this was the first time that it is known to have bloomed north of Iceland (Guðfinnsson *et al*., 2009). The bloom

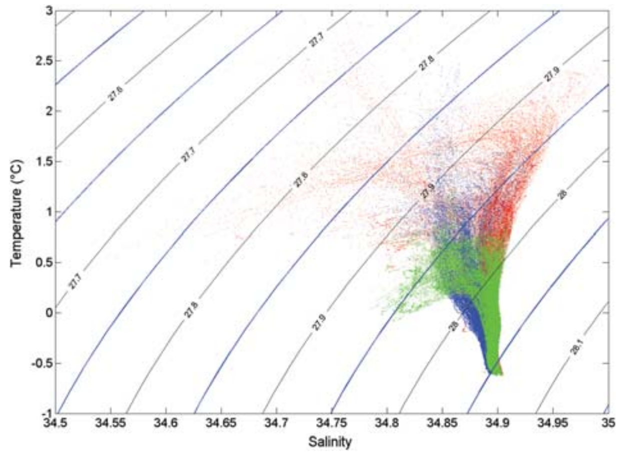

Figure 5. $T-S$ diagram from the MMP for three different periods. The red dots are from 1 September 2007 to 5 February 2008, the green dots from 5 February 2008 to 4 July 2008, and the blue dots from 4 July 2008 to 28 October 2008.

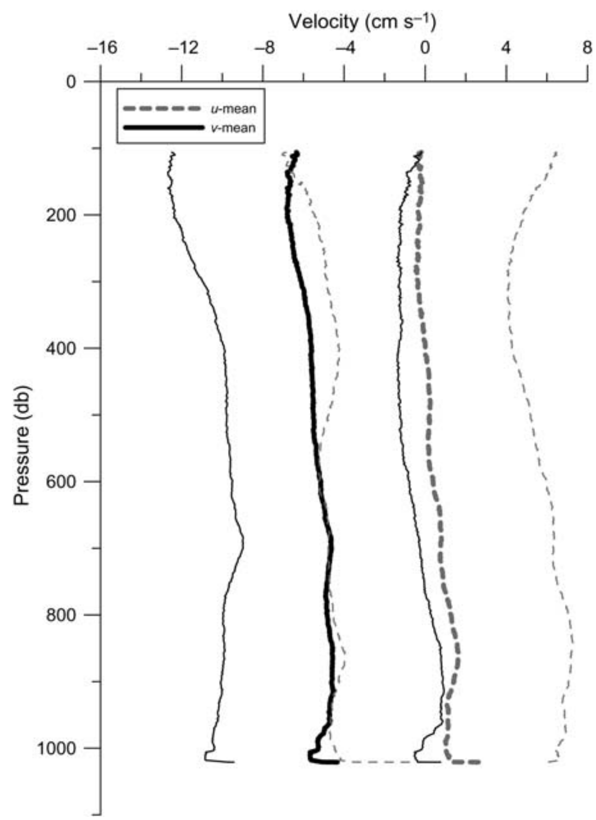

Figure 6. A time average of the velocity (thick lines) at the MMP. The E–W component is the dashed line and the N–S component the solid line. The corresponding thin lines show the standard deviations.

might be connected with increased flow of AW and especially the increased temperature in the AW entering the North Icelandic shelf area with the NIIC, as documented by Jónsson and Valdimarsson (2012). The image shows an extensive bloom over the North Icelandic shelf. Figure 9 shows that the AW is spread along the Kolbeinsey Ridge well north of 68°N. East of the Ridge, the bloom was present in the area of the AW seen on the CTD section and appeared to have been incorporated passively in the anticyclonic circulation.

Discussion and conclusions

The main components of the circulation near the Kolbeinsey Ridge have been described. The MMP revealed a relatively steady barotropic current with a mean speed of 0.05 m s^{-1} towards the south, and the vmADCP data reveal the current to be ∼15–20 km wide. Measurements at the Hornbanki section farther west with a vmADCP (Jónsson and Valdimarsson, 2004b) and on several sections along the continental slope north of Iceland with a lowered ADCP (Våge *et al.*, 2011) revealed similar features for the width of the current and its vertical structure. Closer to the crest of the Ridge, the vmADCP data showed a 15–20-km wide northward current of ∼0.10–0.15 m s^{-1} carrying AW north along the Ridge. The data from the MMP indicated that there has to be a steady flow of AW northwards along the western flank of the Kolbeinsey Ridge, because AW was observed there regularly. As the width of the AW flow is not well known and its speed was only measured for 1 d, it was not meaningful with the present data to estimate the flux of AW to the north along the Ridge. However, in view of the transport of AW with the NIIC through Denmark Strait of ∼0.88 Sv (Jónsson and Valdimarsson, 2012), the transport of AW along the Kolbeinsey Ridge could be a substantial proportion of that. Some of this water is recirculated as it is entrained into the NIJ, then flows back towards the west along the Icelandic continental slope with the NIJ.

Recently, it has been suggested that the NIIC and water-mass transformation in the interior of the Iceland Sea play a role in the formation of the NIJ (Våge *et al.*, 2011). As the research reported here shows substantial interaction between the NIIC and the deep Iceland Sea near the Kolbeinsey Ridge, this area might well be important for the water-mass transformation and the formation of the NIJ, as suggested by Våge *et al.* (2011). The results presented here show that sometimes at least the NIJ reaches towards the surface and is then capable of recirculating AW also in the surface layer. This is in accord with the observation of Valdimarsson and Malmberg (1999) that surface drifters reaching the area north of Iceland from the west did not cross the Kolbeinsey Ridge but drifted north along the Ridge and then southwest with Arctic waters from the north. The barotropic nature of the current at the MMP from 100-m deep to the bottom, and the frequent presence of AW at the MMP down to 200–300 m, shows that this recirculation of AW is likely a permanent feature of the circulation.

The AW that does not recirculate flows over the Ridge and is swept to the east, presumably by the East Icelandic Current, and subsequently becomes incorporated into an anticyclonic gyre with a diameter of ∼60 km. The seamount east of the Ridge may help to channel the flow southwards and create the gyre. This flow feature east of the Ridge was evident in the vmADCP data as well as in the CTD data, and it has also been seen in satellite images. Within the gyre, the isolines of temperature and density submerged, and there was an accumulation of AW into a layer about 200-m thick. Perhaps, the occurrence of this anticyclonic eddy on two occasions during this period of observation is indicative of it being a semi-permanent feature of the circulation in the area. A challenge for the future will be to quantify the fluxes of AW

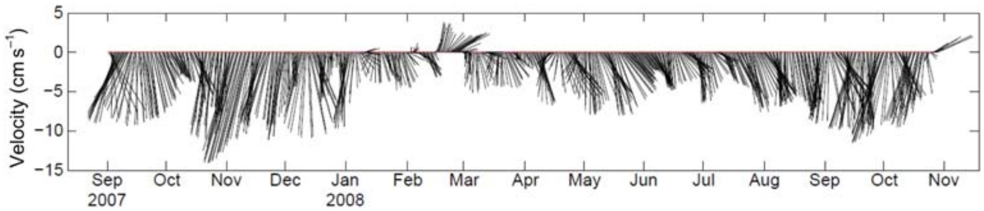

Figure 7. Stick diagram of 5-d running mean of the vertically averaged current from the MMP.

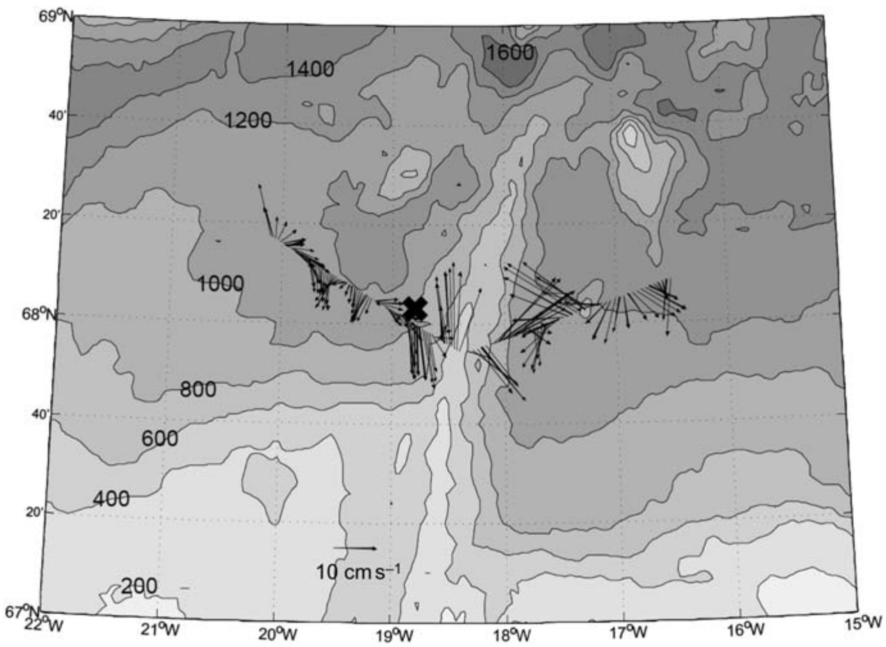

Figure 8. The current averaged over the uppermost seven bins, i.e. down to ~120 m, as measured with the vmADCP in June 2008. The CTD sections in June 2008 were taken along the same sections. The cross indicates the position of the MMP.

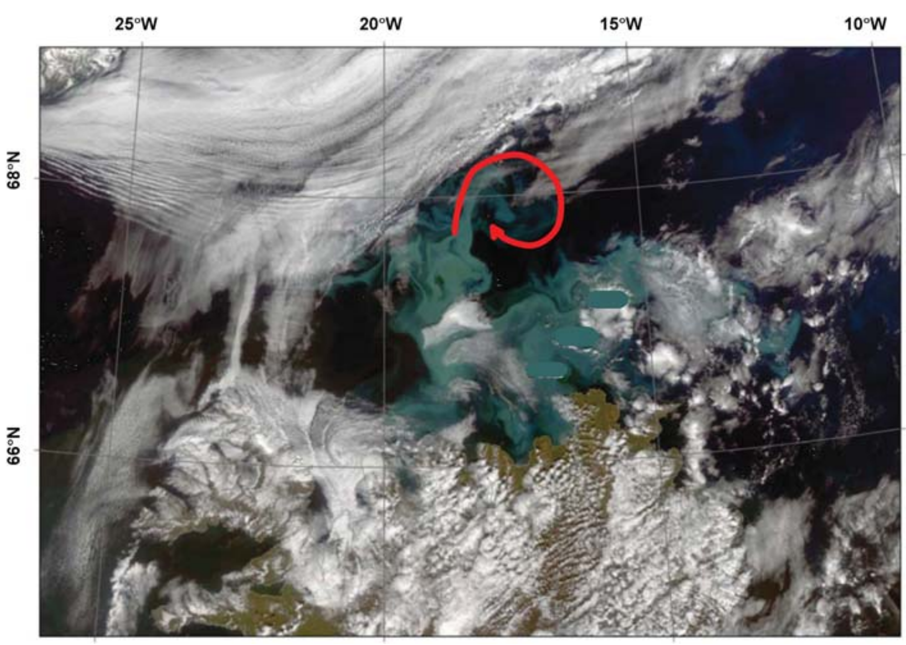

Figure 9. Distribution of a coccolithophorid bloom on 10 August 2008 (image courtesy of the MODIS Rapid Response Project of NASA/GSFC; after Guðfinnsson *et al.*, 2009).

discussed here and to shed more light on the associated water-mass transformations.

Summer/autumn catches of capelin are often concentrated along the Kolbeinsey Ridge (Vilhjálmsson, 2002). The main spawning grounds for capelin are south of Iceland, and the eggs and larvae are transported by currents to and along the west coast of Iceland and partly through the Denmark Strait with the NIIC. 0-group capelin have subsequently been seen spreading northwards along the Kolbeinsey Ridge (Pálsson *et al*., 2009), and in August 2007 and 2008, they were abundant over the southern part of the Ridge, with peak concentrations around 68°N. The anticyclonic eddy described here can act as a retention area for larvae and might be important for the 0-group capelin sometimes seen aggregating around the Kolbeinsey Ridge; clearly, this subject is deserving of further study in future.

Acknowledgements

The research leading to these results received funding support from the European Union's Seventh Framework Programme (FP7/2007–2013) under grant agreement 212643. We thank Robert S. Pickart for lending us the MMP for the study and for his help in processing the data.

References

Guðfinnsson, H. G., Ólafsdóttir, S. R., and Jónsdóttir, I. 2009. Kalkþörungaflekkur norðanlands í ágúst 2008 [Coccolithophorid bloom north of Iceland in August 2008]. Technical Report Hafrannsóknastofnunin (Marine Research Institute), Reykjavík, 145: 60–65 (in Icelandic).

Jónsson, S. 2007. Volume flux and fresh water transport associated with the East Icelandic Current. Progress in Oceanography, 73: 231–241.

Jónsson, S., and Valdimarsson, H. 2004a. An ocean current over the continental slope northwest of Iceland carrying Denmark Strait overflow water from the Iceland Sea to Denmark Strait. ICES Document CM 2004/N: 04. 11 pp.

Jonsson, S., and Valdimarsson, H. 2004b. A new path for the Denmark Strait Overflow Water from the Iceland Sea to Denmark Strait. Geophysical Research Letters, 31: L03305.

Jónsson, S., and Valdimarsson, H. 2012. Water mass transport variability to the north Icelandic shelf, 1994–2010. ICES Journal of Marine Science, 69: 000–000.

Pálsson, Ó. K., Gislason, A., Guðfinnsson, H. G., Gunnarsson, B., Ólafsdóttir, S. R., Pétursdóttir, H., Sveinbjörnsson, S., *et al.* 2012. Ecosystem structure in the Iceland Sea and recent changes to the capelin (*Mallotus villosus*) population. ICES Journal of Marine Science, 69: 000–000.

Pálsson, Ó. K., Valdimarsson, H., Ólafsdóttir, S. R., Guðfinnsson, H. G., Gíslason, Á., Pétursdóttir, H., and Sveinbjörnsson, S. 2009. Rannsóknir á vistkerfi Íslandshafs og vistfræði loðnu að sumarlagi [Ecosystem properties of the Iceland Sea and capelin ecology during summer]. Technical Report Hafrannsóknastofnunin (Marine Research Institute), Reykjavík, 145: 54–59 (in Icelandic).

Schlitzer, R. 2008. Ocean Data View. http://odv.awi.de.

Stefánsson, U. 1962. North Icelandic waters. Rit Fiskideildar, 3. 269 pp.

Våge, K., Pickart, R. S., Moore, G. W. K., and Ribergaard, M. H. 2008. Winter mixed layer development in the central Irminger Sea: the effect of strong, intermittent wind events. Journal of Physical Oceanography, 38: 541–565.

Våge, K., Pickart, R. S., Spall, M. A., Valdimarsson, H., Jónsson, S., Torres, D. J., Østerhus, S., *et al.* 2011. Significant role of the North Icelandic Jet in the formation of Denmark Strait overflow water. Nature Geoscience, 4: 723–727, doi:10.1038/NGEO1234.

Valdimarsson, H., and Malmberg, S. A. 1999. Near-surface circulation in Icelandic waters derived from satellite tracked drifters. Rit Fiskideildar, 16: 23–39.

Vilhjálmsson, H. 2002. Capelin (*Mallotus villosus*) in the Iceland–East Greenland–Jan Mayen ecosystem. ICES Journal of Marine Science, 59: 870–883.

Handling editor: Audrey Geffen