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State of the eastern North Atlantic subpolar gyre:
The Extended Ellett Line Programme
Annual Report No. 2

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ABSTRACT

The Extended Ellett Line is a hydrographic section between Iceland and Scotland that is occupied annually by scientists from the National Oceanography Centre (NOC) and the Scottish Association for Marine Science (SAMS), UK. The measurement programme began as a seasonally-occupied hydrographic section in the Rockall Trough in 1975, building on early surface observations made underway from ocean weather ships. In 1996 the section was extended to Iceland, sampling three basins: the Rockall Trough, the Hatton-Rockall Basin and the Iceland Basin. This report presents a summary of data from the Extended Ellett Line programme as well as an overview of activities and analysis from the programme. Historical and recent physical data are analysed to calculate time series of temperature and salinity of the upper ocean and Labrador Sea Water in the eastern subpolar gyre. The most recent Extended Ellett Line cruise (May 2013) is shown as temperature, salinity and density sections.

KEYWORDS:

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1. Introduction

The Extended Ellett Line is a hydrographic section between Iceland and Scotland that is occupied annually by scientists from the National Oceanography Centre (NOC) and the Scottish Association for Marine Science (SAMS), UK. The measurement programme began as a seasonally-occupied hydrographic section in the Rockall Trough in 1975, building on early surface observations made underway from ocean weather ships. In 1996 the section was extended to Iceland, sampling three basins: the Rockall Trough, the Hatton-Rockall Basin and the Iceland Basin (Figure 1). These three basins form the main routes though which warm saline Atlantic water flows northwards into the Nordic Seas and Arctic Ocean. The section crosses the eastern North Atlantic subpolar gyre; as well as the net northward flow there is a large recirculation of the upper layers as part of the wind-driven gyre. During its passage through the region, the warm saline water is subjected to significant modification by exchange of heat and freshwater with the atmosphere. The two deep basins (Rockall Trough and Iceland Basin) contain southward flowing dense northern overflow waters, and Labrador Sea Water in the intermediate layers.

This report presents a summary of temperature and salinity data from the Extended Ellett Line programme, alongside a review of recent and current research, and details of the impact of the research. The historical data set is analysed to calculate time series of temperature and salinity of the upper ocean and Labrador Sea Water in the eastern subpolar gyre. The most recent Extended Ellett Line cruise (May 2013) is shown as temperature, salinity and density sections.

The Extended Ellett Line programme is jointly led by Penny Holliday at NOC and Stefan Gary at SAMS. For more detailed information visit the website: projects.noc.ac.uk/ExtendedEllettLine/

2. Current Research

In 2013 a peer-reviewed summary of the history of, and discoveries from, the Extended Ellett Line programme was published in Oceanography, the magazine of The Oceanography Society (Holliday and Cunningham, 2013). The article summarised research since sampling started in the region in 1948. It concludes with the message that while the time series can be supplemented with additional data from autonomous vehicles such as floats and gliders, only ship-based surveys can provide the high quality physical, chemical, and biological data that are necessary for understanding the changing environment in all depths of the ocean. The ship-based observations are also required for calibrating data from autonomous vehicles; without ship-based surveys the data from the floats and gliders become less valid.

A study of changing nutrient concentrations in the upper waters of the Rockall Trough (Johnson et al, 2013) showed that the declining values from 1996 to the mid-2000s was a direct result of the decreasing proportion of subpolar water masses reaching the basin. The decline in subpolar water was associated with a weakening subpolar gyre circulation. Since the mid-2000s the upper water properties have been more stable, and small changes likely the result of changes in the source regions for the warm water.

Meanwhile, a number of strands of new research are underway, including deriving a mean full depth velocity section from nearly 20 years of LADCP measurements (Elizabeth Comer, masters student at NOC), understanding interannual to deadal variability in carbon storage (Matthew Humphries, PhD student at NOC), long-term changes the volume transport through the section, and quantifying the long-term variability and uncertainty in physical properties from the section.

3. Impact

The Extended Ellett Line programme regularly provides advice to the public, government and policymakers through the media of climate status reports. The two most prominent reports are the annual ICES Report on Climate (IROC, Beszczynska-Moller and Dye, 2013), and the Annual Report Card of the Marine Climate Change Impacts Partnership, (MCCIP, http://www.mccip.org.uk, MCCIP 2013, Dye et al, 2013a, Dye et al, 2013b). Both use the Extended Ellett Line data along side other time series to build a picture of the ocean conditions over time. The main conclusions of the 2013 IROC (data from 2012) were that temperatures and salinity in the eastern subpolar region decreased to levels seen in early 2000s, while temperatures in the Norwegain and Barents Seas were above average, and upper layers of the northwestern subpolar region were warm in summer 2012. Salinity was high in the Greenland Sea and along the path of the East Greenland Current, but the surface waters of the subpolar gyre appeared to be freshening. The MCCIP ARC has as one of its key findings that ocean temperatures continue to show an overall upward trend despite short-term variability; they cite the example of the average coastal sea surface temperature that was lower in 2008-2012 than in 2003-2007, and this is also seen in the records from the Extended Ellett Line (see below).

Extended Ellett Line analyses have contributed to the enormous body of literature used to form the AR5 report by Working Group I of the Intergovernmental Panel on Climate Change (IPCC, http://www.ipcc.ch and www.climatechange2013.org, IPCC et al, 2013). Holliday et al, (2008) forms part of the evidence that the upper ocean of the North Atlantic is vigorously variable in salinity, and that changes in the subpolar region are advected into the Arctic. The report notes that while it is clear that there are times when more subtropical water is advected into the subpolar region, there is some debate about the causal mechanisms, and what the role of cross-equatorial transport of salt is.

4. Collaborative Work

The Extended Ellett Line forms part of the design for the international OSNAP array (Overturning in the Subpolar North Atlantic Programme www.ukosnap.org). The OSNAP array was designed to segue into the eastern part of the Extended Ellett Line in order to optimise sampling and to make use of existing observations and knowledge. OSNAP will use gliders and moorings to measure volume and heat flux through the subpolar region including the Iceland Basin, the Hatton-Rockall Basin and the Rockall Trough, and both programmes will benefit from this co-ordinated approach. The OSNAP observations programme begins in summer 2014.

The 2014 Extended Ellett Line survey (June-July) will be a joint cruise between this project, UK OSNAP, and RAGNARoCC (Radiatively Active Gases from the North Atlantic Region and Climate Change), a NERC-funded project. By scheduling surveys for all these programmes together we are maximising the resources available for shiptime, as well as optimising potential for analysis.

The Extended Ellett Line is a partner in GO-SHIP (Global Ocean Ship-based Hydrographic Investigations Programme www.go-ship.org) which is an organisation that "brings together scientists with interest in physical oceanography, the carbon cycle, marine biogeochemistry and ecosystems ... to develop a sustained global network of hydrographic sections as part of the Global Ocean / Climate Observing System". GO-SHIP has document the fact that "despite numerous technological advances over the last several decades, ship-based hydrography remains the only method for obtaining high-quality, high spatial and vertical resolution measurements of a suite of physical, chemical, and biological parameters over the full water column. Ship-based hydrography is essential for documenting ocean changes throughout the water column, especially for the deep ocean below 2 km (52% of global ocean volume not sampled by profiling floats)".

The Extended Ellett Line programme devotes significant resources to training students (undergraduate, masters levels and PhD). The extensive historical data resources is held in matlab form to be instantly accessible by students, and is used for several projects and dissertations each year. Each cruise has several berths set aside for students who come to learn new skills, collect data for a project or test their new sensors and techniques. Since 1996 students from 25 different universities and centres have benefitted from free places on Extended Ellett Line cruises; in 2013 we hosted students from University of Liverpool, University of Bristol, University of Southampton and University of Highlands and Islands.

5. The May 2013 Iceland-Scotland hydrographic section

The 2013 Iceland-Scotland section was carried out on RRS *James Cook* cruise JC086 in May. Colin Griffiths (SAMS) was principle scientist and details of the full suite of data collected can be found at *www.bodc.ac.uk/data/information_and_inventories/cruise_inventory/report/13389/*. The cruise enjoyed good weather throughout and the section was completed without interruption. Figure 2 shows the potential temperature, salinity and potential density for the full section.

6. Temperature and salinity time series for the upper ocean

The Extended Ellett Line upper ocean data are presented as time series of potential temperature and salinity (Table 1 and Figure 3). The Rockall Trough time series is well-established (eg Holliday et al, 2000, Beszczynska-Moller and Dye, 2013); the "upper ocean" is calculated as an average of data from 30-800 dbar between Rockall and the outer Scottish continental shelf (black dots in Figure 1). The 800 dbar limit is selected because it marks the top of the permanent thermocline, or the base of the dominant water mass, the Eastern North Atlantic Water. By ignoring the very surface layer we hope to reduce temporal aliasing. However it should be noted that the upper ocean is subject to a seasonal cycle in properties (deep winter mixing to 600-800m depth, and spring/summer surface warming), and some aliasing of the seasonal cycle is inevitable. The Rockall Trough part of the Extended Ellett Line began in 1975 (black dots in Figure 1); present day conditions are warm and saline in the upper ocean compared to the long-term mean despite a recent decline in both parameters (black lines in Figure 3). Between 1975 and 1995 the mean temperature of the upper ocean in the Rockall Trough was 9.2±0.3 °C. A warming trend from 1995 to 2005 reached a peak of 10.1°C before cooling to 9.3°C in 2013. Upper ocean salinity in the Rockall Trough was at a minimum in the late 1970s (35.27) during the Great Salinity Anomaly, rose to a maximum around 1983 (35.37), decreased in the 1990s, then rose again to a maximum of 35.41 in 2010. Salinity in 2013 was notably low, and this change has been observed in other time series in the eastern subpolar North Atlantic (IROC 2013, in prep).

The upper ocean in the Hatton-Rockall Bank (red dots in Figure 1) is defined in the same way (30-800 dbar) because the permanent thermocline is found at similar depths (Figure 2). The shorter time series shows a similar pattern of variability as the Rockall Trough though the amplitude of the interannual variability is higher (red lines in Figure 3). In the Iceland Basin (blue dots in Figure 1), the upper ocean is defined as 30-600 dbar since the permanent thermocline is shallower here (Figure 2). Different water masses are present in the Iceland Basin, and the region is an area of active modification of mode waters. The time series of temperature and salinity show similar patterns of variability as the other two basins, but the multi-year trend is less clear (blue lines in Figure 3).

7. Temperature and salinity time series for intermediate waters

The intermediate layers of the two deep basins, the Rockall Trough and Iceland Basin, are filled with Labrador Sea Water (LSW). The core of the LSW can be identified by a layer of well mixed, lowstratification water; the signature of its origins as a surface water mass subjected to very deep convective mixing in winter. Formally this can be detected as a minimum in potential vorticity calculated at the two deepest stations, Station M in the Rockall Trough (57.30°N 10.38°W) and at station IB12 in Iceland Basin (60.0°N 20.0°W). The evolution of the LSW properties in the two basins is rather different (Table 2 and Figure 4); in the Rockall Trough, temperature and salinity has been rather stable over the past 15 years, and both remain low compared to the early part of the time series. In the Iceland Basin, there is a slight trend of increasing temperature and salinity of LSW since the late 1990s.

Table 1. Time series of temperature and salinity of the upper ocean in the Rockall Trough (30-800 dbar), Rockall-Hatton Basin (30-800 dbar) and Iceland Basin (30-600 dbar).

Date	**Rockall Trough**		**Hatton-Rockall Basin**		**Iceland Basin**	
	Potential Temp °C	Salinity	Potential Temp °C	Salinity	Potential Temp °C	Salinity
1975.34	8.84	35.304				
1975.51	9.14	35.284				
1975.86	9.50	35.303				
1976.25	8.96	35.271				
1976.39	9.02	35.269				
1977.29	8.83	35.281				
1977.35	8.78	35.274				
1977.64	9.22	35.280				
1978.30	8.84	35.297				
1978.43	8.89	35.301				
1978.61	9.14	35.288				
1978.69	9.24	35.322				
1978.85	9.54	35.307				
1979.39	8.88	35.309				
1979.71	9.54	35.344				
1979.83	9.33	35.340				
1980.34	8.98	35.338				
1981.08	9.14	35.364				
1981.30	9.14	35.347				
1981.53	9.50	35.331				
1981.79	9.56	35.334				
1983.40	9.22	35.363				
1983.63	9.35	35.373				
1984.90	9.52	35.357				
1985.07	9.25	35.368				
1985.36	9.06	35.353				
1985.64	9.46	35.352				
1987.03	9.17	35.329				
1987.33	8.87	35.341				
1988.47	9.30	35.332				
1989.07	9.32	35.322				
1989.35	8.81	35.297				
1989.60	9.18	35.321				
1989.90	9.52	35.339				
1990.49	9.08	35.320				
1990.67	9.29	35.308				
1992.74	9.26	35.314				
1993.37	9.09	35.313				
1993.69	9.38	35.305				
1994.21	8.85	35.320				
1994.35	8.60	35.298				
1994.63	9.10	35.303				
1994.90	9.42	35.321				
1995.58	9.35	35.338				
1996.75	9.12	35.277	8.46	35.194	8.75	35.210
1997.70	9.72	35.358	9.01	35.272	8.76	35.218
1998.40	9.38	35.369	9.07	35.320	8.66	35.263

1999.70	9.65	35.370	9.07	35.288	8.93	35.226
2000.11	9.56	35.372				
2000.38	9.28	35.353				
2001.35	9.26	35.350	8.62	35.263	8.11	35.207
2003.30	9.60	35.401				
2003.56	9.91	35.407				
2004.54	9.88	35.402	9.41	35.332	8.96	35.265
2005.80	9.93	35.391			8.67	35.237
2006.82	10.13	35.390	9.70	35.332	8.97	35.227
2007.66	10.02	35.396	9.57	35.333	8.92	35.243
2008.39	9.90	35.409				
2009.46	9.77	35.411	9.16	35.344	8.44	35.261
2010.38	9.63	35.412	9.02	35.313	8.28	35.230
2011.42	9.56	35.401	9.05	35.311	8.49	35.246
2012.59	9.68	35.374	9.37	35.290	9.03	35.230
2013.37	9.38	35.369	9.05	35.267	8.06	35.180

Table 2. Time series of temperature and salinity of the Labrador Sea Water in the Rockall Trough (Station M, 57.30°N 10.38°W) and Iceland Basin (Station IB12 60.0°N 20.0°W).

Date	**Rockall Trough**		**Iceland Basin**	
	Potential Temp °C	Salinity	Potential Temp °C	Salinity
1975.34	3.76	34.983		
1975.51	3.63	34.967		
1975.86	3.71	34.986		
1976.25	3.96	34.981		
1976.39	3.55	34.951		
1977.29	3.54	34.967		
1977.35	3.59	34.965		
1977.64	3.71	34.953		
1978.30	3.48	34.972		
1978.61	3.61	34.962		
1978.69	3.99	34.999		
1978.85	3.80	34.971		
1979.39	3.86	35.001		
1979.71	3.62	34.981		
1980.34	3.47	34.991		
1981.08	3.89	34.974		
1981.30	3.44	34.979		
1981.79	3.37	34.978		
1983.63	3.45	34.972		
1985.36	3.67	34.944		
1985.64	3.81	34.946		
1987.03	3.46	34.952		
1987.33	3.48	34.952		
1988.47	3.67	34.961		
1989.07	3.93	34.968		
1989.35	3.70	34.971		
1989.60	4.02	34.974		
1989.90	3.64	34.955		
1990.49	3.61	34.947		
1990.67	3.47	34.917		
1992.74	3.24	34.942		
1993.37	3.42	34.941		
1993.69	3.67	34.925		
1994.21	3.51	34.940		
1994.35	3.38	34.943		
1994.63	3.73	34.931		
1994.90	3.81	34.937		
1995.58	3.61	34.931		
1996.75	3.49	34.932		
1997.70	3.46	34.927	3.45	34.888
1998.40	3.62	34.936	3.22	34.891
1999.70	3.39	34.931	3.42	34.898
2000.11	3.31	34.926		
2000.38	3.15	34.931		
2001.35	3.27	34.924	3.11	34.890
2003.30	3.38	34.924		
2003.56	3.33	34.929		

2004.54	3.37	34.912	3.46	34.894
2005.80	3.23	34.940		
2006.82	3.30	34.923	3.54	34.908
2007.66	3.21	34.927		
2008.39	3.88	34.942		
2009.46	3.47	34.931	3.55	34.912
2010.38	3.53	34.930	3.56	34.910
2011.42	3.53	34.929	3.80	34.918
2012.59	3.27	34.924	3.70	34.914
2013.37	3.74	34.946	3.78	34.916

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Figures

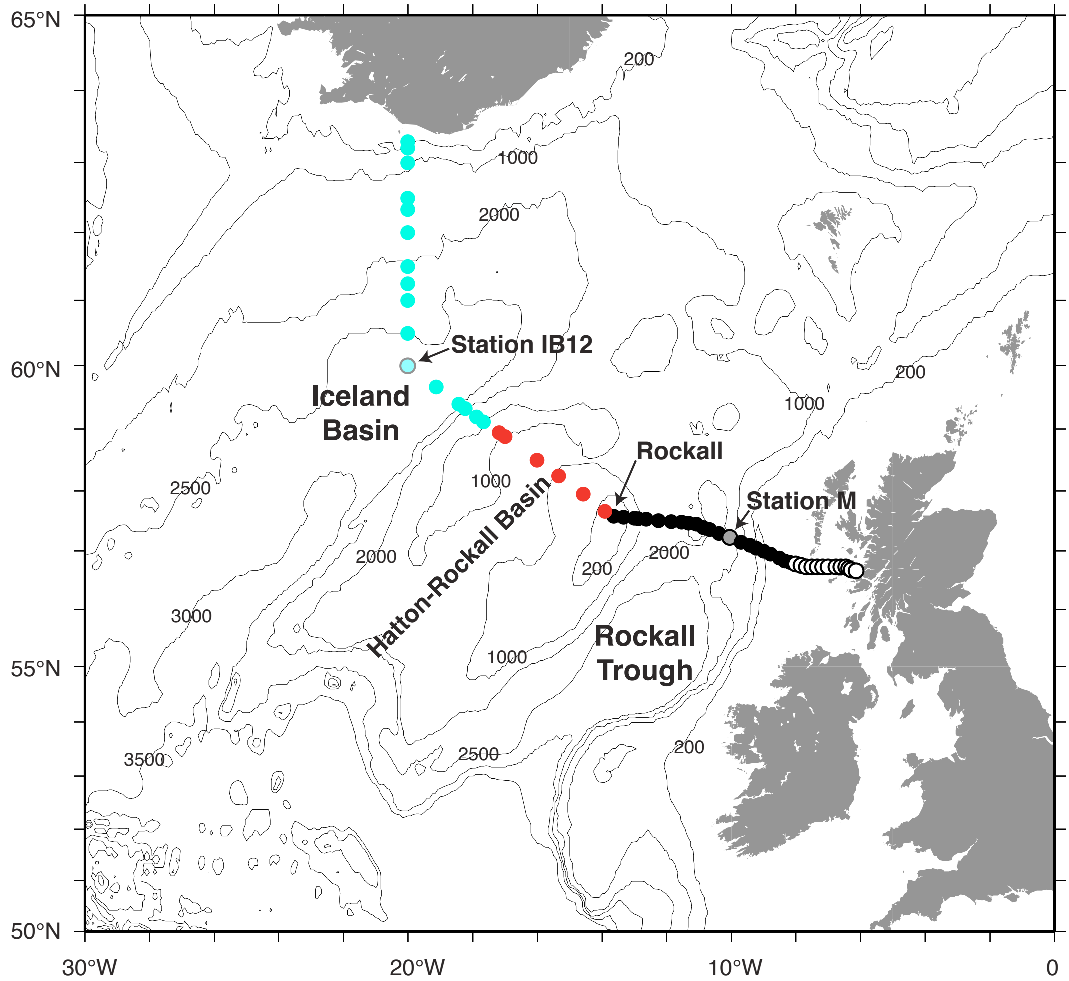

Figure 1. *Location of the Extended Ellett Line, a hydrographic section between Iceland and Scotland. Each dot represents the position of a standard station, and the different colours indicate the stations used in calculating the time series shown here. Open circles are continental shelf stations, filled black dots are Rockall Trough stations, red dots are Hatton-Rockall Basin stations, blue dots are Iceland Basin Stations. Stations M and IB12 are labelled; these are the deep stations where Labrador Sea Water properties are examined. Bathymetry contours are labelled in metres (200, 1000, 2500, 3000, 3500m).*

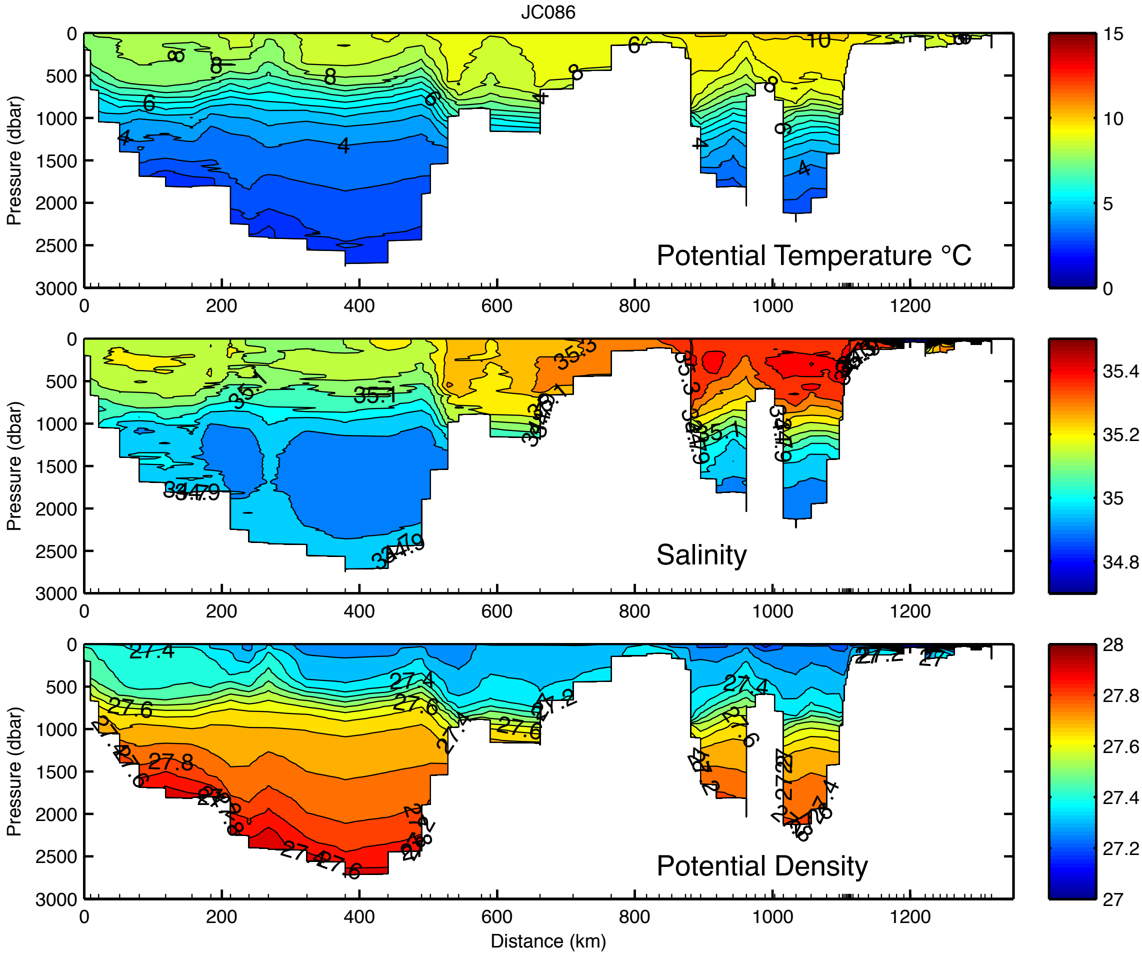

Figure 2. *Temperature, salinity and density of the eastern North Atlantic subpolar gyre; the Extended Ellett Line in May 2013. The section runs north to south, horizontal axis given in kilometres from the first station off the Iceland coast, last station is on the Scottish continental shelf.*

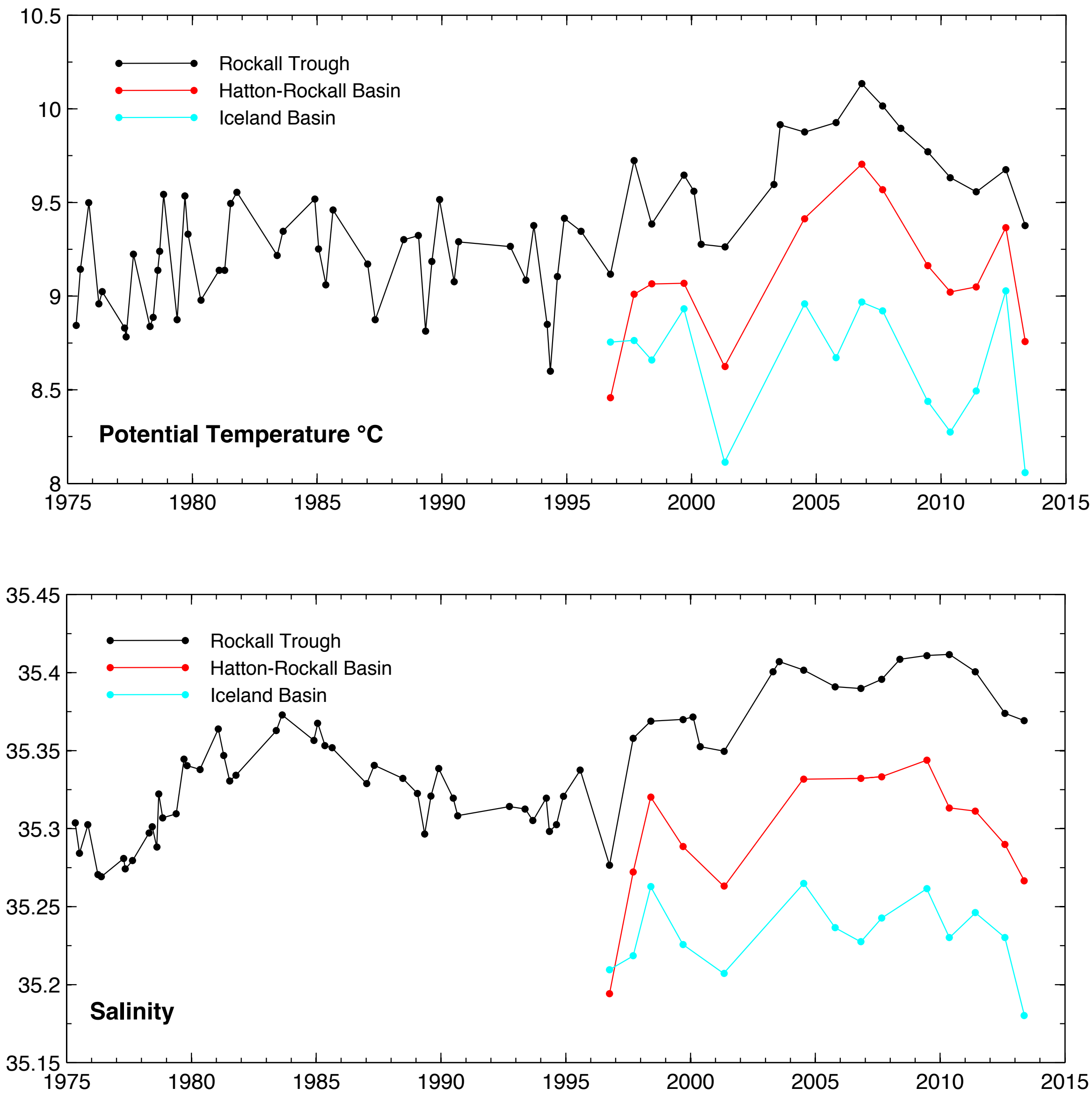

Figure 3. *Temperature (top panel) and salinity of the upper ocean in the Rockall Trough (black), Hatton-Rockall Basin (red), and Iceland Basin (blue). Upper ocean defined as 30-800m in Rockall Trough and Hatton-Rockall Basin, and as 30-600m in Iceland Basin. Continental shelf stations are not included in this figure (see Figure 1).*

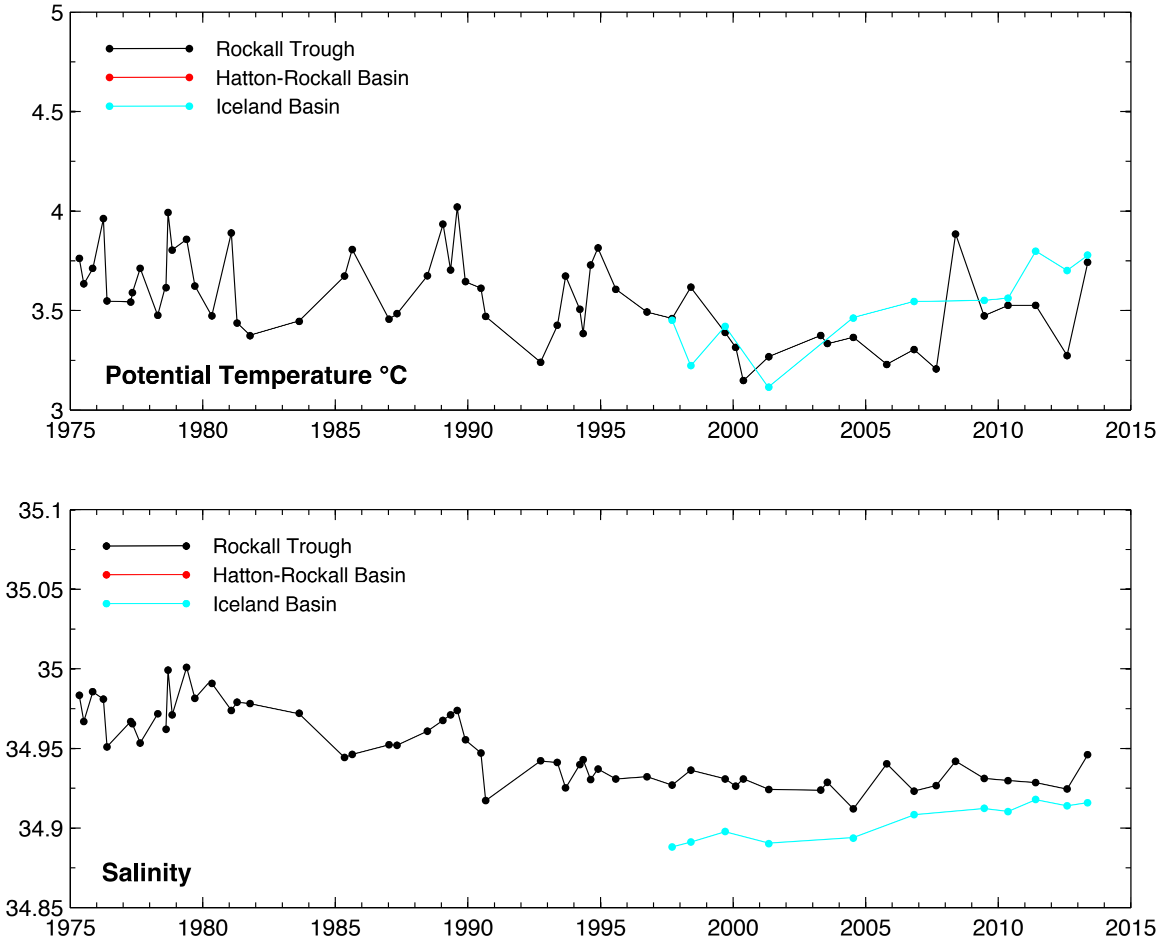

Figure 4. *Temperature (top panel) and salinity of the Labrador Sea Water in the Rockall Trough (black) and Iceland Basin (blue). Properties extracted from deep (1800-2000 dbar) potential vorticity minimum at station M in Rockall Trough (57.30°N 10.38°W) and at station IB12 in Iceland Basin (60.0°N 20.0°W). The Hatton-Rockall Basin is too shallow to contain LSW.*