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The Extended Ellett Line

Discoveries From 65 Years of Marine Observations West of the UK

BY N. PENNY HOLLIDAY AND STUART A. CUNNINGHAM

ABSTRACT. Shallow and deep branches of the Meridional Overturning Circulation pass through the Rockall Trough and Iceland Basin where measurements of salinity and temperature have been made for 65 years. There is a very small number of decadal-scale time series in the world ocean, so this long-term data collection represents an unusually rich resource for climate science. The early data sets of surface temperature and salinity collected by ocean weather ships provided a previously unseen picture of the annual cycle of these properties as well as multiyear variability. In 1975, regular, repeated sampling of the full-depth deep ocean began to reveal the variability of water masses and details of their circulation. Here, we describe the history of sampling in the region and the main scientific discoveries about ocean circulation and variability made using these data. Continuing sustained observing of temperature, salinity, nutrients, and carbon from ships will contribute to the international focus in the subpolar gyre over the next decade.

INTRODUCTION

Across the world ocean, there are a relatively small number of places where we have long-term (multidecadal) records of full-depth, deep ocean temperature and salinity. Many of the long deep-ocean records that do exist are around the fringes of the North Atlantic, and they often began as environmental surveys for fisheries management (Dye et al., 2012). Remote sensing, Argo floats, and ocean gliders have greatly increased the amount of marine data available globally in the upper 2 km, but there is still much that these long deep-ocean time series can tell us that other observations and models cannot. The Extended Ellett Line (EEL), a hydrographic section between Scotland and Iceland (Figure 1), is the latest incarnation of a measurement program that has been generating ocean observations west of the UK for 65 years. Data from the time series has been published in nearly 50 journal articles, many PhD theses, and in research and climate status reports. Here, we present the history of the time series, review the significant discoveries about ocean circulation and variability derived from the section, and consider future opportunities for continuing exploitation of this rare oceanographic resource.

THE GLOBAL SIGNIFICANCE OF THE ROCKALL TROUGH AND ICELAND BASIN

A key component of the global climate system is the Meridional Overturning Circulation (MOC), which carries heat and salt northward in the upper layers of the Atlantic Ocean and cooler, fresher water southward in the deep layers. In the subpolar North Atlantic, the northward transport takes place largely in the North Atlantic Current, which travels through the Iceland Basin and Rockall Trough in a series of jets and eddy trains, continuing into the Nordic Seas and Arctic Ocean. The returning deep branches are made up of water cooled and freshened in the Arctic, the Nordic Seas, and the subpolar North Atlantic. By making measurements between the UK and Iceland, we can investigate the dynamics and variability of the northward-flowing warm, saline water, including the interaction between the wind-driven cyclonic circulation of the subpolar gyre and the MOC. Around half of the returning dense water flows through the Iceland Basin, so by combining measurements from this region with partner programs that capture the remaining dense flows, we can understand the key processes driving them.

Conditions in the subpolar gyre are important for skillful decadal climate predictions, including the location of the Atlantic Intertropical Convergence Zone and the number of tropical storms (Dunstone et al., 2011). Important climate impacts, including rainfall in the African Sahel, Amazon, Western Europe, and parts of the United States, are associated with subpolar gyre and North Atlantic variability. Present-day ocean and climate models are still unable to accurately represent the MOC in the subpolar region; only by understanding the physics of the system can we hope to improve the models.

SURFACE SAMPLING BY OCEAN WEATHER SHIPS, 1948 TO 1996

The history of the EEL began in 1948, when Jack R. Lumby of the Fisheries Laboratory in Lowestoft, UK, realized that use could be made of the regular passage of ships to Ocean Weather Stations Alfa (62°N, 33°W), India (59°N, 19°W), and Lima (57°N, 20°W) established in late 1947 (Ellett and Jones, 1994). Lumby had devised a surface sampler that towed a thermometer and sampling bottle for five minutes in the upper few meters of the sea. In 1948, the samplers were deployed from weather ships steaming from their base on the River Clyde to the Ocean Weather Stations (Figure 1). The Fisheries Laboratory calibrated the thermometers, and salinity samples were sent to the Laboratory of the Government Chemist in London for titration (errors estimated at ± 0.10; Turrell et al., 1999). From 1956 onward, samples were taken from engine room intakes, and from mid-1961, salinity was determined at Lowestoft by salinometers, which reduced the errors. Surface sampling continued in this way until the mid-1990s; most UK weather ships ceased operation in the early 1980s, but Ocean Weather Ship *Cumulus* (Figure 2a) continued to service Lima until 1996 (http://www.varenwasleuk.nl/weerschip_cumulus.htm).

The first published description of the surface sampling showed that the mean annual cycle in the surface waters had a temperature minimum in March and maximum in August, while the salinity minimum was in late summer (August to October) and the maximum in May (Ellett and Martin, 1973; Figure 3). Twelve hydrographic sections taken between 1963 and 1968, on a section from Malin Head, Northern Ireland, to Rockall Bank were used to describe the main physical features as we understand them today: a warm, saline upper layer (9.5–12.0°C, 35.40–35.44, 0–500 m) with the highest salinity in the east, a deep thermocline from 900–1,200 m, and below that, cooler, fresher water with flat isopycnals (3°C, 34.96; Ellett and Martin, 1973).

The upper water column was mixed to 500–600 m in winter, which allowed the winter sea surface temperature and salinity to be taken as representing the conditions in the upper layer on interannual time scales (Ellett and Martin, 1973). The winter surface time series from 1948 to 1971 showed decadal-scale variability superimposed on year-to-year variations (Figure 4); most notably, the end of the 1940s was a cold and fresh period, the 1950s were characterized by rising temperatures and salinity, and the 1960s by falling temperatures, but fairly stable (slightly increasing) salinity. Ellett and Martin (1973) speculated that the cooling in the early 1960s might have been a result of prolonged periods of colder air reaching the region as a result of anomalous atmospheric pressure fields. The apparent cooling after 1960 may have been a result of changes in the way temperatures were recorded (Sherwin et al., 2012).

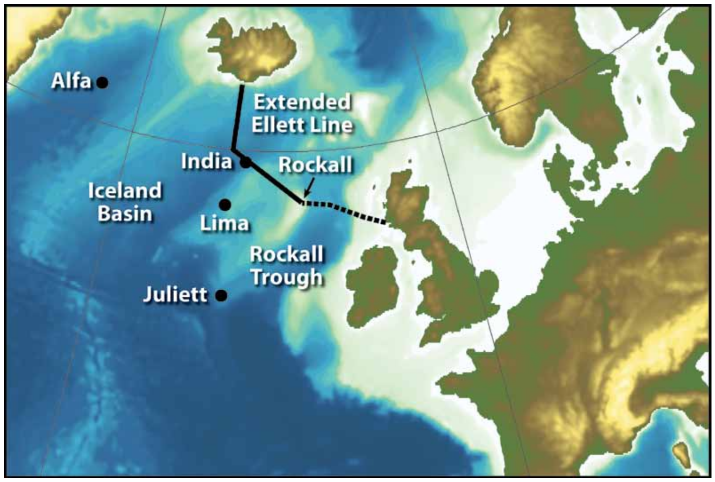

Figure 1. Location of the Extended Ellett Line, the hydrographic time series that began as a section between Scotland and Rockall in 1975 (dotted line). Sampling from ships bound for the Ocean Weather Stations (black dots) provided surface salinity and temperature records from 1948 to 1996.

THE ANTON DOHRN SECTION (ELLETT LINE), 1975 TO 1996

A program of deepwater sampling in the Rockall Trough was initiated in 1975 by a team of physical oceanographers led by David Ellett of the Scottish Marine Biological Association (SMBA, later the Scottish Association for Marine Science, SAMS). The rationale was to

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explore the deep ocean adjacent to the UK in order to observe and help explain long-term variability recognized from surface sampling. The "Anton Dohrn Section" ran from the Sound of Mull on the continental shelf out across the Rockall Trough at 57°N, passing over Anton Dohn Seamount and reaching the tiny rocky outcrop of Rockall (Figure 1). Plans for the newly commissioned Natural Environment Research Council (NERC) research vessel *RRS Challenger* were adapted to give the ship the endurance to undertake the deep ocean work (Figure 2b). The location of the section was chosen as the narrowest part of the channel where the 20 standard stations could be completed in fewer than two days. The temperature and salinity profiles were logged from instruments known as STDs (salinity, temperature, depth) from 1975–1978 and CTDs (conductivity, temperature, depth) until 1996. Temperature data were checked by the use of reversing thermometers, and salinity samples for calibration were collected in Nansen bottles at the surface and seafloor of each station for shore-based salinometer analysis. Recognizing the importance of the annual cycle in temperature and salinity of the upper layers, the program included data collection four times per year in the early years.

David Ellett championed the Anton Dohrn Section (Figure 2c). Some of the cruises suffered from technical problems with the instruments, leading to very noisy data; however, David Ellett was able to process and calibrate most, but not all the data sets collected (Holliday, 2002). In recognition of the contribution that this quiet, modest, and kind man had made to the field of oceanography, the section became known as the "Ellett Line," and Ellett was one of five distinguished scientists honored for their services to long-term measurements at the International Council for the Exploration of the Seas (ICES) Decadal Symposium in 2000 (Dickson et al., 2003). David Ellett officially retired from SAMS in 1994, and died in 2001.

The first understanding of the origins and long-term variability of the Rockall Trough water masses was based on the time series. Ellett (1978) described the temperature and salinity variations in the deepwater masses, identified as Gulf of Gibraltar Water at 900–1,400 m (now called Mediterranean Outflow Water), Labrador Sea Water (LSW) centered on 1,800 m, and below that, Norwegian Sea Water that had overflowed the Wyville-Thomson Ridge at the north of the basin (now called Wyville-Thomson Overflow Water). Ellett showed that the deep waters were relatively unchanged since the 1960s, but discussed the influence of atmospheric conditions in their source regions and the potential effects of changing volumes entering the basin. These ideas would be taken up, researched, and explained by PhD students Penny Holliday and Clare Johnson

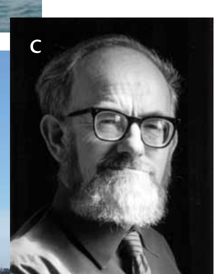

Figure 2. (a) Ocean Weather Ship *Cumulus. Reproduced with permission from Jan Fernhout, http://www.varenwasleuk.nl/weerschip_cumulus.htm* (b) RRS *Challenger*, platform for 57 of the 63 Ellett Line hydrographic sections from 1975 to 1996, affectionately known as the "Clanger." © *Natural Environment Research Council* (c) David Ellett, founder of the deep ocean time series between Scotland and Rockall. (d) RRS *Discovery* leaving the National Oceanography Centre for the last time. Since 1996, most of the occupations of the full Extended Ellett Line from Scotland to Iceland have been completed on RRS *Discovery*; in November 2012, the 50-year-old ship completed its final scientific voyage. © *N.P. Holliday*

some 20 and 30 years later.

Ellett (1980, 1982) put the interannual changes in Rockall Trough properties into wider context by comparing them to variations observed at UK Ocean Weather Stations Juliett (52°30'N, 20°W), India, and Lima, and a time series in the Faroe-Shetland Channel. Ellett (1982) was the first to suggest that the LSW variations in the Rockall Trough followed that same pattern as temperature and salinity changes observed in the central Labrador Sea where it was last exposed to the atmosphere. The LSW characteristics are determined by air-sea fluxes during deep winter convection (reaching to 500–2000 m) and are retained as it spreads throughout the northern North Atlantic in a layer 1,000–2,000 m below the sea surface. Many years later, the pattern of salinity and temperature variations in the Labrador Sea was used to estimate the time it takes for LSW to circulate to the eastern North Atlantic (Read and Gould, 1992; Cunningham and Haine, 1995; Sy et al., 1997).

Ellett (1980, 1982) suggested that consequential changes in salinity could be tracked from the upper layers of the Labrador Sea to intermediate layers south of the Rockall Trough (Ocean Weather Station Juliett) within a year, then into the northern Rockall Trough and the Iceland Basin (both about a year after being observed at Juliett). These

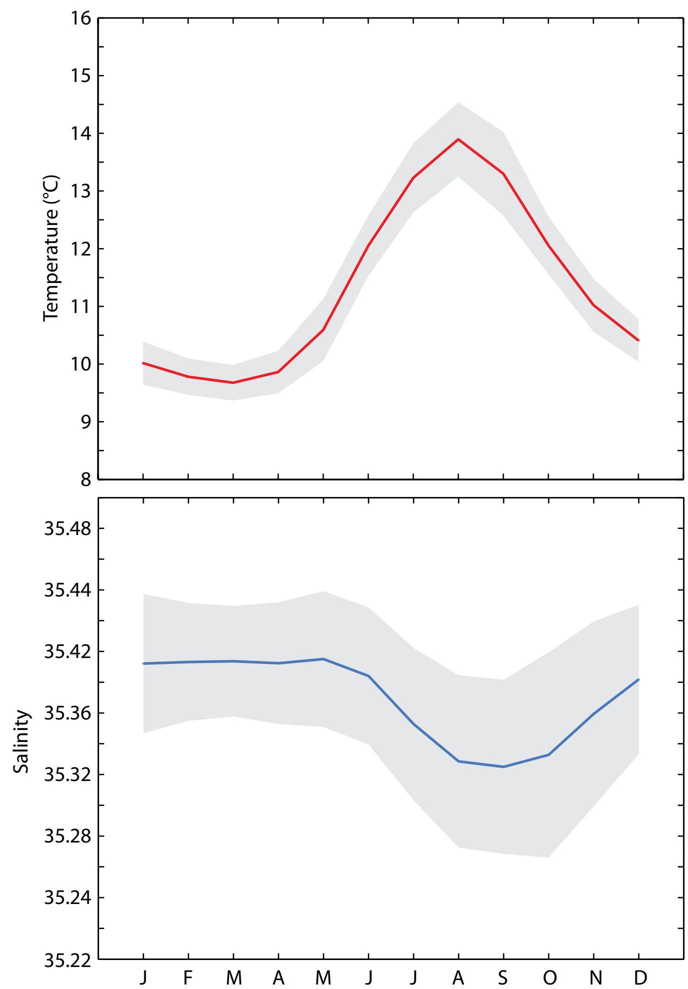

Figure 3. The annual cycle of surface temperature (top) and salinity (bottom) in the Rockall Trough, derived from underway sampling from the weather ships from 1948 to 1992 (adapted from Ellett and Jones, 1994). Gray shading represents ± 1 standard deviation.

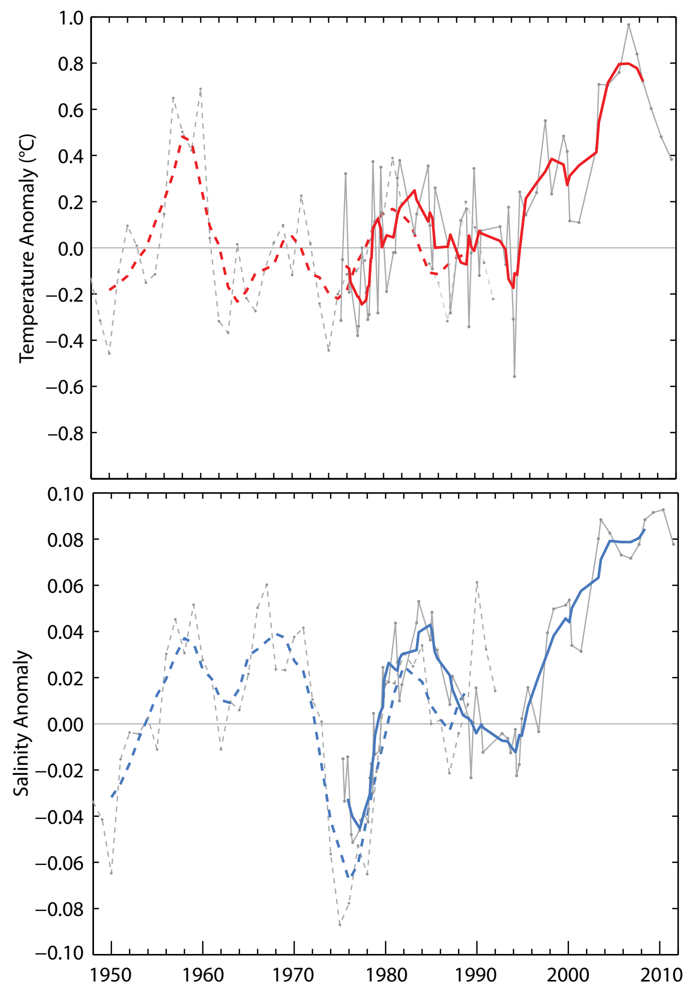

Figure 4. Decadal variability of upper ocean properties in the Rockall Trough, 1948 to 2011. Temperature (upper panel) and salinity (lower panel) are shown as anomalies from the 1976 to 1992 averages, the period when ocean weather ship time series overlap with full-depth ocean sampling. The dashed lines show winter (DJF) surface data from ocean weather ships, and the solid lines show the mean of the 0–800 m upper ocean layer taken from all Ellett Line and Extended Ellett Line cruises (various months). The thicker, colored lines show five-point running means.

changes could then be observed a further year later in the Faroe-Shetland Channel, from where the water flows to the Arctic via the Nordic Seas. He speculated that there was a range of processes at work: "The data give us no clear indication as to whether advection rates were varying, whether more Subarctic Intermediate water was being formed, or less Gibraltar water, or if the oceanic polar front had shifted position." Dickson et al. (1988) and Belkin et al. (1998) more fully developed the idea of advected salinity anomalies, demonstrating that very low salinity events that had their origins in the Arctic propagated around the upper layers of the subpolar North Atlantic. However, it was a further 20 years before the hypothesis of shifts in the polar front was more fully explored.

Although Ellett and Martin (1973) had detected a high salinity current on the edge of the Scottish continental shelf, it was first fully described in Booth and Ellett (1983) and named as the Scottish continental slope current. The persistently northward-flowing current was found above 700–800 m on the shelf break, with a high salinity and temperature core slightly inshore of the maximum current (average 0.1 ms^{-1}, transport estimated as 0.5 Sv, where 1 Sv = 10^6 m^3s^{-1}). Later research showed the persistence of this slope current, driven by a northward, increasing pressure gradient along the length of the Northwest European shelf, from the Iberian Peninsula through the Faroe-Shetland Channel (Huthnance and Gould, 1989).

The first decade of the Ellett Line provided an overview of Rockall Trough hydrography (Ellett et al., 1986) and a new description of the key water masses: eastern and western North Atlantic Central Waters plus Subarctic Intermediate Water and Gulf of Gibraltar Waters in the upper layer, Labrador Sea Water at 1,800 m, and Wyville-Thomson Overflow Water at 800–1,200 m and at 2,000 m. The literature of the first half of the 1980s contained a proliferation of new names for water masses in the North Atlantic, and Ellett et al. (1986) carefully explained how each one mentioned above related to and contributed to the characteristic waters of the Rockall Trough. Current meter measurements showed for the first time the very high level of mesoscale eddy activity in the deep water of the basin (see also Booth, 1988). The volume transport through the basin was estimated as 2.7 Sv, with 0.5–1.5 Sv carried in the slope current, representing a little under half of the warm Atlantic water flowing into the Nordic Seas and eventually the Arctic. The paper presented a synthesis of surface current measurements from current meters, drogued drifters, and drift bottle tracks in the form of a hand-drawn map (Figure 5). This view of the region's circulation is still accepted today.

STRETCHING THE SECTION TO ICELAND: THE EXTENDED ELLETT LINE, 1996 ONWARD

The present-day EEL program grew out of a significant threat to the Ellett Line. In January 1996, SAMS ran the last occupation of the Ellett Line on RRS *Challenger*. The marine physics group was disbanded, and it looked as though the time series would be drawing to an end. Concerned by the potential loss of this valuable marine climate resource, Raymond Pollard at the Southampton Oceanography Centre (SOC) led the incorporation of annual sections and scientific analysis into the center's World Ocean Circulation Experiment (WOCE) program. The objective was to quantify the mean and variability of properties and transport of Atlantic water flowing into the Nordic Seas east of Iceland, and of the returning dense overflow water. To meet this objective, the section across the Rockall Trough needed to be extended to Iceland, and annual sections were planned.

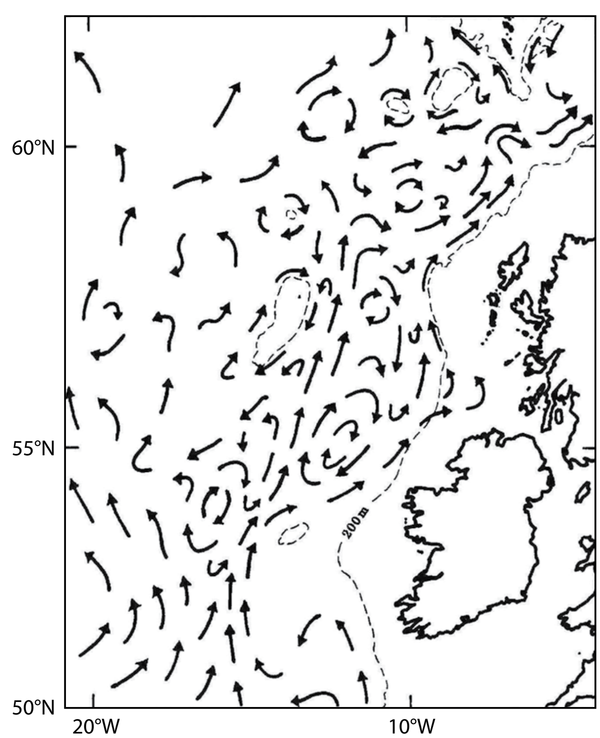

Figure 5. The pattern of upper layer circulation in the Rockall Trough estimated from a variety of sources (Figure 6 in Ellett et al., 1986). *Reproduced with permission from Cambridge University Press*

The first EEL occupation was part of a WOCE cruise on RRS *Discovery* (Figure 2d). The cruise aimed to define the pathways and volume transport of North Atlantic Current fronts by mapping the transformation pathways of subpolar mode water and identifying the origin of high salinity water in the northern Iceland Basin. The section was designed to capture exchange between the northern Rockall Trough and the Iceland Basin by taking a northern route from Rockall across major underwater banks and then heading northwestward to Iceland. For the following three years, the ship time required for the EEL was incorporated into other SOC North Atlantic WOCE cruises on RRS *Discovery*. In 1997, the route of the section was simplified to run from Rockall to 60°N, 20°W and from there northward to Iceland, establishing the EEL standard station positions that have been used ever since (Figure 1).

In a summary of the first two decades of the Ellett Line data, Holliday et al. (2000) showed that the upper and lower layers of the basin varied independently; salinity varied in the upper 800 m (amplitude 0.10), with minima in the late 1970s and early 1990s, a maximum around 1985, and increasing salinity in the late 1990s (Figure 4). In contrast, the deep LSW freshened notably in the mid-1980s, then again in 1990, after which the salinity remained fairly stable, implying occasional inflow of LSW. The new estimate of Rockall Trough transport was a mean of 3.7 ± 2.4 Sv, of which 3.0 ± 2.1 Sv was in the slope current (Holliday et al., 2000). The interannual variability of the slope current transport was linked to periods of enhanced flow of unusually warm water into the North Sea with subsequent effects on the ecosystem there (Reid et al., 2001). Data from the early WOCE cruises revealed that the pathways of the two main fronts of the North Atlantic Current both passed through the Iceland Basin, but there was a distinct zonal shift in the location of the fronts compared to a similar survey in 1991 (Pollard et al., 2004). The data also showed that some of the warm, saline Rockall Trough water recirculated into the northern Iceland Basin, influencing physical conditions there.

By 1999, SAMS had re-established a marine physics presence, and SAMS and SOC reached an agreement to run the EEL as a joint program. The practical way to share ship-time costs was for each center to lead the cruise in alternate years, with both centers contributing to staffing the cruises and analyzing data. The first joint SAMS/SOC cruise took place in early 2000. In some senses, the cruise was not a success, being severely hampered by atrocious weather and record-breaking waves (Holliday et al., 2006), but it did establish a successful joint venture pattern that has endured. An important aspect of the new joint venture was a significant training program for students and new staff to acquire sea-going skills and data sets (around 80 students participated in the cruises between 2000 and 2012).

A scientific priority during this time was to address the open questions posed by Ellett some 20 years earlier: what are the key processes that influence the variability of temperature and salinity in the Rockall Trough? How does the atmosphere influence conditions through exchange of heat, freshwater, and momentum? An examination of heat and freshwater budgets of the trough's upper layer showed that variations in air-sea heat and freshwater fluxes were an order of magnitude too small to account for the observed changes in upper ocean temperature and salinity (Holliday, 2003). Instead, the key factor influencing the properties was the position of the subpolar front to the south and west of the Rockall Trough. When the subpolar front was situated further east, the trough contained a higher proportion of relatively cooler and fresher subpolar gyre water; conversely, when the front was further west, the region was influenced more strongly by warm, saline subtropical water. The zonal shift in the subpolar front was later shown to arise from a North Atlantic-wide change in the circulation and strength of the subpolar gyre that profoundly influences regional ecology (Hátún et al., 2005, 2009). The effects of this balance of subpolar versus subtropical water influence in the Rockall Trough is felt as far away as the Arctic Ocean; from the mid-1990s to late in the first decade of the 2000s, the subpolar front stayed persistently in a western position and anomalously warm and saline water propagated through the Nordic Seas and into the Arctic Ocean (Holliday et al., 2008).

Rockall Trough waters influence conditions on the continental shelf, despite the presence of a strong coherent northward slope current that could potentially form a barrier to incursions of oceanic water onto the shelf. Water does periodically move onto the shelf, bringing higher salinity and replenishing nutrients (Huthnance, 1995; Hydes et al., 2003). The shelf waters sampled by the EEL exhibit an interannual variability of up to 1.0–1.5°C (Inall et al., 2009), though the dominant mode of variability is the seasonal cycle (amplitude 3.2°C). The variability follows a similar pattern to that observed in the deep upper waters of the Rockall Trough, highlighting the important influence of the open ocean.

In 2007, the EEL became part of the

UK-wide Sustained Observations program funded by NERC. The scientific aim is to observe key North Atlantic MOC components (shallow and deep) and thus contribute to understanding of the North Atlantic response to climate change. The original agreement for sharing ship time and analysis continues between SAMS and SOC (now called National Oceanography Centre, NOC).

The most recent significant discovery from the EEL is the periodic presence of Wyville-Thomson Overflow Water that influences temperature and salinity at the depth of the permanent pycnocline (800–1,200 m) and is thought to sometimes flow southward at depth on the western side of the basin (Johnson et al., 2010). Early hydrographic data (Ellett and Martin, 1973) and the erosion of bottom sediments on Feni Ridge (Howe et al., 2001) suggested the presence of overflow water in the basin, but for the past three decades its influence was thought to be minimal. It is now recognized that this episodic southward flow needs to be measured and accounted for when calculating climatically important heat transport through the Rockall Trough.

The range of data collected on the EEL has grown over the years; the core measurements of full-depth temperature and salinity have been enhanced by the addition of underway meteorological measurements, nutrient and oxygen samples from the CTD water bottles, current measurements from shipborne and lowered ADCPs (acoustic Doppler current profilers), tracer chemistry, and carbon system and biological parameters. Since 1975 there have been 82 occupations of the Ellett Line and EEL, and students and staff at SAMS and NOC are exploring this treasure trove of data. Data are available from the British Oceanographic Data Centre (http://www.bodc.ac.uk), and more information is available at http://projects.noc.ac.uk/ExtendedEllettLine.

FUTURE SCIENTIFIC PRIORITIES AND NEW WAYS TO MEASURE THE OCEAN

One of the preeminent scientific issues of the twenty-first century is understanding and quantifying our changing climate. An imperative for modern marine science is "to understand how the ocean circulation varies on interannual to decadal time scales and to quantify the impacts of varying ocean circulation on climate, biological productivity, the cryosphere, etc." (Bryden et al., 2012). Given the importance of the North Atlantic subpolar gyre to global ocean circulation and climate predictability, there is an imperative to continue and enhance the EEL observations (physics, chemistry, and biology) that are documenting variability on these time scales, as well as the EEL analysis that has explored causes and effects of ocean variability at the eastern margin and its role in climate variability. To enhance the existing time series, higher frequency observations will be made to properly describe the amplitude of subannual and seasonal variability. From 2014, ocean gliders (remotely controlled robotic vehicles) will cross the Rockall Trough and Iceland Basin once a month taking high temporal and spatial resolution temperature and salinity profiles of the upper waters. Subsurface (Argo) floats drift with the currents at depth (usually 2,000 m) and rise once a month to take temperature and salinity profiles, data that are immediately telemetered ashore for a near-real-time view of circulation. Floats will be deployed within the Rockall Trough and Iceland Basin; some will leave the area, but we can expect that others will enter the region, having been deployed elsewhere. Moored instruments can measure currents, temperature, and salinity at very high temporal resolution, and they have the potential to continuously monitor the key climate system parameters of volume, heat, and salt transport through the Rockall Trough. Regular ship-based hydrographic surveys with high accuracy and high precision analytical equipment and highly trained scientific staff will continue in order to calibrate measurements by satellites and autonomous or disposable instruments back to traceable absolute standards.

The priorities for analysis in the immediate future are to understand the physics of the subpolar gyre, including the storage and fluxes of carbon, heat, and freshwater, and the links among atmospheric forcing regimes, circulation, and convection in the subpolar gyre and the MOC. As part of these objectives, the new decadal record of variability afforded by the extension of EEL into the Iceland Basin will be fully explored. The EEL will continue to be part of international collaborative measurement and modeling programs to address these and other questions.

ACKNOWLEDGEMENTS

The acquisition and management of a 65-year long (and growing) marine time series requires the efforts of many people at sea and ashore, including technicians, ships' officers and crews, data managers, and scientists. Here, we recognize the particular efforts of principal scientists as key coordinators and fund-raisers. In chronological order, they are D. Ellett, R. Bowers, A. Edwards, D. Meldrum, J. Gage,

J. Gordon, J. Graham, C. Griffiths, H. Leach, R. Pollard, S. Bacon, D. Smythe-Wright, S. Cunningham, N.P. Holliday, W. Turrell, J. Allen, J. Read and T. Sherwin. The EEL scientific program will continue into the future under the leadership of Penny Holliday at NOC and Stuart Cunningham at SAMS.

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