

UHI Research Database pdf download summary

Wyville Thomson Ridge Overflow Water

Johnson, Clare; Sherwin, Toby; Smythe-Wright, Denise; Shimmield, Tracy; Turrell, William

Published in:
DEEP-SEA RES PT I

Publication date:
2010

Publisher rights:
Copyright © 2017 Elsevier B.V.

The re-use license for this item is:
CC BY-ND

The Document Version you have downloaded here is:
Peer reviewed version

The final published version is available direct from the publisher website at:
[10.1016/j.dsr.2010.07.006](https://doi.org/10.1016/j.dsr.2010.07.006)

[Link to author version on UHI Research Database](#)

Citation for published version (APA):

Johnson, C., Sherwin, T., Smythe-Wright, D., Shimmield, T., & Turrell, W. (2010). Wyville Thomson Ridge Overflow Water: Spatial and temporal distribution in the Rockall Trough. *DEEP-SEA RES PT I*, 57(10), 1153-1162. <https://doi.org/10.1016/j.dsr.2010.07.006>

General rights

Copyright and moral rights for the publications made accessible in the UHI Research Database are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights:

- 1) Users may download and print one copy of any publication from the UHI Research Database for the purpose of private study or research.
- 2) You may not further distribute the material or use it for any profit-making activity or commercial gain
- 3) You may freely distribute the URL identifying the publication in the UHI Research Database

Take down policy

If you believe that this document breaches copyright please contact us at RO@uhi.ac.uk providing details; we will remove access to the work immediately and investigate your claim.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21

Declining nutrient concentrations in the northeast Atlantic as a result of a
weakening Subpolar Gyre

Clare Johnson¹, Mark Inall¹, Sirpa Häkkinen²

¹ SAMS, Scottish Marine Institute, Oban, Argyll, PA37 1QA, Scotland.

² NASA Goddard Space Flight Center, Code 615, Greenbelt, MD 20771, USA.

Corresponding author:

Clare Johnson, SAMS, Scottish Marine Institute, Oban, Argyll, PA37 1QA, Scotland.

Email: cljo@sams.ac.uk

Phone: +44 (0)1631 559421

22 **Abstract**

23

24 Between 1996 and the mid-2000s the upper waters (200-700 m) of the Rockall Trough
25 became warmer (+0.72 °C), saltier (+0.088) and reduced in nitrate and phosphate (-2.00 μM
26 and -0.14 μM respectively). These changes, out-with calculated errors, can be explained by
27 the varying influence of southern versus subpolar water masses in the basin as the Subpolar
28 Gyre weakened and contracted. Upper water properties strongly correlate with a measure of
29 the strength of the Subpolar Gyre (the first principal component of sea surface height over the
30 subpolar North Atlantic) prior to the mid-2000s. As the gyre weakens, the upper layers of the
31 trough become warmer (r -0.85), more saline (r -0.86) and reduced in nitrate and phosphate (r
32 +0.81 and r +0.87 respectively). Further the proportion of subpolar waters in the basin
33 decreases from around 50 % to less than 20 % (r +0.88). Since the mid-2000s the Subpolar
34 Gyre has been particularly weak. During this period temperatures decreased slightly (-0.21
35 °C), salinities remained near constant (35.410 ± 0.005) and phosphate levels low and stable
36 ($0.68 \pm 0.02 \mu\text{M}$). These relative lack of changes are thought to be related to the maximum
37 proportion of southern water masses within the Rockall Trough having been reached. Thus
38 the upper water properties are no longer controlled by changes in the relative importance of
39 different water masses in the basin (as prior to the mid-2000s), but rather a different process.
40 We suggest that when the gyre is particularly weak the interannual changes in upper water
41 properties in the Rockall Trough reflect changes in the source properties of the southern
42 water masses. Since the early-2000s the Subpolar Gyre has been weaker than observed since
43 1992, or modelled since 1960-1970. Hence upper waters within the Rockall Trough may be
44 warmer, saltier and more depleted in nitrate and phosphate than at any time in the last half
45 century.

46 **Keywords**

47 Subpolar Gyre, Rockall Trough, Atlantic Water, nutrients, time-series, variability

48

49 **Highlights**

- 50 • Decreasing nutrients in upper waters (UW) of Rockall Trough 1996 to mid-2000s.
- 51 • Result of decreasing proportion of subpolar water masses as Subpolar Gyre
52 weakened.
- 53 • Since mid-2000s UW properties more stable as v weak gyre no longer direct control.
- 54 • Rather UW changes related to variations in source water mass characteristics.

55 1. Introduction

56

57 The eastern subpolar North Atlantic, including the Rockall Trough, is important for the
58 exchange of waters with the Nordic Seas to the north and the regulation of western European
59 climate. The Rockall Trough has been sampled at least annually since 1975 (with the
60 exceptions of 1986 and 2002) along the Ellett Line section (Fig. 1). Whilst only temperature
61 and salinity data were collected during early cruises, nutrient measurements (nitrite plus
62 nitrate – referred to as nitrate in this paper, phosphate and silicate) have been routinely made
63 since 1996. Although the physical oceanography of the area, both in terms of one-off surveys
64 and temporal variability, has been described by several authors (e.g. Ellett *et al.*, 1986;
65 Holliday *et al.*, 2000; New and Smythe-Wright, 2001; Ullgren and White, 2010), information
66 on the distribution of nutrients is limited. Concentrations of all three nutrients increase with
67 depth, with particularly large vertical gradients in the upper 150 m and between 750-1000 m
68 (Sherwin *et al.*, 2012). Additionally a large increase in silicate concentrations is observed
69 below around 2000 m due to the influence of the silicate-rich Antarctic Bottom Water
70 (McGrath *et al.*, 2012b). The surface waters show the largest variability in nutrient
71 concentrations (Sherwin *et al.*, 2012) due to biological depletion in spring and summer (Ellett
72 and Martin, 1973; White *et al.*, 1998). However, between 150-750 m concentrations increase
73 only slowly with relatively low seasonal and interannual variability (Sherwin *et al.*, 2012).
74 Concentrations between 0-700 m, corresponding to the warm and saline Atlantic Waters in
75 the area, have relatively low nutrient concentrations ranging between 7.42-18.60 $\mu\text{mol kg}^{-1}$,
76 0.48-1.10 $\mu\text{mol kg}^{-1}$ and 2.44-9.35 $\mu\text{mol kg}^{-1}$ for nitrate, phosphate and silicate respectively
77 (McGrath *et al.*, 2012b). In the upper 300 m, south of $\sim 55^\circ\text{N}$, an east-west gradient is
78 sometimes observed with slightly higher concentrations in the relatively cooler and fresher
79 waters found in the west of the Rockall Trough (nitrate +1.4 $\mu\text{mol kg}^{-1}$, phosphate +0.1 μmol
80 kg^{-1} , silicate +0.9 $\mu\text{mol kg}^{-1}$). This has been attributed to the influence of higher nutrient
81 waters from the North Atlantic Current (McGrath *et al.*, 2012b).

82

83 Only a single paper has presented a first-look at the interannual variability of nutrients in the
84 basin (Sherwin *et al.*, 2012). Between 1996 and 2009 phosphate concentrations in the upper
85 waters (0-800 m) of the Rockall Trough decreased by 0.17 μM . It was speculated that this
86 was related to an increased influence of low phosphate subtropical waters in the basin as the
87 Subpolar Gyre weakened and contracted north-westwards. Changes in horizontal advection
88 have been found to be important in determining nutrient concentrations in the eastern

89 subtropical North Atlantic (Oschlies, 2001) and Norwegian Coastal Current (Frigstad *et al.*,
90 2013).

91

92 This study is a thorough exploration of the preliminary analysis of Sherwin *et al.* (2012). A
93 comprehensively quality-checked Ellett Line dataset, with calculated errors, is presented.

94 This is the first published time-series of its kind in the subpolar North Atlantic and is used to
95 investigate the controls on the temporal distribution of upper water nutrient concentrations in
96 the Rockall Trough.

97

98

99 **2. Upper and intermediate water masses in the Rockall Trough**

100

101 The Rockall Trough is bounded to the east by the European Shelf and to the west by a series
102 of banks separating it from the Iceland Basin (Fig. 1). Although the northern limit of the
103 trough is delimited by part of the Greenland-Scotland Ridge (the Wyville Thomson Ridge),
104 the southern basin opens onto the Porcupine Abyssal Plain. Four water masses potentially
105 influence the upper layers (< 700 m) of the Rockall Trough: that entering via the Shelf Edge
106 Current (North Atlantic Water, red, Fig. 1), that entering from the Bay of Biscay region
107 (Eastern North Atlantic Central Water, cyan, Fig. 1), that entering via the North Atlantic
108 Current (Western North Atlantic Central Water, purple, Fig. 1) and that entering from the
109 Subpolar Gyre to the west (modified - Western North Atlantic Central Water, green, Fig. 1).
110 These are discussed in turn before the underlying intermediate water masses are briefly
111 introduced.

112

113 *2.1. Upper water entering via the Shelf Edge Current*

114 The Shelf Edge Current (SEC) in the Rockall Trough is thought to be a persistent northward-
115 flowing feature although further south in the Bay of Biscay seasonal flow reversals are
116 observed (Pingree and Le Cann, 1989). The current is most readily identified by high salinity
117 water (> 35.36) located between the seasonal and permanent pycnoclines (extending to the
118 surface in winter) over the continental slope (Booth and Ellett, 1983; Hill and Mitchelson-
119 Jacob, 1993). Although the SEC is usually observed over the upper slope (Burrows *et al.*,
120 1999), its signature sometimes extends over the lower slope and into the eastern Rockall
121 Trough (Booth and Ellett, 1983; Holliday *et al.*, 2000).

122

123 As the SEC carries the warmest and saltiest water within the trough, known as North Atlantic
124 Water (NAW), it must originate to the south of the basin (White and Bowyer, 1997). Indeed
125 its temperature-salinity characteristics lie close to those of Eastern North Atlantic Central
126 Water (ENAW) (Hill and Mitchelson-Jacob, 1993) which forms south of the Rockall Trough.
127 However, it should be noted that the NAW within the SEC is warmer, more saline and less
128 dense than the ENAW found offshore at the same latitude (Holliday *et al.*, 2000). Nutrient
129 concentrations within NAW are relatively low (Table 1) again indicating a southern source.
130 [Upper water nutrient concentrations, particularly in the case of nitrate and phosphate,
131 decrease southwards from the Subpolar Gyre towards the Subtropical Gyre (Garcia *et al.*,
132 2010). This is related to declining winter convection depths, and the associated reduction in
133 replenishment of upper water nutrients by mixing with underlying higher-nutrient
134 intermediate waters (Louanchi and Najjar, 2000).]

135

136 *2.2. Upper water entering from the Bay of Biscay area*

137 The predominant water mass in the upper layers of the Rockall Trough during two survey
138 periods (1963-1968 and 1975-1998) was ENAW (Arhan *et al.*, 1994; Ellett and Martin, 1973;
139 Holliday *et al.*, 2000). This water mass originates from the Bay of Biscay area which is a
140 region of weak currents located between the Subtropical and Subpolar Gyres. Here, waters
141 that have entered via the North Atlantic Current (NAC) are subject to winter convection and
142 cooling leading to an increase in salinity for a given temperature (Pollard *et al.*, 1996; Pollard
143 and Pu, 1985). As they move northwards, salinity is thought to be further increased by
144 mixing with underlying Mediterranean Overflow Water (MOW) (Ellett *et al.*, 1986; Harvey,
145 1982), although this exchange is likely to be limited to certain geographic locations (Pollard
146 *et al.*, 1996). Similarly to NAW, nutrient levels in ENAW are relatively low (Table 1)
147 reflecting its southern formation area

148

149 *2.3. Upper water entering via the North Atlantic Current*

150 The NAC transports warm and saline Western North Atlantic Central Water (WNAW) from
151 the western North Atlantic across the Mid Atlantic Ridge into the eastern North Atlantic (e.g.
152 Arhan, 1990; Read *et al.*, 2010; Sy *et al.*, 1992). The current exists in a series of branches
153 with the eastern-most sometimes entering the Rockall Trough (e.g. New and Smythe-Wright,
154 2001; Orvik and Niiler, 2002; Otto and van Aken, 1996) and at other times flowing to the
155 west of Rockall Bank (e.g. Bacon, 1997; Pollard *et al.*, 2004; Read, 2001). These differences
156 are likely to be related to changes in the strength of the Subpolar Gyre (Holliday, 2003)

157 which is discussed in section 3. WNAW is cooler and fresher than ENAW (Table 1) as well
158 as having higher nutrient concentrations (McGrath *et al.*, 2012b).

159

160 2.4. Upper water entering from the west

161 The coolest and freshest Atlantic Waters within the subpolar North Atlantic are those found
162 to the northwest of the northernmost branch of the NAC. These waters are a mixture of
163 WNAW carried in the NAC, and SubArctic Intermediate Water (SAIW) found further to the
164 west and north (Harvey and Arhan, 1988; Holliday, 2003). We use the term modified-
165 WNAW (mod-WNAW) to denote this water mass. Mod-WNAW is known to have
166 influenced the Rockall Trough in the early 1950s (Tulloch and Tait, 1959), in 1978 (Dooley
167 *et al.*, 1984) and partially in 1996 (Holliday, 2003). Again the influence of mod-WNAW in
168 the Rockall Trough is thought to vary with the strength of the Subpolar Gyre (Hátún *et al.*,
169 2005; Holliday, 2003). Nutrient concentrations within this water mass are higher than those
170 found in ENAW or NAW (Table 1) due the relatively nutrient rich nature of the Subpolar
171 Gyre (Garcia *et al.*, 2010).

172

173 2.5. Underlying intermediate water masses

174 In the southern-most Rockall Trough the upper waters are underlain by MOW in the east and
175 SAIW to the west (Ullgren and White, 2010). MOW is best identified by its high salinity
176 (35.5-35.6) and is found below ~ 700 m, whilst SAIW is a relatively fresh (< 34.90) water
177 mass at a similar density level (Pollard *et al.*, 2004; Reid, 1979). Both water masses have
178 higher nitrate and silicate concentrations than seen in any of the four upper water masses
179 (Table 1). The signatures of MOW and SAIW are lost in the southern Rockall Trough
180 through mixing (Ullgren and White, 2010) leaving Wyville Thomson Ridge Overflow Water
181 (WTOW) as the dominant intermediate water mass in the northern and central basin (Johnson
182 *et al.*, 2010). This water mass is found below 600-700 m. Its temperature and salinity
183 properties lie on a mixing line between the upper waters and the overflow water that enters
184 the Rockall Trough over the Wyville Thomson Ridge (Johnson *et al.*, 2010). WTOW's
185 temperature and salinity are lower than those of the upper waters whilst nutrient
186 concentrations are higher (Table 1). This nutrient signature is suspected to be related to the
187 remineralisation of nutrients in the lower oxygen layer (between 800-1200 m in the Rockall
188 Trough) which is a permanent feature in the eastern subpolar North Atlantic, rather than
189 being directly attributable to the signature of WTOW itself (Johnson, 2012).

190

191 3. Temporal variability of upper water mass distribution

192

193 Temperature and salinity in the north-eastern subpolar North Atlantic vary on a variety of
194 time-scales. Interannual and decadal variability cannot be simply explained by changes in
195 local air-sea heat and freshwater fluxes (de Boissésion *et al.*, 2012; Hátún *et al.*, 2005;
196 Holliday, 2003; Thierry *et al.*, 2008); or by variations in source properties of the constituent
197 water masses (Hátún *et al.*, 2005; Holliday *et al.*, 2000). Instead, they are more likely to be
198 caused by advective changes in the relative amounts of southern to subpolar waters in the
199 area. These advective changes are linked to fluctuations in the strength of the Subpolar Gyre
200 and associated adjustments in the position of the Subpolar Front (e.g. Bersch *et al.*, 1999;
201 Hátún *et al.*, 2005; Holliday, 2003; Thierry *et al.*, 2008). This front (blue dashed line, Fig. 1)
202 marks the northernmost limit of the NAC and is the boundary between subpolar and
203 subtropical water masses (Pollard *et al.*, 2004).

204

205 When the Subpolar Gyre strengthens it expands south-eastward and enters the Iceland Basin
206 and Rockall Trough. This movement is associated with a similar extension of the subpolar
207 SAIW and mod-WNAW which in turn block the northward movement of southern-origin
208 waters (e.g. Häkkinen and Rhines, 2009). Hence upper waters within the Rockall Trough
209 become cooler and fresher (Hátún *et al.*, 2005; Holliday, 2003). Conversely, when the
210 Subpolar Gyre weakens the Subpolar Front contracts north-westwards. As the gyre
211 weakened between 1991 and 1996 it retreated westward by 300 km along 54 °N (Pollard *et al.*
212 *et al.*, 2004) whilst the 7 °C isotherm shifted north-westward as the gyre continued to weaken
213 between 1995 and 2006 (Thierry *et al.*, 2008). This contraction of the Subpolar Gyre leads to
214 a decline of western waters, and increase in southern waters, in the eastern subpolar North
215 Atlantic (e.g. Bersch, 2002). Thus upper waters in the Rockall Trough become warmer and
216 more saline (Hátún *et al.*, 2005; Holliday, 2003).

217

218 A measure of the strength the Subpolar Gyre can be obtained from the first principal
219 component of sea surface height (SSH) over the subpolar North Atlantic, christened the
220 ‘subpolar gyre index’ by Hátún *et al.* (2005). Since 1992 this has been derived from altimeter
221 data (Häkkinen and Rhines, 2004, 2009) and shows a trend of weakening between 1996 and
222 the present day (Fig. 3.a). By using models the strength of the gyre has been estimated back
223 to 1960 (de Boissésion *et al.*, 2012; Hátún *et al.*, 2005; Lohmann *et al.*, 2009). This

224 combined model and observed record suggests that the Subpolar Gyre is currently weaker
225 than at any time since 1960-1970.

226

227

228 **4. Methods**

229

230 Since 1996 the Ellett Line has been jointly maintained by the Scottish Association for Marine
231 Science (SAMS) and the National Oceanography Centre, Southampton (NOC) with two
232 occupations by Marine Scotland - Science (MS-S) (Table 2). Although each laboratory used
233 the standard colorimetric technique with an autoanalyser (e.g. Grasshoff *et al.*, 1999), the
234 methods were not identical. Various procedures were used to ensure the quality of the data
235 including the use of standards and on some cruises reference materials. However, a number
236 of analytical issues with nitrate and phosphate analyses were encountered, some of which are
237 mentioned in the corresponding cruise reports. In particular nitrate data from D321, D340
238 and D365 were elevated due to matrix effects affecting the cadmium column's pH and
239 therefore efficiency (T. Brand, pers. comm.). This problem has now been rectified for
240 subsequent analyses, but nitrate data from these three cruises is poor quality and was
241 therefore not used within this study. By contrast, no known issues with silicate analyses
242 exist. Additionally, there is little inter-cruise variability between 200-700 m for silicate
243 profiles, unlike for nitrate and phosphate (Table 3). Whilst this partially suggests low natural
244 variability for silicate, it also indicates high inter-laboratory and high inter-cruise consistency
245 and the absence of outlying data. Thus, silicate data do not appear to have been affected by
246 analytical problems and we find no reasons to suspect the quality of the data.

247

248 Temperature and salinity data have previously been investigated and have been found to be of
249 a high quality (Holliday *et al.*, 2000; Johnson, 2012) although severe spiking effected the
250 upper 150 m of data from D242. All CTD data and the majority of nutrient data were
251 obtained from BODC (www.bodc.ac.uk) with the remaining nutrient data obtained directly
252 from the analysing laboratory.

253

254 *4.1. Removal of poor-quality and outlying nutrient data*

255 As we find no contra-indications to the silicate data being of a good quality (see above), the
256 empirical relationships between silicate and nitrate, and silicate and phosphate, were used to
257 identify and remove outlying and poor quality nitrate and phosphate data. Any silicate data

258 with quality flags from the originating laboratory were disregarded before the relationships of
259 silicate with nitrate and phosphate respectively were calculated. Below a silicate
260 concentration of 11 μM (i.e. for upper and intermediate waters) a second order polynomial
261 best described the mode calculated for incremental silicate concentrations for both nitrate and
262 phosphate. Data within \pm one standard deviation of the mode curve were regarded as good
263 quality data, whereas data outside of this boundary were discounted for the purposes of this
264 work.

265

266 Data were further checked by considering (for each cruise) the number of stations which
267 sampled the upper waters (200-700 m), and the total number of good quality data points
268 within the upper waters across the entire Ellett Line section. To ensure that the data were
269 representative of the basin as a whole, at least two stations had to have been occupied east of
270 the Anton Dohrn Seamount (which is located approximately half way across the Ellett Line at
271 11 °W) and at least two stations to the west. If, in total, less than four stations were sampled
272 across the whole section, or less than eight good quality data points existed, then the
273 appropriate data from that particular cruise were discounted. For cruises with five or more
274 stations, and greater than 10 data points, data were assumed to be of good quality. Those
275 cruises with intermediate characteristics (i.e. four stations occupied, or eight or nine data
276 points), were considered individually to ensure that poor quality data were excluded and also
277 that good quality data were not discarded.

278

279 Using the above criteria, the majority of cruises were classed as being good quality although
280 around 15 % of data were discarded. Two cruises were disregarded for phosphate (0703S and
281 D351), four for nitrate (0703S, D321, D340 and D365) and one for silicate (0703S). For
282 D321, D340, D351 and D365 this was the result of poor quality and outlying data, whilst for
283 0703S data were of a high quality but only available for three stations in the western trough.
284 A further cruise (P300_2) fitted the 'intermediate characteristics' category for nitrate. This
285 was processed using the methods in sections 4.2 and 4.3 with a decision of inclusion being
286 made at the final stage.

287

288 *4.2. Integration of data*

289 In order to create a value representative of the upper waters as a whole for each Ellett Line
290 station during a particular cruise, data were first linearly interpolated onto a regular 50 m
291 vertical grid before being trapezoidally integrated between 200-700 m. Integrated values

292 were only calculated for stations with a total depth greater than 700 m to avoid bias towards
293 shallower waters. The upper limit for integration (200 m) was chosen to eliminate the effects
294 of the seasonal pycnocline whilst the lower limit (700 m) ensured that only Atlantic Waters
295 and not the underlying intermediate WTOW were sampled. Although absolute values differ
296 with choice of upper and lower integration depths, the temporal patterns remain almost
297 unchanged which suggests that the approach is robust and that calculated values are
298 indicative of the upper waters. Integrated values for both the nutrient and physical variables
299 do not show a relationship with month of the year suggesting that interannual variability
300 dominates over seasonal signals and that no seasonal corrections need to be applied (Fig. 2).

301

302 *4.3. Calculation of mean and errors*

303 As the integrated dataset for an individual cruise was fairly small, data were bootstrapped so
304 that a mean value and associated error (indicating the reliability of the mean) could be
305 calculated for each variable. Bootstrapping is a standard technique that creates replicate
306 datasets by subsampling the original data repeatedly (Emery and Thomson, 2001). In this
307 case the integrated dataset for each variable (from an individual cruise) was subsampled 2000
308 times and a mean calculated for each of the ‘artificial’ datasets. Following the method of
309 Rippeth and Inall (2002), the total mean (for each variable during a particular cruise) was
310 defined as the average of the 2000 calculated means, and the error as the spread of the central
311 95 % of these means. All bootstrapped data, including those for the cruise that fitted the
312 ‘intermediate characteristics’ for nitrate data quality (P300_2), approximated a normal
313 distribution indicating that this approach is valid. (The bootstrapped data from cruises that
314 were discounted using the criteria listed in section 4.1 did not display a normal distribution.)
315 Nitrate from P300_2 was therefore included within this study.

316

317 *4.4. Check of N:P and interannual consistency*

318 As a final check of data quality the N:P was calculated and the data examined for interannual
319 consistency. The mean N:P for all cruises (15.7 ± 0.4) was fairly consistent and only slightly
320 higher than other values published in the literature (14.0-15.1) for the Rockall Trough area
321 (Hydes *et al.*, 2001; Tanhua *et al.*, 2009; White *et al.*, 1998).

322

323 Throughout the time-series interannual consistency for all parameters was good with the
324 exception of the nitrate data collected in 2010 (D351, circle, Fig. 3.e). Using the near-
325 constant relationship between N and P, nitrate values in 2009 and 2011 were estimated

326 between 10.0-11.7 μM (grey lines, Fig. 3.e). However, the measured nitrate concentration in
327 2010 is 12.9 μM suggesting that the value may be artificially elevated. Alternative
328 possibilities are: that both the nitrate and phosphate were high in 2010, that the N:P ratio
329 changed (by ~ 5) in 2010, or that the 2007-2011 phosphate concentrations are artificially low.
330 Such a large change in either the nutrient concentrations or N:P within a single year seems
331 unlikely. As the phosphate data between 2007 and 2011 were analysed by two different
332 laboratories, analytical error is less probable. As such, the 2010 nitrate value, despite having
333 passed the quality-checking procedures (section 4.1) is treated with caution.

334

335 4.5. Defining water masses

336 In order to investigate the relative influence of the four upper water masses to the Rockall
337 Trough, the physical and chemical characteristics of these water bodies were defined in
338 addition to the properties of the underlying intermediate water masses (Table 1). Interannual
339 means were used where-ever possible in order to take account of some of the natural
340 variability of the water masses. The properties for ENAW, mod-WNAW and WNAW were
341 averages of data collected between 1955 and 2006 published in the World Ocean Atlas 2009
342 (Antonov *et al.*, 2010; Garcia *et al.*, 2010; Locarnini *et al.*, 2010). Definitions were taken
343 from 400 m, to approximate integration between 200-700 m, at appropriate locations for the
344 individual water masses (black circles, Fig. 1). The definitions for ENAW and WNAW lie
345 on the respective standard curves often used in the literature (Harvey, 1982; Iselin, 1936). As
346 the SEC is a narrow feature it is not refined by the World Ocean Atlas. Hence, physical
347 characteristics were obtained from the annual mean calculated from Ellett Line data between
348 1975 and 1998 (Holliday *et al.*, 2000) whilst the nutrient properties were obtained from a
349 single occupation in 2006 (Johnson, 2012). Mean nutrient values for MOW and SAIW were
350 calculated from the core of the two water masses (850m and 700 m respectively) in the
351 southernmost Rockall Trough in 2004 (Johnson, 2012). These are similar to those measured
352 in 2006 and 2008-2010 over a range of depths (McGrath *et al.*, 2012b). For the physical
353 characteristics of MOW and SAIW the end-member definitions of Reid (1979) and Pollard *et al.*
354 (2004) respectively were chosen. Mean temperature and salinity characteristics for
355 WTOW were obtained from Ellett Line data between 1975 and 2007 (Johnson *et al.*, 2010),
356 for this study the temperature and salinity at around 800 m is used. Nutrient values were
357 obtained from the quality checked data used in this study, again at 800 m. Again these
358 compare favourably to those reported by McGrath *et al.* (2012b).

359

360 **5. Temporal variability of upper water mass properties**

361

362 As the Subpolar Gyre weakened between 1996 and the mid-2000s (Fig. 3.a), the upper waters
363 (mean 200-700 m) of the Rockall Trough became warmer and more saline. Overall, between
364 1996 and 2003, salinities increased by +0.088 (Fig. 3.b) whilst temperatures rose from 9.12
365 °C in 1996 to a peak of 9.76 °C in mid-2004 (Fig. 3.c). A small reversal in this trend,
366 coincidental with a slight strengthening of the Subpolar Gyre, was seen in 2000-2001 when
367 salinity and temperature fell by -0.025 and -0.16 °C respectively. After 2003 salinities
368 remained near constant (with the majority of variability within the 95 % confidence limit) and
369 temperatures fell (-0.21 °C) although the Subpolar Gyre first strengthened slightly before it
370 continued to weaken.

371

372 Phosphate concentrations, although exhibiting an overall decrease with time (-0.14 μM,
373 1996-2011), were more variable (Fig. 3.d). Mean phosphate levels in the upper waters
374 initially decreased by -0.10 μM between 1996 and 1998 before concentrations rose to 0.76-
375 0.80 μM in 1999, 2000 and 2001. This increase was contemporaneous with a decrease in
376 salinity and temperature as the Subpolar Gyre temporarily strengthened in 2000. As the gyre
377 again weakened, and temperature and salinity rose, phosphate concentrations decreased to
378 0.71 μM in 2003. However, values between 2004 and 2006 were elevated (0.78-0.80 μM)
379 although salinities remained constant and temperatures increased slightly. Finally, as the
380 Subpolar Gyre continued to weaken, phosphate concentrations between 2007 and 2011
381 remained near constant at 0.68 ± 0.02 μM with all changes within calculated errors.

382

383 The trends in nitrate with time (Fig. 3.e) imitated those of phosphate. Concentrations initially
384 decreased from 12.78 μM in 1996 to 12.05 μM in 1998 as temperature and salinity rose and
385 the Subpolar Gyre weakened. Levels were high in 1999 (12.87 μM) before dropping slightly
386 to 11.91-12.31 μM in 2000 and 2001. Concentrations fell to 10.75 μM in mid-2003 when the
387 Subpolar Gyre again weakened and temperature and salinity were high. As for phosphate,
388 nitrate values in 2004, 2005 and 2006 were elevated (12.37-12.59 μM) although no strong
389 change was seen in temperature or salinity. In 2008 the lowest concentration was observed
390 (10.59 μM) which coincided with a low phosphate value, a high salinity and a relatively high
391 temperature.

392

393 Silicate levels within the upper waters of the Rockall Trough (Fig. 3.f) have remained more
394 constant than temperature, salinity, phosphate or nitrate between 1996 and 2011 with the
395 majority of variability within calculated errors. However, at the start of the record some
396 statistically significant changes are observed. Concentrations initially decreased by $-0.44 \mu\text{M}$
397 between 1996 and 1998, coincidental with the increase in temperature and salinity, and
398 reduction in nitrate and phosphate values. In 1999 higher silicate concentrations were
399 observed, again contemporaneous with the observed increase in nitrate and phosphate levels
400 and approximately concurrent with the falling temperature and salinity. Since 2004 silicate
401 levels have been near constant ($5.15 \pm 0.14 \mu\text{M}$) with variations within the calculated errors.
402 This period is coincident with the period of near constant salinity.

403

404

405 **6. Possible causes of changing nutrient levels**

406

407 Nutrient levels within oceanic upper waters can be effected by: vertical exchange with
408 underlying water masses, horizontal advection, or non-conservative local biogeochemical
409 processes. If changes in vertical and/or horizontal exchange explain the majority of
410 variations in the nutrient record within the Rockall Trough, then biogeochemical processes
411 can be discounted as a predominant control. Thus vertical and horizontal exchanges are first
412 examined.

413

414 *6.1. Changes in depths of winter convection*

415 Changes in ocean-atmosphere heat fluxes, the interannual magnitude of which is related to
416 the depth of winter convection, cannot explain the observed changes in temperature between
417 0-800 m in the Rockall Trough (Holliday, 2003). However, the possible effect of
418 increasing/decreasing winter mixed layer depth and erosion of underlying water masses on
419 the nutrient record needs to be investigated further. In the southern Rockall Trough the
420 winter mixed layer has not been observed to exceed 470 m (McGrath *et al.*, 2012a; Ullgren
421 and White, 2010). As MOW and SAIW are found below ~ 700 m (Pollard *et al.*, 2004; Reid,
422 1979) it seems unlikely that these two water masses can contribute significantly to the
423 nutrient budget of the upper waters. Whilst convection in the central trough usually reaches
424 600-700 m (Ellett *et al.*, 1986; Holliday *et al.*, 2000; Meincke, 1986), it has been observed to
425 extend to 750-800 m during some periods (Ellett and Martin, 1973). Hence, although in the

426 majority of years the underlying WTOW (found below 600-700 m) should not be eroded to
427 any great extent, during some winters it may be mixed into the overlying waters.

428

429 The mixed layer depth (MLD) for each February between 1996 and 2011 was calculated
430 using data downloaded from the U.K. Meteorological Offices EN3 (version 2a) database
431 (<http://www.metoffice.gov.uk/hadobs/en3/>). This resource combines data from ships,
432 moored buoys and ARGO floats and is 1x1 degree resolution (Ingleby and Huddleston,
433 2007). The MLD, following convention (e.g. Hughes, 2010), was defined as the depth at
434 which the temperature deviates by 0.5 °C from the surface temperature (here defined by that
435 at 15 m). This was calculated for 12 individual grid squares within the Rockall Trough (56-
436 58 °N, 10-13 °W) and averaged to create a final value (Table 4). Mean MLD ranged from
437 440 m to 780 m whilst the maximum MLD varied between 540 m and 970 m. There is no
438 overall trend in either the mean or maximum MLD between 1996 and 2011, suggesting that
439 vertical mixing cannot be the primary control on the observed changes in upper water
440 properties within the Rockall Trough. This is confirmed by the lack of correlation between
441 upper water properties and mean or maximum MLD (not shown, r values between -0.33 and
442 +0.19). However, as the MLD is greater than the vertical extent of the upper waters (600-700
443 m) it may be an important process in some years.

444

445 To investigate this further, the signature of the underlying WTOW at 800 m is plotted in
446 property-property space along with the mean upper water characteristics between 1996 and
447 2011 (Fig. 4). If vertical mixing is important one would expect the upper water properties to
448 trend towards those of the underlying water, this is not seen for any year. This is particularly
449 clear in nitrate-salinity and silicate-salinity space (Fig. 4. c-d) due to the high nutrient content
450 of the intermediate water. This again suggests that winter convection is not the primary
451 control on upper water properties within the Rockall Trough, but also that it is not an
452 important process for any individual year between 1996 and 2011.

453

454 6.2. Changes in horizontal advection

455 Variations in the salinity of the upper waters of the Rockall Trough have been attributed to
456 changes in the relative importance of southern versus subpolar water masses (Hátún *et al.*,
457 2005; Holliday, 2003). Further, it is hypothesised that nutrient concentrations may similarly
458 be controlled (Sherwin *et al.*, 2012). To investigate this, the dataset was plotted in property-
459 property space along with definitions for the four upper water masses thought to influence the

460 Rockall Trough (Table 1). Those water masses entering the basin from the south (ENAW
461 and NAW) are warm, saline and relatively depleted in nutrients. In contrast the water mass
462 carried in the NAC (WNAW) and that which enters from the west (mod-WNAW) are cooler,
463 fresher and have higher nutrient concentrations. Water properties clearly lie within the area
464 expected if ENAW, NAW and mod-WNAW mix (grey shading, Fig. 4) with nutrient
465 concentrations increasing as salinity decreases. As NAW characteristics in temperature-
466 salinity space are within the properties expected if ENAW and mod-WNAW mix (Fig. 4.a), it
467 is not possible (using these two variables alone) to distinguish the relative importance of
468 ENAW and NAW to the upper waters of the basin. In phosphate-salinity space (Fig. 4.b) and
469 nitrate-salinity space (Fig. 4.c) however, ENAW, NAW and mod-WNAW each have distinct
470 properties. Hence we can see that all three of these water masses influence the upper water
471 column of the Rockall Trough. (WNAW does not appear to be an important contributor to
472 the upper waters of the basin as indicated by the lack of apparent mixing between either
473 ENAW or NAW, and this water mass in temperature-salinity space (Fig. 4.a).) It is therefore
474 proposed that interannual changes in upper water nutrient concentrations are predominantly
475 caused by changes in the relative contributions of low nutrient southern-origin water masses
476 (ENAW and NAW) and higher nutrient subpolar mod-WNAW. Further, we are able to show
477 that the influence of mod-WNAW was greatest in the late 1990s (blues, Fig. 4), whilst
478 ENAW and NAW were the dominant water masses within the Rockall Trough in the late
479 2000s (oranges and reds, Fig. 4).

480

481 *6.3. Changes in local biogeochemical processes*

482 Nutrient concentrations appear to be predominantly controlled by horizontal advection
483 suggesting quasi-conservative behaviour (i.e. their distribution is determined by physical
484 rather than biochemical processes). However, to examine this further data from individual
485 years were investigated in property-property space. When plotted against each other,
486 temperature and salinity approximate a straight line between 200-700 m indicating mixing
487 between two end-members. Hence, if the nutrients are also behaving quasi-conservatively, a
488 linear mixing line should also be observed in temperature-nutrient space (Anderson and
489 Sarmiento, 1994). This is observed for all years except 2004, 2005 and 2006 when nitrate
490 and phosphate values for a given temperature are higher than expected between ~ 100-700 m.
491 This indicates an additional local source of these nutrients within the water column.
492 Although this maybe an unknown water mass with only a chemical signature, a more likely
493 explanation is remineralisation within the water column (Anderson and Sarmiento, 1994).

494 **7. Temporal variability in proportion of southern versus subpolar water masses**

495

496 Having established that nutrient concentrations in the upper waters of the Rockall Trough are
497 predominantly controlled by changes in the proportion of southern versus subpolar water
498 masses within the basin, we now calculate the changes in the relative contribution of these
499 water bodies with time. Using the following equations, it is possible to calculate the
500 individual proportion of the three water masses (ENAW, mod-WNAW and NAW) at a
501 particular point in property-property space (i).

502

503
$$S_i = m_{ENAW} S_{ENAW} + m_{NAW} S_{NAW} + m_{mod-WNAW} S_{mod-WNAW}$$

504
$$X_i = m_{ENAW} X_{ENAW} + m_{NAW} X_{NAW} + m_{mod-WNAW} X_{mod-WNAW}$$

505
$$1 = m_{ENAW} + m_{NAW} + m_{mod-WNAW}$$

506

507 where S_i is the salinity at point i and S_{ENAW} , S_{NAW} and $S_{mod-WNAW}$ the salinities of ENAW,
508 NAW and mod-WNAW respectively. X_i , X_{ENAW} , X_{NAW} and $X_{mod-WNAW}$ are the potential
509 temperature, or phosphate, or nitrate concentrations, at point i , and of the water masses
510 ENAW, NAW and mod-WNAW respectively; whilst m_{ENAW} , m_{NAW} and $m_{mod-WNAW}$ are the
511 unknown proportions of the three water masses. The problem is over-determined; therefore
512 the method was repeated three times using the relationships of salinity with: potential
513 temperature, phosphate, and nitrate. As the outputs from the salinity-phosphate and salinity-
514 nitrate models were nearly identical, a mean was computed using results from just the
515 salinity-temperature and salinity-phosphate models (filled black circles, Fig. 5). Additionally
516 a range (black lines, Fig. 5) between the highest and lowest output values was calculated to
517 give an idea of the error associated with the method. For cruises when the phosphate data
518 failed the quality checking procedures (Section 4.1), the water mass proportions were
519 determined using the salinity-temperature relationship alone (black circles, Fig. 5). As some
520 remineralisation is suspected for nitrate and phosphate in 2004, 2005 and 2006, and the
521 method assumes conservative behaviour (Tomczak, 1981), the water mass proportions for
522 these three years were also only determined using the salinity and temperature data.

523

524 Between 1996 and 2011, as the Subpolar Gyre weakened, the proportion of mod-WNAW
525 within the upper waters of the Rockall Trough decreased (Fig. 5). Conversely the proportion
526 of water masses entering the basin from the south (i.e. ENAW and NAW) rose during the
527 same period by a similar amount. This trend was observed whether potential temperature,

528 phosphate or nitrate was used (in conjunction with salinity) within the mixing model. When
529 the gyre was strong, such as in 1996, the upper waters were composed of approximately 50 %
530 mod-WNAW and 50 % southern origin water masses. However, when the gyre was
531 particularly weak, such as from 2009 onwards, the upper water column was almost entirely
532 composed of ENAW and NAW whilst mod-WNAW contributed less than ~ 20 %.

533

534

535 **8. Effect of the Subpolar Gyre**

536

537 There appears to be a strong link between variations in the upper waters of the Rockall
538 Trough and changes in the strength of the Subpolar Gyre. To investigate this further, the
539 mean properties of the upper waters were plotted against the observed subpolar gyre index
540 (Fig. 6). A strong relationship between all variables, except silicate, and the strength of the
541 Subpolar Gyre is found for an index greater than -4.5 cm (marked by grey lines, Fig. 6).
542 Above this point, as the gyre weakened salinity and potential temperature increased ($r = -0.86$
543 and $r = -0.85$ respectively) whilst phosphate and nitrate concentrations decreased ($r = +0.87$ and r
544 $+0.81$ respectively). Further, the proportion of mod-WNAW within the basin decreased (r
545 $+0.88$). For temperature and salinity this relationship holds for the whole of the 36 year Ellett
546 Line record.

547

548 The Subpolar Gyre was particularly weak in the 2000s with the index falling below anything
549 observed since 1992 (Fig. 3.a) or modelled since 1960-1970 (de Boissésion *et al.*, 2012;
550 Hátún *et al.*, 2005; Lohmann *et al.*, 2009). Below an index value of -4.5 cm, reached
551 between 2004 and 2006, and after 2010, the relationship between the strength of the gyre and
552 upper water properties in the Rockall Trough breaks down. Salinity remained near constant
553 (35.410 ± 0.005) whilst potential temperature decreased (-0.21 °C) although at a slower rate
554 (relative to the gyre index) than the warming observed as the gyre weakened. This result
555 suggests that once a gyre index of -4.5 cm has been reached, further weakening of the
556 Subpolar Gyre has little effect on these variables. The relationship between a particularly
557 weak Subpolar Gyre and nutrient concentrations is more difficult to interpret due to data
558 quality problems (Section 4.1) and the higher values observed in 2004-2006 (circles, Fig. 6.c-
559 d). However, the 2011 phosphate concentration is similar to those observed for a gyre index
560 slightly greater than the -4.5 cm threshold.

561

562 9. Discussion and conclusions

563

564 Between 1996 and the mid-2000s, the upper waters (200-700 m) of the Rockall Trough
565 became warmer (+0.72 °C) and more saline (+0.088), whilst phosphate and nitrate
566 concentrations decreased (-0.14 µM and -2.00 µM respectively). From 2007 onwards,
567 salinities remained high and near constant (35.410 ± 0.005) and temperatures fell slightly (-
568 0.21 °C). Phosphate concentrations continued to fall until 2007 after which all variations
569 were within calculated errors. There is insufficient nitrate data to state confidently how its
570 concentrations changed after 2007 although it is expected that it will be similar to phosphate.
571 Whilst some changes were observed in silicate levels these were smaller than for the other
572 variables and after 2004 not statistically significant. It is not known why silicate
573 concentrations are temporally more stable although possibilities include its different
574 chemistry (Levitus, 1993) and the less clear distinction between the Subpolar and Subtropical
575 Gyres in terms of silicate concentrations (Louanchi and Najjar, 2000).

576

577 Variations in winter MLD have been discounted as the primary control on interannual
578 changes in upper water properties within the Rockall Trough, additionally there are no
579 indications of the process being important in any individual year. However, it is likely that it
580 plays some part in provision of nutrients to the upper waters of the Rockall Trough. For the
581 majority of the record, nutrient concentrations appear to behave quasi-conservatively with
582 their distribution between 200 and 700 m being controlled by physical processes. However,
583 the nitrate and phosphate concentrations in 2004, 2005 and 2006 are elevated for a given
584 temperature. This suggests remineralisation within the water column (Anderson and
585 Sarmiento, 1994) and hence some non-conservative behaviour. It is not known why this
586 occurs in these three years and not in other years, although possibilities are higher primary
587 productivity or cruise timing in relation to the spring and summer blooms.

588

589 The observed interannual trends in upper water properties within the Rockall Trough, prior to
590 the mid-2000s, are best explained by variations in the relative importance of southern versus
591 subpolar water masses in the basin. These variations are driven by changes in horizontal
592 advection of water masses as the strength of the Subpolar Gyre alters. After the mid-2000s
593 this relationship breaks down and the system changes to one where the upper water properties
594 are affected by other processes.

595

596 9.1. Prior to the mid-2000s

597 Between 1996 and the mid-2000s, the upper water properties within the Rockall Trough,
598 including nitrate and phosphate concentrations, were determined by the strength and extent of
599 the Subpolar Gyre. As the Subpolar Gyre weakened and contracted north-westwards, the
600 upper waters of the Rockall Trough were increasingly dominated by the southern water
601 masses of ENAW and NAW. Conversely, the influence of mod-WNAW which entered the
602 basin from the Subpolar Gyre to the west decreased. As ENAW and NAW are warmer,
603 saltier and lower in nutrients relative to mod-WNAW, the upper waters of the Rockall
604 Trough became warmer and more saline whilst nitrate and phosphate concentrations fell. We
605 found no evidence of water carried within the North Atlantic Current (WNAW) in the
606 Rockall Trough. This is in agreement with Holliday (2003) whose data also suggests that the
607 main source of the southern waters in the basin is the intergyre Bay of Biscay region (i.e.
608 ENAW). However, it apparently contradicts drifter data that shows a pathway shift after
609 2000 with southern branches of the NAC bringing water from the western subtropical North
610 Atlantic to the Rockall Trough after this date (Häkkinen and Rhines, 2009). One possible
611 explanation is that this saline water is indistinguishable from ENAW although we have no
612 evidence of this. Whether the southern water masses originate from the west or east, the
613 important message is that as the Subpolar Gyre weakens the Rockall Trough becomes
614 warmer, more saline and reduced in nutrients as the influence of southern water masses
615 increases and the proportion of subpolar mod-WNAW decreases.

616

617 Above a threshold value of -4.5 cm (i.e. prior to the mid-2000s), upper water properties
618 within the Rockall Trough, including nitrate and phosphate concentrations, show a strong
619 correlation with the subpolar gyre index. Changes in phytoplankton abundance also have a
620 strong relationship with this index (Hátún *et al.*, 2009). If phytoplankton numbers increase as
621 the Subpolar Gyre weakens, nutrient concentrations may correspondingly decrease and,
622 whilst still having a strong correlation to the gyre index, have a biological rather than
623 advective cause. However, in the southern and central Rockall Trough, and Bay of Biscay
624 region, the phytoplankton colour index (which approximates phytoplankton abundance) is
625 actually negatively correlated with the gyre index (Hátún *et al.*, 2009). As the Subpolar Gyre
626 weakens the number of phytoplankton in these areas decreases with an analogous reduction
627 in nutrient uptake expected. As such, if changes in phytoplankton abundance have any effect
628 on nutrient concentrations within the upper layers of the Rockall Trough, an increase between
629 1996 and 2011 is likely rather than the observed decrease. Thus we can conclude that nitrate

630 and phosphate levels are predominantly affected by changes in advection related to the
631 strength of the Subpolar Gyre rather than changes in associated biological activity. Further, it
632 is interesting to speculate that the temporally varying amount of nutrients advected to the
633 Rockall Trough as the Subpolar Gyre strengthens and weakens enhances the observed
634 variations in phytoplankton abundance.

635

636 The conclusion that changes in horizontal advection is the primary control on temperature
637 and salinity variability in the Rockall Trough between 1996 and the mid-2000s confirms and
638 strengthens previous findings (Hátún *et al.*, 2005; Holliday, 2003). However, this is the first
639 study to show that nutrient concentrations in the area are also strongly affected by changes in
640 the Subpolar Gyre and the relative dominance of subpolar versus southern water masses.

641 Nutrient concentrations within the eastern subtropical North Atlantic appear to be dominated
642 by changes in horizontal advection (Oschlies, 2001) as is a record within the Norwegian
643 Coastal Current, albeit with a strong superimposed anthropogenic signal (Frigstad *et al.*,
644 2013). In contrast changes in winter mixed layer depth are thought to be more important in
645 the Iceland Sea (Ólafsson, 2003) and western subtropical North Atlantic (Oschlies, 2001).

646

647 *9.2. Post mid-2000s*

648 The relationship between the strength of the Subpolar Gyre and upper water properties in the
649 Rockall Trough breaks down when a threshold of -4.5 cm is reached (i.e. after the mid-
650 2000s). Below this value, when the Subpolar Gyre is particularly weak, salinities remain
651 near constant whilst temperatures decrease slightly. Due to the low nutrient concentrations
652 within southern-origin waters, it is speculated that phosphate and nitrate concentrations also
653 remain relatively low. However, further data is required to test this hypothesis. We suggest
654 that the maximum possible influence of southern waters (and thus minimum proportion of
655 subpolar waters) is reached when the gyre index is around -4.5 cm. Indeed the contribution
656 of southern-origin water masses (ENAW and NAW) to the upper layers of the Rockall
657 Trough from 2006 onwards was greater than ~ 80 %. If this hypothesis is true, further
658 weakening of the Subpolar Gyre will not lead to an additional increase in southern water
659 masses, or reduction of subpolar waters, within the basin. Hence, the system changed in the
660 mid-2000s from one where upper water properties are controlled by variations in the relative
661 importance of different water masses (driven by changes in the strength of the Subpolar
662 Gyre), to one controlled by other processes. Between 2007 and 2011, upper water
663 temperatures have decreased by around -0.2 °C, whilst salinities have remained near constant

664 since 2004. We speculate that upper water properties in the trough during this time were
665 controlled by variations in the ENAW signature in the source region that were advected into
666 basin.

667

668 Between 2007 and 2010 mean upper water (5-300 m) temperatures in the southern Bay of
669 Biscay fell by ~ 0.5 °C whilst salinities remained near constant from 2006 to 2010 (Hughes,
670 2010). Although the core of ENAW in the Bay of Biscay is around 350 dbar, salinity and
671 temperature changes at this depth often have a similar signature higher in the water column
672 (Somavilla, 2013). Hence, the 5-300 m time-series can be used to give an idea of how
673 ENAW characteristics vary in its formation area. It is interesting that the temperature and
674 salinity changes in the upper 300 m within the Bay of Biscay from the mid-2000s onwards
675 are similar to those observed upstream in the Rockall Trough.

676

677 9.3. Conclusion

678 In this paper we have shown that interannual changes in upper water nutrient concentrations
679 within the Rockall Trough are predominantly controlled by variations in the relative amount
680 of different water masses in the basin. Whether the trough is dominated by cooler, fresher,
681 higher nutrient subpolar mod-WNAW, or warmer, saltier and lower nutrient NAW and
682 ENAW, is determined by the strength of the Subpolar Gyre and whether it extends into the
683 Rockall Trough or lies to the northwest of the basin. Mean upper water temperatures and
684 salinities for the whole of the Ellett Line record (1975 to mid-2000s) show strong correlations
685 with the subpolar gyre index (not shown, $r = -0.77$ and $r = -0.79$ respectively). This indicates that
686 the strength of the Subpolar Gyre was the primary influence on the temperature and salinity
687 of upper waters in the Rockall Trough not just between 1996 and the mid-2000s, but also for
688 at least the previous two decades. We speculate that the nutrient concentrations within the
689 upper waters of the basin may have been similarly controlled from 1975 to 1996. Although
690 nutrient measurements through time are far more sporadic, nitrate, phosphate and silicate
691 concentrations within the upper waters from 1963-1965 were $13 \mu\text{M}$, $0.8 \mu\text{M}$ and $5\text{-}6 \mu\text{M}$
692 respectively (Ellett and Martin, 1973). This is consistent with a strong Subpolar Gyre and a
693 relatively high influence of mod-WNAW within the Rockall Trough.

694

695 Since the mid-2000s the Subpolar Gyre has been weaker than anything observed since 1992
696 (Häkkinen and Rhines, 2009), or modelled since 1960-1970 (de Boissésion *et al.*, 2012;
697 Hátún *et al.*, 2005; Lohmann *et al.*, 2009). As such the interannual variability in the

698 properties of upper waters in the Rockall Trough are no longer directly affected by the
699 strength of the Subpolar Gyre with the maximum proportion of southern-origin water masses
700 reached in the mid-2000s. Instead we suggest that variability within the basin now reflects
701 changes in the source properties of ENAW which are advected northwards. The very weak
702 state of the Subpolar Gyre suggests that upper water temperatures and salinities may
703 currently be higher than at any point in the last 40-50 years. Indeed winter sea surface
704 records (approximating the average temperature and salinity between 0-800 m) from the
705 Rockall Trough show that similar temperatures and salinities have not been observed since at
706 least 1948 (Holliday and Cunningham, 2013; Sherwin *et al.*, 2012). If present nutrient
707 concentrations within the eastern subpolar North Atlantic are also particularly low, this may
708 have implications for primary productivity and ecological pathways in both the offshore and
709 coastal environments. Interannual temperature variations in Scottish coastal waters correlate
710 significantly with changes in the upper waters of the Rockall Trough (Inall *et al.*, 2009). As
711 the nutrient budget of the shelf is dominated by oceanic inputs (Huthnance *et al.*, 2009), the
712 Subpolar Gyre may not only be an important control on offshore nutrient budgets, but may
713 also similarly affect coastal waters.

714

715

716 **Acknowledgements**

717

718 We thank all crew, scientists and technicians involved in the collection and processing of data
719 during the numerous Ellett Line cruises used within this paper. The Ellett Line is funded by
720 the UK National Environment Research Council with Marine Scotland - Science trips funded
721 by the Scottish Executive. We also acknowledge the useful discussions with Professor Toby
722 Sherwin and the comments of the two reviewers which greatly improved this manuscript.
723 This work was funded by the University of the Highlands and Islands and the Department for
724 Environment, Food and Rural Affairs.

725 **References**

726

- 727 Anderson, A., Sarmiento, J., 1994. Redfield ratios of remineralisation determined by nutrient
728 data analysis. *Global Biogeochemical Cycles* 8, 65-80.
- 729 Antonov, J., Seidov, D., Boyer, T., Locarnini, R., Mishonov, A., Garcia, H., Baranova, O.,
730 Zweng, M., Johnson, D., 2010. World Ocean Atlas 2009, Volume 2: Salinity. In: Levitus, S.
731 (Ed.). NOAA, p. 184 pp.
- 732 Arhan, M., 1990. The North Atlantic Current and subarctic intermediate water. *Journal of*
733 *Marine Research* 48, 109-144.
- 734 Arhan, M., de Verdière, A., Mémery, L., 1994. The eastern boundary of the subtropical North
735 Atlantic. *Journal of Physical Oceanography* 24, 1295-1316.
- 736 Bacon, S., 1997. Circulation and fluxes in the North Atlantic between Greenland and Ireland.
737 *Journal of Physical Oceanography* 27, 1420-1435.
- 738 Bersch, M., 2002. North Atlantic Oscillation-induced changes of the upper-layer circulation
739 in the northern North Atlantic. *Journal of Geophysical Research* 107 (C10), Art. No. 3156.
- 740 Bersch, M., Meincke, J., Sy, A., 1999. Interannual thermocline changes in the northern North
741 Atlantic. *Deep Sea Research* 46, 55-75.
- 742 Booth, D., Ellett, D., 1983. The Scottish continental slope current. *Continental Shelf*
743 *Research* 2, 127-146.
- 744 Burrows, M., Thorpe, S., Meldrum, D., 1999. Dispersion over the Hebridean and Shetland
745 shelves and slopes. *Continental Shelf Research* 19, 49-55.
- 746 de Boissésion, E., Thierry, V., Mercier, H., Caniaux, G., Desbruyères, D., 2012. Origin,
747 formation and variability of the Subpolar Mode Water located over the Reykjanes Ridge.
748 *Journal of Geophysical Research* 117, doi:10.1029/2011JC007519.
- 749 Dooley, H., Martin, J., Ellett, D., 1984. Abnormal hydrographic conditions in the Northeast
750 Atlantic during the 1970s. *Rapports et Proces-verbaux des réunions, Conseil International*
751 *pour l'exploration de la Mer* 185, 179-187.
- 752 Ellett, D., Edwards, A., Bowers, R., 1986. The hydrography of the Rockall Channel - an
753 overview. *Proceedings of the Royal Society of Edinburgh* 88B, 61-81.
- 754 Ellett, D., Martin, K., 1973. The physical and chemical oceanography of the Rockall
755 Channel. *Deep Sea Research* 20, 585-625.
- 756 Emery, W., Thomson, R., 2001. *Data analysis methods in physical oceanography*. Elsevier.
- 757 Frigstad, H., Andersen, T., Hessen, D., Jeansson, E., Skogen, M., Naustvoll, L., Miles, M.,
758 Johannessen, T., Richard, G., Bellerby, J., 2013. Long-term trends in carbon, nutrients and
759 stoichiometry in Norwegian coastal waters: evidence of a regime shift. *Progress in*
760 *Oceanography* 111, 113-124.
- 761 Garcia, H., Locarnini, R., Boyer, T., Antonov, J., Zweng, M., Baranova, O., Johnson, D.,
762 2010. World Ocean Atlas 2009, Volume 4: Nutrients (phosphate, nitrate, silicate). In: Levitus,
763 S. (Ed.). NOAA, p. 398 pp.
- 764 Grasshoff, K., Kremling, K., Ehrhardt, M., 1999. *Methods of seawater analysis*. Wiley-VCH.
- 765 Häkkinen, S., Rhines, P., 2004. Decline of the subpolar North Atlantic circulation during the
766 1990s. *Science* 304, 555-559.
- 767 Häkkinen, S., Rhines, P., 2009. Shifting surface currents in the northern North Atlantic
768 Ocean. *Journal of Geophysical Research* 114, doi:10.1029/2008JC004883.
- 769 Harvey, J., 1982. θ -S relationships and water masses in the eastern North Atlantic. *Deep Sea*
770 *Research* 29 (8), 1021-1033.
- 771 Harvey, J., Arhan, M., 1988. The water masses of the central North Atlantic in 1983-84.
772 *Journal of Physical Oceanography* 18, 1855-1875.

773 Hátún, H., Payne, M., Beaugrand, G., Reid, P., Sandø, A., Drange, H., Hansen, B., Jacobsen,
774 J., Bloch, D., 2009. Large bio-geographical shifts in the north-eastern Atlantic Ocean: From
775 the subpolar gyre, via plankton, to blue whiting and pilot whales. *Progress in Oceanography*
776 80, 149-162.

777 Hátún, H., Sandø, A., Drange, H., Hansen, B., Valdimarsson, H., 2005. Influence of the
778 Atlantic Subpolar Gyre on the Thermohaline Circulation. *Science* 309, 19841-11844.

779 Hill, A.E., Mitchelson-Jacob, E.G., 1993. Observations of a poleward-flowing saline core on
780 the continental slope of Scotland. *Deep Sea Research I* 40 (7), 1521-1527.

781 Holliday, N., Cunningham, S., 2013. The Extended Ellett Line: Discoveries from 65 years of
782 marine observations west of the UK. *Oceanography* 26, 9 pp.

783 Holliday, N.P., 2003. Air-sea interaction and circulation changes in the northeast Atlantic.
784 *Journal of Geophysical Research-Oceans* 108 (C8), art. no.-3259.

785 Holliday, N.P., Pollard, R.T., Read, J.F., Leach, H., 2000. Water mass properties and fluxes
786 in the Rockall Trough, 1975-1998. *Deep Sea Research* 47, 1303-1332.

787 Hughes, S., Holliday, N., A. Beszczynska-Möller, 2010. ICES Report on Ocean Climate
788 2009. ICES Cooperative Research Report 304, 67 pp.

789 Huthnance, J., T. Holt, S. Wakelin, 2009. Deep ocean exchange with west-European shelf
790 seas. *Ocean Science* 5, 621-634.

791 Hydes, D., Le Gall, A., Miller, A., Brockmann, U., Raabe, T., Holley, S., Alvarez-Salgado,
792 X., Antia, A., Balzer, W., Chou, L., Elskens, M., Helder, W., Joint, I., Orren, M., 2001.
793 Supply and demand of nutrients and dissolved organic matter at and across the NW European
794 Shelf break in relation to hydrography and biogeochemical activity. *Deep Sea Research II* 48,
795 3012-3047.

796 Inall, M., P. Gillibrand, C. Griffiths, N. MacDougal, K. Blackwell, 2009. On the
797 oceanographic variability of the North-West European Shelf to the west of Scotland. *Journal*
798 *of Marine Systems* 77, 210-226.

799 Ingleby, B., Huddleston, M., 2007. Quality control of ocean temperature and salinity profiles
800 - Historical and real time data. *Journal of Marine Systems* 65, 158-175.

801 Iselin, C., 1936. A study of the circulation of the western North Atlantic. *Papers in physical*
802 *oceanography and meteorology IV*, 101 pp.

803 Johnson, C., 2012. Tracing Wyville Thomson Ridge Overflow Water in the Rockall Trough,
804 University of Aberdeen.

805 Johnson, C., Sherwin, T.J., Smythe-Wright, D., Shimmield, T., Turrell, W.R., 2010. Wyville
806 Thomson Ridge Overflow Water: Spatial and temporal distribution in the Rockall Trough.
807 *Deep Sea Research I* 57, 1153-1162.

808 Levitus, S., M. Conkright, J. Reid, R. Najjar, A. Mantyla, 1993. Distribution of nitrate,
809 phosphate and silicate in the world oceans. *Progress in Oceanography* 31, 245-273.

810 Locarnini, R., A. M., Antonov, J., Boyer, T., Garcia, H., Baranova, O., Zweng, M., Johnson,
811 D., 2010. World Ocean Atlas 2009, Volume 1: Temperature. In: Levitus, S. (Ed.). NOAA, p.
812 184 pp.

813 Lohmann, K., Drange, H., Bentsen, M., 2009. Response of the North Atlantic subpolar gyre
814 to persistent North Atlantic Oscillation like forcing. *Climate Dynamics* 32, 273-285.

815 Louanchi, F., Najjar, R., 2000. A global monthly climatology of phosphate, nitrate and
816 silicate in the upper ocean: Spring-summer export production and shallow remineralisation.
817 *Global Biogeochemical Cycles* 14, 957-977.

818 McGrath, T., Kivimäe, C., Tanhua, T., Cave, R., McGovern, E., 2012a. Inorganic carbon and
819 pH levels in the Rockall Trough 1991-2010. *Deep Sea Research I* 68, 29-91.

820 McGrath, T., Nolan, G., McGovern, E., 2012b. Chemical characteristics of water masses in
821 the Rockall Trough. *Deep Sea Research I* 61, 57-73.

822 Meincke, J., 1986. Convection in the oceanic waters west of Britain. Proceedings of the
823 Royal Society of Edinburgh 88B, 127-139.

824 New, A.L., Smythe-Wright, D., 2001. Aspects of the circulation in the Rockall Trough.
825 Continental Shelf Research 21, 777-810.

826 Ólafsson, J., 2003. Winter mixed layer nutrients in the Irminger and Iceland Seas, 1990-2000.
827 ICES Marine Science Symposia 219, 329-332.

828 Orvik, K.A., Niiler, P., 2002. Major pathways of Atlantic water in the northern North Atlantic
829 and Nordic Seas toward Arctic. Geophysical Research Letters 29 (19),
830 DOI:10.1029/2002gl015002.

831 Oschlies, A., 2001. NAO-induced long-term changes in nutrient supply to the surface waters
832 of the North Atlantic. Geophysical Research Letters 28, 1751-1754.

833 Otto, L., van Aken, H.M., 1996. Surface circulation in the Northeast Atlantic as observed
834 with drifters. Deep Sea Research 43, 467-499.

835 Pingree, R., Le Cann, B., 1989. Celtic and Armorican slope and shelf residual currents.
836 Progress in Oceanography 23, 303-338.

837 Pollard, R.T., Griffiths, M.J., Cunningham, S.A., Read, J.F., Perez, F.F., Rios, A.F., 1996.
838 Vivaldi 1991 - a study of the formation, circulation and ventilation of Eastern North Atlantic
839 Central Water. Progress in Oceanography 37, 167-192.

840 Pollard, R.T., Pu, S., 1985. Structure and circulation of the upper Atlantic Ocean northeast of
841 the Azores. Progress in Oceanography 14, 443-462.

842 Pollard, R.T., Read, J.F., Holliday, N.P., Leach, H., 2004. Water masses and circulation
843 pathways through the Iceland Basin during Vivaldi 1996. Journal of Geophysical Research
844 109 (C4), C04004.

845 Read, J., Pollard, R., Miller, P., Dale, A., 2010. Circulation and variability of the North
846 Atlantic Current in the vicinity of the Mid-Atlantic Ridge. Deep Sea Research I 57, 307-318.

847 Read, J.F., 2001. CONVEX-91: water masses and circulation of the Northeast Atlantic
848 subpolar gyre. Progress in Oceanography 48, 461-510.

849 Reid, J.L., 1979. On the contribution of the Mediterranean Sea outflow to the Norwegian-
850 Greenland Sea. Deep Sea Research 26, 1199-1223.

851 Rippeth, T., Inall, M., 2002. Observations of the internal tide and associated mixing across
852 the the Malin Shelf. Journal of Geophysical Research 107, doi:10.1029/2000JC000761.

853 Sherwin, T.J., Read, J.F., Holliday, N.P., Johnson, C., 2012. The impact of changes in the
854 North Atlantic Gyre distribution on water mass characteristics in the Rockall Trough. ICES
855 Journal of Marine Science 69, 751-757.

856 Somavilla, R., C. González-Pola, A. Lavín, C. Rodriguez, 2013. Temperature and salinity
857 variability in the south-eastern corner of the Bay of Biscay (NE Atlantic). Journal of Marine
858 Systems 109-110, S105-S120.

859 Sy, A., Schauer, U., Meincke, J., 1992. The north Atlantic Current and its associated
860 hydrographic structure above and eastwards of the Mid-Atlantic Ridge. Deep Sea Research
861 39, 825-853.

862 Tanhua, T., Brown, P., Key, R., 2009. CARINA: nutrient data in the Atlantic Ocean. Earth
863 Systems Science Data 1, 7-24.

864 Thierry, V., de Boissésion, E., Mercier, H., 2008. Interannual variability of the Subpolar
865 Mode Water properties over the Reykjanes Ridge during 1990-2006. Journal of Geophysical
866 Research 113, doi:10.1029/2007JC004443.

867 Tomczak, J.R., 1981. A multi-parameter extension of temperature/salinity diagram for the
868 analysis of non-isopycnal mixing. Progress in Oceanography 10, 147-171.

869 Tulloch, D.S., Tait, J.B., 1959. Hydrography of the north-western approaches to the British
870 Isles. Marine Research 1, 1-32.

- 871 Ullgren, J., White, M., 2010. Water mass interaction at intermediate depths in the southern
872 Rockall Trough, northeastern Atlantic. *Deep Sea Research I* 57, 248-257.
- 873 White, M., Bowyer, P., 1997. The shelf-edge current north-west of Ireland. *Annales*
874 *Geophysicae* 15, 1076-1083.
- 875 White, M., Mohn, C., Orren, M., 1998. Nutrient distributions across the Porcupine Bank.
876 *ICES Journal of Marine Science* 55, 1082-1094.
- 877

878 **Table headings**

879

880 Table 1. Properties of upper water masses influencing the Rockall Trough (RT) and
881 underlying intermediate water masses used in this paper. ^a Holliday *et al.* (2000); ^b Johnson
882 (2012); ^c 2009 World Ocean Atlas (http://www.nodc.noaa.gov/OC5/WOA09/pr_woa09); ^d
883 Reid (1979); ^e Johnson (2012); ^f Pollard *et al.* (2004); ^g Johnson *et al.* (2010); ^h this study.
884 WTOW definitions are for 800 m.

885

886 Table 2. Metadata for Ellett Line cruises used in this study. MS-S – Marine Scotland -
887 Science; NOC – National Oceanography Centre (Southampton); SAMS – Scottish
888 Association for Marine Science.

889

890 Table 3. Mean statistical indices for nutrient data collected from 1996 to 2011 between 200
891 m and 700 m at station M in the eastern Rockall Trough.

892

893 Table 4. Mixed layer depth (MLD) in February for the central Rockall Trough (56-58 °N,
894 10-13 °W) between 1996 and 2011 calculated from the Meteorological Office EN3 (v2.a)
895 database (<http://www.metoffice.gov.uk/hadobs/en3/>). MLD was defined as the depth at
896 which the temperature varied by more than 0.5 °C from the surface value (defined at 15 m).

897

898 **Figure headings**

899

900 Figure 1. Schematic of upper water masses and currents influencing the Rockall Trough.
901 Also shown are the location of the Ellett Line time series (black line) and where water masses
902 were defined (black circles). ENAW – Eastern North Atlantic Central Water (cyan); mod-
903 WNAW – modified Western North Atlantic Central Water (green); NAC – North Atlantic
904 Current; NAW – North Atlantic Water (red); SEC – Shelf Edge Current; WNAW – Western
905 North Atlantic Central Water (purple). Contours at 500 m, 1000 m, 2000 m, 3000 m, 4000 m
906 and 5000 m. Labelled bathymetry: BoB – Bay of Biscay; IB – Iceland Basin; IS – Irminger
907 Sea; NS – Nordic Seas; RHP – Rockall Hatton Plateau; RT – Rockall Trough. Blue dashed
908 line: Subpolar Front.

909

910 Figure 2. Plots of mean upper water (200-700 m): (a) salinity, (b) potential temperature, (c)
911 phosphate, (d) nitrate, and (e) silicate against month of the year. Crosses show the
912 bootstrapped mean (between 200-700 m) and error bars the 95 % confidence limit.

913

914 Figure 3. Change of: (a) the observed subpolar gyre index (first principal component of sea
915 surface height), (b) salinity, (c) potential temperature, (d) phosphate, (e) nitrate, and (f)
916 silicate with time. Crosses show the bootstrapped mean (between 200-700 m) and error bars
917 the 95 % confidence limit. Data in (a) are updated from Häkkinen and Rhines (2004, 2009).
918 Grey lines in (e) indicate the estimated nitrate level using the observed N:P, and the circle a
919 suspect value.

920

921 Figure 4. Plots of mean upper water (200-700 m): (a) potential temperature, (b) phosphate,
922 (c) nitrate, and (d) silicate against mean upper water salinity. Colours indicate year. Also
923 shown are water masses (labelled black rectangles, lines or circles) including the signature of
924 WTOW at 800 m (labelled '800 m'). Grey shading: expected properties should ENAW,
925 NAW and mod-WNAW mix.

926

927 Figure 5. Variability of the proportion of subpolar water (mod-WNAW) in the upper waters
928 of the Rockall Trough (black) and strength of the Subpolar Gyre (grey line) with time. Filled
929 black circles represent the mean mod-WNAW proportion calculated with output from mixing
930 models using salinity and temperature, and salinity and phosphate. Black lines show range of

931 values to give an idea of the error associated with the method. Open black circles show the
932 mod-WNAW proportion calculated from the temperature-salinity relationship data alone.

933

934 Figure 6. Plots of upper water (a) salinity, (b) potential temperature, (c) phosphate, (d)
935 nitrate, (e) silicate and (f) proportion of mod-WNAW against the observed subpolar gyre
936 index. Crosses in (a-f) show mean values, error bars in (a-e) the 95 % confidence limit and
937 error bars in (f) the range of values. Circles in (c) and (d) show values from 2004, 2005 and
938 2006 where nitrate and phosphate concentrations show possible evidence of remineralisation.
939 Grey lines indicate an index of -4.5 cm where the relationships between parameters and the
940 strength of the Subpolar Gyre breaks down.

Acronym	S	θ (°C)	[PO₄] (μM)	[NO₃] (μM)	[SiO₃] (μM)
NAW (North Atlantic Water) carried in SEC	35.4 ^a	10.0-10.5 ^a	0.6-0.7 ^b	9.0-11.5 ^b	3.0-5.0 ^b
ENAW (Eastern North Atlantic Central Water) enters RT from south	35.5-35.6 ^c	10.5-11.0 ^c	0.6-0.7 ^c	11.0-12.0 ^c	2.5-5.0 ^c
WNAW (Western North Atlantic Central Water) carried in NAC	35.2 ^c	9.5 ^c	1.0-1.1 ^c	15.0-16.0 ^c	7.5 ^c
mod-WNAW (modified Western North Atlantic Central Water) enters RT from west	35.1-35.2 ^c	7.5-8.0 ^c	1.0-1.1 ^c	15.0-16.0 ^c	7.5 ^c
MOW (Mediterranean Overflow Water) underlies upper waters in south-eastern RT	35.5-35.6 ^d	8.0-10.0 ^d	1.0 ^e	17.6 ^e	10 ^e
SAIW (SubArctic Intermediate Water) underlies upper waters in south-western RT	34.9 ^f	6.5 ^f	1.2 ^e	18.75 ^e	11.1 ^e
WTOW (Wyville Thomson Ridge Overflow Water) underlies upper waters in majority of RT	35.25 ^g	8.0 ^g	1.1 ^h	17.5 ^h	11.0 ^h

Year	Month	Cruise	Analysing Laboratory
1996	Oct.	D223	NOC
1997	Sept.	D230	NOC
1998	May	D233	NOC
1999	Sept.	D242	NOC
2000	Feb.	D245	NOC
2000	May	0700S	MS-S
2001	May	D253	NOC
2003	Apr.	0703S	MS-S
2003	Jul.	P300_2	SAMS
2004	Jul.	P314	NOC
2005	Oct.	CD176	SAMS
2006	Oct.	D312	NOC
2007	Aug.	D321	SAMS
2008	May	0508S	MS-S
2009	Jun.	D340	SAMS
2010	May	D351	NOC
2011	May	D365	SAMS

	median	90th minus 10th percentile	normalised 90th minus 10th percentile
Nitrate	12.57	4.48	0.36
Phosphate	0.75	0.27	0.36
Silicate	5.14	1.15	0.22

Year	min. MLD	max. MLD	mean MLD
	(m)	(m)	(m)
1996	370	800	710
1997	650	970	770
1998	240	540	460
1999	450	800	650
2000	270	800	440
2001	540	660	630
2002	540	660	650
2003	540	660	650
2004	540	660	610
2005	370	800	690
2006	370	540	440
2007	660	800	690
2008	660	660	660
2009	660	800	760
2010	660	660	660
2011	450	970	780











