Wyville Thomson Ridge Overflow Water

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

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Abstract

Between 1996 and the mid-2000s the upper waters (200-700 m) of the Rockall Trough became warmer (+0.72 °C), saltier (+0.088) and reduced in nitrate and phosphate (-2.00 μM and -0.14 μM respectively). These changes, out-with calculated errors, can be explained by the varying influence of southern versus subpolar water masses in the basin as the Subpolar Gyre weakened and contracted. Upper water properties strongly correlate with a measure of the strength of the Subpolar Gyre (the first principal component of sea surface height over the subpolar North Atlantic) prior to the mid-2000s. As the gyre weakens, the upper layers of the trough become warmer (r -0.85), more saline (r -0.86) and reduced in nitrate and phosphate (r +0.81 and r +0.87 respectively). Further the proportion of subpolar waters in the basin decreases from around 50 % to less than 20 % (r +0. 88). Since the mid-2000s the Subpolar Gyre has been particularly weak. During this period temperatures decreased slightly (-0.21 °C), salinities remained near constant (35.410 ± 0.005) and phosphate levels low and stable (0.68 ± 0.02 μM). These relative lack of changes are thought to be related to the maximum proportion of southern water masses within the Rockall Trough having been reached. Thus the upper water properties are no longer controlled by changes in the relative importance of different water masses in the basin (as prior to the mid-2000s), but rather a different process. We suggest that when the gyre is particular weak the interannual changes in upper water properties in the Rockall Trough reflect changes in the source properties of the southern water masses. Since the early-2000s the Subpolar Gyre has been weaker than observed since 1992, or modelled since 1960-1970. Hence upper waters within the Rockall Trough may be warmer, saltier and more depleted in nitrate and phosphate than at any time in the last half century.

Keywords

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

Highlights

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

1. Introduction

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

Only a single paper has presented a first-look at the interannual variability of nutrients in the basin (Sherwin *et al.*, 2012). Between 1996 and 2009 phosphate concentrations in the upper waters (0-800 m) of the Rockall Trough decreased by 0.17 µM. It was speculated that this was related to an increased influence of low phosphate subtropical waters in the basin as the Subpolar Gyre weakened and contracted north-westwards. Changes in horizontal advection have been found to be important in determining nutrient concentrations in the eastern subtropical North Atlantic (Oschlies, 2001) and Norwegian Coastal Current (Frigstad *et al.*, 2013).

This study is a thorough exploration of the preliminary analysis of Sherwin *et al.* (2012). A comprehensively quality-checked Ellett Line dataset, with calculated errors, is presented. This is the first published time-series of its kind in the subpolar North Atlantic and is used to investigate the controls on the temporal distribution of upper water nutrient concentrations in the Rockall Trough.

2. Upper and intermediate water masses in the Rockall Trough

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

2.1. Upper water entering via the Shelf Edge Current

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

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

2.2. Upper water entering from the Bay of Biscay area

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

2.3. Upper water entering via the North Atlantic Current

The NAC transports warm and saline Western North Atlantic Central Water (WNAW) from the western North Atlantic across the Mid Atlantic Ridge into the eastern North Atlantic (e.g. Arhan, 1990; Read *et al.*, 2010; Sy *et al.*, 1992). The current exists in a series of branches with the eastern-most sometimes entering the Rockall Trough (e.g. New and Smythe-Wright, 2001; Orvik and Niiler, 2002; Otto and van Aken, 1996) and at other times flowing to the west of Rockall Bank (e.g. Bacon, 1997; Pollard *et al.*, 2004; Read, 2001). These differences are likely to be related to changes in the strength of the Subpolar Gyre (Holliday, 2003) which is discussed in section 3. WNAW is cooler and fresher than ENAW (Table 1) as well as having higher nutrient concentrations (McGrath *et al.*, 2012b).

2.4. Upper water entering from the west

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

2.5. Underlying intermediate water masses

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

3. Temporal variability of upper water mass distribution

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

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

A measure of the strength the Subpolar Gyre can be obtained from the first principal component of sea surface height (SSH) over the subpolar North Atlantic, christened the ‘subpolar gyre index’ by Hátún *et al.* (2005). Since 1992 this has been derived from altimeter data (Häkkinen and Rhines, 2004, 2009) and shows a trend of weakening between 1996 and the present day (Fig. 3.a). By using models the strength of the gyre has been estimated back to 1960 (de Boissésion *et al.*, 2012; Hátún *et al.*, 2005; Lohmann *et al.*, 2009). This combined model and observed record suggests that the Subpolar Gyre is currently weaker than at any time since 1960-1970.

4. Methods

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

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

4.1. Removal of poor-quality and outlying nutrient data

As we find no contra-indications to the silicate data being of a good quality (see above), the empirical relationships between silicate and nitrate, and silicate and phosphate, were used to identify and remove outlying and poor quality nitrate and phosphate data. Any silicate data with quality flags from the originating laboratory were disregarded before the relationships of silicate with nitrate and phosphate respectively were calculated. Below a silicate concentration of 11 µM (i.e. for upper and intermediate waters) a second order polynomial best described the mode calculated for incremental silicate concentrations for both nitrate and phosphate. Data within ± one standard deviation of the mode curve were regarded as good quality data, whereas data outside of this boundary were discounted for the purposes of this work.

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

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

4.2. Integration of data

In order to create a value representative of the upper waters as a whole for each Ellett Line station during a particular cruise, data were first linearly interpolated onto a regular 50 m vertical grid before being trapezoidally integrated between 200-700 m. Integrated values were only calculated for stations with a total depth greater than 700 m to avoid bias towards shallower waters. The upper limit for integration (200 m) was chosen to eliminate the effects of the seasonal pycnocline whilst the lower limit (700 m) ensured that only Atlantic Waters and not the underlying intermediate WTOW were sampled. Although absolute values differ with choice of upper and lower integration depths, the temporal patterns remain almost unchanged which suggests that the approach is robust and that calculated values are indicative of the upper waters. Integrated values for both the nutrient and physical variables do not show a relationship with month of the year suggesting that interannual variability dominates over seasonal signals and that no seasonal corrections need to be applied (Fig. 2).

4.3. Calculation of mean and errors

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

4.4. Check of N:P and interannual consistency

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

Throughout the time-series interannual consistency for all parameters was good with the exception of the nitrate data collected in 2010 (D351, circle, Fig. 3.e). Using the near-constant relationship between N and P, nitrate values in 2009 and 2011 were estimated between 10.0-11.7 µM (grey lines, Fig. 3.e). However, the measured nitrate concentration in 2010 is 12.9 µM suggesting that the value may be artificially elevated. Alternative possibilities are: that both the nitrate and phosphate were high in 2010, that the N:P ratio changed (by ~ 5) in 2010, or that the 2007-2011 phosphate concentrations are artificially low. Such a large change in either the nutrient concentrations or N:P within a single year seems unlikely. As the phosphate data between 2007 and 2011 were analysed by two different laboratories, analytical error is less probable. As such, the 2010 nitrate value, despite having passed the quality-checking procedures (section 4.1) is treated with caution.

4.5. Defining water masses

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

5. Temporal variability of upper water mass properties

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

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

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

Silicate levels within the upper waters of the Rockall Trough (Fig. 3.f) have remained more constant than temperature, salinity, phosphate or nitrate between 1996 and 2011 with the majority of variability within calculated errors. However, at the start of the record some statistically significant changes are observed. Concentrations initially decreased by -0.44 µM between 1996 and 1998, coincidental with the increase in temperature and salinity, and reduction in nitrate and phosphate values. In 1999 higher silicate concentrations were observed, again contemporaneous with the observed increase in nitrate and phosphate levels and approximately concurrent with the falling temperature and salinity. Since 2004 silicate levels have been near constant (5.15 ± 0.14 µM) with variations within the calculated errors. This period is coincident with the period of near constant salinity.

6. Possible causes of changing nutrient levels

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

6.1. Changes in depths of winter convection

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

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

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

6.2. Changes in horizontal advection

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

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

6.3. Changes in local biogeochemical processes

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

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

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

$$S_i = m_{ENAW}\, S_{ENAW} + m_{NAW}\, S_{NAW} + m_{mod\text{-}WNAW}\, S_{mod\text{-}WNAW}$$
$$X_i = m_{ENAW}\, X_{ENAW} + m_{NAW}\, X_{NAW} + m_{mod\text{-}WNAW}\, X_{mod\text{-}WNAW}$$
$$1 = m_{ENAW} + m_{NAW} + m_{mod\text{-}WNAW}$$

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

Between 1996 and 2011, as the Subpolar Gyre weakened, the proportion of mod-WNAW within the upper waters of the Rockall Trough decreased (Fig. 5). Conversely the proportion of water masses entering the basin from the south (i.e. ENAW and NAW) rose during the same period by a similar amount. This trend was observed whether potential temperature, phosphate or nitrate was used (in conjunction with salinity) within the mixing model. When the gyre was strong, such as in 1996, the upper waters were composed of approximately 50 % mod-WNAW and 50 % southern origin water masses. However, when the gyre was particularly weak, such as from 2009 onwards, the upper water column was almost entirely composed of ENAW and NAW whilst mod-WNAW contributed less than ~ 20 %.

8. Effect of the Subpolar Gyre

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

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

9. Discussion and conclusions

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

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

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

9.1. Prior to the mid-2000s

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

Above a threshold value of -4.5 cm (i.e. prior to the mid-2000s), upper water properties within the Rockall Trough, including nitrate and phosphate concentrations, show a strong correlation with the subpolar gyre index. Changes in phytoplankton abundance also have a strong relationship with this index (Hátún *et al.*, 2009). If phytoplankton numbers increase as the Subpolar Gyre weakens, nutrient concentrations may correspondingly decrease and, whilst still having a strong correlation to the gyre index, have a biological rather than advective cause. However, in the southern and central Rockall Trough, and Bay of Biscay region, the phytoplankton colour index (which approximates phytoplankton abundance) is actually negatively correlated with the gyre index (Hátún *et al.*, 2009). As the Subpolar Gyre weakens the number of phytoplankton in these areas decreases with an analogous reduction in nutrient uptake expected. As such, if changes in phytoplankton abundance have any effect on nutrient concentrations within the upper layers of the Rockall Trough, an increase between 1996 and 2011 is likely rather than the observed decrease. Thus we can conclude that nitrate and phosphate levels are predominantly affected by changes in advection related to the strength of the Subpolar Gyre rather than changes in associated biological activity. Further, it is interesting to speculate that the temporally varying amount of nutrients advected to the Rockall Trough as the Subpolar Gyre strengthens and weakens enhances the observed variations in phytoplankton abundance.

The conclusion that changes in horizontal advection is the primary control on temperature and salinity variability in the Rockall Trough between 1996 and the mid-2000s confirms and strengthens previous findings (Hátún *et al.*, 2005; Holliday, 2003). However, this is the first study to show that nutrient concentrations in the area are also strongly affected by changes in the Subpolar Gyre and the relative dominance of subpolar versus southern water masses. Nutrient concentrations within the eastern subtropical North Atlantic appear to be dominated by changes in horizontal advection (Oschlies, 2001) as is a record within the Norwegian Coastal Current, albeit with a strong superimposed anthropogenic signal (Frigstad *et al.*, 2013). In contrast changes in winter mixed layer depth are thought to be more important in the Iceland Sea (Ólafsson, 2003) and western subtropical North Atlantic (Oschlies, 2001).

9.2. Post mid-2000s

The relationship between the strength of the Subpolar Gyre and upper water properties in the Rockall Trough breaks down when a threshold of -4.5 cm is reached (i.e. after the mid-2000s). Below this value, when the Subpolar Gyre is particularly weak, salinities remain near constant whilst temperatures decrease slightly. Due to the low nutrient concentrations within southern-origin waters, it is speculated that phosphate and nitrate concentrations also remain relatively low. However, further data is required to test this hypothesis. We suggest that the maximum possible influence of southern waters (and thus minimum proportion of subpolar waters) is reached when the gyre index is around -4.5 cm. Indeed the contribution of southern-origin water masses (ENAW and NAW) to the upper layers of the Rockall Trough from 2006 onwards was greater than ~ 80 %. If this hypothesis is true, further weakening of the Subpolar Gyre will not lead to an additional increase in southern water masses, or reduction of subpolar waters, within the basin. Hence, the system changed in the mid-2000s from one where upper water properties are controlled by variations in the relative importance of different water masses (driven by changes in the strength of the Subpolar Gyre), to one controlled by other processes. Between 2007 and 2011, upper water temperatures have decreased by around -0.2 °C, whilst salinities have remained near constant since 2004. We speculate that upper water properties in the trough during this time were controlled by variations in the ENAW signature in the source region that were advected into basin.

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

9.3. Conclusion

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

Since the mid-2000s the Subpolar Gyre has been weaker than anything observed since 1992 (Häkkinen and Rhines, 2009), or modelled since 1960-1970 (de Boissésion *et al.*, 2012; Hátún *et al.*, 2005; Lohmann *et al.*, 2009). As such the interannual variability in the properties of upper waters in the Rockall Trough are no longer directly affected by the strength of the Subpolar Gyre with the maximum proportion of southern-origin water masses reached in the mid-2000s. Instead we suggest that variability within the basin now reflects changes in the source properties of ENAW which are advected northwards. The very weak state of the Subpolar Gyre suggests that upper water temperatures and salinities may currently be higher than at any point in the last 40-50 years. Indeed winter sea surface records (approximating the average temperature and salinity between 0-800 m) from the Rockall Trough show that similar temperatures and salinities have not been observed since at least 1948 (Holliday and Cunningham, 2013; Sherwin *et al.*, 2012). If present nutrient concentrations within the eastern subpolar North Atlantic are also particularly low, this may have implications for primary productivity and ecological pathways in both the offshore and coastal environments. Interannual temperature variations in Scottish coastal waters correlate significantly with changes in the upper waters of the Rockall Trough (Inall *et al.*, 2009). As the nutrient budget of the shelf is dominated by oceanic inputs (Huthnance *et al.*, 2009), the Subpolar Gyre may not only be an important control on offshore nutrient budgets, but may also similarly affect coastal waters.

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Table headings

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

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

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

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

Figure headings

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

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

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

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

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

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

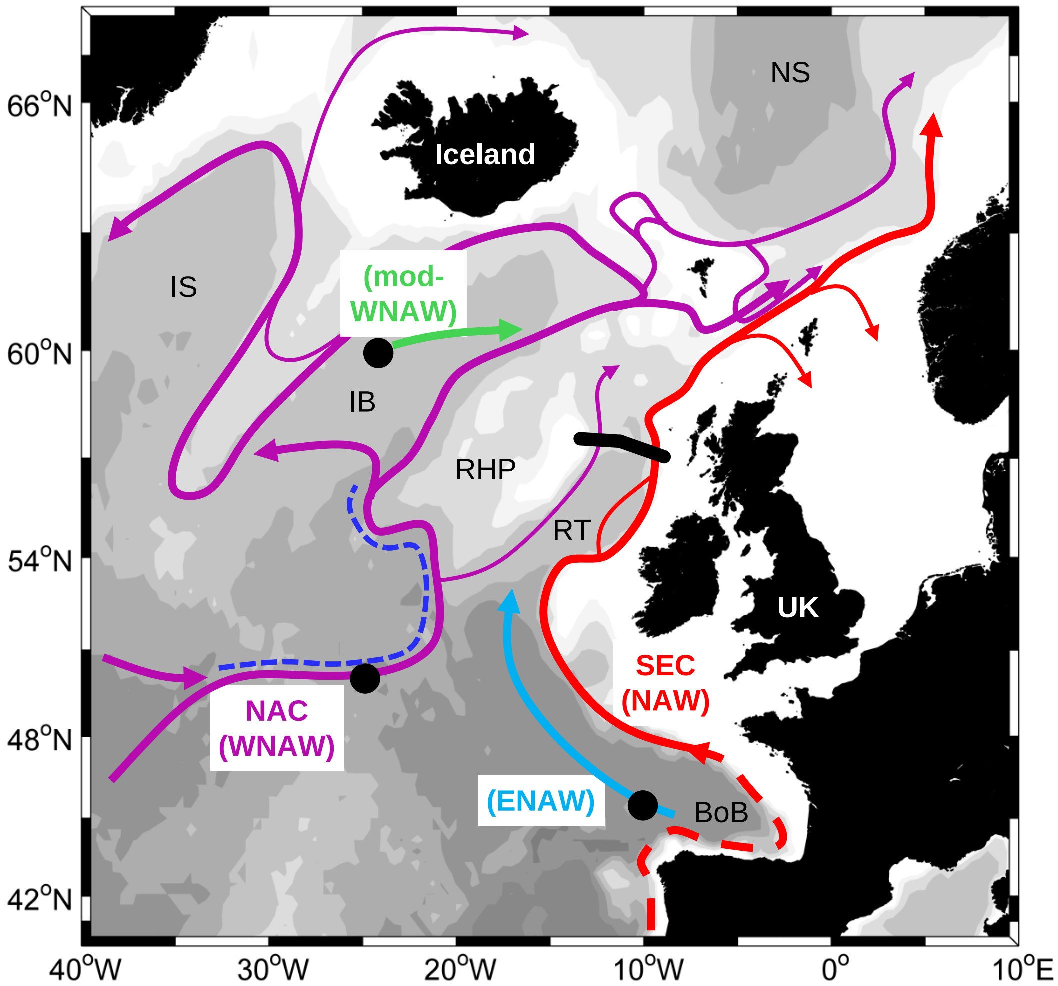
Figure 6. Plots of upper water (a) salinity, (b) potential temperature, (c) phosphate, (d) nitrate, (e) silicate and (f) proportion of mod-WNAW against the observed subpolar gyre index. Crosses in (a-f) show mean values, error bars in (a-e) the 95 % confidence limit and error bars in (f) the range of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

Acronym	S	θ (°C)	$[PO_4]$ (µM)	$[NO_3]$ (µM)	$[SiO_3]$ (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]

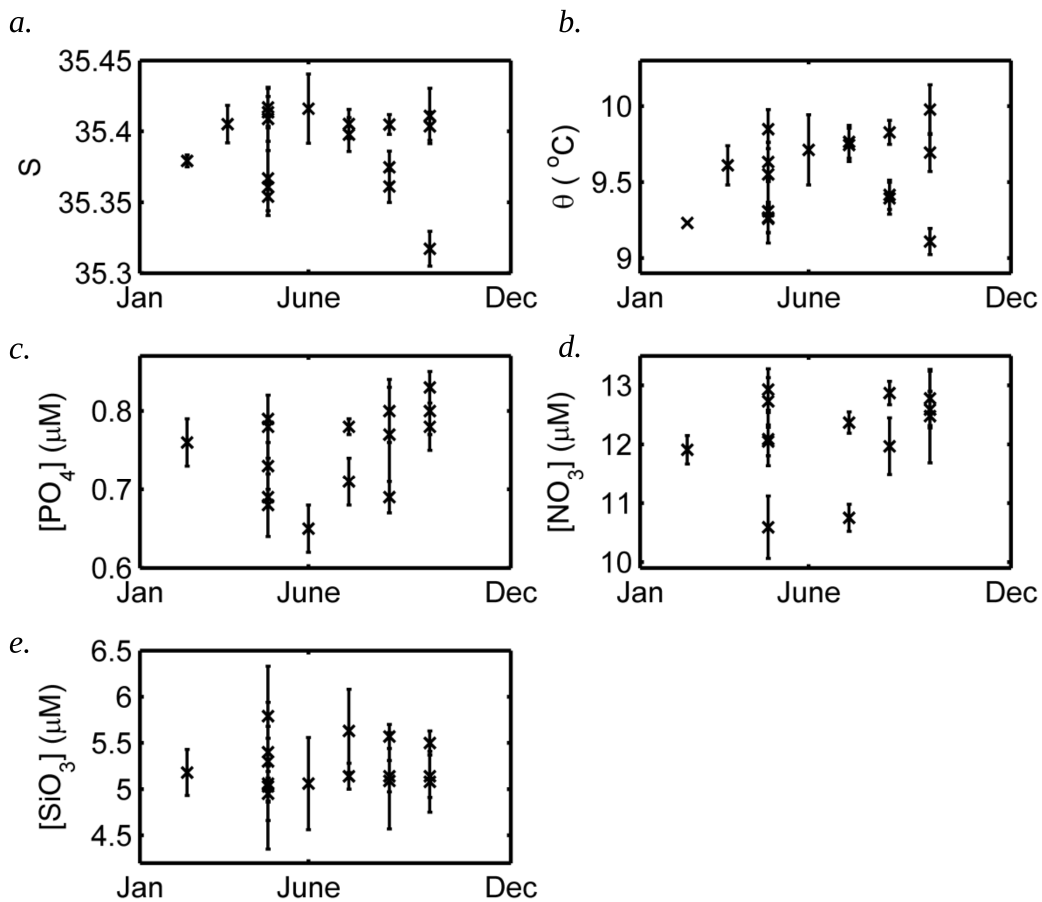
Year	Month	Cruise	Analysing Laboratory
1996	Oct.	D223	NOC
1997	Sept.	D230	NOC
1998	May	D233	NOC
1999	Sept.	D242	NOC
2000	Feb.	D245	NOC
2000	May	0700S	MS-S
2001	May	D253	NOC
2003	Apr.	0703S	MS-S
2003	Jul.	P300_2	SAMS
2004	Jul.	P314	NOC
2005	Oct.	CD176	SAMS
2006	Oct.	D312	NOC
2007	Aug.	D321	SAMS
2008	May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

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

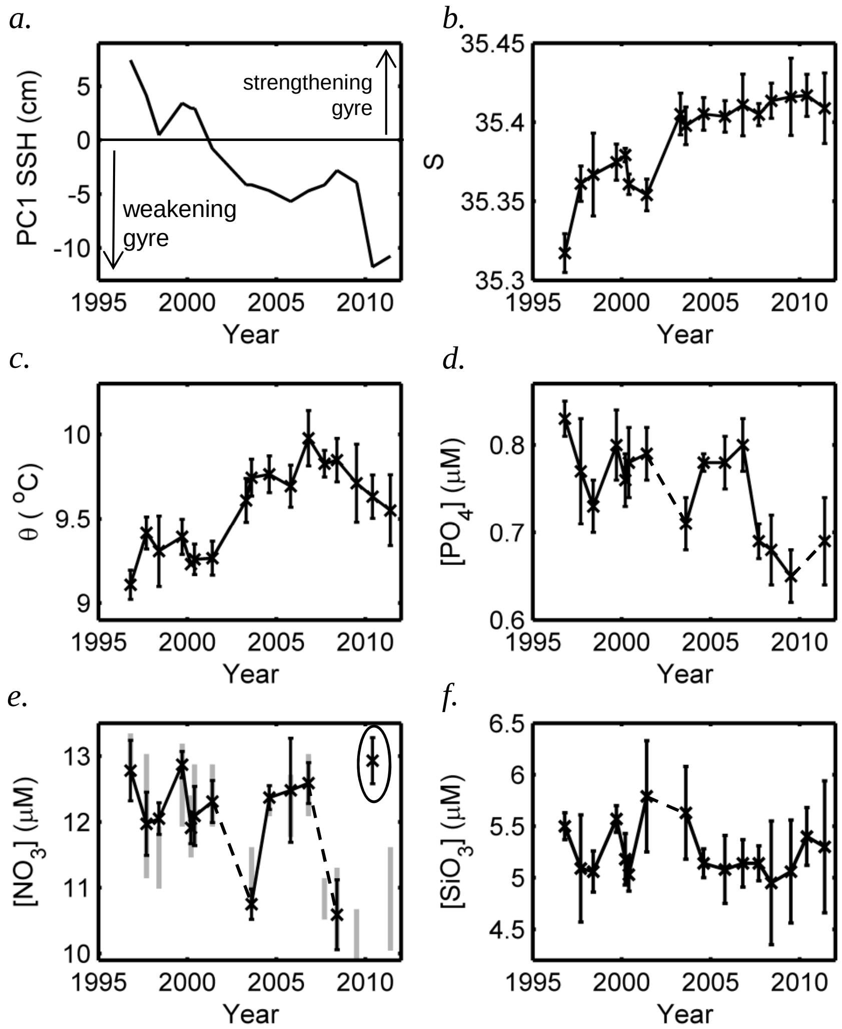
Year	min. MLD (m)	max. MLD (m)	mean MLD (m)
1996	370	800	710
1997	650	970	770
1998	240	540	460
1999	450	800	650
2000	270	800	440
2001	540	660	630
2002	540	660	650
2003	540	660	650
2004	540	660	610
2005	370	800	690
2006	370	540	440
2007	660	800	690
2008	660	660	660
2009	660	800	760
2010	660	660	660
2011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



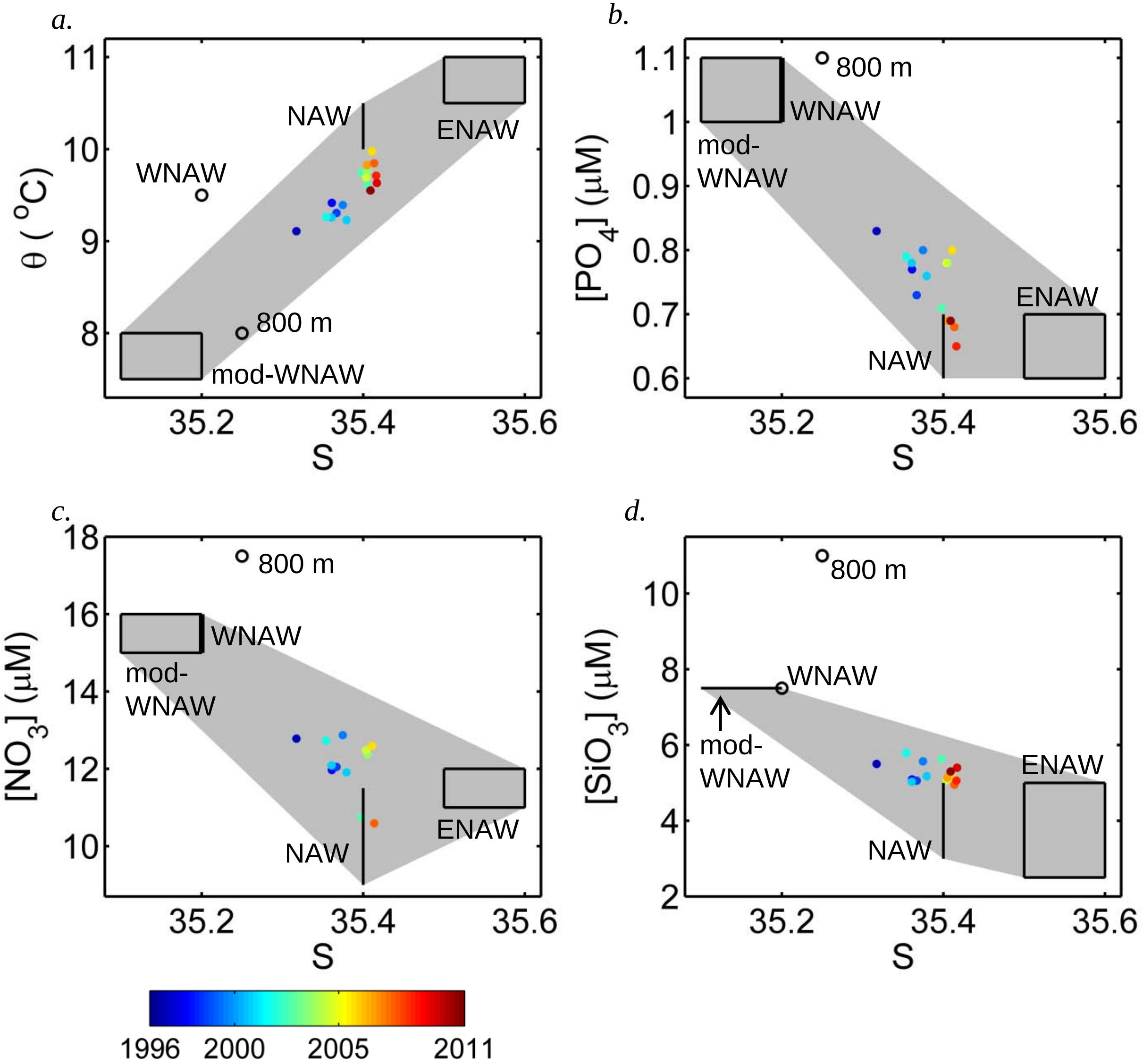
66°N
60°N
54°N
48°N
42°N
40°W
30°W
20°W
10°W
0°
10°E
Iceland
NS
IS
(mod-
WNAW)
IB
RHP
RT
UK
SEC
(NAW)
NAC
(WNAW)
(ENAW)
BoB

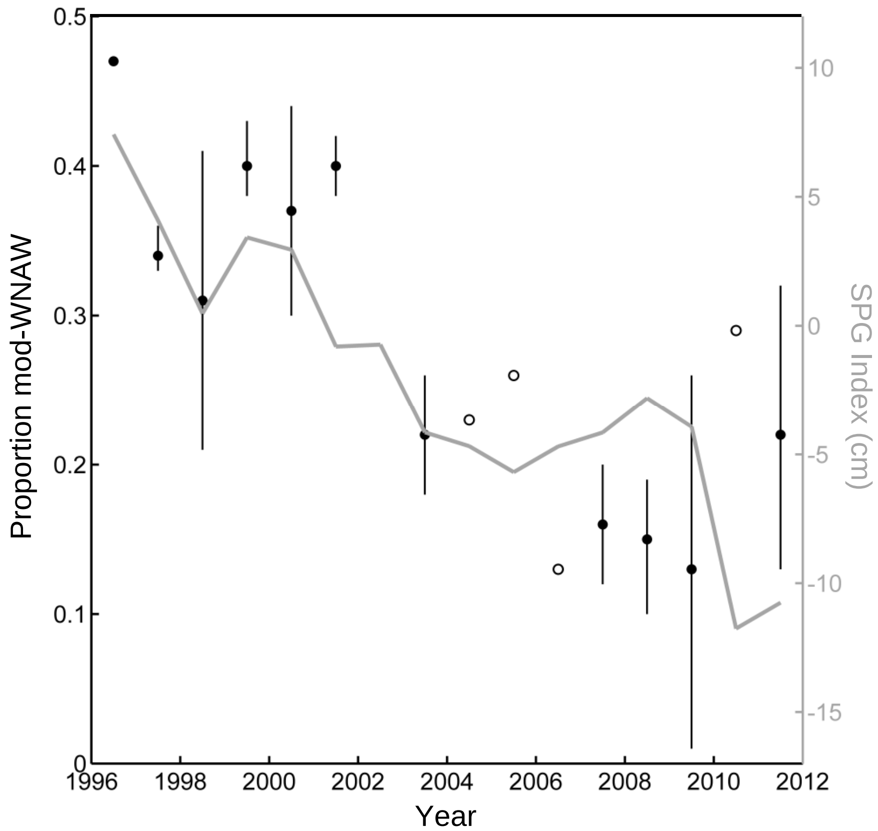


a.
S
35.45
35.4
35.35
35.3
Jan
June
Dec
b.
θ (°C)
10
9.5
9
c.
[PO4] (μM)
0.8
0.7
0.6
d.
[NO3] (μM)
13
12
11
10
e.
[SiO3] (μM)
6.5
6
5.5
5
4.5

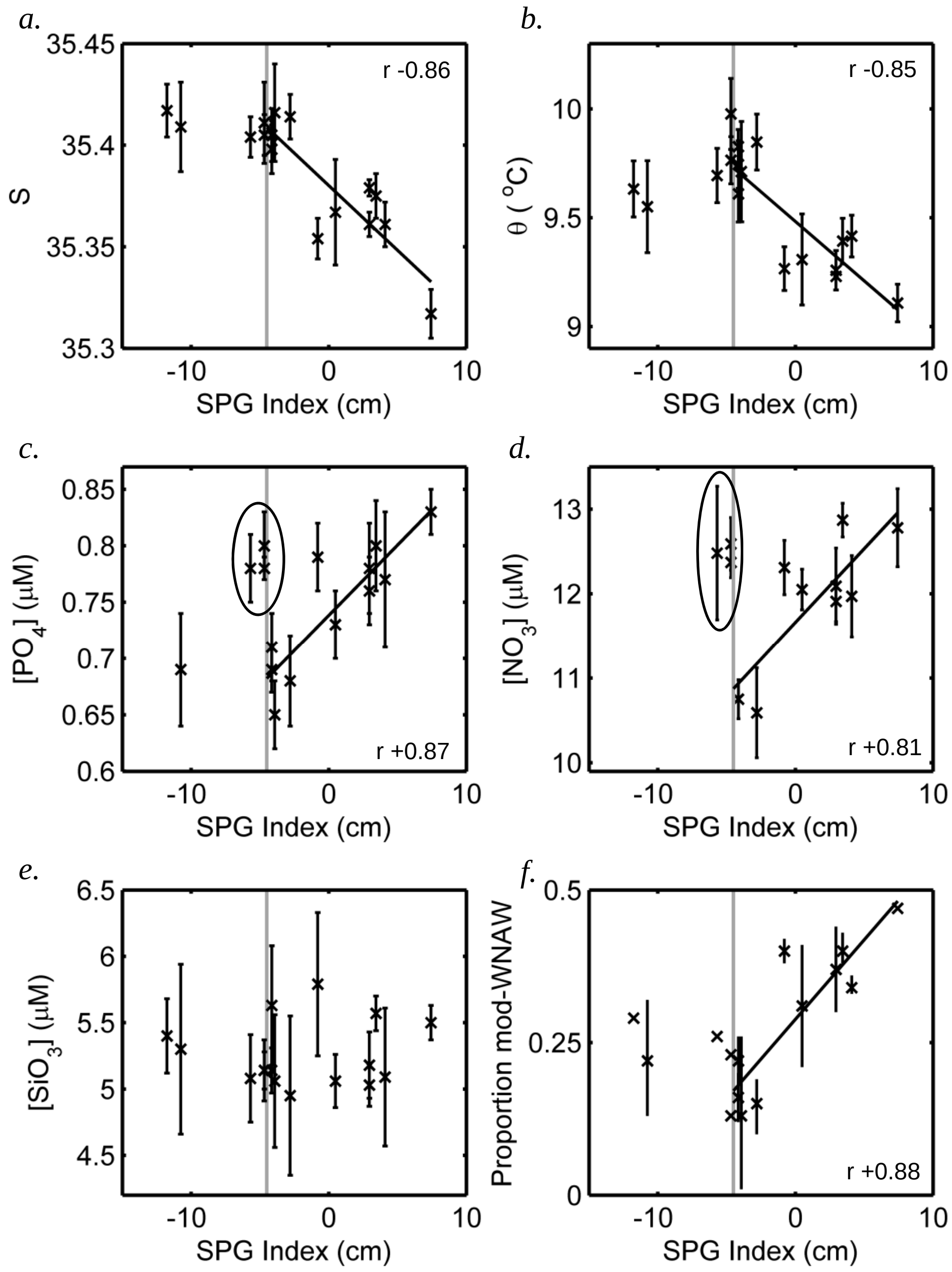


a.
PC1 SSH (cm)
strengthening gyre
weakening gyre
Year
b.
S
Year
c.
θ (°C)
Year
d.
[PO4] (μM)
Year
e.
[NO3] (μM)
Year
f.
[SiO3] (μM)
Year


a.
b.
c.
d.
θ (°C)
S
WNAW
NAW
ENAW
800 m
mod-WNAW
[PO4] (μM)
[NO3] (μM)
[SiO3] (μM)
mod-
WNAW
1996
2000
2005
2011



0.5
0.4
0.3
0.2
0.1
0
Proportion mod-WNAW
10
5
0
-5
-10
-15
SPG Index (cm)
1996
1998
2000
2002
2004
2006
2008
2010
2012
Year



a.
b.
c.
d.
e.
f.
S
θ (°C)
[PO4] (μM)
[NO3] (μM)
[SiO3] (μM)
Proportion mod-WNAW
SPG Index (cm)
r -0.86
r -0.85
r +0.87
r +0.81
r +0.88
35.45
35.4
35.35
35.3
10
9.5
9
0.85
0.8
0.75
0.7
0.65
0.6
13
12
11
10
6.5
6
5.5
5
4.5
0.5
0.25
0
-10
0
10