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Deep drivers of mesoscale circulation in the central Rockall Trough

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This paper is dedicated to the memory of Tim Boyd, former friend, colleague and office mate, who was tragically killed in a freak accident in January 2013. Tim was fascinated by the display of Rockall Trough glider data that evolved in real time on my monitor and was poised to lead glider research at SAMS after I retired (TJS).

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Abstract

Mesoscale variability in the central Rockall Trough between about 56 and 58° N has been investigated using a combination of ship-borne, underwater glider and gridded satellite altimeter measurements. Altimeter observations show that mesoscale features such as eddies and large scale circulation cells are ubiquitous phenomena. They have horizontal length scales of order 100 km with vertical scales of over 1000 m and are associated with mean current speeds (over the upper 1000 m) of $15 \pm 7\,\mathrm{cm\,s^{-1}}$. Monthly area averaged surface Eddy Kinetic Energy (EKE) has substantial inter-annual variability, which at times can dominate a mean seasonal signal that varies from a maximum in May ($74\,\mathrm{cm^2\,s^{-2}}$) to a minimum in October ($52\,\mathrm{cm^2\,s^{-2}}$) and has increased gradually since 1992 at about $1.1\,\mathrm{cm^2\,s^{-2}}$ per year. A five month glider mission in the Trough showed that much of this energy comes from features that are located over 1000 m below the surface in the deep cold waters of the Trough (possibly from eddies associated the North Atlantic Current). The surface currents from altimeters had similar magnitude to the drift currents averaged over 1000 m from the glider in the stratified autumn, but were half the deep water speed during late winter. Although the mesoscale features move in an apparent random manner they may also be quasi-trapped by submarine topography such as seamounts. Occasionally anti-cyclonic and cyclonic cells combine to cause a coherent westward deflection of the European slope current that warms the Rockall side of the Trough. Such deflections contribute to the inter-annual variability in the observed temperature and salinity that are monitored in the upper 800 m of the Trough. By combining glider and altimeter measurements it is shown that altimeter measurements fail to observe a $15\,\mathrm{cm\,s^{-1}}$ northward flowing slope current on the eastern side and a small persistent southward current on the western side. There is much to be gained from the synergy between satellite altimetry and in situ glider observations both in the interpretation of their separate data sets and in aiding glider pilots to steer their vehicles through EKE active regions such as the north-east Atlantic.

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1 Introduction

The northern end of the Atlantic Ocean (south of the Greenland-Scotland Ridge) is dominated by a basin-wide three-dimensional cyclonic interleaving of wind and thermohaline driven water masses known as the Sub-Polar Gyre (SPG). The role that this gyre plays in the Atlantic Meridional Overturning Circulation (AMOC) is not well understood, but its significance is hinted at by evidence from ocean reanalyses which suggest that a recent 50 year increase in the strength of the AMOC south of the SPG is not commensurate with the relatively steady exchange across the Greenland-Scotland Ridge to the north (e.g. Tett et al., 2014). Understanding the circulation of the SPG is critical to studies of the global and local climate, and whilst great effort has been made to characterise the nature of the deep, cold southward flowing boundary currents in the western part, much less is known about the currents in the generally warmer and saltier water in the east.

2 Background

The Rockall Trough is an 800 km long by 200 km wide trench that lies to the west of the British Isles (Fig. 1). At its southern entrance (53° N, 17° W) it is up to 3500 m deep, but it shallows towards the north to a depth of 1000 m at the foot of the Wyville Thomson Ridge (8° N, 60° W) itself about 600 m deep. South of 58.5° N the western side of the Trough is flanked by the Rockall-Hatton plateau (minimum depth of order 100 m), but further north this boundary is populated by a series of deep channels (to 1000 m) and shallow banks that are less than 500 m deep. There are several seamounts in the northern part of the Trough, the most important of which (for present purposes) are the steep sided Anton Dohrn Seamount (ADS) that rises to 500 m at 57.5° N, 11° W and the Hebrides Terrace Seamount at 56°30′ N, 10°30′ W (minimum depth 1000 m).

The problems of quantifying and monitoring circulation on the eastern side of the gyre stem from (i) weak meandering currents with only moderate eastern boundary

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intensification and (ii) the presence of relatively strong mesoscale currents. The general distribution of the currents and water masses in the northern half of the Trough is well documented (see e.g. Ellett et al., 1986; Ellett and Martin, 1973; McCartney and Mauritzen, 2001 and Fig. 1). In the upper layers (to at least 600 m) there is a slow north-eastward flow (~ 0.6 Sv, or $0.6 \times 10^6\,\mathrm{m^3\,s^{-1}}$) of relatively cool water North Atlantic Water (NAW) originating in the North Atlantic Current (NAC) and including water from the Sub-Polar Front in the western Atlantic. This flow is enhanced along the eastern boundary by a slope current down to 500 m, with a width of order 50 km and mean speeds of up to $\sim 0.2\,\mathrm{m\,s^{-1}}$, in which about 3 Sv of warmer, salty Eastern North Atlantic Water (ENAW) from a more tropical source is found (Booth and Ellett, 1983; Holliday et al., 2000; Souza et al., 2001). At intermediate depths (say to 1000 m) there is a mixture of Sub-Arctic Intermediate Water (SAIW) from deep in the NAC and Mediterranean Overflow Water (MOW) from the south (e.g. Reid, 1979; Ullgren and White, 2010) that over decadal timescales interact with each other and with Wyville Thomson Ridge Overflow Water (WTOW) coming from the north (e.g. Ellett and Roberts, 1973; Johnson et al., 2010). At deeper levels (down to about 1800 m) lies low salinity Labrador Sea Water (LSW) that intermittently pulses into the Trough from the south-west (Holliday et al., 2000) whilst deeper again is water with the signature of Antarctic Bottom Water (Figs. 2 and 3).

Although at times mesoscale activity in the northern part of the Rockall Trough has been thought to be weak (e.g. Pollard et al., 1983), hydrographic observations during the JASIN experiment of the summer of 1979 to the west of Rosemary Bank showed that this is not the case. A cyclonic mesoscale eddy with a diameter of ~ 100 km, and internal velocities of order $0.1\,\mathrm{m\,s^{-1}}$, propagated westward through the observation area (at about 59.5° N) with a translation speed of about $1.4\,\mathrm{km\,day^{-1}}$ (Ellett et al., 1983). It is notable that this eddy was coherent to well below 1000 m and had a weak surface signature. Its direction of propagation and water composition indicated to the JASIN group that it was formed by the overflow of WTOW across the ridge.

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Evidence of mesoscale currents is further supported by a synthesis of current meter observations from north of 57° N by (Dickson et al., 1986) who reported a maximum in eddy kinetic energy (EKE) levels at all depths (from current meters) in winter to spring that lagged the peak in wind stress. Subsequent surface drifter studies in the central and northern part of the Trough by (Booth, 1988) and (Burrows et al., 1999) revealed clear evidence of mesoscale eddies. Booth (1988) identified three eddies: a large anti-cyclonic one at 54° N, 15.5° W with a radius of 60 km, a periodic timescale of up to 16 days and an orbital speed of up to 0.8 $m\,s^{-1}$; and two much smaller cyclonic ones, with periods of one to two days and orbital speeds up to 0.35 $m\,s^{-1}$, that rotated anti-cyclonically around the ADS. He attributed the source of these eddies to instability of the slope current near the Porcupine Bank and to Taylor column dynamics over the seamount respectively. More recently (Ullgren and White, 2012) found 35 eddies over a 6 year period from 2001 in the southern part of the Trough between 50° and 56° N using satellite altimetry. Cyclonic eddies tended to enter along the track of the NAC and anti-cyclonic eddies were found along the path of the slope current. The eddies were typically slow moving and their cores had radii of ~ 27 km and an orbital speed of 0.2 $cm\,s^{-1}$. Their energy sources are not certain but from altimetry and current meter observations EKE levels in the Trough had a seasonal peak in spring, so they may have been wind forced, but equally they may have originated from instabilities in the NAC (in the west) and the slope current (to the east). The study also speculated on the presence of northward moving deep eddies of Mediterranean Outflow Water.

More generally, other work has involved large scale studies of circulation of the North Atlantic as a whole based on archived datasets. Satellite altimetry (Heywood et al., 1994; Volkov, 2005) indicates enhanced levels of EKE in the Rockall Trough (order 100 $cm^2\,s^{-2}$) that contrasts with the quiescent Rockall-Hatton Plateau. Surface drifter tracks (Fratantoni, 2001; Jakobsen et al., 2003) across the North Atlantic reveal a similar picture with the latter finding that boundary currents were enhanced by wind stress in winter, which in turn seemed to lead to enhanced instability and the appearance of increased mesoscale activity in spring. A study of intermediate depth drifters (Argo

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floats, RAFOS drifters etc.) indicated EKE levels of order 20 to 40 $cm^2 s^{-2}$ at depths between 1500 and 1750 m in the southern part of the Rockall Trough (Lankhorst and Zenk, 2006).

To sum up, historical observations suggest the Rockall Trough appears to have a moderate level of EKE activity which ranges from a maximum of about 100 $cm^2 s^{-2}$ at the surface to about 25 $cm^2 s^{-2}$ at 1500 m. There appears clear evidence of a seasonal signal with a maximum in spring or early summer that may be related to instabilities formed in the boundary currents. In this study we look in detail at the mesoscale current field in the central part of the Trough focussing on a 12 month period between mid-2009 and mid-2010 using a combination of ship borne observations and satellite altimetry and an underwater glider mission. The latter provides a more complete picture than has been possible to date of the time-varying three-dimensional structure of mesoscale currents in the Trough, and their impact on the circulation and horizontal mixing of the Trough.

3 Methods

3.1 Ship borne CTD and LADCP

Since 1975 the oceanography of the central Rockall Trough between 56.6° N and 57.5° N has been monitored along the Ellett Line (Fig. 1), an annual, and in earlier years seasonal, series of Conductivity-Temperature-Depth (CTD) sections (Holliday et al., 2000; Sherwin et al., 2012). The 2009 Ellett Line section by *RRS Discovery* cruise D340, which was conducted between 16 and 20 June, provides a full depth picture of the temperature, salinity and velocity fields (Figs. 2 to 4). Profiles were measured with a stainless steel Seabird 911 CTD package that was suspended inside a 24 bottle rosette of 20 L water bottles and below which was attached a downward looking 300 kHz Lowered Acoustic Doppler Current Meter (LADCP). The CTD system was lowered at typically 1 $m s^{-1}$ and data were calibrated against water bottle samples. The

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LADCP data were processed using LDEO version IX.5 of the modified "Visbeck" routines (Thurnherr, 2010) which corrects velocity observations for the relative motions of the LADCPs to achieve a quoted accuracy of $< 3\,\mathrm{cm\,s^{-1}}$ when two LADCPs are used. D340 did not have an upward looking LADCP, so individual observations were less accurate than this, but realistic profiles were achieved with smoothing applied over 50 m. On some casts a titanium frame and simple CTD system without an LADCP was used so the number of velocity profiles was less than the CTD ones. The cruise report can be found at www.bodc.ac.uk.

3.2 Satellite altimetry

Weekly syntheses of merged gridded satellite altimeter data were downloaded for the period 14 October 1992 to 7 August 2013 from the Aviso website (www.aviso.oceanobs.com) which provides processed data from all altimeter missions for near real time applications and offline studies. During this period the Trough was covered by the JASON 1 and 2 satellites (cycle time 10 days, track separation 120 km) and the Envisat and ERS-2 Satellites (35 days and 40 km), which together provided a reasonably dense coverage of sea surface observations. Daily and weekly averages of Sea Level Anomaly (SLA) were added to the CNES-CLS09 estimate for the Mean Dynamic Topography (MDT) between 1993 and 1999 to produce an Absolute Dynamic Topography (ADT) on a 1/3° Mercator Grid. The meridional grid spacing is thus 37.1 km and the zonal spacing ranges from 21.0 km at 55.5° N to 19.4 km at 58.5° N. Surface geostrophic currents (eastward, northward as u, v cm s^{-1} respectively) were derived by Aviso from the SLA and MDT using the thermal wind equation. The MDT heights are based on the observations of SLA over 15 years by altimeters and of the Geoid over 4 years by the Gravity Recovery and Climate Experiment (GRACE), a satellite observation programme run by NASA. Since the horizontal resolution of GRACE (200 km) is comparable to the width of the Rockall Trough the MDT does not resolve the slope currents (as will be shown later).

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3.3 Underwater glider

Continuous observations of temperature and salinity along with depth averaged current down to 1000 m were made by an underwater glider operated by the Scottish Association for Marine Science in an exercise to evaluate a new way to monitor temperature and salinity along the Extended Ellett Line (which includes its extension to Iceland). The glider was deployed from a fast RHIB on 12 October 2009 on the Scottish Shelf at 56.56° N, 7.48° W and made its way westward over the shelf edge to deep water by 18 October (dive 235, Table 1). In the subsequent 4.5 months it completed 8 transits across the Trough between the 500 m isobaths along an (approximately) WNW–ESE track between 56.40° N, 9.05° W at the edge of the shelf to 57.22° N, 12.52° W on the eastern flank of Rockall (about 250 km apart, Fig. 5), with each round trip taking about 4 weeks. It was finally recovered on 9 March 2010 near the shelf edge following a mechanical failure.

The glider (SG156) was a battery operated long range autonomous underwater vehicle constructed by Seaglider Fabrication, University of Washington (Eriksen et al., 2001). Its descent and ascent vertical velocities were typically 0.1 $\mathrm{m\,s^{-1}}$ so it took about 6 h to complete a full dive during which time it travelled about 5.5 km against the ambient current at a horizontal speed of roughly 0.25 $\mathrm{m\,s^{-1}}$. Its principal oceanographic instrument was an unpumped version of the Seabird SBE41 conductivity-temperature (C-θ) system that was modified to minimise power consumption. Up to dive 476 C-θ was measured at 10 s (or about 1 m) intervals down to 30 m, then every 30 s to 200 m and every 60 s to 1000 m. For the rest of the mission the frequencies became every 5 s to 100 m, 10 s to 500 m and 60 s to 1000 m. A potential problem with the unpumped SBE41 is salinity spiking as the glider travels through a pycnocline even though the vertical velocity is small. Lag corrections are applied before salinity is computed from the raw data (e.g. Perry et al., 2008) and extensive tests were undertaken to assess the magnitude of the problem here (for example, by comparing ascending and descending temperature–salinity, or θS, plots). For the most part the up and down profiles were self-consistent, probably because sharp pycnoclines in the water column are absent during winter, but artificial salinity spiking may be present in the seasonal thermocline during autumn (Fig. 3). The overall accuracy of the salinity observations are confirmed by the coincidence of glider and D340 θS profiles below 10 °C in Fig. 3. Furthermore there was little evidence of fouling on recovery, and pre- and post-mission CTD calibrations by Seabird Electronics indicated that there had been negligible drift in any of the sensors.

The surface positions of the glider were accurately determined from GPS fixes. Dive averaged ambient current velocities (or "drift" velocities) were computed using an algorithm based on a theoretical model of the glider's hydrodynamic performance through the water which determines the difference between the expected and measured surfacing position at the end of each dive. However, this calculation is sensitive to the accuracy of the glider's internal compass and in post-processing it was found that a significant difference existed in the mean drift velocity measured during the eastward and westward transitions of the Trough (about 0.07 and 0.1 $\mathrm{m\,s^{-1}}$ southward respectively). Theoretical tests of possible error scenarios demonstrated that difference can be explained by a non-linear error in the compass measurements (a similar error has been reported by (Merckelbach et al., 2008) for a different glider system). As a result it was not possible to determine basin-wide transport. Other theoretical tests, however, indicated that local eddy currents were reasonably well measured.

3.4 Data analysis

The spatial mean EKE in the central Rockall Trough between latitudes 56 and 58° N and longitudes 9° and 13° W was computed from the sum of the SLA and MDT currents as

$$\mathrm{EKE} = (\mathrm{var}u + \mathrm{var}v)/2$$

(where var is variance). Error in the mean of N observations of EKE (err) was computed as

$$\mathrm{err} = \mathrm{SD(EKE)}/\sqrt{N}$$

where SD is the standard deviation of the observations.

For Table 1 and Fig. 6 glider data from a specific transit of the Trough were averaged into 0.1° longitude (ca. 6 km) wide meridional bins (see Fig. 5). The mean positions of the dives within a bin were then computed and the values of other data were determined by interpolating horizontally to the centre positions of the bins. The mean transit speeds and their SDs were derived by averaging individual speeds from the dives listed in Table 1. Density anomalies, shown as σ_t in Fig. 6, from each downward and upward dive were averaged into 5 m vertical bins and then smoothed in the vertical with a 25 m half width Hamming filter before they were averaged into a longitudinal bin.

In order to compare the different Aviso and glider data sets directly time series of ADT and surface currents were derived by interpolation of the 3-D (in space and time) Aviso observations to produce a time series of spot values that coincided in the time and position with the glider observations at every dive. They were then processed and averaged in the same way as the glider data.

4 Background observations

4.1 The evolution of temperature and salinity

During June 2009 the seasonal thermocline was well established in the upper 100 m of the water column and there was clear evidence in the salinity signal of the influence of the slope current, in the upper 500 m on the eastern side, spreading across to the centre of the Trough (Fig. 2). The deep thermocline (about 7.5 °C) which was located at about 800 m to the west of the ADS descended to about 1000 m on its eastern side (Figs. 2 and 3). The deep part of the water column was marked by gradual decreases in temperature and salinity with depth.

Seasonal warming and freshening of the surface layers on both sides of the Trough prevailed until October but after that, during Mission 1, stratification weakened so that by February the upper 500 m was uniformly mixed. By and large the profiles of potential

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temperature (θ) and S in the upper 1000 m on the eastern side of the Trough were well behaved and almost equally mixed between NAW in the centre of the Trough, and the more saline ENAW. To the west of the seamount, however, away from the influence of the shelf edge current, the changes in the profile appeared more dynamic with an apparent interleaving between ENAW and the cooler and fresher NAW. This side of the Trough also experienced a remarkable increase in both θ and S below about 200 m as NAW appeared forced down by as much as 800 m. The probable reason for this increase is discussed later.

4.2 The velocity field during *Discovery* cruise D340

The LADCP sections (Fig. 4) dispel any notion that the currents in waters of the central Trough are either slow or vertically uniform. There was a fast southward flowing current along flank of the Rockall Trough and a suggestion of an extensive feature that filled the space west of the ADS. It source was a pronounced surface depression of the ADT running down the western side of the Trough. The sea surface had a particularly steep slope on the western side of the ADS (Fig. 7) which complemented the westward uplift of the deep pycnocline centred on 900 m (Figs. 2 and 3) and the strong meridional currents observed by the LADCP (Fig. 4). However, the LADCP current observed flowing northward along the upper edge of the Malin Shelf appears as a weak southward flowing current in the Aviso representation. The Aviso surface current was also weaker than its southward flowing LADCP counterpart along the flank of the Rockall Bank. The inconsistencies in the comparisons at the boundaries could be due to shallow water tidal currents, although they provide a strong impression that the meridional ADT surface currents are badly represented at the edges of the Rockall Trough. This point will be taken further with the glider observations.

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4.3 Temporal variations in Eddy Kinetic Energy

The monthly means of the weekly averaged surface EKE in the central Rockall Trough from Aviso gridded altimetry have increased at a rate of 1.1 $cm^2 s^{-2} year^{-1}$ since 1992 (Fig. 8b) with an inter-annual linear correlation coefficient of $R = 0.65$. The reason for this long upward trend is not clear: whilst it does not seem to correlate with the strength of the North Atlantic Oscillation (e.g. Hurrell, 1995) it matches a concurrent increase in temperature and salinity in the upper 800 m of the Trough and could be related to changes in local circulation due to the westward retreat of the SPG in the northern Atlantic (Hatun et al., 2005; Johnson et al., 2013). During the period between May 2009 and April 2010, which covers the in situ observations described here, mean surface EKE levels (66 $cm^2 s^{-2}$) were about 11 $cm^2 s^{-2}$ larger than the long term average. EKE was relatively high in June 2009 (about 84 $cm^2 s^{-2}$) although the highest level for the 12 months was over 100 $cm^2 s^{-2}$ in the middle of November 2009 (Fig. 8a). This latter peak occurred after a steady increase from about 55 $cm^2 s^{-2}$ at the start of the mission and was much more than a SD away from the mean levels for November and December (Fig. 8c). It was followed by a steady decline to about 40 $cm^2 s^{-2}$ by the middle of January. Thus, in the 12 months from May 2009 to April 2010 the seasonal variation in EKE levels was anomalous compared the long term average where the peak occurs in May (67 $cm^2 s^{-2}$) and is at a minimum in October (45 $cm^2 s^{-2}$, Fig. 8c).

4.4 The evolution of ADT and surface currents during the glider mission

As Fig. 5 implies, and Fig. 9 shows, the surface waters of the central Rockall Trough were continually disturbed by slow moving eddies and other mesoscale motions. Early in the mission (on 20 October) an elliptical cell with a cyclonic circulation and a NE–SW major axis diameter of about 200 km occupied the deep water immediately SW of the ADS (A_C, Fig. 9a), whilst immediately to the south of it lay an anticyclonic circulation of similar size (B_A). A strong east to north-eastward current (> 20 $cm s^{-1}$) marked the boundary between them. During the first part of November A_C moved NE onto the

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seamount, where it intensified and seemed to become anchored until the middle of December, with a circular diameter of about 100 km and current speeds in excess of 20 cm s^{-1} (Fig. 9b and c). Meanwhile B_A drifted eastward to the north of the Hebrides Terrace Seamount and a cyclonic cell (or eddy) started to drift into the picture from the SW corner (C_C, Fig. 9b). By the middle part of November a westward flowing current with maximum surface speeds in excess of 0.3 m s^{-1} had formed in the southern part of the region (D). From then on the pattern of alternating cyclonic and anti-cyclonic eddies persisted throughout December (Fig. 9c) whilst they slowly lost energy until by 9 January average EKE in the region had weakened to < 50 cm^2 s^{-2} (Figs. 8a and 9d). Nevertheless these cells were still sufficiently intense to be able to drive a pronounced anti-cyclonic circulation westward across the Trough between the two seamounts. From then on mesoscale activity increased a little so that by 5 February an anti-cyclonic circulation (E_A), which may have evolved from B_A, had become trapped on or close to the ADS with current speeds a only little less than the earlier A_C. At the same time the broad cyclonic circulation, C_C, had become established in the southern part of the region (Fig. 9e). Finally, by the start of March E_A had weakened a little above the ADS, whilst C_C had disappeared and a new cyclonic eddy, F_C, had appeared close to the Malin Shelf edge between the ADS and the Hebrides Terrace Seamount.

Overall, the mesoscale motions in the deep water of the Rockall Trough seemed to be distributed in a fairly arbitrary arrangement, although the circulations were arranged like gears in a pattern of anti-cyclonic/cyclonic cells. It is intriguing that both anti-cyclonic and cyclonic cells were able to occupy the top of the ADS, and it appears that the precise sense of circulation was determined more by the regional arrangement of the cells than by a local dynamic balance formed by the seamount itself.

A word of caution is necessary here. Later analysis will question the validity of the background MDT in the Rockall Trough and in particular throw doubt on the intensity on the anti-cyclonic circulation between the ADS and the Hebrides Terrace Seamount.

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5 Sub-surface glider observations winter 2009/10

Satellite altimeter observations of ADT and surface velocity give valuable information about the spatial and temporal scales of mesoscale variability in the Rockall Trough, but they provide a poor representation at boundaries and cannot reveal detail of the structure below the surface. Ship borne sections such as those of D340 help to address these omissions but are of necessity rare. By contrast, the underwater glider provides an opportunity for measurements of the density structure and velocity field that through the use of repeated sections help to construct a more complete picture of the variability below the surface.

5.1 Glider profiles and drift currents

It is quite difficult to navigate a glider precisely in a field of apparently random mesoscale currents that have a similar speed to its forward velocity. During its mission the glider encountered ambient current speeds of over $24\,\mathrm{cm\,s^{-1}}$ in 25 % of the dives and at such times it might either be stopped dead, forced sideways or backwards, or race forward (hence the uneven spacing of the dive positions in Fig. 5). As a precaution (since this was its first mission) the glider was kept outside the 500 m isobath so that it did not measure the strength of the slope currents in the shallower water on either side of the Trough. The original plan had been to pass across the top of the ADS along the Ellett Line route, but this was abandoned after transit 4 because the opposing currents near the seamount were too strong in the early part of the mission. Furthermore it was not easy to get near the seamount during most eastward transits because the southward flowing current close to the Rockall Bank tended to drag the glider from the intended course when it turned east.

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5.2 Changes in temperature and salinity profiles across the Trough

At the beginning of the mission the surface temperature and salinity at the shelf edge were about 12.6 °C and 35.45 respectively (Fig. 3) fractionally warmer and fresher than that observed by D340 on 19 June (12.3 °C and 35.47). The temperature and salinity sections of the upper 200 m from transit 1 were generally similar to those from D340. Over winter, between mid-October 2009 and the end of February 2010, surface stratification was gradually eroded and deepened so that by March the upper 500 m was almost isothermal and isohaline (Figs. 3 and 6). By contrast the θS profiles below about 600 m (9.5 °C and 34) remained very similar apart from vertical displacement due to the mesoscale motions. In many transits the near surface isopyncals were roughly horizontal, whereas those deeper in the water column (below about 600 m or $\sigma_t \sim 27.3\,\mathrm{kg\,m^{-3}}$) had large and uneven variations in depth (with undulations up to 200 m high and 50 km wide) across the Trough.

Over the course of the mission many of the changes in the track of the glider were correlated with the ambient drift velocities and the undulating depth of the deep isopycnals (Fig. 6). (These correlations were observed to steadily evolve in real time as the plots from successive dives were updated on the mission console.) It is clear from Fig. 6 and Table 1 that mesoscale variations in the depths of the deeper layers of the Trough were associated with current speeds of typically 10 to 20 $\mathrm{cm\,s^{-1}}$ (averaged over the upper 1000 m). A good example of this association is seen in transit 1 (18 to 31 October) when a cold dome of the deep isotherms stretched across almost the entire the Trough at about 57° N driving a south-westward current on its northern side.

5.3 Interaction between glider track and mesoscale currents

By the time the glider turned eastward from the Rockall Bank on 31 October the basin wide deep doming of A_C had concentrated on the western side of the Trough (Fig. 9a) and as a result it was initially forced southward by its western flank (west of 12.5° W in transit 2). It was then swept eastward along the interface between the southern side

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of A_C and the northern side of B_A until it was picked up by the eastern side of the anti-cyclonic circulation and deflected south-eastward. The isopycnals at 1000 m in B_A were now significantly deeper than when A_C occupied the eastern side of the Trough.

To the end of 2009 the glider observations tended to corroborate the sea surface undulations observed by the altimeters. However, from the end of transit 2 (12 November) a deep water doming of the isopycnals appeared between about 9.5 and 10.5° W that seems to have been associated with the presence of lighter water in the upper 300 m of the slope current and is not readily apparent in the ADT. At this time the Aviso current speeds along the transits were at their maximum (and greater than those observed by the glider) but from then on until the end of the mission drift speeds averaged over 1000 m from the glider were always 2 times greater than those computed from altimetry (Table 1).

In transit 4 an uplift of deep isopycnals at about 9.8° W drove a southward current between 10 and 10.5° W in response to the presence of a cold core that was most pronounced below 800 m. Similar currents can be seen on the northern side of the Hebrides Terrace Seamount on the eastern side of the Trough at about 56.5° N, 10° W in transits 7 and 8 on the western side of the cold core of eddy F_C (see Figs. 6b and 9f). There were other, less pronounced, examples in the glider record of doming of the deep water driving surface currents that extended at least to 1000 m. In every case these currents appear to have coincided with variations in the ADT and the inferred surface current.

6 Direct comparison of the glider and altimeter current measurements

6.1 Comparison of individual observations

The average current speed along individual tracks measured by the glider drift was often much greater that that observed by Aviso, particularly once the seasonal stratification had been eroded by the start of 2010 (Table 1). During the June 2009 cruise the

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LADCP measured currents depth averaged to 1000 m that were nearly twice as large as the equivalent Aviso surface currents (also Table 1). Over the mission as a whole the eastward components of velocity were fairly closely correlated (0.69, Table 2 and Fig. 10a) whilst the correlation between the northward components was poorer (0.41 and Fig. 10b). One explanation may be due to the smoothing that is introduced by gridding the altimetry data, although the satellite altimeter coverage of the Rockall Trough was quite dense at that time and smoothing would not explain the difference between the northward and eastward components of velocity. So these results are a little surprising and merit further investigation particularly as there is some doubt about the accuracy of the Geoid across slope regions as used for the MDT currents by Aviso (see Fig. 11a).

6.2 Correcting for errors in the MDT velocity field

The extent to which the steady MDT velocity field (Fig. 11a), which is derived from a coarse determination of the Geoid, deviates from the true background velocity field can be determined by averaging all the simultaneous glider and altimeter currents along all tracks into 10′ of longitude bins along a mean track, including those that were previously omitted but ignoring velocities $> 30\,\mathrm{cm\,s^{-1}}$ (see Fig. 5). The justification is outlined in Appendix A. It is important to note that the eastward (i.e. across Trough) components of the temporal mean velocities from the glider (G_{M1}) and Aviso (A_{M1}) are strongly correlated ($R = 0.92$, Table 2) with a constant of proportionality (α, Appendix A) that looks close to 1 in Fig. 11c. (The results of the correlation analysis in Table 2 suggest that $\alpha \sim 1.3$, but tests showed that the precise value of α is not critical.) On this basis it is also assumed that $\alpha = 1$ for northward currents and that the striking difference in the glider and Aviso measurements in this direction (Fig. 11b) can be attributed to errors in the MDT current field along the track (A_ε). This error was calculated from (A5) with $\overline{U} + G_\varepsilon$ set to 0 for convenience and is shown by the black lines and vectors in Fig. 11. The true background current (U) can be estimated by mentally adding the black arrows to the blue MDT field arrows along the track in Fig. 11a. The two compo-

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nents of A_ε were interpolated along the mean glider track and used to correct individual Aviso measurements (making no allowance for any variation of A_ε with latitude). This improved the correlation between the corrected northward Aviso and glider currents from 0.41 to 0.73 (Table 2 and Fig. 10b and d). The equivalent correction for the eastward currents did not improve the correlation (Fig. 10a and c), which suggests that most of the improvement in the northward component is due to the domination of the slope current error (see Fig. 11). It is evident that the MDT fails to produce the slope currents northward along the European edge and southward along the eastern flank of Rockall. Although the anomalous MDT current field to the south of the ADS appears to be robust (since the standard error in the estimates of the mean background current are small, Fig. 11) it can be explained when combined with the anomaly in the slope current. Taken together these anomalies suggest that the extensive anti-cyclonic cell northward and over the Hebrides Terrace Seamount is also an artefact of the MDT.

The mean northward transport through the Trough is between 0.6 and 3.6 Sv (Holliday et al., 2000) which, with a cross-sectional area 250 km wide and 1000 m deep, implies that $\overline{U}$ is between 0.9 and ±0.7 cm s^{-1}. A dashed line at −0.9 cm s^{-1} has been added to Fig. 11b to indicate an assumed true zero line. With this adjustment it appears that from its western edge at about 9.7° W the mean European slope current builds in strength to about 13.5 cm s^{-1} above the 500 m isobath at 9.1° W. Westward of this longitude to a meridian southward of the western edge of the ADS at 11.4° W the mean flow is S or SSW with a maximum of about 6 cm s^{-1} at 10.5° W. West again the mean current flows northward around the western side of the ADS with a mean speed of 3 to 4 cm s^{-1}. Finally at the very western end of the track, on the eastern flank of Rockall, the mean equator-ward slope current is of order 5 cm s^{-1}. The general agreement of this pattern with the schematic mean circulation pattern described in (Ellett et al., 1986) provides confidence with this analysis.

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7 Discussion

The central Rockall Trough is populated with mesoscale eddies or cells that appear trapped in the deep water where they push each other randomly around on time scales of months. During the glider mission these eddies had transient currents that, integrated over the top 1000 m of the water column, had a mean speed of about 15 cm s^{-1} (Table 1). It is clear from the glider σ_t profiles and sections (Fig. 6), and from the LADCP measurement of D340 (Fig. 4), that they extend well below 1000 m, the maximum depth range of the glider. This suggests that their origins, which must be from further south, are similar to those described by (Ullgren and White, 2010), i.e. from instabilities of the frontal regions of the North Atlantic Current and the slope current.

The amount and spatial extent of mesoscale variability in the Rockall Trough seems to have an impact on the stability of the northward propagating current slope current along the western edge of the European shelf, which has a mean speed of comparable magnitude. In some of the sections reported by (Holliday et al., 2000) slope current water appears to be spread across the Trough. The vertical profile of water west of the ADS, which at 500 m was cooler and fresher than that to the east in June 2009, had become much warmer and saltier and adopted an eastern looking profile by February 2010 (Fig. 3). During the intervening period, starting around the beginning of December and continuing through to the end of February, there was a sustained period of north-westerly geostrophic flow extending from the Hebrides Terrace Seamount at 10.5° W, 56.5° N towards the Rockall Bank (D in Fig. 9). From the ADT plots the speed of this current was typically 20 cm s^{-1} so it would take of order a week to cross the Trough. Using a width of this current from Fig. 9d of 25 km, and an assumed depth of 1000 m, gives its rate of transport as 5 Sv. A current of this magnitude, which is much larger that the ambient currents in the central Trough, sustained over a period of 3 months would certainly be big enough to explain the apparent excursion of slope current water away from the European side onto the Rockall side. This is taken as evidence that the mesoscale activity in the Trough can lead to substantial horizontal

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exchange in the upper 1000 m. Variable currents of this nature must contribute to the inter-annual variability reported for the upper 800 m observations of temperature and salinity along the Ellett line (Holliday et al., 2000; Sherwin et al., 2012).

It is noted from the Aviso observations that there was a tendency for the mesoscale structures to become stuck in the vicinity of the local seamounts and, in particular, both anticyclonic (in November) and cyclonic (in February) eddies appeared trapped on the Anton Dohrn. This is surprising given that the full vertical extent of these eddies is much deeper that the top of the seamount (500 m) which was not anticipated by (Booth, 1988) who suggested that Taylor columns form with closed streamlines over the Anton Dohrn. Whilst both senses of circulation satisfy that requirement there is no evidence that the seamount itself generated the eddies, or that cyclonic circulation is preferred over anti-cyclonic.

It remains to add some final comments about the use of glider data in this investigation. It would not have been possible to undertake such a detailed description and analysis of the mesoscale variability without the repeated measurements of the in situ conditions in the Rockall Trough by the glider. Its CT observations provided the information about the depth of the eddies, and the drift data, despite being compromised by a suspect compass, gave irrefutable evidence that the surface currents inferred from satellite altimetry should not be assumed to decrease with depth when the water column is mixed.

But this warning may only apply to currents with relatively short time scales because over longer time scales the two measurement systems seem to observe currents of similar velocities. The apparent success of combining glider and Aviso observations averaged over a 6 month period to determine the difference in the background mean currents suggest that glider observations may provide a practical methodology for improving the definition of the Geoid in other regions where the existing MDT is suspect.

The synergy derived from the combined use of glider and altimeter observations also provides valuable information about the state of a transient velocity field that can help glider pilots operating in the north Atlantic. Very often a glider will encounter an

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unexpected current, and reference to the contemporary SSA field can provide a pilot with useful information for charting a course to avoid, or make use of it.

8 Conclusions

The principal findings of this investigation are that:

1. Much of the surface and deep mesoscale current field in the Rockall Trough is driven by deep circulations that appear to be associated with eddies that originated from the North Atlantic Current.

2. Surface currents appear to be much stronger during the autumnal period of seasonal stratification than in late winter when the upper Trough is mixed to a depth of 600 m.

3. In late 2009, during a period of unusually large EKE activity, a deflection of the slope current, caused by a serendipitous arrangement of some deep mesoscale features, resulted in a large quantity of slope water being advected to, and thereby warming, the upper 500 m of the western side of the Trough.

4. The background MDT field of the Aviso CNES-CLS09 data set fails to pick up the slope currents either side of the Rockall Trough and may also introduce a fictitious anti-cyclonic circulation north of the Hebrides Terrace Seamount.

Data policy

All data used here are freely available on the web. The AVISO products can be found at www.aviso.oceanobs.com/duacs and the glider and Ellett Line data at the British Oceanographic Data Centre (www.bodc.ac.uk).

Appendix A: Deriving background mean currents along the glider track from altimeter and glider measurements

It is useful to define the true background current field across the Rockall Trough, $\overline{U}+U(x)$ defined below, and although neither the Aviso nor the glider velocity measurements can do this on their own they can be combined to provide a credible result that throws light on the accuracy of the MDT current field. In theory the Aviso current anomalies should be relative to $\overline{U}+U(x)$, but at present this is not possible because the MDT uses a poorly resolved measurement of the Geoid. This appendix demonstrates that by computing the difference between the two measurement systems, suitably averaged over the period of Mission 1, it is possible to determine the error in the velocities of the MDT along the track and hence find $U(x)$ (if not $\overline{U}$). There are a couple of practical problems that have to be recognised: (i) Aviso measures surface currents, whilst the glider measures the mean over 1000 m, and (ii) there was an unknown compass error in the glider that led to a spurious mean current. In practise it turns out that these problems are not critical.

Assume that the true current normal to the mean glider track across the Rockall Trough (x) is given by

$$\boldsymbol{U}(x,t)=\overline{U}+U(x)+u_S(x,t)+u_T(x,t) \tag{A1}$$

where $\overline{U}$ is the mean current averaged across the Trough; $U(x)$ is steady anomaly to the mean current along the track; and $u_S(x,t)$ and $u_T(x,t)$ are respectively short period and long period velocity anomalies. Assume also that over the 6 month period of Mission 1 u_S averages to zero, but that u_T integrates to a finite quantity $U_{\mathrm{M1}}(x)$, the anomalous seasonal current during Mission 1. The true mean velocity along the track for this period, $\hat{U}_{\mathrm{M1}}(x)$, is then given by

$$\hat{U}_{\mathrm{M1}}(x)=\overline{U}+U(x)+U_{\mathrm{M1}}(x) \tag{A2}$$

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The temporal averaged drift current measured by the glider is:

$$G_{\mathrm{M1}}(x) = \hat{U}_{\mathrm{M1}}(x) + G_{\epsilon} \tag{A3}$$

where G_{ϵ} is the anomalous current due to the compass error (assumed uniform across the Trough); and for clarity any other errors in the glider measurements are small and average to zero.

The equivalent surface current measured from altimetry is simply:

$$A_{\mathrm{M1}}(x) = \alpha U_{\mathrm{M1}}(x) + A(x) \tag{A4}$$

where αU_{M1} is derived from the ADT with α the ratio of Aviso surface velocities to the glider drift current; $A(x)$ is the mean current derived from the MDT; and other errors are assumed to be small and random. Note that because of the errors in the MDT, $A(x) \neq \overline{U} + U(x)$.

Assuming that $\alpha = 1$ (see main text for a justification) then the difference between the two velocity fields is found by subtracting Eq. (A4) from (A3) and using Eq. (A2):

$$G_{\mathrm{M1}}(x) - A_{\mathrm{M1}}(x) = \left[\overline{U} + G_{\epsilon}\right] + [U(x) - A(x)] \tag{A5}$$

The first term in square brackets comprises the mean current across the Rockall Trough plus the anomalous current due to the error in the glider compass. Both these currents are likely to be of similar order (a few cm s^{-1}) and cannot be separated, so it not possible to determine $\overline{U}$ directly from the present set of glider measurements. Other methods are possible (see text). The second term in square brackets is the error in the mean current along the transit of the MDT, i.e. $A_{\epsilon} = U(x) - A(x)$.

If instead of using the ADT we use the SLA (i.e. set $A(x) = 0$) then $U(x)$ can be determined simply from Eq. (A5) and $U_{\mathrm{M1}}(x)$ from Eq. (A4). The choice is arbitrary, but in the present case the ADT has been used so that the focus is on the error in the MDT currents along the track.

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Table 1. Summary of the dives used in most of the calculations and transit plots described below and (bottom row) equivalent speeds from the Ellett Line section during D340. Drift and SD speeds are the scalar mean values per transit. (W) and (E) indicate direction of travel. Notes: (i) Transit 3 – shortly after dive 370 Talisker was stopped by a strong eastward current S of the ADS and was sent south until dive 500; (ii) Transit 6 – between dives 647 and 673 a meridional transit was run through an eddy W of the ADS; (iii) mean current speed in the top 50 m (other D340 speeds are averaged over 1000 m).

Transit	Dive nos	Start	End	Glider drift speed ($cm\,s^{-1}$)	Aviso surface speed ($cm\,s^{-1}$)
1 (W)	235:304	18 Oct	31 Oct	16.3 ± 7.6	$14.8 \pm 8.$
2 (E)	304:353	31 Oct	12 Nov	15.2 ± 7.0	13.9 ± 7.8
3 (W)	[353:370 500:532][(i)]	12 Nov	29 Dec	11.3 ± 5.8	14.1 ± 3.6
4 (E)	532:592	29 Dec	13 Jan	12.7 ± 6.3	8.8 ± 4.4
5 (W)	592:636	13 Jan	25 Jan	15.5 ± 7.3	7.8 ± 4.3
6 (E)	[636:647 673:708][(ii)]	25 Jan	14 Feb	17.3 ± 6.1	6.8 ± 3.5
7 (W)	708:742	14 Feb	23 Feb	18.0 ± 8.1	9.9 ± 4.3
8 (E)	742:780	23 Feb	05 Mar	16.0 ± 7.8	8.4 ± 3.3
Average	235:780			15.3 ± 7.0	10.6 ± 4.9
D340 (LADCP)	–	Jun 2009		17.0 (20.2[(iii)])	9.1

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Table 2. Values of the constants C_v, m_v, C_u, m_u in the linear relationships between the glider drift (u_G, v_G) and Aviso surface (u_A, v_A) velocities $u_A = C_u + m_u u_G$ (eastward) and $v_A = C_v + m_v v_G$ (northward) along with the correlation coefficients, R_u and R_v, and the number of observations, n. The fit to Aviso data (standard font) and glider data (bold font) are shown. The best fit will be somewhere between the two. There is a marked improvement in the correlation of the individual northward currents once A_ϵ is applied. Observations were smoothed over about one day with a 4 point Hamming window and subsampled. The meridional averages are the red and blue curves in Fig. 11b and c.

Transits	n	Eastward C_u	Eastward m_u	Eastward R_u	Northward C_v	Northward m_v	Northward R_v
Meridional averages	23	1.9 **1.4**	1.2 **1.4**	0.92	1.4 **120**	0.11 **25**	0.07
Individual observations	128	3.9 **1.6**	0.70 **1.5**	0.69	3.7 **13**	0.36 **2.2**	0.41
With A_ϵ correction	121	3.6 **1.5**	0.65 **1.3**	0.69	2.9 **5.4**	0.50 **1.0**	0.73

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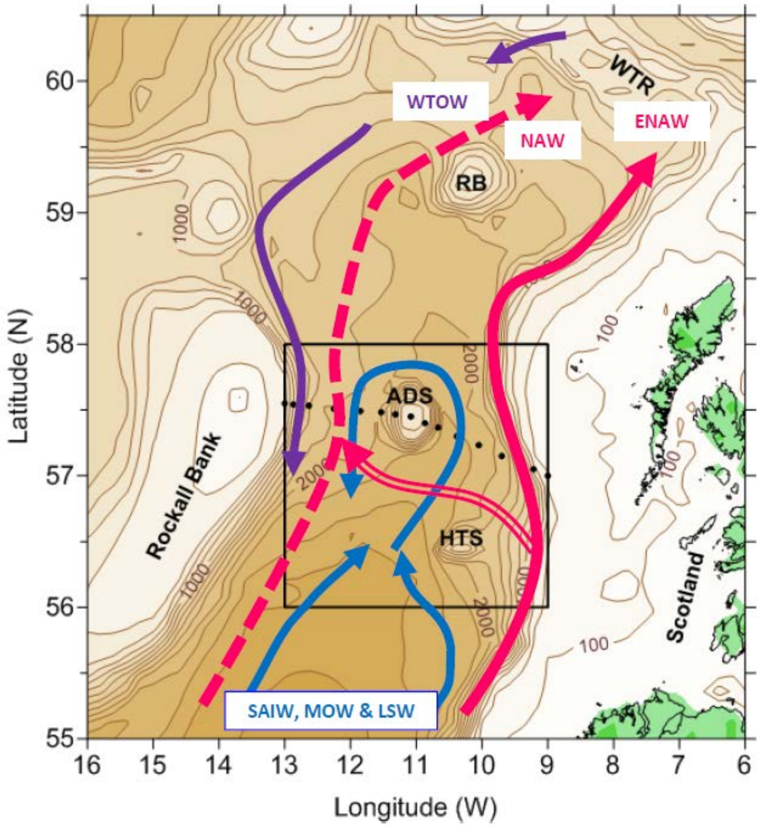

Figure 1. Map of Rockall Trough with bathymetry (m) and the major currents. Acronyms not in the text are WTR: Wyville Thomson Ridge; RB: Rosemary Bank; HTS: Hebrides Terrace Seamount. D340 stations are shown as a series of black dots. The red "tramway" is the alternative route of ENAW identified in this paper. The black box outlines the area that EKE is averaged over in Fig. 8.

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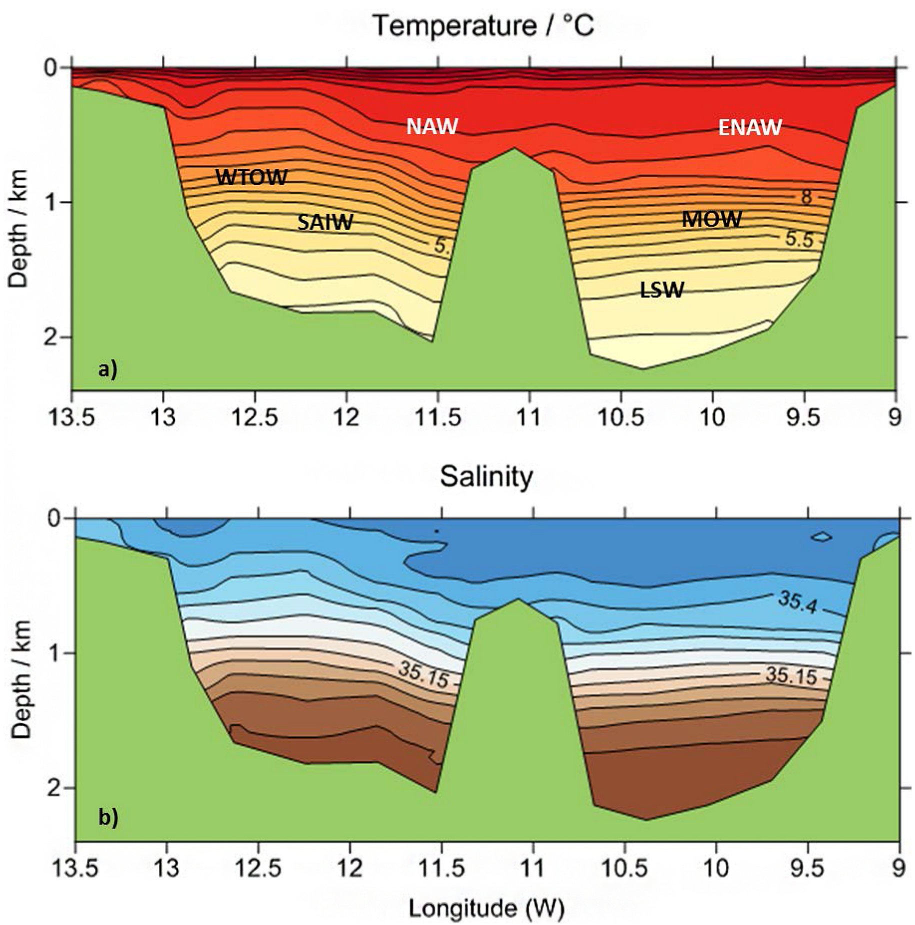

Figure 2. **(a)** Temperature and **(b)** salinity sections through the Anton Dohrn Seamount in mid-June 2009. Water masses are indicated, with those in black being much diluted at 56° N.

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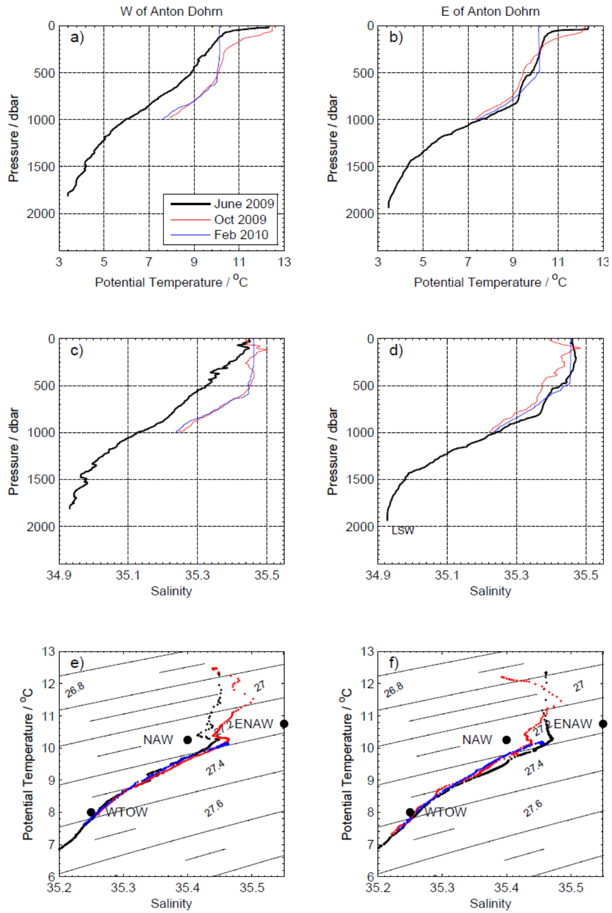

Figure 3. Temperature and salinity profiles and θS plots either side of the Anton Dohrn Seamount from cruise D340 (full depth, black) and Mission 1 (to 1000 m, red and blue). Glider data are averages of the up and down casts. For positions see Fig. 7.

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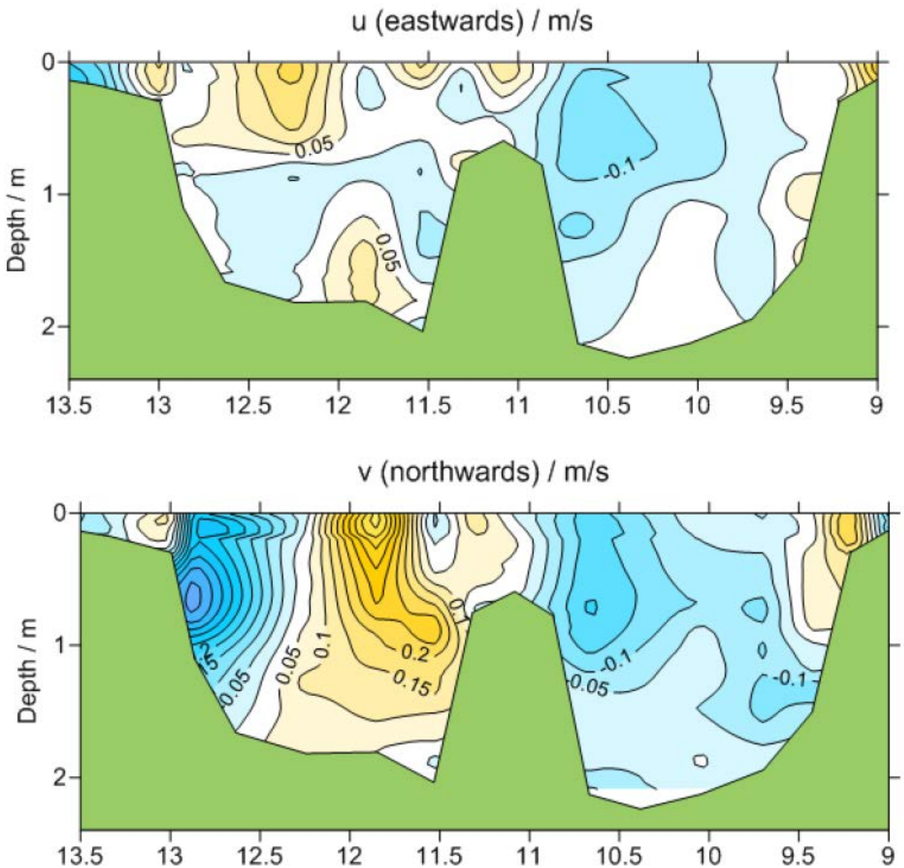

Figure 4. Full depth LADCP section in mid-June 2009.

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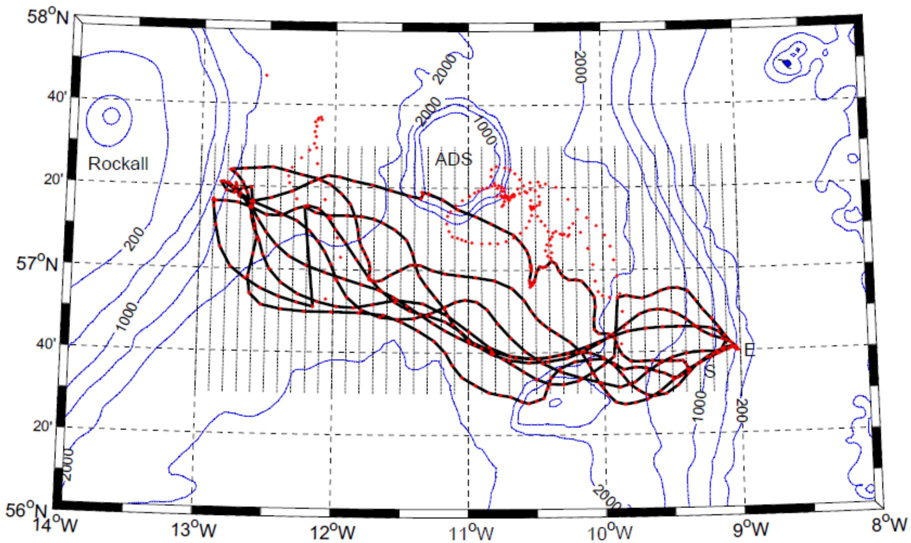

Figure 5. Glider track in the Rockall Trough from 18 October 2009 (S) to 5 March 2010 (E). Isobaths (in blue) are in m. Red dots are the dive positions. The track is not drawn between those points omitted in Table 1 and Fig. 6. Vertical dashed lines delimit the zonal averaging bins.

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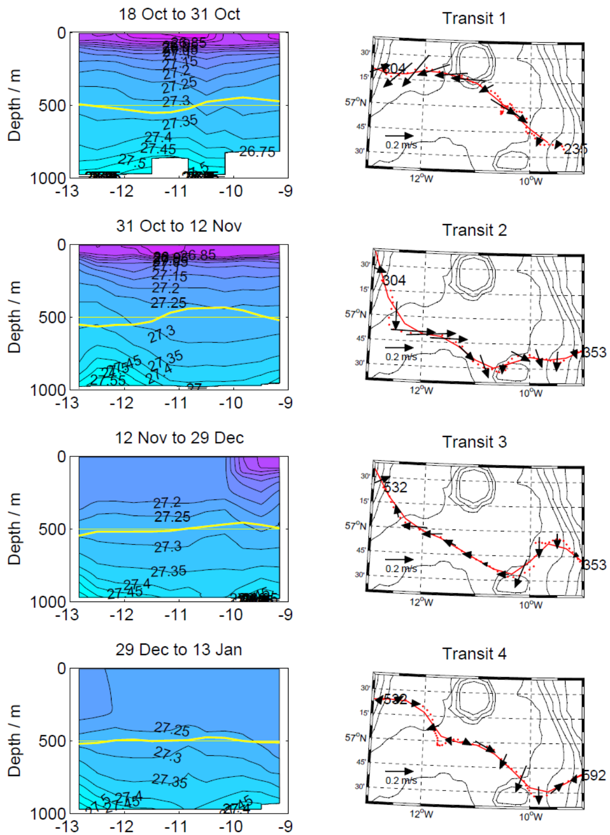

Figure 6.

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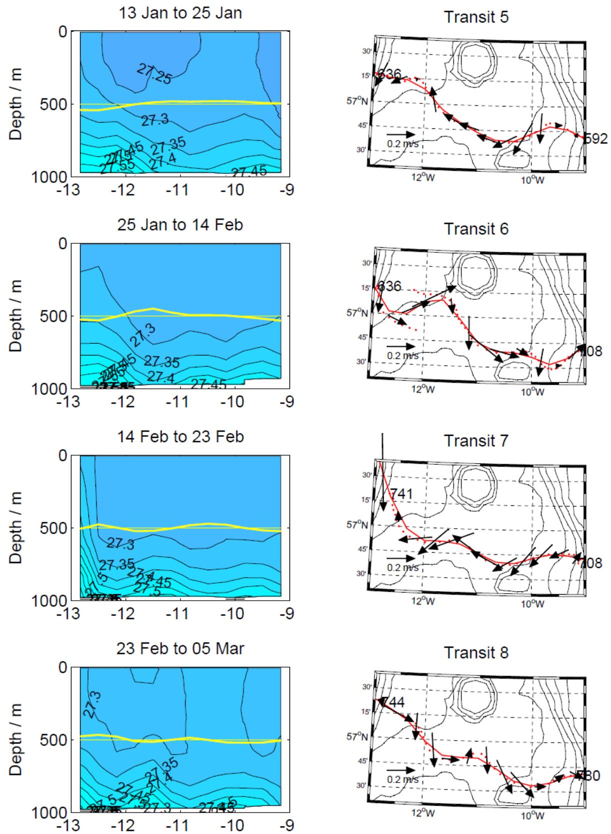

Figure 6. Summary of the observations from each of the 8 glider transits of the Rockall Trough. **(a)** Transits 1 to 4; **(b)** transits 5 to 8. LH column: density anomaly sections ($kg\,m^{-3}$) to 1000 m along the red track shown in the accompanying map. Also the ADT (plain yellow line) plotted as cm about 500 m (dashed yellow line). RH column: drift velocity vectors derived from the glider overlaid on the original dive positions (the dotted red line).

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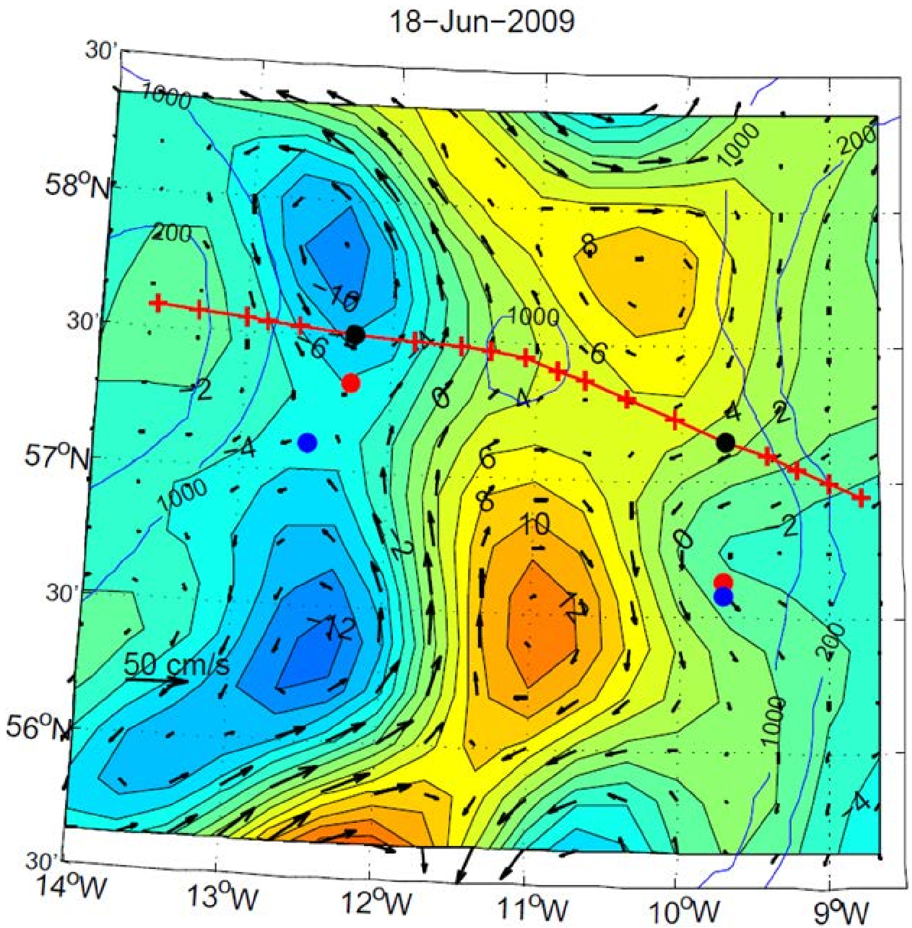

Figure 7. ADT (cm) and associated surface velocities in the central Rockall Trough on 18 June 2009 from Aviso gridded data. In red is the track of D340. The dots are the positions of the profiles shown in Fig. 3. The 200 and 1000 m isobaths are shown in blue.

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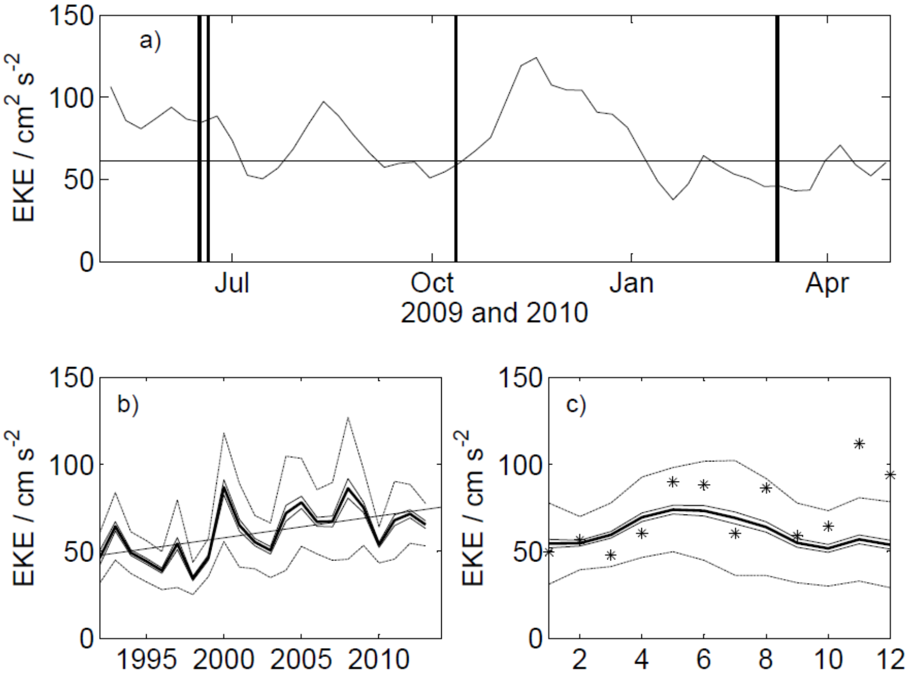

Figure 8. Mean EKE (cm^2 s^{-2}) in the area bounded by 56° N, 13° W and 58° N, 9° W (see Fig. 1) from altimetry. **(a)** Weekly EKE from 1 May 2009 to 30 April 2010. Vertical lines mark the times of the Ellett Line section (June 2009) and the start and end of glider Mission 1 (October 2009 and March 2010). **(b)** Weekly averages binned by year with the annual mean (thick line), bounded by the error in the mean (thin lines) and SD (dashed lines). Also shown is the trend EKE = 1.1(year no.) − 2100 (straight line). **(c)** As **(b)** but binned by month and with no trend line. "+" are the monthly averages between May 2009 and May 2010.

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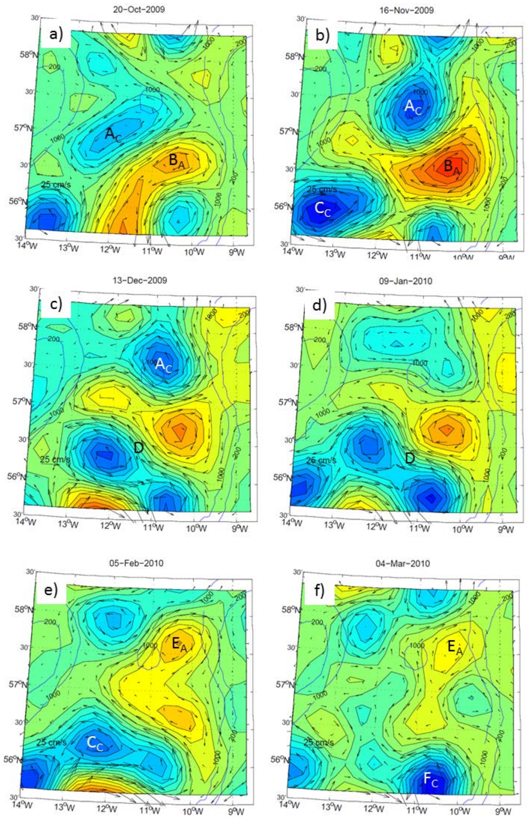

Figure 9. Snapshots of ADT (with the same colour scale as Fig. 7) and associated surface currents (scaled by the 25 cm s^{-1} arrow hear the bottom right hand corner) sampled every 27 days during Mission 1. Each panel shows the anomaly about the area monthly mean to reduce the effect on colour scaling due to the seasonal variation in steric height.

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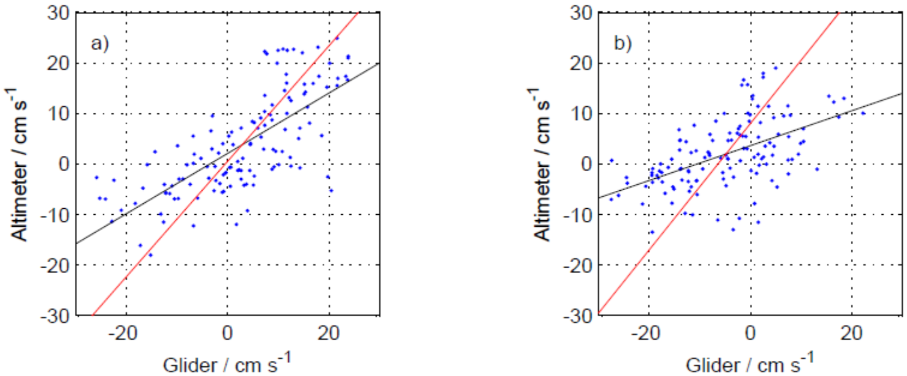

Figure 10. Scatter plot of glider vs. altimeter speeds. **(a)** east; **(b)** north. Correlation lines ($cm\,s^{-1}$) are fitted to Aviso (black) and to the glider (red), and correspond to values in Table 2. Altimeter values have been interpolated in time and space to coincide with the glider observations.

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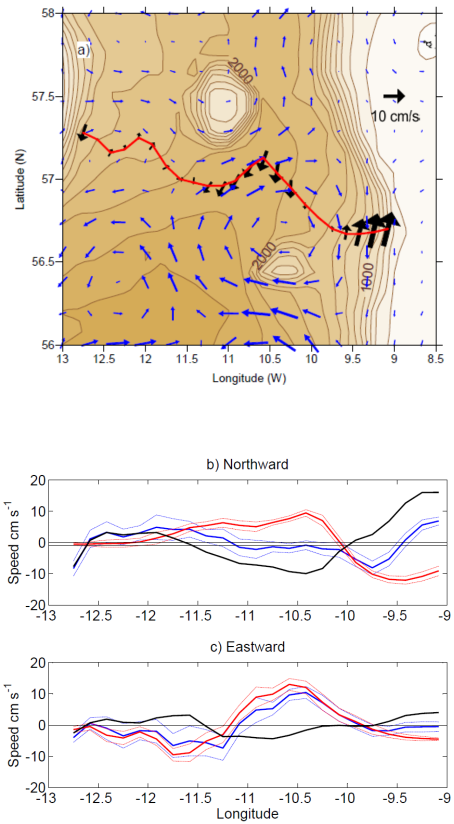

Figure 11. (a) MDT currents from Aviso (thin blue arrows) and mean absolute current along the glider track derived from Eq. (A5), thick black arrows. **(b)** Northward and **(c)** eastward currents from simultaneous Aviso (red) and glider (blue) observations averaged over the whole mission into 10′ longitude bins with the dotted lines being the standard error in the mean. The black lines are the difference between the Aviso currents that are displayed as vectors in **(a)**. The dashed line in **(b)** is an estimate of the true origin due to the mean current through the Trough.

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