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Eddy
Rockall
Instability
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Topography

Tourbillon
Rockall
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Topographie

Eddies in the Rockall Trough

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ABSTRACT

Ten drogued drifting buoys were deployed at four locations in the Rockall Trough; of these, seven were caught in eddy motions which persisted for periods of between 12 and 36 days. Two distinct forms of eddy were found, both of which are shown to occur in typical conditions, the mechanisms being topographic.

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RÉSUMÉ

Tourbillons dans le chenal Rockall (Atlantique Nord)

Dix bouées dérivantes ont été mises à l'eau en quatre endroits dans le chenal Rockall. Sept d'entre elles ont été prises dans des tourbillons pendant des durées variant de 12 à 36 jours. Deux types de tourbillons ont été observés; ils se produisent dans des conditions caractéristiques liées à la topographie.

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INTRODUCTION

Rockall Trough, bounded to the East by the continental shelf and to the West by Rockall Bank (Roberts *et al.*, 1979) is the channel by which the North Atlantic current flows into the Norwegian Sea (Ellett *et al.*, 1986). To study the near surface circulation, a series of ten drifting buoys with drogues at depths between 16 and 166 m (Fig. 1) were released by the Scottish Marine Biological Association (SMBA) in four deployments between May 1983 and January 1984 (Tab. 1). Details of the buoy and the drift tracks are given by Booth and Meldrum (1987 *a; b*). Position tracking was by Service Argos with 10-12 fixes per day. The buoy and rigging were designed to minimize surface drag by both wind and waves (Booth, 1981); the buoyant tether, included to decouple the vertical motions of the buoy and drogue, helped to reduce the drag in waves. Including a drag contribution from surface currents, the slip velocity past the drogue was estimated to be less than 1.3×10^{-3} of the surface wind velocity.

The general drift was north-eastwards (Fig. 2) with high speeds over the continental slopes. One buoy travelled westwards anticyclonically around Rockall Bank, another came southwards, and two crossed the

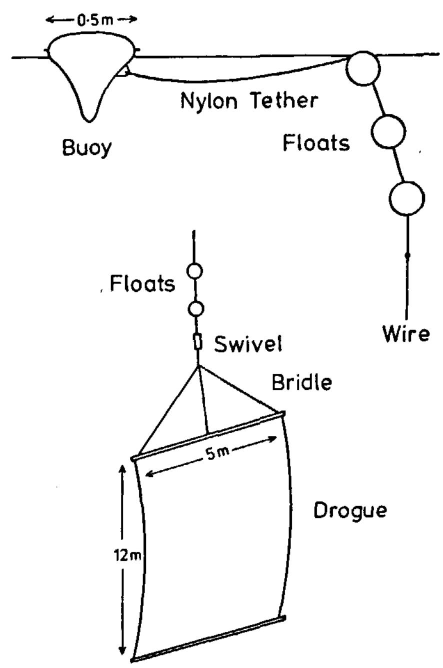

Figure 1
Schematic diagram of buoy and drogue. Note the different scales: the buoy is 0.57 m in length and 0.50 m in diameter, whereas the frontal area of the drogue is 60 m².

Table 1
Details of buoy deployments.

Deployment	Date	Position	Buoy no.	Drogue depth (m)	End of record
A	16 May 83	54°50′N 15°29′W	72	16	27 Oct 83
			75	66	21 Sep 83
			76	166	16 Dec 83
B	12 Dec 83	59°30′N 9°00′W	74	16	30 Apr 84
			73	66	3 Jun 84
			78	116	10 Mar 84
			80	166	13 Mar 84
C	25 Jan 84	57°32′N 11°42′W	82	116	21 Jul 84
			79	166	2 Jul 84
D	25 Jan 84	57°22′N 10°53′N	77	116	28 Aug 84

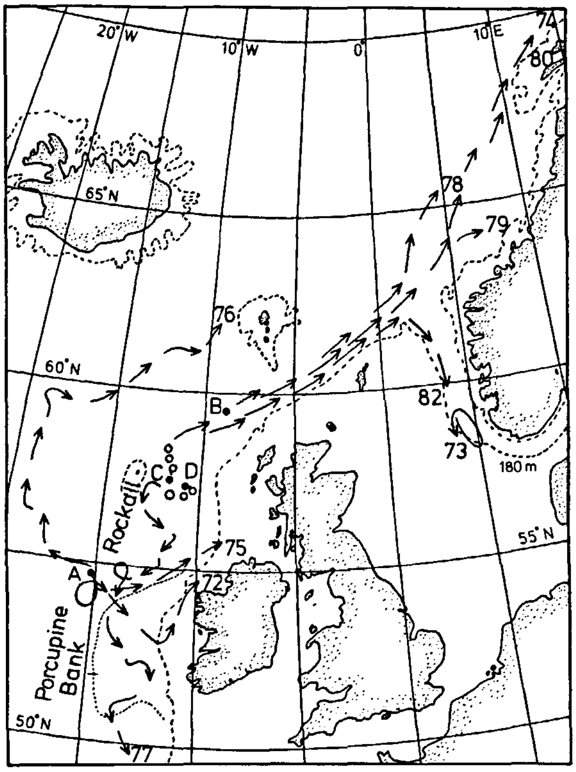

Figure 2
Summary of drift tracks for the ten buoys. Solid circles and letters indicate deployment positions; numbers correspond to buoy number and are positioned near the end of each track; open circles indicate eddies. The dashed line is the 100 fathom (180 m) contour which indicates the edge of the continental shelf and the dotted line is the outline of Porcupine Bank.

slope towards the continental shelf; the rest passed through the Faeroe-Shetland Channel and into the Norwegian Sea or the Norwegian Trench. Within the trough the tracks were irregular except for some strong eddy motions. These fall into two groups: an anticyclonic eddy to the west of Porcupine Bank, west of Ireland, and a series of small cyclonic eddies around Anton Dohrn, a seamount in the centre of Rockall Trough. Although a considerable quantity of current meter data from this region is already in archive, there is little indication of short period oscillations: isolated moorings cannot detect slow moving eddies. With just the present buoy data, therefore, plus some additional CTD data collected by SMBA, the two forms of eddy are examined to determine whether or not they are typical and thus important sources of turbulent kinetic energy.

THE PORCUPINE EDDY

Soon after deployment during May 1983, three buoys, 72 (16 m), 75 (66 m), and 76 (166 m), became trapped in a large anticyclonic eddy (Fig. 3). The radius of the largest orbit was 60 km, and the periodic times, of between 3 and 16 days, increased with radius. Peak orbital speeds were greater than 0.8 m s^{-1}, although typical speeds were half this value. Vorticity increased with decreasing radius and ranged from 1.2×10^{-5} s^{-1} for the largest orbit to 5.5×10^{-5} s^{-1} for the smallest orbit (Fig. 3). Thermistors in the buoy hulls showed that the eddy centre was cold, with a radial gradient of 10^{-2} K km^{-1}. During May 1984 and at 100 km to the North-East, buoy 77 (116 m) also orbited an anticyclonic eddy, with a periodic time of 9 days and a radius of 23 km. Further evidence of eddy activity in this region is found in IR satellite images. Although the region is rarely cloudless, a few of the available images show pairs of opposing vortices in the temperature pattern, sometimes at the end of a tail which originates near the slope. Radii of the vortices are typically 20-30 km, and two or three pairs, spread in a line parallel to the shelf edge, can occur simultaneously

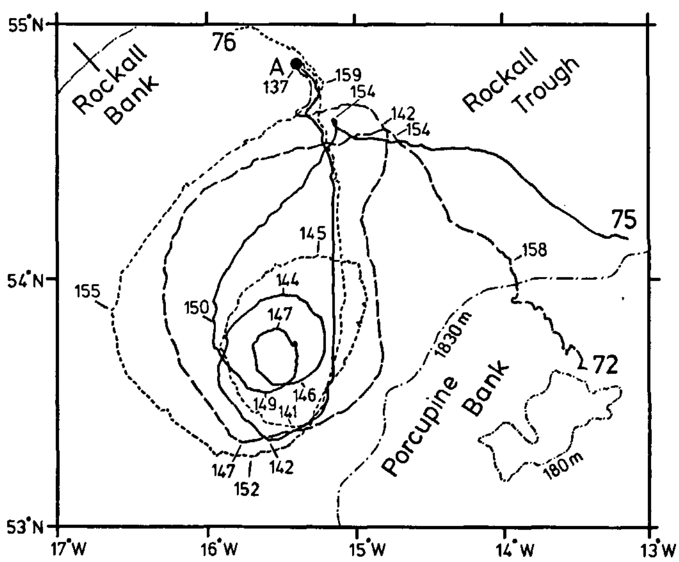

Figure 3
The Porcupine eddy. The solid circle indicates location of deployment. Large numerals give buoy number, small numerals are days of year 1983.

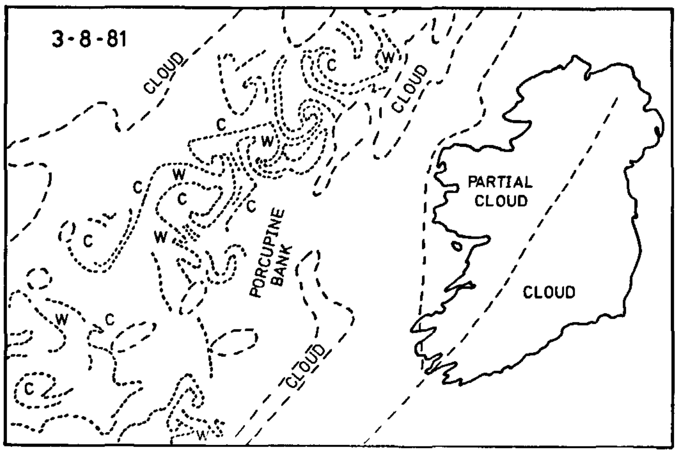

Figure 4

Line tracing of satellite infra-red image for 3 August 1981. W and C indicate the warm and cold sides of the lines (original image courtesy of the Department of Electrical Engineering and Electronics, University of Dundee.)

(Fig. 4). There is also some evidence of eddy activity in the hydrographic data of Tulloch and Tait (1959). Their interpolated gyre in the near-surface geostrophic velocities was large and elongated, but the distances between the sections which cut the shelf edge were rather larger than the radii mentioned above. Velocities normal to transects did, however, reverse within distances of 50 km.

It thus appears that this region, west and north of Porcupine Bank, is active with eddies. To confirm that it is typically so, a source of energy must be sought; instability of the nearby slope current is a possibility.

The poleward slope current is persistent, winter and summer, and has been found between Porcupine Bank and the Wyville-Thomson Ridge (Booth, Ellett, 1983; Huthnance, 1986). The total transport is over 10^6 m^3 s^{-1}, and current speeds are typically 0.1 m s^{-1}, greater over the Scottish slope but sometimes less over the Porcupine slope where the variations of the northward component can be greater than the mean (Norris, MacDougall, 1986). The driving force is a longshore surface elevation gradient (Huthnance, 1984), and the current appears in density sections as a buoyant core, inside which the current exhibits little shear down to the permanent pycnocline at a depth of near 1000 m (Booth, Ellett, 1983).

As pointed out by Huthnance (1986), barotropic instability is unlikely; the gradient in potential vorticity is dominated by a Coriolis and depth term, fh^{-2} $(\partial h/\partial x)$ (h=depth, f=Coriolis parameter, and x=cross slope distance) which does not reverse sign for the simple shaped slope, thus satisfying the condition for stability (Collings, Grimshaw, 1980). This applies even when following the slope around to the northern edge of Porcupine Bank. The dispersion relation for a triangular profiled jet over an appropiate topographic step (Niiler, Mysak, 1971) supports this result of stability (Fig. 5 *a*).

If, however, we consider the slope current as hugging the shelf edge, with the current extending to depths well below the shelf, the rotating tank results of Griffiths and Linden (1981) for instabilities of buoyant

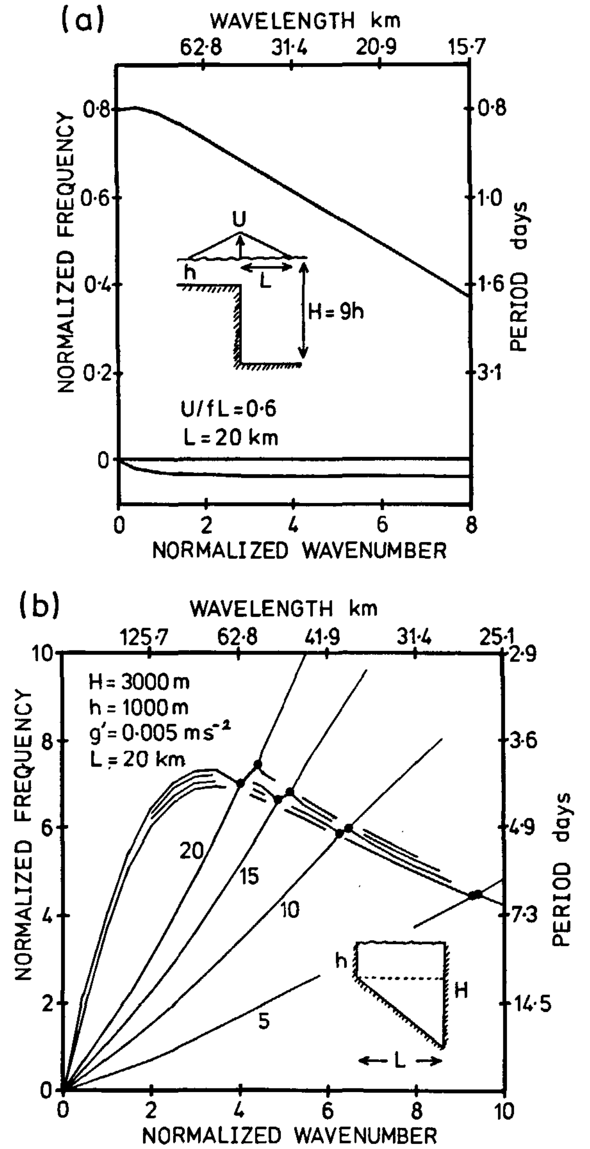

Figure 5

Dispersion curves for: a) barotropic current over a topographic step simulating the shelf edge; and b) baroclinic current in a channel with sloping bottom to simulate the continental slope, where the current in the bottom layer is zero and in the top layer as indicated alongside each curve in units of cm s^{-1}. *Regions of instability are shown by heavy lines between dark circles. For both simulations, the Coriolis parameter, f, was* 1.16×10^{-4} s^{-1}.

coastal currents are applicable. Note that the tank instabilities generated vortex pairs. Two parameters determine the possibility of instability: a Froude number, $F = f^2 L^2/g' h_1$ (where L is the current width, g' is the reduced gravity and h_1 is the thickness of the current layer), and the ratio of the layer thicknesses, γ. For the Porcupine slope, L=30 km, $g' = 5 \times 10^{-3}$ m s^{-2}, $h_1 = 1000$ m and F=2.4, which for $\gamma = 0.5$ suggests an instability with a wavelength of about 10 times the current width. Killworth (1980) has also attempted to determine the bounds of instability but with a parameter, λ, the ratio of the horizontal scale to the internal deformation radius, which in the Rockall Trough area is approximately 7 km (Emery *et al.*, 1984). For a current profile $v = \mathrm{sech}^2 x$ across the slope and with $\lambda = 4$, $\gamma = 0.5$, and $\beta = \partial f/\partial x = 0$, the West Porcupine slope is well within the baroclinically unstable region of the parameter space. Note that Griffiths and Linden (1981) also found that the coastal

Table 2
Properties of the most unstable baroclinic waves from Mysak and Schott's (1977) dispersion relation for a channel applied to the outer Porcupine slope (see *Fig.* 5 b).

Current speed cm s^{-1}	Wavelength km	Periodic time days	*e* folding time days
5	27.0	6.5	231.5
10	39.3	4.9	46.3
15	50.3	4.3	24.4
20	59.8	4.0	16.0

current became unstable only when its width was several times larger than the internal deformation radius.

Neither of these approaches includes bottom topography. In general, however, the isopycnals are not steeper than the slope, as for example in the Denmark Strait (Smith, 1976), except near the top of the slope (Dickson, McCave, 1986). To include topography, the dispersion relation from Mysak and Schott's (1977) channel model, originally applied to the Norwegian slope, was calculated for the outer slope (Fig. 5 *b*). Instabilities occur at typical upper layer velocities of between 0.05 and 0.20 m s^{-1} (Tab. 2). Estimating eddy radius as 1/4 of the wavelength, both the radii and periodic times are two or three times smaller than the observed values. Such a discrepancy is not surprising: the simplifications assumed are extreme and the observed eddies may have altered since their formation. Furthermore, the two buoys that crossed the slope, 72 and 77, both showed oscillations with short periods of only 3 days. Taken together therefore, there is sufficient evidence to suggest that baroclinic instability can occur on the west Porcupine slope and that the time and length scales are of the same order as those of the observed eddies found nearby. The reason for apparent enhanced eddy activity in this region compared to other slope regions is not at present known, but with an energy source established for typical conditions, eddies in the area must be common and thus contribute to the large scale energy transfer in the Rockall Trough.

ANTON DOHRN EDDIES

Anton Dohrn is a circular seamount in the middle of Rockall Trough. It rises steeply from a bottom plain at 2100 m, breaking through the main thermocline, to a shallowest depth of 520 m (Roberts *et al.*, 1974). Its radius is 25 km. During January 1984, three buoys were released around the edge of the seamount; two buoys, 79 (166 m) and 82 (116 m), to the West, the third, 77 (116 m), to the East. As a group they rotated anticyclonically around the seamount, buoy 77 completing a half revolution before departing [a recent current meter mooring on the south-east slope of Anton Dohrn seamount for 7 months, has also indicated an anticyclonic circulation, which was occasionally interrupted by reversals or cyclic motion (Griffiths, pers. comm.)]. Individually, each buoy orbited a series of small cyclonic eddies. Buoys 79 and 82 remained in phase for 5 cycles with orbital speeds of 0.3 m s^{-1} and a periodic time of 1.6 days (Fig. 6). The buoys drifted

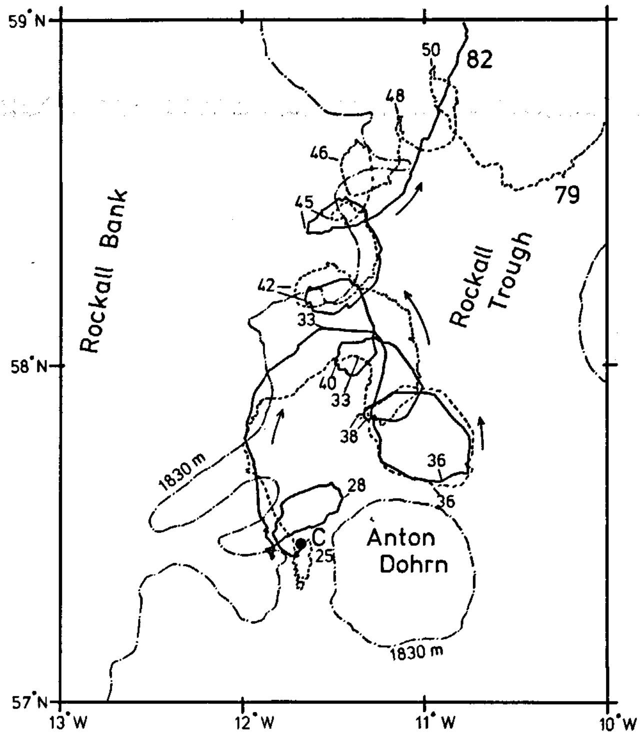

Figure 6
Cyclonic eddies in tracks of buoys 79 and 82, both deployed to the west of Anton Dohrn seamount. Small numerals indicate day of year 1984. Full line = buoy 82, dashed line = buoy 79.

northwards in open loops. Buoy 77 displayed the most persistent series, 20 cycles in all (Fig. 7 and 8). The period changed abruptly twice, from 2.4 to 1.1 days and then for the final orbit to 3 days. Orbital speeds were 0.35 m s^{-1}. Vorticity ranged between 3.8×10^{-5} s^{-1} for the last, large orbit and 7.2×10^{-5} s^{-1} for the small orbits to the south of the seamount. Two months later and 120 km further south, buoy 77 picked up another series of cyclonic eddies, although these were less intense than the initial series. Other buoys rotated around isolated cyclonic gyres over the Norwegian slope, but these were probably

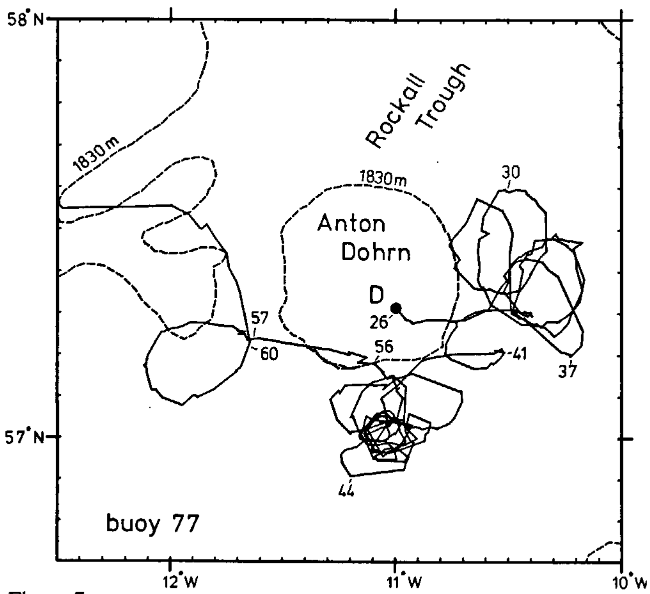

Figure 7
Cyclonic eddies in the track of buoy 77. Small numerals indicate day of year 1984.

locally generated rather than originating from the Rockall Trough. The cyclonic eddy activity around Anton Dohrn appears to be intense; again a process to supply the energy must be sought.

A general anticyclonic circulation around the seamount suggests a Taylor column. Other seamounts are sites of such columns (Meincke, 1971; Royer, 1978; Owens, Hogg, 1980; Gould *et al.*,, 1981; Genin, Boehlert, 1985). Indeed, a Taylor column interacting with bottom, southward-flowing Norwegian Sea water has already been used to explain the distribution of sediments around Anton Dohrn seamount (Roberts *et al.*, 1974). Hydrographic data provide further evidence: uplifting of isotherms over the seamount are found. The most marked case from all the SMBA surveys between 1975 and 1983 was that of October 1981 (Fig. 9 and 10) during the seasonal period of weak, low-frequency kinetic energy (Dickson *et al.*, 1986). Near-surface temperatures, however, were found to increase over the seamount during summer and autumn, when the seasonal thermocline was well established. Warm surface patches in the vicinity of Anton Dohrn can be found in IR images, although the pattern is rarely clear. The warm area appears to be associated with a rise in the seasonal thermocline.

For an obstacle with non-vertical sides, closed streamlines form only if the obstacle is taller than a critical height which depends on the stratification, the shape of the obstacle, and the Rossby number, $R = U/fL$ where U = background current and L = obstacle radius (Huppert, 1975). With a second non-dimensional number, $B = NH/fL$ (where H = ocean depth and N = Brunt-Väisälä frequency) the dependence on shape is decreased. With $N = 2 \times 10^{-3}\ s^{-1}$ (Emery *et al.*, 1984), $H = 2000$ m, $L = 25$ km, and thus $B = 1.3$, Huppert's results predict that a Taylor column will occur if the height of the seamount is greater than 1.5 RH, where the constant depends somewhat on the shape of

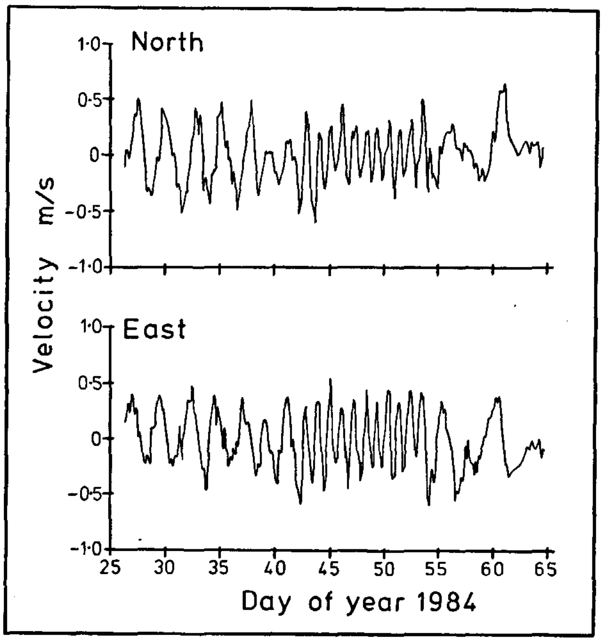

Figure 8

North and east drift velocities for buoy 77 showing regular cycles of cyclonic eddies.

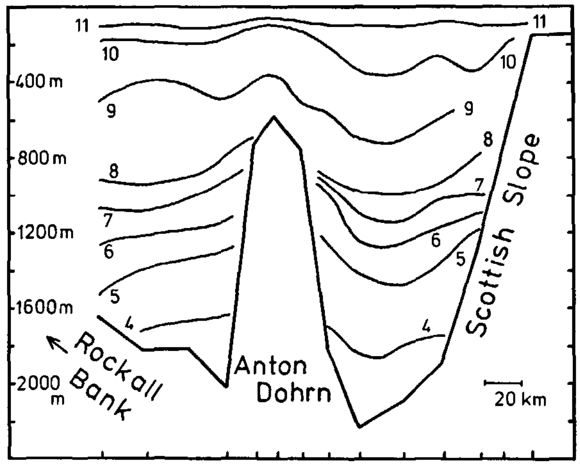

Figure 9

Isotherms on an east west section (see *Fig.* 10) *across Anton Dohrn seamount, October* 1981, *in* °C.

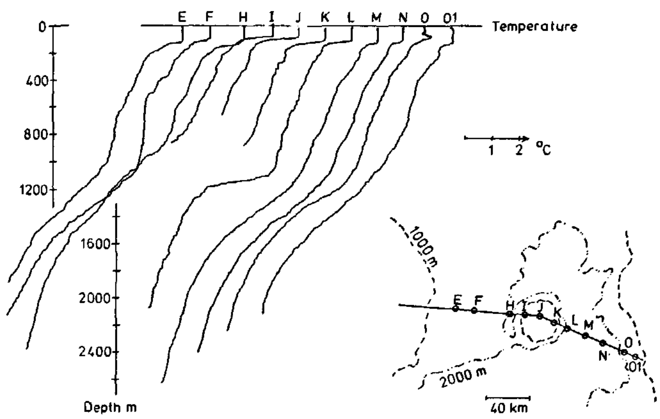

Figure 10

Temperature profiles over Anton Dohrn seamount, October 1981. *Profiles from adjacent stations are displaced by* 1 *K.*

the seamount. Using a typical low-frequency speed of $0.1\ m\ s^{-1}$ for the background current (Booth, 1983), which is rarely steady, the critical height is less than 100 m. For strong currents of $0.4\ m\ s^{-1}$, it is less than 400 m. Even if we consider that part of the seamount above the main thermocline, the condition for a Taylor column is easily satisfied.

Above the seamount, the vertical deflection of isotherms decays with height, the *e*-folding height, h_s, being Lf/N for strong stratification (Owens, Hogg, 1980). During the winter, N is small in the upper water column, and $h_s = 1500$ m, but because the mixed layer is deep (Ellett, Martin, 1973; Ellett *et al.*, 1986), no surface signature can be expected. During the summer, the near-surface value of N increases to $10^{-2}\ s^{-1}$, decreasing h_s to 300 m. The seasonal stratification is therefore sufficiently strong to dampen the isotherm doming. The seasonal thermocline is, however, lifted, thereby decreasing the mixed layer thickness and restricting the distribution of incoming heat.

When the incident flow is temporally varying, there is an interesting development in the current pattern around an obstacle with a Taylor column. As the flow increases, fluid over the obstacle is advected off, its column is stretched, and it gains cyclonic vorticity. This cyclonic eddy is then advected anticyclonically around the obstacle to the righthand side in the northern hemisphere, or if the incident flow is strong enough, away from the obstacle. The problem has been studied by Huppert and Bryan (1976). For $B = 1.3$, their results show that when the background flow, U, reaches a value of $0.9\, hf\,L/4H$, which for Anton Dohrn is $0.5\ m\ s^{-1}$, the cyclonic eddy is shed away. Therefore, except in very rare strong background flows, cyclonic eddies generated by a varying current remain near the seamount; near the surface, however, where the Taylor column is weak due to vertical decay, we might expect that a weaker background flow would be capable of advecting away and thus shearing the eddy.

In the Rockall Trough, the background flow is variable. Long-term current meter records from positions east and west of the seamount (stations M and F of Fig. 10) show that the barotropic tidal velocity is small, $0.05\ m\ s^{-1}$, and that the timescale of variations in the non-tidal current is typically 5 to 15 days (Booth, 1983). In an increasing flow, the time scale for generation of a cyclonic vortex is L/U, which is typically 1 to 3 days. The lifetime of the vortex, on the other hand, can be at least 10 days, as shown by the track of buoy 77 (Fig. 7 and 8). In an irregular background flow with variable speed, water originally over the obstacle is unlikely to return, and the cyclonic eddies are not annulled. Thus with the time scales above, more than one cyclonic eddy can exist simultaneously near the seamount, and when the Taylor column decays, these are free to be advected away.

The buoys provide the only direct evidence of these cyclonic eddies. Indirect evidence may be found in local hydrographic data, for which the temperature-salinity relationship is narrow (Ellett *et al.*, 1983). Note the very sharp thermocline at station L on the eastern slope of Anton Dohrn seamount in Fig. 10. This sharp thermocline could be the signature of an expanding near-surface water column, that is, a cyclonic eddy. If so, cyclonic eddies are common: sharp thermoclines were observed near the slopes of Anton Dohrn on several occasions (4 of the 7 sections across the seamount made between 1981 and 1983). Thus Anton Dohrn seamount and the other two similar seamounts in the Rockall Trough, Rosemary Bank and Hebrides Terrace Seamount, are sources of cyclonic eddy energy and thus contribute to the mixing in the Trough.

CONCLUDING REMARKS

Compared to the southern and northern parts, the central region of the Rockall Trough is well mixed. This is evident from temperature-salinity diagrams for the water column above 1000 m, the depth of the main thermocline, but excluding the seasonally mixed upper layer. The curves for a section across Anton Dohrn (Ellett *et al.*, 1983; 1986) and for a section between Porcupine and Rockall (Ellett, 1979) are considerably more uniform than those from the north Rockall Trough (Ellett *et al.*, 1983) or from the southern entrance (Ellett, 1979). A summary diagram has been presented by Ellett *et al.* (1986). We envisage eddies, generated by either mechanism described above, decaying and driving large scale stirring together with associated vertical motions and mixing.

Based on current meter data, the eddy kinetic energy in the central region of Rockall Trough (moorings at stations M and F of Fig. 10) is greater than in the northern or southern parts, with a possible exception of the extreme north over the slopes of the Wyville-Thomson Ridge (Dickson *et al.*, 1986). Eddies may be the source of this energy. Indeed, spreading the near-surface energy of one Porcupine eddy over the southern half of Rockall Trough would provide a large fraction of the Eulerian turbulent kinetic energy as measured for the 3-27 day band. Moreover, slow moving Anton Dohrn eddies could account for high current velocities found at stations M and F, the eddies being generated and advected away during periods of high background eddy kinetic energy, thus reinforcing the seasonal cycle observed (Dickson *et al.*, 1986). Current meter data, CTD data, IR images, and the buoy data all indicate that eddies are active in the Rockall Trough between latitudes 53.5° N and 58°N. These eddies are most probably shed from topography, which in this region is irregular and has steep slopes.

Two types of eddy have been described: 1) an anticyclonic eddy, generated by baroclinic instability in the poleward slope current above the edge of Porcupine Bank, and probably one of a vortex pair as seen in IR images; 2) a smaller cyclonic eddy generated by vortex shedding from Anton Dohrn seamount during the development of a Taylor column. Both can be generated under typical conditions and are believed to be common, thus contributing to the large scale turbulent energy and stirring in the Rockall Trough.

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