TU Delft
Bibliotheek
Prometheusplein 1
Postbus 98
2600 MG DELFT

Telefoon: 015 - 2784636
Fax: 015 - 2785673
Email: Helpdesk.doc@Library.TUDelft.NL

Datum: 18-nov-04

Bonnummer: 835182

Aan: VLAAMS INSTITUUT VOOR DE ZEE
VISMIJN
PAKHUIZEN 45-52
B-8400 OOSTENDE
BELGIE

Tav:

Aantal kopieën: 12

Uw referentie(s): 1769052 1769052

Artikelomschrijving bij aanvraagnummer: 835182

Artikel: Observations of a density-driven recirculation of the Scot
Auteur: Hill, AE; Horsburgh, KJ; Garvine, RW; Gillibrand, PA; Sles
Tijdschrift: ESTUARINE COASTAL AND SHELF SCIENCE
Jaar: 1997 **Vol.** 45 **Aflevering:** 4
Pagina(s): 473-484 **Plaatsnr.:** 0765

Estuarine, Coastal and Shelf Science (1997) 45, 473–484

Observations of a Density-driven Recirculation of the Scottish Coastal Current in the Minch

A. E. Hill[a], K. J. Horsburgh[a], R. W. Garvine[b], P. A. Gillibrand[c], G. Slesser[c], W. R. Turrell[c] and R. D. Adams[c]

[a]*School of Ocean Sciences, University of Wales, Bangor, Marine Science Laboratories, Menai Bridge, Ynys Môn LL59 5EY, U.K.*
[b]*College of Marine Studies, University of Delaware, Newark, DE 19716, U.S.A.*
[c]*Scottish Office Agriculture Environment and Fisheries Department, Marine Laboratory, PO Box 101, Victoria Road, Aberdeen AB9 8DB, U.K.*

Received 9 February 1996 and accepted in revised form 27 September 1996

In April/May 1995, five satellite-tracked drifters, drogued at 15 m depth, were deployed in the southern part of the channel (the Minches) between the mainland of Scotland and the Outer Hebridean islands. Drifter trajectories provide direct evidence for a near-surface, cyclonic flow around the South Minch consistent with a baroclinic flow of buoyant, fresh coastal water around a tongue of dense, saline Atlantic water which extends into the centre of the channel from the south. This results in the southward recirculation of part of the north-flowing Scottish coastal current which is then diverted to flow to the west of the Outer Hebridean island chain. The results point to the necessity to include baroclinicity in hydrodynamic models of the region. The circulation pattern also has implications for the dispersal of contaminants and planktonic larvae, including those of the commercially important shellfish, Norway lobster (*Nephrops norvegicus*).

Keywords: drifters; density-driven; baroclinic; recirculation; Norway lobsters; Scottish coastal current; Minch; Scotland west coast

Introduction

Drifter releases, especially if targeted upon well-defined density structures, can reveal valuable information about the dynamics of shallow coastal seas. This paper describes the results of one such Lagrangian experiment, conducted west of Scotland (Figure 1), which provides the first direct confirmation of an aspect of the circulation implied by tracer fields and initially referred to by Craig (1959). The results are of wider significance because they point to a generic form of circulation which may be found in other shelf sea areas.

The experiment was conducted in the southern part of the channel between the Scottish mainland and the Outer Hebridean island chain (Figure 1). From its narrowest part northward, the channel is usually referred to as the Minches (Little Minch and North Minch). This paper will use the name ' South Minch ' to refer to the region bounded by a line from Barra Head to Tiree in the south and extending to the Little Minch in the north (Figure 1). The same region is sometimes referred to as the northern Sea of the Hebrides (McKinley *et al.*, 1981). Bottom topography in the South Minch [Figure 2(a)] is complex, on account of a series of shallow banks on its eastern side. West of these banks, however, the water is deep (>250 m south-east of Barra) with the bottom rising very steeply towards the eastern coasts of the Outer Hebrides.

The oceanography of Scottish coastal waters has been described by Craig (1959), Ellett (1979) and Ellett and Edwards (1983). High salinity (>35·0) water of Atlantic Ocean origin is found on the deeper (>100 m) outer parts of the shelf (Figure 3). Inshore, the low-salinity (<35·0) Scottish coastal current flows northward carrying a mixture of Irish and Clyde Sea waters from the North Channel. These waters are subject to further slight dilution by inputs of fresh water from the fjordic sea-lochs along the Scottish west coast (Craig, 1959; McKay *et al.*, 1986).

The distinctive feature of the salinity field in the South Minch, and the subject of this paper, is the pronounced meander in the surface isohalines (e.g. Figure 3). This feature, remarked upon by Craig (1959), is a persistent feature from year to year (e.g. Ellett, 1979; McKinley *et al.*, 1981; Simpson & Hill, 1986). Freshwater discharge from the Outer Hebrides

0272–7714/97/040473+12 $25.00/0/ec960198

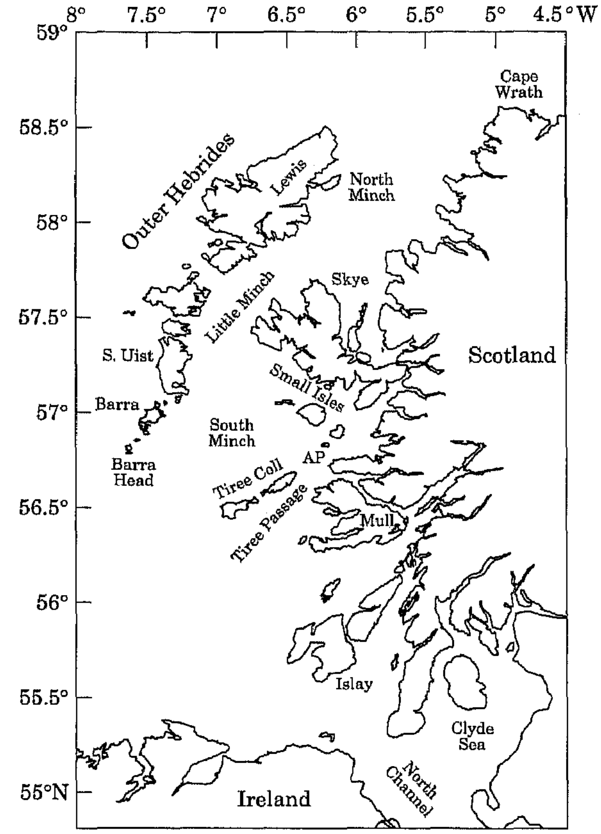

FIGURE 1. Location map. AP, (Ardnurmurchan Point).

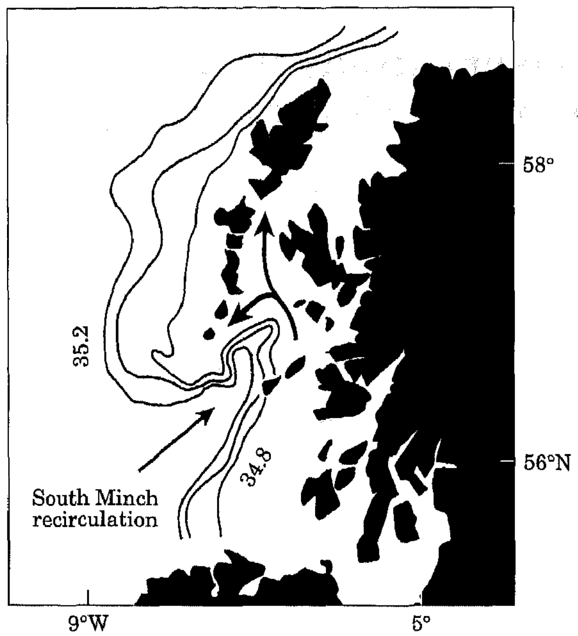

FIGURE 3. Surface (5 m) salinity distribution on the Hebridean shelf in May 1982 (adapted from Simpson & Hill, 1986).

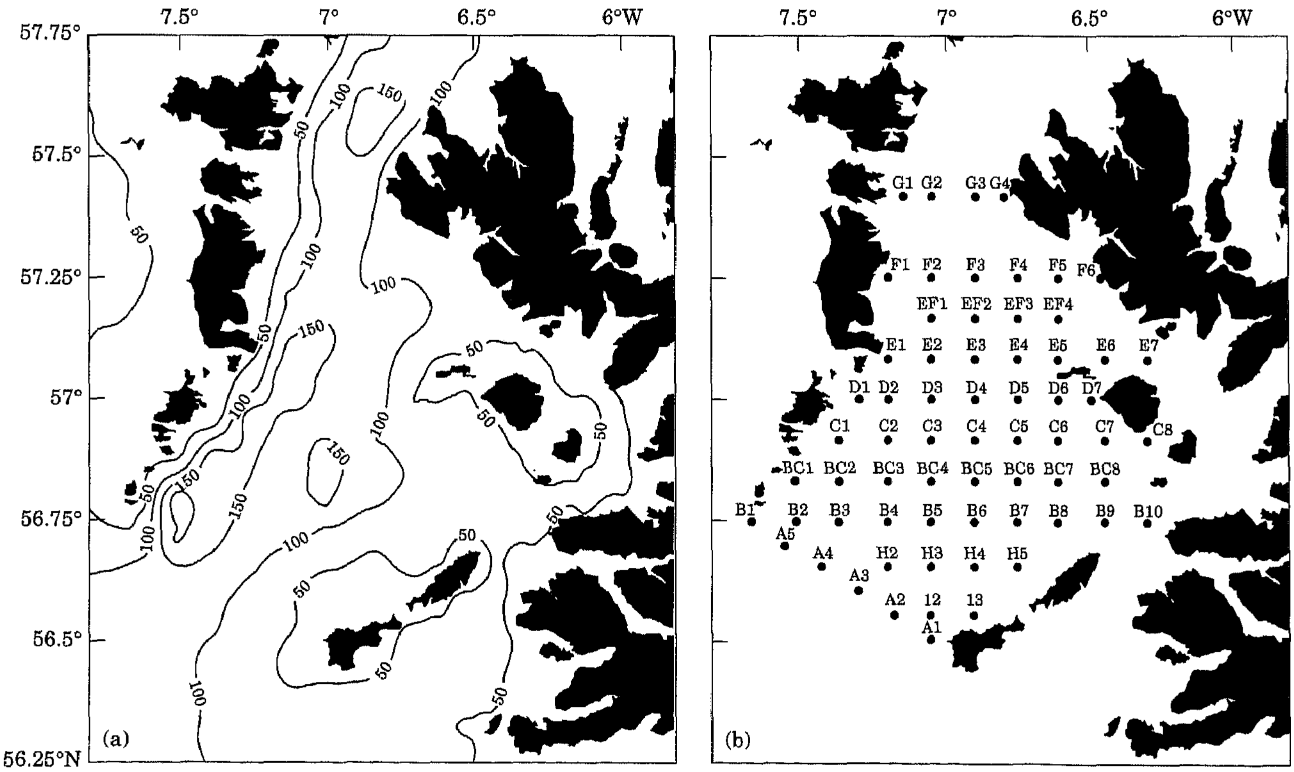

FIGURE 2. (a) Depth contours (m), and (b) CTD stations occupied in the South Minch during *Clupea* Cruises 1 and 2.

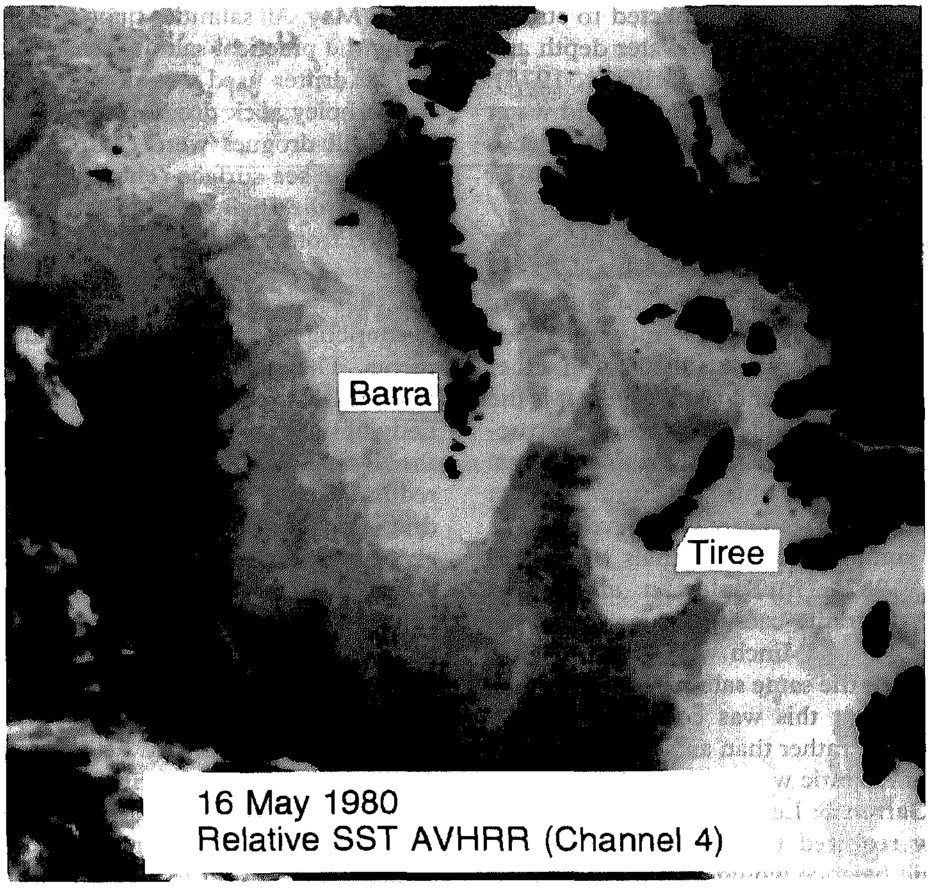

FIGURE 4. Satellite infra-red image of the Sea of the Hebrides including the South Minch, 16 May 1980.

is small, $\sim 32\,m^3\,s^{-1}$ (Craig, 1959), indicating a non-local source for the low-salinity water close to the outer islands. Crucially, the same isoline meander is visible in maps of radio-caesium (McKinley *et al.*, 1981; McKay *et al.*, 1986) which confirms that the Irish Sea (into which ^{137}Cs is discharged from the Sellafield nuclear reprocessing plant) is the origin of these waters.

The following advective interpretation can be placed upon the salinity distribution; the coastal current branches as it enters the South Minch with part of the flow continuing northward through the Little Minch and the remainder diverted to the western side of the channel, then flowing southward down the east coast of the outer islands, rounding Barra Head and resuming its northward course along the western side of the outer islands. This was the interpretation given by Craig (1959) who suggested that flow bifurcation in the South Minch resulted in a coastal water volume transport partition in the ratio 2:3 passing respectively through the Little Minch and west of the outer islands. In contrast, budget calculations by McKay *et al.* (1986), based on a comprehensive survey of the surface ^{137}Cs distribution in July 1981 and a single current meter record west of the outer islands, were used to infer that the coastal current divided into $9 \times 10^4\,m^3\,s^{-1}$ and $2 \times 10^4\,m^3\,s^{-1}$ passing through the Little Minch and west of the Outer Islands, respectively. Their overall estimate of coastal current transport, $11 \times 10^4\,m^3\,s^{-1}$, agreed with that of Craig (1959).

An alternative interpretation, consistent with the same tracer distributions, is that the fresh coastal water flows northward through the South Minch and, on approaching the narrow constriction of the Little Minch, some of the fresh coastal water diffuses down the east coasts of the Outer Hebridean islands (i.e. there may not necessarily be a southward flowing current down the eastern side of the outer islands). The meander-like structure is also visible in satellite infra-red images such as that from 16 May 1980 (Figure 4) which shows cold surface waters on both the eastern and western sides of the South Minch, with warmer water along the central axis. The cold water against the eastern coasts of the Outer Hebrides cannot be locally produced by tidal stirring because close to these coasts, the water is expected to stratify in spring–summer owing to the large water depth and weak tidal currents (e.g. Pingree & Griffiths, 1978). This reinforces the interpretation that the cold water against the east coasts of Barra and South Uist is transported there either by horizontal advection or diffusion.

Sections across the South Minch in April–May 1995 (e.g. Figures 7 and 9 later) show the isohaline meander to be the surface manifestation of a dome of saline Atlantic water which extends into the deep channel from the south and which is flanked on either side by wedges of fresher, colder coastal water. It is the temperature contrast that enables the meander structure to be seen in infra-red imagery. From historical data, it would appear that this structure is most pronounced during spring, is fairly well developed in autumn, but in summer the isopycnals are more horizontal (Hill, 1987). McKinley *et al.* (1981) pointed out that the radio-caesium content of the saline water in the South Minch was slightly higher than that of water with the same salinity further south, and they suggested that this was consistent with a fairly static saline dome rather than an active incursion into the channel of Atlantic water. If the dense dome is indeed static (Garrett & Loder, 1981; Hill, 1996), the expected flow required to maintain the density field in geostrophic balance would be cyclonic (anticlockwise) at the surface, consistent with the hypothesized circulation around the South Minch.

In spite of the indirect evidence, there are almost no direct measurements of currents in this region except for a reported southward residual flow of order 0·05 m s^{-1} against the east coast of South Uist based on a 10-day current meter record obtained in July 1983 (Simpson & Hill, 1986). To test the existence of the suggested flow pattern, satellite-tracked drifters were released into the South Minch on two occasions during the Spring 1995.

Methods

The study was conducted from the Fisheries Research Vessel *Clupea* during Cruises 6/95 (12–21 April, Julian days 102–111, 1995; hereafter termed Cruise 1) and 8/95 (1–10 May, Julian days 121–130, 1995; hereafter termed Cruise 2). On both cruises, hydrographic variables were measured on the grid of stations shown in Figure 2(b) using a Seabird Sealogger CTD calibrated with water samples and reversing thermometers. On Cruise 1, the grid, with the exception of Lines BC and EF, was sampled from 14 to 20 April, and on Cruise 2, the complete grid was occupied from 1 to 8 May. All salinities quoted have been determined using the practical salinity scale (Unesco, 1978).

The drifter used was composed of a surface buoy and a holey sock drogue, 0·7 m diameter and 2·5 m long. All drogues were centred at a depth of 15 m below the sea surface (chosen to avoid grounding on some of the shallower banks). The drogue was suspended from its own float which was in turn tethered horizontally to the surface buoy with a 2 m long line. This arrangement reduces wave rectification by decoupling the drogue from the surface buoy displacements. The surface buoy derived its buoyancy from four floats attached to spars through the cylindrical body of the buoy. This arrangement is patterned after the Davis CODE drifter and has been shown to reduce wave rectification (Davis *et al.*, 1982). The drag area ratio for the system is $R=48$ which is expected to reduce the wind slip below 0·01 m s^{-1} in a wind of 10 m s^{-1} (Niiler *et al.*, 1995). The buoy was equipped with a System Argos transmitter, a conductivity sensor and a thermistor that permitted measurement of water conductivity and temperature at 1 m depth.

The observed density field obtained on Cruise 1 was used to guide the first batch of drifter deployments on 19 April (Julian day 109) 1995. Four of these were repositioned at new locations on 2–3 May (Julian days 122–123) 1995, at the beginning of Cruise 2. All drifters, except Drifter 4, were finally recovered on 7 May (Julian day 127) 1995. The remaining drifter travelled to the north of Cape Wrath (58°52.3′N, 5°00.2′W; Figure 1) before an automatic internal switch-off mechanism was activated 65 days after deployment; the drifter was eventually recovered off the Orkney Islands.

A wind record at 12 m altitude from Tiree covering the period 10 April to 12 May 1995 was obtained from the Glasgow Weather Centre (Figure 5). Tiree is a low, relatively flat island (<75 m above the sea level) so that the wind direction is representative of that over the wider area of interest. The durations of the first and second drifter deployments, DD1 and DD2, respectively, are indicated on the figure, which presents stick vectors of 3 hourly mean winds using the oceanographic convention.

Results

Drifter deployment 1 (12–21 April 1995)

Figure 6(a) shows that the four drifters, deployed on 19 April on the eastern side of the South Minch, crossed to the western side, travelled southwards and then rounded Barra Head before moving northwards

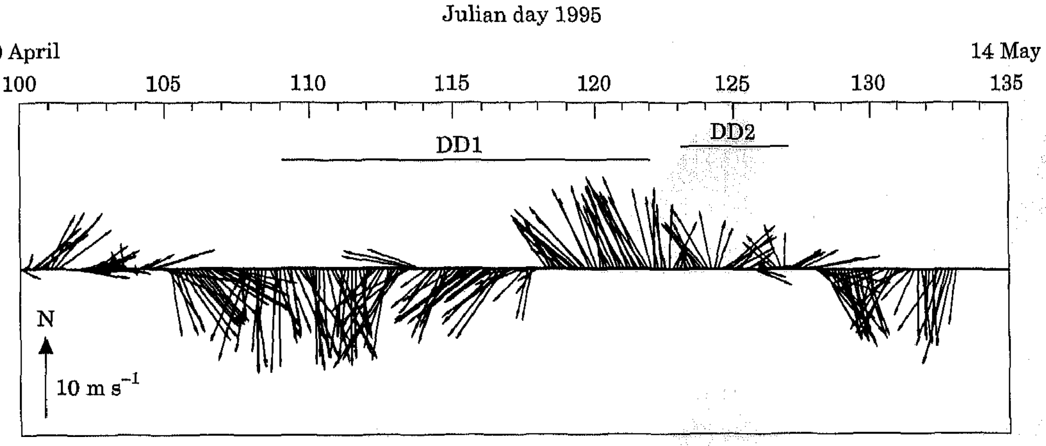

FIGURE 5. Wind vectors (3 h averages) at an altitude of 12 m at Tiree. The durations of the two sets of drifter deployments referred to in the text are denoted by DD1 and DD2.

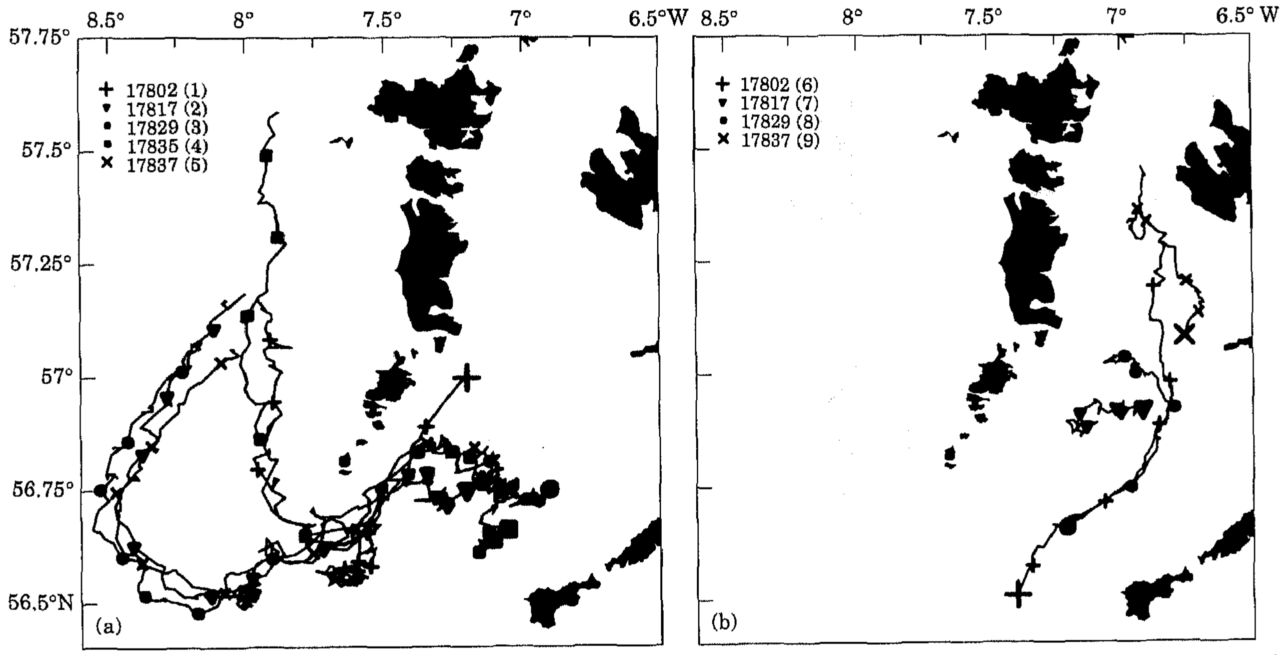

FIGURE 6. Drifter trajectories. Large symbols indicate release sites, and small symbols along each track are at daily intervals. Numbers in brackets are drifter numbers referred to in the text. All drifters were drogued at 15 m depth. (a) five drifters released on 19 April (Julian day 109), four of which were recovered on 2 May 1995. The track of Drifter 4 is shown truncated on 2 May 1995 (Day 122) but it continued to drift northwards reaching (58°52.2'N, 5°W) before automatic switch-off on Day 174, 1995. (b) Four drifters released on 2–3 May (Julian day 122–123) and recovered on 7 May (Day 127) 1995.

on the western side of the Outer Hebridean islands. The symbols along each track are at daily intervals and so give an indication of drifter speed. The congruence of near-neighbour tracks (e.g. Drifters 2, 3 and 5) is remarkable and shows little evidence of diffusion. Drifter 1, deployed east of Barra, moved quickly southwards with a mean speed of $\sim 0{\cdot}4\ \mathrm{m\ s^{-1}}$ between Julian days 109 and 111. The drifter was arrested between Julian days 111 and 116 south of Barra Head, apparently caught in an eddy. The drifter travelled northwards away from the eddy between Julian Days 116 and 117, thus its ejection from the eddy preceded the shift in wind direction which occurred on Julian day 118 (Figure 5). After its ejection, this drifter, along with Drifter 4, appeared to take a more inshore route northwards on the western side of the islands, where as Drifters 2, 3 and 5 travelled to about 8°30'W, then turned north-eastwards, before they finally converged on the tracks of the others.

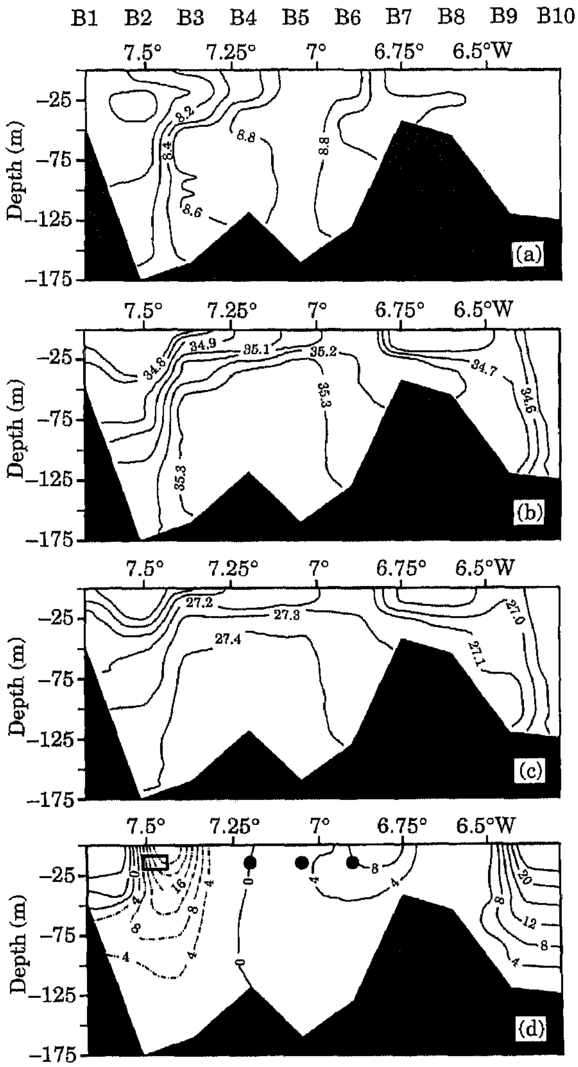

FIGURE 7. Section B at 56°45′N [Figure 2(b)] occupied from 14 to 15 April 1995 during Cruise 1 (a) temperature (°C), (b) salinity, (c) density (σ_t) and (d) geostrophic velocity (cm s^{-1}) relative to an assumed level of no motion at the sea-bed. In (d), solid and dashed contours represent northward (into page) and southward (out of page) flows, respectively. The centres of drogues released close to this section on 19 April 1995 are shown as solid circles projected onto the section. The rectangular box shows where all five drifters crossed B-section moving southwards.

Figure 7 shows the B-section [Barra Head to Ardnurmurchan Point; for location see Figures 1 and 2(b)] at latitude 56°45′N, sampled on 14–15 April 1995. This section was chosen for presentation because of the number of drifter trajectories that passed across it. Temperature variation across the section [Figure 7(a)] was fairly small (<1 °C) and the most pronounced feature was the dome of saline (>35·0) water centred on Station B4 which was flanked by wedges of fresher water on either side [Figure 7(b)]. The density field was controlled by salinity and consequently also had a dome structure [Figure 7(c)].

Geostrophic velocities normal to the section were calculated relative to an assumed level of no motion at the sea-bed and are shown in Figure 7(d). Solid and dashed contours indicate flow into the page (northward) and out of the page (southward), respectively. The chosen reference level is consistent with the notion, referred to previously, that the dense, saline dome is static. Consequently, the geostrophic calculations might be expected to characterize the flow best above the dome (between Stations B2 and B6, say). Four of the 19 April drifter releases (Drifters 2–5) were clustered close to B-section and the solid circles in Figure 7(d) represent meridional projections of the drogue centres onto the section (only three circles appear on the diagram because Drifter 5 was released due north of Drifter 4, hence both of these release sites project onto the middle circle near 7°W). Three of the drifters were located in the region of weak northward geostrophic flow and did indeed move initially northward [Figure 6(a)], although it must be remembered that the CTD section was not contemporaneous with the drifters crossing the section. Drifter 2 was located above the stagnation zone and initially moved very slowly before moving westwards. The rectangular box on Figure 7(d) shows where all five drifter tracks crossed B-section moving southwards and corresponded well to the location of the predicted (0·2 m s^{-1}) southward geostrophic flow down the western side of the channel. The ensemble mean Lagrangian southward velocity component of all five drifters (averaged over 24 h) as they crossed the B-section in April 1995 [Figure 6(a)] was 0·2 m s^{-1} which is comparable with the computed geostrophic current.

The drifter trajectories have been superimposed upon a map showing the height above 175 m depth of the density (σ_t)=27·3 isopycnal which can be used to provide a picture of the spatial extent of the dome for both survey periods (Figure 8). The drifter tracks corresponded reasonably well to contours of this parameter, and the southward flow in April down the east coasts of the outer islands matched particularly well with the steeply sloping western flank of the dome [Figure 8(a)].

Drifter deployment 2 (1–10 May 1995)

Figure 6(b) shows trajectories from the second, shorter, drifter deployment which began on 2–3 May 1995. Guided by the first set of results, the second batch of drifters was released over a wider extent of the eastern margin of the saline dome in order to

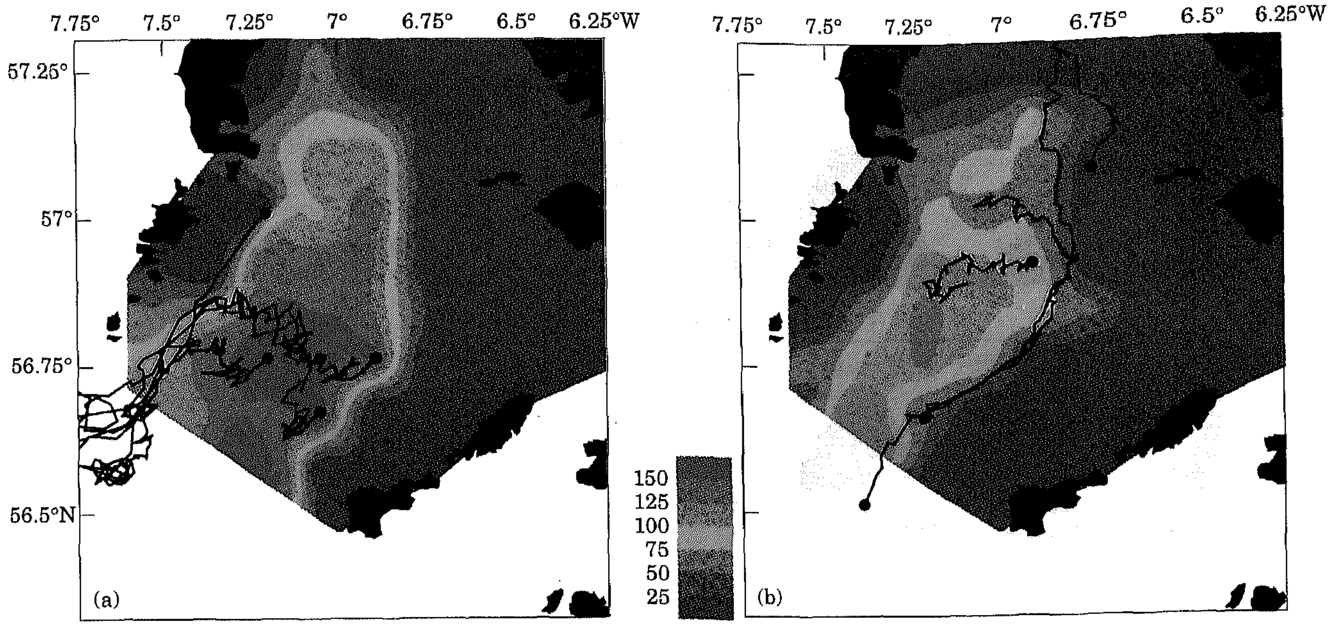

FIGURE 8. (a) height above 175 m depth of the density (σ_t)=27·3 isopycnal. (a) between 12 and 21 April 1995 with the batch 1 drifters superimposed, (b) between 1 and 10 May 1995 with the batch 2 drifters superimposed. Regions where the σ_t=27·3 isopycnal is absent or deeper than 175 m are indicated by zero (blue shading).

examine: (1) whether drifters released further north would also recirculate southwards; and (2) whether drifters released further to the south would enter the region. During this deployment, the B-section was sampled for the second time on 5–7 May 1995 (Figure 9) and showed a broadly similar saline dome structure, although with gentler isopycnal slope on the western side of the channel [Figure 9(c)] and correspondingly weaker geostrophic flow [Figure 9(d)]. In May, two drifters (7 and 8) showed a tendency to turn westwards. The remaining two drifters travelled northwards, towards the Little Minch, confirming the branching of the coastal current. The northward movement of Drifter 6 into the region from an initial position west of Tiree [Figure 6(b) and 8(b)] is also consistent with the view of Ellett (1979) and McKay *et al.* (1986) that the coastal current enters the Minch both through the Tiree Passage and by a route west of the islands of Tiree and Coll. The location where Drifters 6 and 8 crossed the B-section moving northwards is indicated by the square in Figure 9(d) and corresponded with the region of maximum predicted northward geostrophic flow. The drifter tracks corresponded well with the topography of the σ_t=27·3 isopycnal, particularly in showing the location of the branching region [Figure 8(b)].

Analysis of drifter response to winds

To assess the influence of the local wind drift upon the motion of the drifters, the authors examined to what extent the observed trajectories resemble those expected if the drifters behaved merely as wind-driven objects. In a region such as the Minch, the wind-driven flow will exhibit a complex dependency on topography, bathymetry and flow direction. Consequently, a relatively simple approach was adopted which can be justified *a posteriori* by the poor agreement between actual tracks and the predicted wind-driven trajectory. It is assumed that the drifters are subject to a drift law of the form, $u(t+\delta t)=fW(t)\cos a$, where u and W are drifter and local wind speeds, respectively. Here, t is time, δt is the lag in current with respect to the wind, f is the wind to water transfer coefficient, and a is the angular deflection of the drift velocity with respect to the wind. For the first deployment, DD1, the authors have taken $a=0$ (as in Brown, 1991), varied f between 0·01 and 0·04, and plotted the predicted trajectories in Figure 10. Lag times, δt, between 0 and 48 h were applied and the optimal track (which most closely resembled the actual track) shown in Figure 10 was obtained with δt=0 h and $f\sim$0·01. The authors chose to present drifter 1 from Figure 6(a) since it is the only drifter which resembles the virtual trajectory predicted by the above law, and thus shows the clearest indication of a possible wind-driven contribution. In contrast, the other four drifter trajectories for the same period bear no resemblance at all to the virtual track in Figure 10. Moreover, if the observed drifter trajectories were merely due to local wind drift, all drifter trajectories would have the same shape. The difference in shape between

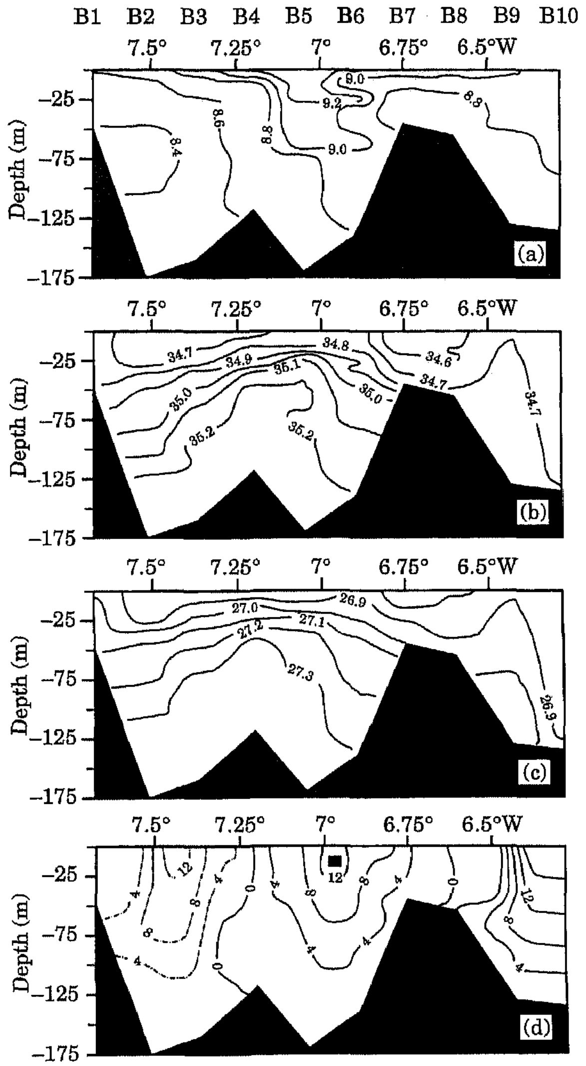

FIGURE 9. Section B occupied on 5–7 May 1995 during Cruise 2. The square shows where Drifters 6 and 7 both crossed the section travelling northwards. (a) Temperature (°C), (b) salinity, (c) density and (d) geostrophic velocity (cm s^{-1}).

individual trajectories thus provides the most compelling argument that the drifters do not simply respond to the local wind, but are subject to an underlying spatially varying flow pattern.

In May, the surface wind drift response produced a generally northward movement but did not account for the westward-turning tendency of Drifters 7 and 8 [Figure 6(b)]. In order for the virtual track to account for the motion of Drifter 6 in May, a value $f > 0{\cdot}04$ would be required. The difference in the best-fit values of f between deployments provides further evidence that processes other than the local winds affected drifter motion. Table 1 shows the results of a correlation between fluctuations in wind speed and fluctuations in drifter speed, $\langle u-\bar{u}, W-\overline{W}\rangle$, where overbars indicate means, calculated over the entire duration that drifters remained within the South Minch (i.e. Julian days 109–114 for Cruise 1 and 122–127 for Cruise 2). Drifter velocity components, u, were calculated between successive Argos fixes, and W is the mean wind calculated over the same temporal interval (for zero lag). The poor correlations further demonstrate that local wind drift has only a small influence.

Discussion

There are two competing hypotheses for how low-salinity Scottish coastal water might be transported to the western side of the Outer Hebridean islands. The tracer plume might simply broaden (by diffusion) as it spreads northward along the Scottish coast until it is sufficiently wide for tracer to reach west of the Outer Hebridean island chain. This tracer behaviour was demonstrated in a numerical simulation of ^{137}Cs dispersal (Prandle, 1984). However, the 30 km resolution of that model, which covered the entire northwest European shelf, only just resolved the Minch. The high resolution (1/12° × 1/12°) model of Davies and Xing (1996) shows that it is possible for tracer to be carried directly outside the island chain without entering the Minch. On the other hand, detailed observations of caesium and salinity tracer fields (McKinley *et al.* 1981) suggest that, during spring at least, there is a recirculation of the coastal current within the South Minch. Tracer fields alone do not distinguish between advective and diffusive processes. These observations now provide unequivocal support for the view that meandering of isohalines in the South Minch is due to a genuine recirculation (advection). The significance of a transport path west of the islands is that water of inshore origin (labelled with anthropogenic contaminants) is brought into close proximity with the continental shelf edge, thereby increasing the potential for exchange with the open ocean. Prandle (1984) suggested that up to one-third of radiocaesium discharged into the Irish Sea could be lost from the shelf seas to the deep ocean north west of Scotland.

The candidate mechanisms for driving the cyclonic recirculation in the South Minch include two barotropic processes, tidal rectification and topographic steering of larger scale (e.g. wind-driven) flows. A third driving mechanisms is the baroclinic pressure gradient associated with the observed dome of dense, saline Atlantic water. Davies and Xing (1996) have used a three-dimensional model to investigate the response of the Malin-Hebrides shelf to forcing

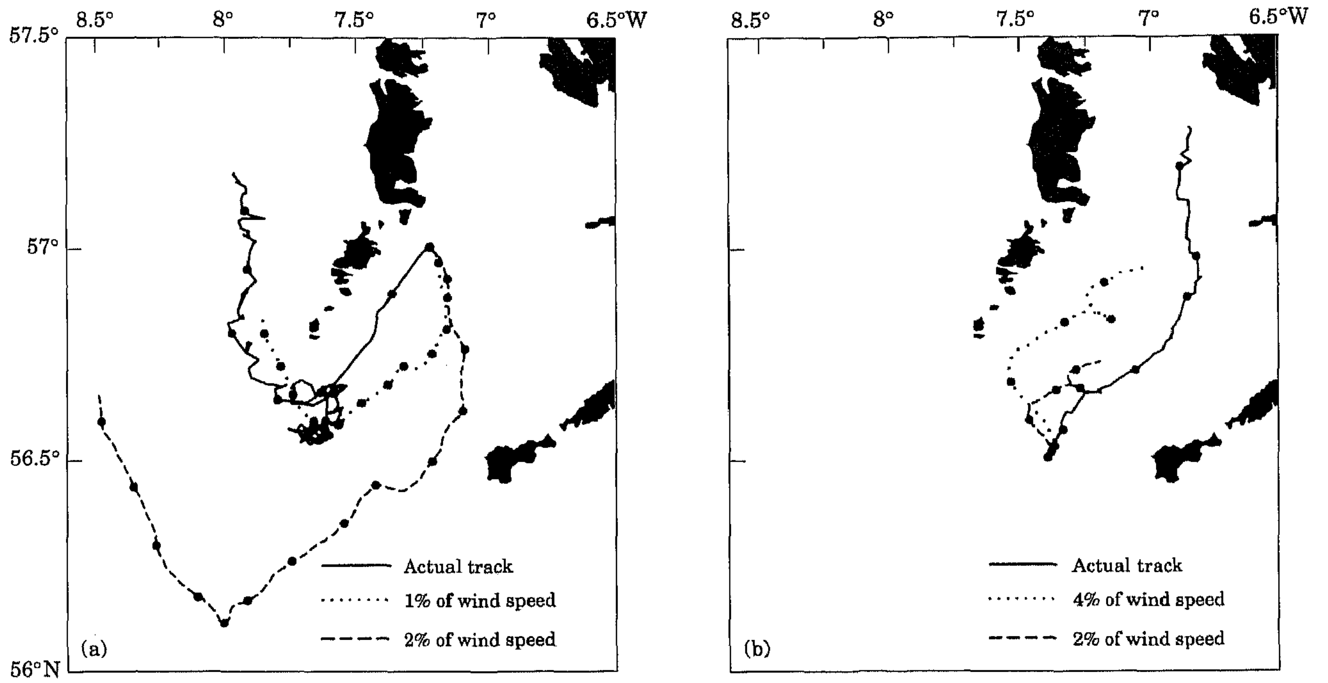

FIGURE 10. Virtual drifter trajectories determined from an assumed surface drift velocity in the direction of the wind with magnitude given by a fixed percentage of the wind speed. Winds at Tiree have been used. Solid circles indicate daily intervals. In (a), the solid line shows the actual trajectory of Drifter 1 during the first deployment [Figure 6(a)]; in (b), the solid curve shows the track of Drifter 6 during the second deployment [Figure 6(b)].

by tides, local winds and upstream inflows. The barotropic model (i.e. no horizontal density gradients included) shows negligible Eulerian tidal residuals in the deep waters of the South Minch. The model shows the wind-driven, near-bottom circulation to exhibit a southward recirculation in the South Minch for winds blowing from the west or south; a wind stress of 0·1 N m^{-2} (equivalent to a characteristic wind speed of $\sim$10 m s^{-1}) produces currents with speeds of order 0·02 m s^{-1}. A uniform inflow of 0·01–0·1 m s^{-1} through the North Channel (representing the effect of non-local, upstream forcing) generates a similar recirculation with flow speeds also of order 0·01–0·1 m s^{-1}. Although the spatial pattern of flow in the South Minch can be partly accounted for by barotropic-forcing mechanisms, the observed (Lagrangian) drifter velocities are much larger ($\sim$0·2 m s^{-1}) than the characteristic (Eulerian) velocities predicted by the model. Given the small tidal current amplitudes in the deep South Minch, the tidal Stokes drift is unlikely to account for the difference. The discrepancy in flow magnitude is almost certainly accounted for by baroclinicity as indicated by the geostrophic estimates [Figure 7(d) and 9(d)].

The following hypothesis is proposed for the establishment of the South Minch circulation regime. Weak barotropic circulation in the South Minch encourages the initial cyclonic transport of fresh coastal water around the dense, saline Atlantic water which occupies the deep entrance to the Minch. In so doing, the barotropic circulation establishes the baroclinic density field. Geostrophic adjustment between the fresh coastal water and the saline Atlantic water leads to a dome-like density structure flanked by wedges of fresh water. Once this structure is formed, the resulting, stronger baroclinic circulation reinforces the original barotropic motion and is able to co-exist with it, maintaining the dome in thermal wind balance. The process described above may be relevant in other shelf seas, for example, the northern North Sea where the Dooley current (which has an important baroclinic component) may be maintained by large-scale topographically steered flow along the 100 m isobath south of the Fladen Ground (Figure 11; e.g. Turrell *et al.*, 1990, 1992; Hill, 1993). A more detailed examination of this hypothesis and the density-driven dynamics of the South Minch will require the application of a fully three-dimensional baroclinic coastal ocean model (e.g. Backhaus, 1985; Blumberg & Mellor, 1987).

There are other shallow sea locations where dome-like density structures drive intense cyclonic surface circulations. Hill (1993) and Hill *et al.* (1994), for example, have described a closed cyclonic gyre in the

TABLE 1. Correlation coefficients, ρ, between fluctuating parts of wind and drifter velocities (u and v denote eastward and northward components of velocity, respectively)

Lag (h)	Drifter	1	2	3	4	5
Cruise 1						
0	ρ_u	−0·06	0·06	0·01	−0·14	−0·24
	ρ_v	0·30	0·06	0·19	0·04	−0·02
12	ρ_u	−0·16	0·15	0·07	−0·07	0·31
	ρ_v	0·12	−0·06	0·03	0·01	−0·35
24	ρ_u	−0·14	0·19	0·14	0·10	0·35
	ρ_v	−0·15	−0·19	−0·19	−0·09	−0·21
n-2		72	61	72	62	55
5%		0·23	0·25	0·23	0·25	0·26
1%		0·30	0·32	0·30	0·32	0·34
Cruise 2						
0	ρ_u	0·00	−0·04	−0·29	−0·02	
	ρ_v	0·16	−0·04	0·11	−0·22	
12	ρ_u	−0·19	−0·12	−0·18	−0·19	
	ρ_v	0·05	0·00	0·16	0·11	
24	ρ_u	−0·09	−0·17	0·03	−0·19	
	ρ_v	−0·14	0·01	0·18	0·24	
n-2		74	54	67	54	
5%		0·22	0·26	0·24	0·26	
1%		0·29	0·34	0·31	0·34	

Correlations were determined between Julian days 109 and 114 for Cruise 1 and Julian days 122–127 for Cruise 2. Values presented are for drifter velocity fluctuations lagging the wind by 0, 12 and 24 h. n-2 is the degrees of freedom, and 5% and 1% significance points are shown.

Irish Sea where an isolated, static dome of cold, dense bottom water forms each summer as winter water is trapped beneath the thermocline after the onset of thermal stratification. Unlike the Irish Sea system, the South Minch circulation is not a closed circulation because the saline water mass that controls it has the form of an elongated tongue rather than an isolated lens. The density structure at the shallow head of the Gulf of California (Mexico) also has a dome-like form (Bray, 1988) and probably drives a similar cyclonic surface circulation.

This study has implications for the environmental management of the Minch. The shoreline of the Minch contains wilderness areas of outstanding natural beauty; there are over 60 designated sites of special scientific interest and numerous areas important to cetaceans, seals and seabirds including three areas designated as of international importance to birds. These results highlight that inclusion of the baroclinic circulation will be essential in order to obtain satisfactory predictions from oil and chemical spill models in the South Minch.

There are important fisheries in the Minch, particularly for the benthic decapod, Norway lobster (*Nephrops norvegicus*), which inhabits the extensive mud substrates of the region (Figure 11). Adult females release planktonic larvae into the water column each year from March to July. Settlement onto mud of juvenile *Nephrops* is thought to be essential for survival (Bailey *et al.*, 1995). The circulation regime can thus be expected to play an important role in controlling the numbers of larvae present over particular *Nephrops* grounds at settlement time.

In the South Minch, *Nephrops* larvae released into the flow stagnation zone above the saline dome [see Figures 7(c) and 9(c), for example] could be retained above the mud substrate from which they were hatched, and eddies, such as the one that trapped Drifter 1, might also assist the retention of some larvae close to their hatching sites. However, many larvae entrained into the recirculating branch of the coastal current are likely to be lost to the South Minch population. The drifter tracks suggest that the small *Nephrops* ground south-west of Barra (Figure 11) could be seeded by larvae originating in the South Minch. Moreover, on the basis of the track of Drifter 4 (and its last recorded position off Cape Wrath), it also appears that it would be possible (within the known larval duration) for some of the larvae that are carried west of the islands to ultimately enter the North Minch ground, or even the Noup ground (Figure 11).

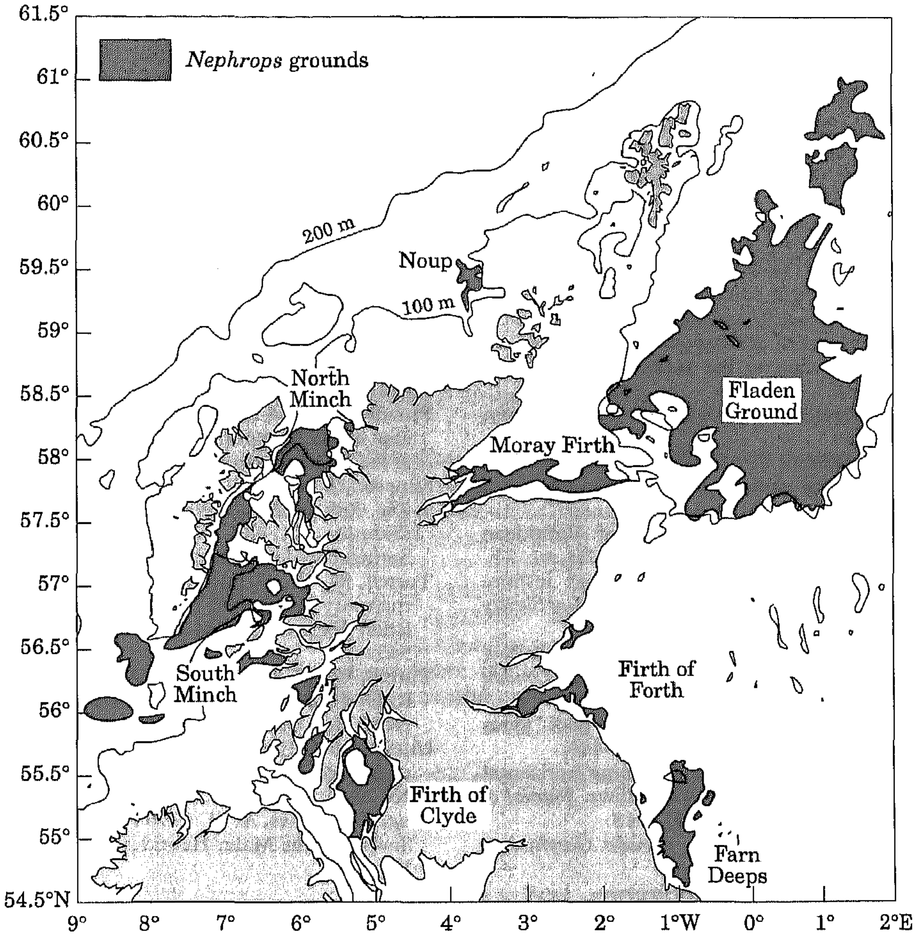

FIGURE 11. *Nephrops norvegicus* grounds around Scotland.

The previous discussion assumes *Nephrops* larvae behave as passive tracers whereas, in common with many marine larvae, active vertical migration could also affect dispersal (e.g. Hill, 1995). The application of a baroclinic coastal ocean model, with *Nephrops* larval transport represented by particle tracking (perhaps incorporating vertical migratory behaviour), would assist a more quantitative examination of these questions.

Although the drifter observations presented are limited in duration and are confined to the spring regime, they constitute the first direct current measurements within the region and provide confirmation of a bifurcation and partial recirculation of the Scottish coastal current in the South Minch. However, it would be unwise to infer a permanent circulation solely on the basis of relatively short drifter deployments, although the consistency with indirect inferences about the circulation is encouraging. Further deployments in the region over the entire seasonal cycle are obviously desirable. The observations point strongly to the importance of horizontal density gradients in driving the flow and the observations are sufficient to demonstrate that any future modelling approach in this region must take full account of baroclinic dynamics.

Acknowledgements

The authors are grateful to Captain George Geddes and the officers and crew of the FRV *Clupea*. Technical assistance was provided by Dave Boon and Anne Hammerstein. RWG participated in this work whilst on sabbatical leave from the University of Delaware and received support from the US National Science Foundation under Grant INT-9413299 and the Sir Kirby Laing Fellowship of the School of Ocean Sciences, University of Wales, Bangor. The study was partly funded by an award, GR3/9601, to AEH from the UK Natural Environment Research Council and by a Collaborative Research Grant, 940566, from NATO to RWG and AEH.

References

Backhaus, J. O. 1985 A three-dimensional model for the simulation of shelf sea dynamics. *Deutsche Hydrogrographische Zeitschrift* **38**, 165–187.

Bailey, N, Chapman, C. J., Alfonso-Dias, M. & Turrell, W. R. 1995 The influence of hydrographic factors on *Nephrops* distribution and biology. *ICES CM 1995/Q:17 Poster (mimeo).*

Blumberg, A. F. & Mellor, G. L. 1987 A description of a three-dimensional coastal ocean model. In *Three Dimensional Coastal Ocean Models* (Heaps, N. S. ed.). Coastal and Estuarine Sciences No. 4, American Geophysical Union, Washington, 208 pp.

Bray, N. A. 1988 Thermohaline circulation in the Gulf of California. *Journal of Geophysical Research* **93**, 4993–5020.

Brown, J. 1991 The final voyage of the Rapaiti. A measure of sea surface drift velocity in relation to the surface wind. *Marine Pollution Bulletin* **22**, 37–40.

Craig, R. E. 1959 Hydrography of Scottish coastal waters. *Marine Research 1958 (2)*, 30 pp.

Davis, R. E., Dufour, J. E. Parks, G. P. & Perkins, M. R. 1982 Two inexpensive current-following drifters. Scripps Institution of Oceanography Reference No. 82–28.

Ellett, D. J. 1979 Some oceanographic features of Hebridean waters. *Proceedings of the Royal Society of Edinburgh* **77B**, 61–74.

Ellett, D. J. & Edwards, A. 1983 Oceanography and inshore hydrography of the Inner Hebrides. *Proceedings of the Royal Society of Edinburgh* **83B**, 143–160.

Garrett, C. J. R. & Loder, J. W. 1981 Dynamical aspects of shallow sea fronts, *Philosophical Transactions of the Royal Society of London* **A 302**, 653–681.

Hill, A. E. 1996 Spin-down and the dynamics of ' dense pool ' gyres in shallow seas. *Journal of Marine Research* **54**, 471–486.

Hill, A. E. 1995 The kinematical principles governing horizontal transport induced by vertical migration in tidal flows. *Journal of the Marine Biological Association of the UK* **75**, 3–13.

Hill, A. E. 1993 Seasonal gyres in shelf seas. *Annales Geophysicae* **11**, 1130–1137.

Hill, A. E. 1987 *The Dynamics and Variability of the Scottish Coastal Current*. PhD Thesis, University of Wales, Bangor, U.K.

Hill, A. E., Durazo, R. & Smeed, D. A. 1994 Observations of a cyclonic gyre in the western Irish Sea. *Continental Shelf Research* **14**, 479–490.

McKay, W. A., Baxter, M. S. Ellett, D. J. & Meldrum, D. T. 1986 Radiocaesium and circulation patterns west of Scotland. *Journal of Environmental Radioactivity* **4**, 205–232.

McKinley, I. G., Baxter, M. S., Ellett, D. J. & Jack, W. 1981 Tracer applications of radiocaesium in the Sea of the Hebrides. *Estuarine, Coastal and Shelf Science* **13**, 69–82.

Niiler, P. P., Sybrandy, A. S., Bi, K., Poulain, P. M. & Bitterman, D. 1995 Measurement of the water-following capability of holey sock and tristar drifters. *Deep Sea Research I* **42**, 1951–1964.

Pingree, R. D. & Griffiths, D. K. 1978 Tidal fronts on the shelf seas around the British Isles. *Journal of Geophysical Research* **83**, 4615–4622.

Prandle, D. 1984 A modelling study of the mixing of ^{137}Cs in the seas of the European continental shelf. *Philosophical Transactions of the Royal Society of London* **A 310**, 407–436.

Simpson, J. H. & Hill, A. E. 1986 The Scottish coastal current. In *The Role of Freshwater Outflow in Coastal Marine Ecosystems* (Skreslet, S., ed.) NATO ASI Series, Vol. G7: 295–308. Springer-Verlag, Berlin, Heidelberg.

Turrell, W. R., Henderson, E. W. & Slesser, G. 1990 Residual transport within the Fair Isle Current during the Autumn Circulation Experiment (ACE). *Continental Shelf Research* **10**, 521–543.

Turrell, W. R., Henderson, E. W. Slesser, G. Payne, R. & Adams, R. D. 1992 Seasonal changes in the circulation of the northern North Sea. *Continental Shelf Research* **12**, 257–286.

Unesco 1978 Eighth report of the joint panel on oceanographic tables and standards. *Unesco Technical Papers in Marine Science*, No 28.

Xing, J. & Davies, A. M. 1996 A numerical model of the long term flow along the Malin-Hebrides shelf. *Journal of Marine Systems* **8**, 191–218.