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Near-surface recirculation over Georges Bank

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Abstract—Satellite-tracked drifters with drogues centered near-surface (5 m) and below the seasonal thermocline (50 m) were launched during late winter and spring of 1988 and 1989 in the northern Great South Channel in the western Gulf of Maine to investigate the regional circulation as part of the South Channel Ocean Productivity Experiment (SCOPEX). Many of the near-surface drifters became entrained in the clockwise gyre over Georges Bank, and eight drifters made a total of 16 complete circuits around the bank during the stratified season. The average recirculation period of these eight drifters was 48 days, and the average drifter speed around the bank was 12 cm s^{-1}. There is no clear evidence from the drifter data that the strength of the clockwise gyre over the bank increased with time during the stratified season. On average, these drifters (i) followed a relatively narrow path around the bank, except over the eastern end of the bank where three preferred paths were observed, (ii) moved fastest over the northern and southern flanks of the bank, (iii) did not enter a core area of 3500 km^2 centered at 41°17′N, 68°00′W, approximately 30 km southwest of the topographic center of the bank, and (iv) stopped circling the bank by the end of November, due in part to strong wind events that appeared to drive drifters off the bank. Curiously, none of the near-surface drifters moved from the southern flank of Georges Bank onto the New England shelf as might be expected from continuity of flow along the outer shelf; instead, the drifters that circled the bank tended to move off the bank along its southern flank. None of the drifters with drogues centered at 50 m appeared to recirculate around Georges Bank. Copyright © 1996 Elsevier Science Ltd

INTRODUCTION

The sub-tidal flow over Georges Bank is often described as a clockwise eddy or gyre. Huntsman (1924) was one of the first to note that the mean flow tended to be cyclonic over the deep basins and anticyclonic over the offshore shoals along the North American northeast shelf, and his chart showed clockwise circulation around Georges Bank and Nantucket Shoals. This idea was enhanced by Bigelow's (1927) classic analysis and description of the "dominant non-tidal summer circulation" of the Gulf of Maine (GOM), which showed a clockwise circulation around Georges Bank and an anticlockwise circulation in the central GOM (Fig. 1, upper). Walford (1938) discussed the non-tidal recirculation over Georges Bank after analyzing drift bottle data in relation to the survival of haddock eggs and larvae.

Later, Bumpus and Day (1957), Day (1958), and Bumpus (1973) used data from lightships and the results of drift bottle studies to establish a strengthening of the Gulf of Maine and Georges Bank gyres during the summer months as a result of stratification, and interruptions in the gyre circulation during strong wind events. Bumpus (1976) reported on the use of radio-tracked drifters over Georges Bank, and Butman *et al.* (1982) reviewed

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long-term Eulerian and Lagrangian current measurements to demonstrate clearly the clockwise flow pattern around Georges Bank inferred by Bigelow (1927) and Bumpus (1973, 1976). These direct observations suggest that the residual clockwise circulation is a permanent feature of the regional summer subsurface circulation, and that some fraction of the shelf water that flows southwestward along the southern flank of Georges Bank turns and flows northward through the center and eastern side of the Great South Channel (GSC) to feed the narrow jet on the northern flank of Georges Bank and recirculate around the bank.

This pattern of clockwise mean flow around Georges Bank has been attributed by Butman *et al.* (1987) to (i) rectification of the strong semi-diurnal tidal currents over the variable bottom topography of the bank, (ii) horizontal density gradients that intensify in summer, (iii) an externally imposed along-shelf pressure gradient, and (iv) windstress. The mean flow component due to tidal rectification was first predicted by Loder (1980) using an analytic barotropic model, and the barotropic numerical model of Greenberg (1983) shows a northward inflow of order 2–5 cm s^{-1} over the center and eastern side of the GSC. Butman and Beardsley (1987) suggest that a monthly mean subsurface clockwise circulation exists around the bank throughout the year, and the recirculation around Georges Bank can be strongest in late summer and early fall. Butman *et al.* (1987) summarized deployments of Lagrangian drifters with 10 m windowshade drogues centered at 10 m, but only one complete recirculation around Georges Bank was made by these drifters. Lynch and Namie (1993) used a three-dimensional model to characterize tidal and residual currents on detailed topography over Georges Bank. Namie *et al.* (1994) presented a numerical study of the seasonal variability in the subtidal circulation over the bank that demonstrated a strengthening of the residual circulation over Georges Bank during the stratified season, and Chen *et al.* (1995a) recently described how background vertical stratification can increase the tidal-rectified mean flow over Georges Bank.

In 1988, the South Channel Ocean Productivity EXperiment (SCOPEX) was begun to investigate springtime aggregations of right whales in the Great South Channel region, and the interactions between these whales and their main zooplankton prey, the copepod *Calanus finmarchicus* (Kenney and Wishner, 1995). The right whale is an endangered species, with only a few hundred individuals left in the northwest Atlantic population. Almost every spring, for at least the last 15 years, nearly the entire population of right whales has gathered for about a month in the northern GSC. The SCOPEX program attempted to understand this phenomenon, as well as the broader issues of ecosystem "hot spots" and the implications of zooplankton patchiness on trophic transfer. The purpose of the SCOPEX 1988–1989 field program was to study whale/plankton/environment interactions, especially whale behavior in relation to copepod distributions, copepod aggregations and their structure and causes, primary and secondary production and its relationship to the zooplankton aggregations, and the role(s) of currents and water stratification in forming and maintaining the zooplankton aggregations.

One component of the SCOPEX field program was the deployment of satellite-tracked drifters to characterize the regional Lagrangian circulation (and possible advection of zooplankton) in the northern GSC. Chen *et al.* (1995b, 1995c) describe the variability of water properties and currents in the GSC observed during SCOPEX, and Beardsley *et al.* (1996) describe the spacial variability in zooplankton abundance observed near feeding right whales. We focus in this paper on the movement of the drifters that leave the northern GSC and enter the clockwise flow around Georges Bank. Our purpose is to describe

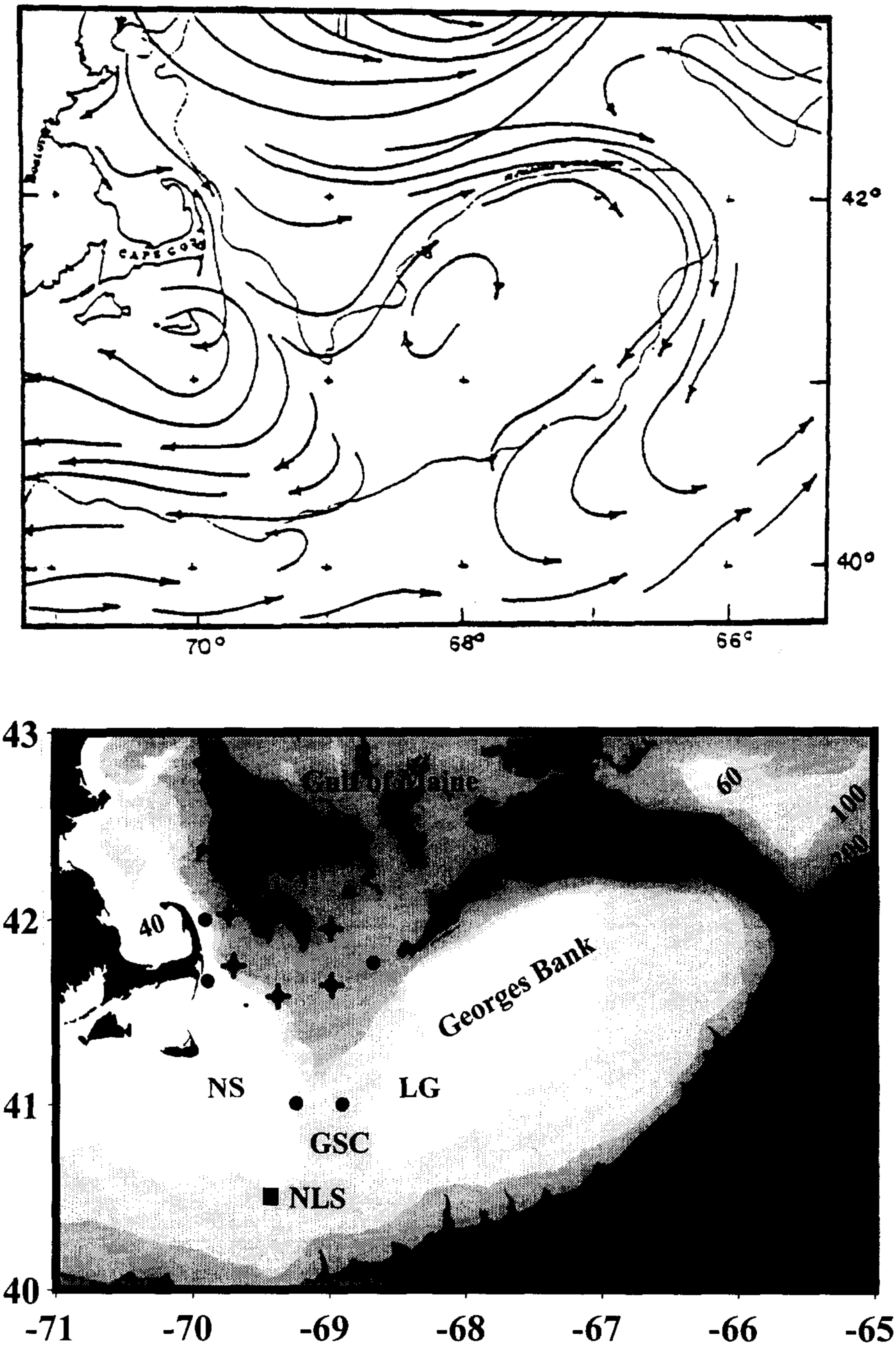


Fig. 1. Upper: Bigelow's (1927) subtidal summer circulation schematic in the Gulf of Maine showing a clockwise circulation around Georges Bank. Lower: the initial deployment locations in 1989 of 13 near-surface drifters (solid circles) and six deep drifters (crosses) near the Great South Channel (GSC). Also shown are the locations of Nantucket Shoals (NS), Georges Bank, Little Georges Shoal (LG), the central Gulf of Maine, and the Northeast Channel (NEC), and the Nantucket environmental buoy (solid square). Water depth is indicated by shading with the transition isobaths labeled in meters.

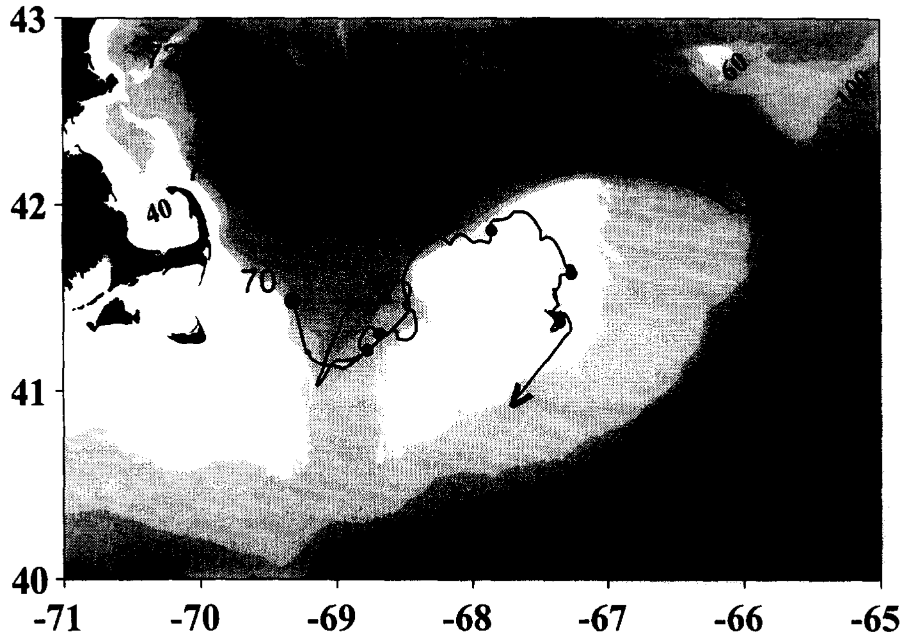


Fig. 2. Low-pass filtered near-surface drifter trajectories of three drifters deployed in March 1988. Along the drifter trajectories solid circles are plotted for the first day of each month and every succeeding 10 days. The distance between the solid circles provides a relative measure of the mean drifter velocity along the trajectory. A distance of 1° latitude divided by 10 days gives a mean velocity magnitude of 12.7 cm s^{-1}.

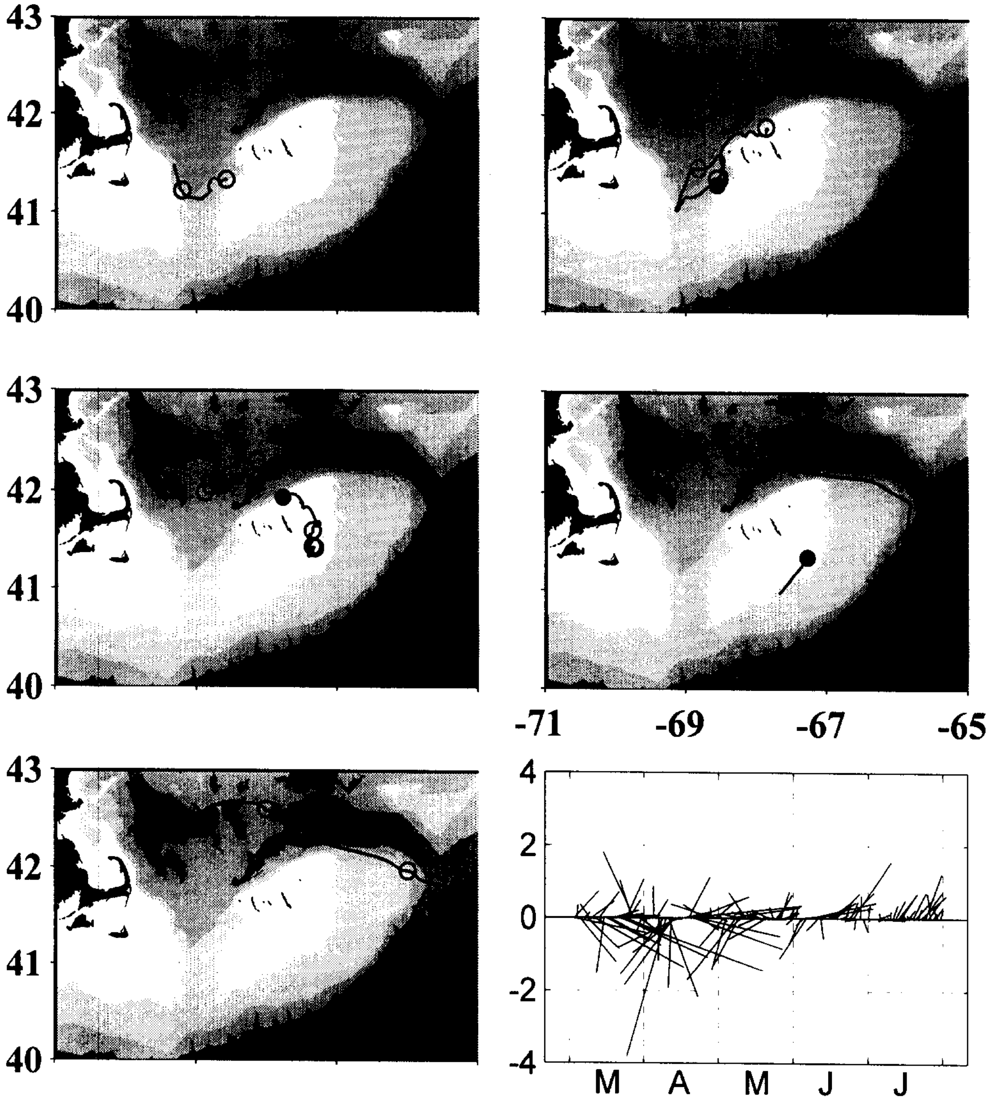


Fig. 3. Low-pass filtered trajectories of the three near-surface drifters shown on Fig. 2 plotted by month. Along the drifter trajectories solid circles are plotted for the first day of each month (i.e. the starting position) and open circles are plotted every succeeding 10 days. The lower right panel shows the corresponding low-passed windstress in dynes cm^{-2}. A distance of 1° latitude divided by 10 days gives a mean velocity magnitude of 12.7 cm s^{-1}.

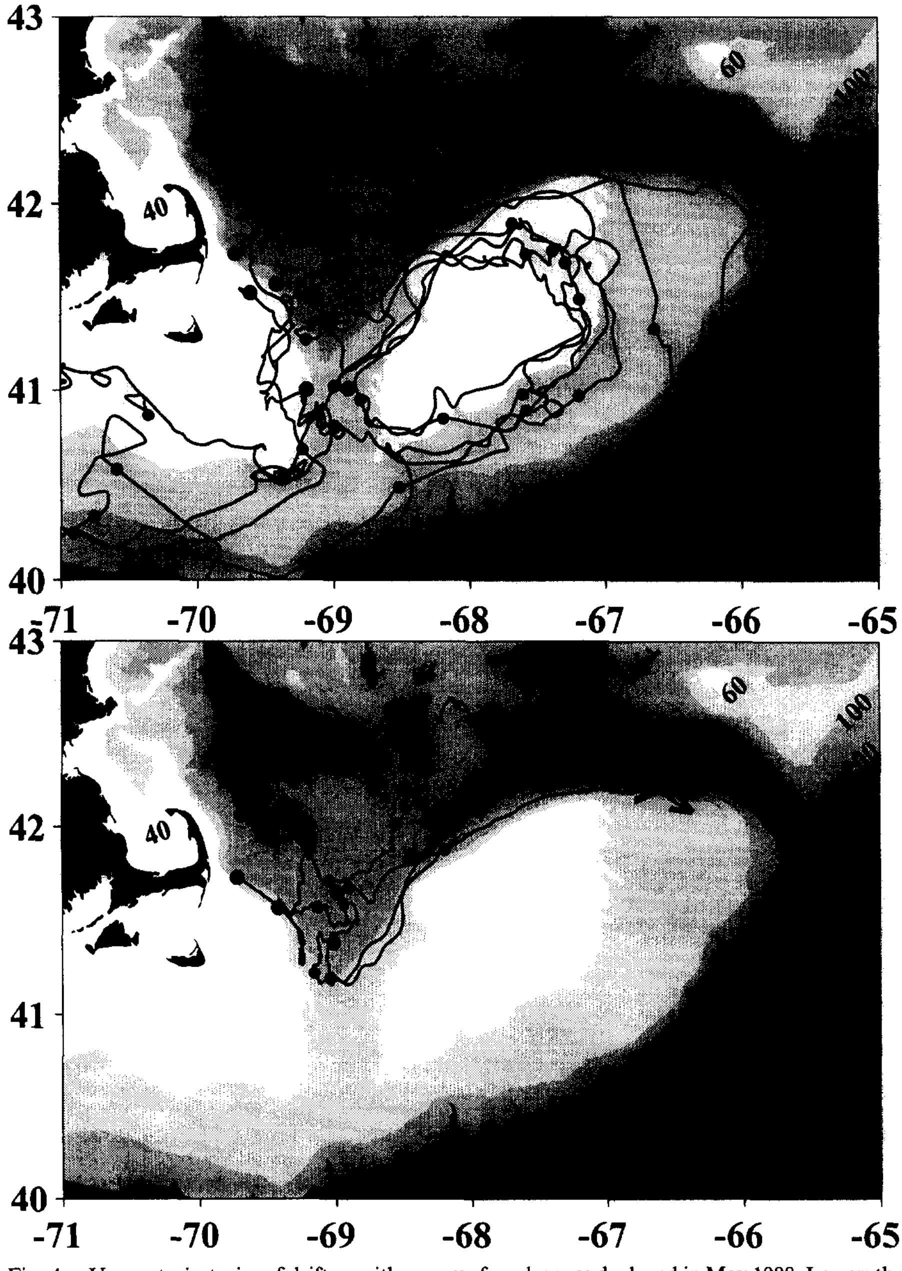


Fig. 4. Upper: trajectories of drifters with near-surface drogues deployed in May 1988. Lower: the 1988 deep drifter trajectories with drogues centered at 50 m. Shown here are the low-pass filtered drifter positions. Along the drifter trajectories solid circles are plotted every 20 days. Each drifter trajectory has been truncated when the drifter stopped transmitting or left the shelf. A distance equal to 1° latitude divided by 20 days gives a mean velocity magnitude of 6.4 cm s^{-1}.

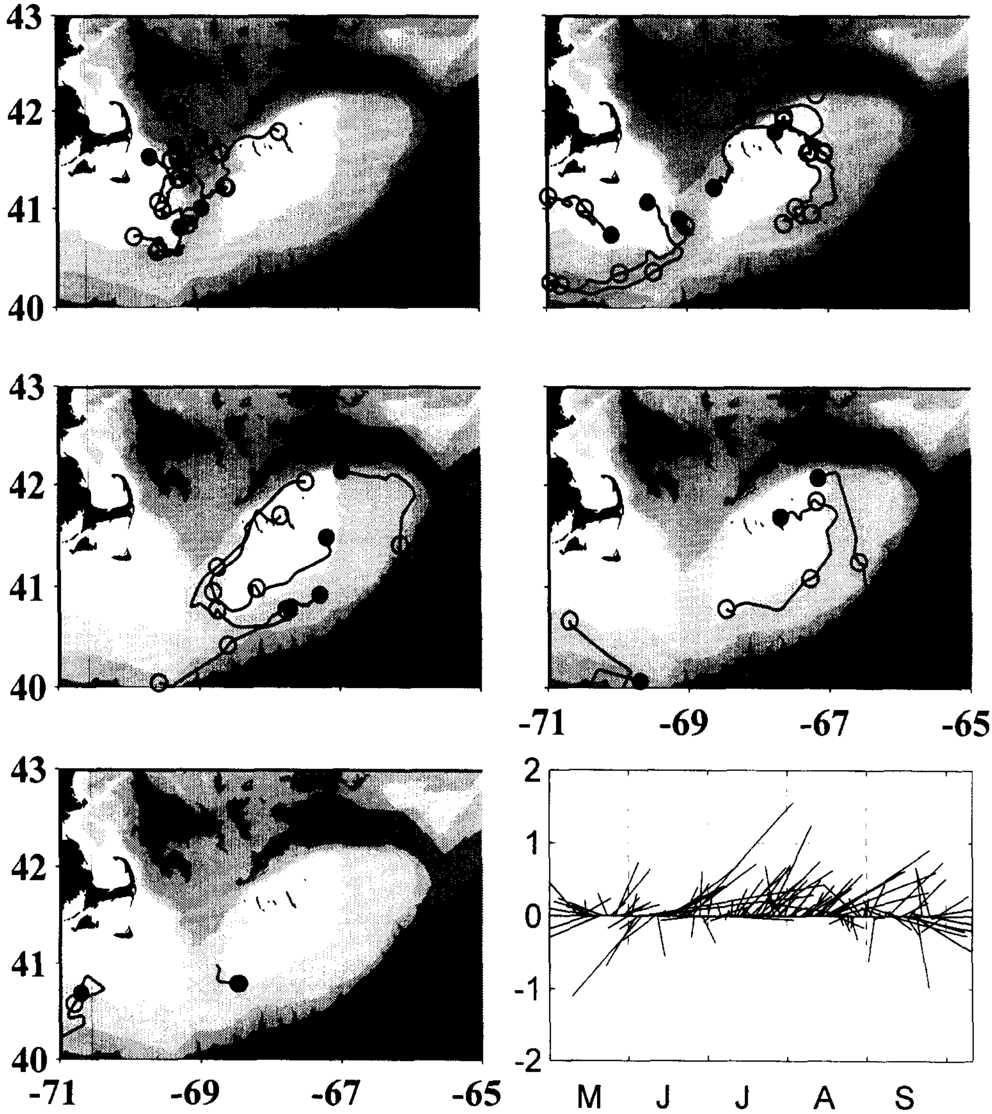
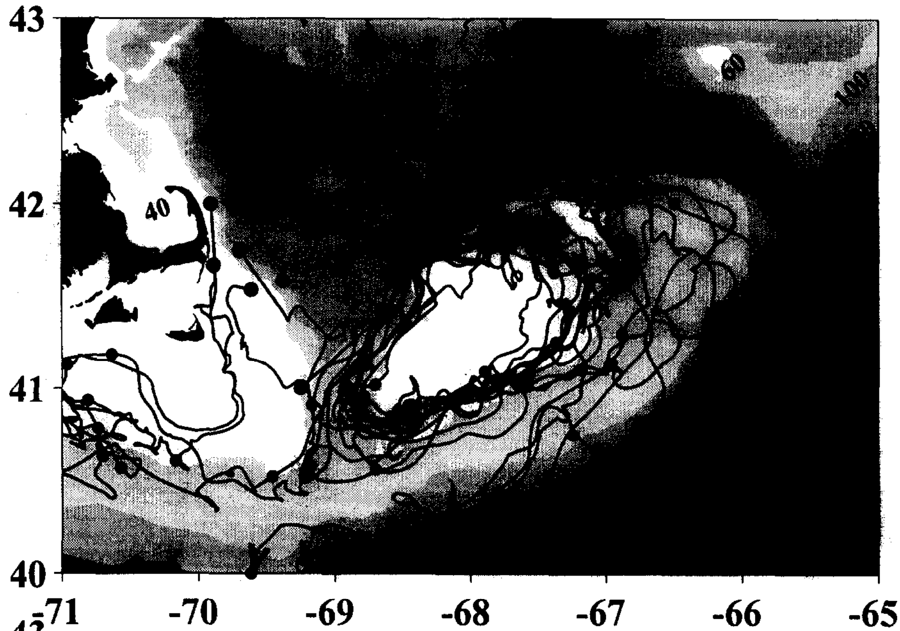


Fig. 5. Monthly low-pass filtered trajectories of the near-surface drifters shown in Fig. 4 (upper) plotted by month. Along the drifter trajectories solid circles are plotted for the first day of each month and open circles are plotted every succeeding 10 days. The lower right panel shows the windstress in dynes cm^{-2}. A distance signal to 1° latitude divided by 10 days gives a mean velocity magnitude of 12.7 cm s^{-1}.



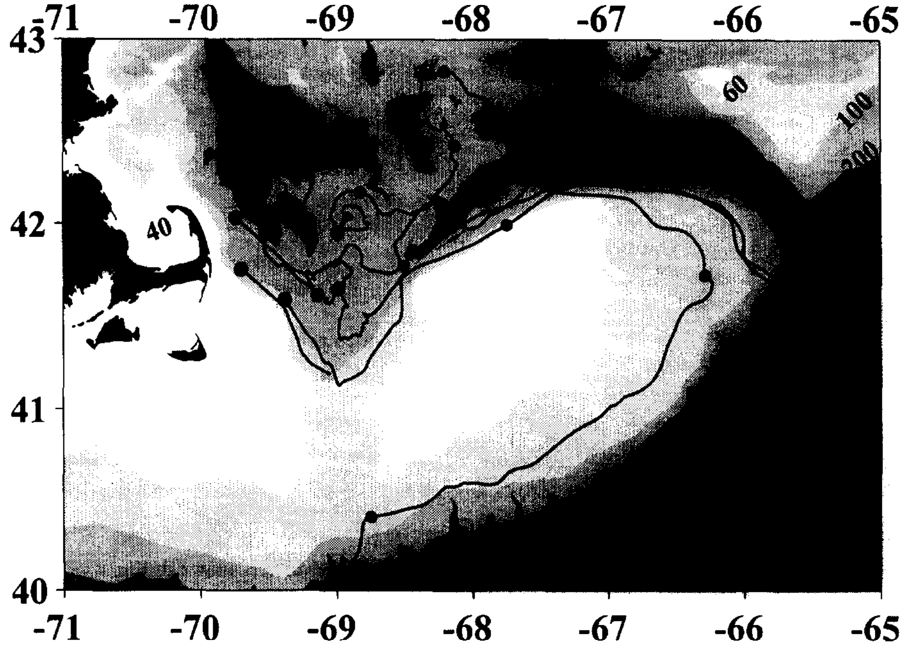


Fig. 6. Upper: trajectories of drifters with drogues centered near-surface (5 m) deployed in June 1989. Lower: the trajectories of drifters with drogues centered at 50 m. Shown here are the low-pass filtered drifter positions. Along the drifter trajectories solid circles are plotted every 20 days. Each drifter trajectory has been truncated when the drifter stopped transmitting or left the shelf. A distance of 1° latitude divided by 20 days gives a mean velocity magnitude of 6.4 cm s^{-1}.

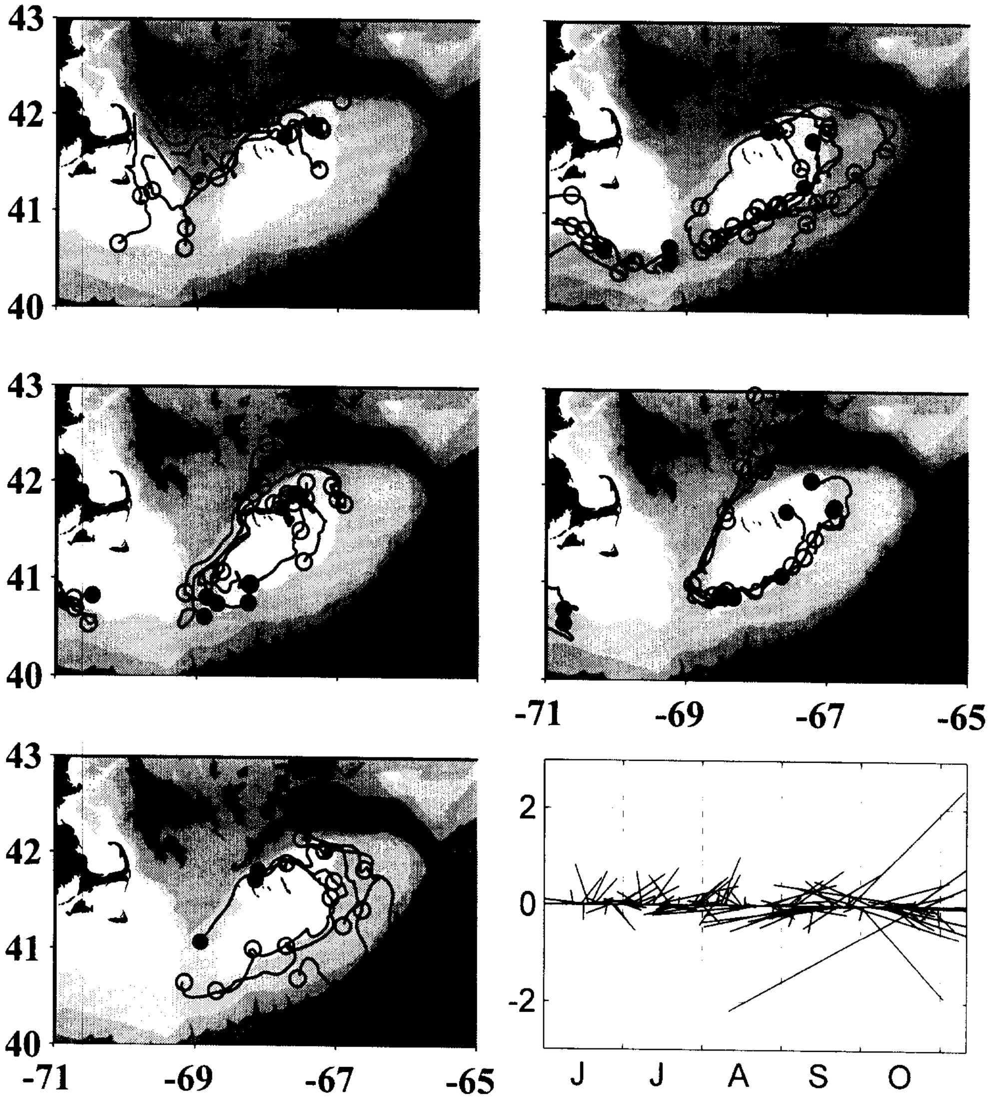


Fig. 7. Low-pass filtered trajectories of the near-surface drifters shown in Fig. 6 (upper) plotted by month. Along the near-surface drifter trajectories solid circles are plotted for the first day of each month and open circles are plotted every 10 days. The lower right panel shows the corresponding windstress in dynes cm^{-2}.

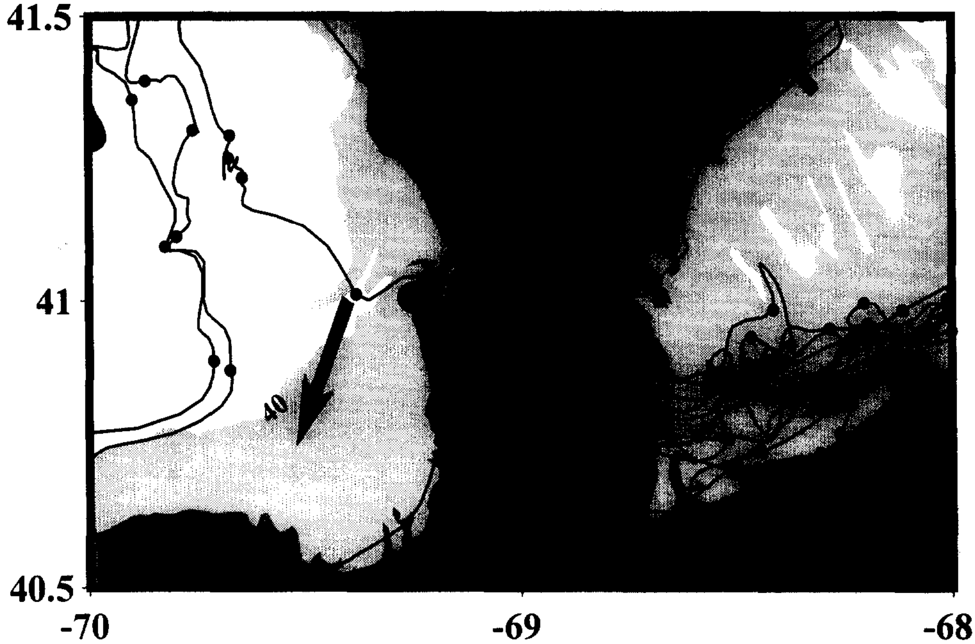


Fig. 8. Expanded view of the 1989 near-surface drifter trajectories in the GSC region shown in the upper panel of Fig. 6. Large dots show the initial deployment locations and large solid arrows indicate the general direction of the drifter movement.

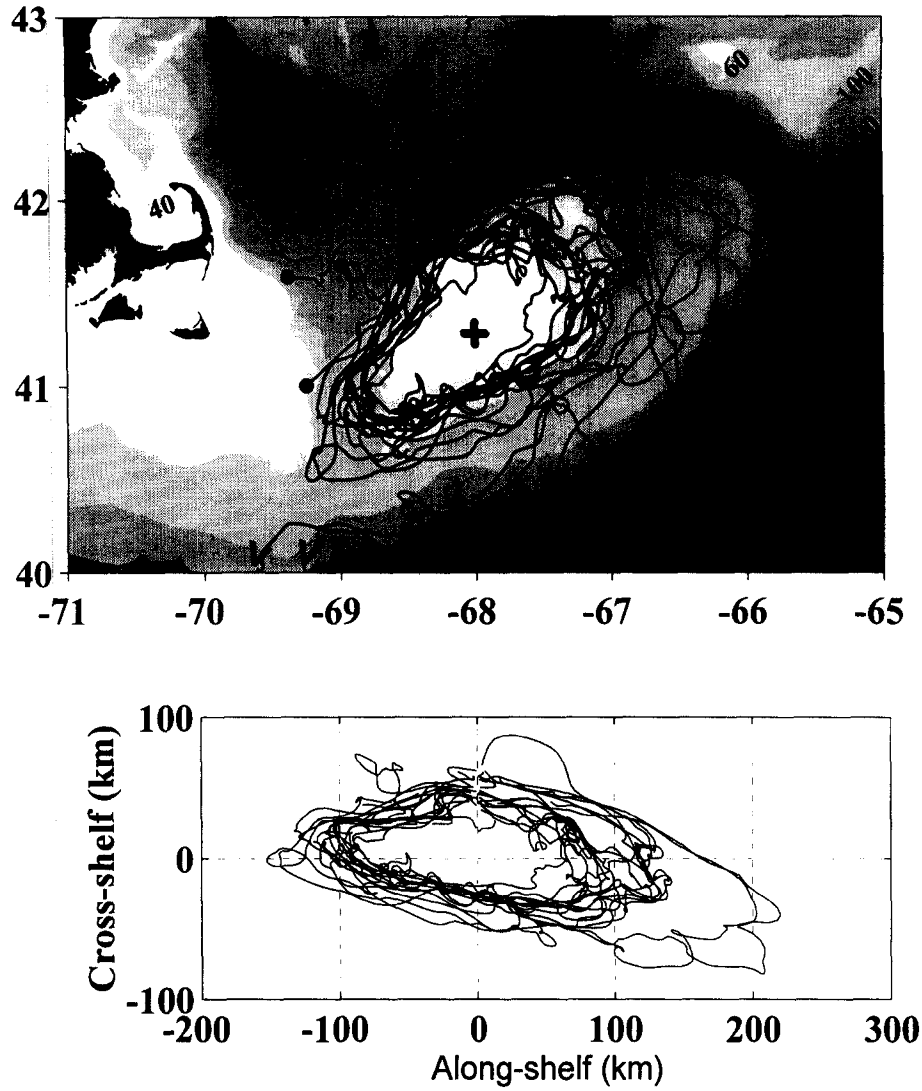


Fig. 9. Upper: tracks of the eight drifters that recirculated a total of 16 times around Georges Bank during 1988–1989. The drifter starting position is denoted by a solid circle. The mean center of the recirculation region is located with a plus symbol. Lower: the same drifter trajectory data plotted relative to the mean center of the recirculation. The x-axis has been rotated counterclockwise approximately 25° to correspond with the principle axis of the recirculating trajectories (and the approximate along-bank orientation of the bank itself). Note the three different paths of recirculation over the eastern flank of Georges Bank. The mean center of the recirculation was found by averaging the tracks over only the inner of the three characteristic path groups.

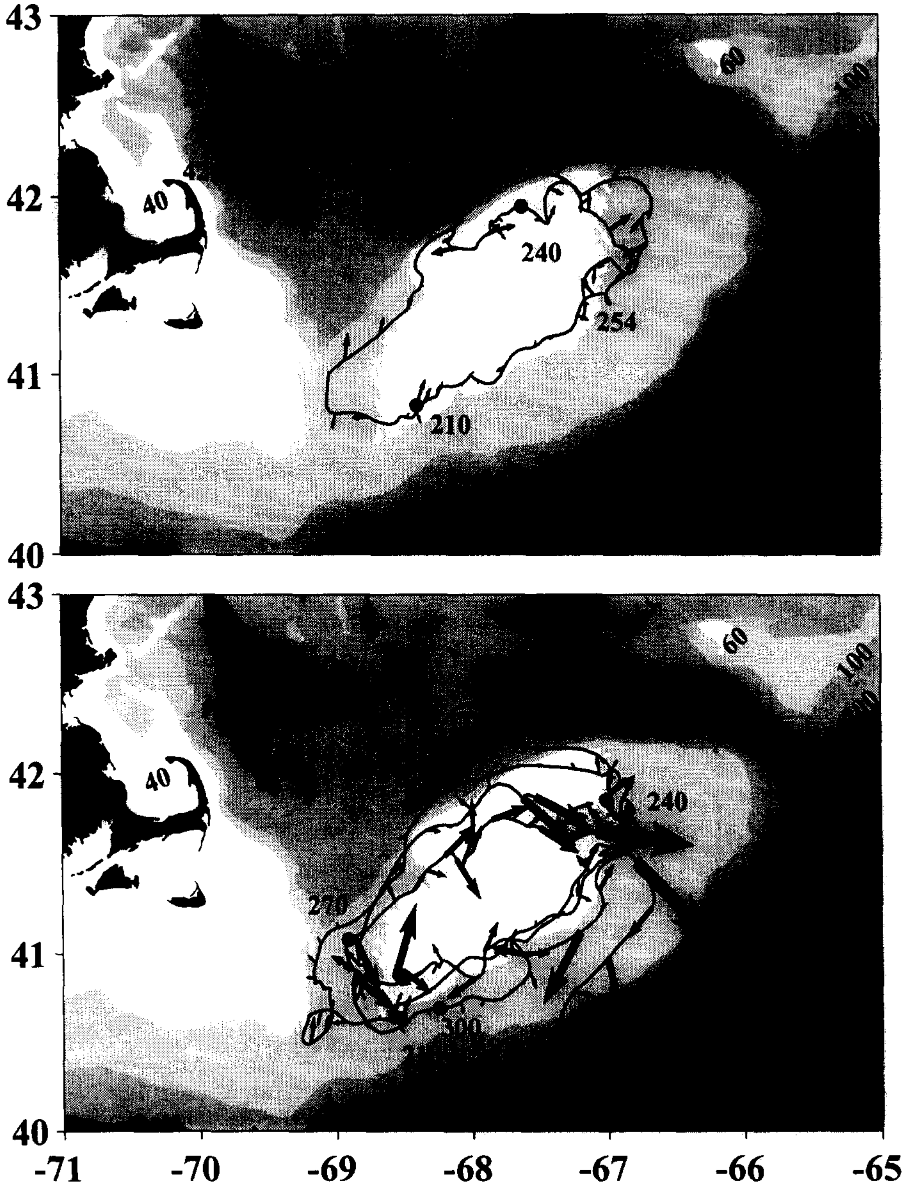


Fig. 14. Daily low-pass-filtered vector windstress shown along the tracks of drifter 42 (upper) and 43 (lower) in 1989. The drifter ID number and the yearday of deployment are shown by a large solid circle and smaller solid circles are plotted and labeled every 30 days thereafter.

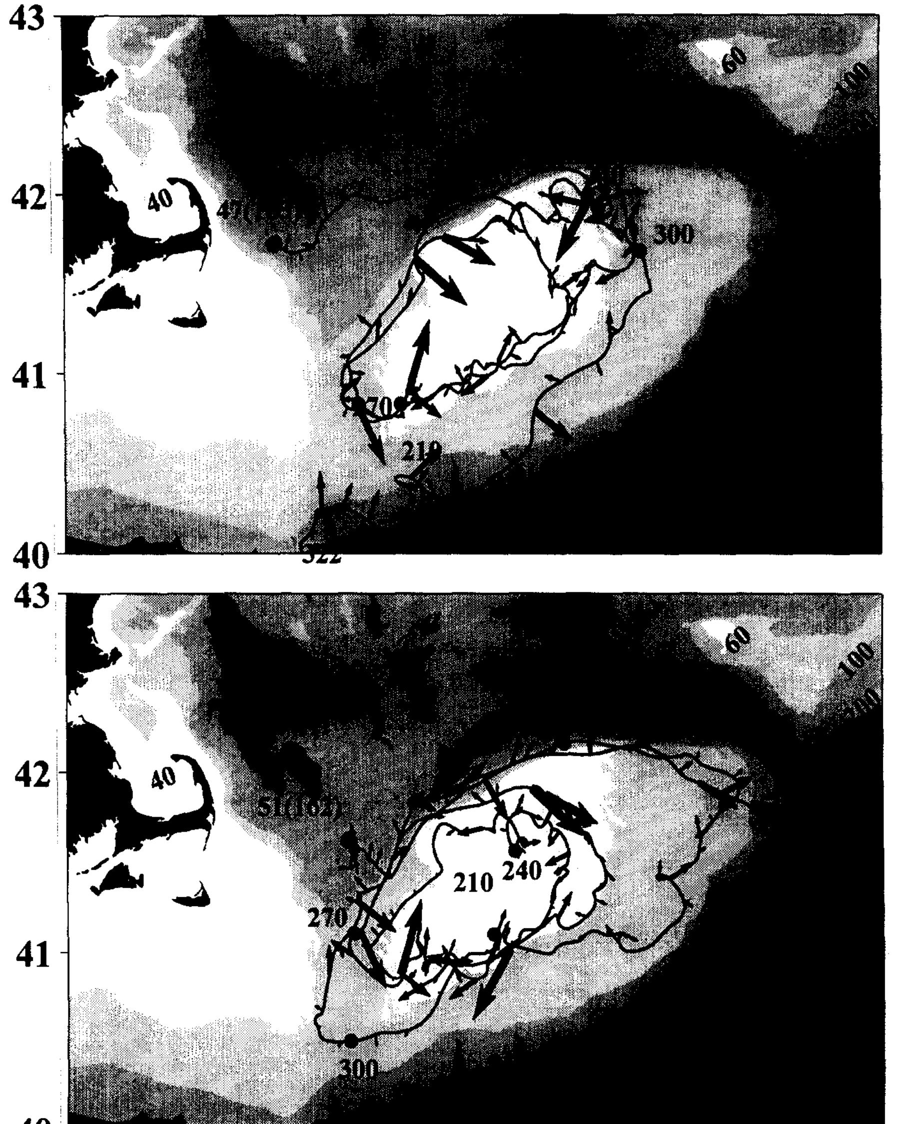


Fig. 15. Daily low-pass filtered vector windstress shown along the track of drifter 47 (upper) and 51 (lower) in 1989. The drifter ID number and the yearday of deployment are shown by a large solid circle and solid circles are plotted and labeled every 30 days thereafter.

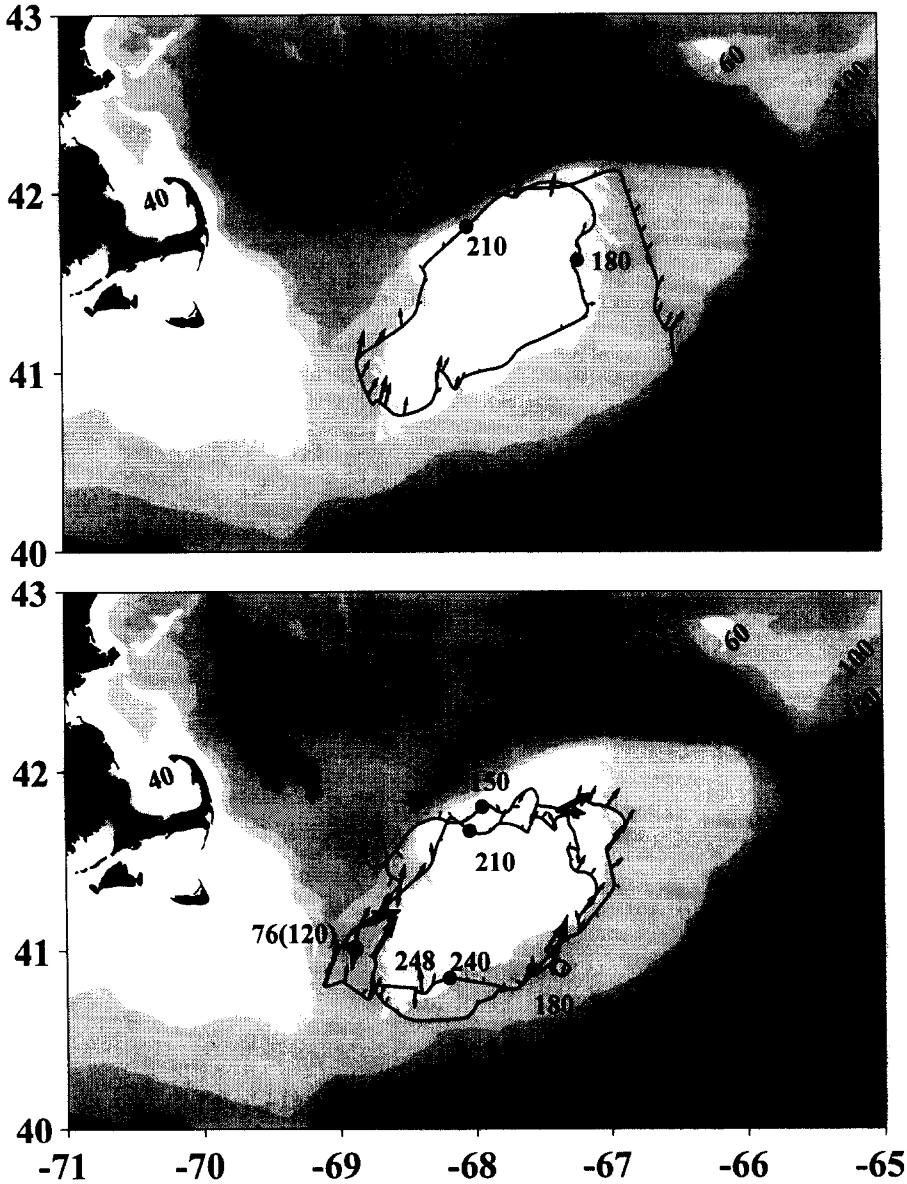


Fig. 16. Daily low-pass filtered vector windstress shown along the tracks of drifter 73 (upper) and 76 (lower) in 1988. The drifter ID number and the yearday of deployment are shown by a large solid circle and solid circles are plotted and labeled every 30 days thereafter.

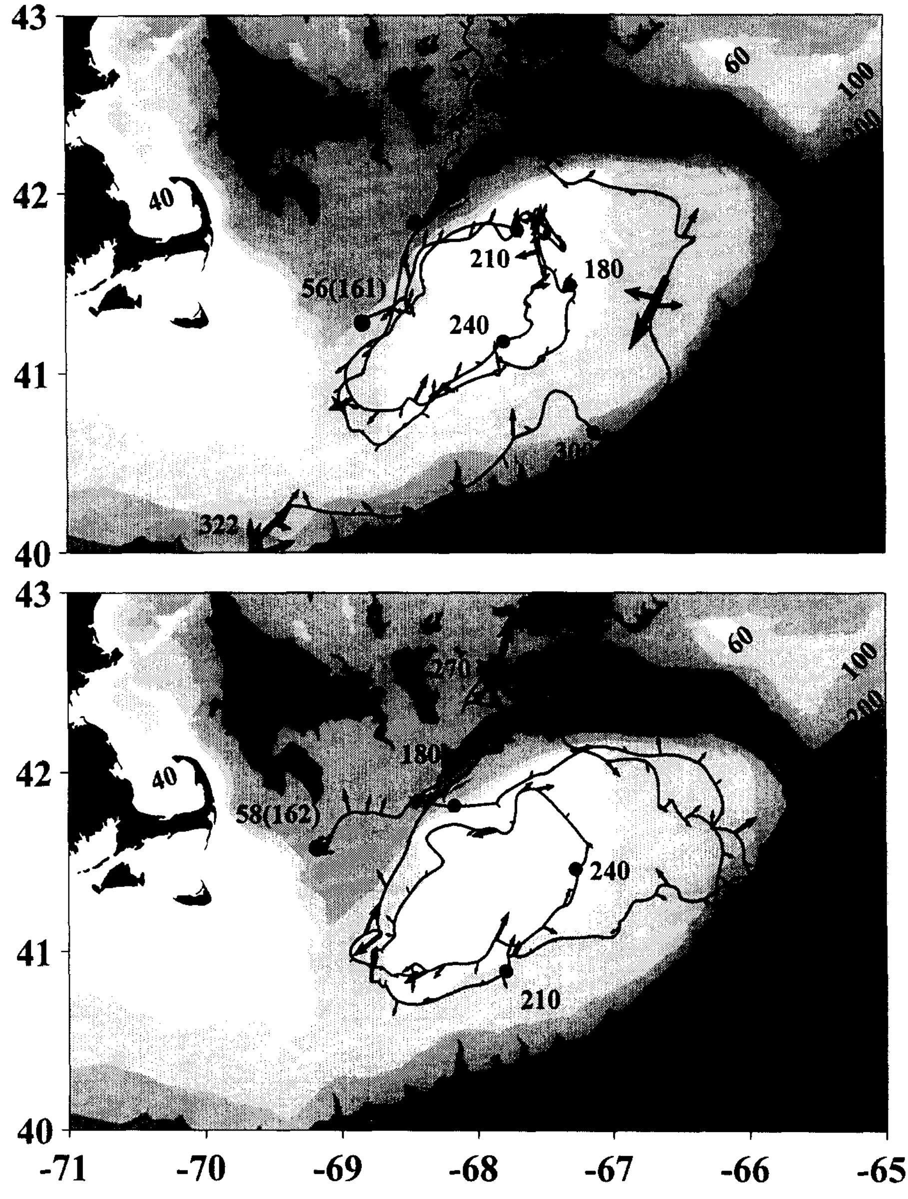


Fig. 17. Daily low-pass filtered vector windstress shown along the track of drifter 56 (upper) and 58 (lower) in 1989. The drifter ID number and the yearday of deployment are shown by a large solid circle and solid circles are plotted and labeled every 30 days thereafter.

recirculation over Georges Bank as revealed by the SCOPEX drifter data. We present a description of the 1988–1989 drifter trajectories, and then discuss in more detail the trajectories of those drifters which made at least one complete circuit around the bank.

THE SCOPEX DRIFTER EXPERIMENT

During SCOPEX, we deployed Low-Cost Drifters (LCDs) manufactured by John Dahlen and his engineering group at Draper Lab., Cambridge, MA. The drifters transmitted location, sea surface temperature, drogue tension, and battery status typically 6–8 times per day via ARGOS. Each drifter consisted of a small cylindrical (40-cm diameter by 20-cm deep), low-windage surface buoy designed to house the radio transmitter, antenna, and batteries, attached with an 8 mm wire-jacketed tether to either (i) a holey sock drogue 60 cm in diameter by 5 m long centered at a depth of 5 m with a 2.5 m tether, or (ii) a holey sock drogue 60 cm in diameter by 20 m long centered at a depth of 50 m with a 40 m tether. For a wind speed of 10 m s^{-1} at 10 m height, the estimated drifter slip velocity due to the wind is about 1.1 cm s^{-1} for the drifters with near-surface drogues and about 2.6 cm s^{-1} for the drifters with drogues centered at 50 m (Limeburner *et al.*, 1995; Niiler *et al.*, 1995). Tables 1 and 2 show the various drogue/tether size configurations, drifter start times, record lengths, and the initial deployment positions.

Table 1. *Summary of satellite-tracked drifters deployed in the Great South Channel (GSC) near Georges Bank (GB) in the southwestern Gulf of Maine (GOM) during* 1988. *Listed are the drifter identification number (ID), drogue center depth, the general trajectory, initial location, start date, and length of the raw drifter position time series over the shelf*

Drifter ID	Drogue Depth (m)	Drifter Path	Latitude	Longitude	Start Date (yd)	Record Length (days)
			Drogue Near-Surface			
70	5	GB S Flank	41.485°N	69.320°W	77	84
71	5	Out NE Channel	42.096°N	69.782°W	76	113
72	5	Out NE Channel	42.655°N	70.054°W	74	136
73	5	GB Recirculation	42.062°N	69.685°W	120	120
74	5	Out SW GOM	41.520°N	69.613°W	119	68
76	5	GB Recirculation	41.008°N	68.887°W	118	132
79	5	Wilkinson Basin	41.892°N	69.190°W	120	65
81	5	Out NE Channel	41.649°N	68.990°W	119	82
82	5	GB S Flank	41.382°N	69.010°W	118	85
83	5	Out SW GOM	41.005°N	69.197°W	118	137
84	5	GSC	41.730°N	69.720°W	120	13
87	5	Out SW GOM	41.493°N	69.128°W	136	48
89	5	GB S Flank	41.567°N	69.419°W	119	155
			Drogue in Deeper Layer			
75	50	GB NE Flank	42.062°N	69.685°W	120	89
77	50	GSC	41.567°N	69.419°W	119	23
78	50	GB NW Flank	41.892°N	69.190°W	120	96
85	50	GB NE Flank	41.382°N	69.010°W	118	61
86	50	GSC	41.730°N	69.720°W	120	20
88	50	GB NW Flank	41.649°N	69.990°W	119	46

Table 2. Summary of satellite-tracked drifters deployed in the Great South Channel (GSC) in the southwestern Gulf of Maine (GOM) during 1989. Listed are the drifter identification number (ID), drogue center depth, the general trajectory, initial location, start date, and length of the raw drifter position time series over the shelf

Drifter ID	Drogue Depth (m)	Drifter Path	Latitude	Longitude	Start Date (yd)	Record Length (days)
			Drogue Near-Surface			
41	5	Out SW GOM	41.997°N	69.910°W	162	132
42	5	GB Recirculation	42.132°N	69.382°W	162	93
43	5	GB Recirculation	42.148°N	68.853°W	162	169
46	5	Out SW GOM	41.749°N	69.701°W	161	157
47	5	GB Recirculation	42.030°N	69.738°W	162	162
48	5	Out SW GOM	41.677°N	69.888°W	161	57
51	5	GB Recirculation	41.645°N	68.985°W	160	167
53	5	Out SW GOM	41.535°N	69.610°W	160	115
55	5	GB NW Flank	41.000°N	68.907°W	159	4
56	5	GB Recirculation	41.005°N	69.247°W	159	162
57	5	GB NW Flank	41.764°N	68.678°W	143	23
58	5	GB Recirculation	41.584°N	69.377°W	160	130
59	5	GB NS Flank	41.948°N	68.992°W	161	41
			Drogue in Deeper Layer			
40	50	Out NE Channel	42.030°N	69.738°W	162	40
44	50	GSC	41.749°N	69.701°W	161	8
45	50	Out NE Channel	41.584°N	69.377°W	160	36
50	50	W GOM	42.132°N	69.382°W	162	64
52a	50	GB N Flank	41.645°N	68.985°W	160	55
52b	50	Brown's Bank	42.991°N	65.986°W	223	42
54	50	GB NS Flank	41.948°N	68.992°W	161	105

The drifter raw position data were first linearly interpolated to a uniform 6 h time-series of latitude and longitude. These series were then low-pass filtered with a parabolic-linear filter with a 33 h half-amplitude period (Flagg *et al.*, 1976) to eliminate tidal and inertial motions. Drifter velocities were then computed by a simple backward difference. To examine the influence of the wind on the low-pass drifter velocities, wind time-series were obtained from the Nantucket Shoals NOAA environmental buoy 44 010 and then converted into windstress time-series using the neutral drag law of Large and Pond (1981). Time is expressed here in GMT yeardays (yd) for 1988 and 1989 to simplify comparison between drifters.

In each of the years 1988 and 1989, 13 drifters were deployed with drogues centered near-surface at 5 m to track the flow in the relatively low-salinity water above the seasonal pycnocline, and six drifters with drogues centered below the seasonal pycnocline at 50 m to track the relatively cold Maine Intermediate Water at a depth above the sill depth of the GSC. The 1988 deployment positions were similar to the 1989 deployment positions (Fig. 1, lower).

1988 *late winter deployment*

In early March 1988, a pilot cruise was made to the western Gulf of Maine to map the developing spring halocline and deploy three near-surface drifters (Figs 2 and 3). Drifter 70 was deployed east of Nantucket Island on the western side of the GSC, and drifters 71 and 72 were deployed to the north of the GSC (upstream of where the large whale and zooplankton concentrations were believed to exist later during the month of May). Drifter 70 first moved along the northeastern flank of the GSC, then moved north and southwest during a southwestward wind event to complete an elongated closed path before continuing to move along the western flank of Georges Bank, and then southward over the top. Drifter 70 stopped transmitting in mid-June. Drifters 71 and 72 remained north of Cape Cod for 3–4 months, generally moving clockwise around Wilkinson Basin but without a well-defined circulation pattern. These two drifters were deployed farther north than any other SCOPEX drifters, and they finally moved eastward over the northeast flank of Georges Bank (along similar paths but at different times) and then across the shelf and shelfbreak near the Northeast Channel during late June and early July. These drifter observations imply that a dominant southward-flowing freshwater plume was not present over Wilkinson Basin in the western Gulf of Maine during early spring 1988, which is consistent with the hydrographic results presented by Chen *et al.* (1995b, 1995c).

1988 *spring deployment*

Ten near-surface drifters and six deep drifters were deployed in the GSC during April 1988. The near-surface drifter trajectories (Fig. 4, upper, and Fig. 5) indicate the near-surface flow in the southwestern GSC, west of 69°W and over Nantucket Shoals, was southward (mean speed ≈ 9 cm s^{-1}), with some water flowing out of the Gulf of Maine and onto the New England shelf proper. The near-surface flow in the central and eastern GSC, near and east of 69°W and over the western parts of Little Georges Shoal (the very shallow western part of Georges Bank), was eastward and northeastward, with some water flowing into the Gulf of Maine through the GSC (mean speed ≈ 10 cm s^{-1}) from the southern flank of Georges Bank. In the northwestern GSC, the flow split east of Nantucket Island near the 100-m isobath, with some water flowing southward out of the Gulf of Maine and some water flowing eastward to begin recirculating around Georges Bank. There also appeared to be a highly variable cyclonic near-surface circulation above the deepest part of Wilkinson Basin centered about 42°30′N, 69°30′W.

The deep drifters generally moved slower than the near-surface drifters in the northern GSC region (Fig. 4, lower). They initially moved southeastward and southward west of 69°W and then turned northeastward east of 69°W. Two drifters set in the western GSC entered a stagnation region of relatively low velocity near 41°30′N, 69°20′ W before moving towards Georges Bank. Three of the drifters moved along the northern flank of the bank and at least one drifter moved eastward over the northern flank (mean speed ≈ 12 cm s^{-1}) and along the 100-m isobath towards the eastern tip of the bank. Unfortunately, these drifters stopped transmitting before they left the Northeast Peak region.

1989 *spring deployment*

A total of 13 drifters with drogues centered near-surface at 5 m and six drifters with drogues centered at 50 m were deployed in the GSC during early June 1989. During the deployment, a regional CTD/ADCP survey was made by Limeburner and Beardsley (1989) to map the low-salinity surface plume usually observed east of Cape Cod in late spring. Chen *et al.* (1995b) found that a large surface plume of low-salinity water had formed southeast of Cape Cod, with minimum salinities less than 31 psu in its core. The plume extended eastward from the western side of the GSC and was approximately 10-m thick over most of its extent. At least five near-surface drifters were deployed into the plume.

The trajectories of the near-surface drifters deployed in 1989 (Fig. 6, upper and Fig. 7) showed a variety of spatial structures and preferred paths of flow in the southwestern GOM, which can be summarized as follows. During June–July 1989, the nearshore flow in the western GSC west of 69°W was southward and southwestward, with some water flowing out of the GOM and westward onto the New England shelf as was observed in 1988. Two drifters deployed near the coast of Cape Cod moved southward toward Nantucket Island, and one drifter initially entered Nantucket Sound but was soon advected eastward out of Nantucket Sound and then southward and southwestward around Nantucket Shoals. Other near-surface drifters deployed east of Cape Cod in water depths greater than 100 m moved southeastward toward Georges Bank and entered into the clockwise flow around the bank. Several drifters deployed in the northern GSC moved directly eastward and northeastward along the northern flank of Georges Bank, passing north of the 20-m crests of Cultivator and Georges Shoals before turning south and southwestward after passing the eastern end of the crest of the bank. These trajectories indicate that the near-surface flow east of Cape Cod and Nantucket Island split, with water inshore of 100 m generally flowing southward out of the Gulf of Maine and water offshore of 100 m flowing southeastward toward Georges Bank to eventually join the clockwise flow around the bank.

Over the northern flank of Georges Bank near 68°W, the eastward moving drifters entered a region where three different flow patterns were observed. Three drifters moved into a northward loop of 50–100 km diameter in the Gulf of Maine before re-entering the recirculation west of 67°W. Other drifters recirculating around Georges Bank moved along one of two common paths located over the eastern flank of the bank. The split in these paths near 42°N, 67°20′W may be associated with the long shallow sand ridge (water depths over the crest less than 20 m) that is oriented northwestward and located just west of the region avoided by the drifters.

Near-surface drifters on the southern flank of Georges Bank tended either to move southwestward along the 50–80 m isobaths before turning sharply northeastward to follow the same isobath band over the northwest flank of Georges Bank or to move off-bank. In the central GSC area most of the recirculating drifters in 1989 moved northward through the GSC east of its north–south axis (of maximum depth) which lies near 69°05′W (Fig. 8). Since many of these drifters entered this region in water less than the GSC sill depth of between 70 and 80 m (located near 40°33′N, 69°05′W), these drifters remained over the western flank of Georges Bank while moving northward through the GSC. Two drifters moved along the mid-shelf past the north–south axis before turning north and moving northeastward around Georges Bank. It is interesting to note that none of the near-surface drifters moved from the southern flank of Georges Bank onto the New England shelf as might be expected from continuity of shelf-water flow along the outer shelf (Beardsley *et al.*, 1985; Manning and Beardsley, 1996); instead, the drifters that circled the bank tended to move off the bank along its southern flank during fall.

The deep drifters (Fig. 6, lower) moved more slowly than the near-surface drifters in 1989. The three deep drifters deployed in the northern GSC and southern Wilkinson Basin region initially moved southeastward west of 69°W and then turned northeastward east of 69°W. One drifter followed a cyclonic path over Wilkinson Basin with a diameter of approximately

30 km and a period of 29 days. Another deep drifter began flowing eastward over the northern flank of Georges Bank, and then looped northward 90 km into the Gulf of Maine near 68°30′ before returning to the northern flank of the bank near 67°30′W. Two drifters followed a very similar path (but at different times) around the northeastern flank of the Georges Bank, and then moved offshore. One drifter moved around Georges Bank and then southwestward along the southern flank, but moved offshore near the GSC instead of recirculating or moving onto the New England shelf.

DISCUSSION

During the 1988–1989 SCOPEX field program, eight drifters with drogues centered near-surface at 5 m (two in 1988 and six in 1989) made a total of 16 complete circuits around Georges Bank (see Fig. 6, upper, for the trajectories). These drifters generally followed a narrower track over the western end of Georges Bank than over the eastern region, where at least two preferred tracks are seen. The geographical center of these trajectories is located at about 41°17′N, 68°00′W (denoted by the plus symbol in Fig. 9), about 30 km southwest of the topographic center of the bank. It is striking that none of the SCOPEX drifters ever passed into this shallow central region, which includes Little Georges Shoal and has an area of about 3500 km^2.

To facilitate statistical analysis, the complete drifter data set was truncated to include only position data from complete circuits around Georges Bank. If a drifter made one and a half circuits around the bank, only data from the first whole circuit were retained. This gave a total of 16 complete circuits around Georges Bank, which are plotted relative to the geometric center in Fig. 9, lower. The axes have been rotated 25° counterclockwise, so that the x and y coordinates (which reflect the orientations of the major and minor axes of the drifter positions) are aligned approximately in the along- and cross-bank directions, respectively. The major axis is about three times the minor axis, and there appears to be generally three paths of recirculation over the eastern flank of Georges Bank. A total of nine drifters followed the shortest inner track, five drifters the middle track, and two drifters followed the outer track. It also appears that during recirculation, some drifters deviated up to 50 km from the main track and made a loop or eddy before returning to the main track and continuing around the bank.

Previous work by Bumpus (1976) and Butman *et al.* (1987) describe an intensification with time in the mean clockwise circulation around Georges Bank during the stratified season. While the SCOPEX drifters suggest that the near-surface recirculation only occurs during the stratified season, there is little evidence that the period or length of time for a drifter to make a complete circuit changed significantly with time over the stratified season. The period of each drifter circuit is plotted against the duration of that circuit in Fig. 10. For the 16 complete circuits, the recirculation period ranged from 32 to 78 days, with a mean period of 48 days and a standard deviation of 11 days. The longest period, 78 days, occurred with one of the pilot drifters deployed in March 1988. This drifter slowly moved around the bank, often stalling for weeks, before beginning a persistent around-bank motion after day 170. The shortest period, 32 days, occurred from yearday 230–262, 1989. The limited data (Fig. 10) suggest that while the near-surface recirculation does not speed up significantly during the stratified season, all drifters stop recirculating by yearday 320. Two drifters deployed in 1989 actually made three complete circuits around Georges Bank before leaving the bank by December.

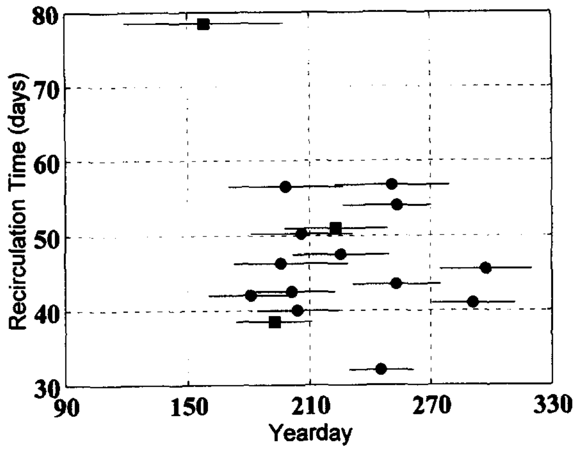


Fig. 10. The recirculation period or time taken in days for a drifter to make one complete circuit of Georges Bank plotted as a function of yearday. A solid square indicates the center of the period during 1988 and an solid circle marks the center of the period during 1989.

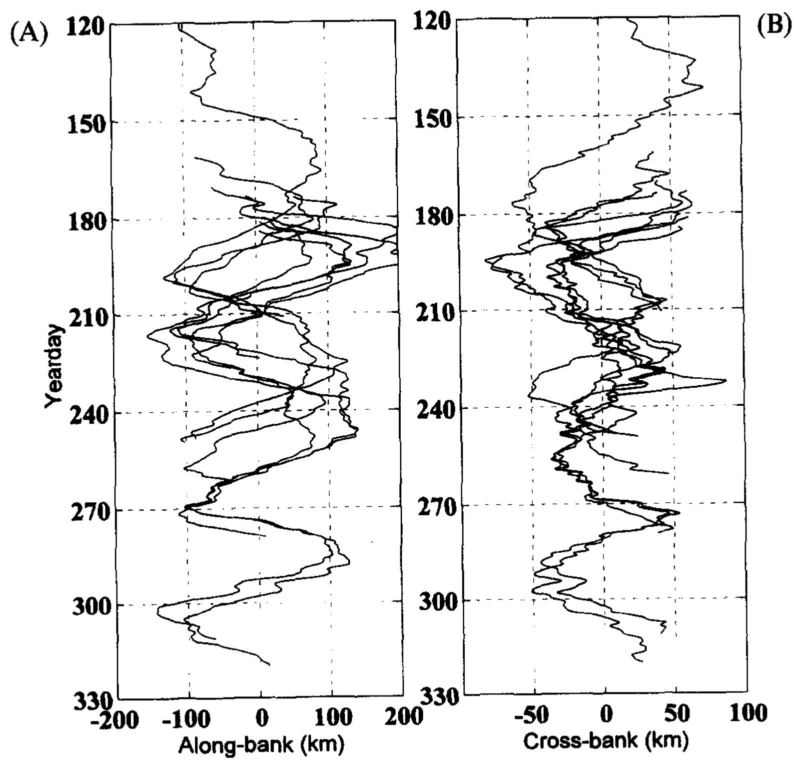


Fig. 11. Along-bank (A) and cross-bank (B) displacements of the eight recirculating drifters during 1988–1989 relative to the mean center of the recirculation on Georges Bank plotted vertically as a function of yearday. The along- and cross-bank directions correspond to the rotated x- and y-axes.

The relative movements of the eight recirculating drifters (Fig. 11) have an approximate periodicity of 40–60 days, consistent with the drifter recirculation periods (Fig. 10). Since the negative along-bank peaks and the positive cross-bank peaks are sharpest in Fig. 11, the drifters generally transited the eastern flank of Georges Bank more slowly than the western flank, and similarly the southern flank more slowly than the northern flank. Many of the drifters moved around Georges Bank as small groups with phase differences of less than 180° (as indicated by the clustering of the position time-series), which may reflect the limited area over which the drifters were originally deployed.

The position data of the recirculating near-surface drifters are replotted (Fig. 12, upper) as a function of radial distance of the drifter position from the geometric center of the eight trajectories and polar angle from the $+y$ direction, which is directed towards 335°T. The radial distance of the recirculating drifters from the geometric center varied from about 50 km over the northern and southern flanks of the bank to over 150 km over the eastern (around 90°) and western (around 270°) flanks. The largest radial distance (Fig. 9, upper), greater than 200 km, occurred for two drifters that followed a path close to the 80 m isobath

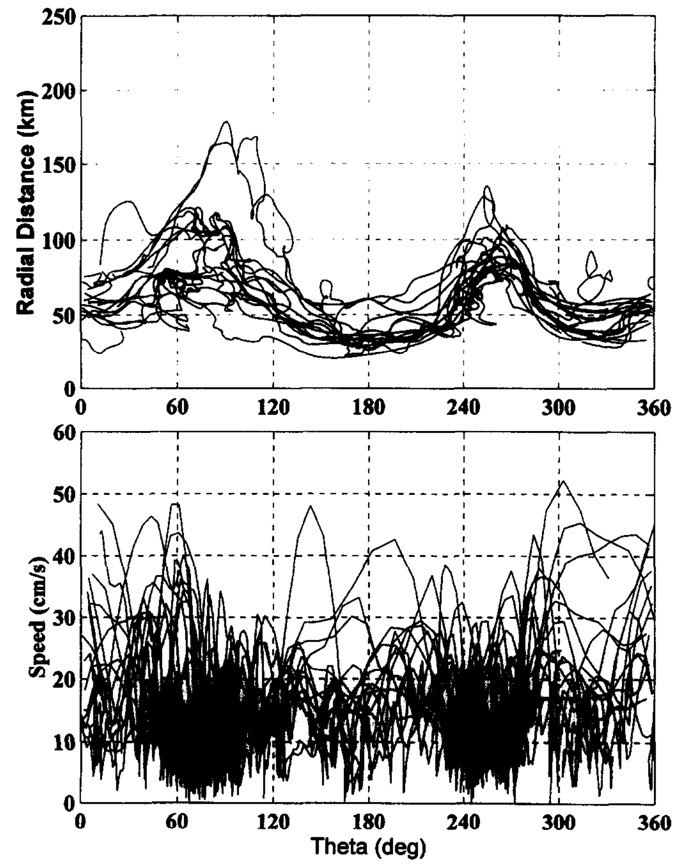


Fig. 12. Upper: the radial distance of a recirculating drifter to the mean center of the recirculation as a function of polar angle in the rotated coordinate system. Lower: drifter speed as a function of angular position. Each line corresponds to an individual circuit around the bank.

around the northeastern flank of the bank. Five other drifters followed a similar path around the eastern side at a radial distance of about 130 km.

The subtidal speed of the azimuthal flow component of each recirculating near-surface drifter is plotted in Fig. 12, lower as a function of polar angle. While the speeds were highly variable, there appears to be more observations of low speeds at angles of 80–120° and 250–290°, corresponding to the eastern and western flanks of the bank. The greatest speed is found over the northwestern flank (300°) of Georges Bank (Fig. 12, lower).

The recirculating drifter trajectories were separated into angular bins of 30° around Georges Bank. The mean east and north velocity components were converted to mean speed and direction, and the mean and standard deviation of the radial distance were calculated for each bin. The mean speed and direction (Fig. 13, upper) are shown as a vector plotted at the mean radial position for each bin. The average recirculation track was approximately oval-shaped with a major axis of about 200 km, a minor axis of 80 km, and a mean width of 38 km. The width of the recirculation track was greatest over the eastern flank of the bank due to the multiple paths in this region. The mean vector speeds, computed for each bin, were largest over the northern and southern flanks of the bank, with mean speeds of 15 and 13 cm s^{-1} in the 330–60° bin and the 120–240° bin (Fig. 13, lower). The maximum mean speed of 16 cm s^{-1} occurred in the 30–60° bin. The minimum mean speeds, between 7 and 8 cm s^{-1}, occurred at the easternmost tip of the bank and in the eastern GSC region. The mean speed averaged over all bins was 12 cm s^{-1}.

Animations of the drifters moving as a group around Georges Bank during 1988 and 1989 reveal characteristics of the flow field that are difficult to convey in a few static figures. For example, drifters often stagnated for periods of several days, remaining in a relatively fixed position except for strong tidal oscillations; drifters also often moved around Georges Bank in relatively coherent, non-dispersive groups, and suddenly separated into different recirculation paths or left the recirculating flow completely. Two drifters, separated by about 60 km in the along-bank direction over the southern flank, made nearly simultaneous single clockwise loops of radius 10–15 km during yeardays 292–296 (see Fig. 11). The cause of this coherent motion is unknown. The complete SCOPEX drifter and windstress data set and software to make animations are available from the authors over Internet (see Appendix for instructions) and on the CD-ROM accompanying this issue.

The surface wind field over Georges Bank has sufficient coherence that we can use the wind measurements made at the Nantucket NOAA environmental buoy 44 010 (40°30′N, 69°26′W) and the Large and Pond (1981) neutral drag law to crudely estimate the windstress in time along each recirculating drifter trajectory. Vector coherences computed between the drifter velocity and windstress while the drifters were over the bank were not significant (Crosby *et al.*, 1993), but qualitatively it appears that wind events can influence drifter movement over Georges Bank. For example, when drifter 43 was located on the eastern flank of the bank in late November 1989, an eastward windstress of about 5 dynes cm^{-2} veered southeastward for two days (yeardays 325–326) and drifter 43 moved quickly to the shelf break with a mean and maximum speed of 32 cm s^{-1} and 44 cm s^{-1}, then off-bank (Fig. 14, lower). After leaving the bank (200-m isobath), drifter 43 continued to move south and southeastward for about five days with typical speeds between 20 and 40 cm s^{-1}, until becoming entrained briefly in the Gulf Stream. During this period, there were no warm-core rings evident south of the bank in satellite imagery (J. Bisagni, personal communication, 1992). Drifter 51 also completed three complete circuits around the bank in 1989 and showed a similar response to the same strong windstress event (yeardays 325–

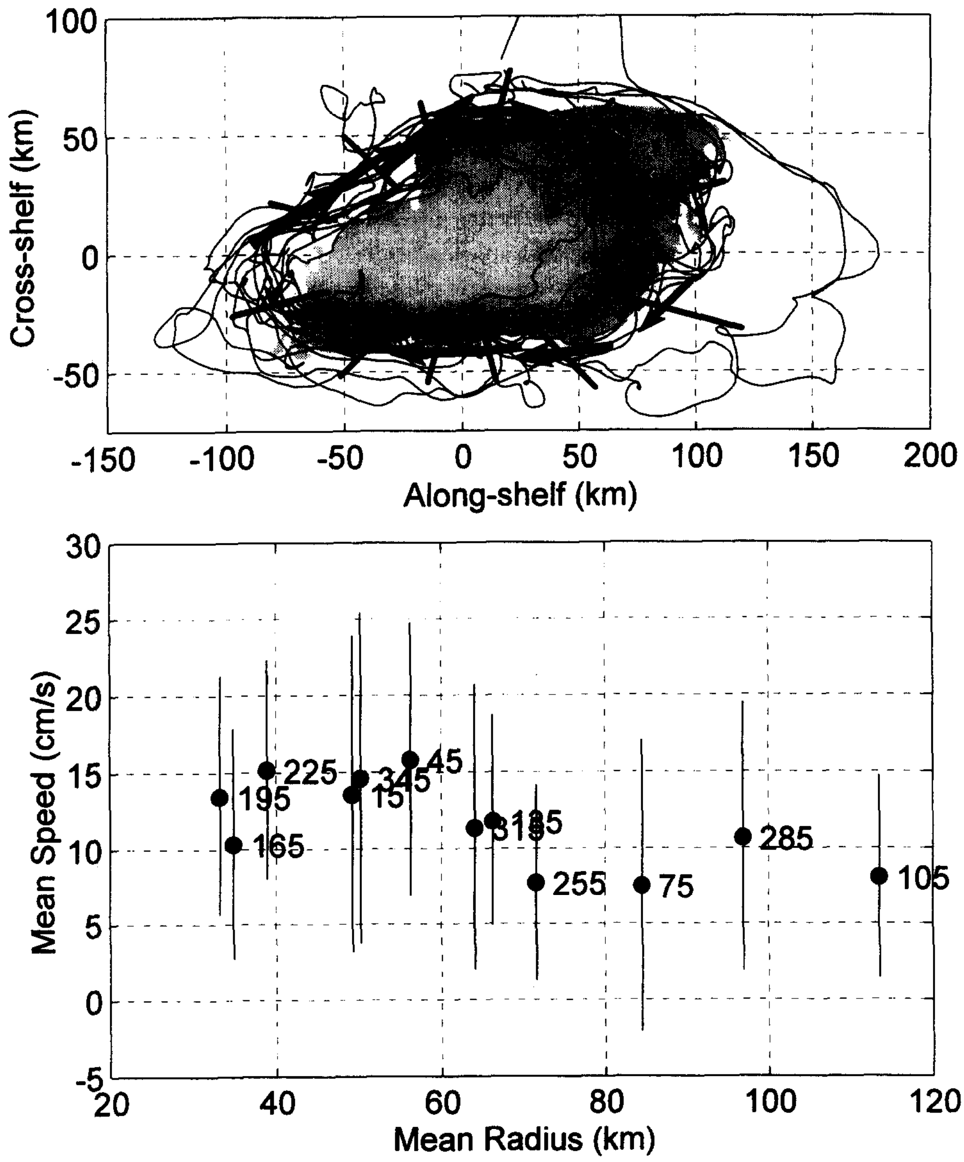


Fig. 13. Upper: the mean position and characteristic width (i.e. ± one standard deviation) and the mean velocity of the drifter recirculation tracks shown in sectors of width 30° around Georges Bank. The relative speed scale for the vectors shown is 20 cm s^{-1} = 50 km. Lower: mean (±one standard deviation) speed plotted as a function of the mean radius of the trajectories for each 30° bin, with the mid-point of each bin denoted.

326) in late November 1989 (Fig. 15, lower). It was located over the eastern flank of the bank at the start of the event and then moved off-bank during the event with a mean and maximum speed of 22 cm s^{-1} and 26 cm s^{-1}, and then continued off-bank, however, once drifter 51 reached about the 1000-m isobath, this drifter turned to the northeast, and entered the Northeast Channel before data transmission stopped within the 2000-m

isobath. The response of these two drifters to this wind event is qualitatively consistent with the theoretical ideas of Gawarkiewicz (1993), who studied the response of a highly idealized circular bank to strong wind forcing and found that the surface Ekman transport and the around-bank flow combined over the downwind right side of the bank to force surface water off the bank.

Other mechanisms (e.g. warm-core rings, entrainment features, frontal instabilities, topographic waves) must exist to disturb the near-surface recirculation, since other drifters left the recirculation around the bank along the southern flank without any clear linkage to strong wind events as evidenced by drifter 73 (Fig. 16, upper), drifter 47 (Fig. 15, upper), and drifters 56 and 58 (Fig. 17). Both drifters 73 and 58 left the bank towards its eastern end during periods when warm-core rings were located southeast of the bank (J. Bisagni, personal communication, 1992). On yearday 225, a large ring was located about 190 km southeast of where drifter 237 left the 200-m isobath; however, there is no clear evidence that the drifter became entrained in this ring. On yearday 289, a small ring and entrainment feature were located about 120 km southeast of where drifter 58 left the 200-m isobath. This drifter moved quickly across the outer bank with speeds as high as 40 cm s^{-1} on yeardays 287 and 288, but then slowed and stopped transmitting about 50 km southeast of the 200-m isobath.

On yearday 300, satellite imagery indicated that the shelfbreak front had been advected offbank towards the southeast, perhaps explaining the large offbank looping of drifter 56 just prior to yearday 300. Both drifters 47 and 56 left the bank south of Nantucket Shoals within three days and 25 km of each other. Drifter 56 crossed the 200-m isobath in yearday 321 and moved slowly eastward until yearday 324 when drifter 47 also left the bank, and both drifters quickly accelerated towards the southeast and east up to speeds greater than 150 cm s^{-1} by yearday 328. We guess that both drifters were entrained into the Gulf Stream since satellite imagery showed no rings south of the bank during yeardays 320–330. Drifters 76 (Fig. 16, lower) and 42 (Fig. 14, upper) stopped transmitting position data while they were still located within the recirculation track.

SUMMARY

Many of the near-surface drifters deployed in the Great South Channel in late spring in 1988 and 1989 became entrained in the clockwise gyre around Georges Bank, and eight drifters made a total of 16 complete circuits around the bank during the stratified season. The average recirculation period of these eight drifters was 48 ± 11 days, and the average drifter speed around the bank was 12 ± 8 cm s^{-1}. In general, these drifters moved faster over the northern and southern flanks of the bank, where the average speeds were 15 ± 10 and 13 ± 7 cm s^{-1}, respectively. There is no clear evidence from the drifter data that the strength of the clockwise gyre over the bank increased with time during the stratified season (May–October) as indicated from moored current data in other years.

The eight recirculating drifters followed a relatively narrow track around much of the bank; however, there appears to be at least three preferred paths over the eastern flank, perhaps due to a large northwest/southeast-oriented sand ridge found in this region. No drifters entered a shallow central area over the western crest of the bank. Strong wind events late in the year appeared to influence a drifter's trajectory around the bank, especially when the drifter was located over the eastern and southern flank of the bank during eastward winds.

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APPENDIX

Animations of the 1988 and 1989 Georges Bank drifter movements are available over the Internet World-Wide Web home page http://globec.whoi.edu/globec-dir/misc-data.html. The animations require a viewer, and sources of easy to install free viewers are given for workstations, PCs, and Mac systems. These animations, a simple PC viewer, and the basic low-passed drifter position and wind stress time-series data are included on the CD-ROM issued with this volume of *Deep-Sea Research II*.