

Recent Observations of the Mean Circulation on Georges Bank¹

B. BUTMAN

U.S. Geological Survey, Woods Hole, MA 02543

R. C. BEARDSLEY

Woods Hole Oceanographic Institution, Woods Hole, MA 02543

B. MAGNELL AND D. FRYE

EG&G, Environmental Consultants, Inc., Waltham, MA 02154

J. A. VERMERSCH

Exxon Production Research, P.O. Box 2189, Houston, TX 77001

R. SCHLITZ

Northeast Fisheries Center, National Marine Fisheries Service, Woods Hole, MA 02543

R. LIMEBURNER

Woods Hole Oceanographic Institution, Woods Hole, MA 02543

W. R. WRIGHT

Northeast Fisheries Center, National Marine Fisheries Service, Woods Hole, MA 02543

M. A. NOBLE

U.S. Geological Survey, Woods Hole, MA 02543

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ABSTRACT

A clockwise circulation around Georges Bank was measured by means of moored current meters, aircraft-tracked surface drifters, and satellite-tracked drifters drogued at 10 m. The strongest flow was in a narrow jetlike current (30 cm s^{-1}) along the northern flank of the bank. The flow of shelf water on the southern flank was westward (10 cm s^{-1}) toward the Middle Atlantic Bight; some of this water flowed northward through the eastern side of Great South Channel and recirculated around Georges Bank. The satellite-tracked drifters and the moored observations indicate that the circulation around the bank was not completely closed and considerable variability occurs in the trajectory of an individual water particle.

1. Introduction

Georges Bank is a shallow submarine bank along the seaward edge of the Gulf of Maine (Fig. 1). The bank is $\sim 300 \text{ km}$ long, 150 km wide, and is separated from Nantucket Shoals by the shallow ($\sim 70 \text{ m}$ deep) Great South Channel. Seaward of approximately the 70 m isobath, the Georges Bank shelf is continuous with the New England shelf to the west. To the north-

east, Georges Bank is separated from the Scotian shelf by the deep (220 m) Northeast Channel which cuts across the outer shelf to the shelf break. The crest of the bank (shallower than 60 m) is shaped into a series of northwest-trending ridges; the tops of some of these ridges are less than 5 m deep.

The water on the crest of Georges Bank (depths shallower than 60 m) is vertically well mixed throughout the year by the strong semidiurnal tidal currents (Colton *et al.*, 1968; Bumpus, 1976; Garrett *et al.*, 1978). In winter, two fronts separate the well-2c). On the southern flank of the bank, the shelf-

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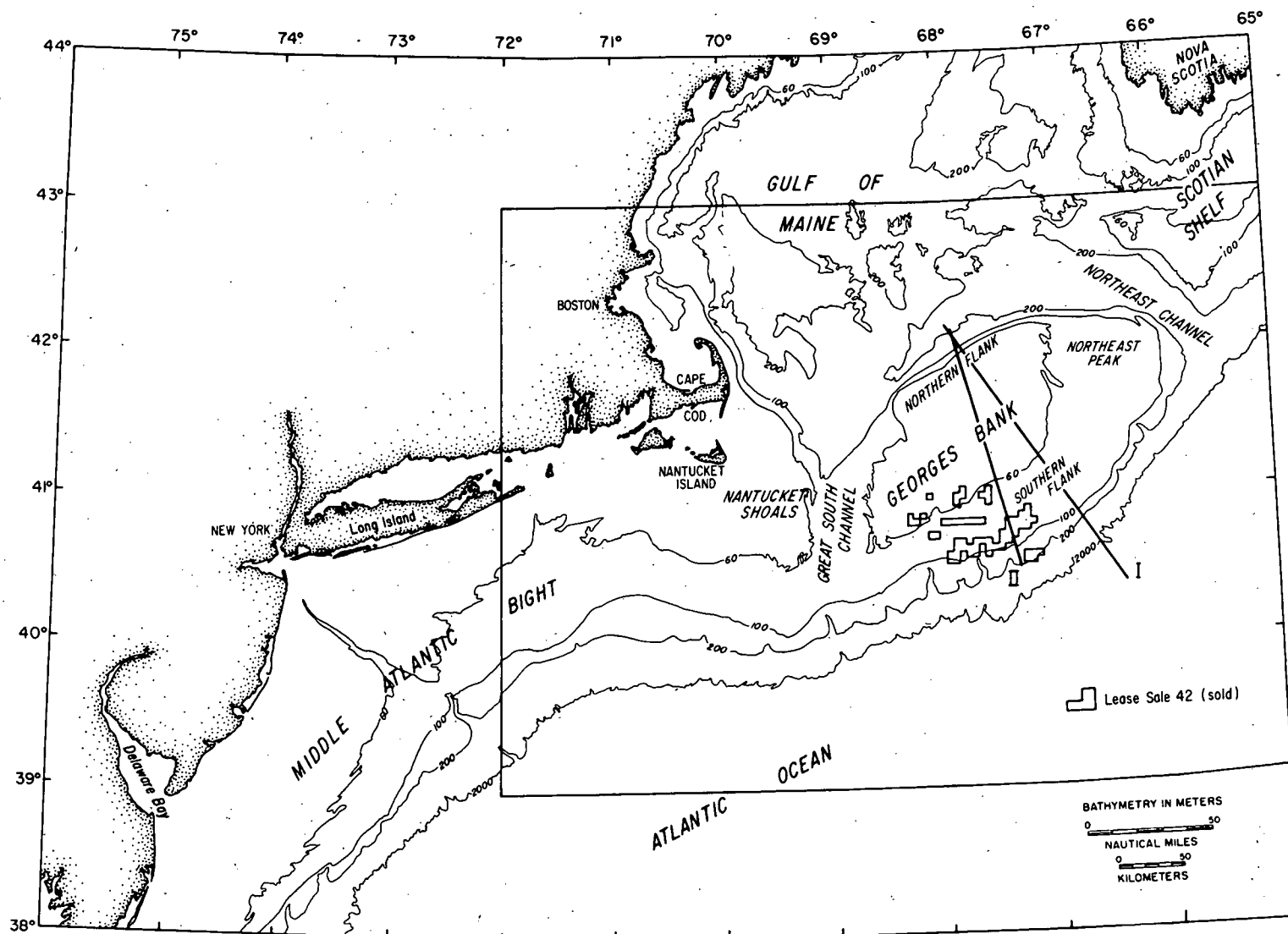


FIG. 1. Map showing the location of Georges Bank on the United States east coast Continental Shelf. The topography is simplified from Uchupi (1968). Water depths on the crest of the bank are less than 5 m in some places. The tracts leased for oil and gas exploration in lease sale 42 are shown along the southern flank of the bank. The boxed area indicates the bounds of the base map used in Figs. 4-7 to present the results of this study.

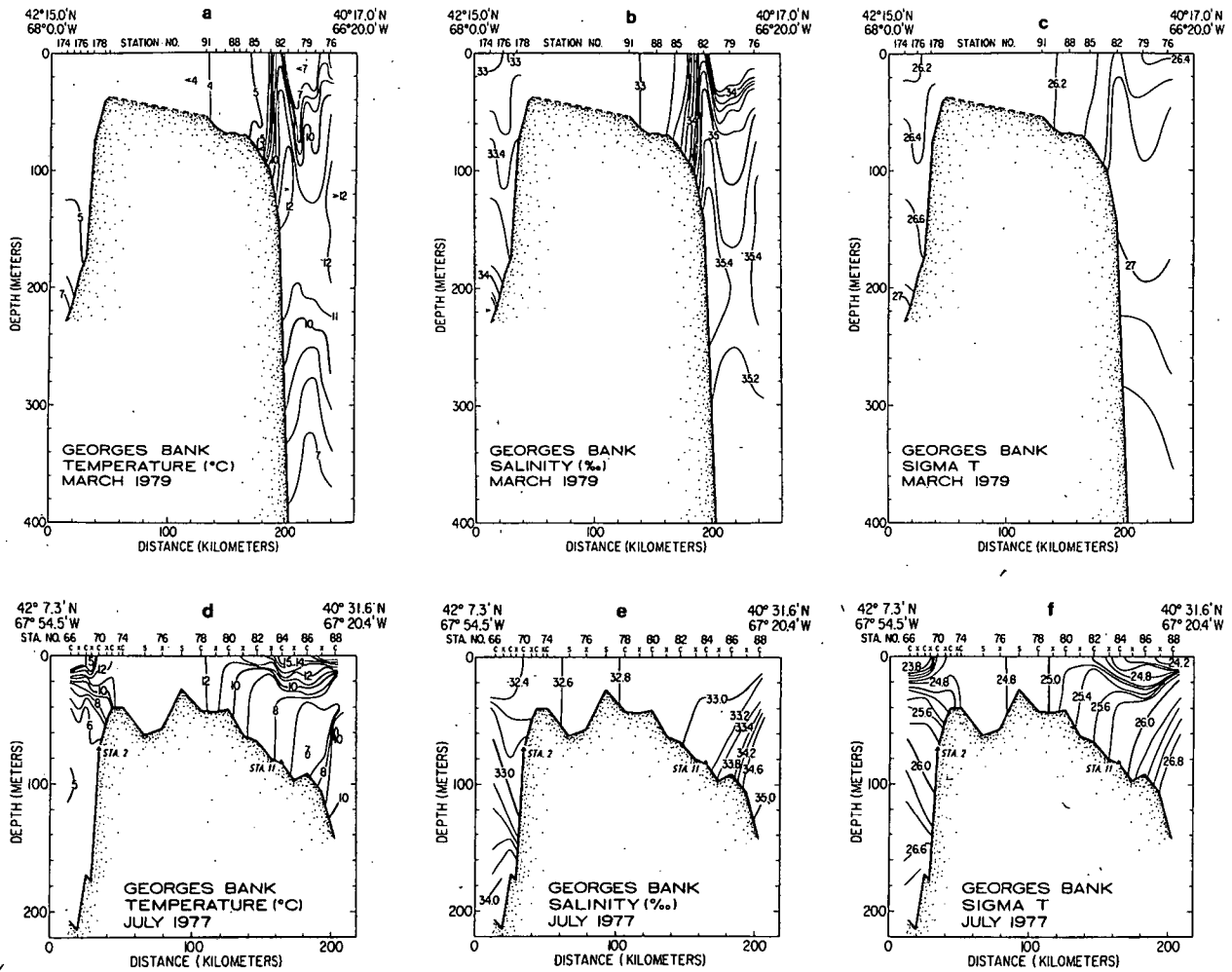


FIG. 2. Typical hydrographic sections across the crest of Georges Bank (looking toward the northeast). (a)–(c). Winter sections of temperature, salinity and sigma- t showing well-mixed water on the crest and on the northern and southern flanks to water depths of 80–100 m. Note the weak salinity and temperature gradients along the north flank in contrast to the strong shelf-water/slope-water front along the southern flank. These sections were taken in March 1979 at the winter temperature minimum (redrawn from EG&G, 1979b). Section location marked I in Fig. 1. (d)–(f). Summer sections of temperature, salinity and sigma- t showing well-mixed water on the crest, tidal fronts at ~ 40 m on the northern flank and at ~ 60 m on the southern flank, the cold band on the southern flank where water core temperatures are less than 7°C , and the shelf/slope-water front which intersects the shelf at ~ 80 m. These sections were taken on 8–9 July 1977. (X indicates stations with temperature observations only, C indicates stations with temperature, salinity and density observations). Section location marked II in Fig. 1.

water/slope-water front intersects the bottom at ~ 80 m and separates cooler, fresher shelf water from warmer, more saline slope water. The shelf-water/slope-water front is similar in structure and continuous with the front at the shelf break in the Middle Atlantic Bight (see Beardsley and Flagg, 1976; Wright, 1976; Mooers *et al.*, 1979). On the northern flank, a second, weaker and deeper front separates Georges Bank water from Gulf of Maine water. In summer (see Figs. 2d–2f), a seasonal thermocline develops over the Gulf of Maine, the slope water, and the water deeper than 60 m on the southern flank. A tidally mixed front forms at approximately the 60 m isobath. A subsurface band of cool water

occurs along the southern flank between the 60 and 100 m isobaths, bounded by the warmer slope water to the south, the warmer well-mixed Georges Bank water to the north, and the seasonal thermocline above.

Studies of the currents on Georges Bank and in the Gulf of Maine using surface and bottom drifters have been conducted to measure the seasonal mean circulation (Bigelow, 1927; Bumpus and Lauzier, 1965; Bumpus, 1973, 1976). These studies have shown a residual counterclockwise circulation in the Gulf of Maine and a clockwise circulation around Georges Bank at speeds of $\sim 5\text{--}10\text{ cm s}^{-1}$ (see Fig. 3). Westward and northward flow into the Gulf of

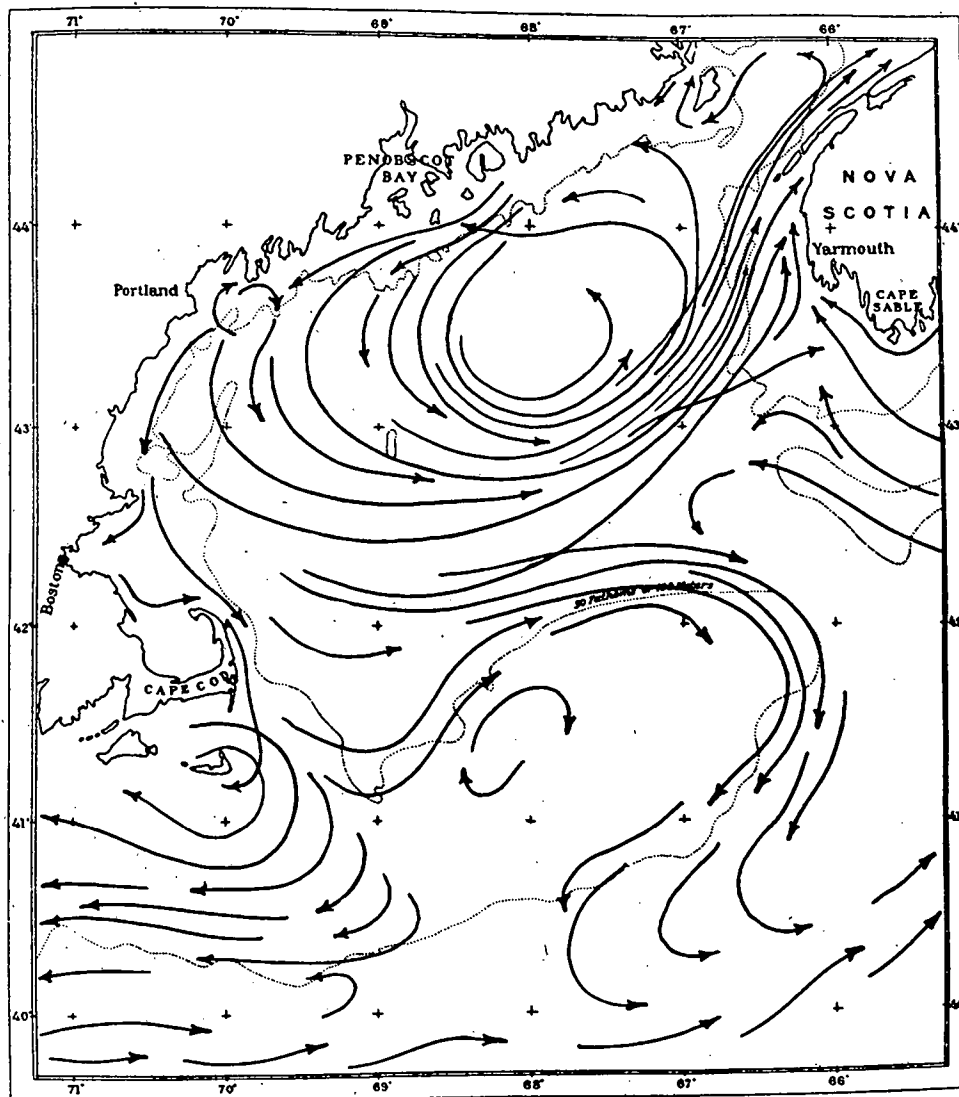


FIG. 3. Bigelow's schematic map of the summer near-surface flow in the Gulf of Maine and on Georges Bank (from Bigelow, 1927).

Maine south of Nova Scotia and southwestward flow out of the Gulf across Nantucket Shoals south of Cape Cod was observed in all seasons. The counter-clockwise circulation in the Gulf of Maine and the clockwise circulation around Georges Bank were strongest in the spring. In summer, the surface circulation in the Gulf of Maine weakened and surface flow at the eastern end of Georges Bank was slightly offshore. In winter, the drift bottle recoveries suggested an offshore southerly flow across Georges Bank and the Gulf of Maine and a continued westerly drift across Great South Channel. Recent measurements conducted on the shelf to the west of Nantucket Shoals and in the Middle Atlantic Bight (MAB) have shown a consistent westward subsurface residual drift of shelf water at speeds of 5–10

cm s^{-1} along the middle and outer shelf (Beardsley *et al.*, 1976; Mayer *et al.*, 1979; Beardsley and Boicourt, 1981). The southwestward flow along the southern flank of Georges Bank is apparently continuous with the southwestward flow in the MAB. Georges Bank is thus the source of much of the water in the MAB and processes on Georges Bank partially determine properties of that water as it enters the MAB south of Nantucket Shoals.

Conceptually, the currents may be divided into a seasonal-mean current, low-frequency current fluctuations (associated with density effects, wind stress, topographic waves, and the ocean circulation), diurnal and semidiurnal tidal currents, and higher frequency current fluctuations associated with surface and internal waves. The previous current drifter stud-

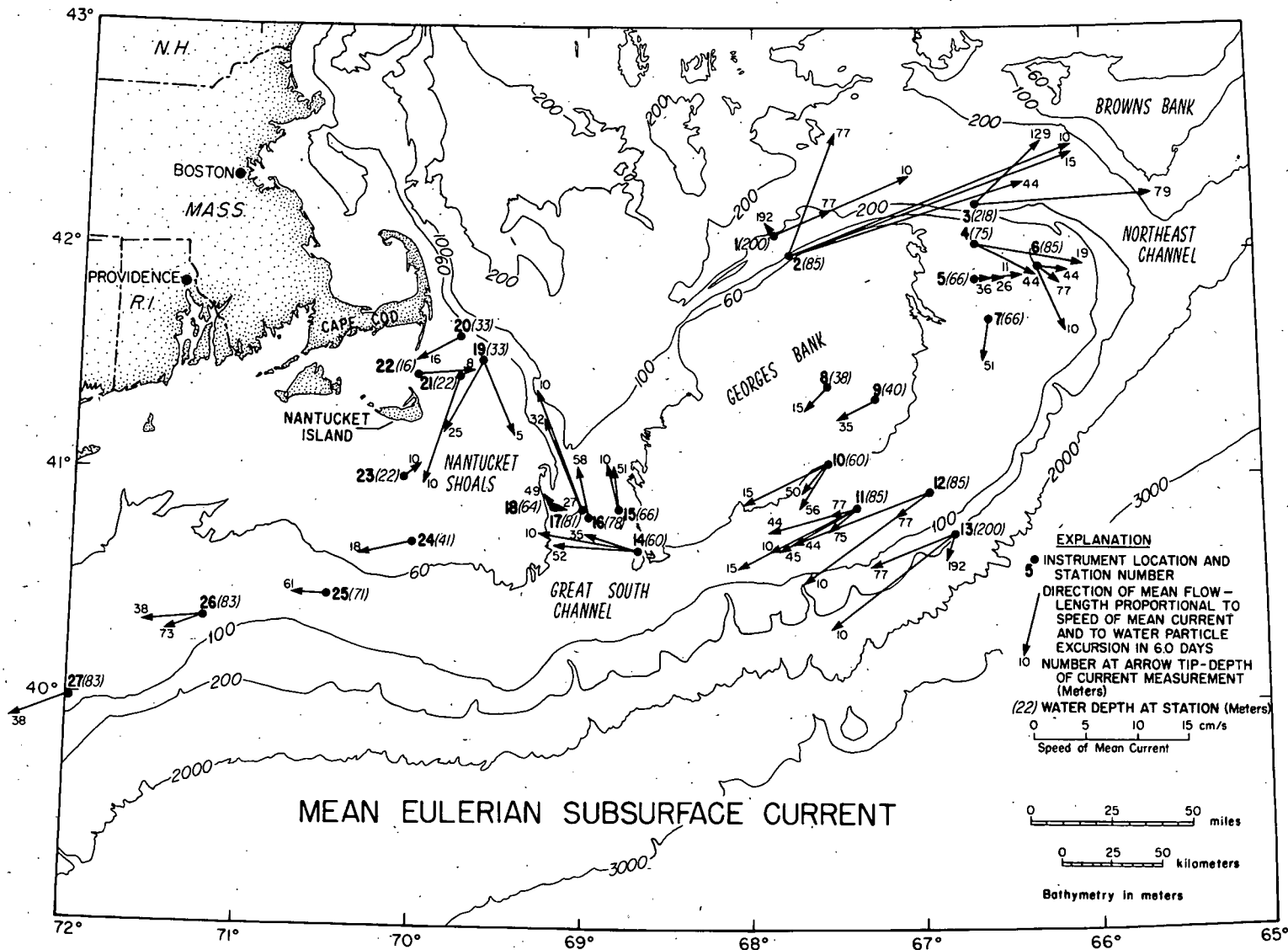


FIG. 4. Mean Eulerian current measurements. The boldface number at origin of vector keys measurement to data in Table 1. The number in parentheses following identifier indicates water depth at that station. The number at the tip of the vector indicates the depth of measurement in meters. The length of the vector is proportional to the mean current speed. The speed scale is such that the length of the current vector is equivalent to the mean displacement of a water particle during a 6-day period at map scale or a 30-day excursion at five times map scale. The current measurements were not synoptic nor of equal duration but are compiled from measurements of varying length (1 month minimum) made at different times during the 4-year period, 1975-79. See text for a discussion of the seasonal variations of the mean flow.

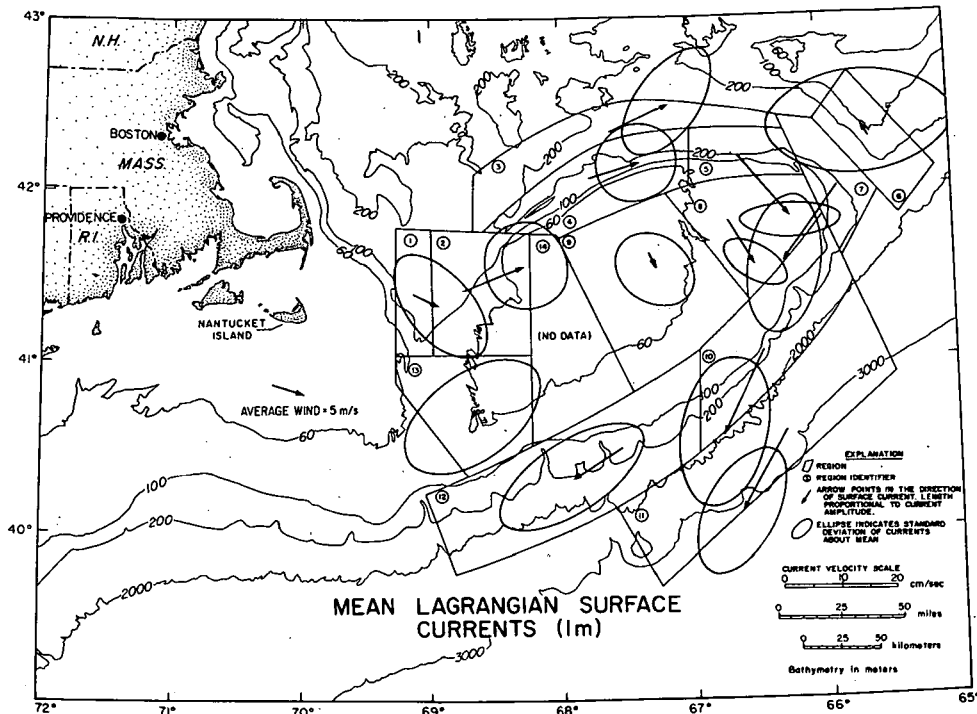


FIG. 5. Surface currents (1 m depth) determined from aircraft-tracked drifters in various regions of Georges Bank (see Table 2 for details of the observations). Each vector represents the mean current for all drifters within that region. The standard deviations of current in each region are represented by the half-axis lengths of the ellipses. The ellipse orientations were chosen to maximize the variance along the major axis. The size of the ellipse relative to the mean vector is a measure of the reliability of the estimate of the mean and is not a measure of the low-frequency variability of the surface currents. The surface circulation map is derived from a limited data set which comprises the only observations of the very near surface currents. These mean velocity estimates may contain a systematic bias because aircraft-tracking operations could only be conducted during fair weather which generally corresponded to north-westerly wind conditions. This figure is redrafted from EG&G (1979a).

ies inferred only the surface and bottom residual circulation averaged over several months and could not be used to describe either higher frequency currents or currents in the water column. The first direct Eulerian current measurements and additional Lagrangian measurements on Georges Bank and the adjacent shelf were obtained in several field studies conducted from 1975-79 (see the Appendix) designed to investigate the general circulation and current dynamics. These are the first Eulerian current measurements made on Georges Bank since the current-pole measurements of Haight (1942) and the first long-term continuously tracked Lagrangian measurements. This paper presents a description of the observed mean current field obtained from these recent measurements.

2. Field programs

Moored current meters were used to measure the Eulerian current field at depths deeper than 10-15 m from the surface. Aircraft- and satellite-tracked drifters were used to measure the surface and near-surface Lagrangian current field at depths of 1-10 m.

a. Near-surface and subsurface Eulerian measurements

Eulerian current measurements using moored, self-recording current meters were made at 27 locations on Georges Bank, Nantucket Shoals, and the adjacent shelf during 1975-79 (Fig. 4). Most near-surface (depths <15 m from the sea surface) Eulerian measurements were made by instruments suspended beneath slack-moored surface-following buoys. Subsurface measurements at depths >15 m were made with instruments supported on taut subsurface moorings; the mooring flotation was usually placed as deep as possible to minimize wave contamination—typically ~2-3 m above the shallowest instrument. The current meters used were primarily AMF (now EG&G) Vector Averaging Current Meters² (VACM), which have Savonius rotor and small vane current sensors. Other current meters used were the EG&G 102 film recording current meter (which

² Use of brand names in this report is for descriptive purposes only and does not constitute endorsement by the U.S. Geological Survey or the National Marine Fisheries Service.

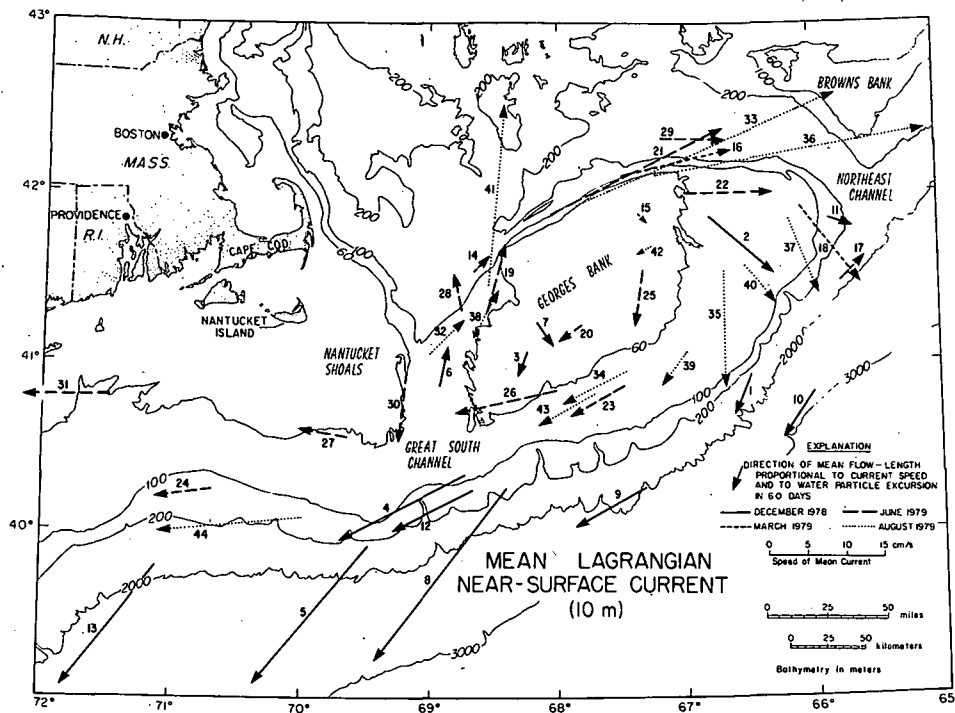


FIG. 6. Representative velocity vectors derived from satellite-tracked drifters deployed with 10 m window-shade drogues centered at 10 m depth. The boldface number keys the measurements to Table 3. Although Fig. 6 suggests a relatively simple picture of the mean circulation, the averaging interval was different for each velocity estimate and the estimates were not synoptic. Because the drifters tended to avoid certain areas of the bank (notably the northwestern shallow area), the spatial density of the velocity estimates is not uniform, and the resulting picture of the circulation probably overemphasizes high velocities. (Data adapted from EG&G, 1980.)

uses current sensors similar to the VACM), the small Savonius rotor and large vane Aanderaa RCM-4 current meter, and the tethered ENDECO propeller current meter. Some of the current measurements were made by a specialized system developed by Raytheon, Inc. using Marsh-McBirney electromagnetic current sensors and *in situ* data averaging and data telemetry (Lobecker *et al.*, 1978). [See Saunders (1976) and Beardsley *et al.* (1981) for a discussion of the accuracies of these instruments. EG&G (1980) presents a comparison of measurements obtained by a VACM and the Raytheon system.] Lighted surface guard buoys were deployed at most mooring sites to mark the instrument locations and to provide some security to the subsurface moorings from fishing activity in the area.

Spatial coverage was greatest on the southern flank of Georges Bank, on the northeast end of the bank, and in the Great South Channel. Fewer current measurements were made on the southeast and southwest corners, the crest of the bank, and along the northern flank. Several positions were maintained as long-term stations to monitor currents for several years to determine seasonal changes in the current structure. Most stations were part of separate local moored-array experiments and were typically occu-

ried only once for a relatively short period of 1–6 months. One month is the minimum averaging period for the mean measurements included in this paper. Recent measurements of currents in the Northeast Channel have not been included in this study because they were made at depths below 100 m from the surface (Ramp *et al.*, in preparation).

b. Surface and near-surface Lagrangian measurements

Lagrangian surface-current measurements were made by surface drifters tracked from aircraft and near-surface measurements by drogues tracked by satellite. Surface drifters, manufactured by Eotech, Inc., were used to measure the currents in the top 1 m of the water column (EG&G, 1978). Six surface-drifter studies were conducted (October–November 1977, January–February 1978 and May–June 1978). In each study about six drifters were deployed in a line at five locations around the bank. In each line, the drifters were spaced 5–15 km apart. The studies lasted 3–6 days during which the drifters were re-located about three times by aircraft using Loran-C navigation. Velocity estimates were determined from the sequential drifter positions. Drifter velocities

TABLE 1. Eulerian current statistics. The data in this table and in Fig. 4 are organized by site number. The primary group that collected the data is indicated in parentheses next to the site number; the acronyms are explained in the Appendix. The instrument type code is: VACM, AMF Vector Averaging Current Meter; 102, EG&G model 102 current meter; 850, Geodyne model 850 current meter; RCM4, Aanderaa current meter; RAY, Marsh-McBirney electro-magnetic meter mounted on a special buoy fabricated by Ratheon Ocean Systems; END, Endeco model 174 current meter. The mooring code is: S, surface mooring; SS, subsurface mooring; and SPEC, the special Raytheon buoy. The current statistics have been computed at most sites in a subjectively determined longshelf/cross-shelf rotated coordinate system. The coordinate orientation angle θ indicates the clockwise rotation of the new primed coordinate system, so that θ is the angle between true north and the new north component, N' . E' and N' are aligned with true east and north when $\theta = 0$. Both the total standard deviation computed from vector averaged 1 h time series and the low-frequency (LF) standard deviation computed from a low-passed time series are presented. The low-pass filters used typically had a half-power cutoff frequency of 0.03 cph. The standard error in each component was computed using the LF standard deviation, the record length, and an assumed correlation time scale for all data of 5 days. (The correlation time scale at station 11 ranged from 1.5 to 7 days.) SD is standard deviation.

Site no.	Lat. N Long. W	Water depth (m)	Instrument depth (m)	Instrument type	Mooring type	Measurement start-stop time*	Record length (days)	Coordinate angle (deg)	E'			N'		
									Mean (\pm SE)	Low-frequency SD (cm s^{-1})	Total SD	Mean (\pm SE)	Low-frequency SD (cm s^{-1})	Total SD
1 (EG&G)	42°04.5' 67°52.4'	200	10	VACM	S	780106-780207 780727-780926 790418-790622	150	62	1.2 (1.3)	7.4	21.5	14.0 (2.8)	15.6	25.5
		200	77	102	SS	780107-780509 780511-780725 790420-790716	277	62	0.6 (0.5)	4.1	10.8	5.8 (0.9)	7.0	8.8
		200	192	102& RCM4	SS SS	770922-780509 780512-780813 781110-790101 790418-790716	450	62	-1.3 (0.5)	4.4	19.5	-0.3 (0.7)	6.4	11.6
2 (EG&G)	41°59.0' 67°47.0'	85	10	VACM	S	780106-780126 780423-780720 790418-790717	191	62	3.5 (0.9)	5.8	26.7	29.5 (1.6)	9.9	20.4
		85	44	102	SS	780423-780720 790717-790927	161	62	4.4 (0.9)	5.4	25.7	23.4 (1.4)	8.2	17.7
		85	77	102	SS	770922-780106 780423-780720 790717-790927	264	62	-8.4 (0.8)	5.5	26.5	9.7 (0.8)	6.2	15.0
(USGS)	41°59.0' 67°47.1'	85	15	VACM	S	760401-760816	114	65	2.6 (0.9)	4.4	27.8	29.1 (1.8)	8.7	20.5
3 (NMFS)	42°12.5' 66°40.8'	218	79	VACM	SS	780915-781102	45	0	17.1 (1.5)	4.6	37.1	1.1 (1.3)	3.9	31.8
			129	VACM	SS	780915-781102	45	0	6.6 (1.7)	5.2	22.3	6.0 (1.4)	4.3	34.6
4 (NMFS)	42°02.0' 66°40.8'	75	19	VACM	S	780914-781103	46	0	10.3 (1.8)	5.7	50.1	-2.0 (1.4)	4.4	64.2
			44	VACM	SS	780914-781103	46	0	5.8 (1.2)	3.8	39.9	-2.9 (1.1)	3.4	51.4

5 (NMFS)	41°52.6' 66°41.2'	66	11	VACM	S	780914-781114	58	0	4.6 (1.7)	5.9	49.4	0.4 (1.0)	3.6	61.7	
			26	VACM	SS	780914-781114	58	0	2.7 (1.1)	3.7	45.8	0.1 (0.8)	2.8	55.3	
			36	VACM	SS	780914-781114	57	0	1.5 (0.9)	3.0	43.0	0.1 (0.8)	2.6	49.8	
6 (EG&G)	41°56.0' 66°20.0'	85	10	VACM	S	790417-790728	99	62	6.7 (1.2)	5.5	61.2	-0.6 (1.6)	7.3	45.4	
			44	102	SS	790417-790527	37	62	1.7 (0.7)	1.9	60.2	2.4 (1.0)	2.8	38.2	
			77	102	SS	790418-790825 790828-791017	174	62	2.3 (0.9)	5.5	44.9	1.2 (0.6)	3.8	25.9	
7 (USGS)	41°41.8' 66°36.2'	66	51	VACM	SS	781001-790311	162	0	-0.7 (0.8)	4.7	38.5	-3.8 (0.8)	4.4	44.5	
8 (USGS)	41°24.0' 67°34.1'	38	15	VACM	S	760401-760816	136	61	0.9 (0.3)	1.4	55.7	-3.1 (0.5)	2.5	42.3	
9 (EG&G)	41°24.0' 67°16.9'	40	35	VACM	SS	780423-780815	114	62	-0.1 (0.3)	1.5	46.7	-4.2 (0.7)	3.2	33.7	
10 (USGS)	41°02.2' 67°33.5'	60	15	VACM	S	781002-781201 790315-790804 790811-791214	328	64	0.0 (0.5)	4.1	41.9	-10.2 (0.8)	6.6	30.0	
			50	VACM	SS	790324-790625 790812-790910	116	64	1.3 (0.4)	2.0	33.9	-3.2 (0.8)	3.6	21.9	
			56	VACM	SS	780121-780509	108	64	2.6 (0.4)	1.9	31.4	-4.3 (1.2)	5.6	21.4	
11 (USGS)	40°51.4' 67°24.1'	85	15	VACM	S	750919-751204 770710-770917 780126-780305 780513-780919	324	58	-1.3 (0.8)	6.1	29.5	-13.0 (2.0)	16.0	25.9	
			85	45	VACM	SS	750509-750831 750919-760114 760818-780509 781003-790228	1,007	58	-0.6 (0.3)	4.0	29.7	-8.6 (0.8)	11.4	23.6
			85	75	VACM	SS	750510-750725 750919-760102 760818-790309	1,113	58	0.4 (0.2)	3.3	25.0	-3.6 (0.4)	6.5	17.2
(EG&G)	40°51.2' 67°24.2'	85	10	RAY	SPEC	780605-780801 781116-790220 790303-790317	172	62	-0.3 (1.1)	6.7	28.1	-9.4 (1.2)	7.3	21.6	
			85	44	RAY	SPEC	771102-771120 781116-790220 790303-790317	147	62	-2.1 (0.9)	4.8	31.3	-8.8 (1.3)	7.1	23.2
			85	77	RAY	SPEC	780605-780914 781116-790220	206	62	-0.6 (0.6)	3.8	24.6	-2.6 (0.9)	6.0	17.1

TABLE 1. (Continued)

Site no.	Lat. N Long. W	Water depth (m)	Instrument depth (m)	Instrument type	Mooring type	Measurement start-stop time*	Record length (days)	Coordinate angle (deg)	Mean (\pm SE)	E'		N'		
										Low-frequency SD (cm s^{-1})	Total SD	Mean (\pm SE)	Low-frequency SD (cm s^{-1})	Total SD
12 (EG&G)	40°55.9' 66°58.2'	85	10	RAY VACM	SPEC S	780618-780828 780908-781210 781230-790507	285	62	1.9 (0.7)	6.6	29.4	-15.2 (1.1)	8.6	22.8
		85	44	RAY 102	SPEC SS	780618-780828 780908-790111 790223-790506 790520-790616 790817-791017	341	62	-2.0 (0.7)	5.6	26.5	-14.4 (1.1)	9.0	21.3
		85	77	RAY RAY 102	SPEC SPEC SS	771205-780106 780618-780828 780908-790110 790223-790418 790508-791017	459	62	0.6 (0.4)	3.9	21.6	-4.1 (0.7)	6.4	15.5
13 (EG&G)	40°43.7' 66°49.0'	200	10	VACM	S	780908-790128 790829-791017	185	62	2.4 (1.6)	9.9	22.1	-15.0 (2.5)	15.0	23.7
		200	77	102	SS	780908-790105 790128-791017	373	62	-1.0 (0.4)	3.9	12.3	-8.7 (1.3)	11.3	16.4
		200	192	RAY 102& RCM4	SPEC SS	780617-780816 780908-790110 790128-790428 790507-790801	348	62	1.8 (0.6)	4.7	19.2	-2.0 (1.3)	11.0	16.4
14 (EG&G)	40°40.0' 68°42.0'	60	10	VACM	S	781109-790115 790524-791016	267	62	-6.1 (0.7)	5.4	50.2	-7.4 (1.0)	7.6	29.8
		60	35	102	SS	781109-790111 790717-791016	158	62	-3.8 (0.7)	4.0	47.1	-3.6 (1.1)	6.2	25.9
		60	52	102	SS	790717-791916	99	62	-4.4 (0.5)	2.4	35.7	-6.8 (0.9)	3.9	17.3
15 (USGS)	40°50.8' 68°48.5'	66	10	VACM	S	780930-790318	169	22	-2.6 (0.9)	5.3	27.8	3.7 (1.4)	8.1	53.7
		66	51	VACM	SS	780930-790129	121	22	-2.0 (0.5)	2.6	24.6	3.7 (1.5)	7.6	43.9
16 (USGS)	40°49.0' 69°00.0'	78	58	VACM	SS	760401-760709	99	16	-2.3 (0.5)	2.1	14.7	4.5 (1.2)	5.3	43.1
17 (WHOI)	40°50.8' 69°01.0'	81	10	VACM	S	780902-781217	107	8	-6.1 (1.8)	8.5	24.2	10.6 (1.8)	8.2	56.3
		81	32	VACM	SS	780902-790129	149	8	-4.9 (1.2)	6.5	22.0	8.1 (1.9)	10.2	55.5

18 (WHOI)	40°52.0' 69°11.0'	64	27	VACM	SS	780904-790128	146	0	1.0 (0.8)	4.2	23.3	-0.3 (1.4)	7.6	47.4
		64	49	VACM	SS	780904-790128	146	0	-1.0 (0.8)	4.3	22.2	1.1 (1.2)	6.4	37.8
19 (WHOI)	41°30.4' 69°35.9'	33	5	END	SS	790117-790318	60	0	3.2 (2.5)	8.6	12.9	-7.2 (3.3)	11.3	52.6
		33	25	END	SS	790117-790318	60	0	-3.7 (1.6)	5.6	9.6	-7.0 (2.2)	7.7	46.3
20 (WHOI)	41°36.4' 69°43.8'	33	16	END	SS	790718-790828	41	0	-4.4 (1.5)	4.4	19.6	-2.3 (1.4)	4.1	32.6
21 (WHOI)	41°26.0' 69°44.1'	22	10	END	SS	790718-790828	41	0	-3.3 (0.5)	1.5	28.9	-10.5 (0.9)	2.5	48.3
22 (WHOI)	41°26.6' 69°59.2'	16	8	END	SS	790718-790828	41	0	5.8 (1.0)	2.9	36.9	0.5 (0.5)	1.5	12.6
23 (WHOI)	40°59.0' 70°04.0'	22	10	END	SS	790719-790828	41	0	1.6 (0.8)	2.4	37.4	1.3 (0.9)	2.7	31.2
24 (USGS)	40°42.5' 70°00.5'	41	18	850	SS	761230-770213	45	23	-4.2 (4.3)	13.0	29.1	-3.0 (1.6)	4.9	21.9
25 (USGS)	40°29.0' 70°30.2'	71	61	VACM	SS	781101-790215	106	18	-3.2 (2.3)	10.7	14.0	-0.9 (1.2)	5.7	10.7
26 (WHOI)	40°21.7' 71°12.0'	83	38	VACM	SS	760223-760703	131	67	1.8 (0.8)	4.1	8.1	-5.8 (1.3)	6.9	10.2
		83	73	VACM	SS	760223-760430	67	67	0.2 (0.8)	3.1	9.3	-4.0 (2.4)	8.9	10.7
27 (WHOI)	39°58.9' 71°57.4'	83	38	VACM	SS	760223-760809	168	58	1.2 (0.6)	3.2	3.0	-6.0 (1.4)	8.2	11.1

* Six-number code: year, month, day.

TABLE 2. Lagrangian current statistics for the aircraft-tracked surface drifters (Fig. 5). The measurements are presented by deployment period and geographical region. In each experiment, velocity estimates were determined from the observed sequential surface drifter positions and corrected for direct wind effects by subtracting 1% of the estimated wind velocity. The velocity estimates were determined over different averaging intervals because of the operational difficulty in relocating drifters on successive days; 68% of the velocity estimates were 1-day averages, 25% 2-day averages, 5% 3-day averages, and 2% 4-day averages. The Georges Bank area was subjectively divided into 13 regions based on a judgment of the relative uniformity of drifter tracks within each region. The mean surface current in each region was computed by averaging the velocities of all drifters that passed through that region; in computing the mean the velocity estimates were given equal weight regardless of duration. The total number of velocity estimates obtained during each 3-8 day tracking period, the dates of the estimates, and the number of estimates from different drifters on each date are tabulated by region for each experimental period. The standard deviation (SD) of the estimates was computed in a coordinate system chosen to maximize the variance along a major axis (Fig. 5); the standard deviation is a measure of the reliability of the mean current estimate. These mean velocity estimates may contain a systematic bias, because in this region aircraft tracking operations could only be conducted during fair weather, which generally corresponded to northwesterly wind conditions. Velocity estimates were not computed for the individual experiment periods when there were fewer than three data points in a region. This table is partially from EG&G (1979a).

Experiment period	Mean current					Dates of averaging interval and number of velocity estimates													
	Region (Fig. 5)	Speed (cm s ⁻¹)	Direction (deg)	SD (cm/s)	Velocity estimates	<u>3-4</u>	<u>4-5</u>	<u>5-6</u>	<u>6-8</u>	<u>8-11</u>									
10/03/77-10/11/77	4	20	074	11	8		4	4											
	9	3	214	11	17		6	7	3	1									
	13	2	241	13	10	5	5												
11/15/77-11/20/77						<u>15-16</u>	<u>15-18</u>	<u>16-18</u>	<u>18-20</u>										
	2	14	070	14	5	2		2	1										
	3	9	077	10	5	2	1	2											
	4	15	064	11	3	1		1	1										
13	10	171	7	3	2		1												
01/30/78-02/03/78 and 02/20/78-02/25/78						<u>30-31</u>	<u>31-1</u>	<u>1-3</u>	<u>20-21</u>	<u>21-23</u>	<u>23-25</u>								
	1	5	015	17	5				4	1									
	2	11	073	10	12				3	5	4								
	3	26	054	23	3				2	1									
	4	6	066	9	14	4	2	1	4	2	1								
	5	16	135	11	5	3	2												
	6	17	284	11	6	3	2	1											
	7	17	222	15	7	3	3	1											
	8	7	168	6	8	2	3	3											
	9	3	156	8	22	5	5	4	2	3	3								
	10	15	208	17	13	7	2		2	1	1								
	11	14	215	11	23	3	6	5	1	3	5								
	12	13	245	18	17					8	6	3							
13	7	079	9	8					3	3	2								
05/22/78-05/24/78 and 06/05/78-06/14/78						<u>22-23</u>	<u>23-24</u>	<u>5-6</u>	<u>6-7</u>	<u>5-7</u>	<u>7-10</u>	<u>10-14</u>							
	3	7	067	6	6	3	3												
	4	11	079	8	16	4	3	3	3		2	1							
	6	11	080	17	8	3	5												
9	4	180	8	15	3	2	2	2	1	4	1								

		No. of velocity estimates by duration								
		1 day		2 day		3 day		4 day		
10/77-6/78 (all data)	10	19	205	17	14	6	5	1	1	1
	11	25	201	18	11	3	5	2	1	1
	12	13	228	16	6			2	2	2
	13	3	272	8	15			4	3	5
	1	5	126	10	7	5	2			
	2	12	069	11	19	6		12	1	
	3	11	063	14	14	10	3	1		
	4	11	073	10	41	32	6	2	1	
	5	15	135	10	6	6				
	6	3	342	20	14	13	1			
	7	16	215	15	9	8	1			
	8	9	157	8	10	7	3			
	9	3	180	9	54	34	14	5	1	
	10	17	207	17	27	24	3			
	11	17	208	14	34	21	13			
	12	13	241	17	25	13	10	2		
	13	1	201	11	36	21	7	5	3	

were corrected for direct wind effects by subtracting 1% of the estimated wind velocity; this correction was determined from the drogue areas above and below the waterline, and confirmed by comparisons of the motions of these drogues relative to "zero leeway markers" (Flynn and Cook, 1978). Velocities of drifters strongly influenced by a Gulf Stream eddy were deleted from the data. The relatively short-lived surface drifters provided limited observations of currents very near (within 1 m of) the surface where conventional moored instruments could not be used.

Near-surface currents were also measured by satellite-tracked drifters deployed with a 2 m × 11 m window-shade drogue centered at a depth of ~10 m. Four seasonal studies were conducted (December 1978, and March, June and August 1979). Typically, five drifters (manufactured by Polar Research Laboratory) were deployed around the margins of the bank in each study and were tracked via the Nimbus-6 satellite at roughly 2-day intervals until they left the Georges Bank region. Although only a few drifters were deployed, the satellite-tracked drifters provided better temporal coverage than the aircraft-tracked drifters and also suggested actual long-term trajectories of individual water particles. Uncertainties in the drifter velocities were caused by wind, current shear and wave effects on the surface buoy and drogue; the total wind and wave-induced error in the drifter velocity is estimated to be ~0.7% of the wind speed (J. R. McCullough, 1980, personal communication).

3. Results

The data show the expected mean clockwise circulation around Georges Bank (Figs. 4-6; Tables 1-3). The circulation is defined by a southwestward flow along the southern flank, a northward flow on the eastern side of the Great South Channel, a northeastward flow on the northern edge of the bank, and an eastward, southeastward and southward flow on the northeast peak. The flow on the southern flank was consistently toward the southwest. The mean flow was strongest near the surface (typically 15 cm s⁻¹ at 10-15 m), weaker at depth (5 cm s⁻¹ 10 m above bottom) and increased offshore [see measurements made at about 10, 45 and 75 m at stations 10-13 (Table 1, Fig. 4)]. The near-surface measurements along the outer edge of the southern flank showed a slight off-bank (southerly) component to the primarily along-bank current (Fig. 4, stations 12 and 13; Fig. 5, regions 10 and 11; Fig. 6, observations 1, 4, 5, 8, 9 and 12). The observations at stations 12 and 13 suggested an on-bank component of flow at mid-depth with respect to the flow at 10 m (Fig. 4). In contrast, the long-term measurements at station 11 (15, 45 and 75 m) showed a slight increase in the off-bank flow with respect to the flow at 15 m.

May-Jun 1979	433		(23)6/5-7/11 -7, -4 ±7, ±8	(24)7/12-8/26 -7, -1 ±10, ±7	
	556	(25)6/2-6/19 -1, -7 ±9, ±10	(26)6/20-6/29 -13, -3 ±10, ±14	(27)6/29-7/25 -6, 1 ±7, ±7	
	616	(28)6/1-6/27 -1, 5 ±6, ±14	(29)9/8-9/21 8, 0 ±11, ±7		
	620	(30)6/1-6/12 -1, -9 ±6, ±11		(31)6/13-6/23 -11, -1 ±14, ±16	
Aug 1979	620	(32)9/15-10/12 4, 4 ±14, ±16	(33)10/13-10/22 33, 13 ±18, ±13	(34)8/27-9/14 -8, -4 ±8, ±12	(35)8/20-8/27 0, -15 ±20, ±12
	735		(36)8/17-8/19 35, 6 ±5, ±21	(37)8/19-8/29 4, -10 ±28, ±18	
	703	(38)9/4-9/7 3, 6 ±13, ±4		(39)9/27-10/17 -3, -4 ±8, ±8	(40)9/17-9/26 4, -5 ±17, ±11
	727	(41)10/5 2, 23 — —	(42)8/20-10/3 and 10/10-10/26 -2, -1 ±10, ±7	(43)10/26-11/22 -7, -4 ±11, ±10	(44)1/23-11/30 -18, -2 ±9, ±12

Key No. for Fig. 6 →	(1)12/26-2/2	← Averaging Interval
Mean velocity (E,N) →	-2, -5	(Dec 78 thru Feb 79)
Low Frequency SD. (E,N) →	±12, ±12	

On the northern side of Georges Bank, a strong flow toward the northeast of $25\text{--}30\text{ cm s}^{-1}$ was observed. This jetlike current was apparently confined to a small band approximately $10\text{--}20\text{ km}$ wide along the steep northern flank, although the northwest-southeast (cross-bank) and northeast-southwest (along-bank) limits of this swift current were not clearly defined by the measurements. The mean flow was generally parallel to the bottom contours around the eastern end of the bank at speeds from 5 to 10 cm s^{-1} . On the crest of the bank, some of the near-surface Lagrangian measurements indicated off-bank flow to the south (Fig. 5, region 9; Fig. 6, observations 3, 7, 15 and 25). The limited Eulerian observations of the currents on the southern side of the crest of the bank showed flow parallel to the local isobaths below 15 m (Fig. 4, stations 8 and 9).

On the eastern side of Great South Channel, the moored observations showed northward mean flow into the Gulf of Maine at $5\text{--}10\text{ cm s}^{-1}$ at depths below 10 m (Fig. 4, stations 15-17). On the western side of the channel (station 18), the moored observations showed little net flow. Northward inflow through the channel had a marked seasonal variation, however (see Section 4). The current just south of Great South Channel (station 14) was westward, similar to the flow along the southern flank (stations 10-12). The 10 m Lagrangian measurements generally supported the Eulerian observations. In the northern end of the channel the drifters indicated net northward and northeastward flow [observations 6, 14, 19, 28, 32, 38 and 41 (Fig. 6)]. One drifter showed southward flow on the western side of the channel (observation 30).

Flow across Nantucket Shoals was southwestward and southward (Fig. 4, stations 19, 21). Between Cape Cod and Nantucket Island, the net flow of Nantucket Sound water was eastward toward the Gulf of Maine (station 22). Some Gulf of Maine water may enter Nantucket Sound near Pollock Rip (station 20). The small northeastward flow observed at station 23 suggests some flow onto Nantucket Shoals south of Nantucket at least in summer. However, hydrographic studies on Nantucket Shoals (Limeburner, 1979; Limeburner *et al.*, 1980) imply a mean south and southwestward flow of water from the Gulf of Maine and Nantucket over most of Nantucket Shoals. Along the middle and outer shelf south of Cape Cod, consistent westward flow was observed (Fig. 4, stations 24-27).

The variance of the low-frequency currents indicates that the daily averaged flow differed considerably from the simple clockwise residual flow pattern suggested in Fig. 4. The along-isobath low-frequency current variability (Fig. 7 and Table 1) was generally larger than the cross-isobath variability, and both components decreased with depth in the water column. The subtidal along-isobath-cur-

rent standard deviation was typically the same amplitude as the mean along-isobath current. In contrast, the amplitude of the cross-shelf-current standard deviation was typically several times the cross-isobath mean. Thus current reversals for periods of several days occurred occasionally in the along-isobath flow and frequently in the cross-isobath flow. Typical water-particle excursions associated with these low-frequency currents were $10\text{--}20\text{ km}$ longshelf and $5\text{--}10\text{ km}$ cross-shelf. Analysis of the long-term current record at station 11 indicated a seasonal change in the standard deviation of the low-frequency current of approximately a factor of 2 from the mean (minimum in spring and summer, maximum in fall and winter). Thus, detailed spatial comparisons of the amplitude of the low-frequency current variability must be done on at least a seasonal basis.

In contrast to the mean and low-frequency currents, which were aligned primarily parallel to the local bathymetry, the standard deviation of the total current was largest in the cross-isobath direction (Table 1). This change in the orientation of the major axis of the current standard deviation was caused by the energetic semidiurnal tidal currents that flow northwest-southeast. Displacements associated with the semidiurnal tidal currents were typically 10 km on the crest of the bank, and a few kilometers on the flanks.

The mean Eulerian current measurements and the characteristic 10 m drifter velocities (Figs. 4 and 6) suggest an intermittently closed subsurface circulation around Georges Bank. Selected trajectories of satellite-tracked drifters (Figs. 8a-8d) show that this inferred pattern of continuous circulation is possible, but also indicates the variability in the around-bank flow. Drifter 620 (Fig. 8a), deployed in August 1979, executed one complete loop around Georges Bank and then continued eastward across the Northeast Channel. In contrast, drifter 433 (Fig. 8b) was deployed in May 1979 on the northeast peak of Georges Bank and moved along the southern flank, across Great South Channel, and into the Middle Atlantic Bight. Drifter 034 (Fig. 8c), deployed in December 1978 on the northeast peak, moved along the southern flank and off the shelf. Drifters 620 and 616 (Fig. 8d), deployed in June 1979, clearly show the bidirectional flow in Great South Channel—northward on the Georges Bank side, southward on the Nantucket Shoals side. The sample drifter trajectories undoubtedly differ from actual water-particle trajectories because of windage, other slippage effects, and the inability of the drogue to follow vertical water motions, especially in the frontal regions. Nevertheless, the drifter results suggest that a subsurface water particle can make a complete circuit of the bank. The tracks also show, however, that the gyre is *not* a closed feature and that considerable vari-

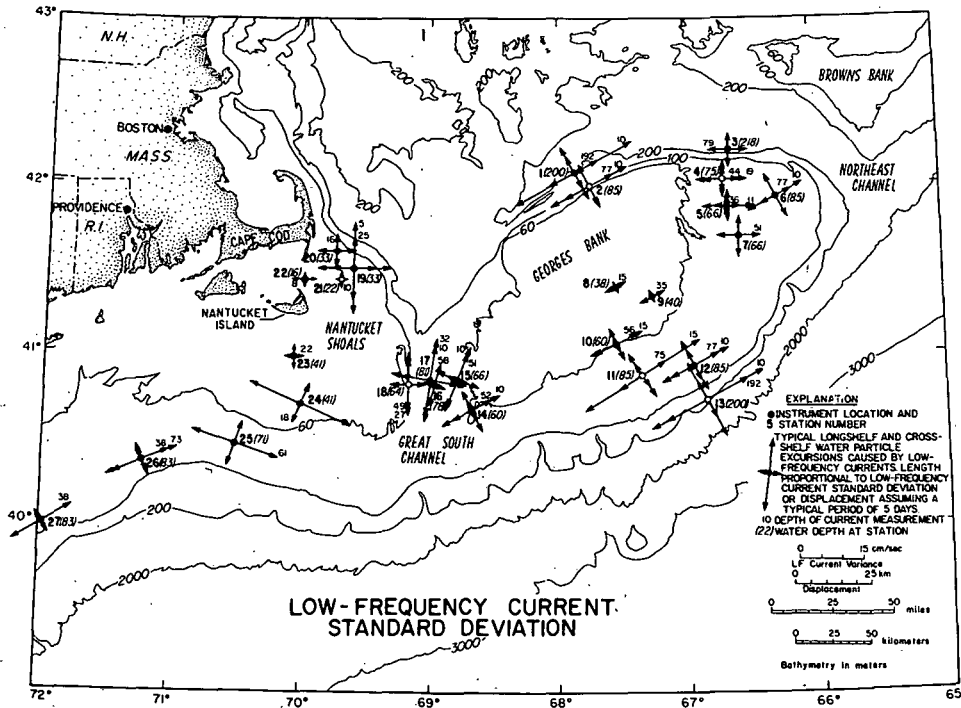


FIG. 7. Schematic representation of cross-shelf and longshelf low-frequency current variability. The subtidal current variability at each station is shown as a cross oriented in the longshelf/cross-shelf direction where the length of each axis is proportional to the observed standard deviation of the low-frequency current components. The boldface number of the origin keys the measurements to Table 1. The number in parentheses following the identifier indicates the water depth at the station in meters, and the number at the tip of the arrow indicates the depth of the measurement in meters. For clarity, only the surface and bottom measurements are shown and stations indicated by an open circle have been displaced slightly from true position. The speed scale is such that actual water particle excursions caused by the low-frequency currents are one-half as large as those shown (if a typical 5-day period is assumed for the subtidal motions).

ability exists in the trajectories of individual water particles.

4. Discussion

The direct Eulerian and Lagrangian current observations confirm the clockwise flow pattern around Georges Bank inferred by Bigelow (1927) more than 50 years ago and more recently by Bumpus (1976). The observations also suggest that the residual clockwise circulation is a permanent feature of the regional subsurface circulation. Although some seasonal variation exists in the strength of this circulation (see below), the long-time-series current observations made on the southern flank of the bank (especially at station 11) clearly demonstrate that the mean subsurface flow in all seasons is toward the west roughly parallel to the local isobaths. Although Bigelow (1927) and Bumpus (1973) did indicate a north-eastward current along the northern flank of the bank, the strength (typically 30 cm s^{-1}) of the observed flow was unexpected.

The 10 m Lagrangian and deeper Eulerian current

data indicate that water in the tidally well-mixed region (Fig. 3) in depths shallower than $\sim 70 \text{ m}$ may recirculate. We estimate the circuit time for a water particle moving along the 60 m isobath to be approximately two months; circuit times may be longer for particles in depths shallower than 60 m. Flow along the southern flank of Georges Bank diverged south of Great South Channel where most flow continued westward along the shelf while some turned northward into the channel. Water in the westward-flowing branch could easily reach the shelf south of Cape Cod in one month. The standard deviation of the low-frequency longshelf current was typically 10 cm s^{-1} . The low-frequency motions (caused by storms, topographic waves, Gulf Stream eddies and rings, for example) of several days duration could cause longshelf particle excursions on the order of 25 km and significantly modify the relatively simple mean flow pattern presented here.

Although the along-isobath component of the Eulerian current field was generally well resolved, the weaker cross-isobath flow that partially determines on-off bank transport of material and nutrients was

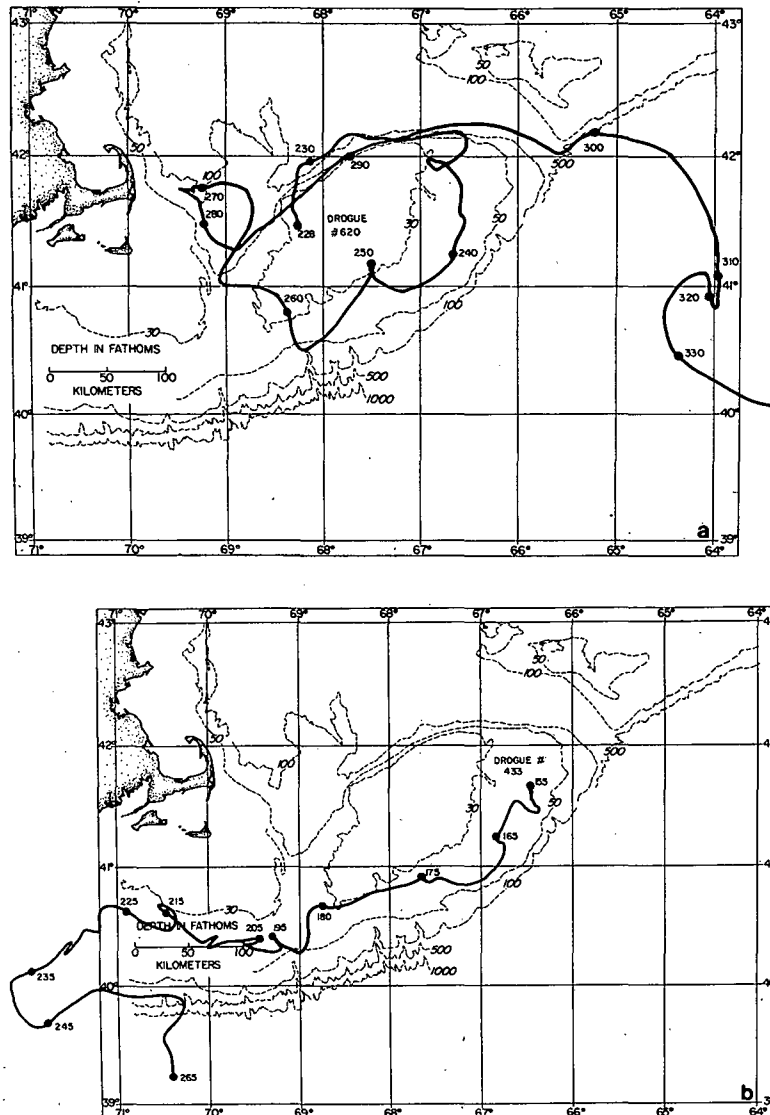
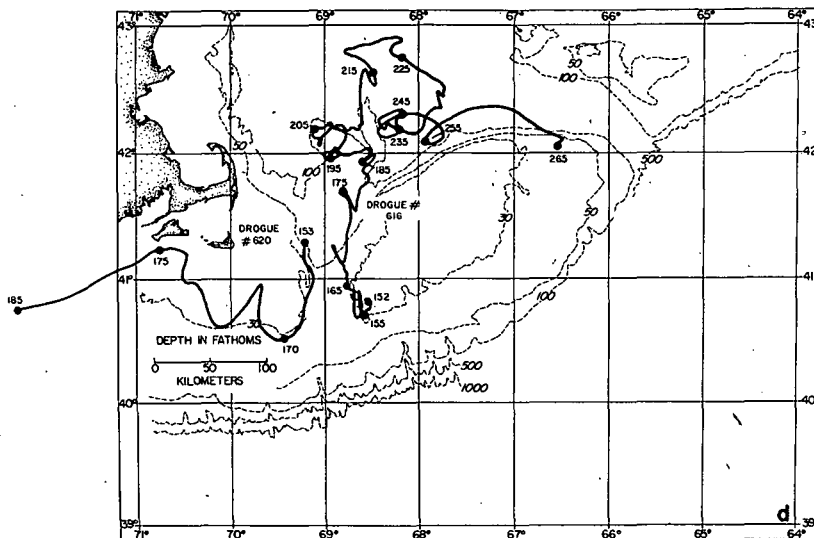
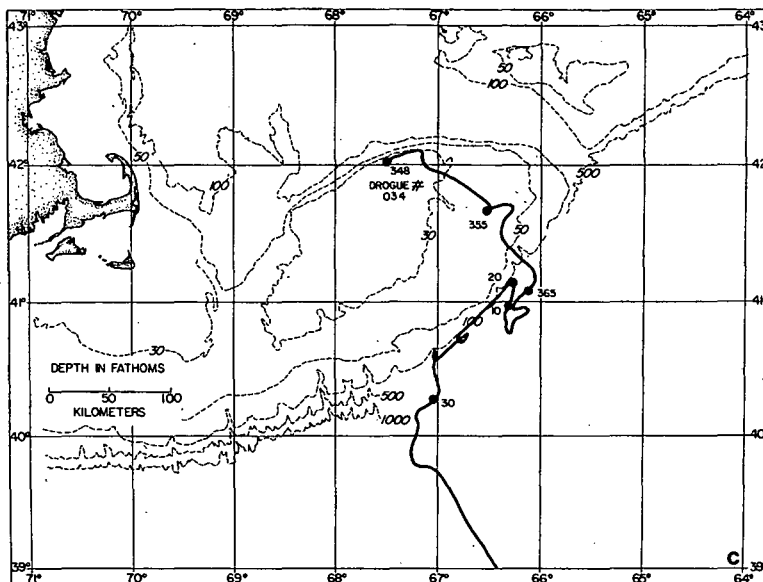


FIG. 8. Tracks of five satellite-tracked drifters deployed on Georges Bank. The drifters were deployed with 10 m window-shade drogues centered at 10 m depth. (a) Drifter 620, August 1979; (b) drifter 433, May 1979; (c) drifter 034, December 1978; (d) drifters 620 and 616, June 1979. Time along each track is given in Julian days. Figs. 8a, 8b and 8c illustrate the variability in trajectories of drogues released on the northern side of Georges Bank; one drogue circulated the bank (Fig. 8a), one traveled west into the Middle Atlantic Bight (Fig. 8b), and one traveled south into the slope water (Fig. 8c). Fig. 8d shows the northward flow on the eastern side of Great South Channel and the southerly flow on the western side.

less well defined. For example, at most stations the estimate of measurement uncertainty (standard error, see Table 1) of the cross-isobath current was of the same order as the mean cross-isobath current; thus conclusions on the net on-off-bank flow must be made with care. In contrast, the standard error of longshelf current was generally much less than the mean along-isobath current. A detailed seasonal analysis of the data, especially in relation to the hydrography and Gulf Stream rings, and dynamical

models are required to determine the on-off-bank transport.

The 10 m drifter results (Fig. 6) were consistent with the Eulerian mean current data (Fig. 4) and the surface-drifter velocities (Fig. 5). The clockwise circulation, the high-speed current on the northern flank, and the near-surface off-bank component of flow on the southern flank were all observed in the 10 m drifter data. These observations suggest that these circulation features on the bank are quasi-per-



manent and have relatively long space and time scales. The Eulerian current-meter measurements, although confined to a few fixed points, are thus representative of the mean current field over a larger area. The drifter measurements, although based on relatively few non-synoptic experiments, closely follow the well-defined time-averaged flow at fixed points.

The 1 m Lagrangian surface current measurements are an extremely limited data set; the drifters were tracked for only a few days and the experiments were conducted during fair weather conditions. In many regions, the uncertainty of the mean current estimate was the same order as the mean current (Table 2, Fig. 5). However, the surface current mea-

surements are included in this paper because they provide direct measurements of the surface currents and are thus a unique data set. The mean along-bank surface-current pattern qualitatively agreed with the subsurface current pattern; in particular, a strong northeastward flow along the northern flank, a flow around the eastern tip of the bank, a southwestward flow along the southern flank, and a slight off-bank flow on the crest were all observed in the surface circulation (Fig. 5). The surface-current observations in the Great South Channel were weak and variable and did not suggest consistent northward inflow into the Gulf of Maine as observed in the subsurface currents. It is not possible with the available data to determine if this lack of inflow indicates a real de-

coupling of the surface currents from the deeper current field or is a result of the very limited sampling and fair-weather bias of the surface measurements. The along-bank surface current is in contrast to the primarily offshore winter surface current pattern inferred from the few surface drift bottle returns in winter by Bumpus and Lauzier (1965). Although the offshore component of surface flow may increase in winter caused by offshore winds (thus the low rate of drift bottle returns), the observations suggest a residual along-bank surface and subsurface flow along the northern, eastern and southern sides of the bank throughout the year.

Georges Bank and the adjacent Nantucket Shoals support a major commercial fishery. The larvae of all species and the eggs of all species except herring drift passively in a neutrally buoyant stage for a period of 1 to possibly 5 months after spawning (Colton and Temple, 1961). The major species generally spawn on Nantucket Shoals, in the Gulf of Maine just north of the Great South Channel, along the northern side of Georges Bank, and on the Northeast Peak (Olsen and Saila, 1976; Colton *et al.*, 1979; Finn, 1980). Previous investigators (see Bumpus, 1973) have suggested that the clockwise circulation would minimize the advection of eggs and larvae away from the central part of the bank and thus partially account for the high productivity of the region. However, Colton and Temple (1961) recognized that the off-bank near-surface drift pictured by Bigelow (Fig. 3) and Bumpus should carry eggs and larvae, thought to be concentrated in the upper 10–15 m, off the bank. However, more recent studies of the larval distribution suggest that the larvae are distributed throughout the water column (Miller *et al.*, 1963; Lough and Cohen, unpublished data, 1980). Although the surface flow along the southern flank may have an off-bank component, the data presented here indicate that the mean currents at depth (Fig. 4) are more closely aligned with the topography of the bank. Thus, although the planktonic eggs and larvae in the surface layer may be advected away from the bank, especially in winter, those below 10–20 m may recirculate around the shallower part of the bank until they enter adult stages and are able to overcome the mean flow. Cross-bank exchange associated with the strong tidal and/or the low-frequency currents, and major episodic advection events such as storms and Gulf Stream rings will also influence the length of time passive organisms remain in the Georges Bank region.

Twichell *et al.* (1981) and Bothner *et al.* (1981) have suggested the importance of the strong tidal currents and the permanent residual westward flow from Georges Bank in determining the distribution of surface sediments along the New England shelf. A surface deposit of fine-grained silt and clay exists on the sea floor south of Cape Cod in water depths

between approximately 60 and 200 m. In contrast, the surface sediments along the rest of the Continental Shelf are primarily sand and contain little silt or clay (Schlee, 1973). Twichell *et al.* (1981) postulate that these fine sediments have been winnowed from the crest of Georges Bank and Nantucket Shoals by the strong tidal currents and storms and that the fine material was carried west along the shelf by the mean current. The material is deposited just west of Nantucket Shoals where the tidal currents decrease. If this hypothesis is correct, the region south of Cape Cod may be a sink for any material discharged into the water column on Georges Bank that behaves in a manner similar to these natural sediments. The Gulf of Maine and the Continental Slope may be other sinks.

The measurements presented here were made over different time periods and in different seasons; thus the circulation pattern shown in Fig. 4 is an operationally-defined mean picture. Preliminary analysis of some of the longer Eulerian time series indicates a significant seasonal variation in the monthly mean currents at different locations. At station 11, the mean flow over the 3-year sampling period at 45 m was southwestward at 8.6 cm s^{-1} (Table 1). The seasonal variation in the longshelf flow was $\sim 6 \text{ cm s}^{-1}$. On an average, the minimum southwestward flow occurred in March ($\sim 5 \text{ cm s}^{-1}$) and the maximum southwestward flow occurred in September ($\sim 11 \text{ cm s}^{-1}$). Synoptic cross-shelf hydrographic sections indicate that much of this seasonal change in the longshelf current was associated with a seasonal change in the cross-shelf density field. Northward monthly mean flow through the Great South Channel also reached a maximum in late summer and fall and a minimum in winter. The weak flow on the western side of the channel (station 18, Fig. 4) was the result of weak northward inflow in late summer and weak southward outflow in winter. On the northern flank of the bank, a preliminary analysis of monthly mean currents at station 2 suggests a minimum north-eastward flow of $\sim 20 \text{ cm s}^{-1}$ in winter and an increase of 10–20 cm s^{-1} in the strength of the jet in late summer. In contrast, monthly mean flow at station 7 on the northeast peak and at station 8 in the shallower well-mixed region of the bank indicated little monthly variation. In summary, a preliminary analysis of the monthly-mean currents at stations 2, 7, 8, 10, 11 and 15–18 suggests that the clockwise circulation around the perimeter of the bank varied seasonally; a maximum subsurface around-bank flow was observed in late summer and early fall [later in the year than reported by Bumpus (1973, 1976)], and a minimum in winter and early spring.

The contributions of tidal rectification, the ocean circulation, the density field and the wind stress to the mean flow on Georges Bank and the seasonal variation of these currents remain to be determined.

Rectification of the strong semidiurnal tidal currents may partially drive the mean flow observed on the northern and southern sides of the bank. Loder (1980) predicted depth-integrated maximum mean Eulerian currents caused by tidal rectification of approximately 25 and 13 cm s^{-1} on the northwest and northern sides of the bank, respectively, and currents of $\sim 6 \text{ cm s}^{-1}$ on the southern flank. Although a detailed comparison between model and observations is difficult because of the idealized topography and the spatial dependence of the tidally induced flow in the depth-integrated model, the predicted Eulerian current magnitudes agree qualitatively with the observed currents, especially in winter when a density-driven component to the around-bank flow is expected to be small. However, Magnell *et al.* (1980) found no simple correlation between the cross-bank tidal current and the mean along-bank flow on the northern side of the bank, although they did observe a correlation between the intensity of the along-bank tidal current and the mean along-bank current. Indirect evidence indicates that the southwestward flow of shelf water along the Middle Atlantic Bight is driven by a longshelf pressure gradient imposed by the off-shelf ocean circulation (for further discussion see Csanady, 1976; Beardsley and Boicourt, 1981); a similar longshelf pressure gradient may partially drive the mean flow along the southern flank of Georges Bank. Many investigators (see Bumpus, 1976) have suggested that cross-bank density gradients caused by differential seasonal heating and mixing contribute to the clockwise circulation around the bank especially in spring and summer. Analysis of the long-term current record at station 11 indicates a seasonal increase in the along-bank flow to the southwest of $\sim 6 \text{ cm s}^{-1}$ at 45 m and no seasonal change at 75 m; a similar variation is predicted by thermal wind and the cross-shelf density field.

A description of the mean current field in the Georges Bank region based on recent direct measurements has been presented. The next step in the analysis of this data set is a detailed description and analysis of the seasonal and higher frequency current variations. Seasonal estimates are needed of the residence time for material and water in different regions of the bank, the source of the water which flows along the southern flank, the volume of water that recirculates around the bank, and the volumes of water which flow west into the Middle Atlantic Bight and off-bank into the slope water. A seasonal description of the flow field should also help to estimate the separate contributions of tidal rectification, the density field and wind stress to the around-bank flow. Comparison of the models of Loder (1980), Hopkins and Garfield (1981) and Csanady (1974, 1976) to these estimates would be more appropriate than to the mean circulation pattern described here.

In summary, these first direct Eulerian current

measurements on Georges Bank have confirmed a subsurface clockwise flow around the Bank and suggested a marked seasonal variation in the flow. A strong flow on the northern flank and persistent northward recirculation through the Great South Channel was observed. The low-frequency variability of the currents was typically the same order as the mean flow, however, and thus the daily-averaged flow pattern often varies from the simple clockwise circulation.

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APPENDIX

Field Programs and Support

This paper presents data from several programs, which received funding from several sources. The principal investigators have coordinated field efforts to the extent possible. The programs (in approximate chronological order), principal investigators, and supporting agencies are acknowledged here.

1. A long-term current-monitoring study initiated in 1975 by the U.S. Geological Survey (USGS) and Woods Hole Oceanographic Institution (WHOI) (R. C. Beardsley, B. Butman and J. A. Vermersch, 1975-76; B. Butman and M. A. Noble, 1977-present). Support from USGS to WHOI: Contracts 14-08-00001-G-197 and 14-08-00001-15615. Support from the U.S. Bureau of Land Management (BLM) to USGS: Memoranda of Understanding (MOU) AA550-MU6-79, AA551-MU8-24, AA551-MU9-4 and AA551-MU0-18.

2. A moored array on the New England shelf deployed simultaneously with a pilot Georges Bank current-meter array (R. C. Beardsley, J. A. Vermersch and B. Butman, 1976) conducted with National Science Foundation (NSF) support. NSF Grant to WHOI: OCE76-01813. BLM MOU to USGS: AA550-MU6-29.

3. A study of bottom currents and sediment transport (B. Butman and M. A. Noble, 1976-present) conducted with USGS-BLM support. BLM to USGS:

MOU AA550-MU6-29, AA551-MU8-24, AA551-MU9-4 and AA551-MU0-18.

4. A study of the physical oceanography of Georges Bank (EG&G, Environmental Consultants, R. Scarlet, B. Magnell, D. Frye and C. Flagg; Raytheon Company, D. Cook, 1977-80) supported by BLM. BLM contracts to EG&G: AA550-CT6-50 and AA551-CT8-46. BLM contracts to Raytheon: AA550-CT6-53 and AA550-CT8-47.

5. A study of hydrography and currents on Nantucket Shoals (R. C. Beardsley and R. Limeburner, 1977-79) conducted with Sea Grant support. U.S. Department of Commerce, NOAA and Office of Sea Grant support to WHOI: Grants 04-7-158-44104 and 04-8-MO1-149.

6. A study of currents in Great South Channel (J. A. Vermersch, R. C. Beardsley and B. Butman, 1978-79) conducted with support from USGS and BLM. BLM MOU AA551-MU8-24 and AA551-MU9-4.

7. A study of currents on the northern side of Georges Bank as part of the larval herring patch study (R. Schlitz and W. R. Wright, 1978) conducted with National Marine Fisheries Service (NMFS) support.

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