One year of nutrient distribution in the Georges Bank region in relation to hydrography, 1975-1976

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ABSTRACT

The distribution of major nutrients in the Georges Bank region was measured during nine cruises between July 1975 and August 1976. The sampling included measurement throughout the water column of nitrate, orthophosphate, silicate, temperature, salinity, and dissolved oxygen. The distributions of the variables and their annual cycles are described.

The space and time distributions of the three nutrients were very similar, with concentrations on the bank and in the adjacent surface waters reaching a maximum in winter and decreasing to near zero in summer. Elevated near-surface values, accompanied by cooler temperatures, occurred repeatedly in the Gulf of Maine east of Cape Cod and inside Northeast Channel. Year-round reservoirs of nutrient-rich water (nitrate approximately 16 μgat/l) were found below 120 m both north and south of Georges Bank, but the reservoir inside the Gulf of Maine must include a substantial fraction of nutrients regenerated in the water column.

1. Introduction

Georges Bank has long been an important commercial fishing ground, supporting large quantities of fish and shellfish. Underlying this fish production is one of the highest production rates in the ocean. Primary production in the bank was first determined by Riley (1941) and more recently by Cohen and Wright (1978), Thomas *et al.* (1978) and Cohen *et al.* (1982). These latter authors found high production throughout most of the year, with low levels only in winter.

The productivity of the bank is in large part attributable to influxes of nutrient-bearing water from surrounding regions—i.e., the Gulf of Maine and the Slope Water—and to on-bank regeneration of nutrients. These mechanisms are controlled in turn by the physical processes that govern circulation and mixing in the bank region and by biological and chemical interactions. Nutrient-bearing Slope Water is available along the southern flank at depths below the shelf edge; some of that water flows through Northeast Channel into the deep Gulf of Maine (Ramp and Ver-

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Table 1. List of cruises conducted from July 1975 to August 1976.

Ship (country)	Cruise number	Date
Albatross IV (USA)	75-07	July 8-18
Belogorsk (USSR)	75-02	Sept. 24-Oct. 10
Belogorsk (USSR)	75-03	Oct. 17-30
Anton Dohrn (FRG)	75-187	Nov. 1-18
Albatross IV (USA)	75-14	Dec. 2-17
Albatross IV (USA)	76-01	Feb. 2-25
Wieczno (Poland)	76-01	April 9-May 4
Albatross IV (USA)	76-03	May 11-21
Albatross IV (USA)	76-05	July 30-Aug. 16

mersch, 1978; Ramp *et al.*, 1980). Some suggestion of nutrient upwelling in the southeastern Gulf of Maine was noted in EG&G (1980), and Schlitz (1982), has identified at least three mechanisms by which the deeper waters of the gulf can be brought up to the level of the bank.

Dissolved nitrate, phosphate and silicate are critical nutrients for phytoplankton growth. The first regular measurements of these nutrients over the entire Georges Bank region were made in 1975 as part of the ICNAF Larval Herring investigations (1971-1978). In this paper, the distribution of nutrients on and around Georges Bank are described, with their seasonal variations, in relation to hydrography, on the basis of cruises made between July 1975 and August 1976. The cruises are listed in Table 1. Those between September 1975 and May 1976 were part of the ICNAF series and followed the same station pattern (Fig. 1).

On each cruise, temperatures were taken with reversing thermometers and/or expendable bathythermograph (XBT). Water samples were taken throughout the water column in Nansen or Niskin bottles and were analyzed for salinity, dissolved oxygen, nitrate (NO_3-N), orthophosphate (PO_4-P) and silicate (SiO_3-Si). The salinity and oxygen analyses were performed on board with salinometers and a modified Winkler titration. The nutrient samples were frozen and stored for subsequent analysis by Technicon Autoanalyzer at University of Rhode Island or the Bigelow Laboratory for Ocean Sciences, under contract with the Northeast Fisheries Center. Charts were drawn for all variables showing horizontal distribution at the surface and 20, 50, and 100 m depth, and vertical distribution at 67 and 68W.

2. Distribution of variables

A cruise-by-cruise description of the changing features of the hydrography and nutrient distributions in the Georges Bank region over the 12-month period can be found in Pastuszak *et al.* (1982). The hydrographic patterns are similar to those described before (Bigelow, 1927; Bumpus, 1976; Wright and Parker, 1976; Butman

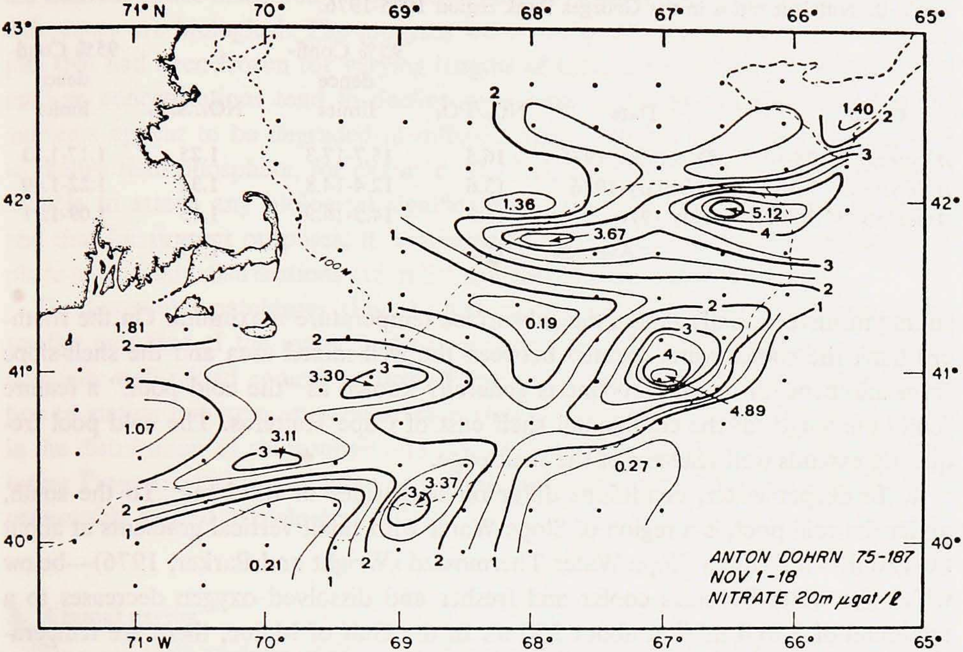

Figure 1. Nitrate distribution at 20 m depth during *Anton Dohrn* cruise 75-187, 1-18 November 1975. Dots show station positions.

et al., 1982; Hopkins and Garfield, 1981), and to avoid repetition, some general features are noted.

1. The water in the shallow (<60 m) central part of Georges Bank is vertically well mixed, by tides and winds, throughout the year. In winter the wind mixing extends deeper, to about 100 m, and the area of vertically homogeneous water is correspondingly larger. As a result of the mixing, surface temperatures on top of the bank tend to be warmer than surrounding water in early winter and cooler in summer.

2. The well-mixed water is separated from the surrounding waters by fronts which are permanent in time but fluctuate in space in response to tides and lower-frequency forcing. On the south the front marks the transition from Georges Bank water to Slope Water which is usually warmer and always much more saline. On the north side of the bank, a weaker front leads to Gulf of Maine water which has T/S characteristics similar to those on the bank.

3. Solar warming in spring and summer develops a strong thermocline everywhere but in the well-mixed region. Summer surface temperatures are usually several degrees warmer in the Slope Water than in the Gulf of Maine. The thermocline breaks down with advent of fall cooling and stronger winds of autumn, and the re-

Table 2. Nutrient ratios in the Georges Bank region 1975-1976.

Cruise	Date	NO_3/PO_4	95% Confidence limits	NO_3/SiO_3	95% Confidence limits
Albatross IV 75-14	December 1975	16.5	15.7-17.3	1.25	1.17-1.33
Albatross IV 76-01	February 1976	13.6	12.4-14.8	1.31	1.22-1.40
Albatross IV 76-03	May 1976	15.7	14.5-16.9	1.15	1.09-1.21
	Average	15.3		1.24	

sulting turnover usually marks the subsurface temperature maximum. On the southern flank the cooler water located between the well-mixed area and the shelf-slope front and beneath the thermocline is generally known as "the cold pool," a feature found the length of the continental shelf east of Cape Hatteras. The cold pool frequently extends well seaward of the shelf edge.

4. In deeper water, conditions differ on both sides of the bank. To the south, under the cold pool, is a region of Slope Water with small vertical gradients at about 80-120 m—the Upper Slope Water Thermostad (Wright and Parker, 1976)—below which the water becomes cooler and fresher and dissolved oxygen decreases to a minimum of 3 to 4 ml/*l* at about 350 m. In the Gulf of Maine, there are temperature and salinity minima at 100 to 150 m, below which is found warmer, more saline water representing a mixture of resident water with Slope Water inflow through the Northeast Channel.

5. Anomalously cold surface water, indicative of upwelling from intermediate depths in the Gulf of Maine, occurs from time to time along the northern edge of Georges Bank. This phenomenon is seen most frequently in two locations, one just east of Cape Cod and the other near the Northeast Peak of Georges Bank.

The nutrient distributions reflected these hydrographic constraints in most respects. In the well-mixed central portion of the bank, the nutrient values were uniform throughout the water column; nutrient distributions showed some indication of the permanent hydrographic fronts; and elevated nutrients were found in the regions where cooler temperatures suggested upwelling. However, there was little evidence in the nutrient distribution of the seasonal thermocline and resulting cold pool; nutrient values invariably increased with depth everywhere but in the mixed layer.

Two other characteristics were evident from the nutrient distribution charts: (1) nitrate, silicate and phosphate had very similar spatial patterns from cruise to cruise; and (2) there was marked mesoscale horizontal patchiness.

The spatial similarity suggested that all three nutrients varied more or less together and, in fact, plots of nitrate vs. silicate and nitrate vs. phosphate for selected cruises showed consistent ratios during the year, despite considerable scatter (Table 2). It appears from Table 2 that there may be statistically significant differences in the nutrient ratios measured on different cruises. However, it is not clear that those differences are biological. The analyses were run at different laboratories on samples that had been frozen for varying lengths of time. Smayda (1976) reported that nutrient concentrations tend to decline over time in frozen samples, and that the nutrients appear to be degraded at different rates, nitrates being more susceptible to change than phosphate, for example. We feel, therefore, that it would be unreasonable to attach any biological significance to the reported differences in ratios, and that for present purposes, it is acceptable to consider that variations in phosphate and silicate distributions are indistinguishable from those of nitrate.

The horizontal patchiness (Fig. 1) was on a scale of tens of kilometers, much smaller that that of the major hydrographic features. It was a feature even of the vertically well-mixed central portion of the bank: nutrient values varied from station to station but were uniform at each station. Similar patchiness has been noted in the distribution of chlorophyll and plankton on Georges Bank (Northeast Monitoring Program, 1981) and elsewhere (National Academy of Sciences, 1980); it is presumably related to biological activity.

3. Annual cycles

For systematic analysis of seasonal changes, the region was divided along a north-south cross section into seven subregions, one on the shallower portion of the bank and three each on the northern and southern flanks. The Georges Bank subregion (GB) was defined as all water shallower than 65 m, representing the well-mixed region. The water from the surface to 65 m was taken as the shallow subregions on the northern (NS) and southern (SS) flanks. From 65 to 120 m on the southern flank (SM) is the Upper Slope Water Thermostad and on the northern flank (NM), 120 m is about at the temperature minimum. Deeper than 120 m on the north (ND) there is Slope Water influence and on the south (SD) Slope Water itself.

Nitrate was picked as representative of all three nutrients. Mean values ($\bar{x}$) and standard deviations (σ) were calculated in each subregion for each cruise for nitrate, temperature, salinity and dissolved oxygen. *Albatross IV* cruise 76-03 (11-21 May) provided Gulf of Maine data only. All observations were included except in the surface layers (GB, NS, SS) where no more than three values, approximately evenly spaced, were used at each station. The results are tabulated in Table 3. The mean values and standard deviations of all four variables on Georges Bank are plotted in Figure 2. Seasonal variation is evident in every case. Most of the variability represented by the σ bars resulted from horizontal rather than vertical variations, as noted earlier. The surface temperature ranged from a high of nearly 14°C in late September to a low of 5°C in February; in all other parameters the cycle was reversed. Nitrate was virtually nonexistent in the summer but increased in the fall, remained high (around 6.5 μgat/l) throughout winter and dropped off rapidly in

Table 3. Mean concentrations of oceanographic variables on Georges Bank and in the adjacent waters on its northern and southern flanks.

Note on Abbreviations:

GB = Georges Bank within 65 m contour
NS = Northern Flank, surface to 65 m
SS = Southern Flank, surface to 65 m
NM = Northern Flank, 65-120 m
SM = Southern Flank, 65-120 m
ND = Northern Flank, 120 m to bottom
SD = Southern Flank, 120-300 m
n = Number of observations
$\bar{x}$ = Mean value
σ = Standard deviation

1. Nitrate (μgat/l)

		Alb. IV 75-07 8-18 VII	*Belogorsk* 75-02 24 IX-10 X	*Belogorsk* 75-03 17-30 X	*Anton Dohrn* 75-187 1-18 XI	*Alb. IV* 75-14 2-17 XII	*Alb. IV* 76-01 2-28 II	*Wieczno* 76-01 9 IV-4 V	*Alb. IV* 76-03 11-21 V	*Alb. IV* 76-05 30 VII-16 VIII
	n	11	28	24	22	12	45	22	No	9
GB	$\bar{x}$	0.3	1.8	2.0	2.2	6.2	6.7	1.9	Data	0.1
	σ	0.3	1.3	1.4	1.3	1.5	2.2	1.8		0.1
	n	No	33	30	37	28	32	14	16	28
NS	$\bar{x}$	Data	2.6	3.7	3.2	6.3	7.7	3.0	0.7	1.6
	σ		3.3	3.7	2.2	2.5	2.4	2.3	1.3	2.8
	n	49	48	30	42	24	29	20	No	60
SS	$\bar{x}$	1.7	2.3	3.3	2.6	4.8	6.1	2.5	Data	1.2
	σ	2.5	2.7	2.9	2.7	1.9	2.0	1.6		1.9
	n	No	27	27	24	19	17	12	23	19
NM	$\bar{x}$	Data	11.1	9.2	9.3	12.1	8.9	7.7	9.6	10.9
	σ		2.6	3.5	3.8	4.0	2.3	4.7	2.8	5.0
	n	27	25	24	23	11	12	14	No	34
SM	$\bar{x}$	7.3	9.5	9.1	8.8	8.3	8.1	5.2	Data	9.2
	σ	3.1	2.6	2.9	3.8	3.7	3.4	2.4		3.0

	n	No	23	27	17	21	24	10	84	39
ND	$\bar{x}$	Data	15.9	12.8	15.2	19.9	12.4	9.5	14.6	18.9
	σ		2.6	3.6	2.7	3.7	3.7	4.2	3.2	2.7
	n	21	13	10	14	No	4	10	No	21
SD	$\bar{x}$	15.1	18.4	16.2	18.0	Data	14.3	13.5	Data	19.3
	σ	5.1	3.5	4.9	5.7		2.9	5.4		3.9
2. Temperature (°C)										
	n	12	36	44	41	12	45	32	No	9
GB	$\bar{x}$	10.90	13.78	12.97	12.48	9.36	5.03	6.22	Data	12.82
	σ	1.63	1.19	1.25	0.80	0.41	0.29	0.19		1.69
	n	21	42	43	60	29	36	42	44	59
NS	$\bar{x}$	11.16	11.63	10.79	10.71	8.94	5.37	5.69	7.11	12.57
	σ	5.32	3.17	2.18	1.03	0.39	0.18	0.38	1.72	4.29
	n	63	48	48	69	20	32	48	No	48
SS	$\bar{x}$	13.31	15.10	14.36	15.57	11.39	5.51	6.59	Data	15.42
	σ	4.31	3.51	3.12	4.45	2.77	0.66	1.40		4.75
	n	21	30	27	41	18	17	24	39	40
NM	$\bar{x}$	5.94	6.51	6.66	7.57	7.50	5.58	5.49	5.98	6.57
	σ	1.07	1.57	1.26	1.56	1.11	0.68	0.45	0.97	1.16
	n	32	23	23	38	9	13	21	No	37
SM	$\bar{x}$	10.85	12.12	12.56	13.77	12.80	7.74	8.58	Data	12.26
	σ	2.45	1.85	1.96	3.43	3.16	2.47	2.68		2.24
	n	22	26	29	33	17	24	23	106	83
ND	$\bar{x}$	7.45	7.43	7.09	7.49	7.53	6.65	6.89	7.27	7.71
	σ	0.64	1.35	1.12	1.21	1.02	1.13	1.20	0.74	0.87
	n	17	15	12	25	No	3	14	No	24
SD	$\bar{x}$	11.17	10.04	11.57	12.36	Data	10.33	10.08	Data	11.85
	σ	2.00	2.21	1.45	2.52		0.78	2.00		1.45

Table 3. (continued).

3. Salinity (‰)

		Alb. IV 75-07 8-18 VII	*Belogorsk* 75-02 24 IX-10 X	*Belogorsk* 75-03 17-30 X	*Anton Dohrn* 75-187 1-18 XI	*Alb. IV* 75-14 2-17 XII	*Alb. IV* 76-01 2-28 II	*Wieczno* 76-01 9 IV-4 V	*Alb. IV* 76-03 11-21 V	*Alb. IV* 76-05 30 VII-16 VIII
	n	11	36	37	15	12	45	29	No	9
GB	$\bar{x}$	32.71	32.37	32.31	32.33	32.41	32.74	32.78	Data	32.62
	σ	0.05	0.21	0.11	0.06	0.09	0.12	0.07		0.05
	n	21	45	45	68	28	34	42	44	59
NS	$\bar{x}$	32.27	32.35	32.23	32.35	32.45	32.85	32.82	32.73	32.54
	σ	0.32	0.26	0.21	0.21	0.12	0.09	0.06	0.20	0.33
	n	63	45	42	69	21	30	48	No	75
SS	$\bar{x}$	33.79	33.41	33.82	34.00	33.57	32.71	33.04	Data	33.62
	σ	1.17	0.99	1.18	1.40	1.19	0.15	0.44		1.10
	n	20	29	27	43	23	17	25	38	40
NM	$\bar{x}$	33.17	33.05	32.87	32.90	32.86	32.69	32.92	33.16	33.27
	σ	0.39	0.52	0.32	0.38	0.28	0.36	0.19	0.40	0.49
	n	31	23	20	39	10	13	22	No	37
SM	$\bar{x}$	34.65	34.27	34.62	34.83	34.38	33.57	33.89	Data	34.65
	σ	1.06	1.09	2.03	1.18	1.34	0.89	0.89		1.06
	n	20	25	24	31	20	23	22	102	83
ND	$\bar{x}$	34.19	34.04	33.67	34.11	33.93	33.67	34.00	34.33	34.42
	σ	0.61	0.70	0.57	0.71	0.66	0.79	0.79	0.59	0.59
	n	19	15	7	23	No	4	12	No	24
SD	$\bar{x}$	35.41	35.34	35.28	35.52	Data	35.27	35.17	Data	35.45
	σ	0.21	0.27	0.20	0.27		0.07	0.39		0.36

4. Oxygen (m/*l*)

		Alb. IV 75-07 8-18 VII	*Belogorsk* 75-02 24 IX-10 X	*Belogorsk* 75-03 17-30 X	*Anton Dohrn* 75-187 1-18 XI	*Alb. IV* 75-14 2-17 XII	*Alb. IV* 76-01 2-28 II	*Wieczno* 76-01 9 IV-4 V	*Alb. IV* 76-03 11-21 V	*Alb. IV* 76-05 30 VII-16 VIII
	n	9	35	45	26	12	44	24	No	9
GB	$\bar{x}$	6.76	5.84	5.92	5.92	6.31	7.48	7.77	Data	5.57
	σ	0.37	0.27	0.21	0.28	0.15	0.82	0.31		0.39
	n	No	40	42	42	28	27	42	24	59
NS	$\bar{x}$	Data	5.96	6.03	6.02	6.40	6.99	7.60	7.13	5.57
	σ		0.27	0.22	0.26	0.33	0.15	0.27	0.35	0.34
	n	51	36	39	48	24	28	48	No	75
SS	$\bar{x}$	6.12	5.59	5.59	5.30	6.03	6.98	7.38	Data	5.20
	σ	0.53	0.58	0.44	0.54	0.43	0.40	0.49		0.53
	n	No	27	27	22	22	17	25	37	40
NM	$\bar{x}$	Data	5.68	5.62	5.44	5.74	6.82	7.10	6.24	5.13
	σ		0.49	0.26	0.43	0.46	1.26	0.41	0.52	0.46
	n	32	19	23	29	11	13	22	No	33
SM	$\bar{x}$	5.25	4.57	4.77	4.57	5.32	6.11	6.30	Data	4.41
	σ	0.66	0.71	0.54	0.82	0.82	1.53	0.81		0.56
	n	No	24	27	26	21	24	21	98	83
ND	$\bar{x}$	Data	4.82	4.98	4.55	4.89	5.87	5.40	4.87	4.16
	σ		0.74	0.51	0.51	0.40	1.41	1.00	0.57	0.46
	n	17	15	11	26	No	4	12	No	24
SD	$\bar{x}$	4.31	3.70	3.83	3.76	Data	4.02	4.21	Data	3.50
	σ	0.49	0.33	0.44	0.32		0.45	0.64		0.25

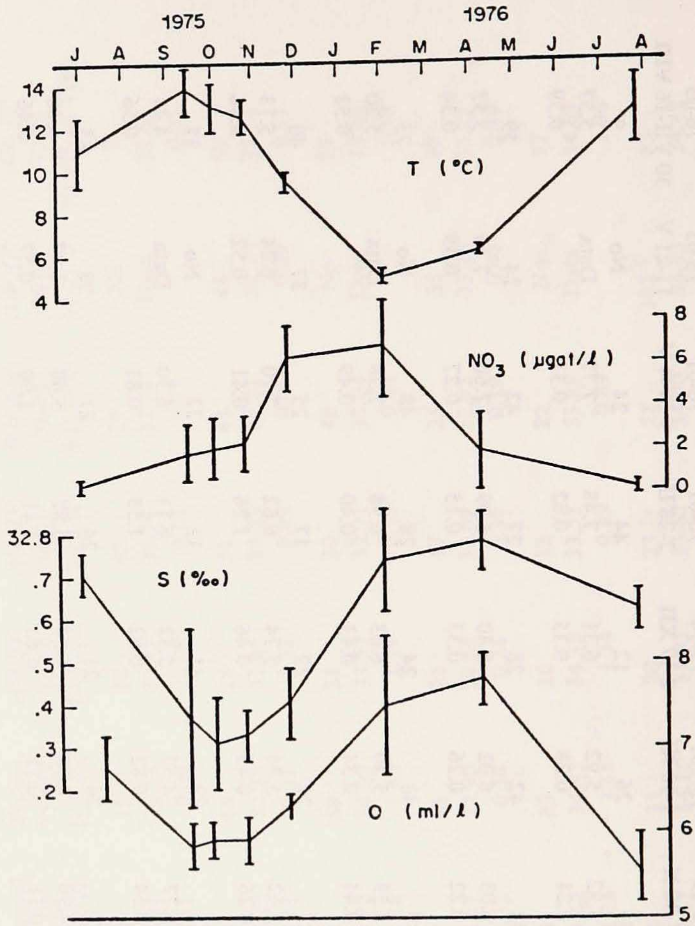

Figure 2. Annual cycles of temperatures, nitrate, salinity and dissolved oxygen over Georges Bank, 1975-1976. Vertical bars represent ± one standard deviation.

early spring. Salinity and dissolved oxygen cycles were very similar, with lows in the fall and highs in the spring. Annual range was above 0.5‰ in salinity and 2 ml/*l* in dissolved oxygen concentration. The relation between temperature and nitrate on Georges Bank is better seen in Figure 3 where the means of the two variables for each cruise are plotted against each other. Nitrate values were at their height in February when the water was coldest and length of day had not increased much beyond the mid-winter minimum. As daylight and insolation increased, the water warmed slightly, the spring bloom commenced and the nutrient concentration dropped rapidly. Nutrients continued to decline during the warming season, reaching a minimum in mid-summer. Afterward they increased, slowly at first as the days

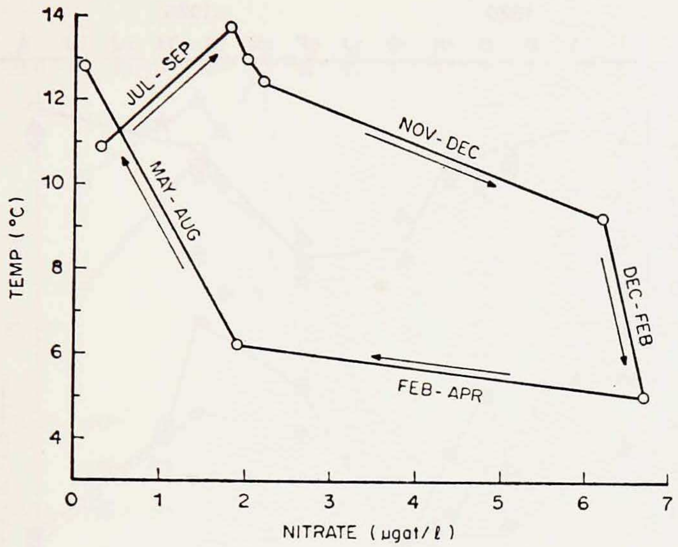

Figure 3. Annual cycle of temperature vs. nitrate on Georges Bank, 1975-1976.

grew shorter and fall overturn began, then more rapidly as cooling water and decreasing daylight inhibited photosynthesis.

Mean values of the four variables in five of the seven subregions are shown in the next four figures. Data for the Northern Mid-water and Southern Mid-water subregions were omitted to avoid cluttering the diagrams. The vertical bars for the two deep subregions (ND and SD) represent the annual mean value ± the mean of the standard deviations for each cruise.

Nitrate (Fig. 4). There is a clear seasonal signal only at the surface where all three subregions showed similar patterns. During the period of nutrient depletion, from April through November, the mean values on Georges Bank were consistently lower than on either flank although in most cases the differences were not statistically significant. In the deep water, the northern and southern subregions exhibited somewhat similar fluctuations but they are probably not significant; the individual values varied over a broad range as indicated by the σ values in Table 3. The overall mean inside the Gulf of Maine (15.0 μgat/l) was slightly lower than in the Slope Water (16.4 μgat/l) as might be expected. Both subregions clearly serve as ample reservoirs of nutrients year-round. The two mid-depth subregions, as expected, had intermediate mean values, slightly higher in the north (9.9 vs. 8.2 μgat/l) but again the individual values in both subregions varied widely.

Temperature (Fig. 5). The strong seasonal cycle in the surface waters penetrated (much diminished) to mid-depth on both sides of the bank, but no seasonality is

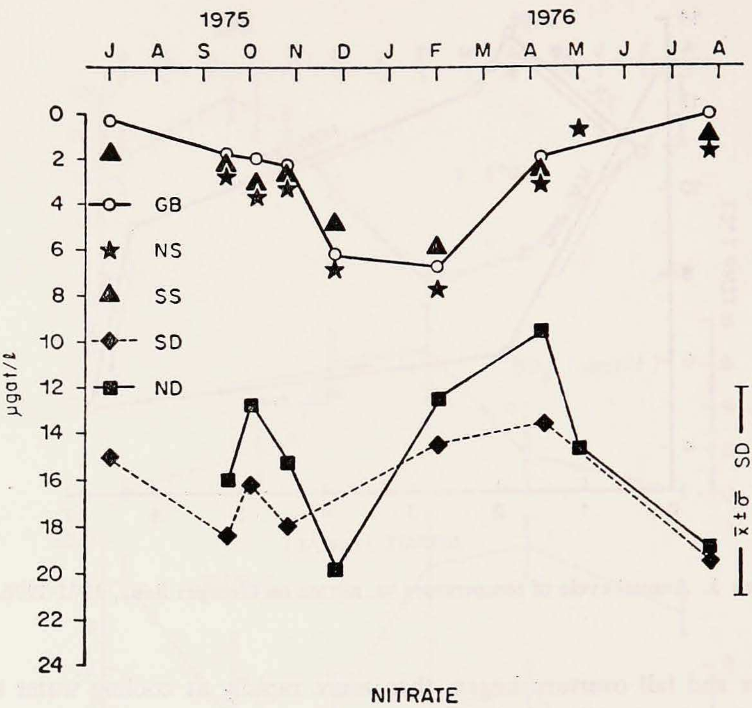

Figure 4. Nitrate cycle in various subdivisions of the Georges Bank region.

evident in the deeper water on either flank. (There was a December maximum in the deep subregion in the Slope Water, as there was at mid-depth, but the difference is well within the σ limits and is probably meaningless.) Three general differences between the Gulf of Maine and Slope Water subregions stand out: the northern subregions are much cooler (by 3° to 5°C, on average) than their southern counterparts; they have much smaller annual range (less than half, at all depths) and the values are much less variable as evidenced by the standard deviations.

Salinity (*Fig. 6*). The seasonal cycle on Georges Bank was surprisingly smooth; that of the surface layers in the Gulf of Maine (NS) was similar but more variable. The wide variation in the Slope Water region (SS) was probably due to fluctuation in the position of the shelf/slope salinity front. In the deep water, the salinity picture was opposite that exhibited by temperature, the water outside the Gulf of Maine (SD) being much steadier in value than that within (ND). However, there was no significant seasonal signal in either subregion. The Slope Water values were, of course, much higher (annual mean 35.35‰) than those in the Gulf of Maine (annual mean 34.04‰). In both mid-depth subregions (NM and SM) there was some suggestion of a February minimum but it was masked in both cases by the

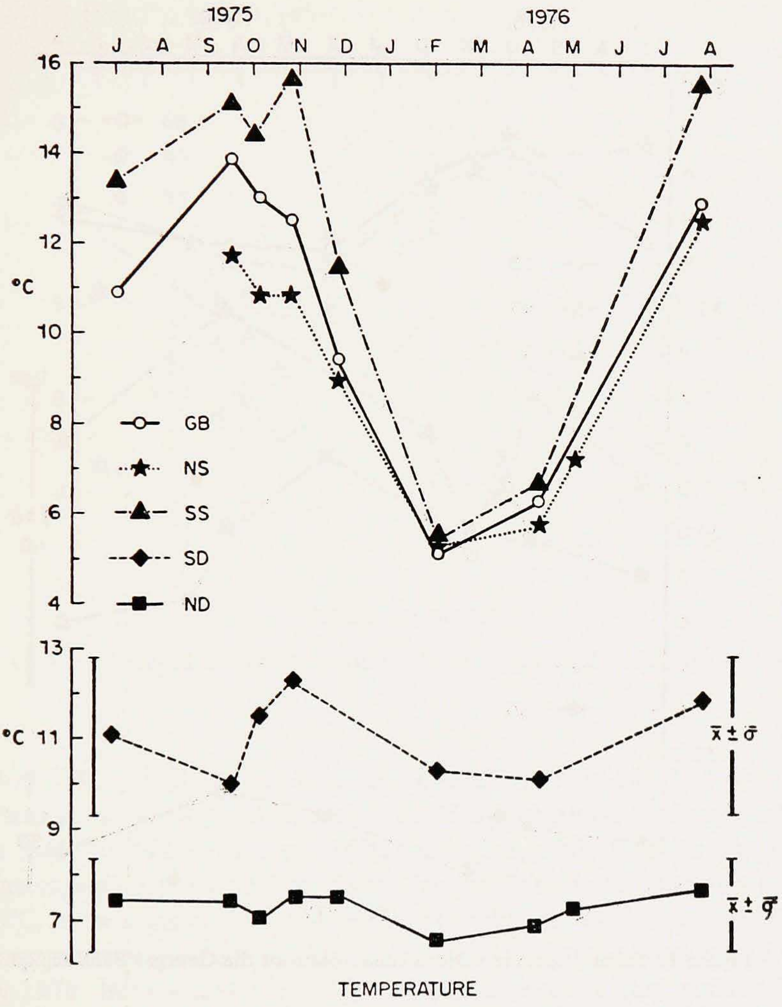

Figure 5. Temperature cycle in various subdivisions of the Georges Bank region.

large variability. Unlike the situation in the deeper layers at mid-depth, the Gulf of Maine exhibited more steadiness than the Slope Water.

Oxygen (*Fig. 7*). The same seasonal pattern (low in fall, high in spring) occurred in all seven subregions and appears satistically significant except in the Slope Water below 120 m (SD). The deep Slope Water subregion was also the lowest in dissolved oxygen content at all times of year, with an overall mean of 3.9 ml/*l* compared with 4.94 ml/*l* in the deep Gulf of Maine (ND). This substantial difference, along with the difference in salinities in the two subregions, confirms that there is very little unadulterated Slope Water in the Gulf of Maine; whatever enters through

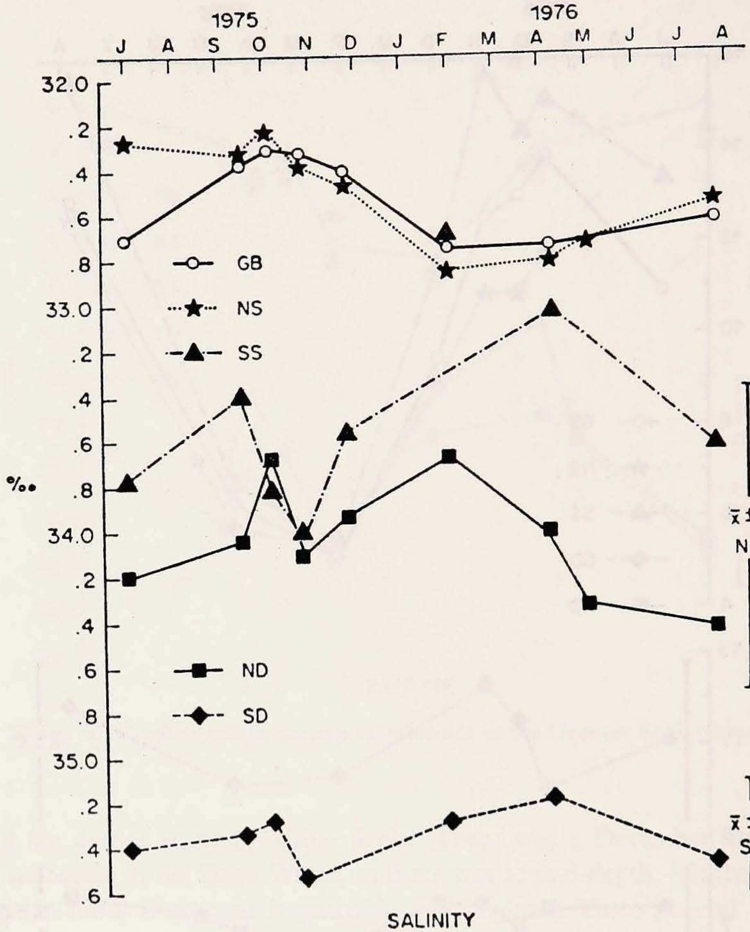

Figure 6. Salinity cycle in various subdivisions of the Georges Bank region.

Northeast Channel is well mixed with the resident water mass as it proceeds into the various basins. In the surface layers, where the water is well mixed and well saturated, oxygen was inversely related to temperature as expected; Georges Bank and the adjacent Gulf of Maine (NS) varied together while the Slope Water (SS) was both warmer and less oxygenated. The intermediate layers both north and south showed greater standard deviation than the waters above and below; NM was higher in oxygen than SM by about 0.8 ml/*l* on average.

4. Discussion and summary

The temperature and salinity values measured in the Georges Bank region in 1975-1976 are generally consistent with the water mass characteristics described

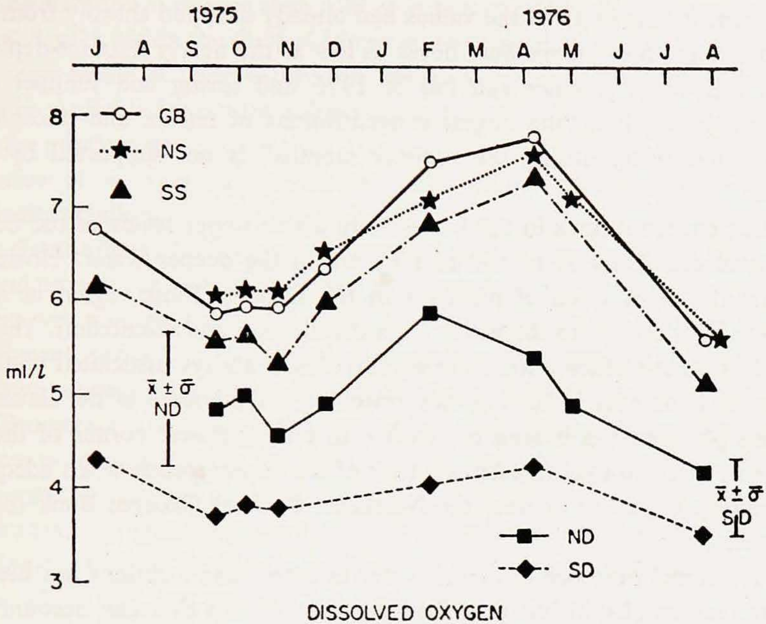

Figure 7. Cycle of dissolved oxygen concentration in various subdivisions of the Georges Bank region.

by Bigelow (1927) and by Hopkins and Garfield (1979, 1981). For example, Bigelow's charts show temperature inside the 65 m isobath on Georges Bank ranging from 3-4°C in March to about 14°C in August, while Hopkins and Garfield (1981), averaging 45 years of data, show Georges Bank water extremes of 3.5°C and 14.6°C, in the same months. In the present study, the warmest average Georges Bank temperature was 13.8°C in September 1975 and the coldest was 5.0°C in February 1976. Both values are within the ranges of the earlier authors but the measurements were not made during their peak months. As might be expected, the salinity picture is less clear: Bigelow (1927), using titration, found little seasonal change on Georges Bank; Hopkins and Garfield (1981) reported a high of 33.0‰ in March and a low of 32.2‰ in August; in 1975-1976 the range was from 32.8‰ in April to 32.3‰ in October, a similar seasonal pattern but a delayed minimum. It appears then that the hydrography of the region during the period reported here was fairly typical.

The nutrient measurements presented here correspond only moderately well with those of Riley (1941) which were made at 120 stations in six cruises on Georges Bank between September 1939 and June 1940. Riley's nitrate and phosphate maxima were similar to ours at all depths and his phosphates followed the same seasonal pattern in the surface layers. However, his near-surface nitrate maximum was in

May, by which time in 1976 the values had already dropped sharply from the mid-winter peak, and his minima were never as low as the nearly nutrient-depleted conditions observed in summer and fall of 1975 and spring and summer of 1976. Riley's conclusion that "the largest concentrations of nitrate and phosphate were in the shallow water during the summer months" is not supported by the later evidence.

Nutrient concentrations in the biologically active upper levels of the ocean cannot be used effectively as tracers as they are in the deeper water. However, it is clear that the distribution of nutrients in the Georges Bank region at any given time are closely related to the water mass distribution and circulation. Thus, anomalously high near-surface nutrient levels are almost always associated with negative temperature anomalies indicating that upwelling is the source of the elevated nutrients. This phenomenon is seen most often in the southwest corner of the Gulf of Maine, east of Cape Cod (present on four of the seven cruises when adequate data were available), and on or near the Northeast Peak of Georges Bank (on four of eight cruises).

The occasional presence of cooler water in both these locations has been known for years. Schlitz (1982) has described the mechanisms that can account for such phenomena. Continuity demands some upwelling in the Gulf of Maine to balance the deep inflow in Northeast Channel. The upwelling east of Cape Cod appears to be partly wind-induced. In the Northeast Peak region there is centrifugal upwelling (Garrett and Loucks, 1976) resulting from interactions of strong oscillating tidal currents with the curving isobaths around the end of Georges Bank. The high nutrient/low temperature water to the northeast may also be part of the easterly jet along the northern flank of the bank, described by Butman *et al.* (1982). This jet, which appears to be a permanent feature, carries upwelled water from east of Cape Cod to the east (Hopkins and Garfield, 1981). The strong gradients in temperature, salinity and nutrients associated with such a jet appear in most of the data sets from 1975-1976 (four out of seven), in both vertical and horizontal plots, but station spacing on the survey grid was too broad to define it properly.

The nutrient concentrations in the deeper waters of the Gulf of Maine were statistically indistinguishable from those in the same depth range in the Slope Water just south of Georges Bank. However, in the previous section, it was shown that both the oxygen and salinity signatures of the Slope Water were considerably diluted in the deep Gulf of Maine. The high nutrients in the deep parts of the gulf are, therefore, only partly a result of the Slope Water inflow. Additional nutrients must be provided by biological regeneration, either in the benthos or in the water column. Schlitz and Cohen (1981) have calculated that the benthic contribution is negligible but regeneration due to zooplankton excretion accounts for nearly half the nitrogen demand of the Georges Bank-Gulf of Maine system. They estimate that bacterial regeneration may account for another 10%. How much of the zooplankton and bacterial regeneration is deeper than 120 m is not known, but these organisms are found at all depths within the Gulf of Maine so the contribution could be significant. Nutrients regenerated at these depths, like those advected in with the Slope Water, would not be available for photosynthesis until transported upward by some mechanism into the photic zone.

This review of one year nutrient measurements on and near Georges Bank leads to five principal findings:

1. The distributions of nitrate, phosphate and silicate were sufficiently alike, both in space and time, that one could be taken to be representative of all three.

2. There was a marked seasonal variation of all variables on Georges Bank and in the adjacent surface layers. Nutrient concentrations reached a maximum in winter, when primary production is at a minimum, and dropped to near zero in summer. Temperature was nearly the reverse but with slightly later extrema; salinity and oxygen were very closely matched with extrema trailing those of nitrate by about two months.

3. Indications of upwelling were found repeatedly at two locations inside the Gulf of Maine: one near the Northeast Peak of Georges Bank and one in the southwest corner of the gulf, just east of Cape Cod.

4. There were year-round nutrient reservoirs in the Gulf of Maine and in the Slope Water on the southern flank of Georges Bank.

5. Salinity and oxygen data from the water below 120 m on both sides of Georges Bank show that there was very little unmixed Slope Water inside the Gulf of Maine. The high nutrient levels there must, therefore, be a result of water column regeneration as well as advection.

Acknowledgments. The authors would like to thank Albert Matte, Donna Busch, Sam Nickerson, and Frank Steimle for help with data; and James King, Ray Cloutier, and Karen Lennon for drawing and copying distribution plots. Ronald Schlitz provided the nitrate-silicate and nitrate-phosphate information.

One of the authors (W. R. Wright) would like to record his gratitude to L. V. Worthington for demonstrating over several years of close association the pleasures of station-making, the importance of careful attention to detail, and the satisfaction of deriving new knowledge about the ocean from good field observations.

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Received: *16 September, 1981;* revised: *1 February, 1982.*