39

NOAA Technical Report NMFS SSRF-739

Bottom-Water Temperature Trends in the Middle Atlantic Bight During Spring and Autumn, 1964-76

Clarence W. Davis

December 1979

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Marine Fisheries Service

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721. National Marine Fisheries Service survey of trace elements in the fishery resource. [illegible]

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U.S. DEPARTMENT OF COMMERCE
Juanita M. Kreps, Secretary
National Oceanic and Atmospheric Administration
Richard A. Frank, Administrator
National Marine Fisheries Service
Terry L. Leitzell, Assistant Administrator for Fisheries

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CONTENTS

Figures

Tables

Bottom-Water Temperature Trends in the Middle Atlantic Bight During Spring and Autumn, 1964-76

CLARENCE W. DAVIS[1]

ABSTRACT

Annual variations of bottom-water temperatures on the continental shelf between Cape Cod and Cape Hatteras were examined for the spring and autumn from 1964 to 1976. Temperatures generally were highest since 1972 during both seasons. For waters between Cape Cod and Hudson Canyon, maximum temperatures occurred in the spring of 1976 (8.3°C) and autumn of 1972 (12.8°); between Cape Hatteras and Hudson Canyon, temperatures peaked in the spring of 1974 (9.0°C) and the autumn of 1972 (15.7°C). Minimum temperatures were in the spring of 1970 (5.1°C) and autumn of 1967 (9.7°C) and in the spring (4.6°C) and autumn (12.1°C) of 1970 in the respective areas.

Some factors that affect bottom-water temperatures, the relationship of the observed temperature variations to temperature fluctuations in other areas of the northwest Atlantic, and the effects of temperature changes on the distribution of several fish species are briefly discussed.

INTRODUCTION

The purpose of this study was to examine bottom-water temperature data collected since 1964 in the area between Cape Cod, Mass., and Cape Hatteras, N.C., to reveal annual variations and any possible warming or cooling trends that may have occurred. Since bottom-water temperatures are less affected by localized and short-term atmospheric phenomena than sea-surface temperatures, they can be linked with the sources of the subsurface water (and thus the direct cause of temperature variations) during warming and cooling periods (Colton 1968). Recent papers by Bowman and Wunderlich (1977) and Wright (1976) and the classic works of Bigelow (1933) and Bigelow and Sears (1935) provide background information to separate water masses and to establish the boundary between shelf water and slope water in the area discussed in this paper. The shelf-slope water boundary is usually in close proximity to the 100 m isobath in all seasons and can be represented by the 10°C isotherm (Wright 1976); these criteria will be used in part to define the causes of observed temperature changes since 1964. A paper by Colton and Stoddard (1973) based on 1940-66 mean temperatures can be used for comparing annual and long-term mean temperature conditions.

Changes in physical and chemical properties of the oceans, including temperature, can directly or indirectly affect fish and shellfish in numerous ways, but generally, there is a noticeable lack of ecological understanding of temperature effects (Brett 1969). Beltz et al. (1974) observed that over 7,000 papers have presented evidence of biothermal relationships, but comparatively few of these involved bottom-water temperatures in the marine environment. Probably the best single reference on the effects of the thermal environment on marine fisheries are the contributions to a symposium held in Rome in 1964 by the International Commission for the Northwest Atlantic Fisheries (1965). Collectively these papers emphasize the need for basic ecological knowledge essential for an adequate understanding of events in the life history of fishes. The use of long-term temperature data may be helpful, either by itself or as a contributing factor in quantitative models, in gaining this understanding.

Because potential users of the following data may require actual temperature values instead of graphical data, certain of the figures and tables involve some redundancy of my analyses. The additional information is considered justified if it will encourage others to examine and use the presented data.

DATA AND METHODS

The data were collected during the period 1964-76 on surveys designed and conducted by the National Marine Fisheries Service, Woods Hole, Mass., (Grosslein 1969) to determine the distribution and relative abundance of groundfish at randomly selected stations, from Cape Hatteras to Cape Cod (Fig. 1). Approximately 125 bottom-water temperatures were obtained during each cruise, mostly at depths between 30 and 200 m, with either mechanical or expendable bathythermographs, the latter being used after 1969.

For analytical purposes, this area, known as the "Middle Atlantic Bight" (Bigelow 1933), was divided into subareas: Cape Cod to Hudson Canyon, termed the Northern Bight; and Hudson Canyon to Cape Hatteras, termed the Southern Bight. There was no sampling south of Hudson Canyon prior to the autumn of 1967 and spring cruises did not commence until 1968.

Methods and rationale for analysis are fully described by Davis (1978). Briefly, the indices derived for

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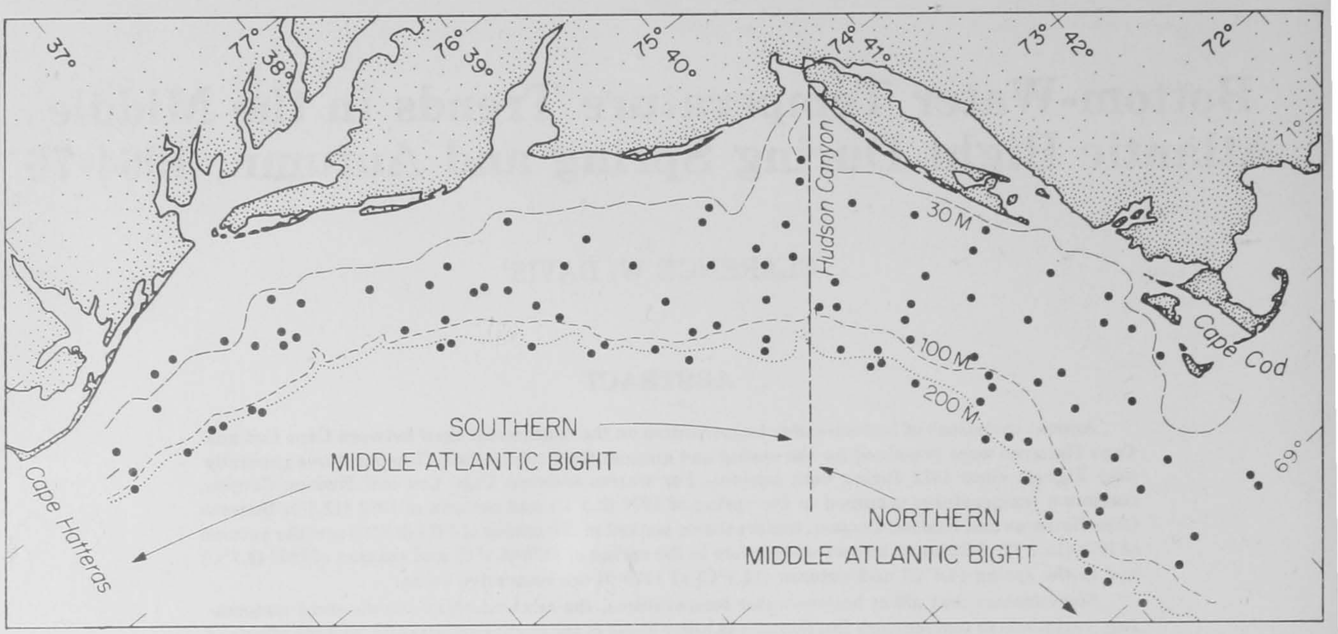

Figure 1.—Middle Atlantic Bight boundaries used in analysis of bottom-water temperature data. (Dots represent typical distribution of randomly selected bottom temperature stations.)

each cruise are based on the percentage of survey area represented by 2°C temperature contour intervals or temperature class intervals (TCI's) (Figs. 2, 3). The midpoint temperature of each TCI was multiplied by the percentage area within that TCI and their total product was divided by 100 to obtain a mean index for each cruise (Tables 1-4). The derived indices are based solely on an areal basis, but the stratified random sampling design allowed representative sampling by depth and geographic areas during each cruise. Since no attempt was made to determine absolute temperature indices, and the same geographic areas were randomly sampled during each cruise, the method chosen for determining relative temperature variations seems justified. A more precise estimate of relative bottom temperatures and elimination of possible bias associated with depth may have been analyzed. However, analytical data was not adequate for all the cruises and my major objective was to determine general temperature indices for rather large geographical areas during the entire seasonal time-series of data collection.

In order to determine year-to-year variation, the observed indices were adjusted by basing individual indices on a time-series mean sampling or reference date for each season (Table 5). Based on charts from Colton and Stoddard (1973) these seasonal reference dates closely approximate the timing of the annual minimum and maximum bottom-water temperature conditions expected in both subareas. Plots of annual bottom-water temperature cycles based on average temperature data by 10-day intervals at Nantucket Shoals and Five Fathom Bank Lightships during 1956-70 from Chase (1972) were used to calculate adjusted temperature values for the Northern Bight and the Southern Bight, respectively. The mean temperatures observed on each cruise were adjusted by adding or subtracting the difference in the mean temperatures at the appropriate lightship on the seasonal reference date and on the mid-date of each cruise. The magnitudes of the adjustments were usually ±0.2°C for the Northern Bight and ±0.5°C for the Southern Bight, but differences as great as 2.8°C were noted in 1970 when three cruise mid-sampling dates were approximately 1 mo earlier or later than their respective seasonal reference dates (Tables 5, 6, 8; Figs. 4, 7, 8). These large differences between observed and adjusted data clearly indicated the need for the adjustments in order to make meaningful comparisons of annual temperature variations. Since a comprehensive analysis of climatological and/or hydrographical conditions which might have revealed the factors responsible for the large differences between observed and adjusted data was beyond the scope of my investigation, these differences are attributed to the asynoptic seasonal sampling in certain years, e.g., 1970 (Table 5).

The observed indices may be considered in situ measurements of the thermal environment and are particularly relevant to synoptic biological observations. The primary objective of the adjusted indices is to measure the relative annual variations that have occurred during each spring and autumn in order to reveal any warming or cooling trends that may have occurred.

Species distribution charts and catches by numbers and pounds landed per ½ h tow observed during the same research cruises that temperature data were collected since 1967 were examined to determine any possible effects of the observed temperature changes. Examples of several of these relationships are briefly described in the Discussion section. Further analyses of these observations are currently being conducted by other members of the Woods Hole Laboratory staff.

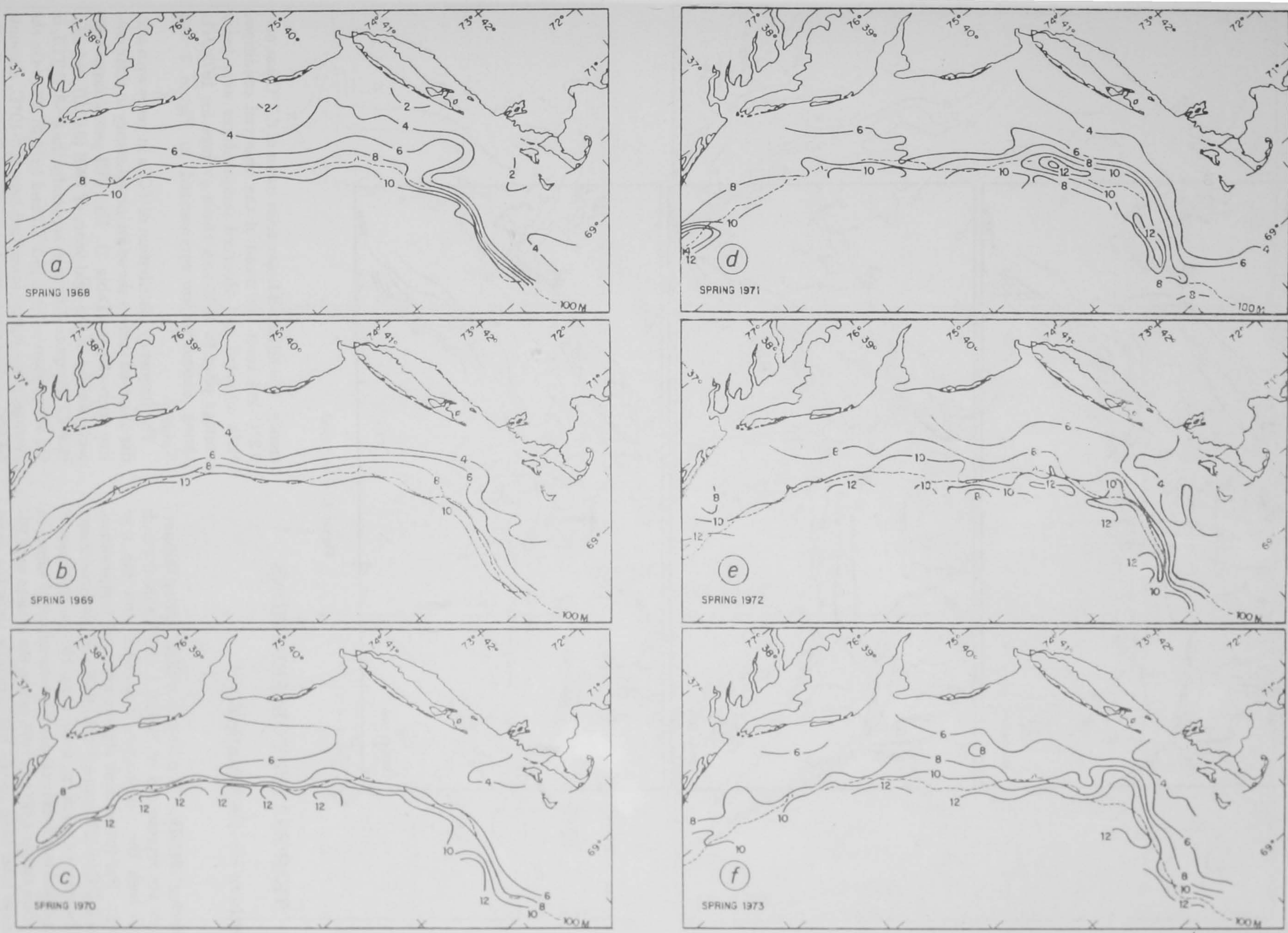

Figure 2.—Distribution of bottom-water temperatures (°C) in the Middle Atlantic Bight during spring 1968-76.

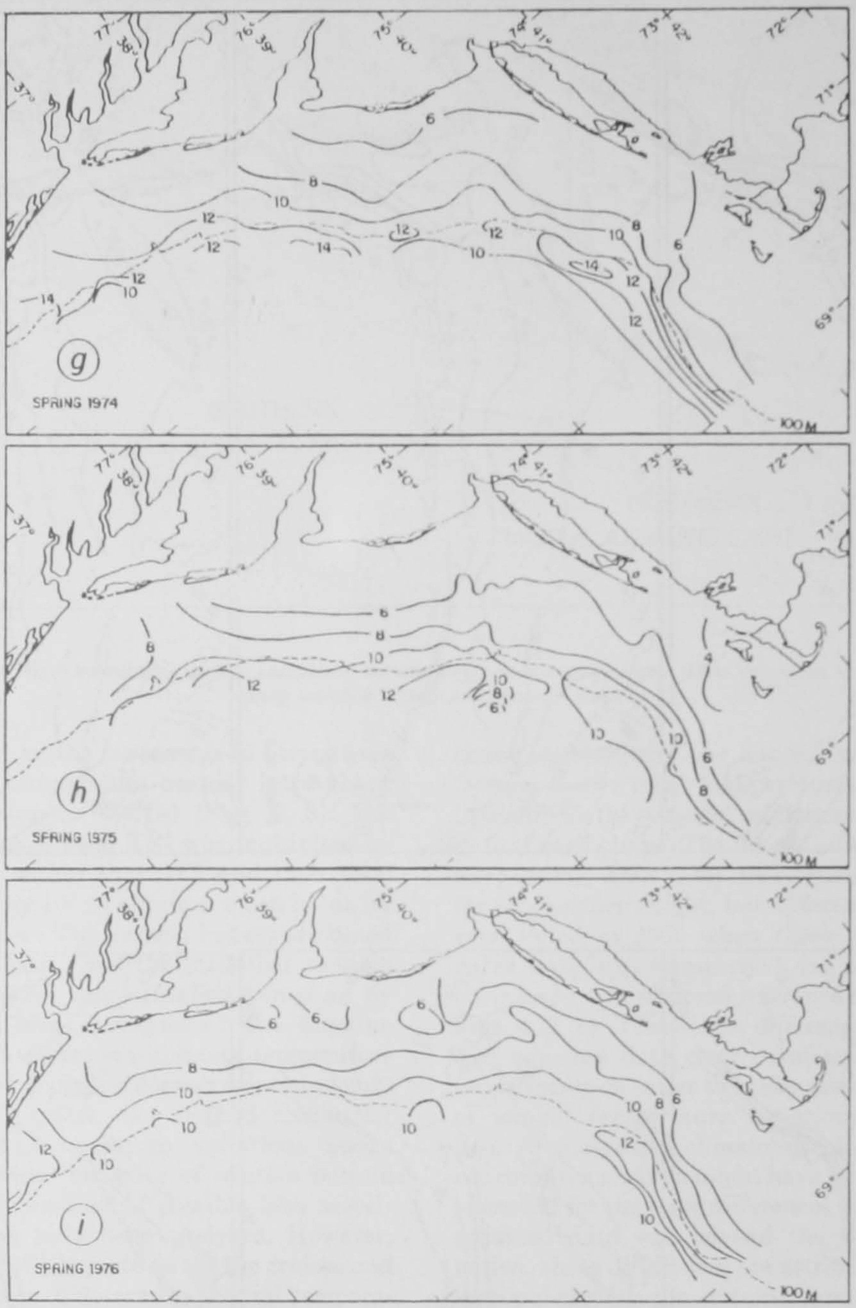

Figure 2.—Continued.

TEMPERATURE OBSERVATIONS

Northern Middle Atlantic Bight

Spring 1968-76.—The Northern Bight spring temperatures are represented in Figure 4 and Table 6 which show both the year-to-year variations and the 9-yr means. The lowest and highest adjusted temperatures were 5.1°C in 1970 and 8.3°C in 1976 and the series clearly illustrates a warming trend since 1970. The observed temperatures coincide closely with the adjusted values in all years except 1970 and 1974 (when the cruises were 20-30 days later than usual) but generally show the same trends. The adjusted time-series mean of 6.7°C was only 0.2°C less than the mean of the observed conditions. Both adjusted and observed temperatures were below average prior to 1972 and above average for 1972. The spring anomalies are summarized in Figure 5 and Table 7.

The frequency distribution of TCI's in years with similar observed indices shows an inconsistency in their relative percentages (Table 1). The TCI percentages were quite similar in the cold years of 1969 (6.0°C) and 1971 (5.9°C) but quite different, especially the 6°-8°C TCI, in the warm years of 1974 (8.1°C) and 1976 (8.2°C). On the average, slope water, identified here as >10°C, accounts for 20% of the total bottom thermal environment. On the

Figure 3.—Distribution of bottom-water temperatures (°C) in the Middle Atlantic Bight during autumn 1964-76.

Figure 3.—Continued.

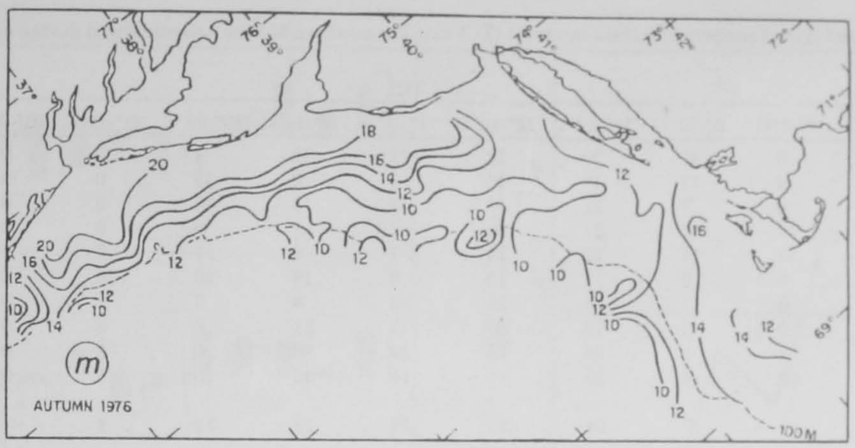

Figure 3.—Continued.

Table 1.—Percentages of temperature class intervals (TCI's) in the northern Middle Atlantic Bight during spring 1968-76.

	TCI							Observed
Year	0°-2°C	2°-4°C	4°-6°C	6°-8°C	8°-10°C	10°-12°C	12°-14°C	index (°C)
1968	3	43	16	12	8	18	0	5.7
1969	0	36	21	14	15	14	0	6.0
1970	0	5	68	7	11	8	2	6.2
1971	0	39	21	4	10	14	2	5.9
1972	0	12	37	21	10	12	8	6.9
1973	0	11	34	16	11	15	12	7.3
1974	0	0	19	43	11	19	8	8.1
1975	0	4	29	30	15	22	0	7.4
1976	0	2	26	20	21	24	7	8.2
Mean	<1	17	30	20	12	16	4	6.9

Table 2.—Percentages of temperature class intervals (TCI's) in the northern Middle Atlantic Bight during autumn 1964-76.

	TCI						Observed
Year	6°-8°C	8°-10°C	10°-12°C	12°-14°C	14°-16°C	16°-18°C	index (°C)
1964	1	40	44	12	3	0	10.5
1965	0	33	53	14	0	0	10.6
1966	0	1	67	32	0	0	11.6
1967	12	45	39	4	0	0	9.7
1968	0	34	30	25	11	0	11.3
1969	0	7	45	32	16	0	12.1
1970	2	27	44	26	1	0	10.9
1971	11	11	38	32	8	0	11.3
1972	0	7	28	44	21	0	12.6
1973	1	4	33	47	15	0	12.4
1974	0	5	36	44	15	0	12.4
1975	1	2	57	34	3	2	11.7
1976	0	10	32	35	23	1	12.6
Mean	2	17	42	29	9	<1	11.5

other extreme, water <4°C averaged about 17% of the area but its high variability (0-46%) probably influences mean conditions as much as the more steady (10-31%) encroachment of slope water onto the continental shelf. The highest annual percentages of water >10°C (1976) and >4°C (1968) resulted in the warmest and coldest indices, respectively.

Table 3.—Percentages of temperature class intervals (TCI's) in the southern Middle Atlantic Bight during spring 1968-76.

	TCI							Observed
Year	2°-4°C	4°-6°C	6°-8°C	8°-10°C	10°-12°C	12°-14°C	14°-16°C	index (°C)
1968	21	30	24	20	5	0	0	6.2
1969	27	37	12	10	14	0	0	5.9
1970	0	24	52	11	8	5	0	7.4
1971	2	38	31	21	5	1	1	6.9
1972	0	14	25	35	23	3	0	8.5
1973	0	17	45	21	15	2	0	7.8
1974	0	3	21	23	36	17	0	9.9
1975	0	24	25	29	16	6	0	8.1
1976	0	8	33	25	29	5	0	8.8
Mean	6	22	30	22	17	4	<1	7.7

Autumn 1964-76.—Bottom temperatures during the autumn in the Northern Bight fluctuated quite dramatically between years since 1964 (Fig. 6, Table 6). Except for a decline in 1975, a warming trend is indicated with maximum adjusted temperatures of 12.6°-12.8°C occurring since 1972. Most dramatic changes in the adjusted indices are the decrease from 12.5°C in 1966 to a minimum of 9.7°C in 1967 followed by an increase to 11.2°C in 1968. Adjusted and observed temperatures exhibited nearly the same annual variations which resulted in nearly identical 13-yr means of 11.6°C and 11.7°C, respectively. The autumn anomalies are shown in Figure 5 and Table 7.

In most cases, years of the same or closely similar observed temperatures had similar TCI percentages (Table 2). The coldest year (1967) had no water >14°C and all years (1969, 1972, 1973, 1974, 1976) that had indices >12°C had only 1% or less of water <8°C and only 10% or less of water <10°C. The 10°-12°C TCI usually dominated in all years and averaged 42% of the total bottom area during the time series.

Southern Middle Atlantic Bight

Spring 1968-76.—Adjusted bottom-water temperatures in the spring in the Southern Bight are characterized by large annual variations and a general warming

Table 4.—Percentages of temperature class intervals (TCI's) in the southern Middle Atlantic Bight during autumn 1967-76.

Year	TCI										Observed index (°C)
	4°-6°C	6°-8°C	8°-10°C	10°-12°C	12°-14°C	14°-16°C	16°-18°C	18°-20°C	20°-22°C	22°-24°C	
1967	0	0	27	29	12	12	16	4	0	0	12.5
1968	0	14	22	18	10	9	8	19	0	0	12.6
1969	0	0	7	21	14	7	18	33	0	0	15.1
1970	6	17	28	21	23	3	1	0	0	0	9.9
1971	0	13	14	27	13	7	8	7	9	1	12.7
1972	0	0	9	17	10	8	18	20	16	2	15.9
1973	0	0	2	25	25	32	8	7	1	0	13.9
1974	0	0	2	29	30	13	11	6	8	0	13.9
1975	0	0	5	29	15	26	26	0	0	0	13.9
1976	0	0	16	25	14	11	12	15	7	0	14.0
Mean	<1	4	13	24	17	13	13	11	4	<1	13.4

Table 5.—Middates of sampling bottom-water temperature data in the Middle Atlantic Bight. Means of sampling dates (bottom line) used as the bases for adjusted indices (see text).

Year	Southern New England		Middle Atlantic Bight	
	Spring	Autumn	Spring	Autumn
1964	No cruise	26 Oct.	No cruise	No cruise
1965	No cruise	11 Nov.	No cruise	No cruise
1966	No cruise	10 Nov.	No cruise	No cruise
1967	No cruise	24 Oct.	No cruise	24 Oct.
1968	15 Mar.	16 Oct.	10 Mar.	15 Oct.
1969	11 Mar.	12 Oct.	10 Mar.	13 Oct.
1970	20 Apr.	20 Oct.	26 Apr.	7 Sept.
1971	12 Mar.	8 Oct.	4 Apr.	8 Oct.
1972	26 Mar.	8 Oct.	13 Mar.	2 Oct.
1973	22 Mar.	7 Oct.	26 Mar.	1 Oct.
1974	1 Apr.	6 Oct.	18 Mar.	29 Sept.
1975	6 Mar.	19 Oct.	13 Mar.	29 Oct.
1976	8 Mar.	11 Oct.	17 Mar.	8 Oct.
Mean	20 Mar.	18 Oct.	22 Mar.	8 Oct.

Table 6.—Observed and adjusted mean bottom-water temperatures in the northern Middle Atlantic Bight during spring 1968-76 and autumn 1964-76.

Year	$\bar{x}$ spring temperature (°C)			$\bar{x}$ autumn temperature (°C)		
	Observed	Adjusted	Change	Observed	Adjusted	Change
1964		No cruise		10.5	10.6	+0.1
1965		No cruise		10.6	11.2	+0.6
1966		No cruise		11.6	12.5	+0.9
1967		No cruise		9.7	9.7	0
1968	5.7	5.7	0	11.3	11.2	−0.1
1969	6.0	6.1	+0.1	12.1	12.3	0
1970	6.2	5.1	−1.1	10.9	10.8	−0.1
1971	5.9	6.0	+0.1	11.3	11.6	+0.2
1972	6.9	6.7	−0.2	12.6	12.8	+0.2
1973	7.3	7.2	−0.1	12.4	12.6	+0.2
1974	8.1	7.7	−0.4	12.4	12.7	+0.3
1975	7.4	7.5	+0.1	11.7	11.6	−0.1
1976	8.2	8.3	+0.1	12.6	12.6	0
Mean	6.9	6.7	+0.2	11.5	11.7	+0.2

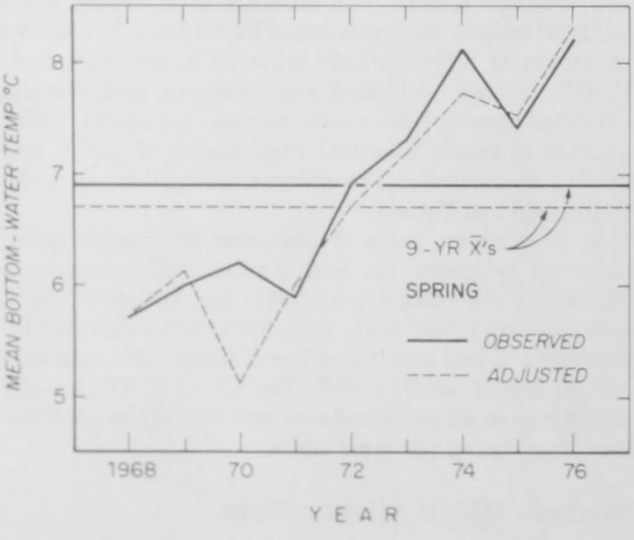

Figure 4.—Observed and adjusted annual and long-term mean bottom-water temperatures in the northern Middle Atlantic Bight during spring 1968-76.

Table 7.—Bottom-water temperature anomalies in the northern Middle Atlantic Bight during spring 1968-76 and autumn 1964-76.

Year	Spring anomalies (°C)		Autumn anomalies (°C)	
	Observed	Adjusted	Observed	Adjusted
1964	No cruise		−1.0	−1.1
1965	No cruise		−0.9	−0.5
1966	No cruise		+0.1	+0.8
1967	No cruise		−1.8	−2.0
1968	−1.2	−1.0	−0.2	−0.5
1969	0.9	0.7	+0.6	+0.6
1970	−0.7	−1.6	−0.6	−0.9
1971	−1.0	−0.7	−0.2	−0.1
1972	0	0	+1.1	+1.1
1973	+0.4	+0.5	+0.9	+0.9
1974	+1.2	+1.0	+0.9	+1.0
1975	+0.5	+0.8	+0.2	−0.1
1976	+1.3	+1.6	+1.1	+0.9
$\bar{x}$ indices	6.9	6.7	11.5	11.7

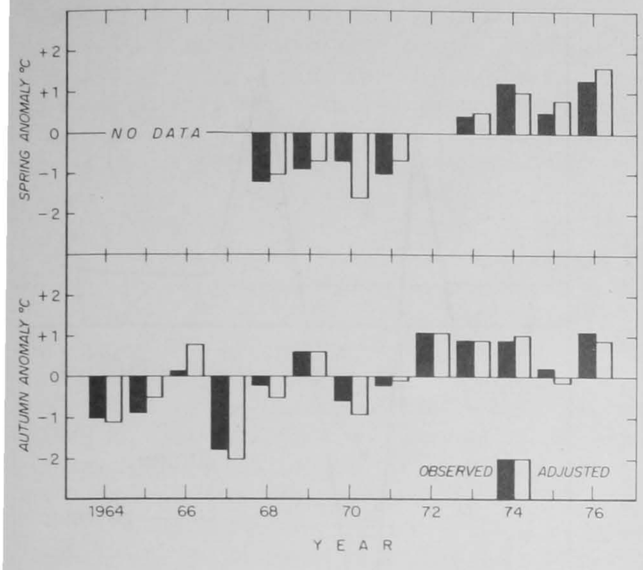

Figure 5.—Observed and adjusted mean bottom-water temperature anomalies in the northern Middle Atlantic Bight during spring 1968-76 and autumn 1964-76. The "O" base lines are based on the seasonal time-series mean temperatures during each season.

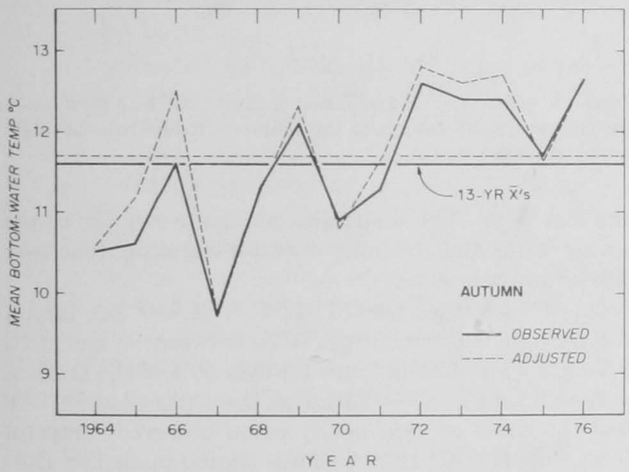

Figure 6.—Observed and adjusted annual and long-term mean bottom-water temperatures in the northern Middle Atlantic Bight during autumn 1964-76.

trend over the data period (Fig. 7, Table 8). The lowest and highest adjusted indices were 4.6°C in 1970 and 10.1°C in 1974 and the 9-yr mean was 7.5°C. Large year-to-year differences were also prevalent among the observed indices and except for 1970 when the spring cruise was nearly a month later than average, the trends are similar to the adjusted values. The lowest observed index was 5.9°C in 1969 and the highest index was 9.9°C in 1974.

Summarization of the annual spring anomalies (Fig. 8, Table 9) shows that all years before 1972 were below and the remaining years to 1976 were above the 9-yr average.

The two coldest years, 1968 and 1969, had no water >12°C and relatively large amounts of water <4°C while the warm years of 1972-76 had none of this cold water and only moderate amounts of this warm water (Table

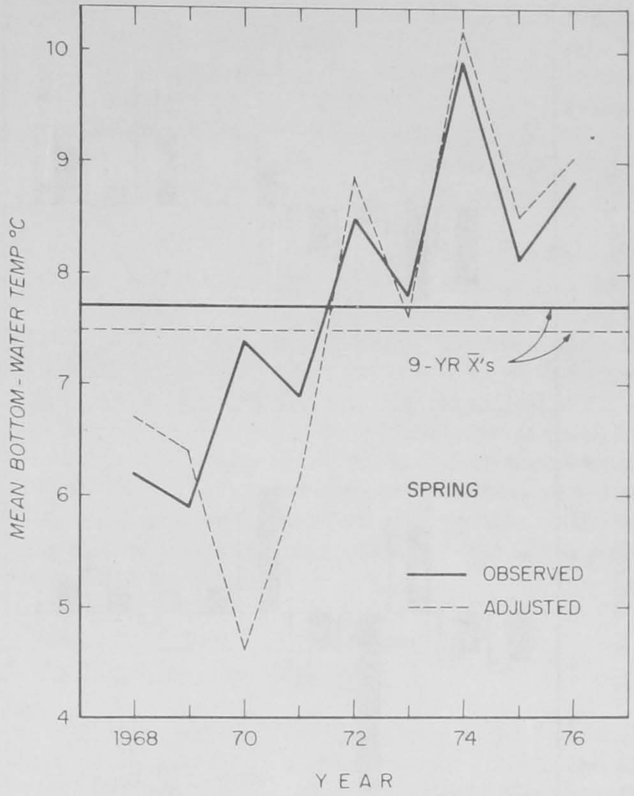

Figure 7.—Observed and adjusted annual and long-term mean bottom-water temperatures in the southern Middle Atlantic Bight during spring 1968-76.

Table 8.—Observed and adjusted mean bottom-water temperatures in the southern Middle Atlantic Bight during spring 1968-76 and autumn 1967-76.

	$\bar{x}$ spring temperature (°C)			$\bar{x}$ autumn temperature (°C)		
Year	Observed	Adjusted	Change	Observed	Adjusted	Change
1967		No data		12.5	12.6	+0.1
1968	6.2	6.7	+0.5	12.6	12.9	+0.3
1969	5.9	6.4	+0.5	15.1	15.3	+0.2
1970	7.4	4.6	−2.8	9.9	12.1	+2.2
1971	6.9	6.1	−0.8	12.7	12.7	0
1972	8.5	8.9	+0.4	15.9	15.7	−0.2
1973	7.8	7.6	−0.2	13.9	13.6	−0.3
1974	9.9	10.1	+0.2	13.9	13.6	−0.3
1975	8.1	8.5	+0.4	13.9	15.0	+1.1
1976	8.8	9.0	+0.2	14.0	14.0	0
Mean	7.7	7.5		13.4	13.8	

3). On the average the TCI distribution did not vary much in the 4°-12°C range but was slightly dominated by the 6°-8°C TCI.

Autumn 1967-76.—The observed, adjusted, and 10-yr mean bottom-water temperatures are shown in Figure 9 and illustrate the extreme variations that occurred in the Southern Bight during the autumn series. Except for 1970 and 1975 when the cruises were about 30 days before and 20 days after the autumn reference date, the observed and adjusted values were relatively equal and show the same variability. The largest decreases (5.2°C

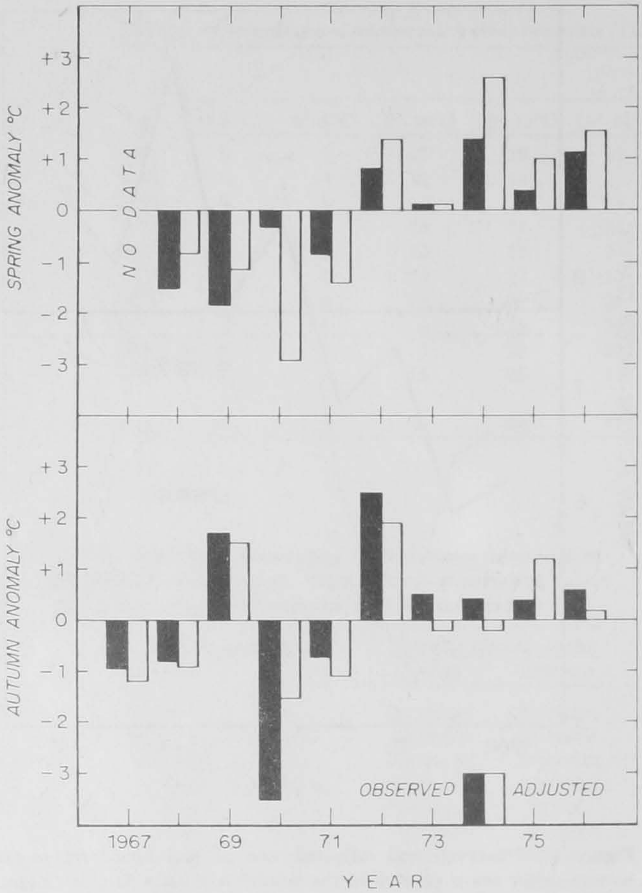

Figure 8.—Observed and adjusted mean bottom-water temperature anomalies in the southern Middle Atlantic Bight during spring 1968-76 and autumn 1967-76. The "O" base lines are based on the seasonal time-series mean temperatures during each season.

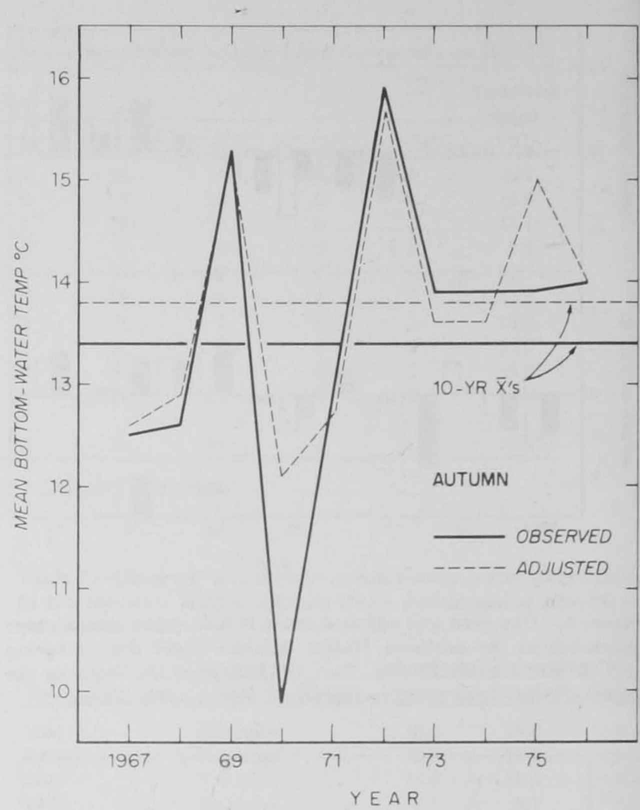

Figure 9.—Observed and adjusted annual and long-term mean bottom-water temperatures in the southern Middle Atlantic Bight during autumn 1967-76.

Table 9.—Bottom-water temperature anomalies in the southern Middle Atlantic Bight during spring 1968-76 and autumn 1967-76.

	Spring anomalies (°C)		Autumn anomalies (°C)	
Year	Observed	Adjusted	Observed	Adjusted
1967	No data		−0.9	−1.2
1968	−1.5	−0.8	−0.8	−0.9
1969	−1.8	−1.1	+1.7	+1.5
1970	−0.3	−2.9	−3.5	−1.7
1971	−0.8	−1.4	−0.7	−1.1
1972	+0.8	+1.4	+2.5	+1.9
1973	+0.1	+0.1	+0.5	−0.2
1974	+1.2	+2.6	+0.5	−0.2
1975	+0.4	+1.0	+0.5	+1.2
1976	+1.1	+1.5	+0.6	+0.2
$\bar{x}$ indices	7.7	7.5	13.4	13.8

for observed and 3.2°C for adjusted) was in 1970, the coldest autumn, while the largest increases (3.3°C for observed and 3.1°C for adjusted) was in 1972, the warmest autumn. The 10-yr adjusted mean index was 13.8°C and the observed mean was 13.4°C.

Figure 8 and Table 9 also show the autumn anomalies which, except for 1969, were negative in the first 5 yr of the series and positive or only slightly negative during the last 5 yr. The anomalies are quite similar to the spring series and generally reflect a warming trend over this latter time period.

On the average, the 10°-12°C TCI was the largest (24%) while the remaining TCI's between 8° and 20°C averaged 11-17% to account for over 90% of the thermal bottom layer (Table 4). Although the warm years 1973-76 had the same or very nearly equal observed temperatures, only the 10°-12°C TCI was similar in all 4 yr. During three nearly equally cold years—1967, 1968, and 1971—the colder and warmer TCI's also varied considerably. One of the colder years (12.7°C in 1971) actually had more or equal amounts of water >16°C than two of the warmer years (13.9°C in 1973-74) but was regulated by a large amount (27%) of water <10°C.

DISCUSSION

Causes of Temperature Variations

Specific identification of water masses is speculative in this paper because supportive salinity data were either nonexistent or unavailable at the time of this analysis. However, other investigations on the relationship of the shelf-slope interface allow some general conclusions to be made based on temperature data alone, at least for the spring observations. Based on the position of the 10°C isotherm (Figs. 2, 3), it can be seen that in the spring there was a greater encroachment of slope water onto the shelf during years of higher temperatures. This increase in volume of slope water coincided with a corresponding decrease in volume of inshore cold water and subsequently resulted in higher temperature indices for the entire area. Wright (1976) summarized southern New England temperature data from 1941 to 1972 and observed that the shelf-slope water boundary on the bottom, as indicated by the 10°C isotherm, was usually about 5-10 km south of the 100 m isobath in March and April and only a couple of kilometers north or south of this depth contour during October and November. He also observed that when the bottom position of the 10°C isotherm was farther offshore, the winter water temperature minimum was low. Figure 2 shows that not only was the 10°C isotherm north of the 100 m contour during the spring warming trend of the 1970's, but that the slope water was warmer than average in the last few years.

The mechanisms which might account for frontal movements are not well understood, but wind stress transport is thought to be significant, although usually of brief duration (Crist and Chamberlin[2]). Size and frequency of Gulf Stream warm core eddies may also cause significant variation in the slope front position by causing a subsurface inshore flow of slope water as a compensation for offshore surface entrainment of shelf water (Morgan and Bishop 1977).

In addition to water being carried onto the shelf from offshore, there is good evidence that some of the water flowing westward south of New England in the early spring originates in the Gulf of Maine-Georges Bank area (Bigelow 1933; Beardsley et al. 1976). Drifts from the east act as cooling agents and indrafts of slope water as warming agents, but solar warming of the water, first and most rapidly at the surface and next to land, is the outstanding feature in the spring (Bigelow 1933). During autumn, as surface cooling and mixing progresses and the summer thermocline is destroyed, bottom temperatures in the deeper strata increase to their seasonal maxima.

Another striking feature of the hydrography in this study area is the pool of cold bottom water that forms during winter mixing, becomes isolated by summer stratification, and persists for several months (Bigelow 1933; Ketchum and Corwin 1964). This cold core may extend from Cape Cod to the offing of Chesapeake Bay along the shelf edge and persist into September (Whitcomb 1970). Warming of these waters is associated with admixture of higher-salinity offshore waters or lower-salinity surface waters (Ketchum and Corwin 1964). Isolated cold cores of bottom water were clearly evident during the autumn cruises in both the Southern and Northern Bights (Fig. 3) and their extent and minimum temperatures are reflected in the observed temperature indices for each subarea. Especially notable is the minimum temperature observed in 1970 in the Southern Bight which was strongly influenced by a large cold pool with minimum temperatures of <6°C (Fig. 3g). The most pronounced effect of this cold pool in the Northern Bight occurred in 1967 when over half the subarea was covered by water <10°C with a relatively large inner core <8°C (Fig. 3d). During the warmest years (1972-74, 1976) and cold pool is either poorly defined, of small size, or made up of water >8°C.

Summarily, at least six phenomena directly or indirectly contribute to the bottom thermal environment of the continental shelf between Cape Cod and Cape Hatteras: 1) location of the slope front; 2) temperature of the slope water; 3) water drift from the east; 4) timing and extent of spring warming and autumn cooling of surface water; 5) size and frequency of Gulf Stream warm core eddies; and 6) size and temperature of the winter-formed "cold pool." To monitor and analyze these varied and complex phenomena presents a formidable task which cannot be accomplished solely on a basis of our survey cruises or data base.

Relationship of Temperatures East and West of Cape Cod

Although there is a rather abrupt general division between the hydrographic properties of the waters east and west of Cape Cod (Bigelow 1933; Parr 1933) these two regions have exhibited similar trends of temperature variability in recent years. The spring warming trend in the Gulf of Maine and on Georges Bank (Davis 1978) is especially similar to conditions in the Middle Atlantic Bight since 1973. Temperature variability in the Gulf of Maine is less because of the greater depths encountered there, but in many instances, the magnitude of annual changes were quite comparable in the other three areas. Bottom-water temperatures are strongly affected by the position of the shelf-slope boundary and vernal warming of shoal inshore waters and the effects of these phenomena have coincided with similar annual temperature trends in both regions during several years. A very rough estimate of average annual bottom temperature conditions (average of adjusted spring and autumn indices) since 1968 is depicted in Figure 10, and except for a couple of anomalous years, similar temperature trends are shown for each area.

Effects of Temperature Variations

Attempts to show environmental effects on fish year-class fluctuations by correlation techniques have generally failed because of difficulties of estimating both the year-class strength and the environmental factor (Gulland 1965). There is also difficulty in comparing distributional changes as related to changes in environmental conditions because population size contributes to the dispersive characteristics of many fishes, and there has been an apparent overexploitation of several fish stocks in the study area in recent years (Clark and Brown 1977). Despite these difficulties some evidence of natural biological changes seems apparent during this recent warm-

[2]Crist, R. W., and J. L. Chamberlin. 1977. Temperature structure on the Continental Shelf and slope south of New England during 1976. Unpubl. manuscr., 27 p. Atlantic Environmental Group, National Marine Fisheries Service, NOAA, Narragansett, RI 02881.

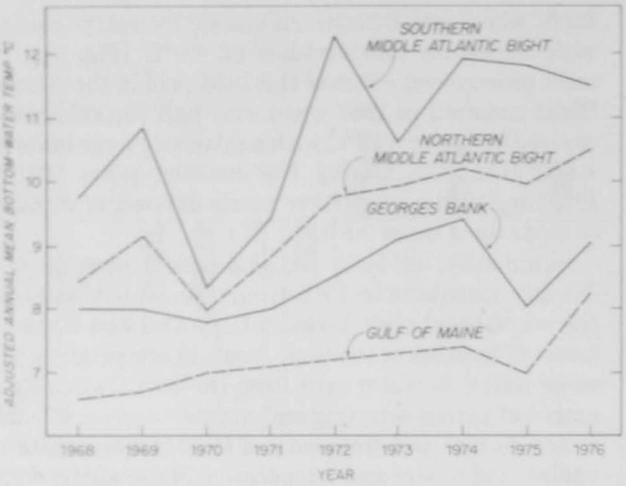

Figure 10.—Adjusted annual mean bottom-water temperature indices in four areas of the western North Atlantic continental shelf, 1968-76. Georges Bank and Gulf of Maine data are from Davis (1978).

ing period. Evidence collected during many of the same research cruises on which temperature data were collected revealed shifts in location and catch of the following species: 1) bluefish, *Pomatomus saltatrix;* relatively large catches in the autumn shifted from southern New England to Georges Bank, an area of unknown occurrence as reported by Bigelow and Schroeder (1953); 2) croaker, *Micropogonias undulatus,* occasional catches during warmer autumns but none during cold years off the North Carolina coasts; 3) mackerel, *Scomber scombrus;* catches normally widespread at most depths, confined mostly seaward of the 100 m contour during the cold springs of 1968-69 and 1971; 4) smooth dogfish, *Mustelus canis;* larger, more frequent and northward catches to southern New Jersey in the spring since 1972; 5) spiny dogfish, *Squalus acanthias;* a probable shift of part of the southern New England population onto Georges Bank during warm springs and catches decreased south of Hudson Canyon during the colder autumns; 6) spotted hake, *Urophycis regius;* generally avoid the coastal cold cells and their autumn catches are associated with the size and distribution of these waters; 7) fourspot flounder, *Hippoglossina oblonga;* during the coldest springs inshore catches small and irregular with concentrations synonymous with the 100 m contour; and 8) northern sea robin, *Prionotus carolinus;* same distributional behavior and catch characteristics as *H. oblonga.* It is not implied that these examples of changes in distributions and/or catches are explicitly related to changes in water temperature, but that some relationships probably exist since most of the species are not commercially fished and their distributions were determined on a basis of research ship surveys.

It should be noted that although Colton (1972) observed no significant changes in the distribution of four species of groundfish from Nova Scotia to Long Island during a cooling period, there was an extension of the southern range of American plaice, *Hippoglossoides platessoides,* and a contraction of the northern range of butterfish, *Peprilus triacanthus.* Also, Taylor et al. (1957) found evidence of northward shifts in the distribution and abundance of several marine animals during a warming period in the Gulf of Maine, but there was no obvious alteration of the general marine fauna.

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