NOAA Technical Report NMFS SSRF-725

Seasonal Bottom-Water Temperature Trends in the Gulf of Maine and on Georges Bank, 1963-75

Clarence W. Davis

May 1978

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

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National Oceanic and Atmospheric Administration
Richard A. Frank, Administrator
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Seasonal Bottom-Water Temperature Trends in the Gulf of Maine and on Georges Bank, 1963-75

CLARENCE W. DAVIS[1]

ABSTRACT

Spring (1968-75) and autumn (1963-75) bottom-water temperatures in the Gulf of Maine and on Georges Bank were analyzed to investigate a suspected warming trend in the region. During the spring the mean temperature in the Gulf of Maine increased rather steadily from a low of 5.4°C in 1968 to a high of 6.4°C in 1974. Various subareas of the Gulf had more frequent and greater oscillations but exhibited the same overall warming trend. Mean spring temperatures on Georges Bank fluctuated from 3.8°C in 1968 to 6.3°C in 1974 and declined by nearly 2°C in 1975 with similar characteristics in eastern, central, and western subareas of the Bank.

During the autumn in the Gulf, bottom-water temperatures reached a minimum of 5.4°C in 1966, increased to a maximum of 8.4°C in 1973 and 1974, but declined to 8.0°C in 1975. Subareas of the Gulf generally showed the same temperature trends from 1963 to 1968; especially notable are the cooling trend west of long. 69°W which commenced in 1971, and a decrease in all five subareas in 1975. Georges Bank temperatures in autumn declined from a maximum of 13.1°C in 1965 to a minimum of 10.4°C in 1969, reached another peak of 12.6°C in both 1973 and 1974, but declined to 11.6°C in 1975. Subareas of Georges Bank generally followed the same pattern with the eastern third of the Bank usually 2°C or colder than either of the other subareas in the autumn.

The average bottom-water temperatures during spring were 5.0°C on Georges Bank and 6.1°C in the Gulf of Maine; temperatures in the autumn were 11.7°C and 7.2°C, respectively, for these areas.

INTRODUCTION

This study summarizes variations in bottom-water mperatures observed during spring (1968-75) and itumn (1963-75) groundfish surveys conducted by the ılf of Maine-Georges Bank area by the National arine Fisheries Service, Woods Hole, Mass. Relatively gh temperatures were observed during 1973 and 1974 d raised the question of whether there had been a sigficant upward trend in average temperatures or simply couple of anomalous years since the surveys began in 63.

Recent papers by Colton and Stoddard (1973), Colton 968a), and Schopf (1967) have summarized the disbution of bottom-water temperatures from 1940 to 67 in the Gulf of Maine and contiguous waters. A conmporary paper by Karaulovsky and Sigaev[2] sumarizes similar data for 1962-72 and provides an interediate comparison between the earlier papers and this esent study. These previous studies are not strictly mparable with the present study because of the ıriability of the data bases and different analytical ethods; nevertheless, comparisons are useful for the entification of long-term trends, and the analyses are nsidered adequate for approximating annual changes spring and autumn bottom temperatures in the Gulf of aine and on Georges Bank.

Numerous authors, including Dow (1966, 1969) and Sutcliffe et al. (1977) for Gulf of Maine waters, have used surface-water temperatures to correlate fish catch with environmental factors. Flowers and Saila (1972) used both surface and bottom temperatures to estimate yield of American lobsters, *Homarus americanus*, and found the latter parameter considerably more accurate.

Although a study of bottom-water temperatures alone represents only a partial analysis of the temperature structure of the region, they are sufficient to reveal major changes in the thermal environment and are particularly relevant to the distribution of benthic organisms. The remainder of the temperature profile, from surface to near bottom, is not included in this study. Salinity profiles are also excluded since only surface and bottom data were routinely obtained until the most recent years. For these reasons, specific identification of subsurface water masses is speculative. It is known, however, that the major source of subsurface water in the Gulf of Maine is the inflow of relatively warm slope water through the Northeast Channel (Bigelow 1927; Colton 1968b). Therefore, major changes in the average bottom-water temperatures in much of the Gulf may be closely related to changes in the volume and extent of this inflow.

Georges Bank water is derived largely from the Gulf of Maine, but it is also sporadically influenced by intrusions of slope water along its southern boundary (Bumpus[3]). In the spring a counterclockwise (cyclonic) eddy is

[1]Northeast Fisheries Center, National Marine Fisheries Service,)AA, Woods Hole, MA 02543.

[2]Karaulovsky, V. P., and I. K. Sigaev. 1976. Long-term variations heat content of the waters on the Northwest Atlantic Shelf. Int.)mm. Northwest Atl. Fish. Res. Doc. 76/2, 9 p.

[3]Bumpus, D. F. 1975. Review of the physical oceanography of Georges Bank. Int. Comm. Northwest Atl. Fish. Res. Doc. 75/107, 32 p.

present in the Gulf of Maine and may either divert into Cape Cod Bay or turn eastward along the northern edge of Georges Bank. Similarly a clockwise (anticyclonic) eddy over Georges Bank causes a persistent westerly drift along the southern edge of the Bank which continues across Great South Channel. During autumn the southern portion of the Gulf eddy breaks down into a drift across the Bank, thus affecting temperatures there (Bumpus and Lauzier 1965). Since the Bank is well mixed vertically by tidal and wind forces throughout most of the year, subsurface temperatures there are influenced largely by air-sea interactions and by advection of deeper waters.

The identification of temperature anomalies on an areal and seasonal basis, along with other supportive data, is useful for interpreting changes in biological phenomena observed during these years. Examples of such changes are discussed in this paper.

METHODS

Bottom temperature data are based on mechanical or expendable bathythermograph observations obtained randomly during spring and autumn groundfish surveys (Grosslein[4]). During each cruise approximately 75-100 observations were made in the Gulf of Maine, mostly in water depths of 100-275 m, and 50-60 observations on Georges Bank (Fig. 1). Only those waters shallower than 100 m on Georges Bank are considered in this report because of high temperature variability of greater depths caused by sporadic excursions of warm slope water along the Bank's southern edge. Raw temperature observations are assumed to be actual bottom temperatures because only a few stations in the inner Gulf of Maine exceeded the maximum depth capability of 275 m of mechanical bathythermographs. Since temperatures below 250 m in most of the Gulf are generally isothermal with depth, 275-m temperatures are representative of bottom temperatures. Expendable bathythermographs, capable of reaching the greatest depths encountered, were used after 1969.

[4]Grosslein, M. D. 1974. Bottom trawl survey methods of the Northeast Fisheries Center, Woods Hole, Massachusetts, USA. Int. Comm. Northwest Atl. Fish. Res. Doc. 74/96, 27 p.

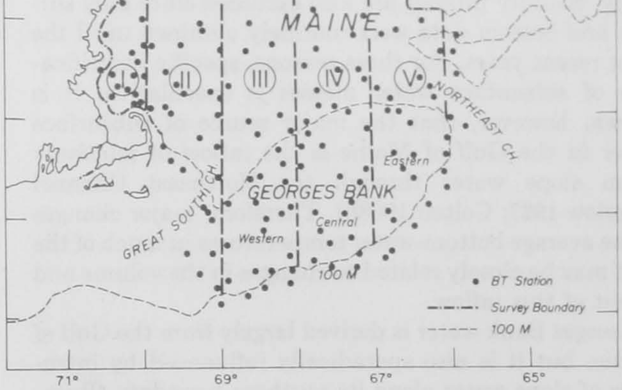


Figure 1.—Gulf of Maine-Georges Bank and subarea boundaries used in analysis of bottom-water temperature data. (Dots represent typical distribution of BT stations).

Both the Gulf of Maine and Georges Bank were analyzed in their entirety and by subareas which are bands of one degree of longitude in width (Fig. 1). Subareas in the Gulf are identified by Roman numerals I-V and Georges Bank subareas are termed Western, Central, and Eastern Georges Bank. Analysis by one-degree segments of longitude was chosen as they define rather distinct physiographic regions of the Gulf and Bank (Table 1) and also this was a convenient arbitrary method of establishing segment boundaries to show suspected temperature differences and trends in varous parts of the study area. Analysis of temperatures by latitude was not attempted, but latitudinal variability has been documented for both the shoal and deep waters of the Gulf of Maine (Bigelow 1927) and Georges Bank (Sigaev[5]).

Contoured isotherms at 1°C intervals were overlaid on 5-min grid charts and the number of units counted to determine the percentage area represented by each 2°C temperature class interval (TCI) (Figs. 2, 3). An index of the mean seasonal bottom temperature was then calculated by multiplying the midpoint temperature of each

[5]Sigaev, I. K. 1974. Characteristic features of the hydrological conditions on the Nova Scotia Shelf and Georges Bank, 1972. Int. Comm. Northwest Atl. Fish. Res. Doc. 74/51, 7 p.

Table 1.—Gulf of Maine and Georges Bank subarea characteristics.

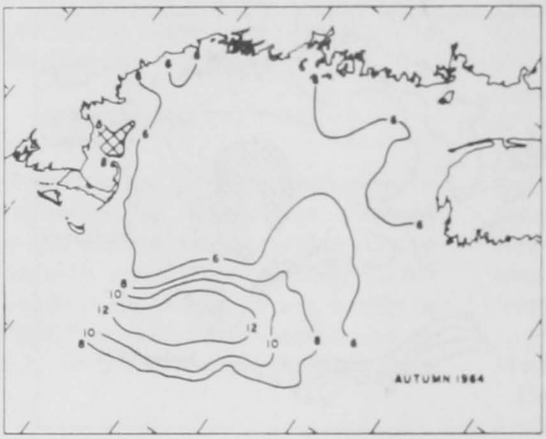
Area	Subarea	Characteristics
Gulf of Maine:	I	Coastal, < 200 m, Jeffreys Ledge and Stellwagen Bank
	II	Western Basin, some banks and ledges
	III	Intermediate between II & IV
	IV	Eastern Basin, mostly>200 m
	V	Coastal western Nova Scotia, entrance Northwest Channel
Georges Bank:	Western	Cultivator Shoal, adjacent Great South Channel
	Central	Georges Shoal, no adjacent channels
	Eastern	Mostly>60 m, adjacent Northeast Channel

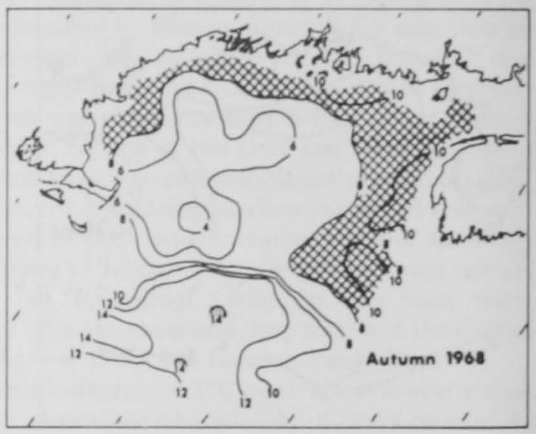
Figure 2.—Distribution of spring bottom-water temperatures, 1968-75. (Dotted areas represent Georges Bank temperatures less than 4°C; gridded areas represent Gulf of Maine temperatures greater than 8°C.)

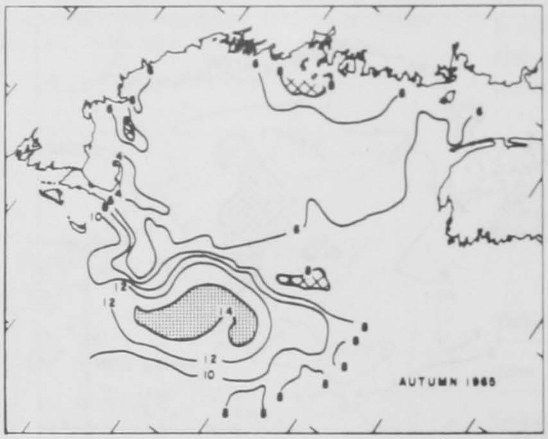

Spring 1968
Spring 1972
Spring 1969
Spring 1973
Spring 1970
Spring 1974
Spring 1971
Spring 1975

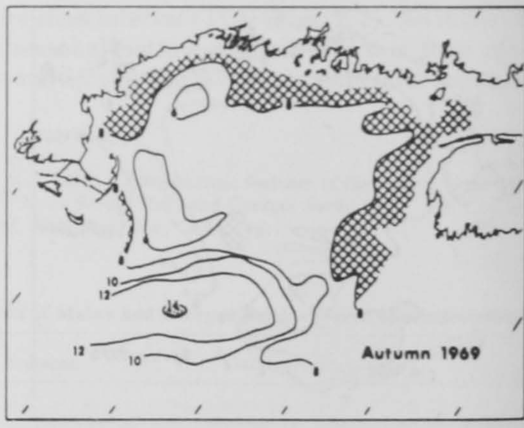

AUTUMN 1963

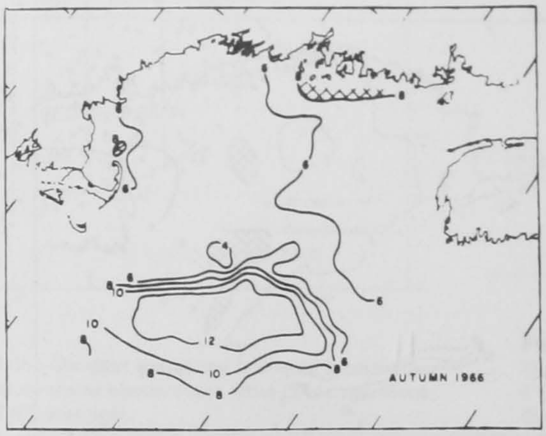

AUTUMN 1967

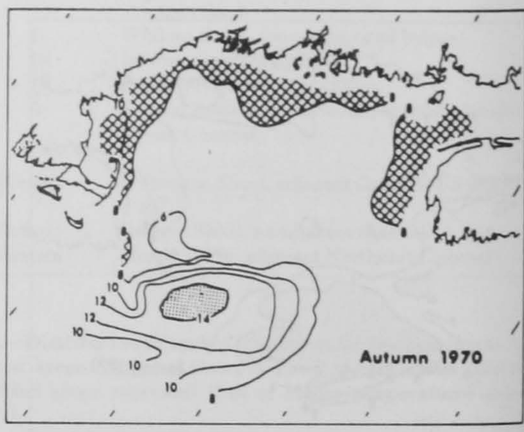

AUTUMN 1964

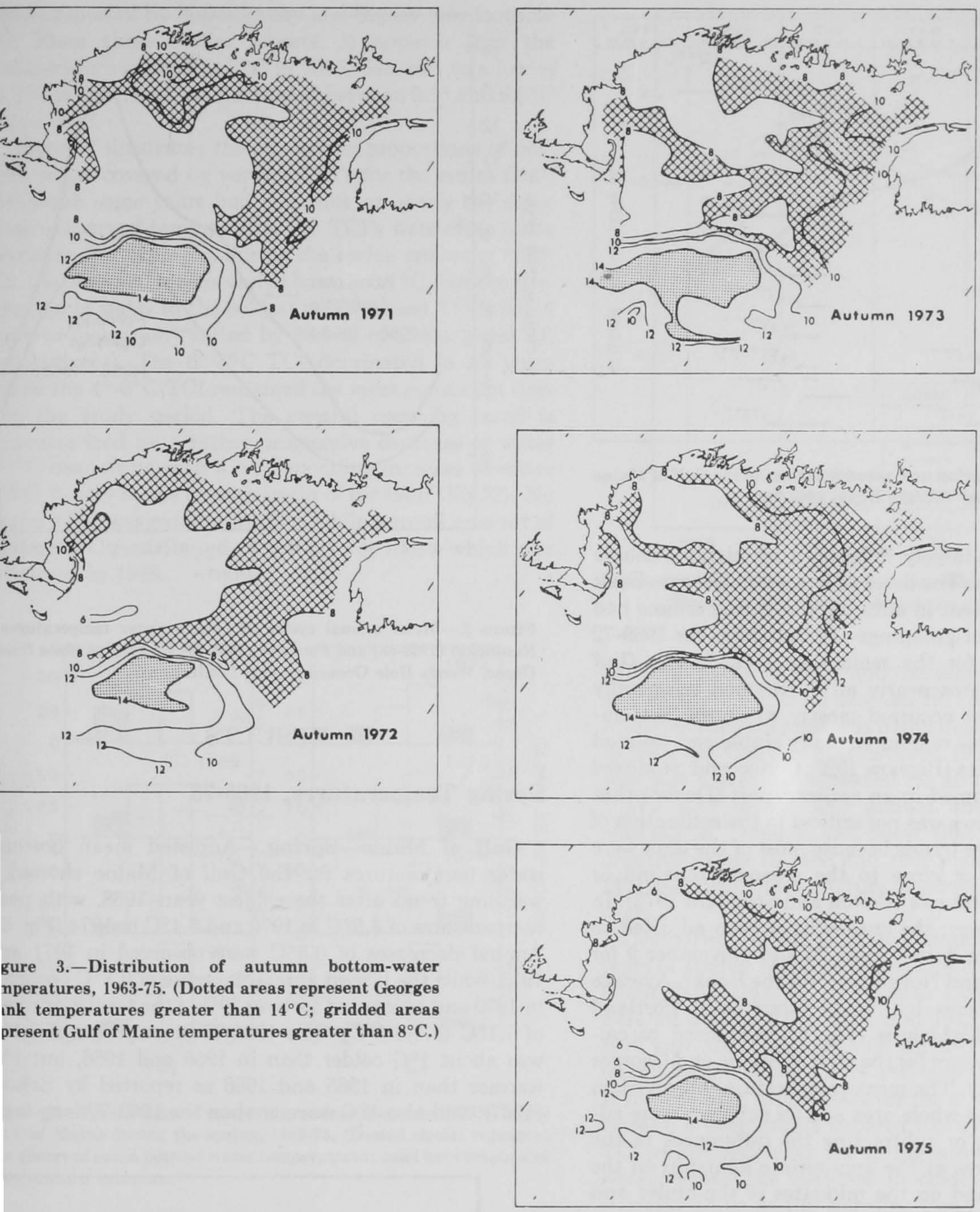

Autumn 1968


AUTUMN 1965


Autumn 1969


AUTUMN 1966


Autumn 1970



gure 3.—Distribution of autumn bottom-water mperatures, 1963-75. (Dotted areas represent Georges ınk temperatures greater than 14°C; gridded areas present Gulf of Maine temperatures greater than 8°C.)

CI by the percentage area within that interval and viding the total by 100. This method was chosen as it ıs not possible to make direct year-to-year compari- ns of station data because randomly located stations ere sampled during each cruise. The stratified random mpling scheme did, however, result in representative mpling by depth and geographic subareas. This ethod also eliminates bias associated with depth riability as the indices derived are based solely on an eal basis and the same geographic areas are used to mpare relative annual differences in bottom-water mperatures. Since no attempt is made to determine solute temperature indices, the method chosen for data analysis seems justified. For illustrative purposes, portions of the histograms of TCI distributions have been shaded to emphasize temperature extremes. For Georges Bank TCI's < 4° and > 8°C in spring (Figs. 7, 9) and < 6° and > 10°C in autumn (Figs. 15, 17) are shaded. For the Gulf of Maine TCI's < 4° and > 6°C in spring (Figs. 11, 13) and < 8° and > 14°C in autumn (Figs. 19, 21) are shaded. The shaded portions of the histograms generally lie outside expected mean bottom temperature conditions.

Dates for the collection of temperature data are shown in Figure 4. The effects of irregular seasonal sampling are difficult to interpret, especially for shoal areas like Georges Bank where seasonal cycles of bottom-water

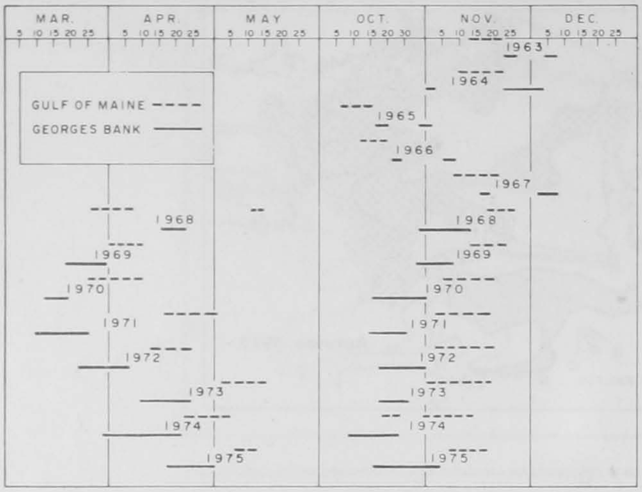


Figure 4.—Dates of spring and autumn cruises in the Gulf of Maine and Georges Bank, 1963-75.

temperatures are largely influenced by highly variable surface conditions. The dates of cruises on Georges Bank were fairly consistent in autumn, but spring cruises had two rather distinct groupings—March dates for 1969-72 and April dates for the remaining 4 yr. In the Gulf autumn cruise dates nearly all overlapped temporally and spring cruises occurred mostly when the bottom-water temperatures remain virtually stable and isolated from surface effects (Bigelow 1927; Colton and Stoddard 1973). It was assumed in an earlier report (Davis[6]) that timing of the cruises was not critical to the estimation of major temperature trends because most of the data were collected during or close to the seasonal maxima or minima in temperatures (Colton and Stoddard 1972). In this report, however, the cruises have been adjusted to common reference dates (April 20 and November 9 for the Gulf; April 4 and November 7 for the Bank). Average bottom temperatures by 10-day intervals at Portland and Nantucket Lightships (Fig. 5) were used to calculate adjusted values for the Gulf of Maine and Georges Bank, respectively. The mean temperatures observed on each cruise for the whole area and its subareas were adjusted by adding or subtracting the differences in the mean temperatures at the appropriate lightship on the reference dates and on the middates of the cruise and subarea samplings. Magnitude of the adjustments was mostly less than 0.4°C in the Gulf of Maine, but was 1°C or more on Georges Bank, especially in the autumn (Figs. 6, 10, 14, 18; Tables 2-5). Finally an annual index for both the Gulf of Maine and Georges Bank was obtained by averaging the spring and autumn indices (Fig. 22).

The reader is alerted to keep in mind which index—observed or adjusted—is used in the text. Adjusted values are intended primarily for examining trends and observed values for comparing habitat conditions, i.e., TCI distributions.

[6]Davis, D. W. 1976. Spring and autumn bottom-water temperatures in the Gulf of Maine and Georges Bank, 1968-1975. Int. Comm. Northwest Atl. Fish. Res. Doc. 76/85, 14 p.

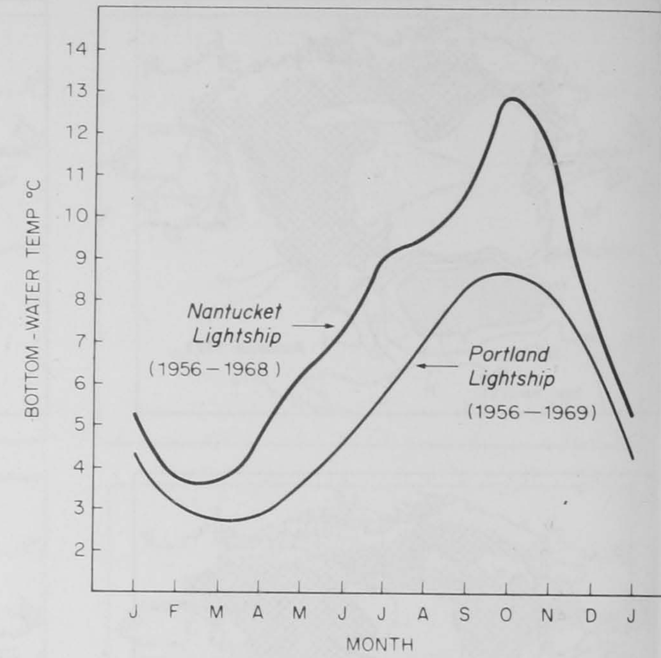


Figure 5.—Mean annual cycles of bottom-water temperatures at Nantucket (1956-68) and Portland (1956-69) Lightships (data from J. Chase, Woods Hole Oceanographic Institution).

RESULTS

Spring Temperatures, 1968-75

Gulf of Maine—Spring.—Adjusted mean bottom-water temperatures for the Gulf of Maine showed a warming trend after the coldest year, 1968, with peak temperatures of 6.5°C in 1970 and 6.4°C in 1974 (Fig. 6). Annual decreases of 0.3°C were observed in 1971 and 1975, while the largest annual increase of 0.8°C occurred in 1970 and accounted for over 70% of the total 8-yr range of 1.1°C (5.4-6.5°C). The 1968-75 mean index of 6.1°C was about 1°C colder than in 1955 and 1956, but 1°C warmer than in 1965 and 1966 as reported by Schopf (1967), and also 1°C warmer than the 1962-72 long-term

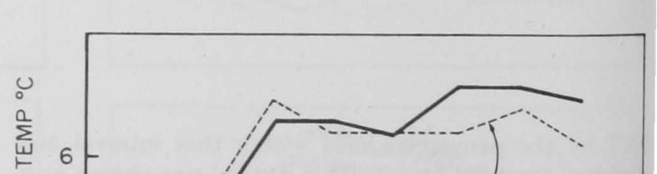
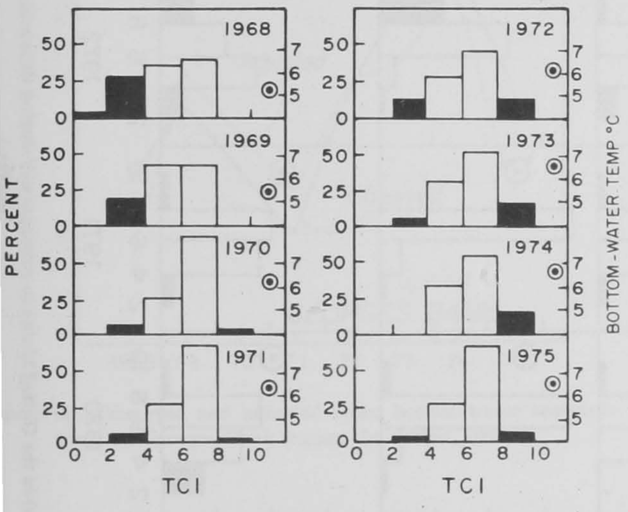


Figure 6.—Observed and adjusted mean bottom-water temperatures in the Gulf of Maine during the spring, 1968-75.

nean reported by Karaulovsky and Sigaev (see footnote 2). From these earlier reports, it appears that the emperature peaked at 7°C in 1955, declined to a low of 1.3°C in 1966, and has fluctuated between 6.1° and 6.5°C since 1970.

Figure 7 illustrates the changes in proportions of bot- om water covered by various TCI's for the entire Gulf. Although some years had the same or nearly the same nean observed temperature, the TCI's were often quite variable. For example, during the spring cruises of 1970- 72, the observed means varied by only 0.1°C, but the per- centage of water in the coldest and warmest TCI's (solid bars in histogram) varied by factors of about 2 and 13, respectively). The 6°-8°C TCI dominated in all years while the 4°-6°C TCI remained the most consistent dur- ng the study period. The general warming trend is characterized by a rather progressive decrease of water <4°C near shore with a corresponding increase of water >8°C mostly in the eastern basin of the Gulf (Fig. 2). No water <4°C was evident in 1974, while a small amount of water <2°C contributed to the coldest index which was observed in 1968.



igure 7.—Percentages of temperature-class intervals (TCI's) in the ulf of Maine during the spring, 1968-75. (Dotted circles represent e observed mean bottom-water temperatures; solid bars emphasize mperature extremes.)

Subareas of the Gulf of Maine—Spring.—Adjusted ndices of the annual mean bottom-water temperature or the Gulf by subareas of one-degree longitude are sum- narized in Figure 8. Analysis by subareas reveals an in- rease in the frequency and magnitude of oscillations etween years with an overall warming trend indicated or each subarea. Subareas I and IV had the lowest and ighest bottom temperatures, respectively, during all ears. This is associated with differences in bathymetry s Subarea I has the most shoal water and nearly all of ubarea IV is greater than 200 m deep. The relative hoalness of Subarea I is also reflected in the large tem- erature variability between years, especially the in- reases between 1969 and 1970 (+1.5°C), and between

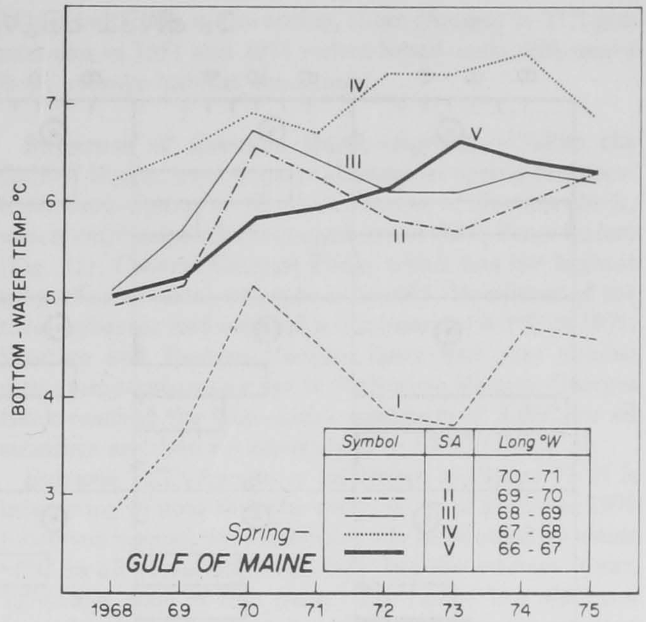


Figure 8.—Adjusted mean bottom-water temperatures in the Gulf of Maine in subareas I-V during the spring, 1968-75.

1973 and 1974 (+1.0°C), and the decreases between 1970 and 1971 (−0.6°C) and between 1971 and 1972 (−0.7°C). A temperature increase was noted in all subareas in 1968-70 with the sharpest rise between 1969 and 1970. In no year was a decrease observed for all five subareas.

The 8-yr means and annual anomalies are summarized in Table 2 and show that all subareas had negative values in 1968 and 1969 and positive values in 1974 and 1975, but a mixture of values in the intervening years.

Comparison of the Gulf by subarea again shows how years of similar mean temperatures can have vastly different TCI's (Fig. 9). In Subarea I the observed means were all 5°C in 1970, 1974, and 1975, but the TCI's in 1970 were about 20% each for the 2°-4°C and 6°-8°C intervals, and 60% for the 4°-6°C interval, while 1974 and 1975 were both nearly 100% for the 4°-6°C interval. Conversely, a deep stable subarea like IV had very similar TCI percentages when the spring means were similar and clearly shows the decrease in coldest and increase in warmest TCI's as the warming trend progressed.

Table 2.—Mean bottom-water temperatures and anomalies for Gulf of Maine, spring 1968-75. Adjusted values are shown in parentheses.

Subarea	Mean	1968	1969	1970	1971	1972	1973	1974	1975
I.	4.2	-1.5	- .7	+ .8	+ .2	- .5	- .2	+ .8	+ .8
	(4.1)	(-1.3)	(- .5)	(1.0)	(+ .5)	(- .3)	(- .4)	(+ .6)	(+ .5)
II	5.9	-1.0	- .8	+ .6	+ .3	- .1	+ .1	+ .3	+ .4
	(5.8)	(- .9)	(- .7)	(+ .7)	(+ .4)	(0)	(- .1)	(+ .2)	(+ .5)
III	6.2	-1.1	- .5	+ .5	+ .3	- .1	+ .2	+ .3	+ .3
	(6.1)	(-1.0)	(- .4)	(+ .6)	(+ .3)	(0)	(0)	(+ .2)	(+ .1)
IV	7.0	- .7	- .5	- .1	- .2	+ .4	+ .6	+ .7	+ .2
	(6.9)	(- .7)	(- .4)	(0)	(- .2)	(+ .4)	(+ .4)	(+ .6)	(0)
V	6.0	-1.0	-1.0	- .3	0	0	+ .8	+ .5	+ .5
	(5.9)	(- .9)	(- .7)	(- .1)	(0)	(+ .2)	(+ .7)	(+ .5)	(+ .4)
Entire Gulf	6.1	- .9	- .6	+ .2	+ .2	+ .1	+ .5	+ .5	+ .4
	(6.1)	(- .7)	(- .4)	(+ .4)	(+ .1)	(+ .1)	(+ .1)	(+ .3)	(0)

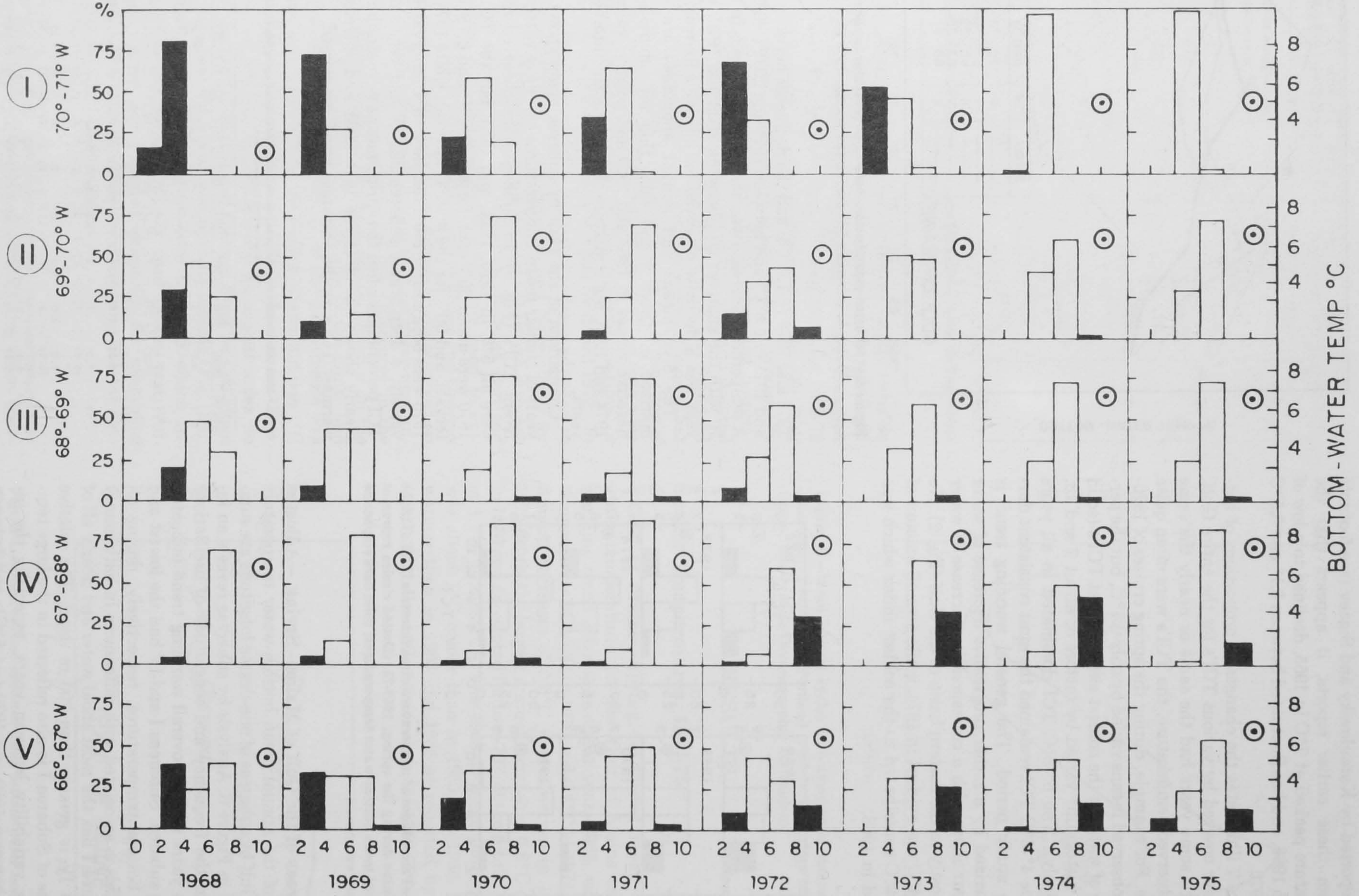
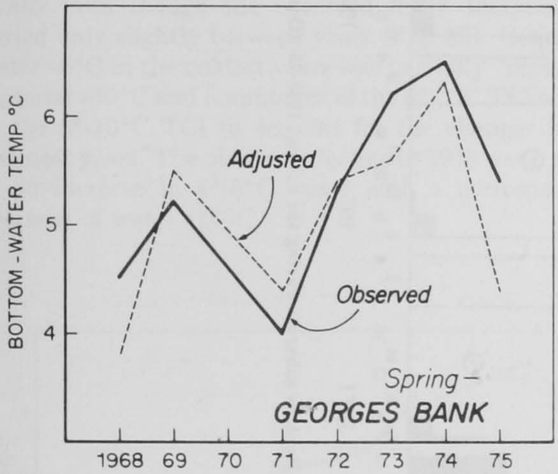


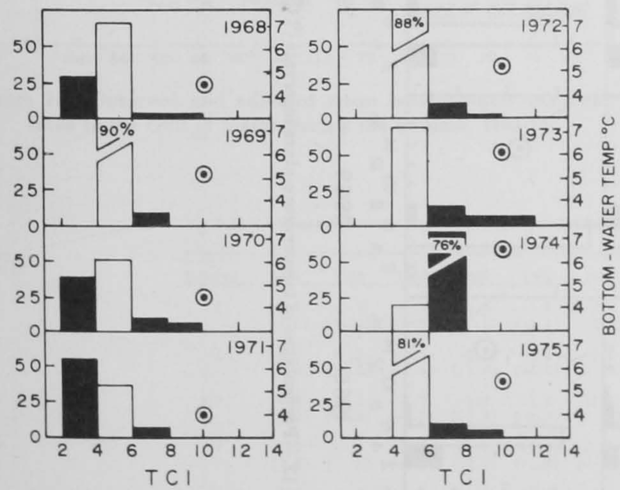
Figure 9.—Percentages of temperature-class intervals (TCI's) in the Gulf of Maine in subareas I -V during the spring, 1968-75. (Dotted circles represent the observed mean bottom-water temperatures.)

Georges Bank—Spring.—Adjusted spring bottom-vater temperatures on Georges Bank (Fig. 10) are haracterized by a low in 1971 of 3.8°C, followed by ather large annual increases to a peak of 6.3°C in 1974, and then a sharp decline of 1.9°C in 1975. The 8-yr nean of 5.0°C is 1°C lower than that reported by Karaulovsky and Sigaev (see footnote 2) for 1962-72, but heir coverage included waters deeper than 100 m which probably accounts for much of the difference. Data from Schopf (1967) indicate a mean Georges Bank bottom-vater temperature in the spring of approximately 6°C in 1955, 4.5°C in 1956, 3°C in 1965, and 3.5°C in 1966.

Georges Bank is usually dominated by the 4°-6°C TCI n the spring which in 1969 accounted for 90% of the area vithin the 100-m isobath (Fig. 11). The minimum (1971) and maximum (1974) observed means were influenced by a replacement of the 4°-6°C TCI with 2°-4°C and 6°-8°C vater, respectively. Since the Bank waters are well mixed vertically in the spring, these changes in TCI percentages in 1971 and 1974 reflect broad-scale differences from average habitat conditions.



gure 10.—Observed and adjusted mean bottom-water temperatures on Georges Bank during the spring, 1968-75.



'igure 11.—Percentages of temperature-class intervals (TCI's) on Georges Bank during the spring, 1968-75. (Dotted circles represent he observed mean bottom-water temperatures.)

Subareas of Georges Bank—Spring.—Unlike the Gulf of Maine, year-to-year changes in spring temperatures were similar in all the subareas of Georges Bank, which emphasizes the homogeneity of these shoal waters (Fig. 12). Central Georges Bank, which has the highest proportion of shoal water, was usually the coldest of the three subareas and reached a minimum of 4.0°C in 1971. Western and Eastern Georges Bank had very similar mean temperatures except in 1968 when Eastern Georges Bank reached the time-series minimum of 3.6°C for all subareas and had an anomaly of −1.7°C (Table 3).

Subarea TCI's for spring are shown in Figure 13. It is interesting to note that the warm years of 1973 and 1975 (observed means) were substantially influenced by water >8°C in all three subareas, but that the warmest year, 1974, had none of this water. The rather low observed mean for the entire Bank in 1968 was mainly the result of a 2°-4°C TCI covering 75% of the eastern subarea; water

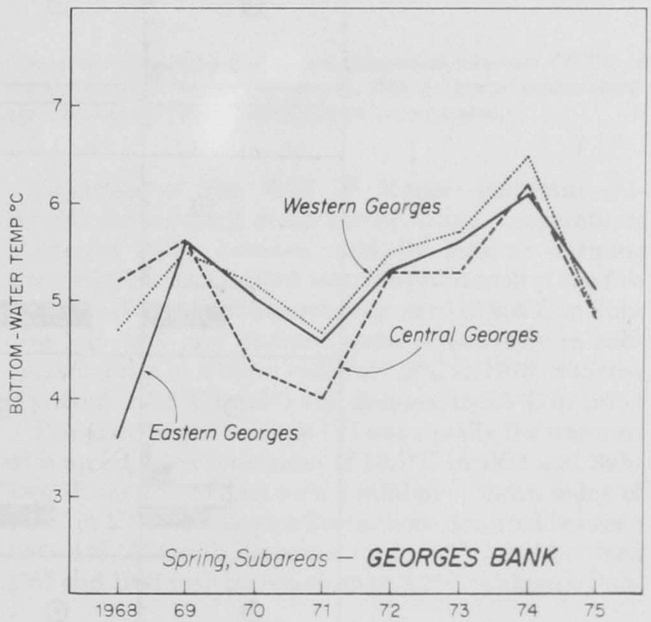


Figure 12.—Adjusted mean bottom-water temperatures on Georges Bank by subareas during the spring, 1968-75.

Table 3.—Mean bottom-water temperatures and anomalies for Georges Bank, spring 1968-75. Adjusted values are shown in parentheses.

Subarea	Mean	1968	1969	1970	1971	1972	1973	1974	1975
Western	5.3	- .7	- .1	- .3	-1.1	0	+ .9	+1.4	+ .2
	(5.3)	(-1.6)	(+ .2)	(- .1)	(- .6)	(- .3)	(+ .5)	(+1.3)	(- .4)
Central	5.1	0	+ .1	-1.0	-1.5	+ .1	+ .7	+1.4	+ .4
	(5.1)	(+ .1)	(+ .5)	(- .8)	(-1.1)	(+ .2)	(+ .2)	(+1.1)	(- .3)
Eastern	5.2	-1.7	0	- .4	-1.0	0	+1.0	+1.2	+ .6
	(5.1)	(-1.5)	(+ .5)	(- .1)	(- .5)	(+ .2)	(+ .5)	(+1.0)	(0)
Entire Bank	5.2	- .7	0	- .6	-1.2	+ .1)	+1.0	+1.3	+ .2
	(5.0)	(-1.2)	(+ .5)	(0)	(- .6)	(+ .4)	(+ .6)	(+1.3)	(- .6)

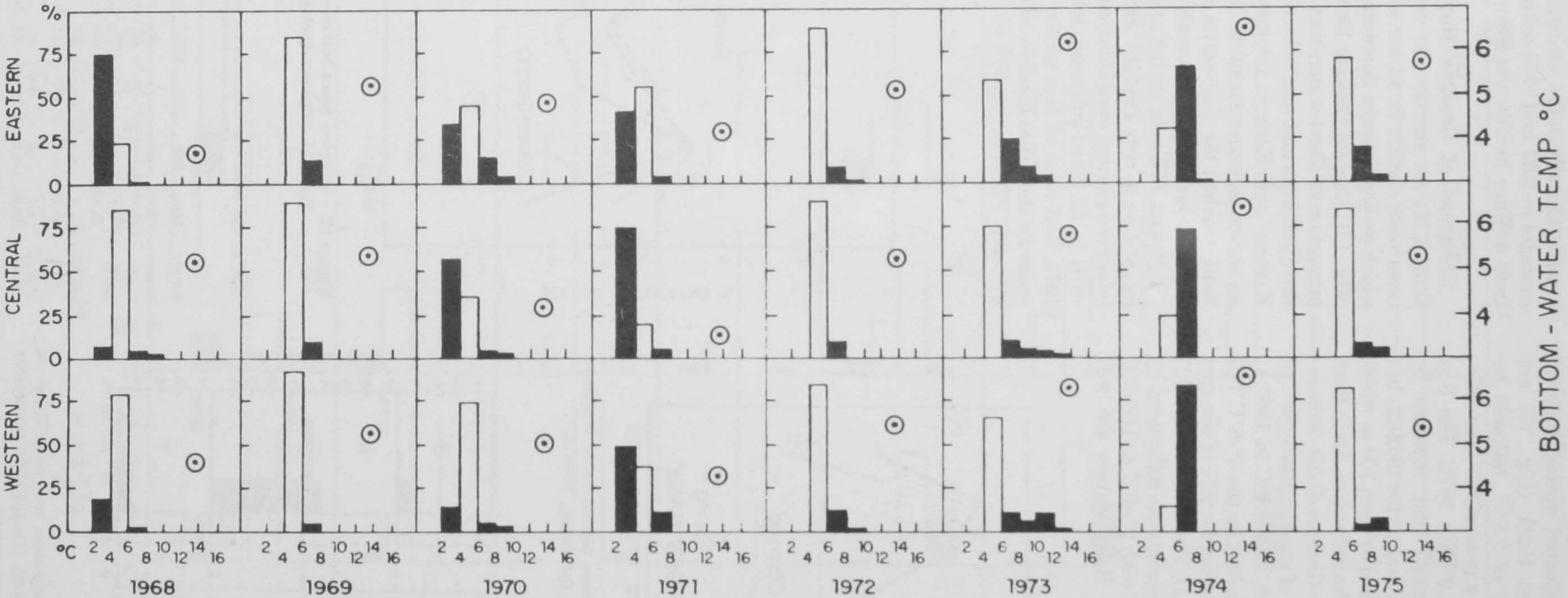


Figure 13.—Percentages of temperature-class intervals (TCI's) on Georges Bank by subareas during the spring, 1968-75. (Dotted circles represent the observed mean bottom-water temperatures.)

his cold occurred there in only two other years, 1970 and 1971.

Autumn Temperatures, 1963-75

Gulf of Maine—Autumn.—Adjusted bottom-water emperatures during autumn in the Gulf of Maine lecreased from a mean of 7.2°C in 1963 to a time-series minimum of 5.4°C in 1966, and then increased to a maximum of 8.4°C in 1973 and 1974 (Fig. 14). The greatest hanges were the 1.5°C decrease between 1963 and 1964 and the 1.5°C increase between 1967 and 1968. Every year after 1967 exceeded the 13-yr mean of 7.2°C, while all prior years had negative anomalies (Table 4). The 1963-75 mean was only 0.2°C warmer than that observed by Karaulovsky and Sigaev (see footnote 2) for 1962-72 and about 1°-1.5°C warmer than in 1964 and 1965 and the same as in 1955 as observed by Schopf (1967).

Temperature class intervals in the Gulf varied annually even though the observed mean temperatures varied only slightly between years (Fig. 15). Generally, water <6°C in the coldest years was partially "replaced" by water >10°C and dominance of the 6°-8°C TCI shifted to the 8°-10°C TCI to account for the changes in the warmest years. The observed decline in 1975 was a result of an increase in 4°-6°C water with a corresponding decrease of water >10°C.

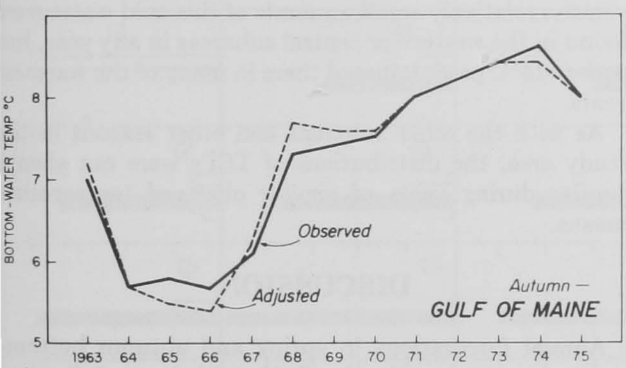


Figure 14.—Observed and adjusted mean bottom-water temperatures in the Gulf of Maine during the autumn, 1963-75.

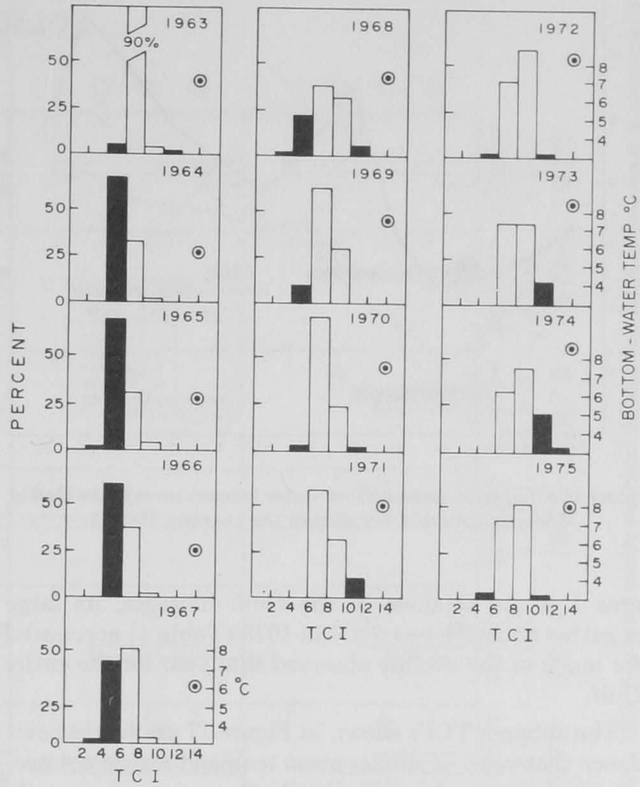


Figure 15.—Percentages of temperature-class intervals (TCI's) in the Gulf of Maine during the autumn, 1963-75. (Dotted circles represent the observed mean bottom-water temperatures.)

Subareas of the Gulf of Maine—Autumn.—Although the adjusted mean bottom-water temperatures fluctuated widely between years, the autumn warming trend which began in 1966 was evident in each of the five subareas (Fig. 16). Temperature peaked at 9.4°C in Subarea I in 1970 and declined quite consistently in subsequent years to a mean index of 7.3°C in 1975; Subarea II peaked at 8.3°C in 1971 and declined to 6.9°C in 1975.

The easternmost subarea (V) was usually the warmest with an adjusted maximum of 10.7°C in 1974 and Subarea II was the coldest with a minimum mean index of 4.6°C in 1966. The largest fluctuations occurred between 1963 and 1964 with decreases up to 2.2°C and between 1967 and 1968 with increases up to 3.2°C. Although Sub-

Table 4.—Mean bottom-water temperatures and anomalies for the Gulf of Maine, autumn 1963-75. Adjusted values are shown in parenthese.

Subarea	Mean	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975
I	7.4 (7.5)	+ .9 (+1.0)	- .9 (- .9)	-1.8 (-2.1)	-1.9 (-2.2)	-1.8 (-1.8)	+1.0 (+1.4)	+ .9 (+1.3)	+1.9 (+1.9)	+ .7 (+ .7)	+1.0 (+1.0)	+ .4 (+ .4)	+ .6 (+ .4)	- .9 (-1.2)
II	6.6 (6.6)	+ .2 (+ .8)	-1.5 (-1.4)	-1.7 (-1.9)	-1.6 (-2.0)	-1.1 (- .9)	- .5 (+ .3)	+ .2 (+ .4)	+ .7 (+ .8)	+1.8 (+1.8)	+ .8 (+ .9)	+1.1 (+1.2)	+ .8 (+ .7)	+ .5 (+ .3)
III	6.8 (6.9)	- .1 (+ .5)	-1.7 (-1.2)	-1.0 (-1.3)	-1.5 (-1.8)	-1.1 (- .9)	- .5 (- .4)	+ .3 (+ .4)	+ .4 (+ .4)	+ .8 (+ .6)	+ .9 (+ .8)	+ .9 (+ .8)	+1.5 (+1.3)	+1.2 (+1.0)
IV	7.5 (7.6)	- .5 (0)	-1.5 (-1.2)	-1.7 (-2.0)	-1.1 (-1.4)	- .9 (- .8)	+ .3 (+ .4)	- .2 (- .1)	- .3 (- .3)	+ .2 (+ .1)	+1.3 (+1.2)	+1.1 (+1.0)	+1.8 (+1.6)	+1.2 (+1.0)
V	8.2 (8.2)	-1.3 (- .9)	-1.8 (-1.4)	-1.5 (-1.7)	-1.7 (-1.9)	-1.2 (-1.0)	+1.1 (+1.3)	+ .2 (+ .3)	- .4 (- .3)	+ .3 (+ .2)	+ .6 (+ .7)	+1.8 (+1.7)	+2.6 (+2.5)	+ .8 (+ .7)
Entire Gulf	7.2 (7.2)	- .2 (0)	-1.5 (-1.5)	-1.4 (-1.7)	-1.5 (-1.8)	-1.1 (-1.0)	+ .1 (+ .5)	+ .2 (+ .4)	+ .3 (+ .4)	+ .8 (+ .8)	+1.0 (+1.0)	+1.2 (+1.2)	+1.4 (+1.2)	+ .8 (+ .8)

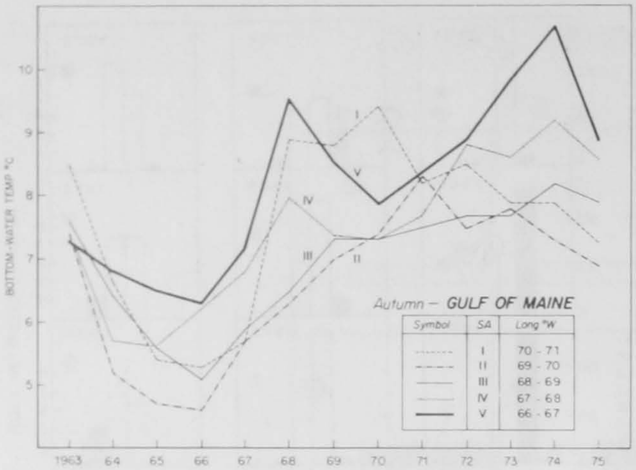


Figure 16.—Adjusted mean bottom-water temperatures in the Gulf of Maine in subareas I-V during the autumn, 1963-75.

area I is the smallest of the Gulf divisions, its large negative anomaly (−1.2°C) in 1975 (Table 4) accounted for much of the decline observed that year for the entire Gulf.

The subarea TCI's shown in Figure 17 are further evidence that years of similar mean temperatures do not necessarily have similar TCI distributions. A good example is shown in Subarea V where the observed means from 1963 to 1967 were all nearly 6.5°C, but the 1963 and 1967 TCI's were vastly different from the 1964-66 TCI distributions. The sharp temperature decline in 1975 in Subarea I was the result of a return of 4°-6°C water that had not occurred there since 1967. The absence of water <8°C in Subareas IV and V was the major factor contributing to the time-series maxima observed for those subareas and also for the entire Gulf of Maine during 1974.

Georges Bank—Autumn.—Autumn bottom-water temperature indices fluctuated widely between years on Georges Bank (Fig. 18) with the two highest adjusted temperatures observed in 1965 (13.1°C) and 1973 (12.7°C); lowest adjusted values were observed in 1967 (10.6°C) and in 1969 and 1970 (10.4° and 10.5°C). The largest annual variations were −2.0°C between 1966 and 1967 and +1.5°C between 1967 and 1968. The 13-yr mean of 11.7°C was about 0.5°C warmer than the 1962-72 long-term mean reported by Karaulovsky and Sigaev (see footnote 2). Data from Schopf (1967) indicate mean autumn Georges Bank temperatures of about 12°C in 1955 and 1961 and 10°C in 1964.

Based on observed means, the two coldest years (1963 and 1967) each had about 20% coverage with 4°-6°C water, but this was the only similarity of TCI distribution in these years (Fig. 19). The two warmest years (1973 and 1974) and several of the intermediate years had very nearly the same TCI distribution. No water >14°C nor <8°C was found in the coldest and warmest years, respectively.

Subareas of Georges Bank—Autumn.—Adjusted bottom-water temperatures clearly show that during the autumn Eastern Georges Bank was consistently colder than the remainder of the Bank by as much as 4°C while Western and Central Georges Bank alternated as the warmest subarea (Fig. 20). A warming trend for the latter two subareas since 1966 is indicated, but is not obvious until 1969 on Eastern Georges Bank. All three subareas exhibited similar increases or decreases of varying magnitude except when only Eastern Georges Bank increased between 1971 and 1972, and only Western Georges Bank increased between 1973 and 1974. Positively adjusted anomalies for each subarea were recorded in 1968 and from 1972 to 1975 (Table 5).

Distributions of TCI's for the subareas of Georges Bank partially explain why the eastern portion was consistently colder than the western or central portions (Fig. 21). A large proportion of water <8°C occurred in the eastern subarea in most years from 1963 to 1971, while very little water >14°C was found there in any year. Conversely, relatively small amounts of this cold water were found in the western or central subareas in any year, but water >14°C predominated there in many of the warmest years.

As with the other subareas and other seasons in the study area, the distributions of TCI's were not always similar during years of similar observed temperature means.

DISCUSSION

Annual fluctuations in spring and autumn bottom-water temperatures in the Gulf of Maine and Georges Bank are obviously related to variations in the volume of relatively cold or warm water which denote change in the composition of these waters. Bigelow (1927) and Colton (1968b) concluded that the volume and composition of

Table 5.—Mean bottom-water temperatures and anomalies for Georges Bank, 1963-75. Adjusted values are shown in parentheses.

Subarea	Mean	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973	1974	1975
Western	12.0 (12.3)	-2.2 (+ .2	-1.2 (- .5)	+ .6 (+ .3)	-1.5 (-1.8)	-3.2 (-1.3)	+ .9 (+ .7)	- .9 (-1.1)	- .2 (- .7)	+1.9 (+1.3)	+1.3 (+ .8)	+1.5 (+ .9)	+2.2 (+1.5)	+ .6 (0)
Central	11.9 (12.3)	-2.7 (- .3)	-1.4 (- .6)	+ .2 (- .5)	- .5 (- .9)	-3.0 (-1.3)	+ .6 (+ .3)	- .2 (- .5)	+ .3 (- .3)	+1.3 (+ .6)	+ .8 (+ .1)	+2.2 (+2.5)	+2.0 (+1.3)	+ .9 (+ .2)
Eastern	9.7 (10.0)	-1.8 (+ .5)	-1.6 (-1.1)	+ .1 (- .5)	- .5 (- .8)	-1.3 (+ .3)	+ .4 (+ .3)	-1.0 (-1.2)	- .7 (-1.1)	+ .3 (- .3)	+ .6 (0)	+2.1 (+1.5)	+2.1 (+1.4)	+1.0 (+ .4)
Entire Bank	11.3 (11.7)	-2.3 (- .5)	-1.3 (+ .4)	+ .6 (+1.4)	- .9 (+ .9)	-2.5 (-1.1)	+ .8 (+ .4)	- .7 (-1.3)	- .2 (-1.2)	+1.1 (0)	+ .9 (- .1)	+2.1 (+1.0)	+1.9 (+ .8)	+ .8 (- .1)

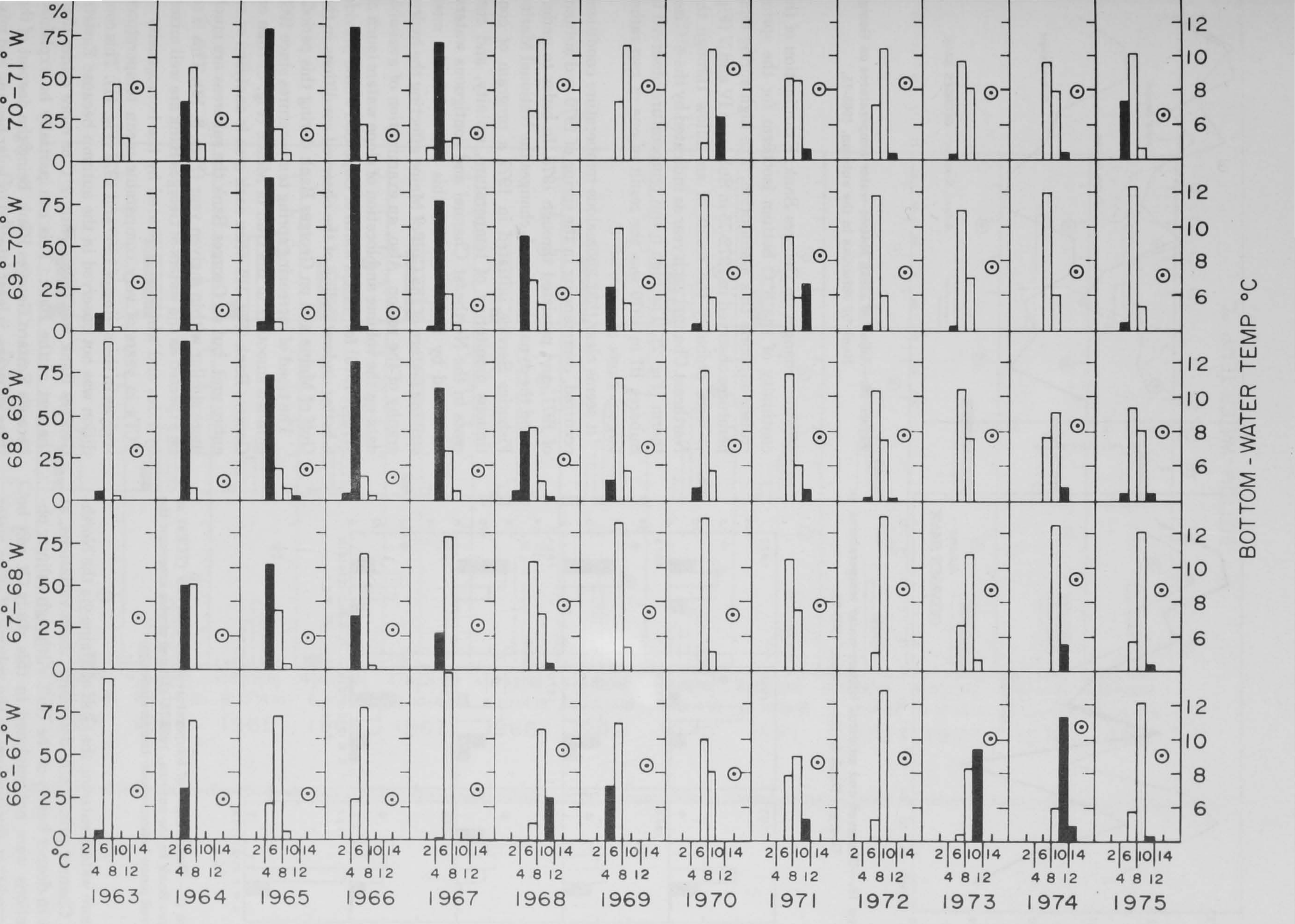


Figure 17.—Percentages of temperature-class intervals (TCI's) in the Gulf of Maine by subareas in the autumn, 1963-75. (Dotted circles represent the observed mean bottom-water temperatures.)

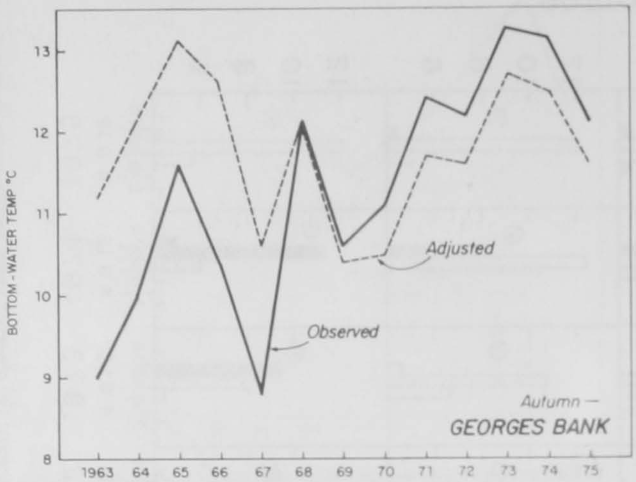


Figure 18.—Observed and adjusted bottom-water temperatures on Georges Bank in the autumn, 1963-75.

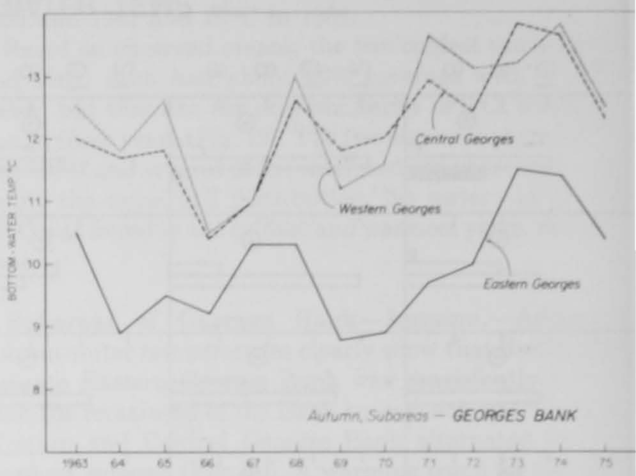


Figure 20.—Adjusted mean bottom-water temperatures on George Bank by subareas in the autumn, 1963-75.

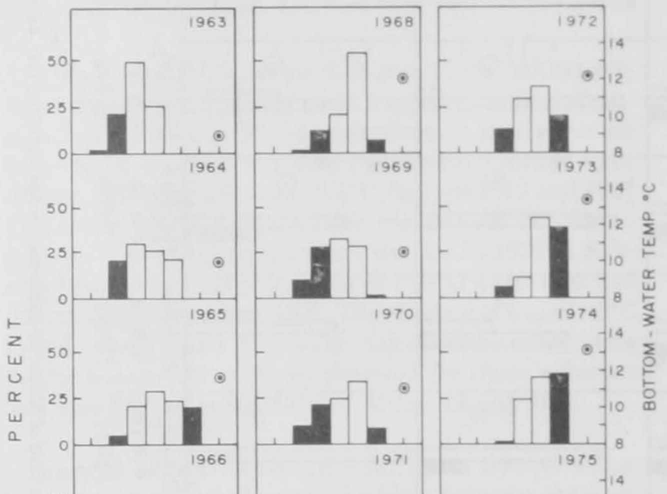


Figure 19.—Percentages of temperature-class intervals (TCI's) on Georges Bank in the autumn, 1963-75. (Dotted circles represent the observed mean bottom-water temperatures.)

offshore waters entering the Gulf of Maine via the Northeast Channel principally determine these variations, at least in deeper basins of the Gulf. Although salinity observations were not analyzed in this study, it can be assumed that fluctuations in the volume of slope water entering the Gulf through the Northeast Channel were mainly responsible for the general temperature trend observed in much of the Gulf and partially affected temperature changes on Georges Bank. Examination of the continuity of the 8°C bottom isotherm for the spring cruises supports this assumption. The high spring temperatures observed in 1972-75 in Subareas IV and V (Fig. 7) were probably the result of an inflow through the Northeast Channel each year as indicated by the 8°C isotherm (Fig. 2). The high mean temperature observed in Subarea III in 1970 was the result of one of two rather large pockets of water >8°C.

It seems clear that anomalous temperature conditions occurred, commencing in the spring of 1970 and autumn of 1971, and persisted through 1975. In order to understand the dynamics of such changes the National Marine Fisheries Service initiated in 1977 a program of continuous monitoring of temperature, salinity, and currents in the Northeast Channel and contiguous waters. As stated by Bigelow (1927) this channel is the most striking feature of the Gulf of Maine affecting the hydrography of the region. Also, an examination of available data on the volume and location of slope waters (such as Wright 1976) for waters south of Cape Cod would provide a better understanding of the observed conditions in the Gulf of Maine and on Georges Bank during this period.

The trend of increasing spring temperatures since 1968 is much smoother in the Gulf of Maine (Fig. 6) than on Georges Bank (Fig. 10) when each area is analyzed as an entire unit, but on Georges Bank the subareas are much more similar within a given year (Figs. 8, 12). This is to be expected as the waters of Georges Bank are well mixed by tides and winds as indicated by the homogeneity of TCI's in years of very comparable mean temperatures such as in the spring of 1969 and 1972 (Fig. 11). This condition was not observed in the autumn because Eastern Georges Bank was consistently 2°C or more colder than the rest of the Bank. This can partially be explained because Eastern Georges Bank, being the deepest of the three subareas, is least affected by solar heating and mixing. Also, a buffering effect is probably from the indraft of cooler slope water through the adjacent Northeast Channel during the autumn.

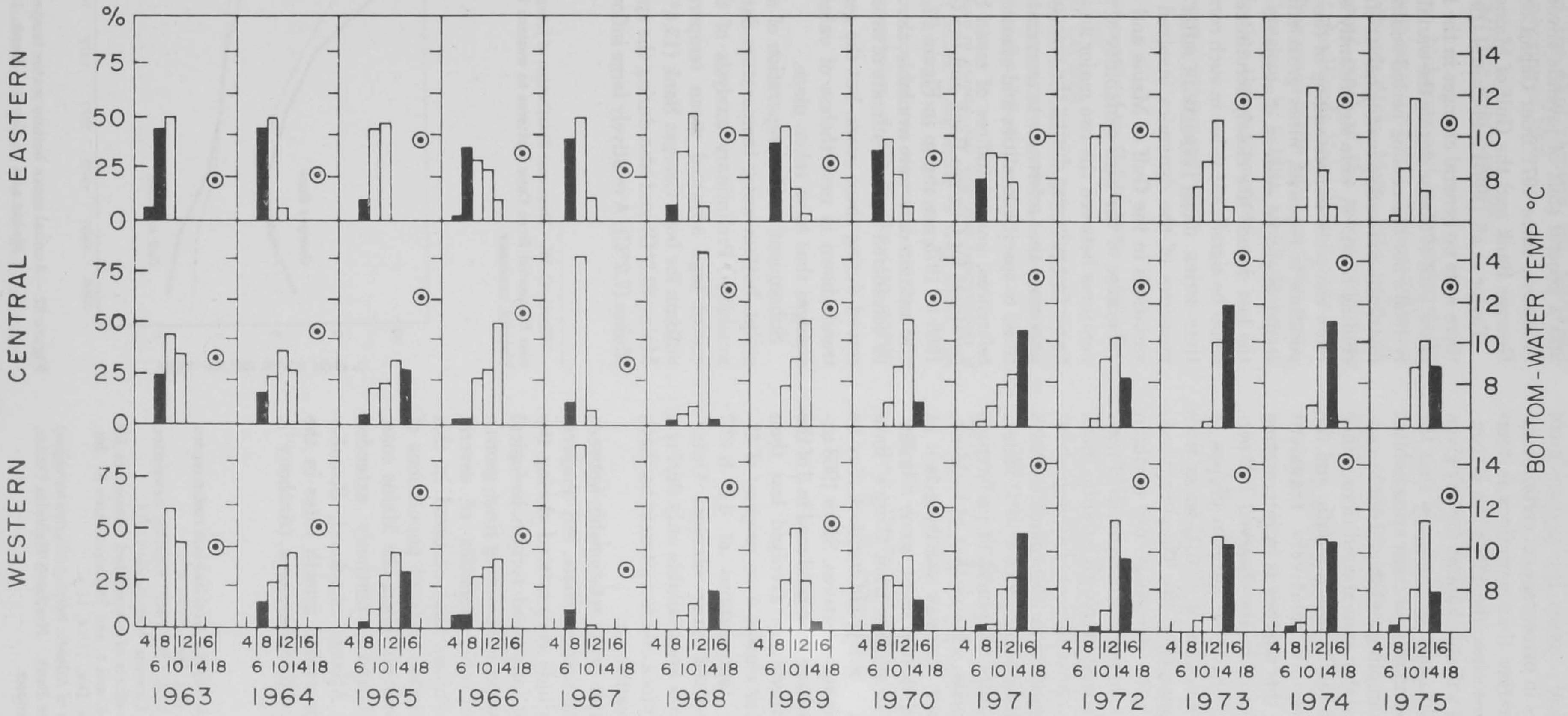


Figure 21.—Percentages of temperature-class intervals (TCI's) on Georges Bank by subareas in the autumn, 1963-75. (Dotted circles represent the observed mean bottom-water temperatures.)

With respect to biological changes, it is perhaps more important to note changes in percentages of certain temperature class intervals rather than variations in temperature means or extremes since the TCI's can be considered areal estimates of suitable habitat for any given species. The reader should again be cautioned that the TCI analysis is intended primarily for comparing habitat conditions at the time of sampling and should not be considered changes between stable annual conditions. Since cruises of some years differed by over a month, and the TCI percentages represent relatively transient phenomena, the value of this analysis is in interpreting how a species may be affected by the observed TCI percentages. For example, during the autumn cruises of 1964-68, relatively large amounts of 4°-6°C water were present in the Gulf of Maine (Fig. 15). These cold conditions were probably quite favorable for northern shrimp, *Pandalus borealis*, in the southern limits of their normal distribution in the western North Atlantic. Both commercial and research cruise indices of shrimp abundance have declined abruptly since 1969 coincident with the rapid decrease and disappearance of 4°-6°C water.

Providing that temperature tolerances or preferences are known for various species, such as that of haddock, *Melanogrammus aeglefinus*, embryos surviving best at about 6°C (Laurence and Rogers 1976), some relationships can be examined. It appears from Clark's[7] data that the year-class strength of 2-yr-old haddock may be related to spawning season temperatures. Since 1968 extremely small year classes have been produced in 2 of the 3 yr that spawning temperatures averaged less than 4.8°C; the two largest year classes were progeny of 5°-6°C temperatures, and temperatures of 6.2°-6.4°C produced intermediate-sized year classes. Unfortunately, these comparisons are available only during a period when the haddock stock and recruitment has been relatively small due to overfishing.

It is unlikely that a simple linear relationship between temperature and spawning success exists, but temperature trends of the magnitude encountered during the past decade undoubtedly influenced certain biological phenomena including changes in spawning time, growth rates, and distributional characteristics of several species. Some notable changes that occurred in this latest warming trend include increased populations of green crabs, *Carcinides maenas*, along the Maine coast (University of Rhode Island[8]); northerly extended seasonal distribution of Atlantic mackerel, *Scomber scombrus*, (Anderson[9]); increased growth rates in the 1970's of Atlantic herring, *Clupea harengus*, (Anthony[10]); and a general shift of juvenile silver hake, *Merlucciu bilinearis*, since 1971 from Cape Cod and westward t Georges Bank and the Gulf of Maine (Davis[11]).

Taylor et al. (1957) and Colton (1972) concluded tha there were no general changes in the faunal compositio of the Gulf of Maine during the warming trend of the ea ly 1950's nor the cooling period ending in 1966, but tha distributional and spawning habits of several species, in cluding haddock, were significantly altered. Although more complete understanding of the net effects of tem perature is required, other gross effects such as thos stated might be evident if available biological data fo the last decade are closely scrutinized. Certainly, ther could be significant value in such correlation analyses c time-series data, especially after we have bette measures of the dynamics involved with temperatur variations in the Gulf of Maine and on Georges Bank

Because of the high variability of bottom-water tem peratures between the two major areas and within thei respective subareas during the seasons under study, it i important that references to temperature trends be iden tified to specific localities and seasons. Contrary to suc references, annual indices of mean bottom-water tem peratures for Georges Bank and the Gulf of Maine fro 1968 to 1975 are shown in Figure 22. Since only sprin and autumn data were available, the annual index mus be considered a gross estimate of average conditions ob served during these years, but the generalized warmin trend shown is nevertheless of value in revealing th changes that have taken place.

Subsequent to the preparation of most of this manu script, bottom-water temperature data for 1976 becam available. Preliminary analysis of the data indicate record high adjusted mean temperatures during th autumn for both Georges Bank (13.4°C) and the Gulf c Maine (9.3°C) and also during the spring in the Gulf c Maine (7.2°C). A relatively large inflow of 8°-10°C wate

[7]Clark, S. 1976. Georges Bank (Subdiv. 5Ze) haddock status report. Int. Comm. Northwest Atl. Fish. Res. Doc. 76/35, 8 p.

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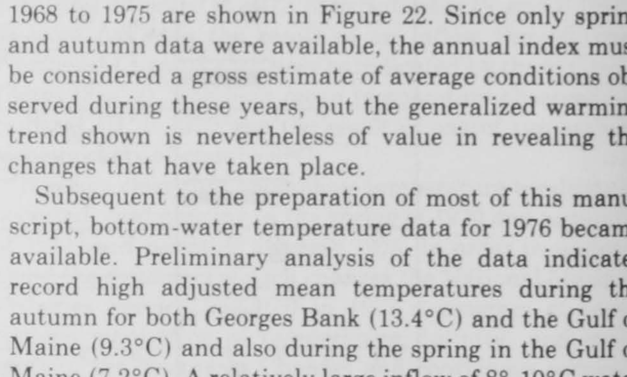

Figure 22.—Annual mean bottom-water temperatures in the Gulf Maine and on Georges Bank, 1968-75.

pparently entered the Gulf through the Northeast hannel during the spring of 1976.

ACKNOWLEDGMENTS

I thank the many biologists and technicians of the ortheast Fisheries Center (NEFC), National Marine isheries Service, Woods Hole, Mass., who collected, nalyzed, and plotted much of the raw temperature ata; Joe Chase of the Woods Hole Oceanographic Initution for providing much of the lightship data; and J. . Colton, M. D. Grosslein, R. Schlitz, and R. Wright of ne NEFC for reviewing this manuscript.

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