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# RECENT TRENDS IN SUBSURFACE TEMPERATURES IN THE GULF OF MAINE AND CONTIGUOUS WATERS

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## ABSTRACT

A comparison was made of 1955-60 and 1961-66 monthly mean 200-meter temperatures in eight one-degree quadrangle areas in the Gulf of Maine and along the Continental Slope between Nova Scotia and Long Island. Temperatures were appreciably colder in all areas during the latter period. The subsurface temperature trends paralleled trends in surface temperatures previously documented. The distribution of temperature at 200 meters along the edge of the Continental Shelf during March, May-June, and September 1965 and 1966 and the distribution of temperature, salinity, and dissolved oxygen on sections made across the Continental Shelf in September 1954, 1965, and 1966 showed that the cooling and warming trends are associated with changes in the composition of the subsurface water. Cold years occur when Slope Water is displaced or modified by Coastal Water of Labrador origin. Warm years occur when Slope Water borders upon the 200-meter isobath and its constituent ratio of Coastal to Central Atlantic Water is low.

## INTRODUCTION

There is clear evidence of an alternation in sea surface temperatures along the coast of New England and the Maritime Provinces (Taylor, Bigelow, and Graham 1957, Lauzier 1965, Stearns 1965). A warming trend began in the early 1940's and reached a maximum during 1952-53. This has been followed by a cooling trend which has continued with only minor checks through 1967. Although less well documented, similar warming and cooling trends have occurred offshore and within water masses (Taylor, Bigelow, and Graham 1957, Lauzier 1965 and 1967, Colton 1968). Most of the published offshore observations have been confined to the Continental Shelf and to depths of 100 meters or less. In this paper an analysis is made of the limited subsurface temperature data in the Gulf of Maine and along the edge of the Continental Shelf from Nova Scotia to Long Island to determine if the trends observed in the surface layers are reflected in the deeper strata.

The subsurface layer, the upper depth limit of which is usually between 150 and 200 meters, is relatively isolated from seasonal factors such as wind stirring and solar heating. Unlike the surface layer which is characterized by pronounced seasonal variations and a complex and unstable temperature and salinity structure, the structure of the subsurface layer is relatively stable and governed by the waters adjacent to it.

Our interest in subsurface temperature trends stems from the fact that if these trends parallel those observed in the surface layers, the faunal communities inhabiting the deeper waters of the Gulf of Maine and the Continental Slope are subject to similar long-term temperature variations as the fauna inhabiting relatively shoal areas of the Continental Shelf. Furthermore, since the temperature-salinity characteristics of subsurface water masses can be used to define their component water types, it should be possible to determine the sources of the subsurface water during periods of warming and cooling and thus the direct cause of the temperature change.

## THE DATA

A tabulation of temperature data from the file of bathythermograph and oceanographic station observations at the Woods Hole Oceanographic Institution revealed that during the warming period of 1945-53 there were an insufficient number of observations to determine valid average subsurface temperature values for any location within the area of concern. Since 1955 there appears to be adequate data to determine monthly subsurface temperatures if several years observations within one-degree quadrangles are averaged. Monthly mean 200-meter temperatures were determined for the periods 1955-60 and 1961-66 within the eight one-degree quadrangle areas shown in Figure 1. Areas I-III are over the three deep basins of the Gulf of Maine, Area IV is at the mouth of the Northeast Channel which separates Georges and Browns Banks, and Areas V-VIII are along the slope of the Continental Shelf. There were relatively few observations for any month within a given year in any quadrangle and these observations were generally weighted in favor of certain days (dates). To offset possible bias in determining monthly means, all data for a given day were averaged and the six-year monthly means based on the daily means rather than on the total number of observations.

The six-year monthly mean temperatures at 200 meters in the eight areas are plotted in Figures 2 and 3. The months and years in which there were temperature data are indicated by check marks. The long-term annual mean 200-meter temperatures are shown by a dashed line. These long-term values are from Schroeder (1963) and are based on one-degree quadrangle averages of all available temperatures in the Woods Hole Oceanographic Institution data collection through 1962. For Areas IV, V, and VI which do not coincide with the whole degree latitude-longitude quadrangles used by Schroeder, long-term 200-meter temperature values from overlapping whole degree quadrangles were averaged.

With only a few exceptions (April - Areas II and IV, June - Area II, September - Area V, October - Areas I and V, and November - Area II) the 1960-66 monthly mean 200-meter temperatures were colder than the corresponding monthly mean temperatures for the period 1955-60. Six of these eight anomalies occurred in months which included 1963 observations. In this year a temporary check in the downward trend of sea surface temperatures occurred both inshore at Boothbay Harbor, Maine (Welch 1967) and offshore over the Grand Banks and Georges Bank (Lee, Corkrum, and Laevastu 1967). In addition the data of Schopf (1967, Fig. 2) show that bottom temperatures on the Scotian Shelf, Georges Bank, Nantucket Shoals, and in the Gulf of Maine were appreciably warmer in July, August, and December 1963 than in these months during 1964 and 1965.

There was no consistent seasonal trend in the 200-meter monthly mean temperatures or in the magnitude of the monthly mean temperature differences for the two time periods in any of the areas. The monthly temperature variation and the magnitude of the monthly temperature differences in the two time periods were least in Area II and tended to be greater along the Continental Slope than within the Gulf of Maine. With the exception of Area V, yearly mean temperatures based on 1955-60 data closely paralleled Schroeder's long-term means. In Area V the 1955-60 yearly mean were appreciably lower (2.3°C) than the long-term mean. With the exception of Area II, the 1960-66 yearly mean temperatures were well below Schroeder's long-term means. In Area II the 1961-66 yearly mean was only slightly lower (0.3°C) than the long-term mean.

Seasonal surface-temperature curves based on monthly mean temperatures at Boothbay Harbor, Maine for the periods 1955-60 and 1961-66 are shown in Figure 4. These surface data show temperature trends similar to those in the subsurface waters, but in most months and areas the difference in the mean 200-meter temperatures for the two six-year time periods were greater than the difference in mean surface temperatures at Boothbay Harbor. Only in Area II was the yearly mean difference at 200 meters between the two time periods (0.6°C) less than at Boothbay Harbor (0.9°C).

In Figure 5 the distribution of temperature at 200 meters along the edge of the Continental Shelf and in the Northeast Channel during March, May-June, and September 1965 and 1966 is compared to the distribution of temperature in this area based on long-term annual mean and minimum 200-meter values. The 1965 and 1966 temperature distributions are based on in situ bathythermograph observations obtained during quarterly environmental surveys conducted by the Bureau of Commercial Fisheries (Colton, et al. 1968). The long-term distributions are based on average and minimum temperatures for one-degree quadrangles given by Schroeder (1963). In both 1965 and 1966 the monthly temperatures adjacent to the 200-meter isobath were colder than the long-term mean temperatures. In most cases the 1965 and 1966 monthly temperatures were warmer than the long-term minimum temperatures. However, in March 1966 the 200-meter temperatures were colder than the long-term minimum temperatures in sections adjacent to the 200-meter isobath off southern New England, the southeast part of Georges Bank, and the Scotian Shelf.

If we consider the contour of the 9° isotherm at 200-meters to be the northern limit of Slope Water (Worthington 1964), the long-term annual mean 200-meter temperature distribution would indicate that in general Slope Water borders upon the 200-meter isobath from Cape Hatteras east to approximately 64°00'W. The distribution of temperature at 200-meters during 1965 and 1966 would indicate that in these years the northern boundary of the Slope Water was considerably south of its average position. Worthington (1964) concluded that any water colder than 9° at 200-meters could be traced to the Labrador Basin. It would appear that the southerly shift in the normal position of the Slope Water in 1965 and 1966 was due to an abnormal influx of Coastal Water of Labrador origin.

The available salinity data are not sufficient to establish subsurface salinity norms for the area as a whole or to compare the 1955-60 and 1961-66 mean salinity characteristics of the subsurface water in any of the eight one-degree quadrangle areas either on a monthly or yearly basis. However, there are a few oceanographic section data suitable for a comparison of the inshore and offshore distribution of chemical and physical properties at the end of the warming trend and during the current cooling trend. In Figure 6 the distribution of temperature, salinity, and dissolved oxygen on sections made along meridian 65°30'W by the Albatross IV in September 1965 and 1966 is compared to the distribution of these properties on a section made along meridian 65°00'W by the Atlantis in September 1954.

Subsurface temperatures and salinities were appreciably higher in 1954 than in 1965 and 1966. At the southern most stations, the 1954 temperature and salinity values were higher in the surface layer as well. If we consider a temperature of 9°C and a salinity of 35 ‰ at 200-meters as roughly defining the northern limit of Slope Water, in 1954 the Slope Water boundary coincided with the 200-meter isobath while in 1965 and 1966 the Slope Water boundary was south of latitude 41°00'N. Dissolved oxygen values at corresponding depths were appreciably higher in 1965 and 1966 than in 1954. In 1954 the dissolved oxygen concentrations at depths of 100, 150, and 200 meters south of the Continental Shelf corresponded closely to values typical of Slope Water and those in 1965 and 1966 to values typical of Coastal Water (McLellan 1957, Table II).

Temperature-salinity data at 150, 200, and 250 meters for the five most southerly Atlantis stations in September 1954 and the four most southerly Albatross IV stations in September 1965 and 1966 are plotted in Figure 7. The Albatross IV data are based on observed values at these depths while the Atlantis data are based on interpolated values. The temperature-salinity curves for Central Atlantic Water, Slope Water, and Coastal Water are also shown. The approximate depths in meters at which waters of various temperature-salinity characteristics are found are indicated by numbers adjacent to the curves. The Central Atlantic Water curve is from Iselin (1936) and is based on observations made in the western Sargasso Sea. The Slope Water curve of Iselin (1936) is for waters off the Scotian Shelf. The Coastal Water curve (McLellan 1957) is based on observations made in the Cabot Strait. In describing this water Worthington (1964) used the term "Labrador-Coastal" instead of "Coastal" to indicate that this water is formed by a mixture of Labrador and Slope Water in the region immediately west of the Grand Banks and to distinguish this subsurface water from the surface water over the Continental Shelf. An excellent summary of the temperature-salinity characteristics, composition, and origin of these water masses is given by McLellan (1957).

The temperature-salinity correlations confirm the conclusions drawn from the section data. The subsurface water bordering the Continental Shelf south of Browns Bank in September 1954 was Slope Water and that in September 1965 and 1966 was Coastal Water. The temperature-salinity characteristics of the Slope Water in 1954 coincide more closely with the Slope Water curve of Iselin (1936) than that of McLellan (1957) and show a greater constituent ratio of Central Atlantic Water than in areas to the east. Indeed, a few of the Atlantis station plots fall to the right of the Central Atlantic curve, but these possibly are a result of errors in interpolation of salinity between the widely-spaced sample depths. The majority of the 1965 and 1966 temperature-salinity values lay between those of the characteristic Coastal Water curve near its area of formation and those of the Coastal Water curve near its western limit of occurrence (Grampus station 10352, McLellan 1957, Fig. 6). The few values which fell in the proximity of the Slope Water curve were based on data from the isolated pools of relatively high temperature and salinity water at Albatross IV stations 9 and 22.

## DISCUSSION

It is evident that the cooling and warming of subsurface waters along the Continental Slope between Nova Scotia and Long Island are due to changes in the composition of these waters. Cold years occur when Slope Water is displaced or modified by Coastal Water of Labrador origin. Warm years occur when the Slope Waters borders upon the 200-meter isobath and its constituent ratio of Coastal to Central Atlantic Waters is low. Bigelow (1927) pointed out that the relatively high temperature and salinity of the bottom water in the deep basins of the Gulf of Maine indicated its offshore origin. He concluded that this water, which enters the Gulf of Maine intermittently via the Northeast Channel, has its source along the slope of the Scotian Shelf and that the cause of the temperature and salinity variations of the deep water in the Gulf of Maine were due to fluctuations in the volume rather than in the temperature and salinity of this inflowing drift. The more recent data presented in this paper demonstrate that the temperature-salinity characteristics of the subsurface waters adjacent to the mouth of the Northeast Channel vary, being colder and less saline during periods of cooling than during periods of warming. Thus, it would appear that trends in subsurface temperatures within the Gulf of Maine can be traced to variations in the composition of these offshore waters as well as to the volume of their indraft through the Northeast Channel. That such is the case, is substantiated by the observations of Lauzier (MS, 1964) showing that in the deep waters in the Bay of Fundy and Emerald Basin, warming and cooling periods were accompanied by an increase and decrease in salinity respectively.

Further evidence that the subsurface temperature trends observed within the Gulf of Maine are linked to variations in the composition of the subsurface waters bordering the Continental Shelf is afforded by the fact that the magnitude of the 1955-60 and 1961-66 monthly mean temperature differences was least in Area II. This area which includes Murry and Wilkinson Basins is the most distant from the Northeast Channel. In addition, the relatively shoal sill to the east of these basins further restricts horizontal communication with the open sea.

These subsurface data support the conclusion drawn from an analysis of temperature trends in the surface layers in the same area (Colton 1968). That is, these temperature trends depend in large measure on the relative position and the degree of mixing of coastal and oceanic water masses. There is evidence to the effect that the changes observed in the relative position and degree of mixing of Coastal, Slope, and Central Atlantic Water along the Continental Slope are due to variations in atmospheric conditions resulting from changes in the position and relative strength of the Icelandic Low. Lee, Corkrum, and Laevastu (1967), have postulated that surface temperature anomalies and their fluctuations over the Grand Banks and Georges Bank can be explained by advection caused by surface winds. Worthington (1964) has suggested that variations in barometric pressure as well as surface winds could cause advective movements of subsurface waters off the Scotian Shelf. It may be, however, that these advective movements of surface and subsurface water masses and

The subsequent warming and cooling trends are more directly related to fluctuations in the strength of the North Atlantic Gyre as suggested by Iselin (1940) and Stommel (1958). In this connection, an analysis of long-term trends in the volume transport of the Florida Current would be most useful.

Existing hydrographic and meteorological data are too fragmentary for a detailed study of long-term fluctuations in the distribution and degree of mixing of coastal and oceanic water masses in the area between Nova Scotia and Long Island. It is doubtful that adequate data for such an analysis will be available in the forseeable future. With existing instrumentation it should be possible, however, to monitor subsurface hydrographic conditions in a critical area such as the Northeast Channel. Such data, even if they consisted solely of time-series bottom temperatures, would greatly increase our capability to measure and predict trends in both subsurface and surface temperatures in the Gulf of Maine and contiguous waters.

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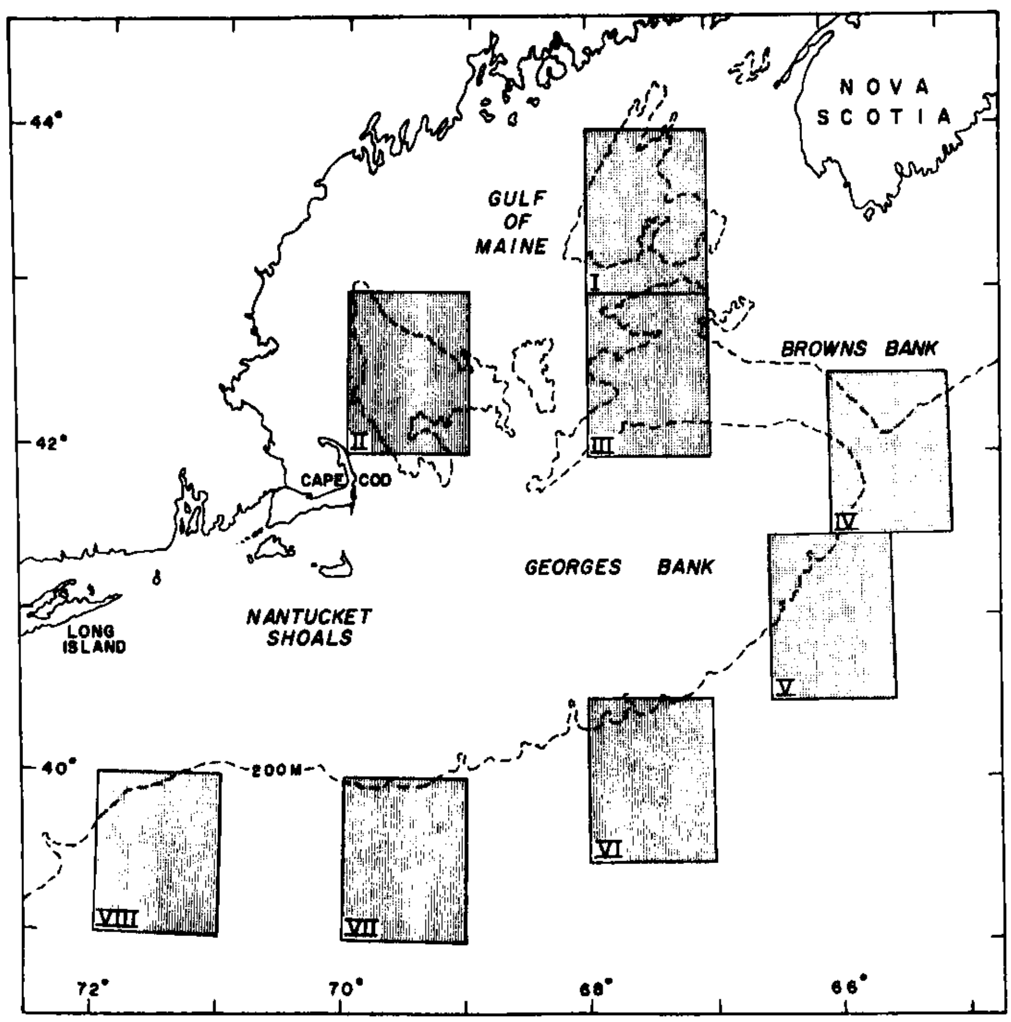


Fig. 1. Orientation chart showing the location of the eight one-degree quadrangle areas.

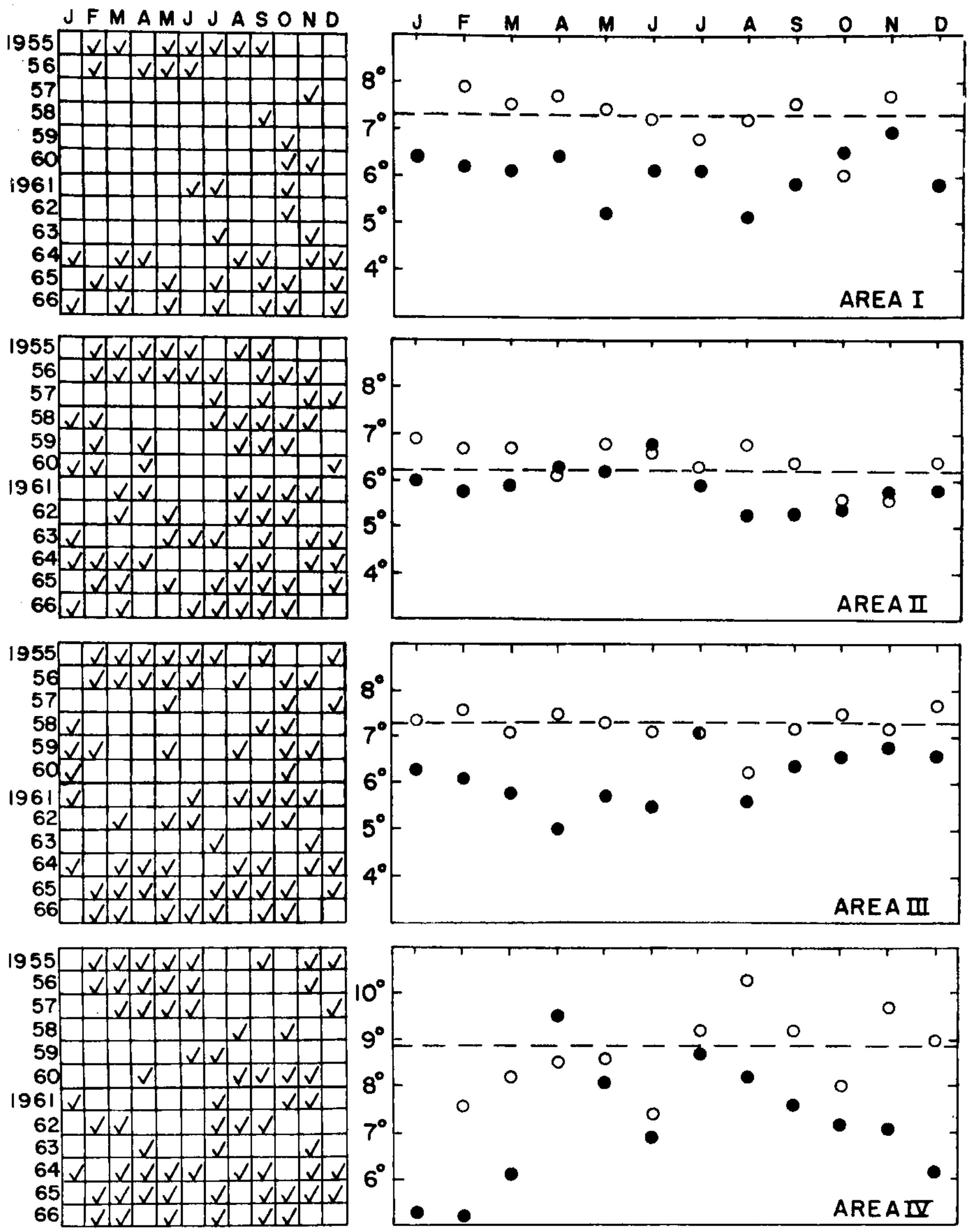


Fig. 2. Monthly and annual mean temperatures at 200 m, Areas I-IV. The 1955-60 monthly means are shown by open circles, the 1961-66 monthly means by closed circles. The long-term annual means are indicated by a dashed line. Check marks indicate the months and years in which there were observations.

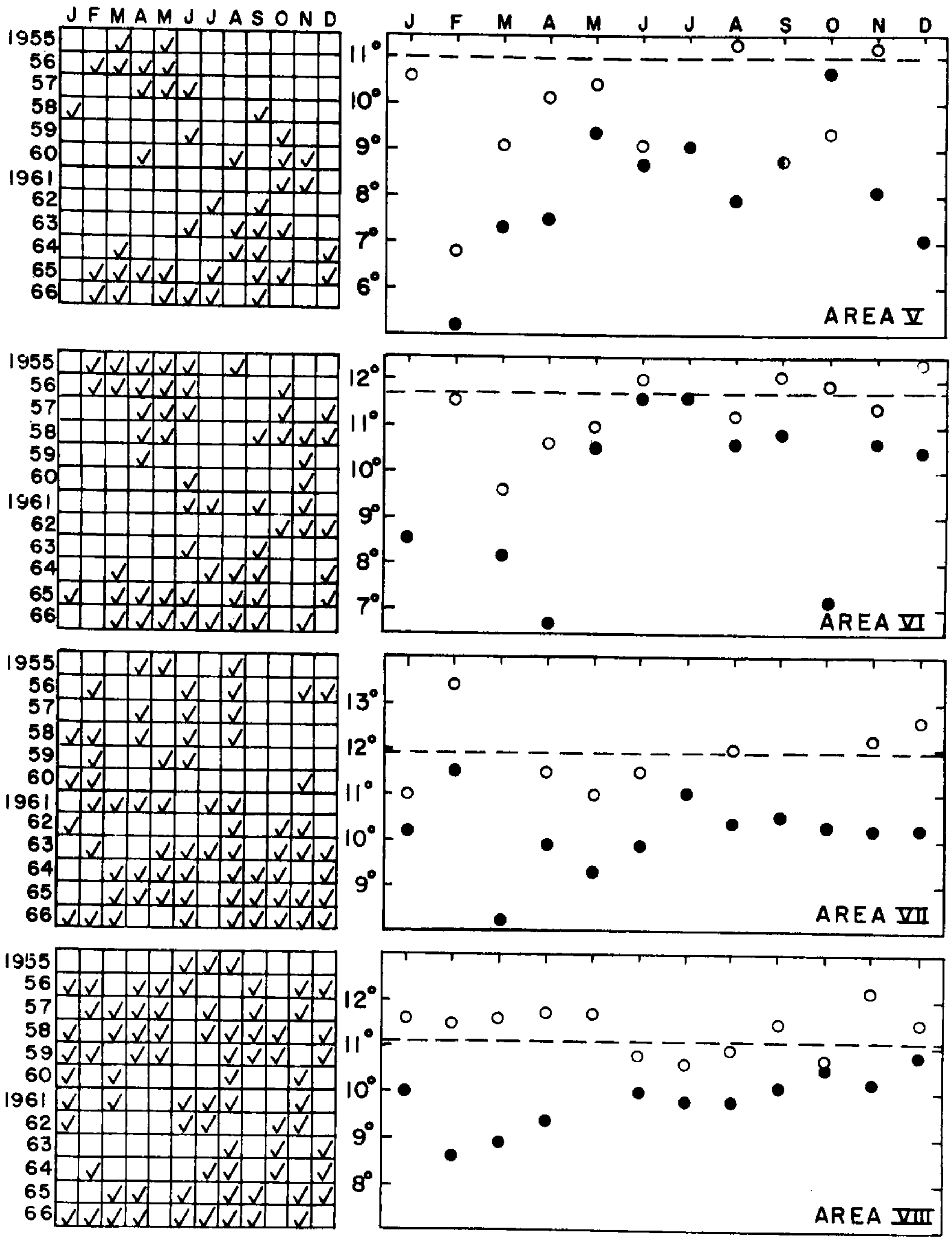


Fig. 3. Monthly and annual mean temperatures at 200 m, Areas V-VIII.

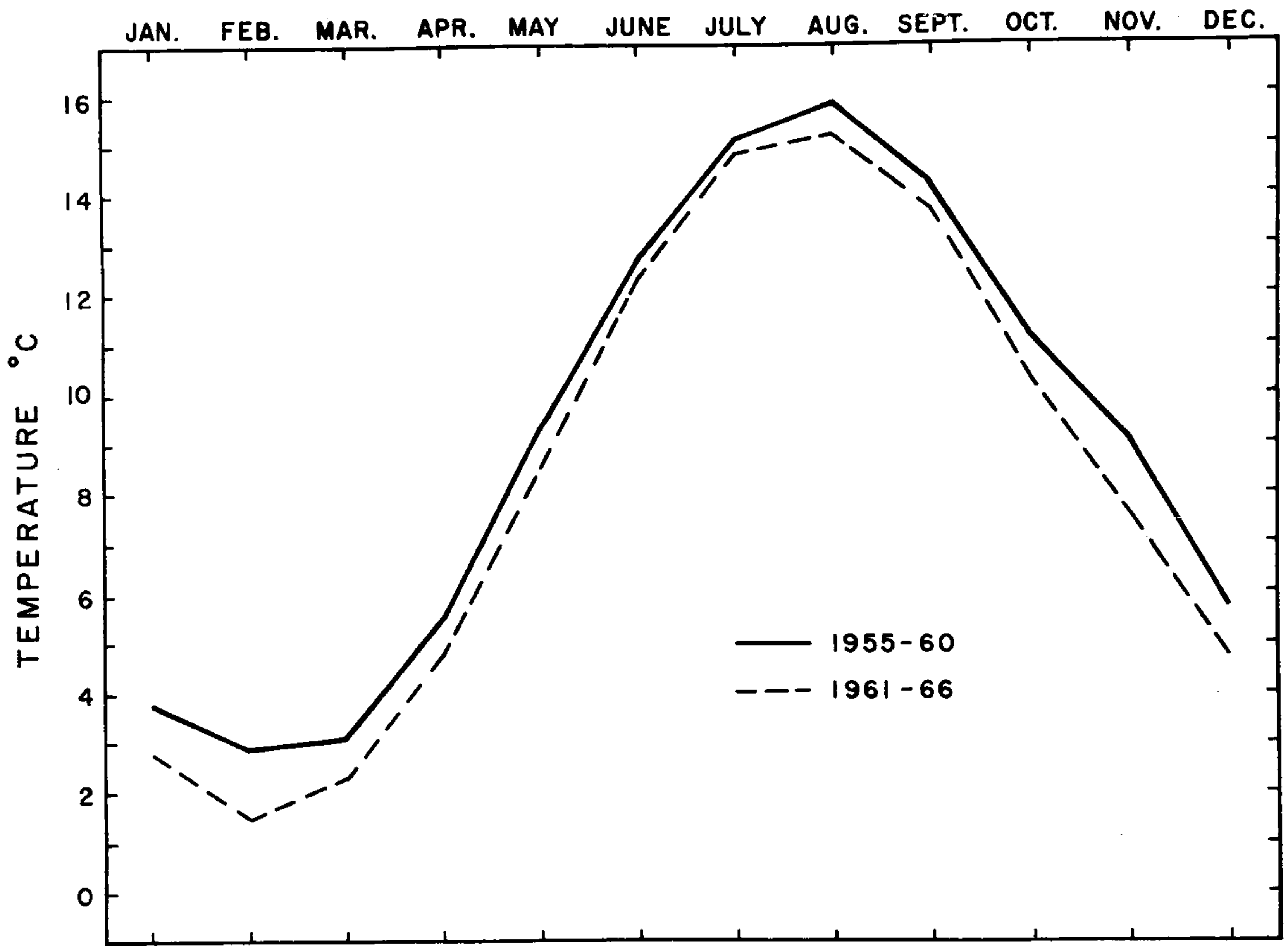


Fig. 4. 1955-60 and 1961-66 mean seasonal temperature curves, Boothbay Harbor, Maine.

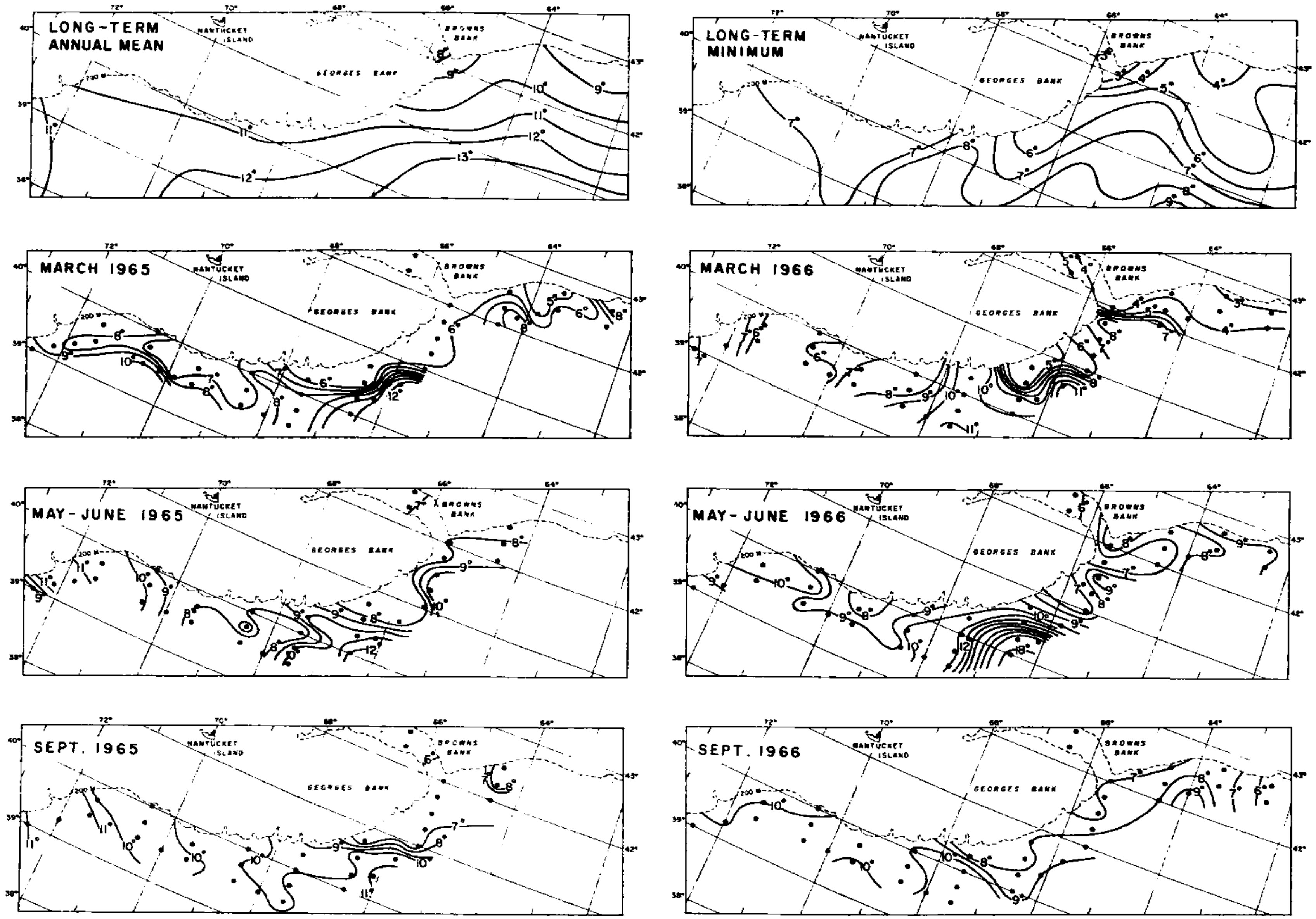


Fig. 5. Comparison of the temperature distribution at 200 m during March, May-June, and September 1965 and 1966 with long-term annual mean and minimum distributions.

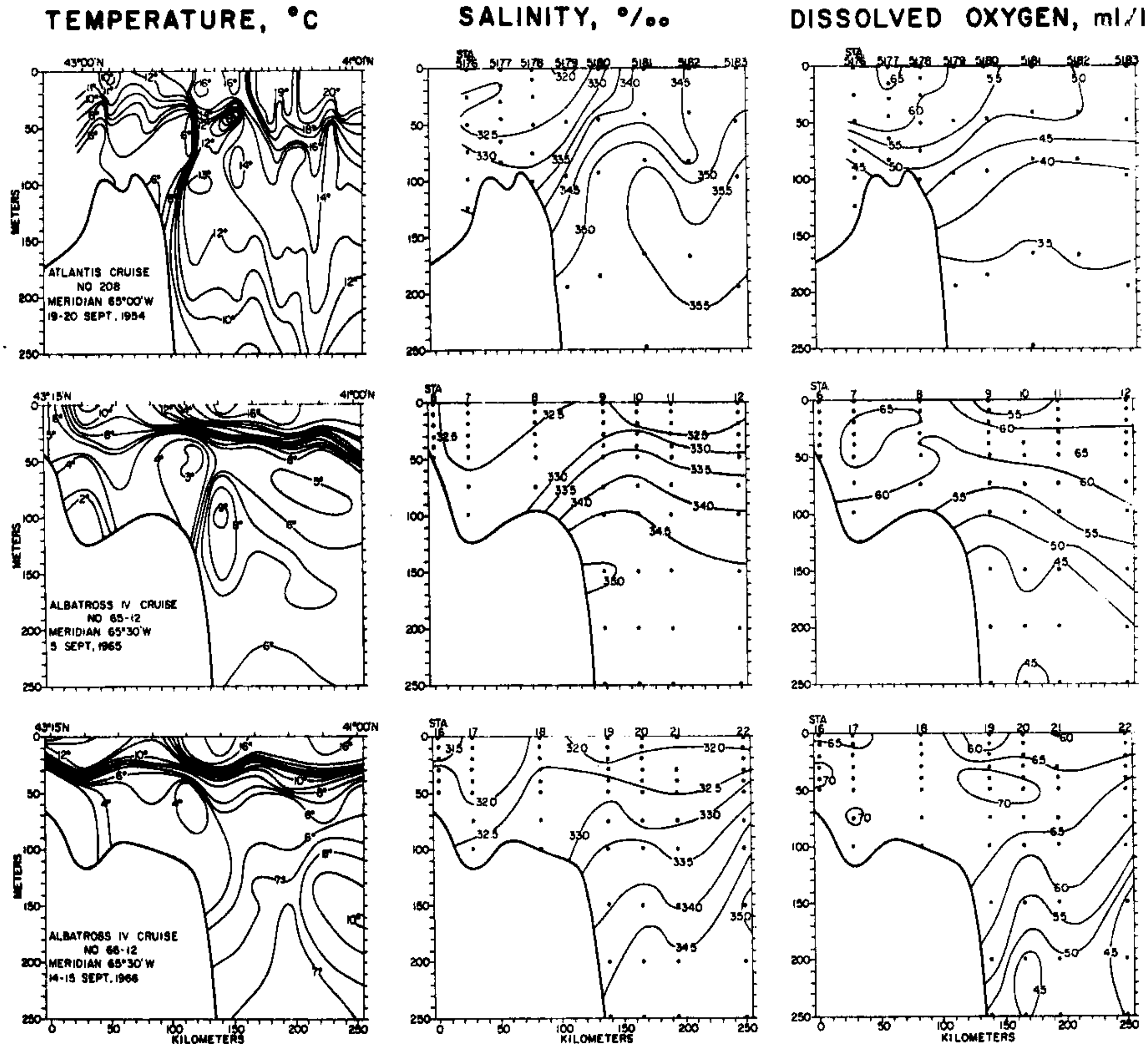


Fig. 6. Temperature, salinity, and dissolved oxygen profiles, September 1954, 1965, and 1966.

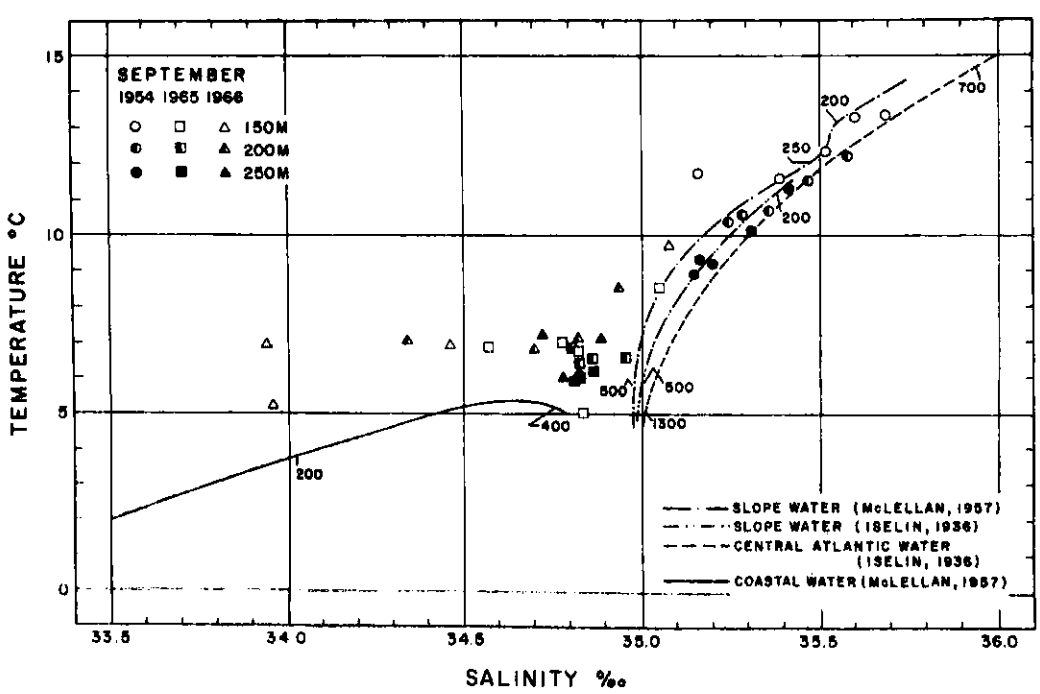


Fig. 7. Temperature-salinity correlations based on *Atlantis* stations 5179-5183, September 1954 and *Albatross IV* stations 9-12 and 19-22, September 1965 and 1966.