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Water Temperatures and Climatological Conditions South of New England, 1974–83

Reed S. Armstrong (editor)

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NOAA Technical Report NMFS 134

A Technical Report of the *Fishery Bulletin*

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Abstract

From 1974 through 1983, we conducted monitoring to provide the first long-term, year-round record of sea water temperatures south of New England from surface to bottom, and from nearshore to the continental slope. Expendable bathythermograph transects were made approximately monthly during the ten years by scientists and technicians from numerous institutions, working on research vessels that traversed the continental shelf off southern New England.

Ten-year (1974–83) means and variability are presented for coastal and bottom water temperatures, for mid-shelf water column temperatures, and for some atmospheric and oceanographic conditions that may influence shelf and upper-slope water temperatures. Possible applications of ocean temperature monitoring to fishery ecology are noted. Some large departures from mean conditions are discussed; particularly notable during the decade were the response of water temperatures to the passage of Gulf Stream warm-core rings, and the magnitude and persistence of shelf-water cooling associated with air temperatures in three successive very cold winters (1976–77, 1977–78, and 1978–79).

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Ocean Temperature Monitoring: Project Background and Some Applications to Fishery Ecology

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Introduction

This volume is the culmination of a decade of environmental monitoring and analysis initiated in 1974 as part of the Marine Resources Monitoring, Assessment, and Prediction (MARMAP) Program of the National Marine Fisheries Service (NMFS). Planning for MARMAP emphasized that changes in abundance and distribution of living marine resources can be satisfactorily understood only through analysis of the influence of both human activity and natural variation in environmental conditions. The plans also recognized that far more information is routinely gathered on human activities, such as fishing, coastal dredging and filling, and pollution, than on the natural variability of the physical environment.

Temperature has long been recognized as a major factor in fishery resource ecology (Taylor et al., 1957). From 1966 through about 1976, surface temperature was surveyed monthly with infrared radiometers carried on Coast Guard aircraft flying standard transects over the width of the continental shelf from Cape Cod to Florida (Deaver, 1975). Lacking, however, were year-round, cross-shelf measurements of water temperature below the surface and, particularly, at and near the bottom, where most finfish and shellfish are concentrated off the northeastern United States (Grosslein and Azarovitz, 1982).

We selected the continental shelf and slope south of New England along 71°W longitude for a multi-year monitoring project. This area was chosen because it appeared that most of the desired data could be obtained economically there by using expendable bathythermographs (XBT's) and by enlisting the cooperation of scientists who traverse these waters on the numerous research vessels home ported at Woods Hole, Massachusetts, and Narragansett, Rhode Island. Furthermore, because average water movement in the area is alongshelf from off southern New England to the Middle Atlantic shelf (Bumpus, 1973; Mayer et al., 1979), it was assumed that conditions in the former area were fairly representative of those in the latter.

The research reported here owes a great deal to the scientific talent and diligence of Robert Wylie Crist (1950–83), who served as project manager for 8 yr until his untimely death. As well as being an exemplary researcher and manager, Lee was a warm and cheerful colleague, always ready to give assistance. To his memory we dedicate this technical report.

The project benefitted at its inception in 1974 from the numerous bathythermograph sections across the southern New England shelf and slope obtained by Redwood Wright, then at Woods Hole Oceanographic Institution, in his study of variability in the offshore limits of shelf water south of New England and Cape Cod (Wright, 1976). Numerous scientists cooperated in making XBT observations throughout the 10-yr project, as acknowledged in the annual summary reports cited in Armstrong (1998a). The major contributions were 59 sections taken from vessels of the National Oceanic and Atomospheric Administration (mostly by NMFS scientists), 47 taken from Woods Hole Oceanographic Institution vessels, 38 from vessels of the Graduate School of Oceanography, University of Rhode Island, 16 from U.S. Coast Guard ships, 10 from ships of the Soviet Union, and 9 from Polish vessels. The project obtained a total of approximately 196 temperature sections from 176 cruises by 35 different ships.

Before the southern New England ocean temperature data could contribute to understanding of fishery ecology, various analyses were necessary. Results of the monitoring were published in annual reports for each of the ten years (see citations in Armstrong, 1998a). These include contoured vertical sections of temperature for individual vessel transects as well as contoured time–depth diagrams of bottom temperatures.

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In this volume, Armstrong (1998a), Wood (1998), Cook (1998), and Chamberlin (1998) extend the analysis to interannual comparisons of water temperatures. Also included are analyses of air temperature (Wood, 1998), winds (Ingham, 1998), and variability in the offshore boundary of shelf water in relation to seasonality and the passage of warm-core rings (Armstrong, 1998b), factors expected to influence water temperatures and for which there were fairly consistent records throughout the project. Each author presents the average conditions for the decade, representing the normal annual cycle, along with an analysis of the variability, and discusses some large departures from mean conditions in association with other data.

Project Background

Previous to this research, the general pattern and seasonal cycle of temperatures in waters south of New England were well known (e.g., Bigelow, 1933; Ketchum and Corwin, 1964). On the basis of daily observations at shore stations, it was known that short-term variations in coastal water temperature are associated with changes in atmospheric weather conditions, particularly insolation and surface air temperature (Taylor et al., 1957) and winds (Lauzier, 1965). However, long-term trends in shore-station temperatures on the northeast coast depend largely on the relative position and degree of mixing of coastal and oceanic water masses (Colton, 1968, 1969). Analyses of bottom temperature on the shelf and upper slope had shown, by examining monthly averages of long-term archive data, that annual temperature range generally decreases and annual temperature extremes occur later with increasing depth (Walford and Wicklund, 1968; Colton and Stoddard, 1973).

The pool of minimum-temperature bottom water that persists throughout the warm season at mid-depth on the southern New England and Middle Atlantic shelf was first charted by Bigelow (1933) and later corroborated by Ketchum and Corwin (1964) as persistent "winter water." From year to year this mass of bottom water varies in intensity; within years it varies in cross-sectional area, onshore–offshore position, and extent of contact with the bottom (Whitcomb, 1970).

In contrast to the marked annual warming and cooling of bottom water at shallow to middle depths on the shelf, temperature on the outer shelf and upper slope, where the slope-water mass is dominant (Wright, 1976), was known to have an annual range of only a few degrees Celsius. Schroeder (1963) noted that greater variations were the result of irregularly occurring advective processes.

The famous mass mortality of tilefish, *Lopholatilus chamaeleonticeps*, from March through May 1882 (Collins, 1884) stimulated interest in advective processes on the outer shelf and upper slope. Millions of tilefish were found dead at the surface in a band extending about 310 km from off Montauk Point, Long Island, to southern Delaware. Although no pertinent water temperatures were measured at the time, biological evidence indicated that the mortality was caused by abnormally cold water temporarily flooding the bottom (Bigelow and Schroeder, 1953). Hachey (1955) pointed out that the probable source of such water was off Nova Scotia, where cold (<4°C) coastal water of Labrador origin normally occupies the bottom along the upper continental slope east of Emerald Bank. Only a far greater-than-normal westward advection of this cold water could have caused the tilefish disaster; however, similar advections of lesser magnitude have often been observed on the slope off Nova Scotia westward of Emerald Bank. Furthermore, in March 1966 an unusually extended advection of the Labrador coastal water was observed on the upper continental slope south of Georges Bank and New England, where bottom temperatures were below 6°C to a depth of 200 m (Colton et al., 1968).

During the ten years of this temperature monitoring project, there was no recognizable incursion of the cold Labrador coastal water into waters south of New England. At bottom depths of 160–200 m the lowest recorded temperature was about 9°C, lasting for perhaps a few weeks during early 1977 (Armstrong, 1998a, Fig. 5). This 10-yr minimum may be attributed to the persistently cold air temperatures during fall 1976 through January 1977 (Wood, 1998, Fig. 4).

At the beginning of the project, research by the U.S. Naval Oceanographic Office on Gulf Stream warm-core rings (Gotthardt, 1973) was providing a new perspective on bottom temperature variation on the outer shelf and upper slope. These rings, large deep-water features, had been discovered decades earlier and were recognized as forming from Gulf Stream meanders that detached from the stream (Iselin, 1936). Nevertheless, the potential impact of a ring on bottom temperatures on the fishing grounds was discovered only when XBT sections were obtained across the outer shelf and upper slope in the New York Bight at less-than-monthly intervals during most of each year in 1972–74 (Applications Research Division, 1974). Of particular pertinence to fishery ecology were sections showing marked effects of a Gulf Stream warm-core ring on bottom temperatures over the upper slope and outer shelf. Where the ring contacted bottom, temperatures were elevated well above normal values. Similar elevations of bottom salinities and current speeds were inferred because rings are composed of high-salinity oceanic water and have strong anticyclonic circulation (Gotthardt, 1973).

The Naval Oceanographic Office also pioneered the use of infrared satellite data, airplane-deployed XBT's, and current measurements taken from research ships to track rings and to investigate their subsurface structure and dynamics (Gotthardt, 1973). Significant findings included:

1. The rings usually formed southeast of Georges Bank and seemed to be irregular rather than seasonal in time of appearance.
2. Following formation, the rings tended to travel erratically in speed and direction, but with net movement generally opposite to that of the Gulf Stream. Thus the proximity of each ring to the outer continental shelf and upper slope varied during its progression past the fishing grounds of Georges Bank, southern New England, and the Middle Atlantic Bight, usually travelling only a few kilometers per day.
3. Some rings persisted for several months and, from an initial surface diameter of around 150 km, decreased in size and strength through their lifetime.

In view of these findings, a specific goal of this project was to examine the frequency, duration, magnitude, and distribution of ring influence on the shelf–slope fishing grounds. Annual summary reports (cited in Armstrong, 1998a) document the irregular times and rates of passage of the 34 rings that moved through the slope water south of New England in 1974–83. The number of rings passing each year ranged from 3 to 7. Armstrong (1998a, b) and Cook (1998) in this volume also report on ring passage during this project.

The rate of warm-core ring production in the Gulf Stream was particularly high during and after the record cold winters of 1976–77 and 1977–78, when Gulf Stream transport strengthened through deepening of the permanent thermocline in the northwestern North Atlantic (Worthington, 1977; Mizenko and Chamberlin, 1979; Celone and Chamberlin, 1980). Thus, in the same years that cold weather chilled the shelf waters below normal (1977 and 1978; see Fig. 5 in Armstrong, 1998a), numerous rings moved large volumes of warm Gulf Stream water into the slope water, and in some cases into contact with the bottom on the shelf and slope. In contrast, in 1984, the year after temperature monitoring off southern New England was terminated, only one ring passed south of New England (Price, 1985).

Application of Ocean Temperature Monitoring to Fishery Ecology

For over 20 years, NMFS has accepted nationwide scientific resource assessment as an ongoing responsibility. Accordingly, the ocean temperature monitoring project was not undertaken simply to investigate environmental conditions on the fishing grounds south of New England. Rather, it was to provide a basis for analyzing the influence of temperature on annual differences in the distribution, movement, reproduction, and other aspects of fish populations.

Examples for discussion of such temperature analysis are taken from Grosslein and Azarovitz (1982), who present distribution maps and summarize ecological information for numerous commercial finfish and shellfish. Among these are the following eight demersal species which undertake seasonal onshore and offshore migrations across the continental shelf south of New England and off the Middle Atlantic states: silver hake, *Merluccius bilinearis*; red hake, *Urophycis chuss*; black sea bass, *Centropristis striata*; scup, *Stenotomus chrysops*; butterfish, *Peprilus triacanthus*; summer flounder, *Paralichthys dentatus*; longfin squid, *Loligo pealei*; and northern shortfin squid, *Illex illecebrosus*. Furthermore, these authors suggest that temperature is a primary environmental factor controlling the seasonal migrations of the majority of these species.

Nonetheless, the actual undertaking of temperature control analysis by fishery ecologists may be hindered by the lack of offshore temperature monitoring data heretofore. Accordingly, the shoreward spring migrations of the species listed above are discussed here to exemplify the use of temperature data from south of New England, and also to point out how variable the influence of temperature conditions may have been during the ten years of monitoring.

In slope water, which is typically present at bottom depths below 150 m, bottom temperature is an unlikely stimulus of shoreward spring migration for overwintering demersal fish. One reason for this is the small seasonal change of bottom temperature: at depths of 160 to 200 m, the 10-yr mean annual cycle had a range of less than 1°C (Chamberlin, 1998, Fig. 1, 2). A second reason is that this low-amplitude annual cycle lagged almost 6 mo behind coastal air and sea-surface temperature cycles (Armstrong, 1998a, Fig. 3; Wood, 1998, Fig. 1, 2; Chamberlin, 1998, Fig. 3, 4). Thus, on the upper continental slope, where the 10-yr mean annual maximum occurred in late January and the minimum in early August, spring was a season not of warming but of slight cooling.

In contrast to conditions on the upper slope, bottom temperatures increase during spring on the outer shelf, where shelf water is normally present (Armstrong, 1998a, Fig. 3), supporting the concept that rising temperatures stimulate shoreward migrations of demersal fish in spring (Grosslein and Azarovitz, 1982). With decreasing depth from 150 to 80 m, the range of mean annual bottom temperatures increases from about 1° to 8°C. Yet the time of year of mean minimum bottom temperature varies little at these depths, occurring in mid-April, about 2 mo later than at the coast (Armstrong, 1998a, Fig. 3; Chamberlin 1998, Fig. 2, 3).

Contoured time–depth diagrams of 10-yr extreme maximum and minimum bottom temperatures (Chamberlin, 1998, Fig. 5) give a general impression of how variable the influence of bottom temperature on shoreward spring migrations may be. For example, during the winter demersal fish sensitive to low temperatures may be driven to deeper water in cold years than in warm years, and thus start their shoreward spring migrations from farther offshore (as much as 70 m greater bottom depth). These diagrams also indicate the extreme differences in bottom temperature that fish would have encountered during 1974 to 1983 while migrating shoreward in the spring near 71°W longitude. For example, if a migration in late April began on the bottom at depths greater than 120 m, under minimum temperature conditions the fish would have encountered water of about 6°C at a bottom depth of 120 m, water of less than 4°C at bottom depths of about 80–40 m, and near the coast, water no warmer than 8°C. In contrast, under maximum conditions the fish would have found bottom water warmer than 12°C to the 80-m isobath, water of 6°C near 40 m, and water of about 11°C near the coast.

The practical objectives of resource assessment, however, require more specific species-by-species and year-by-year analysis of temperature influence on shoreward spring migrations. Especially applicable to such analysis are diagrams of annual bottom temperature anomalies (Armstrong, 1998a, Fig. 5) and bottom temperatures (see citations in Armstrong, 1998a). Differences among the ten years are most readily seen in the anomaly diagrams. For example, April bottom temperatures on the outer shelf notably exceeded the 10-yr mean in 1979, 1980, and 1982, but were below the mean in 1975 and greatly so in 1978. The published annual bottom temperature diagrams provide more detailed information.

A primary biological consideration is to determine the adequacy of landings data in documenting the progression of shoreward migrations of various species in waters south of New England. Are these data sufficiently comprehensive to reveal annual differences in the routes and timing of these migrations? Landings data may also be used to address the question of whether various species remain near bottom throughout migration, thus passing through cold-core bottom water on the shelf, or whether some or all avoid the coldest water by swimming above it.

Results from the NMFS bottom trawl survey in spring 1974 suggest that the timing of shoreward fish migrations south of New England may be quite variable from year to year. Annual spring surveys have aimed to complete the sampling of migrant species in their wintering grounds on the slope and outer shelf in April, before most fish have started their shoreward spring migration. Nevertheless, in 1974, a year of warm winter bottom temperatures, the survey showed that by the end of April, seven of the eight migrant species listed above (at the beginning of this section) had reached the inner shelf south of New England in appreciable numbers (Grosslein and Azarovitz, 1982). Results for the exceptional species, *Illex illecebrosus*, were inconclusive due to low sample size throughout the survey area. Early arrival of the seven species is consistent with the above-average bottom temperatures across the shelf during January through March, followed by near-average temperatures in April (Armstrong, 1998a, Fig. 5).

Data from temperature monitoring may be used to investigate the influence of temperature not only on the route and timing of shoreward spring migrations, but also on related aspects of reproduction. For example, in such species as red hake, scup, butterfish, and longfin squid, which are known to begin spawning soon after their shoreward migration (Grosslein and Azarovitz, 1982), spawning location and timing will be affected by route and timing of migration. Furthermore, to the extent that gonad ripening in migrant species is controlled by temperature, where and when spawning occurs will vary from year to year as a result of different temperatures on offshore wintering grounds and on the shelf during, and subsequent to, shoreward migration.

Understanding the effect of annual variation in location and timing of spawning on the reproductive success of various fish species is important in recruitment studies because of the restrictive food requirements of some groundfish larvae. Cushing (1975, 1982) pointed out that during a critical early stage in planktonic development of some species, survival of larvae may depend on encountering sufficient concentrations of an essential planktonic food. Clearly such encounters depend on the spatial and temporal distribution of the forage organism and on where and when fish larvae are spawned.

Analyzing the role of temperature in ecology is simpler with sedentary benthic species such as the sea scallop, *Placopecten magellanicus*; ocean quahog, *Arctica islandica*; Atlantic surf clam, *Spisula solidissima*; and waved whelk, *Buccinum undatum*, than with mobile finfish and squid. For example, diagrams of 10-yr extreme maximum and minimum bottom temperatures (Chamberlin, 1998, Fig. 5) approximate the range of temperature tolerated during 1974 to 1983 by a 10-yr-old clam found in 1984 near 71°W. Furthermore, in conjunction with comprehensive information on the geographical distribution (including bottom depth) of species, data on extreme bottom temperatures and annual bottom temperature anomalies, as well as annual bottom temperature, can be used to estimate temperatures necessary for repopulation (Hutchins, 1947; Chamberlin and Stearns, 1963). Such an approach should be directly applicable to species like the waved whelk whose young are not planktonic, but emerge in the crawling state from egg capsules attached to the substrate.

These examples of the potential application of ocean temperature monitoring to fishery ecology deal with only one of the factors influencing distribution, abundance, and recruitment of fishes and shellfishes in southern New England waters. Consideration must also be given to natural variations in other environmental factors and to degradation of the environment resulting from human activities. Of most immediate concern, however, is the impact of severe overfishing which has decimated several of the most valuable finfish species since the 1960's (Grosslein and Azarovitz, 1982; Murawski, 1991; Sissenwine and Cohen, 1991).

Acknowledgment

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Bottom Temperatures on the Continental Shelf and Upper Slope: Means, Standard Deviations, and Anomalies

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Introduction

Seasonal and between-year variations in bottom water temperatures are frequently cited as important environmental factors influencing the distribution, abundance, and reproductive success of demersal and benthic marine organisms. The approximately monthly collections of subsurface temperature data off southern New England during 1974–83 offer an opportunity to describe bottom temperatures and examine differing hydrographic regimes for bottom- and near-bottom-dwelling marine organisms across the width of the continental shelf and upper slope.

The work reported here is the completion of a multiyear analysis initiated by Robert W. Crist, to whose memory this volume is dedicated. The methods used in this section were generally developed by him, and the results are mainly based on analyses that he began.

Results presented here represent ten years (1974–83) of expendable bathythermograph (XBT) measurements of bottom temperatures. Monitoring was conducted along a transect on and near 71°W longitude, across the shelf and into the adjacent slope water (Fig. 1). I describe the mean annual cycle over the ten-year period and variations from the mean for each year, from the beach to 200 m depth. Cook (1985) employed some of these same XBT data, from 1977–81, along with complementary data from the New York Bight, to describe and compare bottom temperatures and cold pool conditions between the two areas. Other descriptions of bottom water temperatures that include southern New England shelf waters have generally presented spatial distributions of monthly mean values (Walford and Wicklund, 1968; Colton and Stoddard, 1973) or seasonal mean temperatures (Schopf, 1967; Davis, 1979) based on irregularly spaced data collected over a wide area of the continental shelf.

Data and Methods

Data presented here are derived from diagrams of bottom temperature contoured on a depth–time coordinate plane and published in annual summary reports for each year, 1974–83 (Armstrong, 1986; Chamberlin 1976, 1978; Crist, 1984; Crist and Armstrong, 1985; Crist and Chamberlin, 1979a, b, 1980, 1981, 1983). The method used to construct annual bottom temperature diagrams is described by Chamberlin (1976). Vertical temperature sections were prepared from XBT data obtained by ships transiting along 71°W or within about 30' on either side of this meridian (Fig. 1). From the sections, intersections of isotherms with the bottom were tabulated, plotted on a diagram of bottom depth versus time of year, and contoured (Fig. 2). To complete the bottom temperature diagram to the shore (0 m bottom depth), sea surface temperatures were included from daily observations at the NOAA National Ocean Service tide station at Newport, Rhode Island, and from a recording thermograph placed on the bottom (20 m depth) by the NMFS Northeast Fisheries Center at the navigation tower on Brenton Reef in the mouth of Narragansett Bay (Fig. 1).

During 1974–83, an average of 19 cruises per year were conducted, ranging from a minimum of 15 in 1980 to a maximum of 23 in 1983. The time between cruises ranged from less than a week to approximately two months. The timing of the passage of warm-core Gulf Stream rings across the transect, as determined from interpretations of satellite infrared imagery, was depicted on the diagrams in the annual summaries.

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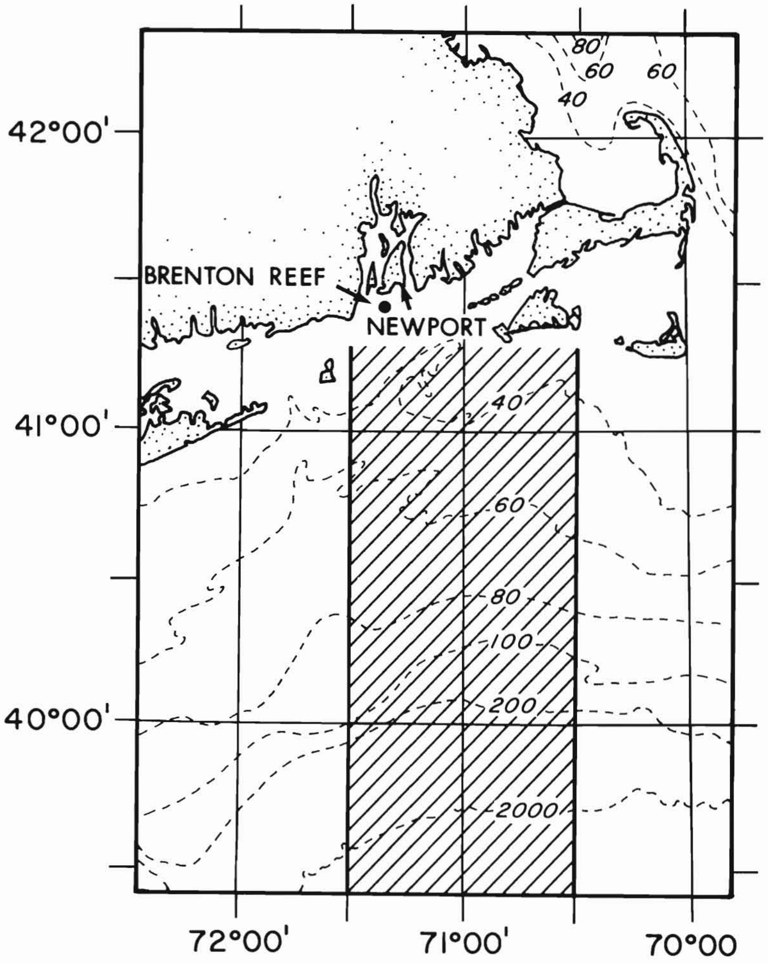

Figure 1

Area along 71°00'W south of New England (shaded region) where expendable bathythermograph (XBT) data were collected for bottom temperature analyses, 1974–83. Also shown are locations of the recording thermograph for 20-m bottom temperatures (Brenton Tower, RI) and the NOAA tide station where shore temperatures were recorded (Newport, Rhode Island). Depth contours in meters.

For this report, the bottom temperature diagrams for each of the ten years were hand-digitized by recording temperature for every tenth day along each 10-m isobath from 0 to 200 m. The annual diagrams extended to 400 m depth, but because coverage beyond the 200-m isobath was more sporadic, this compilation was not extended beyond 200 m. Also, definition of the bottom temperature field at depths greater than 200 m was considered questionable because of the relatively rapid change in bottom depth with distance at those depths in relation to XBT station spacing. The bottom temperatures at 10-day, 10-m-depth intervals were averaged at each grid point to produce ten-year means, and standard deviations around the means were calculated. In addition, anomalies of bottom temperature for each year were calculated by subtracting the 10-yr mean values from the data for individual years at each date–depth grid point.

The 10-yr mean bottom temperatures and standard deviations were contoured on diagrams of bottom depth versus time of year to depict the mean annual cycle and variability about the mean. Also, anomaly values for each year were contoured on diagrams of bottom depth versus time of year to reveal patterns in departures from the mean through the decade. Information on the presence of warm-core Gulf Stream rings in the slope water and on the transect was taken from the annual summary reports.

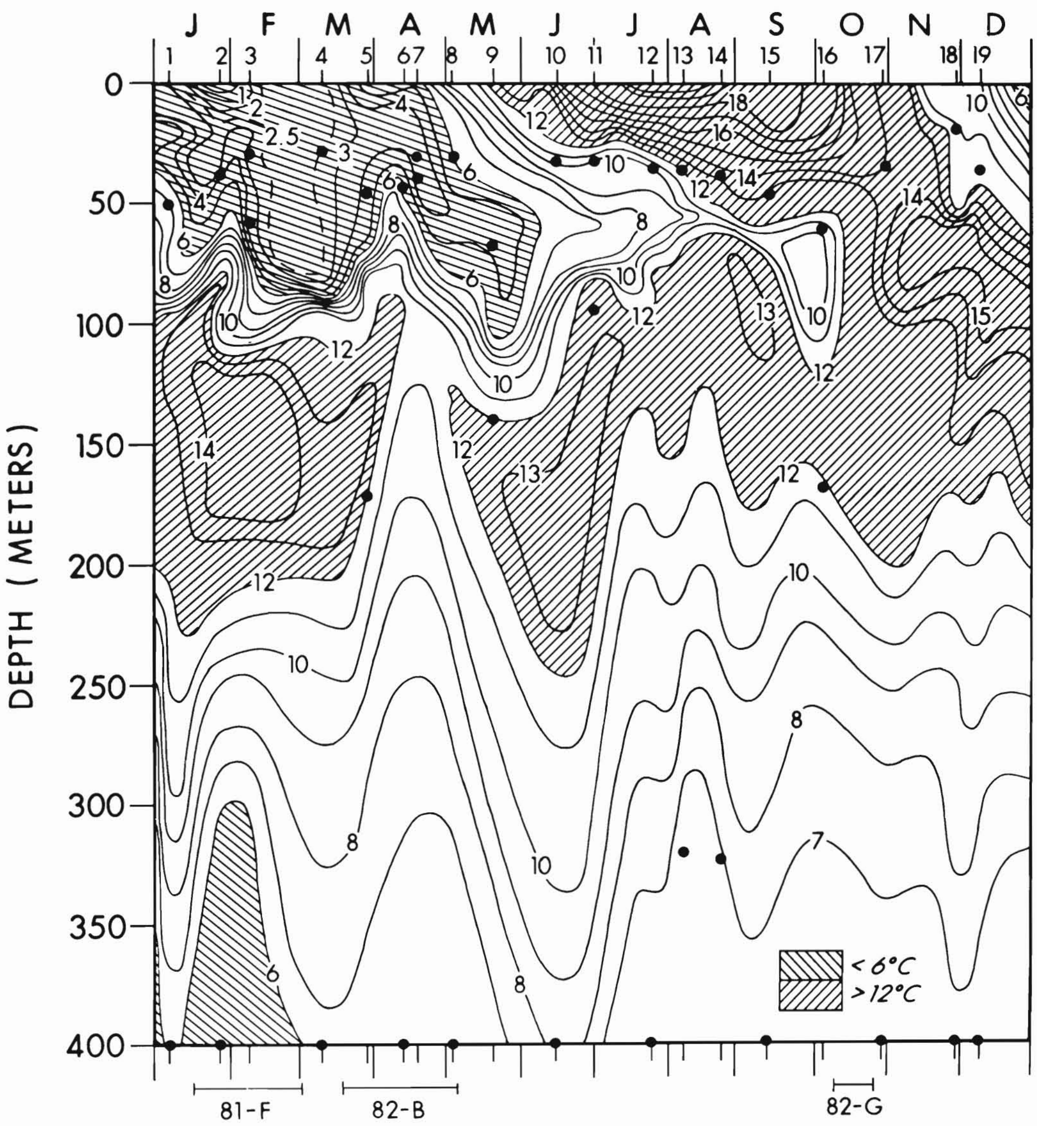

Figure 2

Bottom temperature (°C) on the continental shelf and slope south of New England during 1982. Vertical sections of expendable bathythermograph (XBT) data are numbered sequentially across the top. Heavy dots mark inshore and offshore limits of XBT sampling for each section. Horizontal lines at the bottom indicate duration of warm-core rings south of New England during the year (from Crist and Armstrong, 1985).

Results

Ten-year-mean minimum annual bottom temperatures occurred earliest and were coldest at the coast; they occurred progressively later and were warmer with increasing depth (Fig. 3A). Maximum annual bottom temperatures were earliest and warmest at the coast; they occurred progressively later and, generally, were cooler with increasing depth. A secondary maximum occurred at midshelf depths (centered at 70 m bottom depth). Amplitude of the annual cycle was greatest at the coast (20.5°C) and decreased with increasing depth. At the shelf break (100-m isobath) the amplitude was about 5°C; on the upper slope there was only a weak signal of an annual cycle, with the amplitude amounting to less than 1°C at bottom depths greater than 150 m.

Variability in bottom temperatures around the ten-year means (Fig. 3B) was highest in winter, with the largest standard deviations in February near the 100-m isobath. The largest difference in anomalies for the

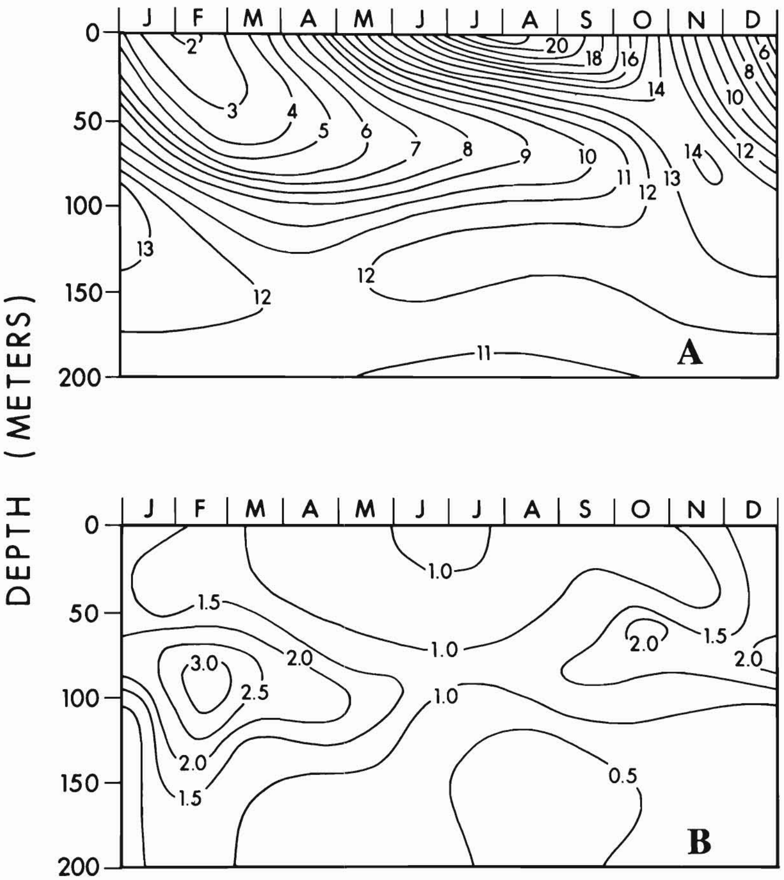

Figure 3

A) Ten-year mean annual cycle of bottom temperature (°C), and B) annual cycle of standard deviation (°C) from the 10-yr mean of bottom temperatures on the continental shelf and upper slope south of New England, 1974–83.

same date was also at this depth in late February, ranging from an anomaly of –5°C in 1979, when the bottom temperature was 5°C, to a +5°C anomaly in 1975, when the bottom temperature was 15°C (Fig. 4). These extremes in anomaly values coincided with the occurrence of the largest anomalies in monthly air temperatures during the ten years: January 1975 and February 1979 (Wood, 1998, Fig. 4), excluding February 1981, when no bottom temperature data were available. In the winters and early springs of 1977, 1978, and 1979, high negative anomalies developed around the 100-m isobath, and bottom waters tended to remain cooler than average through summer and into fall over much of the shelf and upper slope (Fig. 4). These events were associated with three successive unusual years of very cold winter air temperatures (Wood, 1998).

At times, large anomalies in bottom temperature developed with the passage of warm-core rings. For example, in March 1982, warm-core ring 82-B approached the shelf off southern New England, raising bottom temperatures near the 80-m isobath from about 2.5°C in March to about 11°C in April (Fig. 2) with a warm water intrusion from offshore. In May, with offshore flow in the wake of the ring, 80-m bottom temperatures fell to less than 7°C (Crist and Armstrong, 1985). Associated with the ring's passage, bottom temperature anomalies in excess of +5°C developed in April 1982 on the outer shelf and influenced temperatures shoreward to about the 30-m isobath (Fig. 4). By mid-May, in the wake of the ring, the pattern reversed, with negative anomalies prevailing over the outer shelf. The impact on bottom temperatures from the aperiodic passage of warm-core rings is highly variable, depending on the dynamics and structure of the ring, its duration in the area, and proximity of the ring to the continental shelf and slope (Chamberlin, 1982).

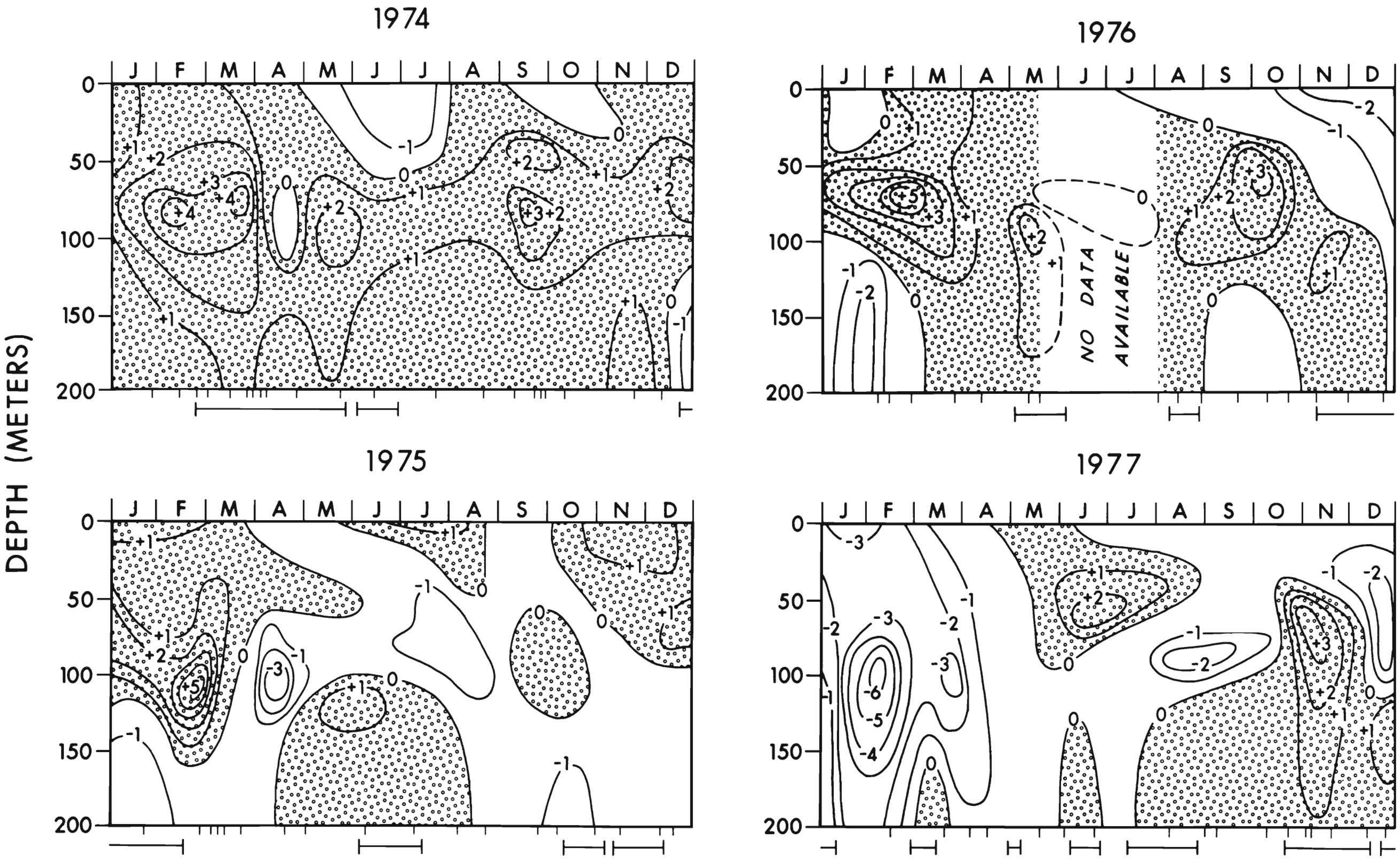

Figure 4

Anomalies (°C) in bottom temperature for each year, 1974–83, referenced to the 10-yr mean annual cycle (Fig. 3). Along the bottom of each graph are indicated the times of vertical sections of expendable bathythermograph data (tick marks) and the presence and duration of warm-core Gulf Stream rings in the slope water (horizontal bars). Shaded regions are warmer (positive anomaly) than the 10-yr mean.

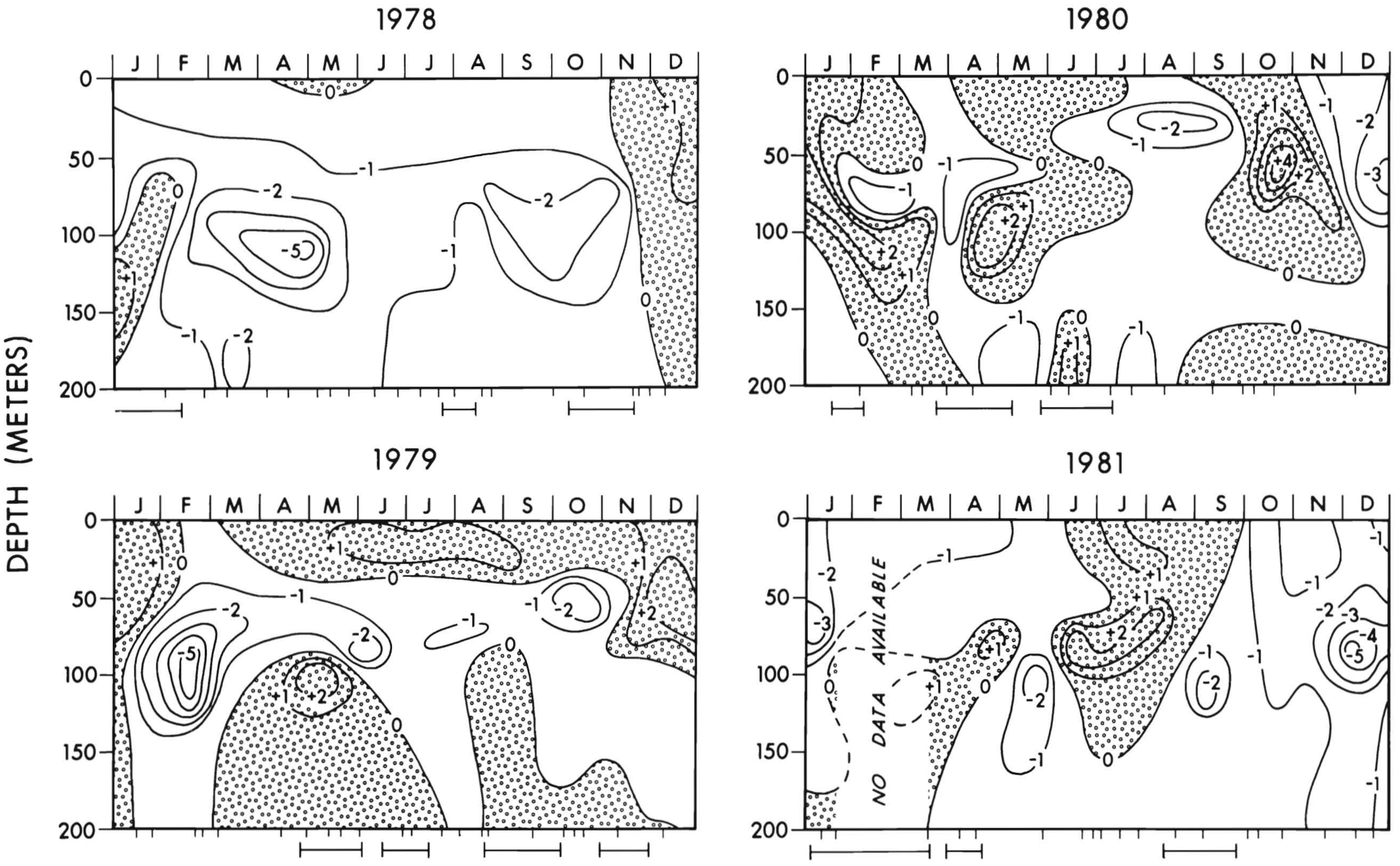

Figure 4 (cont.)

Anomaly (°C) in bottom temperature.

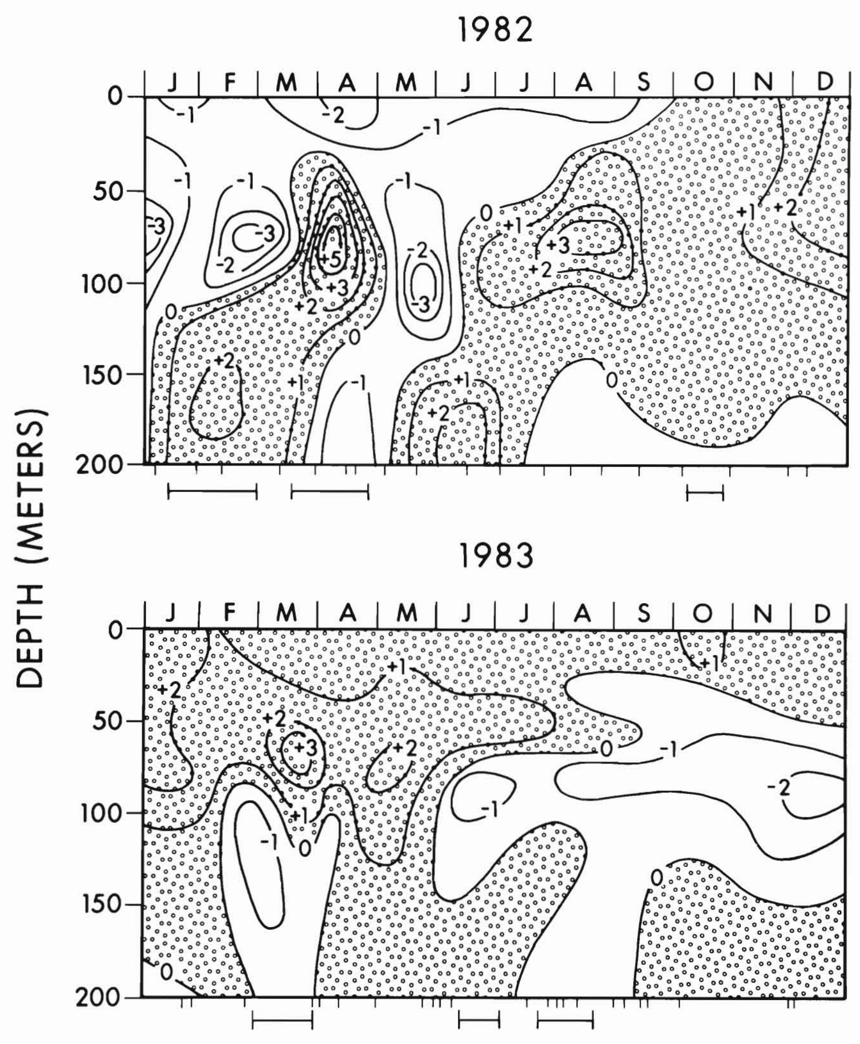

Figure 4 (cont.)
Anomaly (°C) in bottom temperature.

Minimum variability in bottom temperatures occurred during March–May and August–October in nearshore waters (0–30 m), during June–August at the shelf break (100 m), and July–September at greater depths (Fig. 4). The lowest standard deviations were in July–September at bottom depths of about 150 m and greater, where anomalies generally remained within 1°C of the mean throughout the ten years.

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Comparison of Surface and Bottom Water Temperatures with Air Temperatures

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Introduction

The difference between the annual seasonal cycles of bottom and surface temperature is regarded as an important controlling factor in vertical mixing of the water column on the continental shelf (Ingham et al., 1982). The air–sea interactions involved in the warming and cooling of the ocean by the atmosphere, and vice versa, have been studied by various authors (Bjerknes, 1960; Laevastu, 1960; Laevastu et al., 1976; Niiler and Kraus, 1977). In the mid-Atlantic Bight area south of New England, temporary but recurring features such as the "cold pool" are largely the result of surface-layer temperature changes (Bigelow, 1933; Ketchum and Corwin, 1964). Colton (1968) found that coastal sea surface temperature could be used as an indicator of anomalous water-column conditions in shelf waters offshore of New England.

Monthly records of air temperature, coastal water temperature, and surface and bottom water temperatures at the midshelf depth of 70 m were compiled to represent atmospheric and water temperature conditions off southern New England in 1974–83. These data were used to display and compare mean annual cycles and between-year variability during the ten-year period.

Data and Methods

Four time series were selected to represent air and water temperature patterns off southern New England in 1974–83:

Air Temperature

Monthly averages of 3-hourly observations by the National Weather Service, National Oceanic and Atmospheric Administration (NOAA) at Providence, Rhode Island (about 30 km inland) were obtained from Local Climatological Data (LCD) reports prepared and issued by the National Climatic Data Center, NOAA. For comparison with ten-year means, we utilized the long-term, length-of-record (1905–83) monthly means for air temperatures at the Providence weather station, found in LCD reports.

Coastal Sea Surface Temperature

Daily measurements of sea water temperature taken at a tide station off Newport, Rhode Island, were acquired from the National Ocean Service, NOAA. The tidal observation station is located in 9 ft of water about 5.5 km inland from the mouth of Narragansett Bay. We calculated the mean sea-surface temperature for each month of the ten years for which there was an adequate temporal distribution of observations.

Midshelf Surface and Bottom Water Temperatures

Monthly mean values of water temperature at the surface and on the bottom, at a location approximately midway across the continental shelf, were determined from expendable bathythermograph (XBT) transects made at or near 71°W longitude during 1974–83. Monthly mean values were derived from XBT data plots for water temperatures at the 70-m isobath (midshelf) in Cook (1998).

For each of the four sets of monthly data, 10-yr monthly means and standard deviations about the means were calculated and plotted to display average annual cycles and seasonal patterns in air and water temperature variability. Anomalies for each month of the ten years were calculated by subtracting the monthly means from the values for individual months. Anomaly values were plotted to portray conditions for the decade and to display associations between anomalies for different data sets. For each year, the temperature and time of the coldest and warmest months were tabulated.

Results

Minimum temperatures typically occurred in February at the coast and about a month later throughout the water column at midshelf (Table 1, 2; Fig. 1, 2). Annual minimum water temperatures were lowest at the coast and highest at 70-m bottom depth. At midshelf, the minimum usually occurred a month later on the bottom than at the surface. Minimum air temperatures usually occurred in the same month as coastal water temperatures, but were lower.

Maximum annual air temperatures typically occurred in July and about a month later for the sea surface at both coast and midshelf (Table 2; Fig. 2). Maximum temperatures on the bottom did not occur until fall and were about the same as those for surface waters, which were then cooling.

In general, the lowest minimum water temperatures occurred in the years of coldest atmospheric conditions, and the warmest water minimums were associated with the warmest winters on land. However, there was little correlation among the four data sets with respect to higher and lower annual maximum temperatures. The amplitude of the annual cycle (difference between maximum monthly temperature in Table 2 and minimum monthly temperature in Table 1) for water temperatures on the bottom at the 70-m isobath was about one-third that for air temperature and one-half the amplitude of the sea-surface cycle at either midshelf or coastal locations. The length of warming and cooling seasons in atmospheric records and in the sea-surface temperature records were about the same (about 6 mo), but the season of warming on the bottom at midshelf was twice as long (8 mo) as the cooling season (4 mo), with about half the warming on the bottom in the months of October and November (Fig. 1).

As an indication of how representative atmospheric conditions were in 1974–83, the annual cycles of monthly mean air temperature at Providence, based on the 79-yr (1905–83) record and on data for 1974–83, are plotted in Figure 2. The two curves are within 0.5°C for all months except January and October, when the 10-yr means are about 1°C cooler than the long-term values.

Variability around 10-yr monthly means tended to be greater in land air temperature and in bottom-water temperature at the 70-m isobath than in sea-surface temperature (Fig. 3). Land air, coastal sea-surface, and 70-m bottom temperatures showed greatest variability in December through February (and into March for bottom temperatures), with the least variability during spring and summer months. Also, the largest monthly temperature anomalies generally occurred during the winter months (Fig. 4). Sea-surface temperature at midshelf did not exhibit clear seasonal patterns of variability (Fig. 3c). The high standard deviation in June

Table 1

Annual minimum mean monthly temperature (°C) and month of occurrence for southern New England, 1974–83.

			Water					
	Air		Coast		70-m isobath			
	Providence, RI		Surface		Surface		Bottom	
	Temp.	Month	Temp.	Month	Temp.	Month	Temp.	Month
1974	–1.7	Feb	3.3	Jan	5.2	Mar	6.2	Apr
1975	–0.9	Feb	3.6	Feb	5.3	Feb	5.5	Apr
1976	–4.7	Jan	2.4	Jan	4.6	Mar	5.6	Apr
1977	–6.2	Jan	0.0	Jan	2.8	Feb	2.7	Feb
1978	–5.5	Feb	0.6	Feb	2.6	Mar	2.6	Mar
1979	–6.8	Feb	1.1	Feb	2.5	Feb	2.4	Mar
1980	–2.9	Feb	2.6	Feb	3.7	Mar	4.3	Mar
1981	–6.5	Jan	0.9	Feb	3.8	Mar		
1982	–5.8	Jan	1.7	Jan	2.7	Feb	3.4	Mar
1983	–0.3	Jan	3.3	Feb	5.4	Mar	6.4	Apr
Average	–4.1	Jan–Feb	2.0	Feb	3.9	Mar	4.3	Mar–Apr
10-yr mean	–2.9	Jan	2.2	Feb	4.0	Mar	5.0	Mar

Table 2
Annual maximum mean monthly temperature (°C) and month of occurrence for southern New England, 1974–83.

			Water					
	Air		Coast		70-m isobath			
	Providence, RI		Surface		Surface		Bottom	
	Temp.	Month	Temp.	Month	Temp.	Month	Temp.	Month
1974	22.6	Jul	21.1	Aug	21.3	Aug	13.9	Nov
1975	23.5	Jul	21.1	Jul	20.5	Aug	13.5	Nov
1976	21.1	Jul	20.6	Aug	21.0	Aug	14.1	Oct
1977	23.5	Jul	21.7	Aug	22.2	Aug	15.9	Nov
1978	22.1	Jul	21.4	Aug	22.7	Aug	13.7	Nov
1979	23.1	Jul	21.4	Aug	21.6	Jul	14.8	Nov
1980	23.8	Jul	21.7	Aug	22.1	Aug	14.7	Oct
1981	24.2	Jul	21.1	Jul	21.6	Aug	11.6	Nov
1982	23.1	Jul	20.6	Aug	19.7	Aug	15.3	Nov
1983	24.8	Jul	21.1	Jul	20.4	Aug		
Average	23.2	Jul	21.2	Aug	21.3	Aug	14.2	Nov
10-yr mean	23.2	Jul	21.1	Aug	21.2	Aug	14.0	Nov

(>2°C) for sea-surface temperature at the 70-m isobath was associated with the presence of unusually cold water in the surface layer in June 1982 (Cook, 1998), which produced a temperature anomaly of about –4°C (Fig. 4). This was associated with the coldest June since 1926 in the Providence air-temperature records and unusually low sea-surface temperatures for the month off most of the northeastern United States (Wood and Tang, 1988). If the June 1982 value were excluded from the calculation, the June standard deviation would be reduced to 1.3°C, making it more similar to values for midshelf sea-surface temperature for other months (Fig. 3c).

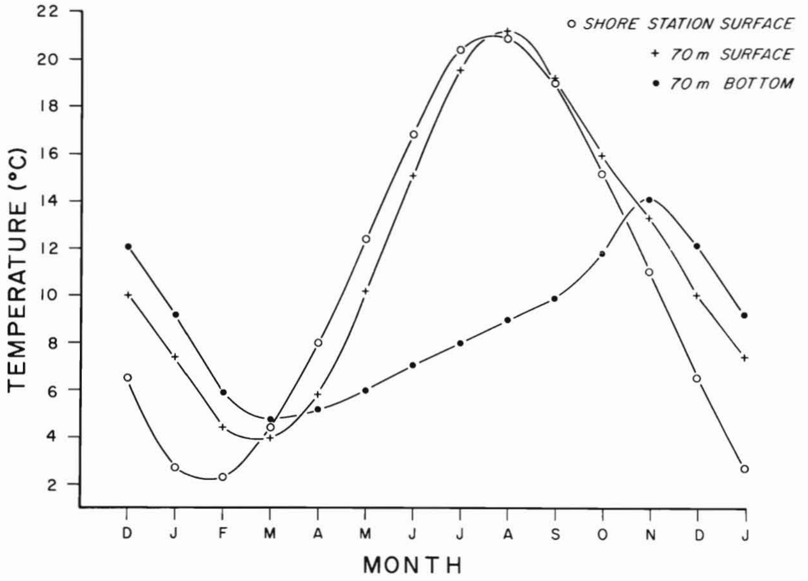

Figure 1
Ten-year (1974–83) mean annual cycle of water temperature off southern New England for coastal surface waters off Newport, RI (Shore Station Surface), surface waters at the midshelf location of the 70-m isobath (70-m surface) and bottom waters at 70-m depth at mid-shelf (70-m bottom).

Monthly anomalies based on 10-yr means of air temperatures (Fig. 4) were mostly due to large month-to-month changes, but water-temperature anomalies exhibited more prolonged and persistent patterns. One prominent feature in the anomaly diagrams is the three consecutive cold winters of 1976–77, 1977–78, and 1978–79, when cold air temperatures prevailed throughout the northeastern United States (Ingham, 1982). During these three years, winter water temperatures at the surface were generally lower than average, and temperatures on the bottom at midshelf remained much lower than average most of the time. Most distinctive of these three cold winters was that of 1976–77, when air temperature was more than 3°C cooler than average during November–January. Water temperatures during these months, and continuing into early spring, were apparently much lower than average at all three locations. A prolonged period of lower-than-average air temperature developed in August 1981 and lasted through August 1982, when air-temperature anomalies were positive for only two of the thirteen months. During this period, cooler-than-average conditions persisted

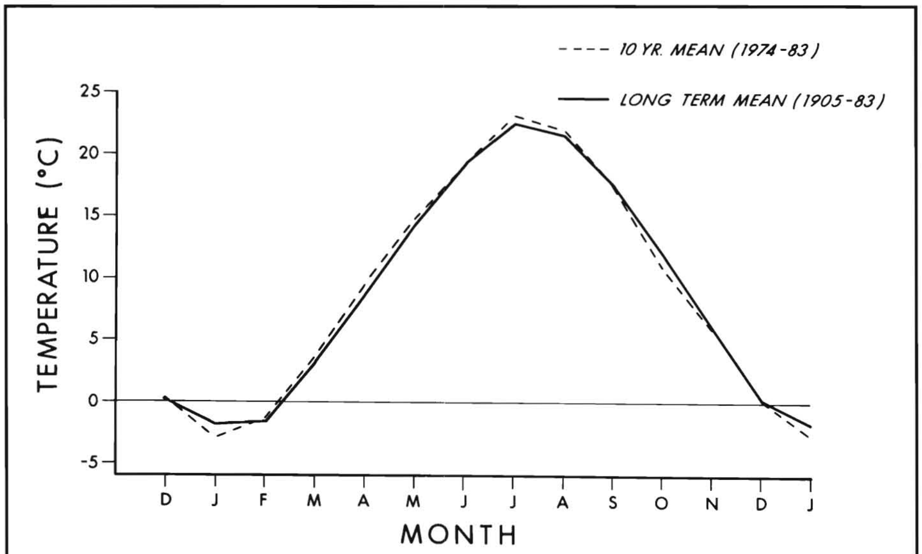

Figure 2
Mean annual cycle of air temperature at Providence, RI from 10-yr (1974–83) and long-term (1905–83) monthly means.

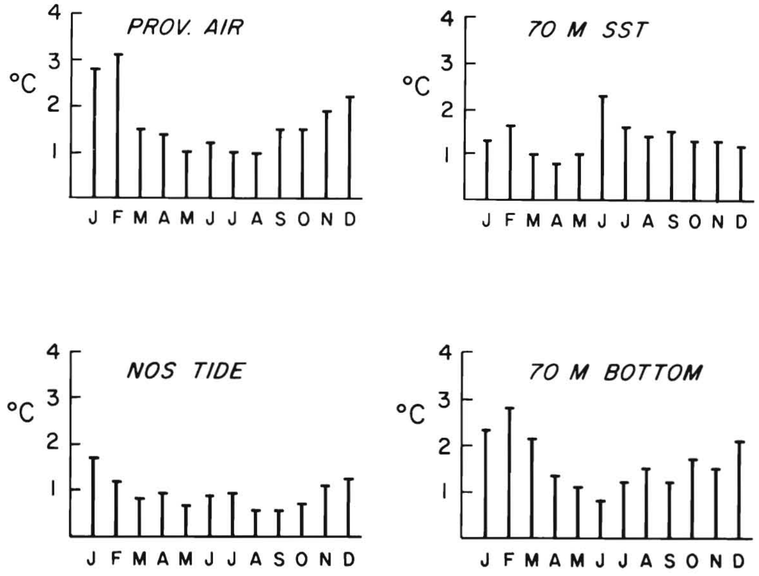

Figure 3
Variability (standard deviation) around 10-yr (1974–83) monthly means of water and air temperature (Fig. 1, 2). PROV.AIR = air temperature at Providence, RI; NOS TIDE = sea-surface temperature at Newport, RI; 70 M SST = sea-surface temperature at midshelf (70-m isobath); 70 M BOTTOM = bottom temperature at midshelf (70-m isobath).

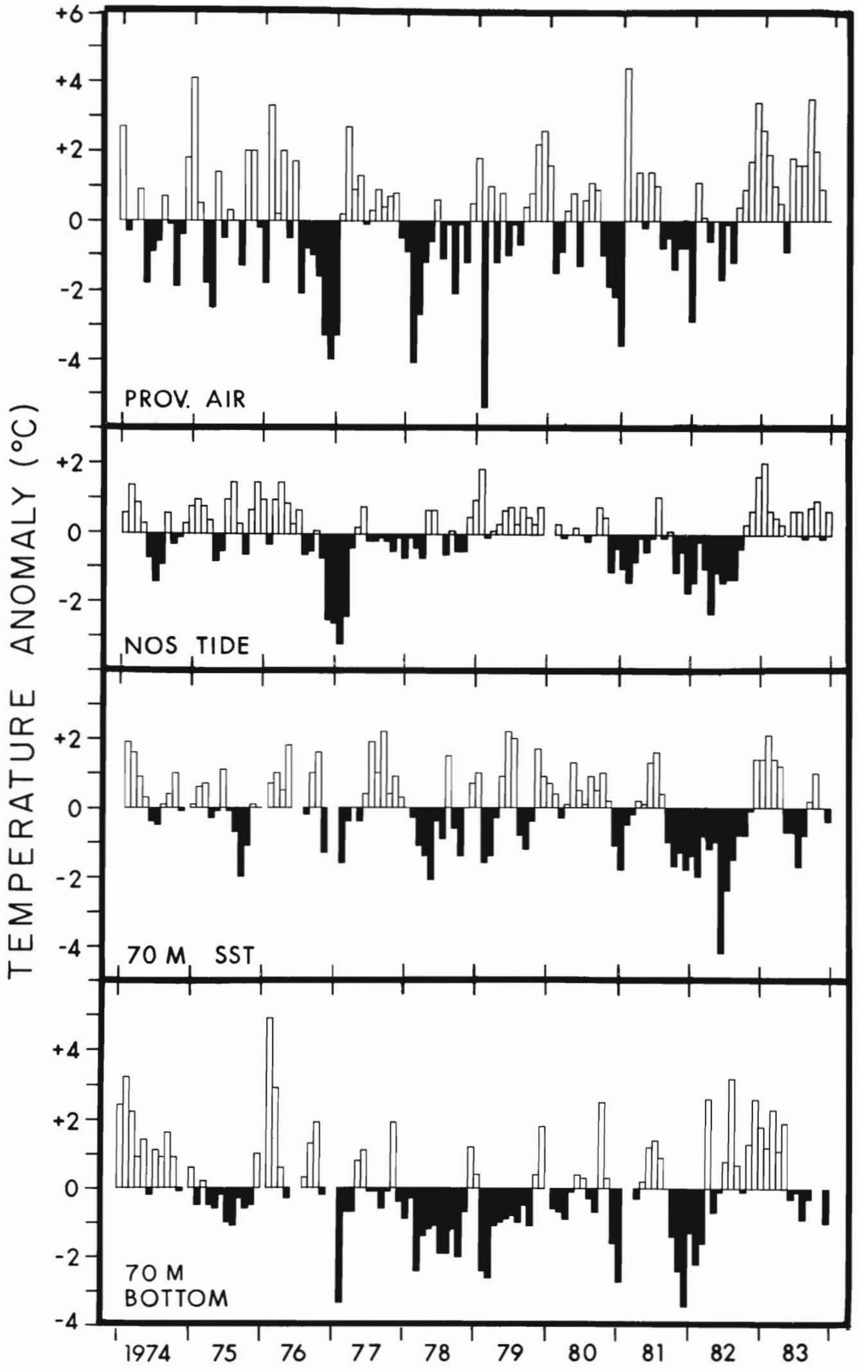

Figure 4

Monthly anomalies of air and water temperatures, referenced to the 10-yr monthly means for 1974–83 (Fig. 1, 2). Positive values are warmer than the 10-yr mean and negative (shaded) are colder. A blank space represents absence of data for the month. PROV.AIR = air temperature at Providence, RI; NOS TIDE = sea-surface temperature at Newport, RI; 70 M SST = sea-surface temperature at mid-shelf (70-m isobath); 70 M BOTTOM = bottom temperature at midshelf (70-m isobath).

for the sea surface at the coast and midshelf. On the bottom at midshelf there were also negative anomalies during this time, but the pattern was interrupted in spring 1982 by the intrusion of warm water from offshore associated with the passage of a warm-core ring (Armstrong, 1998).

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Vertical Thermal Structure of Midshelf Waters

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Introduction

A location at 70 m depth, about midway across the continental shelf, at 71°W longitude was selected to represent the vertical temperature structure of shelf waters off southern New England through the ten years 1974–83. The 70-m isobath is also approximately in the center of the cold pool (Houghton et al., 1982). I examined temperature through time and from the surface to the bottom to portray the annual cycle and between-year variation in midshelf waters.

Data and Methods

To portray the annual water-column temperature structure at midshelf off southern New England, we employed a method similar to that of Hughes and Cook (1984) for New York Bight shelf waters. Vertical profiles of temperature at the 70-m isobath at and near 71°W longitude were constructed from vertical temperature sections of expendable bathythermograph (XBT) data previously constructed for each cruise that made XBT drops in that area. These vertical temperature sections were published in a series of annual reports of bottom temperatures off southern New England (see references in Armstrong, 1998).

Temperature values at the 70-m isobath were plotted and contoured on diagrams of time of year versus depth for each of the ten years. The contoured diagrams were digitized for each 10 m of depth from the surface to the bottom (70 m), and for each 20th day through the year. The temperature values at each 20-day, 10-m interval were averaged over the ten years and plotted, with standard deviations, on a diagram of depth versus time of year to show the 10-yr mean annual cycle. The 10-yr mean temperatures for each date/depth grid point were subtracted from the annual values; the differences between the annual and 10-yr means were contoured on diagrams of depth versus time of year to display annual temperature anomalies. In addition, minimum and maximum surface and bottom temperatures and their dates of occurrence in each year and in the 10-yr mean annual cycle were tabulated.

The analysis employed XBT data from 1974 through 1983 from a total of 179 cruises, on average about 18 cruises per year, ranging from 13 in 1976 to 23 in 1979. The interval between cruises ranged from less than a week to slightly more than two months.

Results

The 10-yr (1974–83) mean annual cycle of water column temperature on the southern New England shelf (Fig. 1) shows the same seasonal pattern as that described by Ketchum and Corwin (1964) for shelf waters off eastern Long Island in 1956–59. From late fall through winter, the waters were vertically almost isothermal, and cooling proceeded steadily until the time of the annual minimum in March. Vertical thermal stratification was established in April. With rapid warming at the surface, but much more gradual warming in deeper waters, the thermocline intensified through spring and summer. During summer the thermocline deepened, and with vertical mixing driven by surface cooling in fall, continued to deepen until reaching the bottom in October. Bottom temperatures rose until the annual maximum was reached in November, when fall overturn was completed, and the water column returned to being nearly isothermal from surface to bottom.

The annual minimum in 10-yr mean temperature at midshelf occurred in March, with waters 0.7°C cooler at the surface than along the bottom (Fig. 1, Table 1). During the period of maximum warming at the surface (May–August), warming rates were about 4°C/mo there but only about 1°C/mo on the bottom. During summer

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the thermocline was most intense, with a vertical temperature gradient of about 0.5°C/m. Annual maximum temperature occurred in August at the surface and was progressively later and lower with increasing depth, such that the annual maximum at the bottom was 100 days later and 7.5°C cooler than at the surface. Amplitude of the annual cycle of temperature at the 70-m isobath was about half as large along the bottom as at the surface. Mainly because of the later annual maximum on the bottom, the warming season on the bottom (about 8 mo) was almost twice that at the surface (about 5 mo).

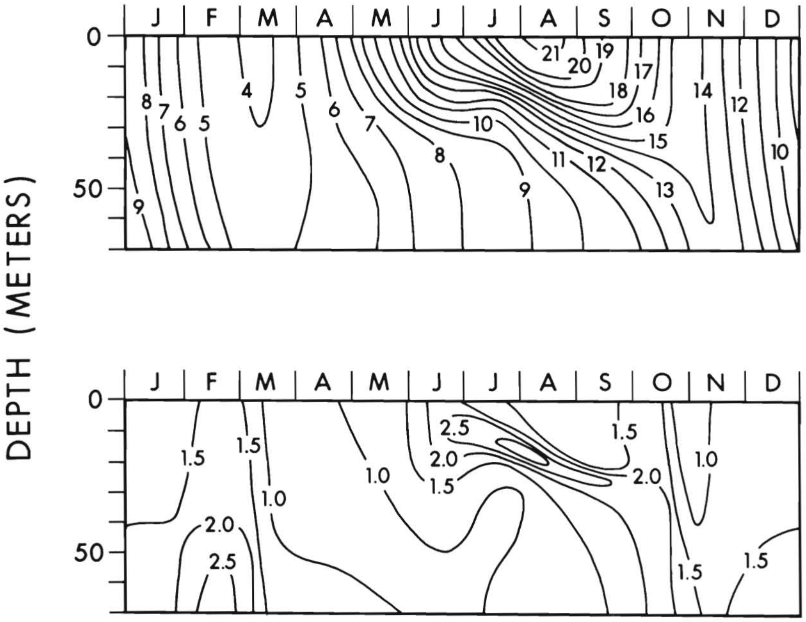

Figure 1

Ten-year (1974–83) mean annual cycle of water-column thermal structure (°C) at midshelf (70 m bottom depth) off southern New England (above) and annual cycle of standard deviation (°C) from the 10-yr mean (below).

Variability between years in water column temperature at the 70-m isobath is shown in the contoured diagrams of standard deviation (Fig. 1) and in the anomaly plots for the 10 years (Fig. 2). Highest variability was during summer, in a layer centered at about 10 m depth in June, which deepened to about 25 m in September (Fig. 1). This layer nearly coincided with the center of the thermocline (Fig. 1). Because of the large vertical temperature gradient in the thermocline, relatively small changes in thermocline depth could produce large temperature anomalies. For example, during summer and early fall 1977, alternating cells of large positive and negative temperature anomalies (Fig. 2) corresponded to short-period changes in thermocline depth. Departures of thermocline depth in 1977 from 10-yr mean positions (using 15°C as an indicator of thermocline depth) were about 15 m

Table 1

Annual minimum and maximum surface and bottom temperatures and their dates of occurrence at midshelf (70 m bottom depth) off southern New England, 1974–83.

	Annual minimum				Annual maximum			
	Surface		Bottom		Surface		Bottom	
	Temp. (°C)	Julian day	Temp. (°C)	Julian day	Temp. (°C)	Julian day	Temp. (°C)	Julian day
1974	4.8	80	4.9	90	21.5	230	15.2	320
1975	4.4	60	5.0	85	21.7	220	14.4	330
1976	4.2	70	5.2	105	21.5	220	14.8	290
1977	2.2	50	2.2	50	23.3	250	17.0	310
1978	2.2	80	2.2	80	24.1	230	15.5	330
1979	1.8	60	1.8	60	24.1	210	16.4	330
1980	3.4	70	3.6	90	22.8	225	16.3	290
1981	3.6	70	3.9	100	22.5	210	13.8	310
1982	2.0	50	2.4	65	20.2	235	16.0	330
1983	5.3	80	5.6	100	22.1	250		
Average	3.4	67	3.7	82	22.4	228	15.5	316
10-yr mean	3.9	65	4.6	75	21.3	220	13.8	320

deeper than average in June and 5 m deeper in August (periods of positive temperature anomalies) and almost 10 m shallower in July and mid-September through early October (negative anomalies). Crist and Chamberlin (1979) thought that these variations probably resulted from changes in shelf water circulation associated with the passage of two warm-core rings and possible advection of cooler waters from southern Georges Bank.

A secondary maximum in standard deviation values (Fig. 1) occurred in winter, particularly in the deeper portion of the water column. High variability in winter bottom temperatures derived from large between-year differences in annual minimum water temperatures and dates of occurrence of the minimum (Table 1), and was associated with large variability in fall–winter air temperatures (Wood, 1998). Annual minimum bottom temperatures (Table 1) in the relatively warm winters of 1976 and 1983 occurred one to almost two months later than in years when air and annual minimum bottom temperatures were coldest (1977, 1978, 1979, and 1982).

Typically, Gulf Stream warm-core rings in 1974–83 had little influence on water temperatures as far onto the shelf as the 70-m isobath. However, there was notable ring influence, as discussed earlier, from the passage of two rings during the summer of 1977. In November 1977 an intrusion of 17°C Gulf Stream water was carried onto the shelf by a ring (Crist and Chamberlin, 1979) and produced the highest annual

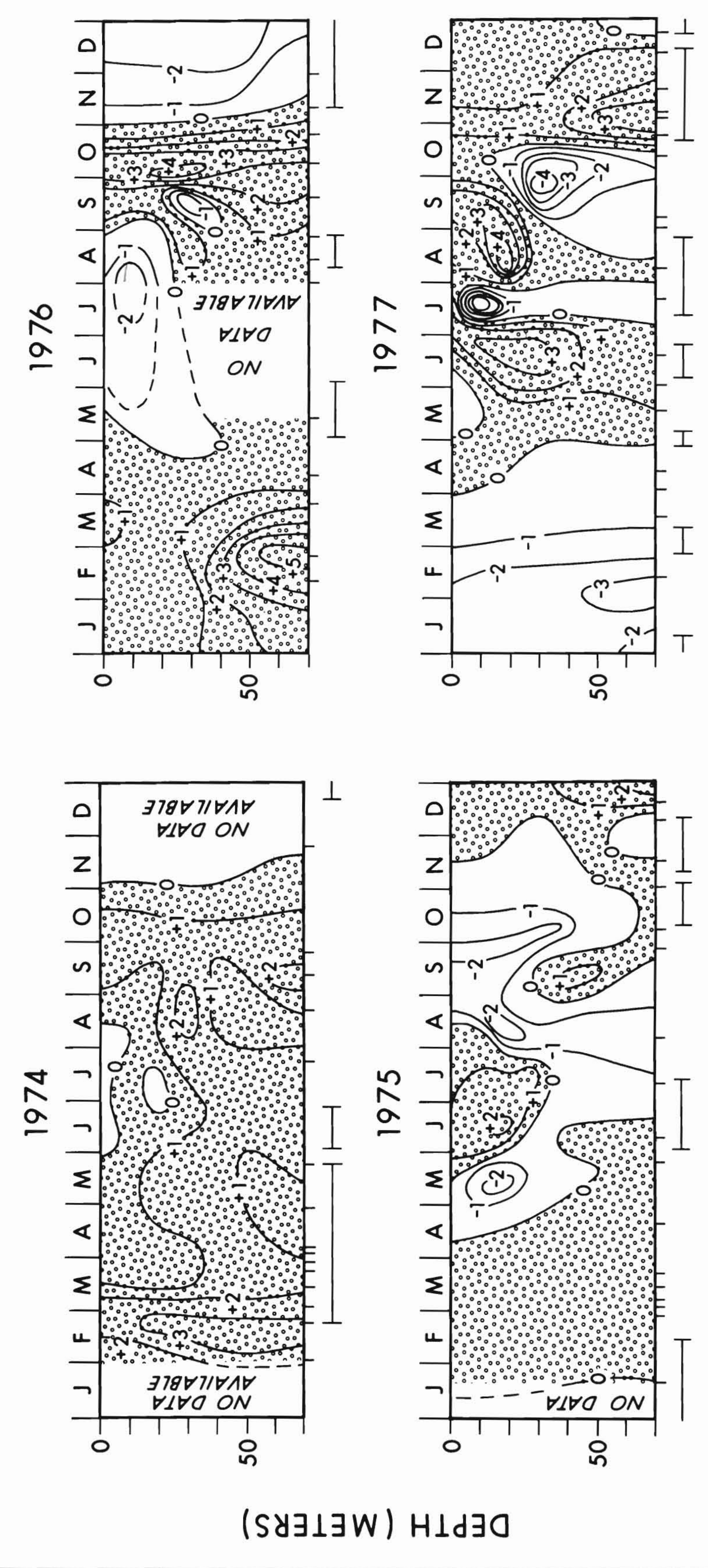

Figure 2

Anomalies (°C) in water-column temperature structure, referenced to the 10-yr mean annual cycle (Fig. 1), for each year, 1974–83. Along the bottom of the graphs are indicated the times of vertical sections of expendable bathythermograph (XBT) data used (tick marks) and the presence and duration in the slope water of Gulf Stream warm-core rings (horizontal bars). Shaded regions are warmer (positive anomaly) than the 10-yr mean.

maximum bottom temperature of the decade (Table 1). During the cold water conditions prevailing during the winter and spring of 1982 (Fig. 2), an intrusion of slope water with a warm-core ring (Crist and Armstrong, 1985) brought anomalously warm water onto the bottom, raising bottom temperatures from about 3°C in March to over 10°C in April.

Other significant events in the annual anomaly diagrams occurred in the summers of 1980, 1982, and 1983. During summer the meridional component of mean monthly wind stress was typically northward; however, in August 1980 and June–August 1983, the meridional component was southward, resulting in westward Ekman transport (Ingham, 1998). During both periods, air temperatures were warmer than average (Wood, 1998), but water temperatures were cooler than 10-yr means, particularly in upper layers (Fig. 2, 1980 and 1983). The water temperature anomalies may have derived from wind-driven transport of cooler water from the east. The largest water temperature anomaly (–6°C) of the 10 years occurred in surface waters in June 1982 (Fig. 2), associated with one of the coldest Junes in air temperature of the century (Wood, 1998). In August 1982, near-bottom waters were more than 4°C warmer than average as the result of an intrusion of slope water from offshore (Crist and Armstrong, 1985).

In general, during 1974 through 1983, temperature anomalies tended to be more consistent from surface to bottom during periods when the waters were unstratified (late fall through winter). Anomalies for waters above and below the thermocline were often of opposite sign during spring and summer, when the water column was stratified. Also, positive or negative anomalies that developed during winter were more likely to persist into spring and summer in sub-thermocline waters than in surface waters.

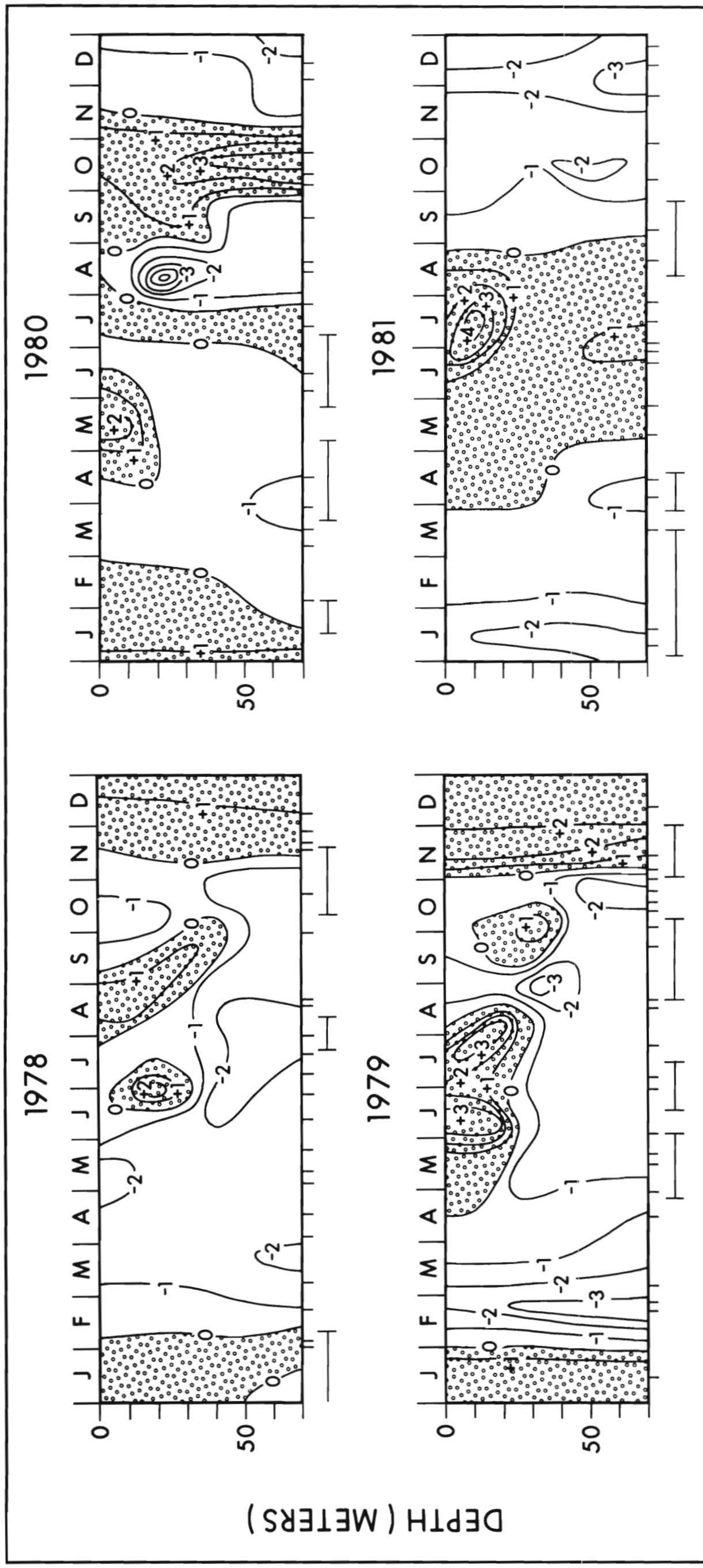

Figure 2 (cont.)
Anomalies (°C) in water column temperature structure.

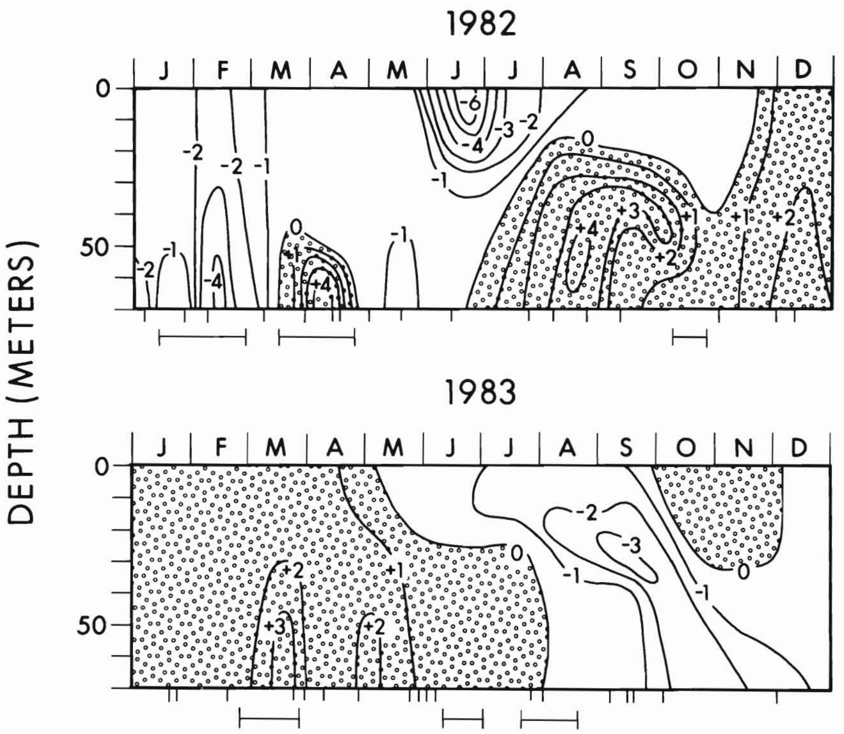

Figure 2 (cont.)
Anomalies (°C) in water column temperature structure.

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Maximum and Minimum Bottom Temperatures on the Continental Shelf and Upper Slope

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Introduction

Herein I present an analysis of maximum and minimum bottom temperatures across the continental shelf and slope south of New England, from the shore to 200 m depth, for 1974–83. I utilize the same data used by Armstrong (1998). Complementing the analyses in Armstrong (1998), Cook (1998), and Wood (1998), this examination provides an additional perspective on the temperature regime of the fishing grounds south of New England. The significance to fisheries research of temperature extremes, and some examples of the utility of this information in fisheries ecology, are discussed in Chamberlin (1998).

Data and Methods

Annual Maximum and Minimum Temperatures and Dates of Occurrence

For each year, 1974–83, maximum and minimum water temperatures on the bottom, and their dates of occurrence, were determined for each 10-m interval of bottom depth from values derived by Armstrong (1998) from bottom temperature diagrams for each year. The diagrams were based on vertical temperature sections from expendable bathythermograph drops along and near 71°W longitude. Armstrong (1998) interpolated bottom temperatures for each 10-day period and each 10-m increment of bottom depth from the coast (0-m bottom depth) to the 200-m isobath.

Ten-Year Maximum and Minimum Temperatures and Dates of Occurrence

From the mean temperatures at 10-day, 10-m bottom depth intervals derived by Armstrong (1998), the 10-yr maximum and minimum water temperatures and dates of occurrence were determined for each 10-m depth increment.

Range of Maximum and Minimum Temperatures and Lengths of Warming and Cooling Seasons

From the interpolated values compiled for each year, the 10-yr ranges in annual maximum and minimum and the range in days between the earliest and latest occurrences of annual maximum and minimum were calculated for each 10-m increment of depth along the bottom. For each depth interval, I calculated differences between the maximum and minimum in the 10-yr mean annual cycle, and between the warmest and coldest values throughout the ten years. In addition, the length of the warming and cooling seasons at each bottom depth interval was determined as the number of days between the maximum and the minimum.

Maximum and Minimum Bottom Temperatures

Ten-year extreme maximum and minimum temperatures at each 10-day, 10-m grid point were determined.

Results

The patterns of maximum and minimum bottom temperatures in the 10-yr mean annual cycle, and the variability in magnitude of extremes and dates of occurrence during the ten years are depicted by graphs (Fig. 1–5) in which bottom conditions are plotted against depth from the coast (0-m bottom depth) to the 200-m isobath.

A principal feature of maximum and minimum mean bottom temperatures (Fig. 1) is the general decrease in

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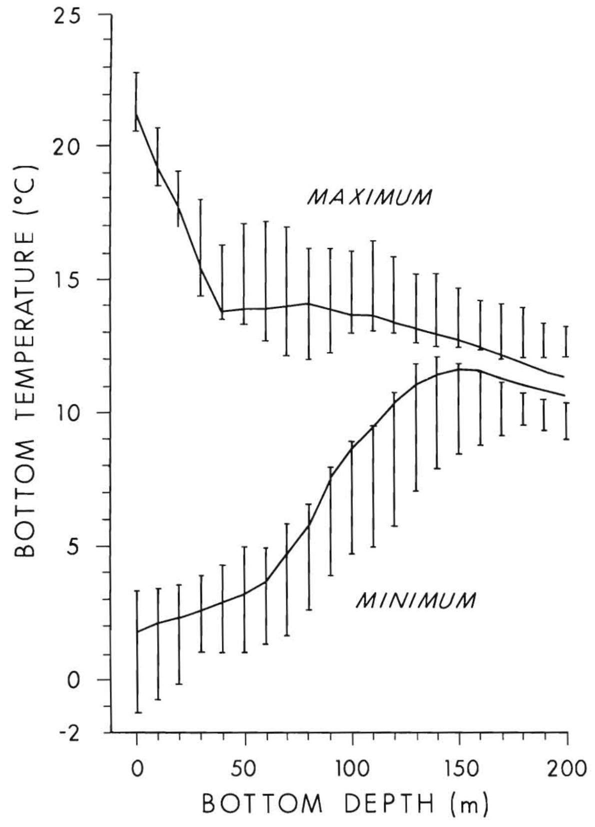

Figure 1
Ten-year (1974–83) maximum and minimum bottom temperatures (°C) on the shelf and upper slope south of New England. Curves represent the 10-yr mean annual cycle; vertical bars indicate the range of extreme values over the 10 years.

the maximum and increase in the minimum with depth, with a corresponding decrease in annual range from 19.5°C at the shore to less than 1°C below 150 m (Fig. 2). Also prominent in Figure 1 is the marked contrast between maximum and minimum curves in rate of change of bottom temperature with depth. A steep linear decrease (7.5°C) of the maximum from the shore to 40 m corresponds with the depth range over which the seasonal thermocline intersects bottom. The more gradual, near-linear rise (1.8°C) in the minimum from shore to 60 m reflects the mixed-water column in the cold season. Maximums were nearly constant from 40 to about 100 m, followed by a gradual and uniform decrease of 2.2°C from 100 to 200 m. Minimum bottom temperatures display a gradual and nearly linear increase (1.8°C) from the shore to 60 m, followed by a steep ascent (8.0°C) from 60 to 150 m. At depths greater than 150 m, minimum bottom temperatures decrease with increasing depth, and generally parallel the maximum curve.

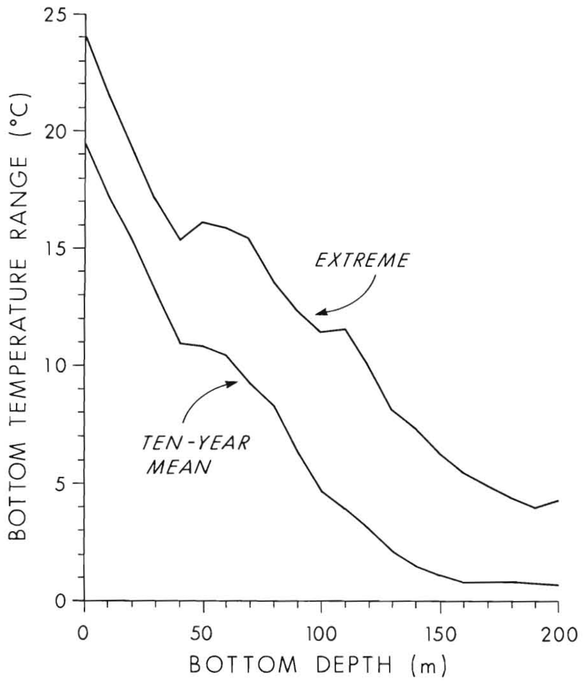

Figure 2
Ranges of bottom temperature extremes plotted in Figure 1. The lower curve represents the 10-yr mean annual cycle; the upper curve represents 10-yr extremes.

Beyond midshelf, the pattern of ranges in extreme bottom temperatures is increasingly dissimilar from the pattern shown by the mean extremes (Fig. 1). The particularly high maximum (17°C) from 50 to 70 m resulted from above-normal bottom warming during the autumn overturn in October 1980 (Armstrong, 1998, Fig. 5; Cook, 1998, Fig. 3). This is also reflected in the increased range of extreme bottom temperatures at 50–70 m (Fig. 2). From 100 to 140 m, the large ranges in the minimum are largely the result of the record cold winters of 1977, 1978, and 1979, as discussed in Armstrong (1998). At depths greater than 150 m, maximum and minimum bottom temperatures are often outside the range of extremes (Fig. 1). In shallower waters, extremes generally occur around the times of maximum and minimum temperature in the 10-yr mean annual cycle. However, at depths greater than 150 m, extremes are typically associated with short-period events (such as the passage of warm-core rings) which could occur at almost any time of the year. Fluctuations in bottom temperature stemming from these irregular events dominate the seasonal signal in the 10-yr means.

The times of year of both maximum and minimum bottom temperature on the shelf tend to occur later with increasing depth (Colton and Stoddard, 1973; Bowman and Wunderlich, 1976). The 10-yr maximum occurs progressively later with increasing depth along the bottom over the entire depth range from 0 to 200 m, with the steepest gradient in date of occurrence on the inner shelf (Fig. 3).

The time lag with depth for 10-yr minimum is less regular than for the maximum (Fig. 3). There is only a 1-mo lag from 0 to 70 m, followed by an increase in rate of lag between 70 and 90 m. Dates for the minimum are about the same from 100 to 150 m, but there is a 3-mo lag between 150 and 160 m. From 160 to 200 m, there is a 15-day lag. At 160 m depth, there are two dates for the 10-yr minimum: one in April continuing the progression of dates in shelf water, and the second in July, associated with the time of the minimum in slope water.

At 200-m bottom depth, the seasons are essentially reversed from coastal conditions. The 10-yr maximum occurs in late January, about 180 days (5.9 mo) later than at the coast, while the minimum is in early August, about 175 days (5.8 mo) later than at the coast.

The seasonal bottom temperature cycle at 170–200 m is of small range (<1°C) and is overshadowed by short-term, nonseasonal temperature variations (Fig. 1). This is reflected in the large range in date of annual maximum and minimum (Fig. 3).

Three distinct patterns in the length of warming and cooling seasons along the bottom (Fig. 4) reflect the differences between times of maximum and minimum bottom temperatures. At the coast, warming and cooling seasons were each about 6 mo; the period of warming increased with depth to more than 8 mo at midshelf (60–70 m). The warming season lasted about 7.5 mo at 80–90 m, increasing to almost 9 mo at 160 m, with corresponding decreases in period of cooling. In slope water at 160–200 m, the warming and cooling seasons were each about 6 mo long, as at the coast. However, seasons in the slope water were essentially reversed from those at the coast.

The contour diagrams in Figure 5 present extreme maximum and minimum bottom temperatures, regardless of year of occurrence, for each 10-day/10-m increment of bottom depth. The largest differences in maximum and minimum temperatures were over the mid- to outer continental shelf, at bottom depths of 60 to 110 m, with the ex-

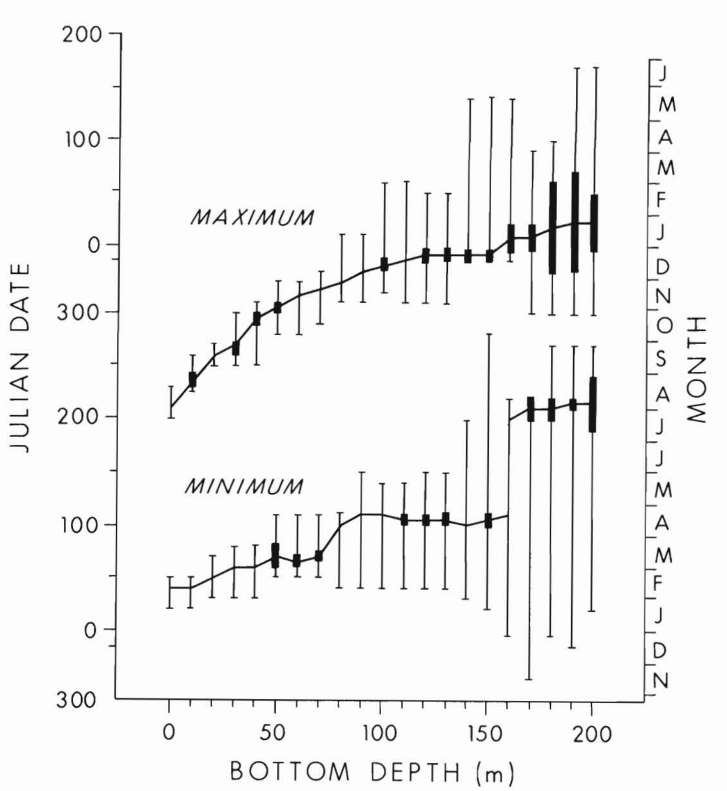

Figure 3

Ten-year (1974–83) maximum and minimum bottom temperatures on the shelf and upper slope south of New England. The curves connect dates of maximum (upper) and minimum (lower) temperatures in the 10-year mean annual cycle. Vertical lines are the ranges of dates throughout the ten years. Vertical bars appear when the same mean maximum or minimum temperature occurred on multiple dates.

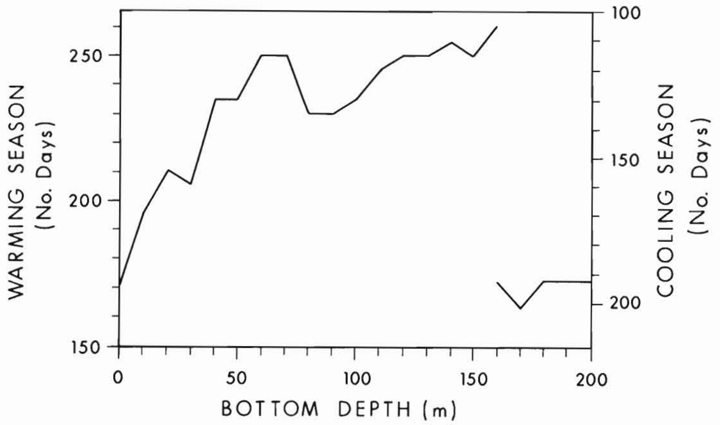

Figure 4

Length of warming and cooling seasons on the bottom on the shelf and upper slope south of New England. Values are differences in date of occurrence of minimum and maximum bottom temperatures in the 10-yr mean annual cycle, 1974–83 (Fig. 3).

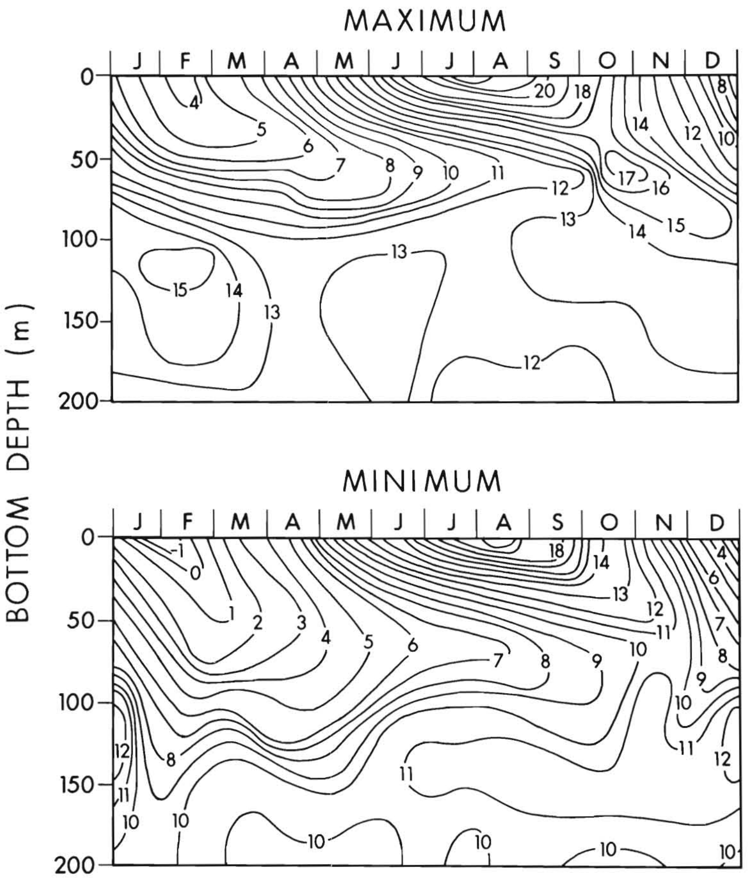

Figure 5
Extreme maximum and minimum bottom water temperatures (°C) on the shelf and upper slope south of New England, 1974–83.

treme difference of more than 9°C at 110 m in February. Major differences between the extreme maximum and minimum occurred on the outer shelf and were associated with the contrast between cold bottom conditions in winter 1977 and spring–summer following the cold winter of 1978; and warm conditions on the bottom in the winters or early springs of 1975, 1976, and 1982 (Armstrong, 1998).

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Mean Monthly Wind Stress and Ekman Transport Conditions

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Introduction

The ocean surface layer is strongly influenced by highly variable wind conditions immediately above the surface. Mixing, evaporation, cooling, and transport are all heavily dependent on the winds. I analyzed wind velocity, wind stress, and Ekman transport conditions for a point representative of the midshelf (70-m isobath) south of New England, near 70°W.

Data

The Pacific Fisheries Environmental Group (PFEG) of the National Marine Fisheries Service utilizes the computers and databases of the Fleet Numerical Oceanography Center in Monterey, California to compute wind stress, Ekman transport, and several other parameters from surface atmospheric pressure records (see Bakun, 1973, for methods). PFEG issues a monthly list which includes mean wind-stress components and Ekman transport components on a 3° grid. I utilized data for the grid point at 39°N 72°W, located in slope water about 230 km south of Montauk Point, Long Island. Because the computations of wind stress and Ekman transport at a point depend on computed pressure-field gradients in the surrounding area, the stress and transport values for a point are representative of this area. The area represented by 39°N 72°W extends about 150 km (half the distance to the next grid point) in all directions, and northward nearly to the 70-m isobath on the shelf off southern New England (Fig. 1).

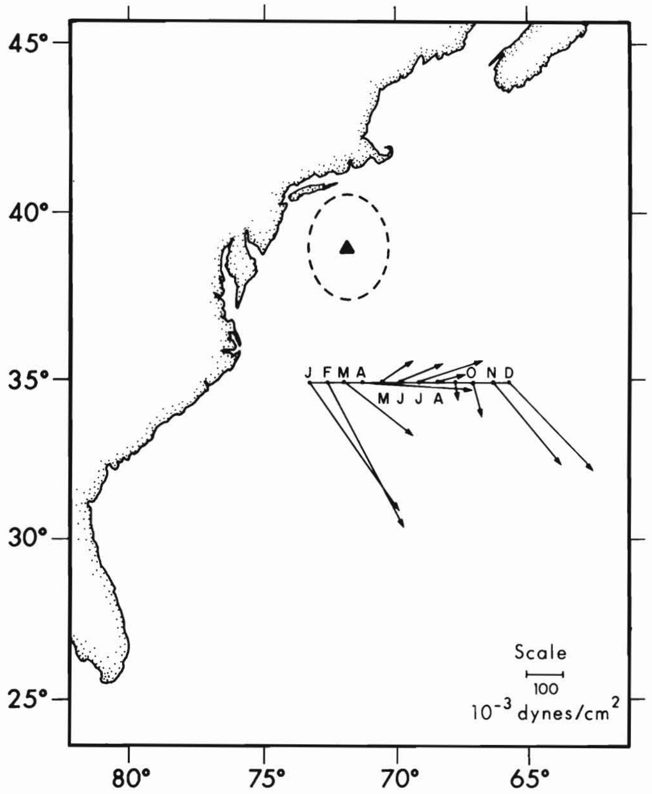

Figure 1
Ten-year (1974–83) mean monthly wind stress (in 10^{-3} dyne/cm^2) off southern New England. Vectors shown are for stress values at 39°N 72°W (triangle) and are representative of the area encompassed by the dashed line.

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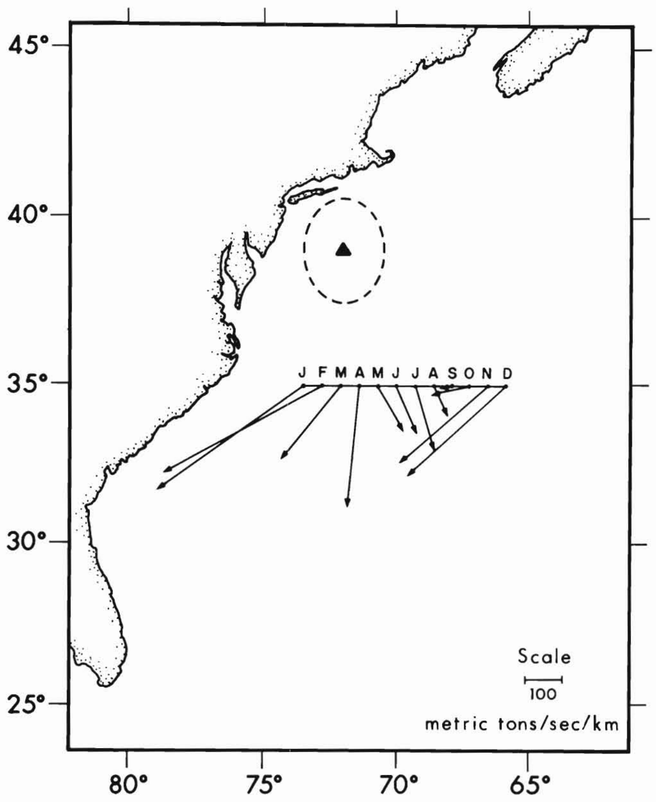

Figure 2
Ten-year (1974–83) mean monthly Ekman transport (in metric ton/sec · km) off southern New England. Vectors shown are for transport values at 39°N 72°W (triangle) and are representative of the area encompassed by dashed line.

Table 1
Ten-year (1974–83) monthly means and standard deviations (SD) of wind stress components at 39°N 72°W (10^{-3} dynes/cm^2).

Month	Meridional 10-yr mean	Meridional SD	Zonal 10-yr mean	Zonal SD	Month	Meridional 10-yr mean	Meridional SD	Zonal 10-yr mean	Zonal SD
Jan	–357.1	285.6	+261.0	230.2	Jul	+ 47.5	50.5	+158.2	96.6
Feb	–404.6	374.7	+206.8	239.8	Aug	+ 24.4	48.0	+ 70.8	46.2
Mar	–141.4	205.4	+176.4	194.4	Sep	– 23.5	35.7	+ 5.9	34.6
Apr	–19.9	159.1	+293.5	209.7	Oct	– 93.1	95.4	+ 17.5	71.0
May	+ 49.8	89.5	+ 87.3	93.4	Nov	–219.9	227.6	+188.4	211.7
Jun	+ 42.5	56.9	+110.3	107.5	Dec	–235.2	165.2	+222.0	187.6

Mean monthly wind stress, Ekman transport, and wind velocity vectors for 1974–83 were computed and plotted (Fig. 1, 2, 3) to establish general seasonal patterns. Wind stress and Ekman transport data were taken directly from the PFEG lists. Wind velocity was back-calculated from wind stress using relations in Bakun (1973, p. 3).

Monthly means and standard deviations were computed for meridional and zonal components of wind stress for the 10-yr period (Table 1, Fig. 4, 5). Anomalies from monthly means were computed for each month of the 10-yr period (Fig. 6, 7). Monthly anomalies (in standard deviations for each month) were computed; those months showing an anomaly more than one standard deviation from the mean in either or both components are listed in Table 2. Monthly mean values of wind stress components, wind stress anomalies,

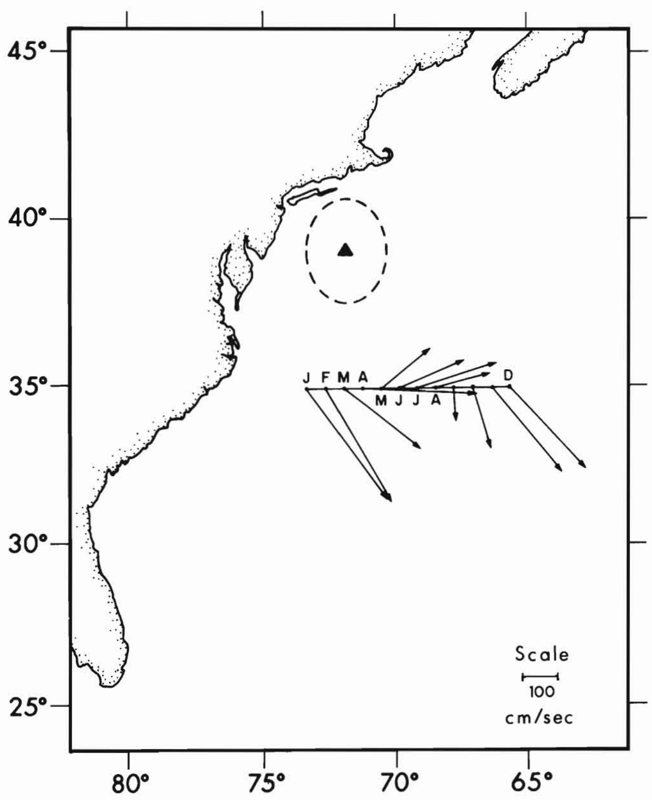

Figure 3

Ten-year (1974–83) mean monthly computed surface wind velocity (in cm/sec) off southern New England. Vectors shown are for values at 39°N 72°W (triangle) and are representative of the area encompassed by dashed line.

Table 2

Anomalies greater than one standard deviation from 10-yr monthly mean wind stress components (meridional or zonal) at 39°N 72°W. (Anomaly values are in standard deviations).

Date	Anomaly		Date	Anomaly		Date	Anomaly		Date	Anomaly	
(YYMM)	Meridional	Zonal	(YYMM)	Meridional	Zonal	(YYMM)	Meridional	Zonal	(YYMM)	Meridional	Zonal
7401	1.02	–0.85	7702	0.97	1.36	7904	0.06	–1.12	8104	2.53	1.38
7406	–2.24	–1.18	7705	–1.01	0.57	7905	1.03	–0.20	8109	–1.69	2.37
7410	–1.10	0.44	7707	–0.56	–1.12	7910	1.32	2.09	8111	–2.31	0.04
7502	1.94	–0.29	7708	0.72	2.06	8001	–1.22	–0.84	8112	–2.44	1.55
7504	–2.59	1.08	7712	1.25	–0.86	8004	0.95	–1.07	8204	–0.13	1.08
7508	–1.05	0.07	7801	1.10	1.36	8006	0.83	1.80	8209	–0.55	–1.12
7512	0.36	–1.02	7802	–1.01	–0.31	8007	2.09	1.84	8210	–1.95	–1.49
7602	1.79	2.03	7805	–0.20	–1.01	8010	–1.10	–1.08	8301	–0.14	–1.25
7605	1.94	1.84	7806	0.99	1.38	8011	–0.43	1.05	8302	–0.69	–1.50
7606	2.28	0.17	7809	–1.44	–1.04	8101	–1.27	0.53	8304	0.48	–1.03
7609	1.16	0.96	7811	0.07	–1.38	8102	1.26	–0.83	8305	1.41	1.48
7701	–1.74	2.52	7812	0.19	1.82	8103	–2.89	2.53	8307	–1.71	1.52

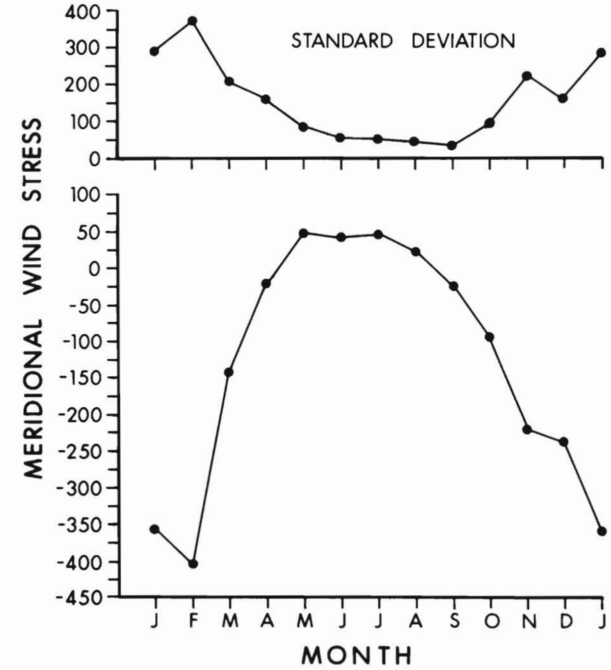

Figure 4
Ten-year (1974–83) mean and standard deviation of monthly meridional wind stress (+ northward) in 10^{-3} dyne/cm^2, off southern New England in the vicinity of 39°N 72°W.

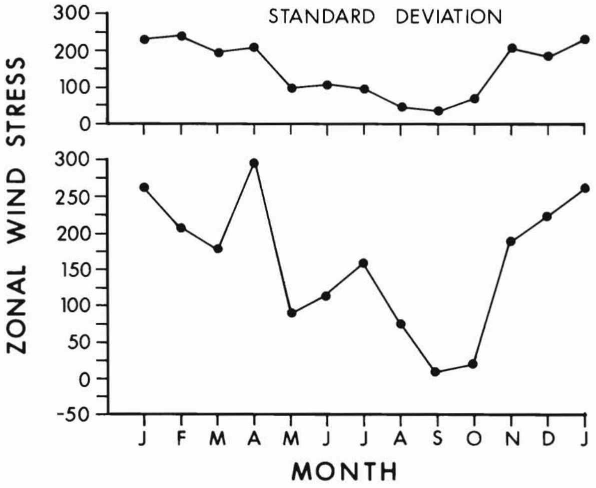

Figure 5
Ten-year (1974–83) mean and standard deviation of monthly zonal wind stress (+ eastward) in 10^{-3} dyne/cm^2, off southern New England in the vicinity of 39°N 72°W.

and Ekman transport components are presented in Table 3.

Results

Plots of wind stress and wind velocity (Fig. 1, 3) show the commonly recognized (e.g., Meserve, 1974; Williams and Godshall, 1977; Beardsley and Boicourt, 1981) seasonal patterns off southern New England: northwesterly winds during all but the summer months, when southwesterly winds prevail. The Ekman transport vectors (Fig. 2) show a similar seasonal progression but 90° to the right of the wind stress vectors.

Examples of the linkage between windfield variation and water column changes can be found most readily by examining the most anomalous winter windfield conditions. One rather long (8-mo) period of negative anomalies in zonal wind stress was September 1982–April 1983 (Fig. 7, Table 3). The largest anomalies in this period occurred in January–February 1983, when normal eastward wind stresses were replaced by strong westward components (Table 3). Bottom water temperature anomalies along 71°W during September–March (Armstrong, 1998) were positive inshore of 100 m depth, probably because of the reduction in seasonal wind-caused cooling.

Another multi-month period of anomalies in zonal wind stress occurred in November 1976–March 1977, when there were relatively strong positive anomalies (Fig. 7). In January and February 1977, these anomalies were 2.52 and 1.36 standard deviations, respectively, from the monthly means (Table 2). This period of unusually strong westerly winds also was noted in an analysis of wind stress data from eleven grid points in the northwestern Atlantic during the 1970's (Ingham, 1982). During this time period, there were also record cold air temperatures in the middle Atlantic states, and bottom water temperature anomalies along 71°W (Armstrong, 1998) were negative, especially during January and February 1977, when they were strongly negative from the coast to beyond the 200-m isobath. Similarly, water column temperatures at mid-shelf were generally cooler than average from surface to bottom (Cook, 1998). The low water temperatures resulted from the cooling effect of unusually strong, eastward wind stresses (cold, westerly and northwesterly winds).

Mean summer wind stresses (Fig. 1) show northward components (southerly winds), but in August 1980 and June–August 1983 the meridional components were southward instead (Table 3). Coincident with these unusual wind stresses, water temperatures at midshelf, especially in the upper water column, were unusually cool (Cook, 1998). The southward wind stress components may have caused a westward transport (Ekman transport) of cooler water from Nantucket Shoals to 71°W.

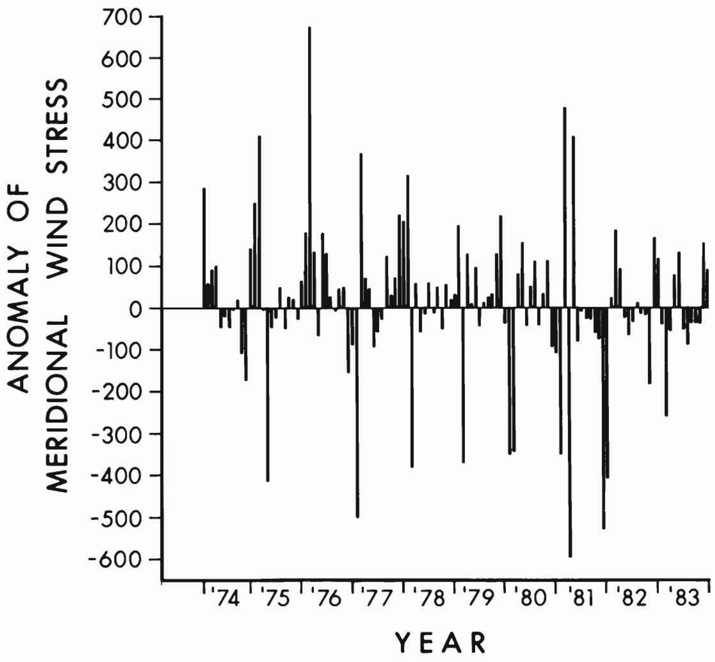

Figure 6
Monthly anomalies from 10-yr (1974–83) mean meridional wind stress (+ northward) in 10^{-3} dyne/cm^2, off southern New England in the vicinity of 39°N 72°W.

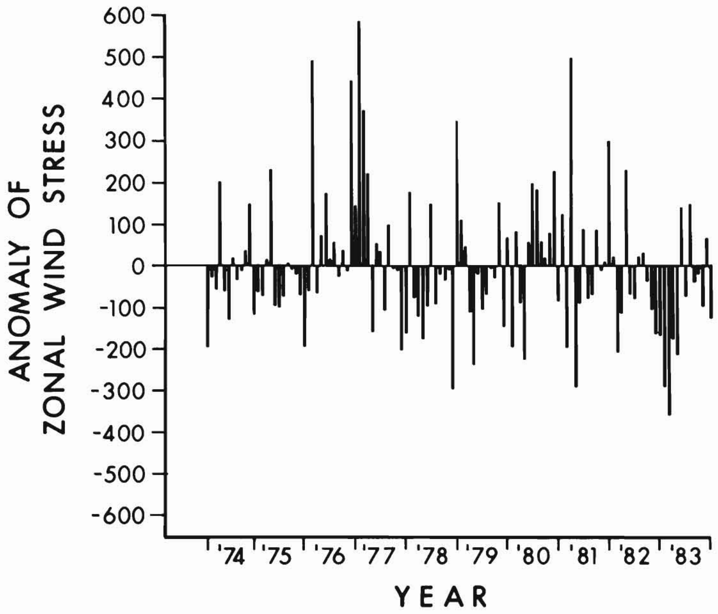

Figure 7
Monthly anomalies from the 10-yr (1974–83) mean zonal wind stress (+ eastward) in 10^{-3} dyne/cm^2, off southern New England in the vicinity of 39°N 72°W.

Table 3

Monthly mean computed wind stress components (10^{-3} dynes/cm^2), wind stress anomalies from 10-yr means, and computed Ekman transports (× 10 metric tons/sec · km) in the vicinity of 39°N 72°W, south of New England. Positive values northward (meridional) or eastward (zonal).

Date (YYMM)	Stress		Stress Anomaly		Ekman Transport	
	Meridional	Zonal	Meridional	Zonal	Meridional	Zonal
7401	–67	66	290.1	–195.0	–7	–8
7402	–431	179	53.6	–27.8	–20	–47
7403	–53	123	88.4	–53.4	–13	–6
7404	77	491	96.9	197.5	–54	8
7405	0	28	–49.8	–59.3	–3	0
7406	23	–17	–19.5	–127.3	2	2
7407	0	174	–47.5	15.8	–19	0
7408	19	35	–5.4	–35.8	–4	2
7409	–11	–2	12.5	–7.9	0	–1
7410	–198	49	–104.9	31.5	–5	–22
7411	–392	330	–172.1	141.6	–36	–43
7412	–97	103	138.2	–119.0	–11	–21
7501	–108	201	249.1	–60.0	–22	–12
7502	–84	137	400.6	–69.8	–15	–9
7503	–143	189	–1.6	12.6	–21	–16
7504	–432	521	–412.1	227.5	–57	–47
7505	4	–3	–45.8	–90.3	0	0
7506	20	11	–22.5	–99.3	–1	2
7507	96	186	48.5	–72.2	–9	10
7508	–26	74	–50.4	3.2	–8	–3
7509	0	–2	23.5	–7.9	0	0
7510	–78	–1	15.1	–18.5	0	–9
7511	–48	119	–28.1	–69.4	–13	–5
7512	–175	31	60.2	–191.0	–3	–19
7601	–177	204	180.1	–57.0	–22	–19
7602	186	694	670.6	487.2	–76	20
7603	–10	113	131.4	–63.4	–12	–1
7604	–87	366	–67.1	72.5	–40	–10
7605	223	259	173.2	171.7	–28	24
7606	172	129	129.5	18.7	–14	19
7607	72	216	24.5	57.8	–24	8
7608	21	45	–3.4	–25.8	–5	2
7609	18	39	41.5	33.1	–4	2
7610	–49	16	44.1	–1.5	–2	–5
7611	–375	630	–155.1	441.6	–69	–41
7612	–324	364	–88.1	142.0	–40	–35
7701	–853	842	–495.9	581.0	–92	–93
7702	–118	534	366.6	327.2	–58	–13
7703	–72	398	69.4	221.6	–44	–8
7704	22	133	41.9	–160.5	–15	2
7705	–41	141	–90.8	53.7	–15	–4
7706	–14	144	–56.5	33.7	–16	–2
7707	19	50	–28.5	–108.2	–5	2
7708	143	166	118.6	95.2	–18	16
7709	0	1	23.5	–4.9	0	0
7710	–23	6	70.1	–11.5	–1	–2
7711	2	–14	221.9	–202.4	2	0
7712	–28	61	207.2	–161.0	–7	–3
7801	–44	234	313.1	173.0	–26	–5
7802	–863	133	–378.4	–73.8	–14	–94
7803	–82	52	59.4	–124.4	–6	–9
7804	–81	117	–61.1	–176.5	–13	–9
7805	32	–7	–17.8	–94.3	1	3

continued

Table 3 (continued)

Date	Stress		Stress Anomaly		Ekman Transport	
(YYMM)	Meridional	Zonal	Meridional	Zonal	Meridional	Zonal
7806	99	259	56.5	147.8	–28	11
7807	36	68	–11.5	–90.2	–7	4
7808	66	52	41.6	–18.8	–6	7
7809	–75	–30	–51.5	–35.9	3	–8
7810	–41	9	52.1	–8.5	–1	–5
7811	–203	–104	16.9	–292.4	11	–22
7812	–204	564	31.2	342.0	–62	–22
7901	–164	367	193.1	106.0	–40	–18
7902	–855	248	–370.4	41.2	–27	–93
7903	–6	62	135.4	–114.4	–7	–1
7904	–11	58	8.9	–235.5	–6	–1
7905	142	69	92.2	–18.3	–7	16
7906	0	7	–42.5	–103.3	–1	0
7907	59	90	11.5	–68.2	–10	6
7908	46	67	21.6	–3.8	–7	5
7909	7	–20	30.5	–25.9	2	1
7910	33	166	126.1	148.5	–18	4
7911	–5	40	214.9	–148.4	–4	–1
7912	–273	288	–37.8	66.0	–31	–30
8001	–707	68	–349.9	–193.0	–7	–77
8002	–823	287	–338.4	80.2	–31	–90
8003	–64	93	77.4	–83.4	–10	–7
8004	131	69	150.9	–224.5	–7	14
8005	9	139	–40.8	51.7	–15	1
8006	90	304	47.5	193.7	–33	10
8007	153	336	105.5	177.8	–37	17
8008	–18	128	–42.4	57.2	–14	–2
8009	9	25	32.5	19.1	–3	1
8010	12	94	105.1	76.5	–10	–1
8011	–317	410	–97.1	221.6	–45	–35
8012	–347	142	–111.8	–80.0	–15	–38
8101	–720	382	–362.9	121.0	–42	–79
8102	–11	8	473.6	–198.8	–1	–1
8103	–735	669	–593.6	492.6	–73	–80
8104	167	583	402.2	289.5	–64	18
8105	–31	0	–80.8	–87.3	0	–3
8106	41	193	–1.5	82.7	–21	4
8107	24	78	–23.5	–80.2	–8	3
8108	–5	2	–29.4	–68.8	0	–1
8109	–84	88	–60.5	82.1	–10	–9
8110	–179	5	–85.9	–12.5	0	–20
8111	–746	196	–526.1	7.6	–21	–81
8112	–639	513	–403.8	291.0	–56	–70
8201	–335	274	22.1	13.0	–30	–37
8202	–302	1	182.6	–205.8	–0	–33
8203	–50	67	91.4	–109.4	–7	–6
8204	–41	519	–21.1	225.5	–57	–4
8205	–16	21	–65.8	–66.3	–2	–2
8206	6	34	–36.5	–76.3	–4	1
8207	55	179	7.5	20.8	–20	6
8208	10	101	–14.4	30.2	–11	1
8209	–43	–33	–19.5	–38.9	4	–5
8210	–279	–88	–185.9	–105.5	10	–30
8211	–52	256	167.9	–163.4	–3	–6
8212	–121	57	114.2	–165.0	–6	–13
8301	–396	–28	–38.9	–289.0	3	–43

continued

Table 3 (continued)

Date (YYMM)	Stress		Stress Anomaly		Ekman Transport	
	Meridional	Zonal	Meridional	Zonal	Meridional	Zonal
8302	–745	–151	–260.4	–359.8	17	–81
8303	–199	–2	–57.6	–178.4	0	–22
8304	56	78	75.9	–215.5	–8	6
8305	176	226	126.2	138.7	–25	19
8306	–12	39	–54.5	–71.3	–4	–1
8307	–39	305	–86.5	146.8	–33	–4
8308	–12	38	–36.4	–32.8	–4	–1
8309	–56	–7	–32.5	–12.9	1	–6
8310	–129	–81	–35.9	–98.5	9	–14
8311	–63	252	156.9	63.6	–28	–7
8312	–144	97	91.2	–125.0	–11	–16

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Variations in the Shelf–Slope Front and the Influence of Warm-core Gulf Stream Rings

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Introduction

Variations in the position of the shelf–slope front and interactions of anticyclonic, warm-core Gulf Stream rings with shelf waters can introduce major changes in currents and water masses over the outer continental shelf and upper slope (Morgan and Bishop, 1977; Ingham et al., 1982) and, at times, the midshelf (Crist and Chamberlin, 1979). Because of the different origins and water mass characteristics of shelf and slope water, the front represents an ecological boundary for living marine resources. Shifts in the front's location may expose marine organisms, particularly bottom-dwelling organisms, to unusual or stressful environmental conditions. Also, since ocean fronts are typically regions of convergent flow, the shelf–slope front may be an area where drifting plankton accumulate, and therefore a region where foraging pelagic fish (Ingham, 1976) and marine mammals (Waring et al., 1993) concentrate.

The shelf–slope front is the permanent boundary that separates less saline and usually cooler shelf water from slope water. On the east coast of the United States, the front is located over or near the outer edge of the continental shelf, is continuous from Cape Hatteras, North Carolina, to Georges Bank, and is present throughout the year. It extends from the surface to the bottom, sloping so that the surface expression is located about 25 to 55 km seaward of the bottom contact (Beardsley and Flagg, 1976). The horizontal salinity gradient across the front is usually about 1 to 2 parts per thousand; the horizontal temperature gradient at the bottom is about 2°–4°C and at the surface is 4°–6°C (Bowman and Wunderlich, 1977). Wright (1976) examined seasonal variation in the position of the front off southern New England and found that the bottom contact was usually near the 100-m isobath, shifting shoreward in fall. At the surface, the front's position was more variable, ranging from 52 km seaward of the 100-m isobath in winter to 72 km seaward of the isobath in late summer (Wright, 1976). Both short-term and seasonal excursions of the front of more than 100 km at the surface off southern New England have been reported (e.g., Armstrong, 1985) and have been attributed to a variety of oceanographic and meteorologic influences. As the front shifts shoreward, shelf water is replaced by usually warmer and more saline slope water. With seaward shifts in the front, shelf water may be carried off the continental shelf.

Warm-core rings are large, anticyclonic eddies that occur in slope water and are formed from Gulf Stream meanders that develop on the shoreward side of the Gulf Stream. When warm-core rings approach the continental shelf, large volumes of shelf water may be removed by entrainment in the circulation of the ring (Bisagni, 1983), and slope water and modified Gulf Stream water may be injected onto the shelf (Chamberlin, 1982), with both processes producing displacements in the position of the shelf–slope front. Warm-core rings are about 200 km in diameter at the surface, extend to depths of at least 2,000 m, and include currents as high as 140 cm/sec (Cheney, 1978). Typically, the rings drift westward and southwestward through the slope water off southern New England.

I compiled data on the monthly positions of the shelf–slope front at the surface and along the bottom and on the presence of warm-core rings in waters off southern New England for ten years, 1974–83, to describe average annual cycles and variability.

Data and Methods

The strong thermal gradients at the surface associated with the shelf–slope front and with warm-core rings, and with interactions of rings with adjacent water masses,

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are often apparent in satellite infrared data and imagery. The presence of warm-core rings off southern New England during 1974–83 was determined from annual reports of bottom temperature, as presented in Armstrong (1998), based on interpretations of satellite infrared data. Warm-core ring passages were recorded as time of year and duration of each ring's presence along the 71°W meridian. To examine the possibility of a seasonal tendency in the occurrence of warm-core Gulf Stream rings, the number of years during the 10-yr period in which rings were present along 71°W on a given Julian Day were summed and plotted against time of year (Fig. 1).

Monthly mean positions of the shelf–slope front at the surface (Fig. 1) were computed from weekly determinations of the front compiled in annual summary reports, 1974–83 (Ingham, 1976; Gunn, 1978, 1979a, b; Hilland and Armstrong, 1980; Hilland, 1981, 1983; Armstrong, 1984, 1985, 1986). For the annual reports, frontal locations along twelve bearings from Cape Romain, South Carolina, to eastern Georges Bank were determined from weekly satellite-derived charts. This analysis employed weekly positions for the bearing along the 120° azimuth from Montauk Point, because this line was nearest the 71°W meridian employed in the studies of warm-core ring tracks and water temperatures presented in Armstrong (1998), Chamberlin (1998), and Cook (1998). The Montauk Point 120° bearing line crosses the 200-m isobath about 20 km west of 71°W. Because the front is typically located near the shelf break, frontal positions were recorded as departures from the 200-m isobath.

Bottom locations of the shelf–slope front were determined from the vertical cross-sections of temperature from expendable bathythermograph (XBT) transects across the continental shelf and slope on or near 71°W longitude, as described in Cook (1998). On the vertical sections, the intersection of the center of the (usually strong) temperature gradient with the bottom was assumed to represent the offshore boundary of shelf water and was taken to represent the frontal location. Subsurface salinity observations were rarely made on the XBT transects, therefore how accurately this thermal gradient feature represents the shelf–slope front could not be determined. Wright (1976) used the intersection of the 10°C isotherm with the bottom to indicate the bottom contact of the front, but, as he noted, this is not always accurate. For each temperature section, the bottom depth at the frontal location was recorded and plotted against time of year. Mid-month positions, recorded as bottom depth, were derived from these plots.

Derived monthly positions of the shelf–slope front at the surface and along the bottom were averaged, by month, for the 10 yr to determine mean annual cycles and estimates of variability (standard deviation) (Fig. 1).

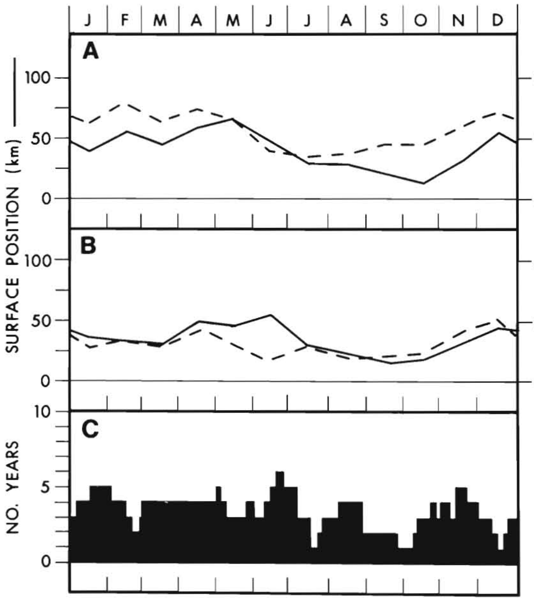

Figure 1
Ten-year (1974–83) average annual cycle and variability of the position of the shelf–slope front at the surface and on the bottom and the presence of Gulf Stream warm-core rings off southern New England. A) Mean position of the front by month. Surface positions are horizontal distances, measured seaward of the 200-m isobath, and bottom contacts are depths of intersection of the front with the bottom. B) Standard deviation of the frontal position, by month. C) Number of years when rings were present in slope water at 71°W longitude: sum of periods of duration of rings by Julian Day (Fig. 2).

Anomalies from the 10-yr monthly means were calculated for each month of the 10-yr period (Fig. 2).

Results

The shelf–slope front was generally farther offshore at the surface and the bottom contact was deeper during winter and spring (Fig. 1A). In late summer and fall, the front was farther shoreward at the surface and in shallower bottom waters. At the surface, the front remained seaward of the 200-m isobath throughout the year and tended to be about 50 km offshore of the 200-m isobath from December through May. From July through November, the front was located farther shoreward, and was about 25 km seaward of the 200-m isobath. Along the bottom, the front was located near the 95-m isobath during the summer and was in deepest water, about 110 m, from December through April. For comparison with the seasonal variation in the position of the front at the surface, the horizontal distance be-

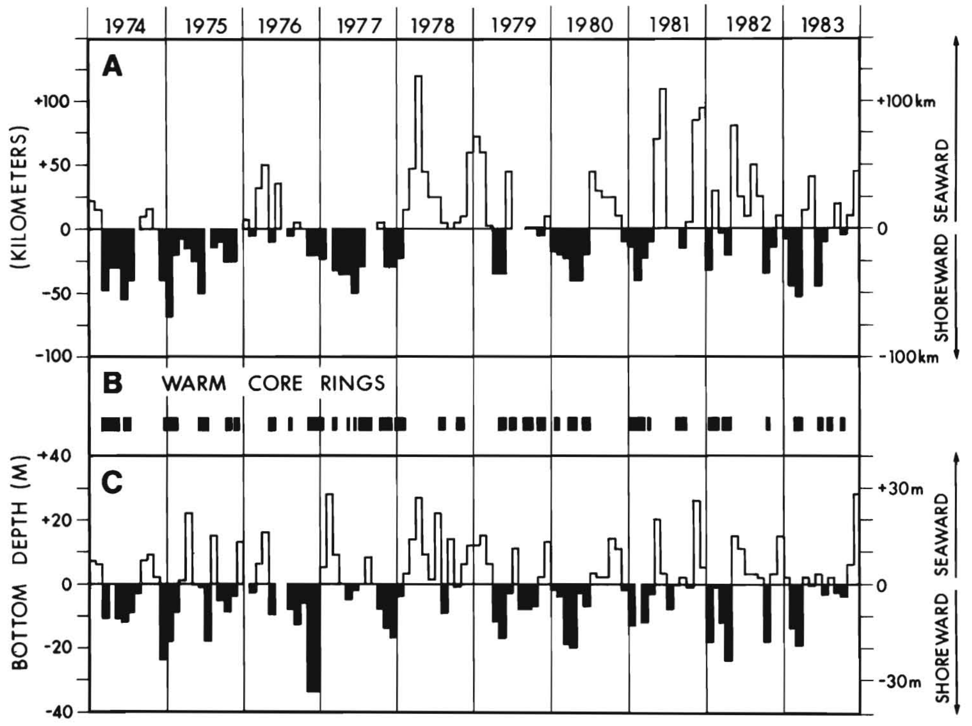

Figure 2

Anomalies in the position of the shelf–slope front off southern New England, 1974–83, relative to the 10-yr monthly means in Figure 1: A) at the surface, in horizontal distance, and C) along the bottom, by bottom depth. Blanks represent absence of data. B) Presence and duration of Gulf Stream warm-core rings at 71°W longitude.

tween the 95- and 110-m isobaths is about 6 km. Averaged for all months of the ten years, the front was located 41 km seaward of the 200-m isobath at the surface and its bottom contact was at 102 m depth (Table 1), i.e., the front sloped so that its location at the surface was about 65 km offshore from its bottom position. These seasonal patterns and positions for the surface and bottom contacts of the front are very similar to those determined for 1941–72 (Wright, 1976).

Variability in the position of the shelf–slope front, expressed as the standard deviation of average monthly frontal position (Fig. 1B), tended to be least in late summer and fall, which was when the front was most shoreward at the surface and in shallowest water on the bottom (Fig. 1A). However, seasonal patterns in frontal positions are somewhat uncertain since the typical standard deviations (±35 km at the surface and ±12 m on the bottom) were comparable in magnitude to seasonal shifts in location of the front. The variation in annual average frontal position during the 10-yr period (Table 1) was similar in magnitude to the 10-yr mean seasonal difference at the surface, although bottom positions were within 5 m of the 99-m isobath in all years except 1978.

A total of 34 warm-core Gulf Stream rings transited the waters off southern New England during 1974–83, with 3 of the rings first appearing near the end of a year and persisting into the beginning of the following year (Table 2). During each year, 3–4 rings were present, except in 1977, when there were 7 rings. The average duration for each ring at the 71°W meridian was about 35 days, ranging from about one week for a ring in 1977 to about three months for a ring in the first half of 1974. Warm-core rings were present off southern New England from as little as 92 days in 1983 to as long as 163 days in 1977, averaging 123 days per year, or about one-third of the time. No distinct seasonal pattern in the presence of warm-core rings was evident, although rings tended to occur less often during late summer and early fall (Fig. 1C), which corresponds to the period of least variability in frontal position (Fig. 1B). They were most often present in late June, when there were rings in six of the ten years.

Anomalies in location of the shelf–slope front at the surface and along the bottom during 1974–83 are shown in Figure 2 as departures from the 10-yr mean monthly position. Also depicted in Figure 2 are the periods

Table 1
Average location of the shelf–slope front at the surface and on the bottom off southern New England during months when warm-core rings were present or absent for each year, 1974–83, and for the decade.

	Surface					Bottom				
		Rings present		Rings absent			Rings present		Rings absent	
	Average location[1] (km)	No. months	Location[1] (km)	No. months	Location[1] (km)	Average location[2] (m)	No. months	Location[2] (m)	No. months	Location[2] (m)
1974	25	5	10	6	45	96	5	94	7	104
1975	14	5	1	5	28	102	6	92	6	111
1976	47	4	24	7	60	94	4	81	5	105
1977	15	8	12	1	25	103	9	99	3	114
1978	68	4	28	8	89	111	4	100	8	116
1979	54	4	38	6	64	103	5	96	7	108
1980	37	4	29	8	41	101	4	93	8	104
1981	62	6	26	6	98	104	5	98	6	109
1982	52	5	35	7	61	101	5	92	7	107
1983	37	5	11	7	56	103	5	95	7	109
Average	41	5	21	6	56	102	5	94	6	109

Note: number of months of values may not sum to 12 in a year because of absence of data for some months.

[1] Surface frontal positions are the horizontal departure of the front from the location of the 200-m isobath, with positive values to seaward.

[2] Bottom frontal positions are the bottom depth of intersection of the front with the bottom.

when warm-core Gulf Stream rings were present in the slope water along 71°W. In general, throughout the 10 yr, excursions of the front at the surface and along the bottom parallel one another. Typically, when the front shifted to offshore of the 10-yr mean monthly position at the surface, the bottom contact was in deeper water; when the front was shoreward of the mean monthly position at the surface, the bottom contact was shallower. However, there were notable exceptions to this pattern. For example, from January through July 1977 (Fig. 2), the front was located shoreward of the 10-yr mean monthly position at the surface, but was generally farther offshore and in deeper water than average, or near the average position, along the bottom. At the surface, the farthest offshore position of the front for the 10 yr was in April 1978 (180 km seaward of the 200-m isobath) and the farthest shoreward position occurred in January 1975 and October 1982 (20 km shoreward of the 200-m isobath). Extremes of bottom contact of the front were in February 1977 (deepest contact at 137 m) and in November and December 1976 (shallowest bottom contact at about the 70-m isobath).

Excursions of the shelf–slope front from the 10-yr mean monthly positions at both the surface and along the bottom often tended to be associated with the presence or absence of warm-core Gulf Stream rings (Fig. 2). When rings were present, the front was usually located father shoreward at the surface and in shallower water along the bottom. In the absence of rings, the front tended to be farther offshore and in deeper water. Horizontal shifts in frontal position in response to the passage of rings were generally larger at the surface than along the bottom, probably due to the fact that the slant of the front makes it more likely to interact with rings at the surface than along the bottom.

Table 2
Frequency and duration of warm-core rings present off southern New England by year, 1974–83.

	Number of rings	Duration (days)
1974	3	128
1975	4[1]	149
1976	3	99
1977	7[1]	163
1978	3[1]	105
1979	4	146
1980	3	107
1981	3	139
1982	3	102
1983	4	92
Average	3.7	123

[1] Includes one ring present at the end of the preceeding year that persisted into the beginning of the noted year.

Not all of the rings had comparable influence on front position, which was likely due to variations in the size and dynamics of the rings and their proximity to the continental shelf (Chamberlin, 1982). An example of the relation between warm-core rings and shifts in frontal location can be seen in the sequence of events in 1980 through early 1981 (Fig. 2). During the first half of 1980, three rings were present and the front was well shoreward and shallower than average. From July through December, no rings were reported, and the front shifted to offshore at the surface and into deeper water at the bottom. From January through April, the front shifted shoreward and into shallower water as two more rings drifted across 71°W longitude.

There was considerable between-year variation in annual mean position of the front at the surface and along the bottom (Table 1), which was not clearly related to either the number of rings present during the year or the total duration of rings in the area (Table 2), nor were the surface and bottom position shifts between years typically in tandem. However, when compiled for months when rings were present versus absent, the annual mean frontal position was always farther shoreward at the surface and in shallower water on the bottom when rings were present (Table 1).

Shoreward movement of the front with the passage of rings results in reduction of the area covered by shelf water. To estimate this reduction, the 10-yr average frontal positions for periods with and without rings (Table 1) were used to calculate the cross-sectional area of shelf water from the coast to the front along 71°W longitude. Assuming the front slopes linearly with depth from the surface to the bottom, the cross-sectional area was 9.1 km^2 for periods with rings and 11.6 km^2 for periods without rings, amounting to a 21% reduction in shelf water cross-sectional area due to rings.

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