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# Oxygen Depletion and Associated Benthic Mortalities in New York Bight, 1976

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U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration

# Foreword

In July 1976, fishermen reported large numbers of dead surf clams and other bottom-dwelling organisms in an 8,600-square-kilometer area of the New Jersey continental shelf. The phenomenon continued through October of that year. During this period scientists from the National Oceanic and Atmospheric Administration (NOAA) expanded their routine surveys and monitoring in the region to determine the extent of the problem and assess the damage to the fisheries. Other researchers—from nearby States, universities, and private groups—joined in the study. They determined that the mortalities were caused by extremely low concentrations of dissolved oxygen and by hydrogen sulfide poisoning in some bottom waters. At the height of the event, dissolved oxygen values in the water were measured at 2 milliliters per liter and sometimes at zero, in an area lying 10 to 100 kilometers off the 150 kilometers of coast between Sandy Hook and Cape May.

Mortalities were greatest among surf clams, ocean quahogs, and other benthic animals. Scientists estimated that by October 1976 more than half of the surf clam population off the central New Jersey coast had died, and that a significant but smaller number of ocean quahogs and sea scallops also died. Lobster catches declined almost 50 percent during the period. As a result, in November the Federal Government declared the New Jersey coast a resource disaster area. Estimates of losses to commercial and recreational fishing industries, and related processing and service businesses, were as high as $550 million. Local fishermen were also concerned about the long-term impact of this event on their fisheries.

This Professional Paper documents what we learned about resource and economic losses caused by the decline in oxygen in these waters during the summer of 1976. It also analyzes coastal oceanographic processes and conditions that affected water quality during this period, especially departures from those conditions that normally occur. Furthermore, this paper considers the possible role that human activities near the affected region may have had in triggering the event. The effects of adverse environmental factors on marine organisms are described as observed in the field and studied in the laboratory. The volume brings together our knowledge of the physicochemical makeup and ecology of these coastal waters. Finally, the likelihood of future oxygen depletion events is discussed.

The research during that summer improved our knowledge of environmental changes in the region. The study indicates the importance of understanding and continuing research into coastal oceanographic processes if we are to manage our marine resources wisely in the future.

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National Oceanic and Atmospheric
Administration

# Acknowledgments

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# Oxygen Depletion and Associated Benthic Mortalities in New York Bight, 1976

# Chapter 1. Historical and Regional Perspective

*Carl J. Sindermann*[1] *and R. Lawrence Swanson*[2]

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## THE 1976 OXYGEN DEPLETION EVENT

In the summer and autumn of 1976, mass mortalities of shellfish and other marine species occurred in the New York Bight, apparently because of extreme oxygen depletion and hydrogen sulfide formation in bottom waters. First reports of a developing problem reached the scientific community during the July 4th weekend. Sport divers, lobstermen, and trawler fishermen observed and reported dead and dying animals of all kinds on fishing reefs and wrecks and on fishing grounds off the northern New Jersey coast. Within a few weeks, mortalities were reported southward some 90 km and seaward some 60 km. Planned surveys and monitoring in the Bight by the National Oceanic and Atmospheric Administration (NOAA) were increased in areal coverage and intensity to determine the extent of the problem and to assess the damage. At its maximum extent, oxygen-deficient bottom water—$< 2.0$ ml/l and sometimes with zero values of dissolved oxygen (D.O.)—was found from Sandy Hook to Cape May, a distance of 150 km along the New Jersey coast in a zone or corridor 10 to 100 km off the coast (fig. 1–1). This environmental event of major proportions involved an 8,600-km$^2$ area of the continental shelf off the coast of New Jersey.

A mass mortality can be described as an unusual and rapid increase in mortality rate, of sufficient proportions to affect significantly the size of a population and to disturb, at least temporarily, the ecosystem of which the population is a part. Mass mortalities may be local, confined to a particular cove or estuary, or they may be widespread, sometimes affecting hundreds of kilometers of coastline. Causes of mass mortalities may be physical, chemical, or biological—or combinations that produce stress beyond the tolerance limit of individuals in the population. Physical causes can include storms, seaquakes, temperature changes and extremes, upwelling, vulcanism, and people-induced changes such as dredging; chemical causes include contaminant chemicals, hydrogen sulfide generation, oxygen depletion, and salinity changes and

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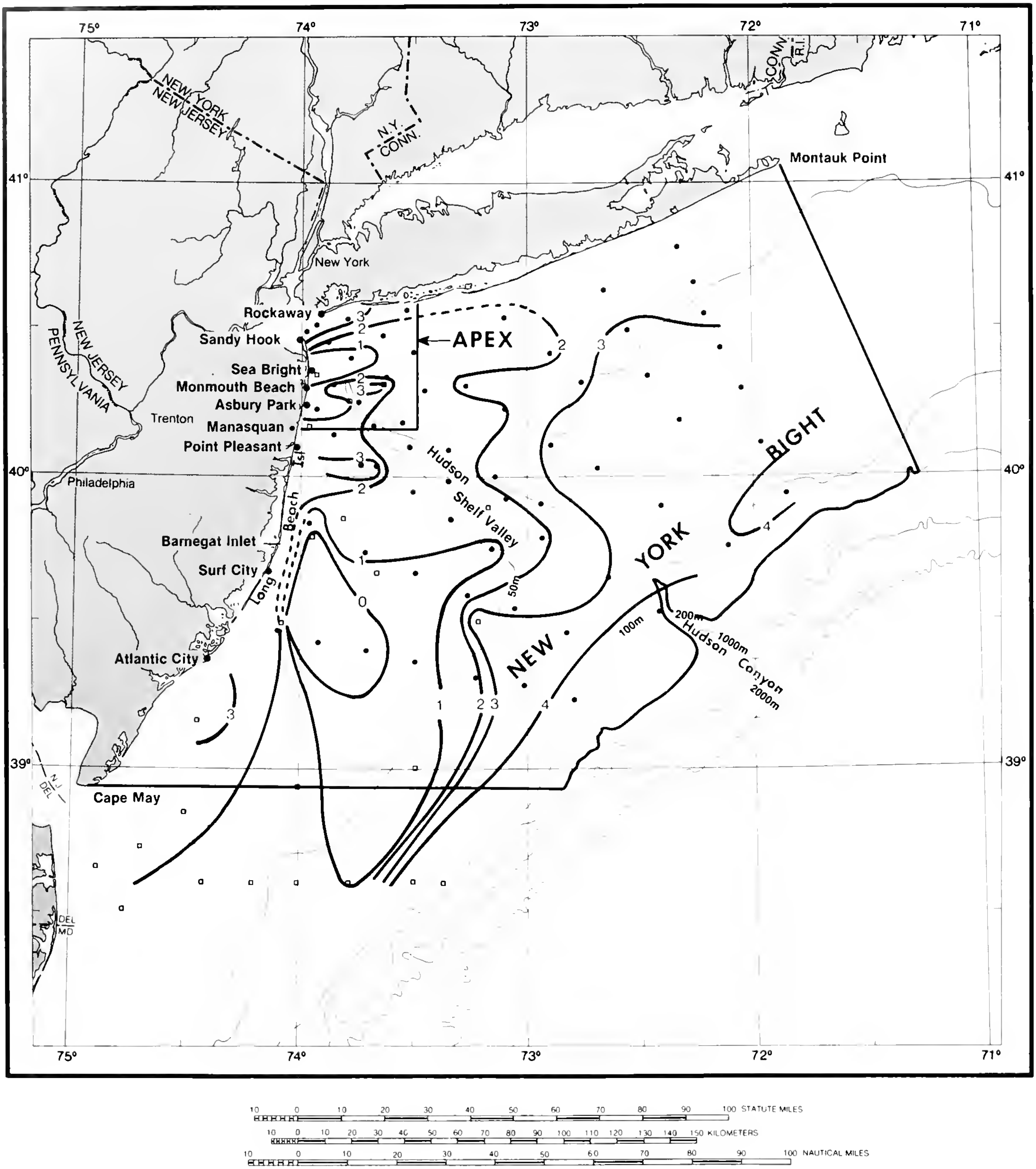


FIGURE 1-1.—Oxygen-depleted bottom water in New York Bight and off New Jersey coast, August-September 1976. Dissolved oxygen content in ml/l. Water-column sampling: Atlantic Oceanographic and Meteorological Laboratories stations, solid circles; National Marine Fisheries Service stations, open squares.

extremes; and biological causes include algal blooms, disease, predation, and toxins.

Scientific literature has reported mass mortalities due to many of the above causes. Probably the most complete report is by Brongersma-Sanders (1957), who exhaustively reviewed all known mass mortalities in the sea. Other reviews include those of Sindermann (1970, 1976).

In the 1976 New York Bight event, bottom water oxygen values were zero and hydrogen sulfide was formed in the central New Jersey coastal area off Atlantic City. Divers consistently reported a brownish flocculent layer beneath the thermocline in much of the affected area. Oxygen depletion persisted until October when lower surface temperatures and mixing broke down the pycnocline and gradually reoxygenated the bottom water.

Fish, lobsters, and mollusks were found dead. Sedentary forms—surf clams, ocean quahogs, and other benthic animals—had the greatest mortalities. From almost continuous surveys, scientists estimated that more than half the surf clam population off the central New Jersey coast—over 100,000 metric tons (t)—had been destroyed by October, with significant but smaller mortalities of ocean quahogs and sea scallops. Lobster catches declined by almost 50 percent during the period. Consequently, the Federal Government declared the New Jersey coast a resource disaster area in November.

The occurrence of mass mortalities in New York Bight is particularly significant considering the heavy stress that humans have placed on these coastal waters and the pending efforts to manage this marine resource more effectively. It is known that people and their activities contribute to the Bight, mostly through the Hudson-Raritan estuarine system, large quantities of carbon and nutrients that would not otherwise get there. Some people considered ocean dumping, particularly sewage sludge dumping within 22 km of the coast, to have been the cause of the oxygen depletion and resultant mass mortalities.

If efficient and effective resource management is to be adopted, then it is essential to understand the complex responses of the marine ecosystem to natural and man-induced stimuli. Given this understanding, prediction of such events can be improved. If the contaminants from human activities are found to play a significant role, management strategies can be adopted to lessen the likelihood of such catastrophic events in the future.

This professional paper examines the extensive data base available in the context of the above issues. The scope of the problem proved so broad and the sources of data so dispersed that many scientists and organizations contributed to the analysis of the causes, extent, duration, and effects of the anoxic condition.

A number of research groups—Federal, State, university, and industry—participated actively in data acquisition and analysis. The National Science Foundation convened a workshop on the problem in October 1976, and the participating research groups organized their own workshops in November 1976. Proceedings of these workshops have been published (Sharp 1976; National Marine Fisheries Service 1977).

Initial indications from these efforts were that severe oxygen depletion developed in the bottom waters in response to a combination of anomalous environmental events superimposed on a coastal area characterized by reduced dissolved oxygen in an average summer.

Atmospheric events included high February-March air temperatures with abnormally high river runoff in February and March, which was before the usual annual spring peak in April; reduction of storm activity during spring and summer to less than half the 25-year average; and a period of 4 to 6 weeks in June-July with unusually persistent south to southwest winds.

Oceanic events included early (February-March) warming of surface waters; early development of the halocline; and a massive bloom of the dinoflagellate *Ceratium tripos* over much of the Middle Atlantic Bight (continental shelf from Montauk Point, N.Y., to Cape Hatteras, N.C.), but concentrated in New York Bight. The bloom began in February, persisted at least until July, and was concentrated at and just below the pycnocline.

Oxygenation in the ocean occurs in the surface layers (photic zone) through air-sea interaction and photosynthesis and through advective processes. Thus, oxygen replenishment of deep waters often comes only from water that has been in contact with the surface layers. With this in mind, a hypothesis was developed that included the following components: 1) superimposition of high oxygen demand from a declining phytoplankton *(Ceratium tripos)* bloom on an area (New York Bight) already characterized by reduced dissolved oxygen in an average summer; 2) sealing off of this organically rich oxygen-demanding water mass early in spring by the early onset of a pycnocline; and 3) disruption of the usual spatial pattern of currents such that the bulk of the oxygen-demanding material is concentrated off the New Jersey coast. These elements supply the ingredients of disaster to marine animals.

## PHYSICAL DESCRIPTION OF THE BIGHT

New York Bight is a 39,000-km$^2$ sector of the Middle Atlantic continental shelf between Montauk Point, N.Y., and Cape May, N.J., approximately 180 km wide from the Hudson-Raritan estuary to the shelf edge. Depths range between 30 and 60 m over much of the Bight, with the inner shelf off New Jersey being somewhat shoaler than that off Long Island. The shelf break generally occurs at a depth of 140 m. The most prominent topographic feature of the shelf is the Hudson Shelf Valley, a broad, shallow channel extending from the Bight Apex seaward to the outer shelf and Hudson Canyon (fig. 1–1). The surface of the shelf is a gently rolling plain that gradually increases in depth from the Apex at the mouth of the Hudson River to the edge of the shelf, a gradient of about 60 m in 100 km. North of the Hudson Shelf Valley the surface is veneered with sand. To the south, the surficial sediments are sand and gravel. Within the valley, nutrient-rich muds have accumulated since the postglacial sea began to rise. Barrier beaches, bluffs, and estuaries are prominent coastal features of the Bight.

Water movements in the Bight are highly variable in space and time. Over the middle and outer portions of the shelf, waters generally move to the southwest, parallel to the bathymetric contours. In the inner (nearshore) portion of the Bight, water movement and structure of the water column vary greatly with dominant seasonal influences. Boundaries between the regimes of the inner and outer Bight are poorly defined and constantly changing. Nevertheless, the inner Bight has two major features:

1. A two-layer flow near the Hudson-Raritan estuary is dominated by the outflow of these rivers. In the surface layer, less dense water flows seaward, generally parallel to the New Jersey coast. In the lower part of the water column, the denser water of the Bight flows into the estuary. Evidence for this two-layer flow is found in current meter measurements, which show a slight imbalance between the much stronger ebb and flood tidal components of currents in the respective layers.
2. A clockwise circulation gyre (at least in the statistical sense) persists outside the region of strong river influence. Its western edge tends to be aligned with the Hudson Shelf Valley.

The importance of the Hudson Shelf Valley to oceanic processes on the shelf is just beginning to be realized. The flow of water can be either up or down valley. Over extended periods of time, the flow has been measured up valley (Beardsley et al. 1976). However, in the inner Bight particulate material tends to be transported seaward and concentrated on the valley floor.

Oceanic conditions in the Bight are largely controlled by the temperate, middle-latitude climate, which is dominated by maritime air from the tropics or subtropics for 9 or 10 months and by arctic air for 2 or 3 months (Lettau et al. 1976). Waters of the Bight undergo pronounced seasonal changes in temperature, salinity, and density. In winter, they are characterized by considerable horizontal and vertical homogeneity. In spring, freshwater outflow begins to establish a pycnocline, particularly over the inner shelf. In summer, heating of the surface layer produces thermal stratification and intensifies the pycnocline. Seasonal variations are great and changes are most rapid in the inner Bight. They decrease seaward over the midshelf region.

A summer feature of deeper midshelf waters is the "cold pool," thought to be relict winter surface water (Bowman and Wunderlich 1977) of local or distant origin. However, the low dissolved oxygen content of this water suggests considerable modification at depth on the shelf (Gordon et al. 1976); and its southwest flow at speeds equal to or exceeding those of adjacent waters (Beardsley et al. 1976) indicate the pool is not stagnant.

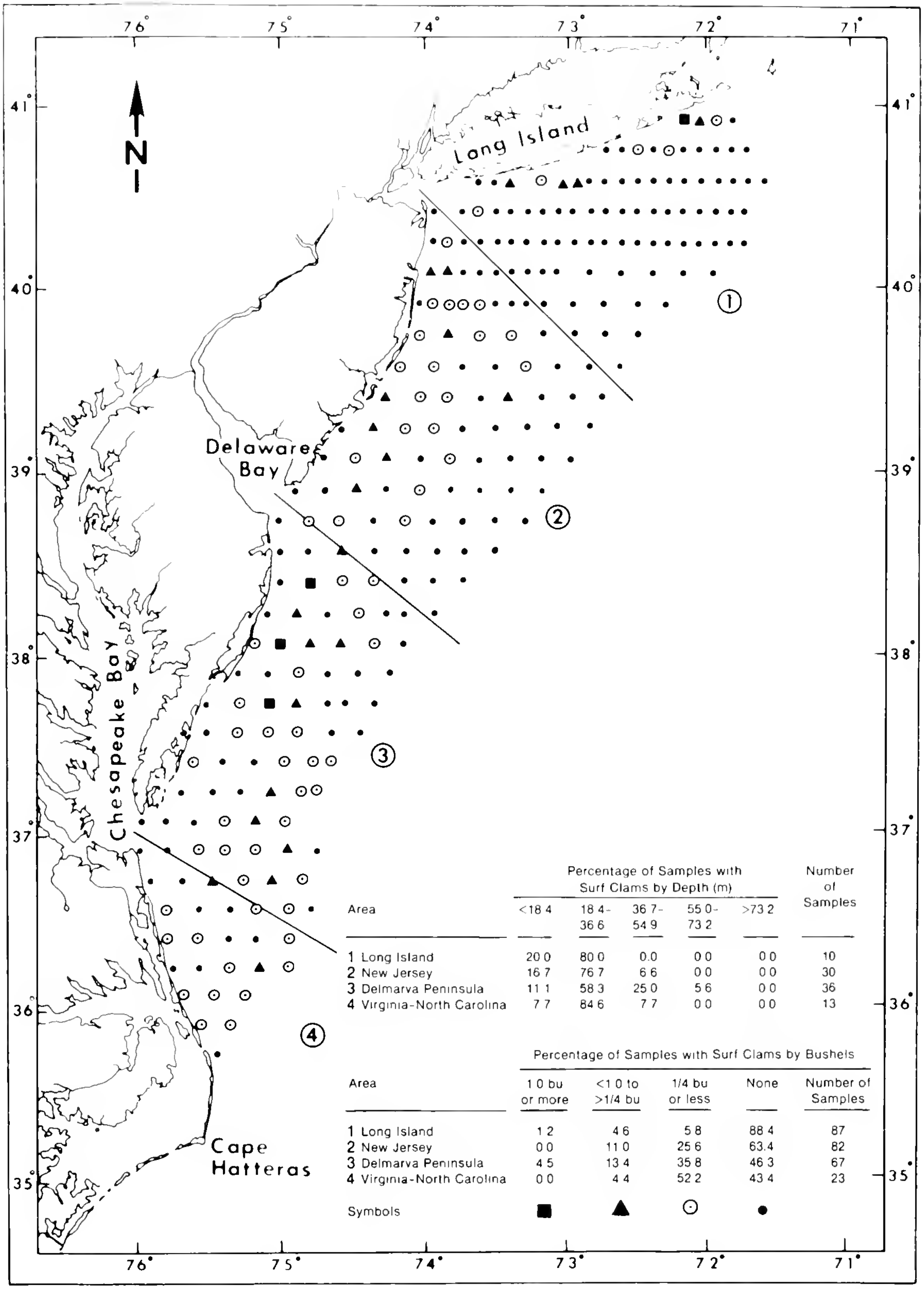
Atmospheric and oceanic processes and their variations play an important role in the chemical and biological processes in the Bight. Also, human activities are known to have altered some chemical and biological phenomena. Knowledge about the extent and magnitude of these interactions is important in understanding oxygen depletion in the Bight.

## FISH AND SHELLFISH STOCKS

The abundant fish and shellfish populations of the Middle Atlantic Bight are important to the Nation's economy. Oceanic species of bivalve mollusks—surf clams, ocean quahogs, and scallops—are more numerous here than in any comparable coastal area in the United States. Surf clams harvested from the Middle Atlantic Bight constitute over 50 percent of the total landed weight of molluscan shellfish in the United States; the fishery for ocean quahogs is expanding rapidly, and populations of sea scallops are fished regularly in deep waters of the Bight.

The National Marine Fisheries Service (NMFS) has conducted surveys of surf clam, ocean quahog, and scallop distribution and abundance in the Middle Atlantic Bight for a number of years. Results of April 6 to May 13, 1976, surveys by the RV *Delaware II* are given in figures 1–2, 1–3, and 1–4. Total estimated biomass of offshore surf clams in the Bight was 875,000 t of meats, with the New Jersey sector containing 207,000 t. Coastal stocks of surf clams in New Jersey (within 5 km of shore) were estimated at 34,000 t. Total estimated biomass of ocean quahogs in the Bight was 2,450,000 t of meats, with the New Jersey sector containing 818,000 t. Biomass estimates for sea scallops in the Bight are not available, but much of the stocks are composed at present of a single strong year class (1972). Scallops occupy about 11,500 km$^2$ of the shelf off New Jersey.

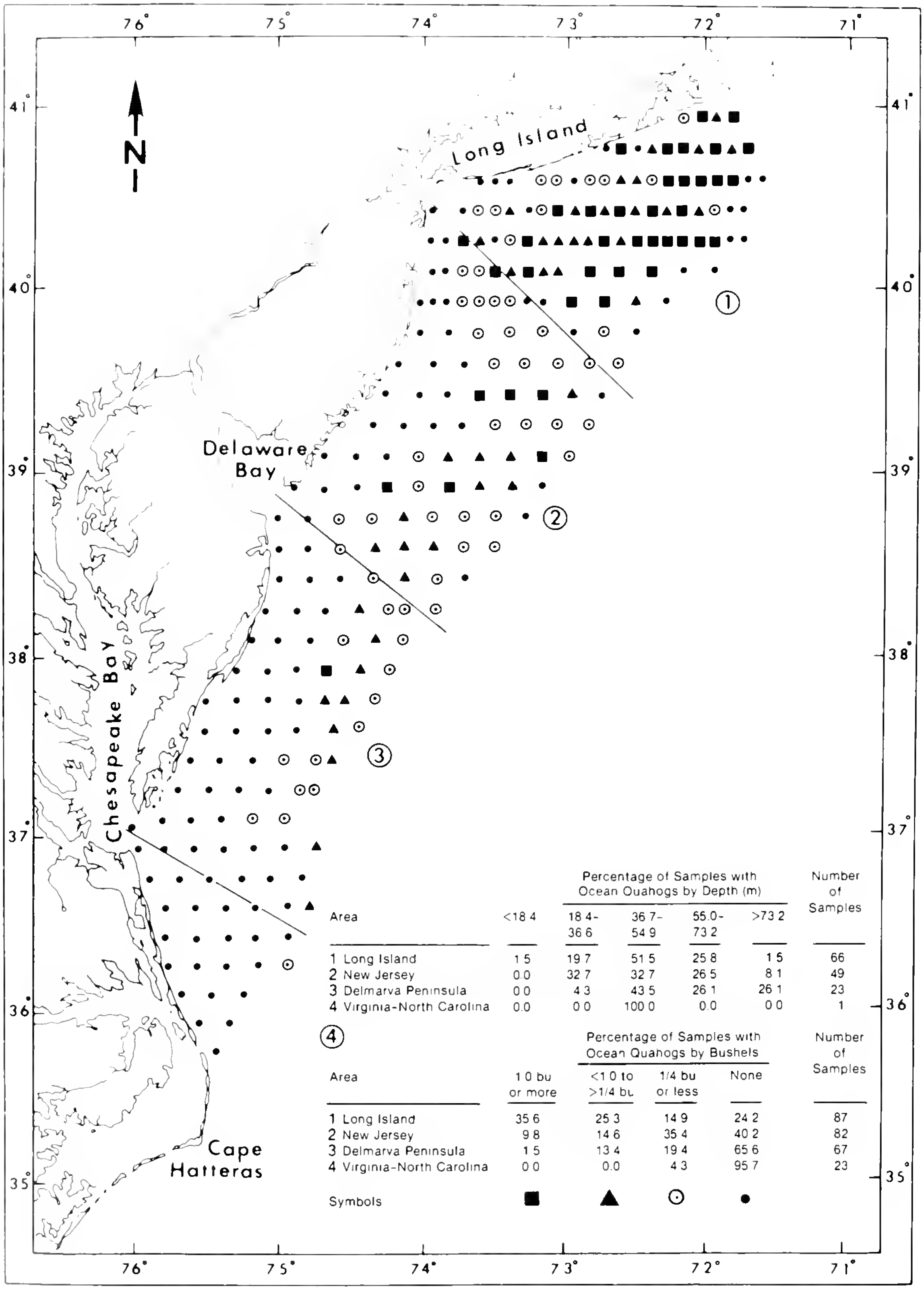
Significant finfish species in the Middle Atlantic Bight include cod, summer flounder, bluefish, striped bass, mackerel, sea bass, and weakfish. A number of these species are taken by recreational as well as commercial fishermen; often the recreational catch predominates. Some species (such as striped bass) are estuarine-dependent; others, such as summer flounder and bluefish, migrate across bathymetric contours to and from the coast, or



| Area | Percentage of Samples with Surf Clams by Depth (m) | | | | | Number of Samples |
|---|---|---|---|---|---|---|
| | <18 4 | 18 4-36 6 | 36 7-54 9 | 55 0-73 2 | >73 2 | |
| 1 Long Island | 20 0 | 80 0 | 0.0 | 0 0 | 0 0 | 10 |
| 2 New Jersey | 16 7 | 76 7 | 6 6 | 0 0 | 0 0 | 30 |
| 3 Delmarva Peninsula | 11 1 | 58 3 | 25 0 | 5 6 | 0 0 | 36 |
| 4 Virginia-North Carolina | 7 7 | 84 6 | 7 7 | 0 0 | 0 0 | 13 |

| Area | Percentage of Samples with Surf Clams by Bushels | | | | |
|---|---|---|---|---|---|
| | 1 0 bu or more | <1 0 to >1/4 bu | 1/4 bu or less | None | Number of Samples |
| 1 Long Island | 1 2 | 4 6 | 5 8 | 88 4 | 87 |
| 2 New Jersey | 0 0 | 11 0 | 25 6 | 63.4 | 82 |
| 3 Delmarva Peninsula | 4 5 | 13 4 | 35 8 | 46 3 | 67 |
| 4 Virginia-North Carolina | 0 0 | 4 4 | 52 2 | 43 4 | 23 |
| Symbols | ■ | ▲ | ⊙ | ● | |

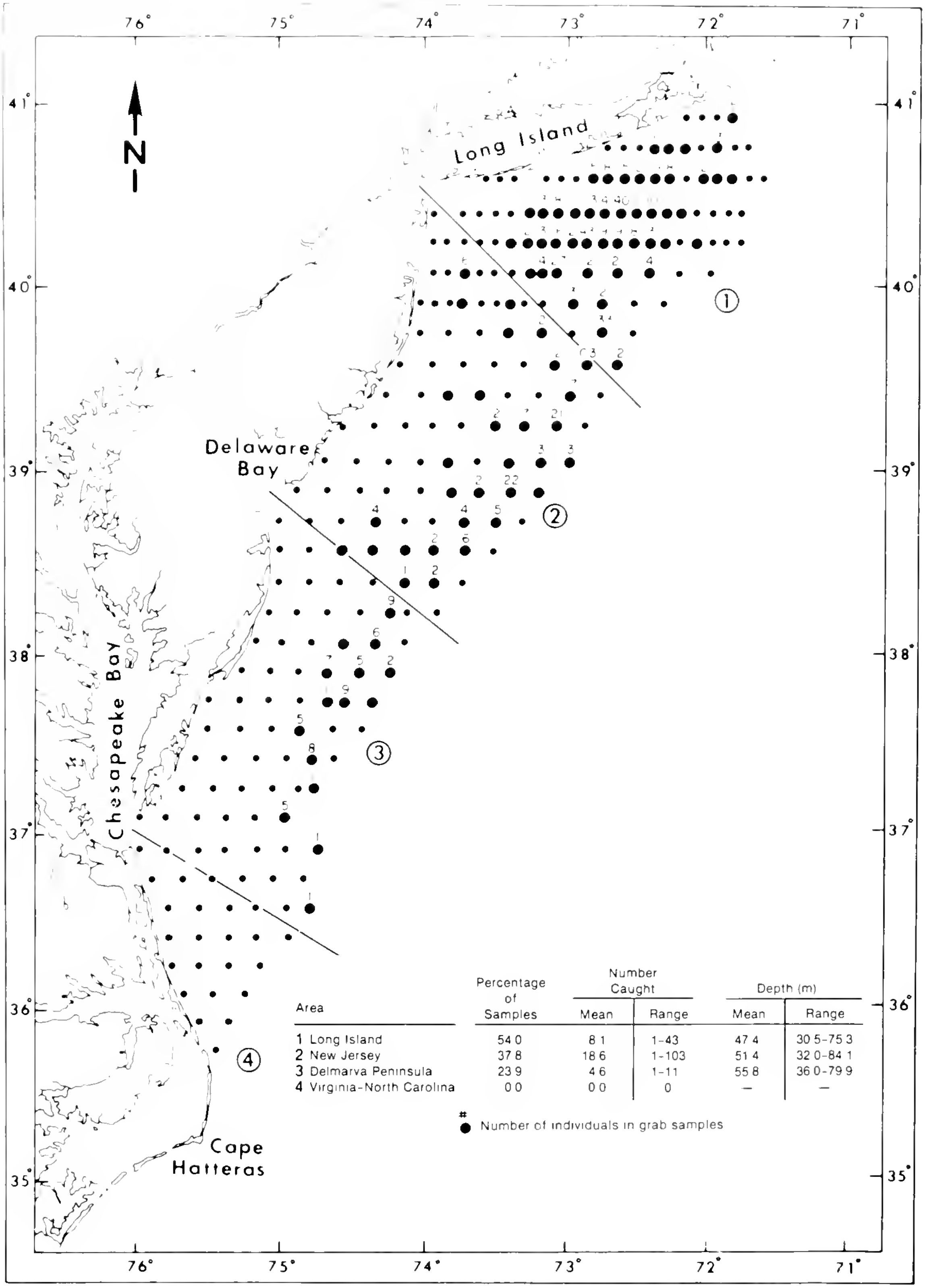
FIGURE 1-2.—Distribution and abundance of surf clams in Middle Atlantic Bight, *Delaware II* shellfish assessment cruise April 6–May 13, 1976.



| Area | <18.4 | Percentage of Samples with Ocean Quahogs by Depth (m)<br>18.4-36.6 | 36.7-54.9 | 55.0-73.2 | >73.2 | Number of Samples |
|---|---|---|---|---|---|---|
| 1 Long Island | 1.5 | 19.7 | 51.5 | 25.8 | 1.5 | 66 |
| 2 New Jersey | 0.0 | 32.7 | 32.7 | 26.5 | 8.1 | 49 |
| 3 Delmarva Peninsula | 0.0 | 4.3 | 43.5 | 26.1 | 26.1 | 23 |
| 4 Virginia-North Carolina | 0.0 | 0.0 | 100.0 | 0.0 | 0.0 | 1 |

| Area | 1.0 bu or more | Percentage of Samples with Ocean Quahogs by Bushels<br><1.0 to >1/4 bu | 1/4 bu or less | None | Number of Samples |
|---|---|---|---|---|---|
| 1 Long Island | 35.6 | 25.3 | 14.9 | 24.2 | 87 |
| 2 New Jersey | 9.8 | 14.6 | 35.4 | 40.2 | 82 |
| 3 Delmarva Peninsula | 1.5 | 13.4 | 19.4 | 65.6 | 67 |
| 4 Virginia-North Carolina | 0.0 | 0.0 | 4.3 | 95.7 | 23 |
| Symbols | ■ | ▲ | ⊙ | ● | |

FIGURE 1-3.—Distribution and abundance of ocean quahogs in Middle Atlantic Bight, *Delaware II* shellfish assessment cruise April 6–May 13, 1976.



| Area | Percentage of Samples | Number Caught |  | Depth (m) |  |
|---|---|---|---|---|---|
|  |  | Mean | Range | Mean | Range |
| 1 Long Island | 54.0 | 8.1 | 1-43 | 47.4 | 30.5-75.3 |
| 2 New Jersey | 37.8 | 18.6 | 1-103 | 51.4 | 32.0-84.1 |
| 3 Delmarva Peninsula | 23.9 | 4.6 | 1-11 | 55.8 | 36.0-79.9 |
| 4 Virginia-North Carolina | 0.0 | 0.0 | 0 | — | — |

\# ● Number of individuals in grab samples

FIGURE 1-4.—Distribution and abundance of sea scallops in Middle Atlantic Bight, *Delaware II* shellfish assessment cruise April 6–May 13, 1976.

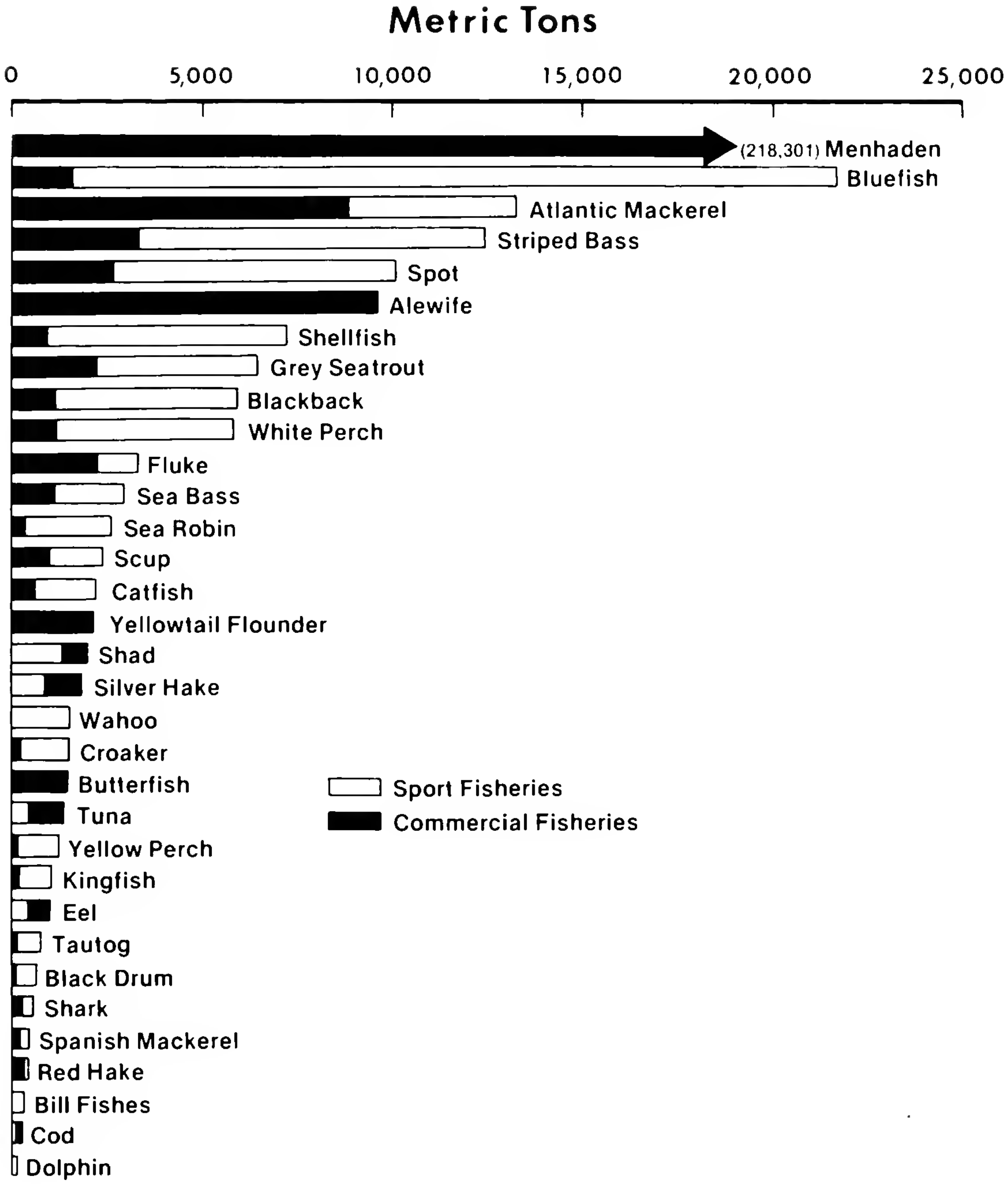


FIGURE 1-5.—Landings of recreational and commercial fish species in Middle Atlantic Bight in 1970. (National Marine Fisheries Service 1973).

along bathymetric contours north and south through the Bight. Until 1977 a few Middle Atlantic Bight species (e.g., mackerel and silver hake) were exploited heavily by foreign distant-water fleets and stocks were reduced. Most of the Middle Atlantic finfish stocks (other than mackerel) of interest to U.S. fishermen have not declined drastically in recent decades. Since 1970 increased landings have been reported for bluefish, and weakfish.

The relative contributions of important Middle Atlantic Bight fish species to recreational and commercial landings are summarized in figure 1–5.

## ORGANIC AND NUTRIENT LOADINGS

Potential eutrophication of Bight Apex waters was identified by Segar and Berberian (1976). Had the 1976 anoxic event been confined to the Apex, an assessment of the cause might have been much simpler. However, the affected region extended nearly to Cape May, which added to the complexity of understanding the situation. Wastes from land (fig. 1–6) contributed to the general degradation of Apex waters and sediments (Swanson 1977). Of these, inputs of organic carbon and nutrients are of primary concern with respect to the oxygen-depletion event.

Mueller and others (1976) summarized average anthropogenic loading of the Bight from various sources. Geographically the sources are direct inputs to the Bight from ocean dumping and atmospheric fallout, flow from the Hudson-Raritan estuary through the Sandy Hook, N.J.—Rockaway, N.Y., transect, and contributions from the Long Island and New Jersey coastal zones. Types of inputs include sewage sludge, dredge spoil, and acid wastes from ocean dumping, atmospheric fallout, municipal and industrial wastewaters, and runoff (gauged and urban). Daily mass loads of carbon, nitrogen, and phosphorus and the percentage contributed by geographic area are given in table 1–1. Figure 1–7 shows the percentage contribution by various sources. The values are estimates of total anthropogenic loading and indicate relative significance of each disposal activity. However, certain limitations must be considered when using the data. The values represent average maximum loads available to the Bight. They do not reflect the amount of any constituent lost by sedimentation, decay, leaching, and biological uptake (Mueller et al. 1976). This analysis of mass loading is important in developing carbon, nutrient, and oxygen budgets. If human activity is considered a significant driving force in causing oxygen depletion, we can more specifically identify priority areas for better management.

TABLE 1–1.—*Daily mass loads of carbon, nitrogen, and phosphorus entering New York Bight from human activities*[1]

| | Mass load | Directly into Bight[2] | Sandy Hook Rockaway transect[3] | New Jersey coast | Long Island coast |
|---|---|---|---|---|---|
| | $10^6$kg/d | Percent | Percent | Percent | Percent |
| Total organic carbon | 2.60 | 37 | 58 | 4 | 0.6 |
| Total nitrogen | 0.52 | 29 | 65 | 4 | 2.0 |
| Total phosphorus | 0.14 | 51 | 45 | 2 | 2.0 |

[1] Source: Mueller et al. 1976.

[2] Ocean dumping and atmospheric fallout.

[3] Hudson-Raritan estuary.

There are of course natural oceanic processes that supply nutrients to the New York Bight. Their relative contributions have been estimated, but are incompletely understood. Any evaluation of relative impacts of anthropogenic loading must include careful consideration of natural processes as well.

## PREVIOUS MORTALITIES AND OXYGEN DEPLETION EVENTS IN NEW YORK BIGHT

Localized mortalities of fish and shellfish have been observed and reported previously from the New York Bight area. Causes of such mortalities usually have not been determined, but several of the mortalities had characteristics similar to the extensive 1976 mortalities.

A fishkill was reported along the ocean side of Jones Beach in Hempstead Bay, N.Y., from September 17 to 22, 1951. Both surface and bottom waters were affected. Observation of large fluke (22–23 kg) among the dead fish suggested that the condition occurred well offshore. The cause of the problem was not positively identified (Perlmutter 1952).

Fishkills were reported off New Jersey in 1968, 1971, and 1974 (Ogren and Chess 1969; Young 1973; Young 1974). There might have been earlier similar events that were not observed or reported. Those documented resemble the event of 1976 in that: 1) sedentary organisms found around reefs and wrecks were killed; 2) reports originated from the same general area; 3) depressed oxygen levels were considered a contributing factor; and 4) suspended flocculent material was present in the water column. The 1976 episode differed from those of previous years in that: 1) it began before the end of June, compared with the August-October period of earlier occurrences, and 2) hydrogen sulfide, not previously reported, was detected in lethal concentrations in 1976. It may have been present but not observed in earlier episodes.

Previous reports of mortalities covered much smaller areas. The 1968 event, which appears to have been the most extensive of the earlier kills, included a zone from Sea Bright to Surf City, N.J., a distance of 70 km, and extended from 1 to about 10 km offshore. The total area

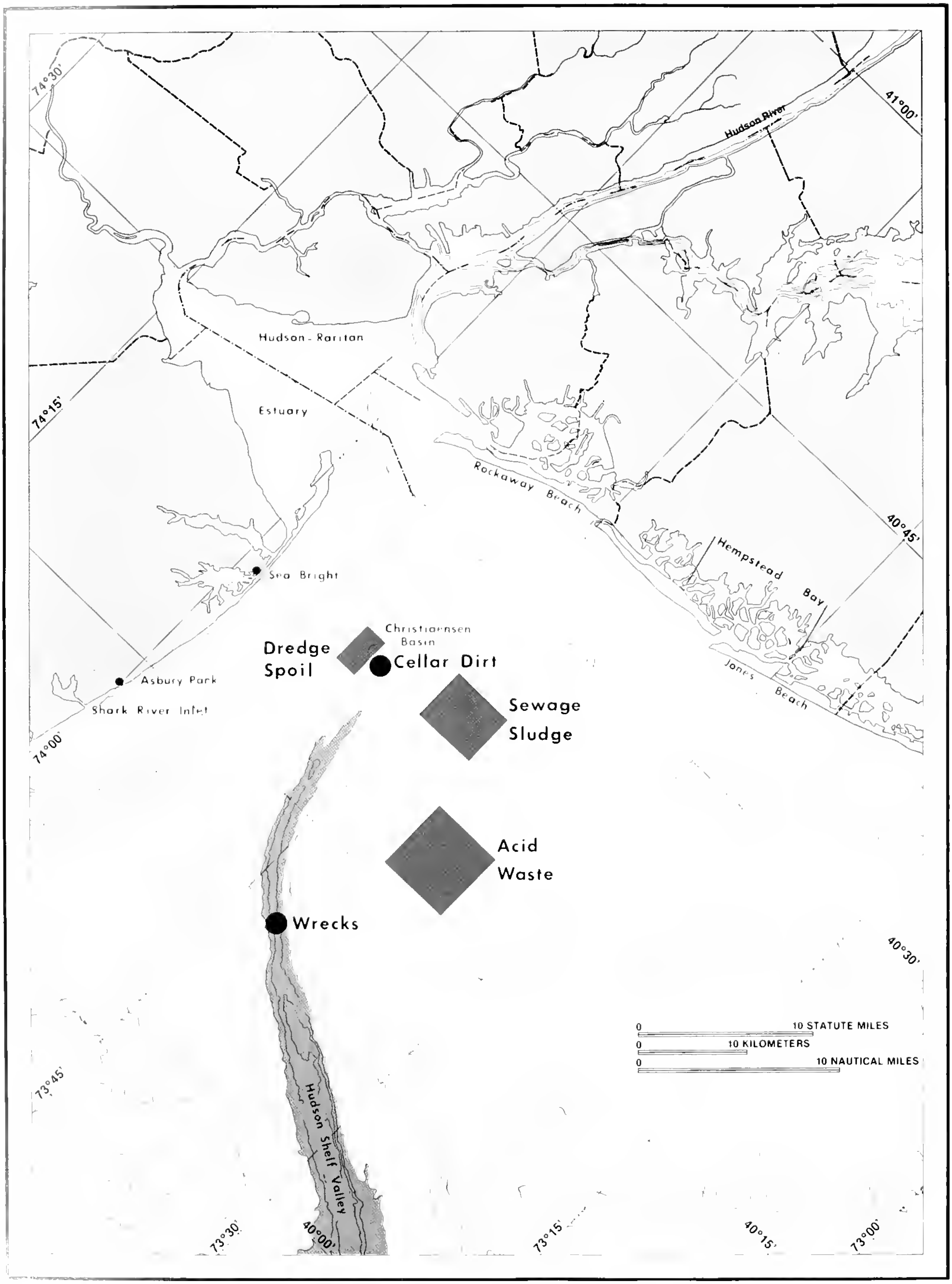


FIGURE 1–6.—Disposal sites in New York Bight Apex, 1976.

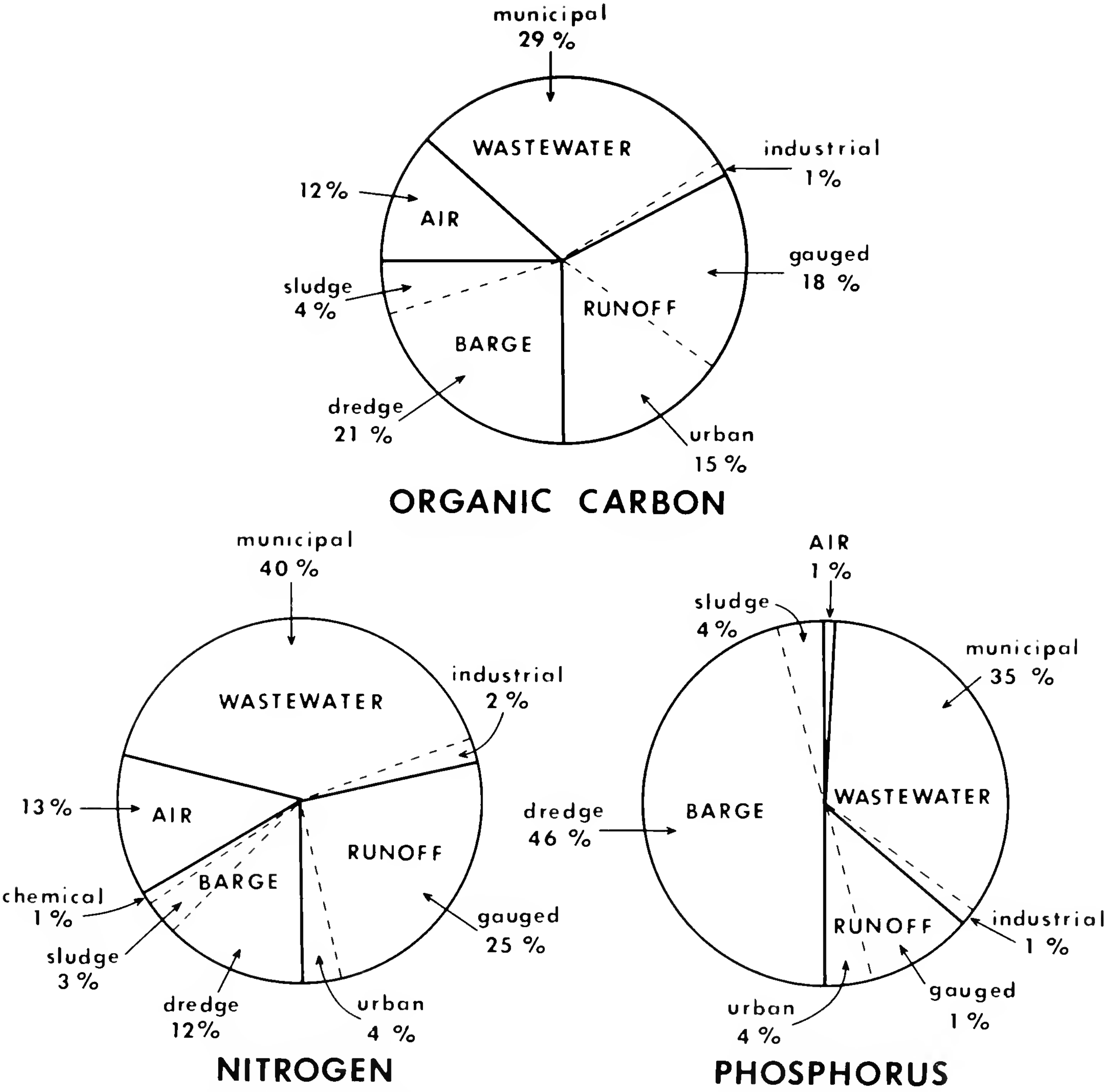


FIGURE 1-7.—Average daily percentage contributions of organic carbon, nitrogen, and phosphorus entering New York Bight from various sources. (Mueller et al. 1976)

was approximately 600 to 800 $km^2$ (Ogren and Chess 1969). Mortalities were reported on and near wrecks and reefs from early September until late October 1968. Species affected were ocean pout, cunner, lobsters, rock crabs, mussels, surf clams, and starfish. More active species such as tautog, black seabass, squirrel hake, conger eels, and round scad apparently were able to escape and were rarely reported among the mortalities. Fauna on wrecks offshore of Barnegat and Atlantic City was normal.

Relevant observations made in the mortality area in 1968 were: 1) mortalities were restricted to waters less than 30 m deep; 2) bottom water temperatures, principally at wreck sites, were 14° to 16° C; 3) bottom-water dissolved oxygen values were less than 1.0 ml/l; 4) a pronounced thermocline existed; and 5) a series of phytoplankton blooms, beginning in July and extending to September, occurred along the New Jersey coast. Reexamination of the same area in May and July 1969 disclosed that oxygen values near the bottom were more than 7.0 ml/l and that wrecks had been repopulated by fish and crustaceans.

No reports are available for 1970, but in early October 1971 lobsters and rock crabs were reported dead on several wrecks 12 km east of Point Pleasant, N.J., at depths of about 30 m, and also at Shark River Inlet (Young 1973). Bottom water temperatures at the wreck sites were high (18° C) and suspended flocculent material was noted low in the water column.

Again, no reports are available for 1972 and 1973, but in August 1974 mortalities of ocean pout were observed on several wrecks off Point Pleasant (J. S. Young, personal communication). Bottom-water dissolved oxygen values were 1.0 ml/l, with heavy suspended flocculent material and bottom water temperatures of 14° to 15° C. In early September 1974 the *Subsea Journal* of the Manta Ray Diving Club of New Jersey reported dead lobsters and rock crabs on a wreck off Long Beach Island, N.J.

Thomas et al. (1976) reported that significant summer depletion of bottom dissolved oxygen in the restricted area of the sludge and dredge material disposal sites, and also in an area close to the New Jersey shore off Asbury Park, occurred during summer 1974. Low dissolved oxygen concentrations have been reported previously in New York Bight dumpsites (Pearce 1972). Dissolved oxygen concentrations in dumpsites were higher in summer 1975 than in 1974 and above the level considered harmful to most marine life.

## OXYGEN DEPLETION IN OTHER COASTAL AREAS OF THE WORLD

There are other coastal areas in the world where extreme oxygen depletion in bottom waters is a frequent, sometimes annual, event (fig. 1–8). Deuser (1975) summarizes the general problem. To our knowledge, however, the New York Bight incident is the first of such magnitude that has occurred along an open coastal area where classical upwelling is not a major factor.

Marine fishkills related to oxygen depletion and hydrogen sulfide buildup have been reported in warm shallow estuaries (May 1973) and in areas of upwelling and mass production of plankton, for example, off South America and Africa (Brongersma-Sanders 1957; Theede et al. 1969).

A coastal upwelling region famous for its low oxygen, hydrogen sulfide production, and periodic mortalities is off the southwest coast of Africa in and near Walvis Bay. Scientific records of mortalities, summarized by Brongersma-Sanders (1947, 1957), extend back to 1837. Dead and dying fish, cephalopods, and bivalves have been observed with great frequency in December and January in the sea and on the beaches between 21° and 25° south latitude. The sea bottom of the region is highly organic, with high hydrogen sulfide content and anoxic bottom waters. Mass mortalities of fish are more severe in some years than in others and are often preceded by red to brown discoloration of the sea from algal blooms. The anoxic area involved is approximately 17,200 $km^2$, but interestingly there is a narrow coastal strip about 6 km wide, extending to a depth of 37 m, where sea life is normal and hydrogen sulfide does not occur.

Similar mass mortalities of marine animals in a zone of upwelling have been reported by Falke (1950) from Concepción Bay, Chile.

Mass mortalities, particularly of benthic fauna, have occurred in the deeper basins of the Baltic, where anaerobic conditions may persist for as long as four years (Segerstråle 1969). Total absence of oxygen beginning in 1957 caused the deeper parts of the Gotland, Gdansk, and Bornholm basins to become lifeless deserts in 1958–59. The total area affected was estimated at 41,200 $km^2$. The stagnation was broken in 1962 by a strong inflow of saline water from the Kattegat. Significantly, great amounts of nutrients accumulated during the stagnation period. These were brought to the surface in 1962, resulting in an enormous increase in plankton populations. A similar event occurred in the early 1930s (Kalle 1943; Meyer and Kalle 1950). This periodic stagnation, broken by saline inflows and followed by uplift of nutrients, favors periodic increase in biological production—unlike other areas of continuous anaerobiasis such as the deep (below 100 m) zones of the Black Sea, which constitute a nutrient sink and are unproductive of sea life.

Oxygen depletion of bottom waters, with accompanying formation of hydrogen sulfide, occurred in Tokyo Bay in 1972 (Tsuji et al. 1973; Seki et al. 1974), presumably related to an extensive red tide. Since red tides are becoming

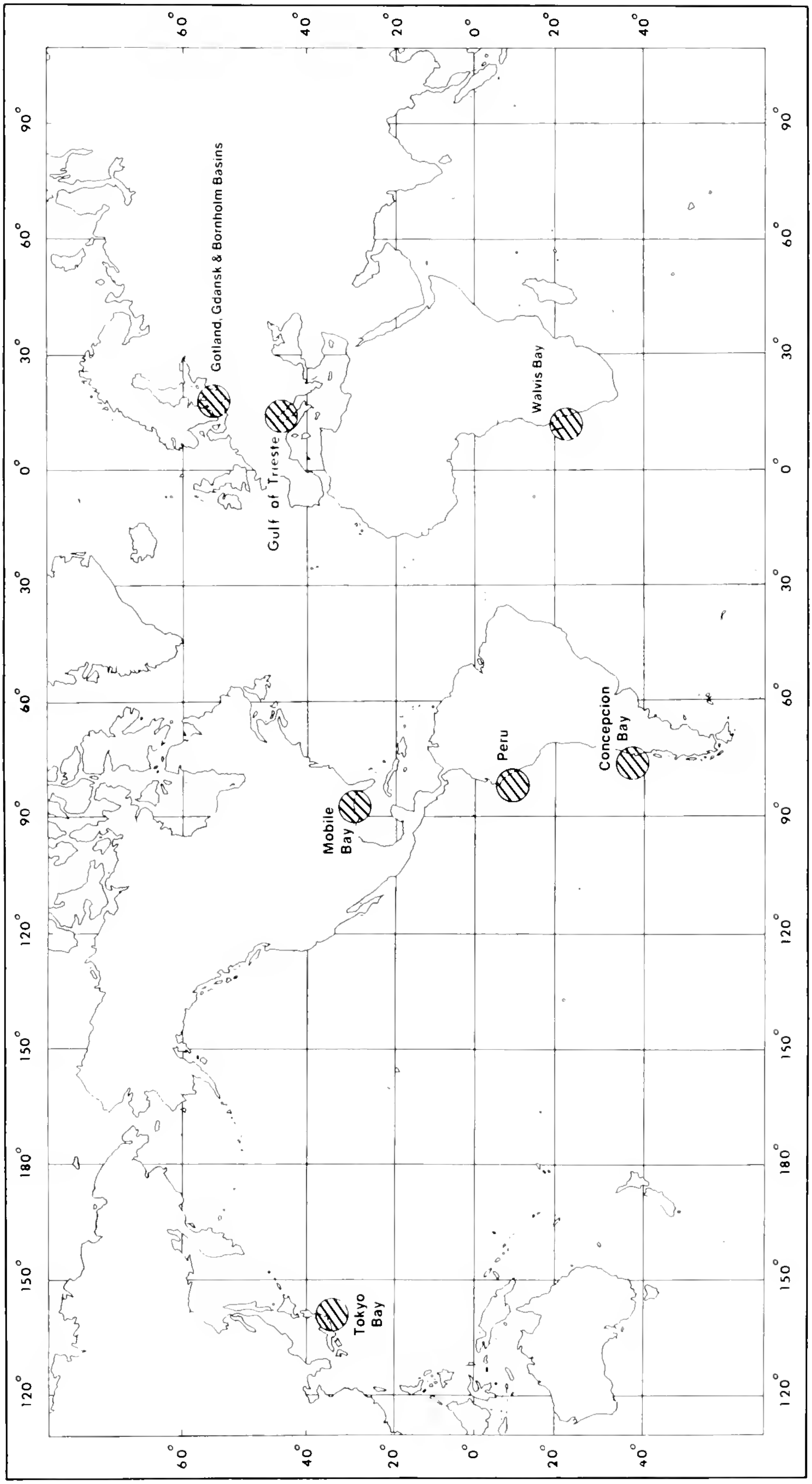


FIGURE 1-8.—Other coastal regions where oxygen depletion has occurred

increasingly frequent in eutrophic bays in Japan as well as elsewhere in the world, anoxic conditions in bottom waters can be expected to increase in severity concomitantly.

Mortalities of benthic organisms, associated with bottom water of low oxygen content, occurred in the Gulf of Trieste in the North Adriatic in 1974 (Fedra et al. 1976). The authors reported scattered areas of decaying organisms in a region formerly characterized by stable benthic populations.

Oxygen depletion has occurred sporadically in Mobile Bay, Ala., one of the largest estuaries of the Gulf of Mexico. Stratification of the water column over a highly organic bottom results in summer oxygen depletion, and occasionally, because of winds, the water mass impinges on beaches. Fish and invertebrates may be trapped in the anoxic water near beaches—often in a disoriented or moribund condition—where they are taken in great numbers by residents. This shoreline phenomenon is called a "jubilee." Loesch (1960) reported 35 such occurrences between 1946 and 1956, but newspaper accounts go back to the 19th century (the earliest is 1867). Oxygen depletion in the bay could have occurred well before colonization of the area in the 1600s, but human activities (particularly dredging operations) have certainly intensified the situation. May (1973) reviewed the history of such events and found no consistent increase in their frequency since 1946. He carried out detailed oxygen determinations during a jubilee in 1971 and found large areas of the bay with less than 0.7 ml/l dissolved oxygen in bottom water. Mortalities of fish, crabs, and oysters were observed.

## SCOPE OF REPORT

The investigations of the 1976 environmental event in the Middle Atlantic Bight make this event one of the best-documented examples of mass mortality in the sea, and of the impacts of such events on resource and food-chain species. It is a textbook-type study that focuses on solving many interrelated problems. Scientific studies on oxygen depletion in the Bight and adjacent coastal waters are continuing, especially since the possibility of repetition of the event at some level of intensity exists for future years.

This report brings together the results of many studies on the 1976 oxygen-depletion event. It examines the geographical extent of oxygen depletion and the environmental conditions preceding and during the event, and compares the 1976 conditions with historical information. Particularly useful in this regard were NMFS resource assessment data and the 1974–76 MESA current meter and water column chemistry data. The latter data sets for 1976 were used in the form of a model to diagnose the fluxes of dissolved oxygen into the affected region. An assessment is made of the causes, including the effects human activities might have had. Impacts on fishery resources and associated socioeconomic aspects are examined. Finally, monitoring and prediction of future events are discussed.

The terms "anoxia" and "anoxic" have been used to describe the 1976 summer oxygen depletion in New York Bight. Anoxic or anoxia refer to a condition where dissolved oxygen values are zero. Zero values did not occur at all times everywhere in the Bight. The terms "anoxia" and "anoxic" were conveniently used during the investigations, and sometimes in this volume, in a less-precise sense to indicate a deficiency of oxygen.

To adequately consider the causes and the major geographic areas of impact, to more appropriately utilize the existing data bases, and to provide continuity of analysis, the Bight was subdivided into areal segments (fig 1–9). These segments were selected to approximate distinctive bathymetric features, such as the Hudson Shelf Valley (H), major regions of oxygen depeltion (J1), and the regions most affected by human activities (A). For the most part, analyses conform to these arbitrarily generated segments throughout the report—except where the idiosyncrasies of individual data sets require some other scheme.

## REFERENCES

Beardsley, R. C., Boicourt, W. C., and Hansen, D. V., 1976. Physical oceanography of the Middle Atlantic Bight, in M. G. Gross (ed.), Middle Atlantic Continental Shelf and New York Bight, *Amer. Soc. Limnol. Oceanogr. Spec. Symp.* 2:20–34.

Bowman, M. J., and Wunderlich, L. D., 1977. Hydrographic Properties, *MESA New York Bight Atlas Monogr.* 1, New York Sea Grant Institute, Albany, N.Y., 78 pp.

Brongersma-Sanders, M., 1947. On the desirability of a research into certain phenomena in the region of upwelling water along the coast of South West Africa. *Proc. Kon Ned. Akad Wetensch* 50(6):659–665.

Brongersma-Sanders, M., 1957. Mass mortalities in the sea, in J. W. Hedgepeth (ed.), Treatise on Marine Ecology and Paleoecology, vol. 1, *Geol. Soc. Amer. Mem.* 67:941–1010.

Deuser, W. G., 1975. Reducing environments, in J. P. Riley and G. Skirrow (eds.), *Chemical Oceanography*, vol. 3, 2d ed., Academic Press, N.Y., 1–37.

Falke, H., 1950. Das Fischsterben in der Bucht von Concepción - Mittlechile (Fish Mortality in the Bay of Concepción - Middle Chile). *Senckenbergiana*, (Frankfurt am Main, Germany), 31(1,2):57–77.

Fedra, K. E., Olscher, M., Scherubel, C., Stachowitsch, M., and Wurzian, R. S., 1976. On the ecology of a North Adriatic benthic community: distribution, standing crop, and composition of the macrobenthos. *Mar. Biol.* 38:129–145.

Gordon, A. L., Amos, A. F., and Gerard, R. D., 1976. New York Bight water stratification, in M. G. Gross (ed.), Middle Atlantic Continental Shelf and New York Bight, *Amer. Soc. Limnol. Oceanogr. Spec. Symp.*, 2:45–57.

Kalle, K., 1943. Die grosse Wasserumschichtung im Gotlandtief vom Jahre 1933/34. *Ann. Hydrogr.* 71:142–146.

Lettau, B., Brower, W. A., Jr., and Quayle, R. G., 1976. Marine Climatology. *MESA New York Bight Atlas Monogr.* 7, New York Sea Grant Institute, Albany, N.Y. 239 pp.

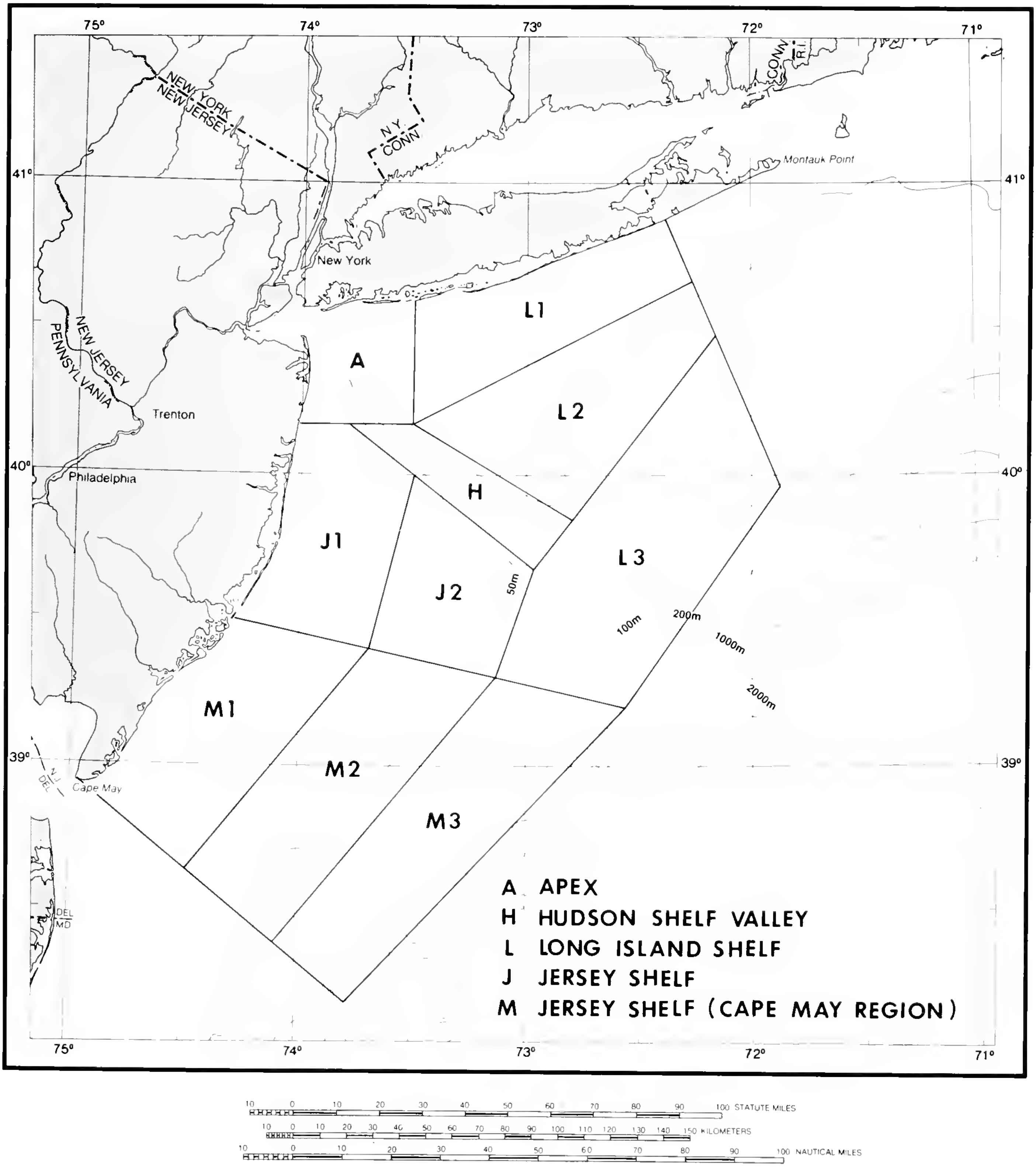


FIGURE 1-9.—Geographic subdivisions of New York Bight for analysis purposes.

Loesch, H., 1960. Sporadic mass shoreward migrations of demersal fish and crustaceans in Mobile Bay, Ala. *Ecology* 41:292–298.

May, E. B., 1973. Extensive oxygen depletion in Mobile Bay, Ala. *Limnol. Oceanogr.* 18(3):353–366.

Meyer, P. F., and Kalle, K., 1950. Die biologische Umstimmung der Ostsee in den letzten Jahnzehnten, eine Folge hydrographischer Wasserumschichtungen? *Archiv fur Fischereiwissenschaft* 2:1–9.

Mueller, J. A., Jeris, J. S., Anderson, A. R., and Hughes, C. F., 1976. Contaminant Imputs to the New York Bight. *NOAA Tech. Mem.* ERL MESA–6, Environmental Research Laboratories, National Oceanic and Atmospheric Administration, Boulder, Colo., 347 pp.

National Marine Fisheries Service, 1973. Sportfish emphasis document, *Middle Atlantic Coastal Fisheries Center Informal Rep.* No. 15, 79 pp.

National Marine Fisheries Service, 1977. Oxygen depletion and associated environmental disturbances in the Middle Atlantic Bight in 1976. *Northeast Fisheries Center, Tech. Ser. Rep.* No. 3, Sandy Hook Laboratory, Highlands, N. J., 483 pp.

Ogren, L., and Chess, J., 1969. A marine kill on New Jersey wrecks. *Underwater Naturalist* 6(2):4–12.

Pearce, J. B., 1972. The effects of solid waste disposal on benthic communities in the New York Bight, in Mario Ruivo (ed.), *Marine Pollution and Sea Life*, Fishing News (Books) Ltd., London, 404–411.

Perlmutter, Alfred, 1952. Mystery on Long Island. *The New York State Conservationist* 6(4):11, The New York Conservation Department, Albany, N.Y.

Segar, D. A., and Berberian, G. A., 1976: Oxygen depletion in the New York Bight Apex: causes and consequences, *Amer. Soc. Limnol. Oceanogr. Spec. Symp.* 2:220–239.

Segerstrale, S. G., 1969. Biological fluctuations in the Baltic Sea. *Progr. Oceanogr.* 5:169–184.

Seki, H., Tsuji, T., and Hattori, A., 1974. Effect of zooplankton grazing on the formation of the anoxic layer of Tokyo Bay. *Estuar. Coastal Mar. Sci.* 2:145–151.

Sharp, J. K. (ed.), 1976. Anoxia on the Middle Atlantic Shelf during the summer of 1976. Report of workshop held in Washington, D.C., October 15 and 16, 1976, Contract No. OCE7700465, Office for the International Decade of Ocean Exploration, National Science Foundation, University of Delaware, Lewes, Del., 122 pp.

Sindermann, C. J., 1970. *Principal Diseases of Marine Fish and Shellfish.* Academic Press, New York, N.Y., 369 pp.

Sindermann, C. J., 1976. Oyster mortalities and their control. *FAO Technical Conference on Aquaculture, Tokyo, Japan,* DOC FIR: Aq. 76/R34, FAO, Rome, 25 pp.

Swanson, R. L., 1977. Status of ocean dumping research in New York Bight. *J. Waterway, Port, Coastal, and Ocean Division ASCE,* vol. 103, no. WW1, Proc. paper 12722, pp. 9–24.

Theede, H., Ponat, A., Hiroki, K., and Schlieper, C., 1969. Studies on the resistance of marine bottom invertebrates to oxygen-deficiency and hydrogen sulfide. *Mar. Biol.* 2:325–337.

Thomas, J. P., Phoel, W. C., Steimle, F. W., O'Reilly, J. E., and Evans, C. A., 1976. Seabed oxygen consumption—New York Bight Apex., in M. G. Gross (ed.), Middle Atlantic Continental Shelf and New York Bight, *Amer. Soc. Limnol. Oceanogr. Spec. Symp.* 2:354–369.

Tsuji, J. P., Seki, H., and Hattori, A., 1973. Results of red tide formation in Tokyo Bay. *J. Water Pollution Control Fed.* 46:165–172.

Young, J. S., 1973. A marine kill in New Jersey coastal waters. *Mar. Pollution Bull.* 4(5):70.

Young, J. S., 1974. Unpublished data on observations of fish mortalities related to wrecks. Sandy Hook Laboratory, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, Highlands, N.J.

# Oxygen Depletion and Associated Benthic Mortalities in New York Bight, 1976

# Chapter 2. Temporal Development of Physical Characteristics

*Robert B. Starr*[1] *and Frank W. Steimle*[2]

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## OBSERVATIONS OF WATER COLUMN

Environmental conditions in New York Bight waters were observed in 1976 by personnel of the Atlantic Oceanographic and Meteorological Laboratories (AOML) on four expanded water-column characterization (XWCC) cruises on NOAA ships *George B. Kelez* and *Researcher* (Hazelworth et al. 1977a, 1977b, 1978; Starr et al. 1977) and by personnel of the Sandy Hook Laboratory of the National Marine Fisheries Service (NMFS) on numerous vessels. Locations of XWCC station sites, and the vertical sections described here, are shown in figure 2–1. As many of these sites as possible were occupied on a repeat basis in April, May, June, and September 1976. This sequence of observations defines the physical conditions of the water column and the associated distribution of dissolved oxygen.

Bight waters consist basically of relatively fresh shelf water with warmer, saltier continental slope water seaward and quite fresh Hudson-Raritan estuarine water at the Apex. Expanded water-column characterization cruise observations indicate that the spring/summer distribution of dissolved oxygen in bottom waters of the Bight is closely related to the strength and depth of the pycnocline. The pycnocline—that part of the water column where density increases rapidly with depth—is an inverse function of temperature and a direct function of salinity.

In the Bight in spring and summer, temperature decreases with depth and salinity increases with depth at a greater rate than during other seasons, causing density to increase rapidly with depth, and the depth of the pycnocline to increase as spring advances into summer. When the pycnocline is well developed, it becomes a surface of density discontinuity and inhibits vertical mixing. Upper and lower limits of the pycnocline were determined from analyses of vertical density gradients based on density (sigma-*t*, $\sigma_t$)[3] values observed at 1-meter intervals of

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[3] Sigma-$t(\sigma_t)$ is defined as $[\rho(S,t)-1]1000$, where $\rho(S,t)$ is the value of seawater density in CGS units at standard atmospheric pressure.

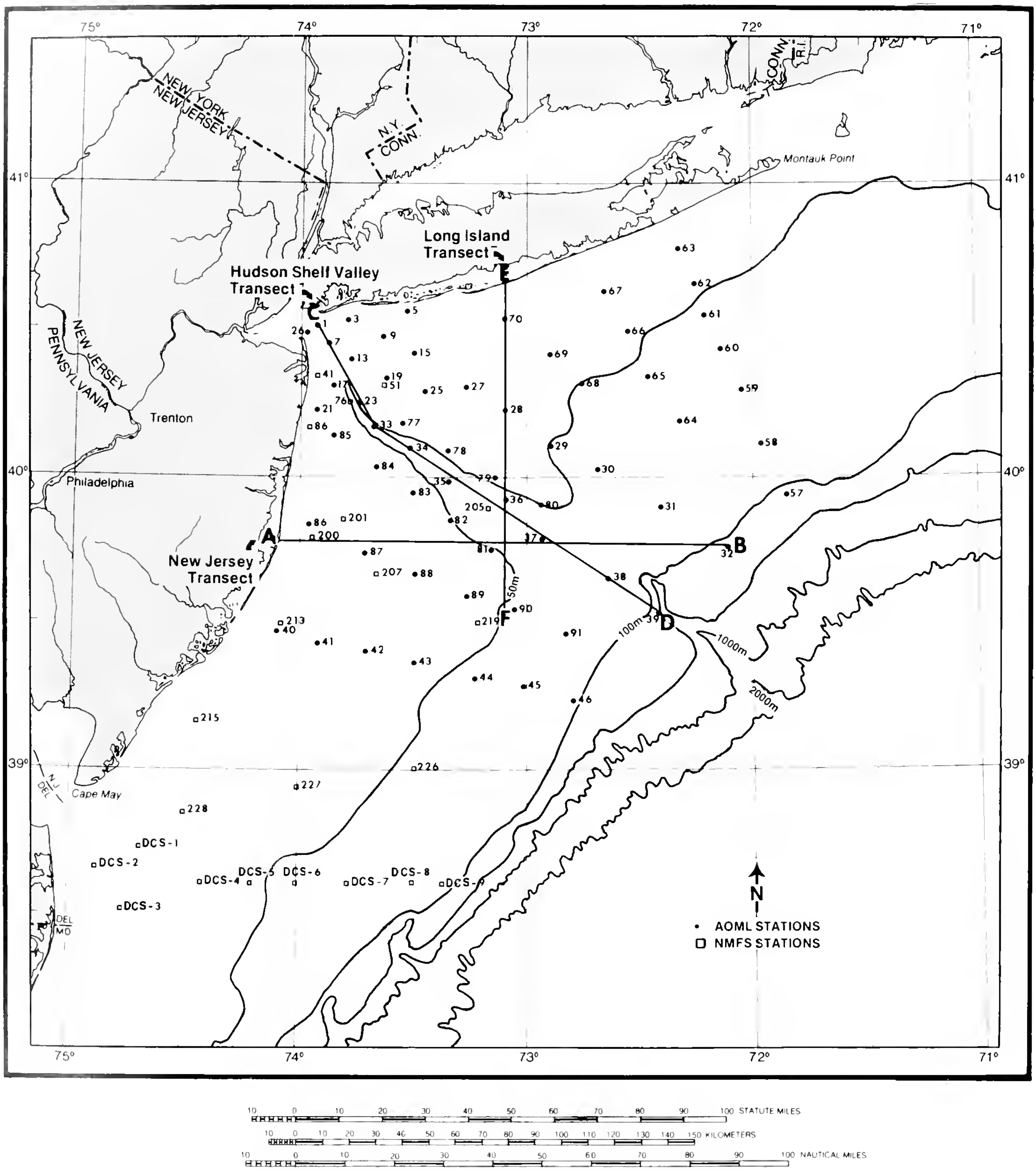

FIGURE 2-1 —Location of water-column sampling stations and sections along which observed values are plotted.

depth. The pycnocline is poorly developed in spring, at which time it is characterized by a weak gradient (more than 0.05 or 0.10 $\sigma_t$ units/m). As the season progresses the pycnocline becomes better developed and is characterized by stronger gradients (as much as 0.10 $\sigma_t$ units/m), and there is greater variability of physicochemical conditions above and below the pycnocline.

## SEASONAL PROGRESSION IN 1976

The 1976 seasonal development of the pycnocline in New York Bight was controlled by two weather/climate-related events. Winter was severe enough to destroy the previous seasonal pycnocline in the shelf water through free and forced convection. The early onset of spring runoff from the Hudson-Raritan estuary established a halocline in the Bight Apex. The dominant flow from the estuary in April was around Sandy Hook and south along the New Jersey coast (fig. 2–2). This dominant flow and the strongly developed halocline disappeared to the east. Virtually no temperature structure is apparent in the April cruise data (fig. 2–3), but a prominent salinity gradient is evident (figs. 2–4 and 2–5). By May, significant stratification is indicated in both temperature and salinity sections (figs. 2–3, 2–4, 2–6, and 2–7). The effect of the seasonal thermocline is evident in figure 2–2. The density structure, which was localized by the outflow of relatively freshwater from the Hudson-Raritan estuary in April, was under the influence of the thermal structure in May throughout the Bight, as indicated by depth of the thermocline.

The strengthening of the halocline-controlled pycnocline by the rapidly developing thermocline was a regional phenomenon. Locally a tongue of warm, low-salinity water extended east and south from the mouth of the Hudson-Raritan estuary at the bottom of the pycnocline in May (figs. 2–6 and 2–7).

Bowman and Wunderlich (1977) examined historical temperature, salinity, and density data for New York Bight. Their findings are presented as monthly mean temperatures, seasonal salinity cycles, and seasonal mean density distributions. Relative to these climatological conditions, the April 1976 surface waters were about 1° to 2° C warmer than normal and bottom waters temperatures were up to 2.5° C warmer than usual. In May, the surface temperature remained slightly above normal, while the bottom temperature (7.5–9.0° C) was normal to slightly (1° C) below normal. Consequently, the Bight water column was as thermally stratified as usual in May, a condition that might have existed earlier.

Turbulent mixing processes are inhibited by stratification. Resistance to overturning (i.e., vertical exchange) in the water column was estimated by computing the change of $\sigma_t$ within the pycnocline. This stability indicator is shown for April in figure 2–8 and for May in figure 2–9. The weak pycnocline offshore and the stronger pycnocline associated with the outflow from the Hudson-Raritan estuary along the northern New Jersey coast is evident in the April cruise observations. One month later, stratification resulting from thermal enhancement of the pycnocline is apparent throughout the region, both inshore and offshore.

By late June, the horizontal temperature gradient at the bottom of the pycnocline increased inshore but did not change significantly offshore (fig. 2–10). However, the surface warmed approximately 7° C (fig. 2–11), and consequently a very strong thermocline developed. The salinity of the Hudson-Raritan outflow increased from 27‰ to 29‰, whereas no significant change occurred in the salinity distribution at the bottom of the pycnocline (fig. 2–12) relative to May (figs. 2–4 and 2–7). The effect of the strong thermocline on the density structure in June (fig. 2–13) is evident when compared to May (fig. 2–2). Consequently, the stability of the Bight-area water column increased significantly in June (fig. 2–14) compared to May (fig. 2–9), except for weakening of the halocline along the northern New Jersey coast associated with the declining Hudson-Raritan outflow (fig. 2–12). Between the halocline-supported, strong stability band along the northern New Jersey coast and the warmer offshore surface water is a relatively less stable zone of water extending southward from Long Island over the inner shelf floor (fig. 2–14).

The June 1976 surface and bottom temperatures of 20° C and 7.5° C, respectively, were about normal as compared to Bowman and Wunderlich (1977). Salinities ranged about 1.0‰ above average; densities, while slightly higher than normal, had a typical gradient (Bowman and Wunderlich 1977). By June, the thermocline became the dominant factor in the stratification and, because of its strength (~ 12.0° C change within a layer 20-m thick), isolated the bottom waters from the surface. The June conditions were the most stable observed in 1976.

The September data probably closely approximate the maximum seasonal development of water column stratification before its destruction by autumnal cooling and wind mixing. Water temperatures at the bottom of the pycnocline (fig. 2–15) were at their maximum and more variable than previously observed. The tongue of warm water was still present south of Long Island; and another tongue was present off central New Jersey. Differences in September and June water temperatures can be seen in figure 2–11, particularly for the Long Island section. Bottom waters, which were consistently colder than 8° C in June and earlier, warmed to about 10° C. A strong thermocline was still evident but was deeper in September. However, when the September data are compared with expendable bathythermograph (XBT) data obtained on a NMFS cruise of August 6–17 (fig. 2–27), surface cooling is suggested. This effect could have resulted from passage of hurricane Belle (discussed later).

By September, the salinity below the pycnocline had changed relative to June (fig. 2–12). It is difficult to compare the September and June salinity distribution at the bottom of the pycnocline because of the few observations in June. However, the salinity sections show a better developed halocline in inshore waters in June, at which time bottom water was more saline off New Jersey and in the shelf valley than in September. Surface water off Long Island (section E–F) was fresher in September than in June. The source of this relatively fresh water appears to be the Hudson-Raritan estuary (fig. 2–12).

The density difference, $\Delta\sigma_t$, was slightly less in September than in June (figs. 2–13, 2–14, and 2–16). By September the signature of the Hudson-Raritan outflow had disappeared, and, except for a relatively weak pycnocline associated with the fresher surface water off southwestern Long Island, there was no significant density difference in the pycnocline off New Jersey and Long Island. However, the pycnocline was weaker in these nearshore localities than offshore.

September presented a different picture than earlier months relative to the norm. Although surface temperatures were typical of the average, bottom waters, which had temperatures of 8° to 9° C (figs. 2–11 and 2–15), were considerably colder than the 12° C described by Bowman and Wunderlich (1977). Because salinity values continued to be somewhat high, densities were still above normal.

Seasonal development of the pycnocline was not reflected by significant changes in the depth or configuration of the pycnocline bottom or the salinity at the bottom of the pycnocline. With the exception of the Hudson-Raritan outflow, the bottom of the pycnocline seemed to be more closely related to the presence of offshore water.

Because of the depletion of oxygen in the subpycnocline bottom layer (ch. 6), the depth of the pycnocline bottom was used to determine the thickness of the bottom layer for the four XWCC cruises (figs. 2–17 to 2–20). The patterns of bottom layer thickness reflect isobathic control. In June, the pycnocline bottom generally was 3 m higher in the water column off New Jersey than off Long Island (fig. 2–19). However, the depth of the ocean floor is considerably less off New Jersey so that the thickness of the subpycnocline layer was about 3 to 5 m less than off Long Island. By September the bottom of the pycnocline was observed at greater depths off Long Island, which tended to equalize the thickness of the subpycnocline layer off the two coasts.

## OXYGEN DISTRIBUTION

Dissolved oxygen (D.O.) was determined by Winkler titration on all water samples collected at discrete depths with a Rosette multisampler attached to the conductivity-salinity-temperature-depth (CSTD) sensor. On the May and June cruises D.O. also was monitored with an oxygen probe on the CSTD, which functioned on a majority of the stations of these two cruises. Although slow in response time, this electrode allows a more accurate determination of the depths of oxygen maxima and minima than the discrete Winkler analyses.

The distribution of average D.O. concentration in the subpycnocline layer for May and June is shown in figures 2–23 and 2–24. These distributions were derived by averaging all the Winkler-determined oxygen values below the pycnocline at each station for each of these months. The decrease in available oxygen and increase in patchiness of its distribution between May and June are evident.

The vertical sections of D.O. for April, May, June, and September were determined from the water samples (figs. 2–21 and 2–22). The April oxygen range of 6.0 to 7.5 ml/l was what would be expected for weakly stratified waters at that time of year. In May oxygen levels began to reflect the onset of stratification, with some depletion to under 5 ml/l in the bottom water and some increase to as much as 9 ml/l near the top of the pycnocline. In June, a very strong gradient in oxygen values developed through the pycnocline (figs. 2–13 and 2–22). High values (over 9 ml/l) near the top of the pycnocline occurred offshore and low values (as little as 0.5 ml/l) were present below the pycnocline, particularly near the head of the Hudson Shelf Valley. Over the shelf valley, the minimum oxygen values were not observed at the bottom but in the 30- to 40-m depth range.

By September, the high oxygen values in the top of the pycnocline disappeared so that the D.O. in the mixed surface layer had average values of about 5.25 ml/l. Below this, seaward over the shelf, the oxygen gradient was very strong, from 5 ml/l to 2 ml/l between 20 and 30 m depth. On the inner shelf floor (fig. 2–22), D.O. values were well below 2 ml/l, and off New Jersey below 1 ml/l. Close to shore, the oxygen content was below the detection limit of the Winkler titration. Offshore, in continental slope water, oxygen values ranged between 4 and 5 ml/l. As observed earlier in the Hudson Shelf Valley, the minimum generally was not at the bottom except near the head of the valley in Christiaensen Basin.

The D.O. probe values were used to determine the depth of the main oxygen minimum above the bottom (figs. 2–25 and 2–26). In both cases, the minimum "grounded" in the vicinity of northern New Jersey and was terminated by the relatively highly oxygenated discharge from the Hudson-Raritan estuary, which in this location averaged about 5 ml/l, and showed no significant gradient across the pycnocline (figs. 2–21 and 2–22). The oxygen minimum was always below the base of the pycnocline but its distance from the bottom generally decreased from May to June except in the Hudson Shelf

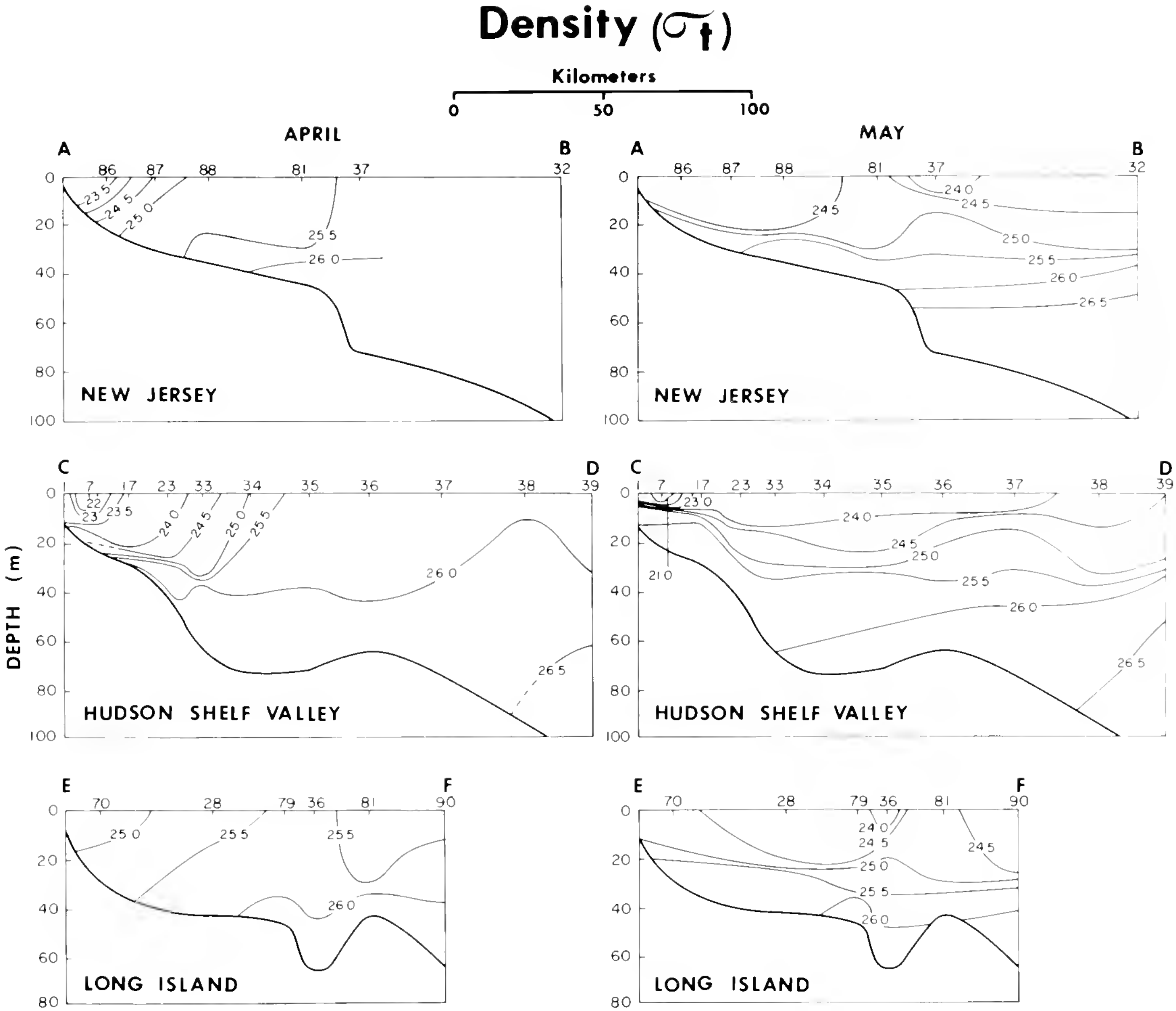

FIGURE 2-2 —April and May 1976 density($\sigma_t$) sections

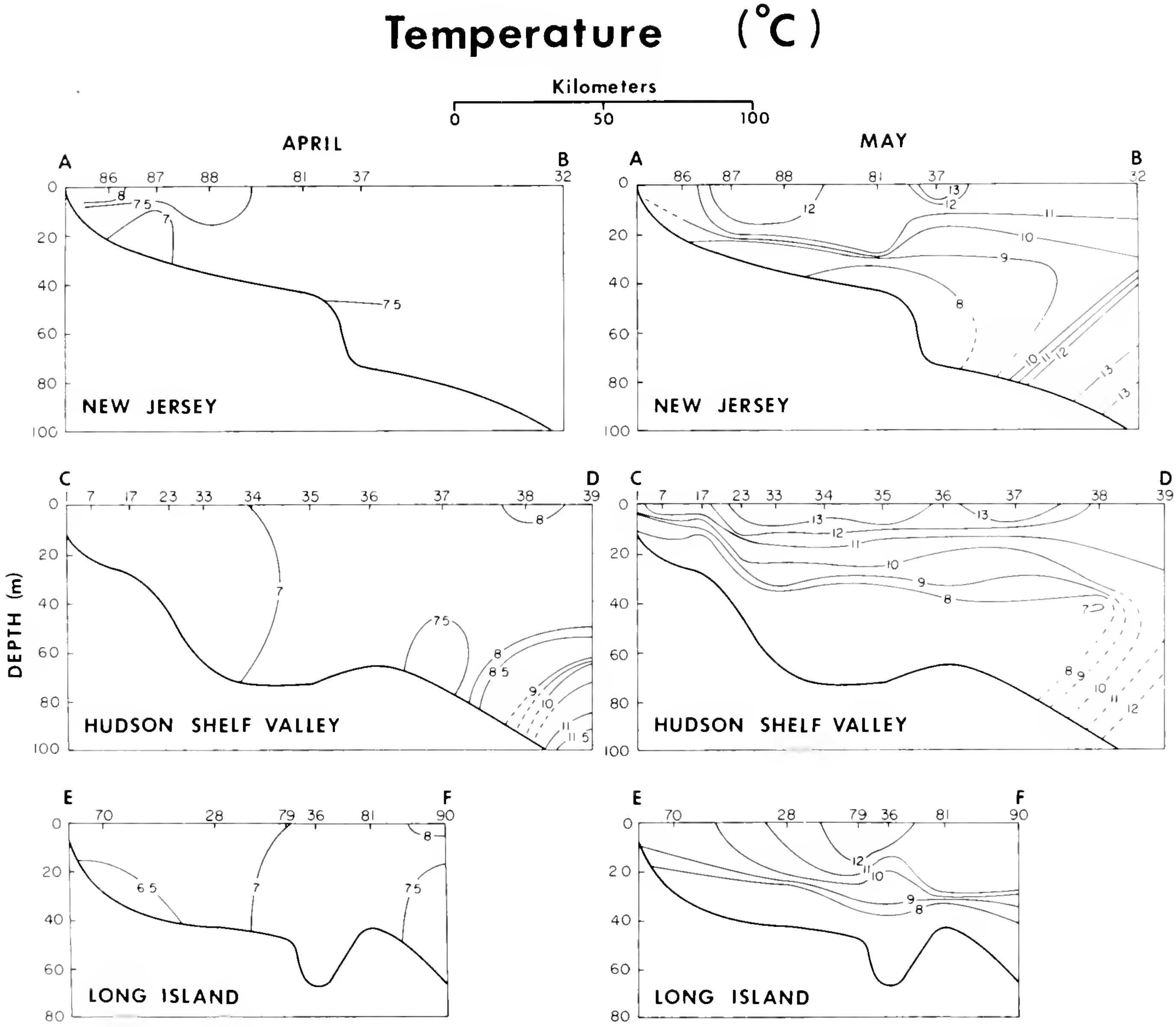

FIGURE 2-3.—April and May 1976 temperature (°C) sections.

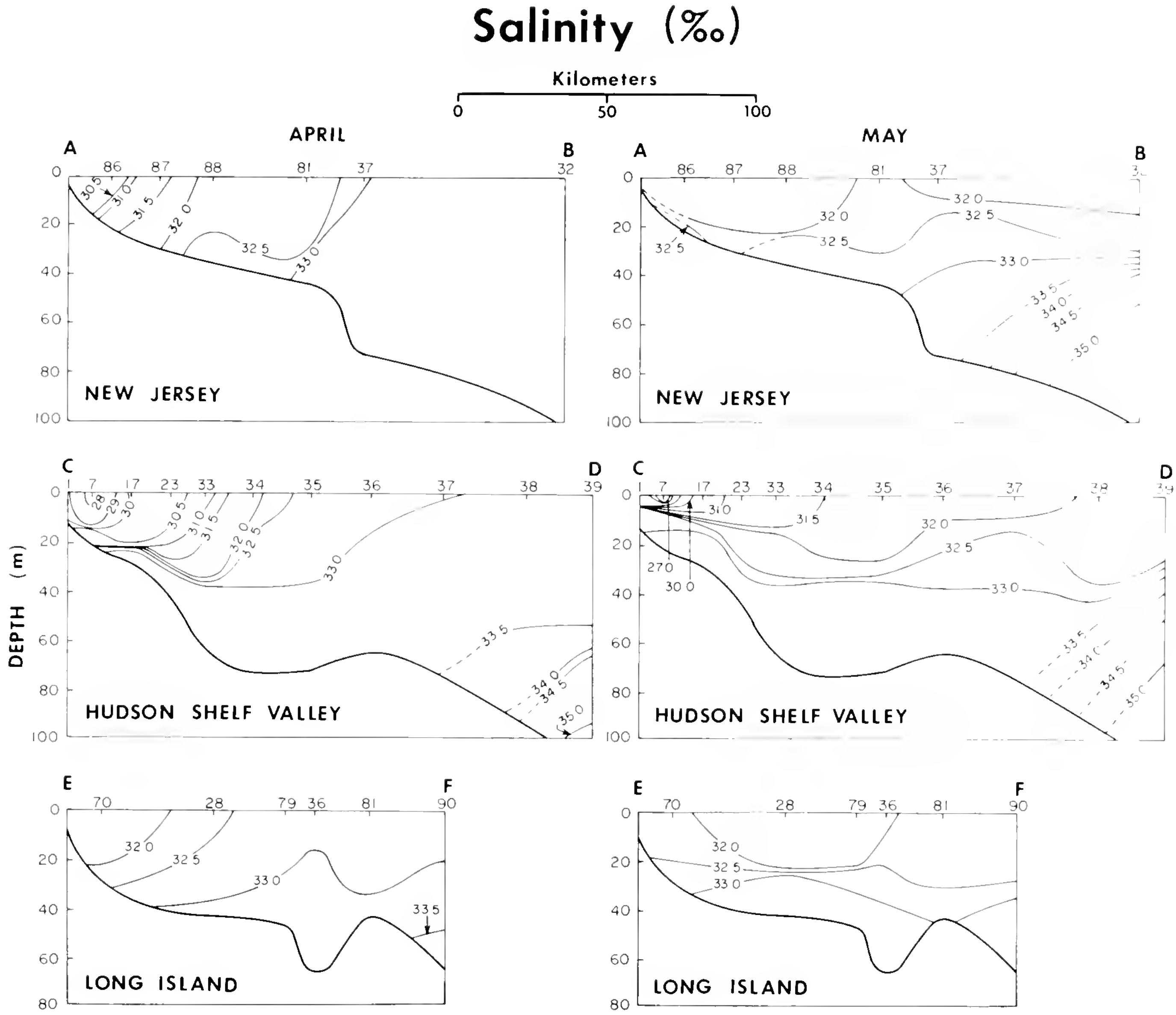

FIGURE 2-4.—April and May 1976 salinity (‰) sections.

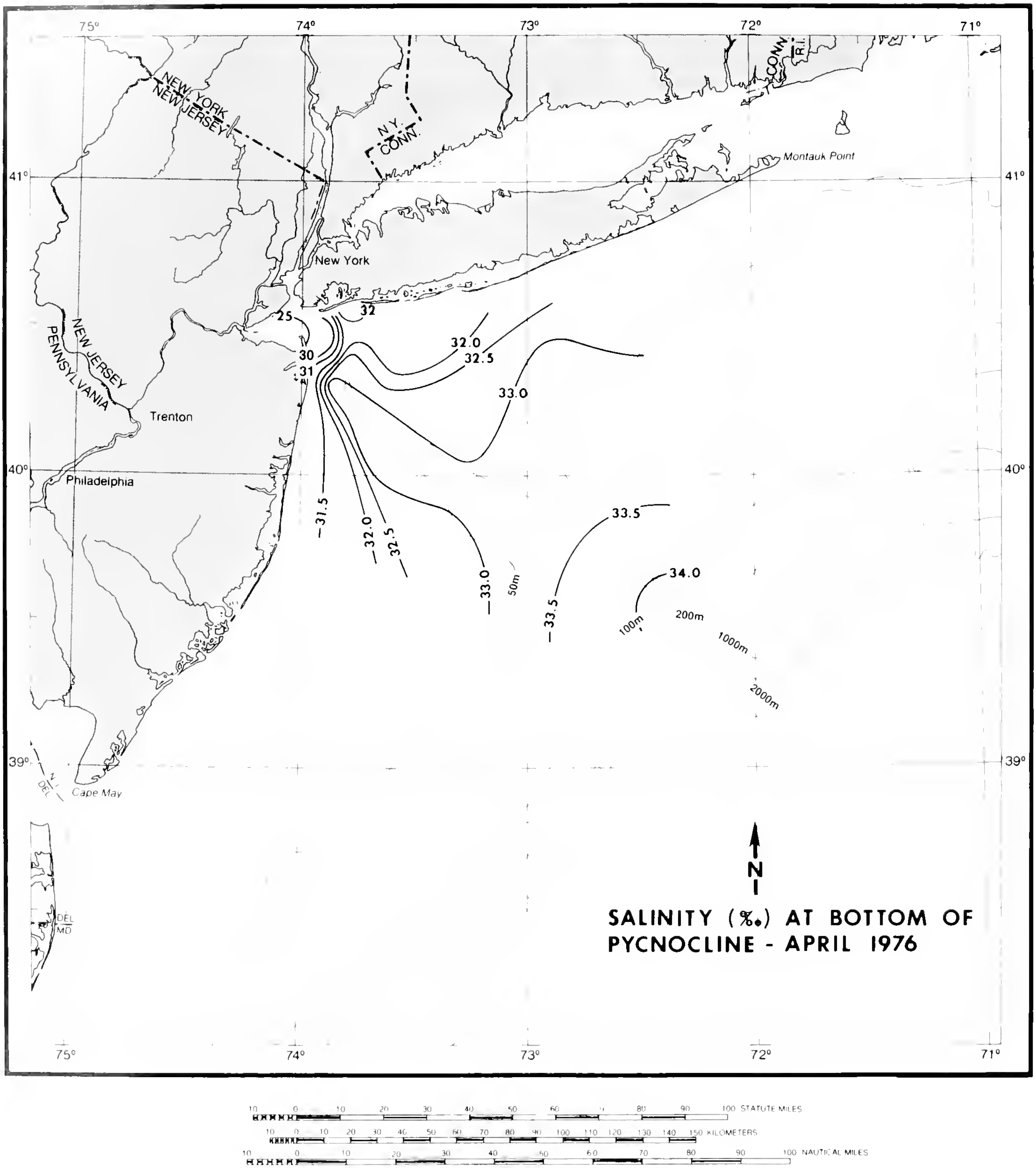

FIGURE 2-5.—April 1976 distribution of salinity (‰) at bottom of pycnocline.

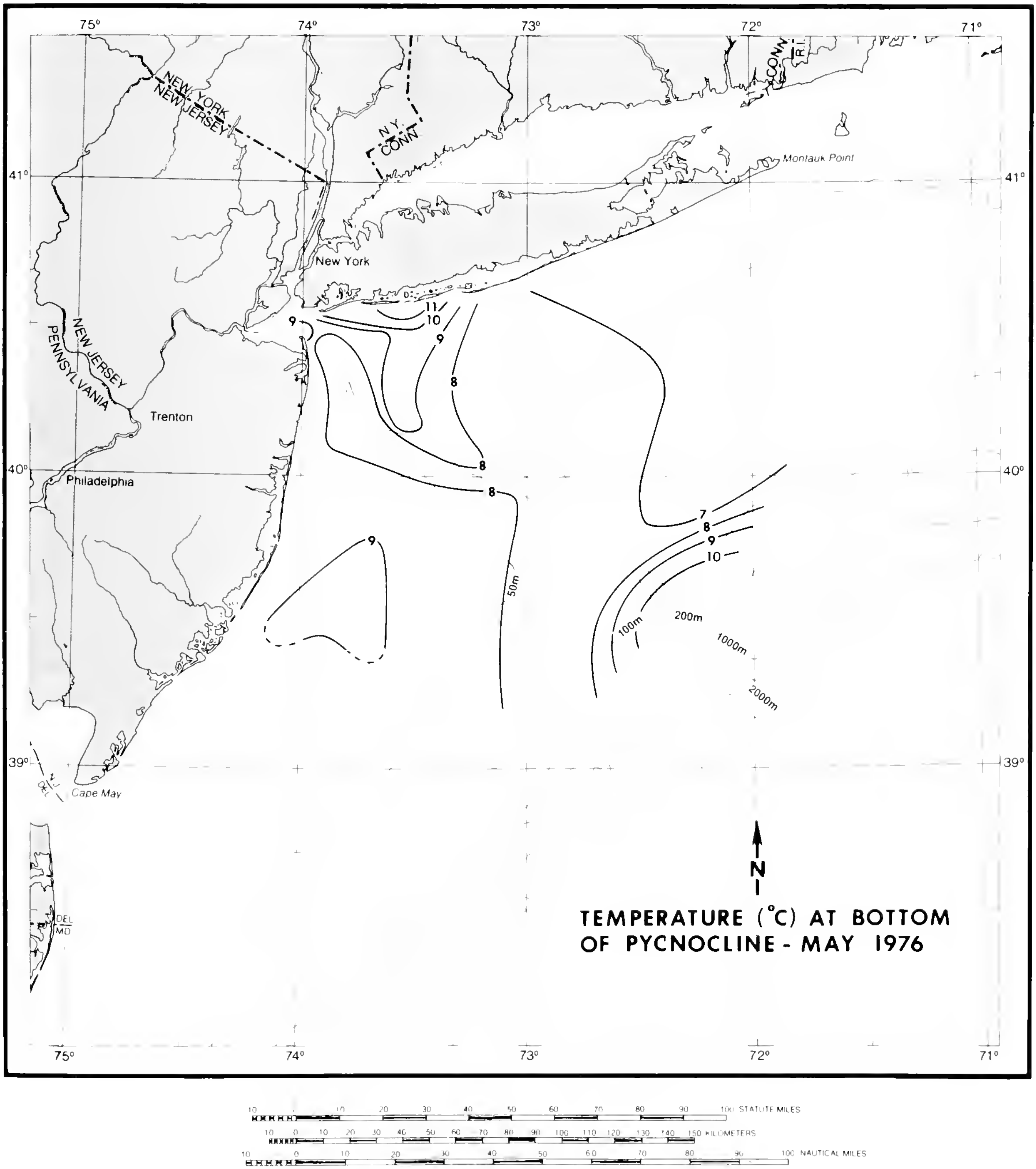

FIGURE 2-6.—May 1976 distribution of temperature (°C) at bottom of pycnocline.

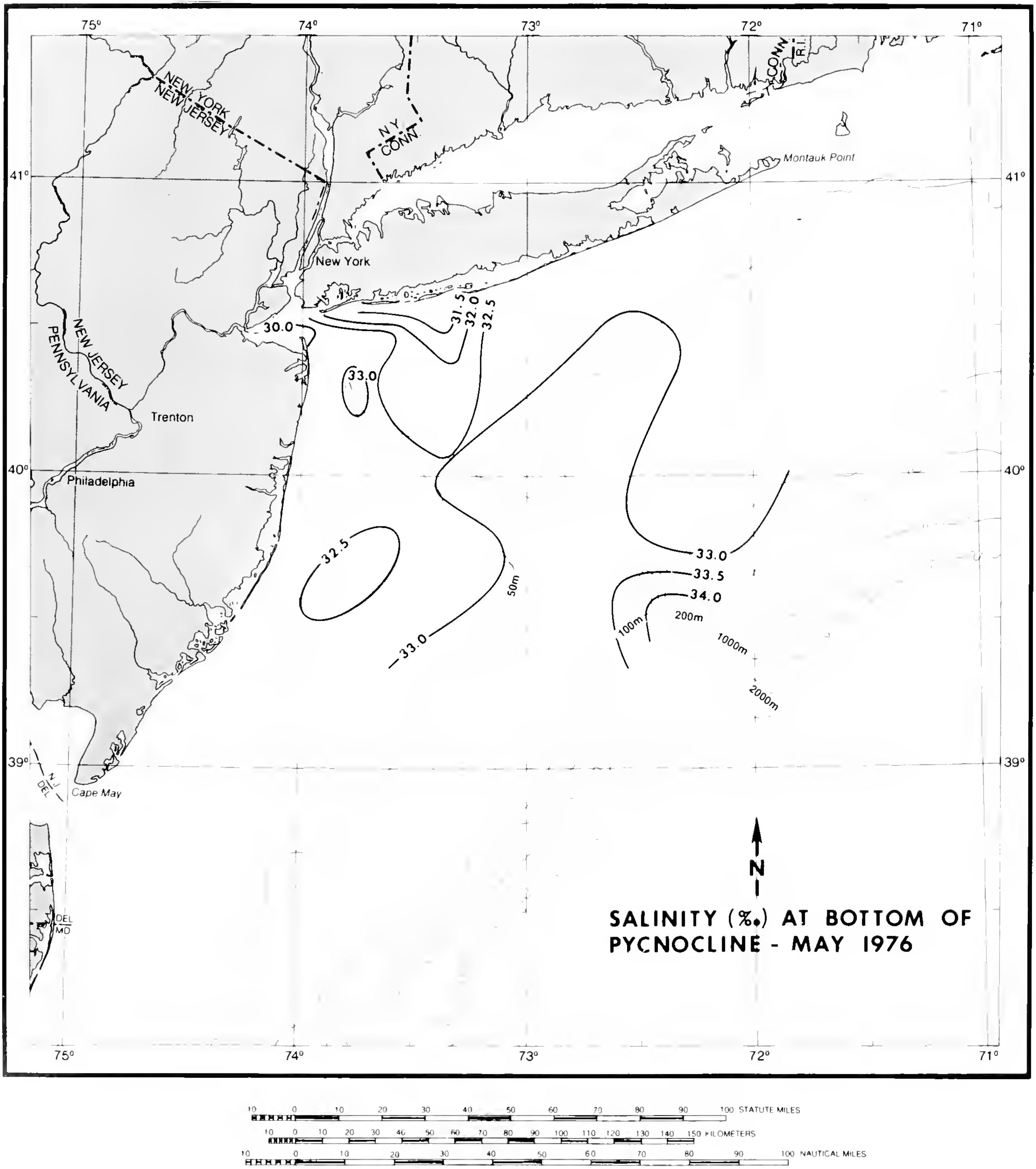

FIGURE 2-7.—May 1976 distribution of salinity (‰) at bottom of pycnocline.

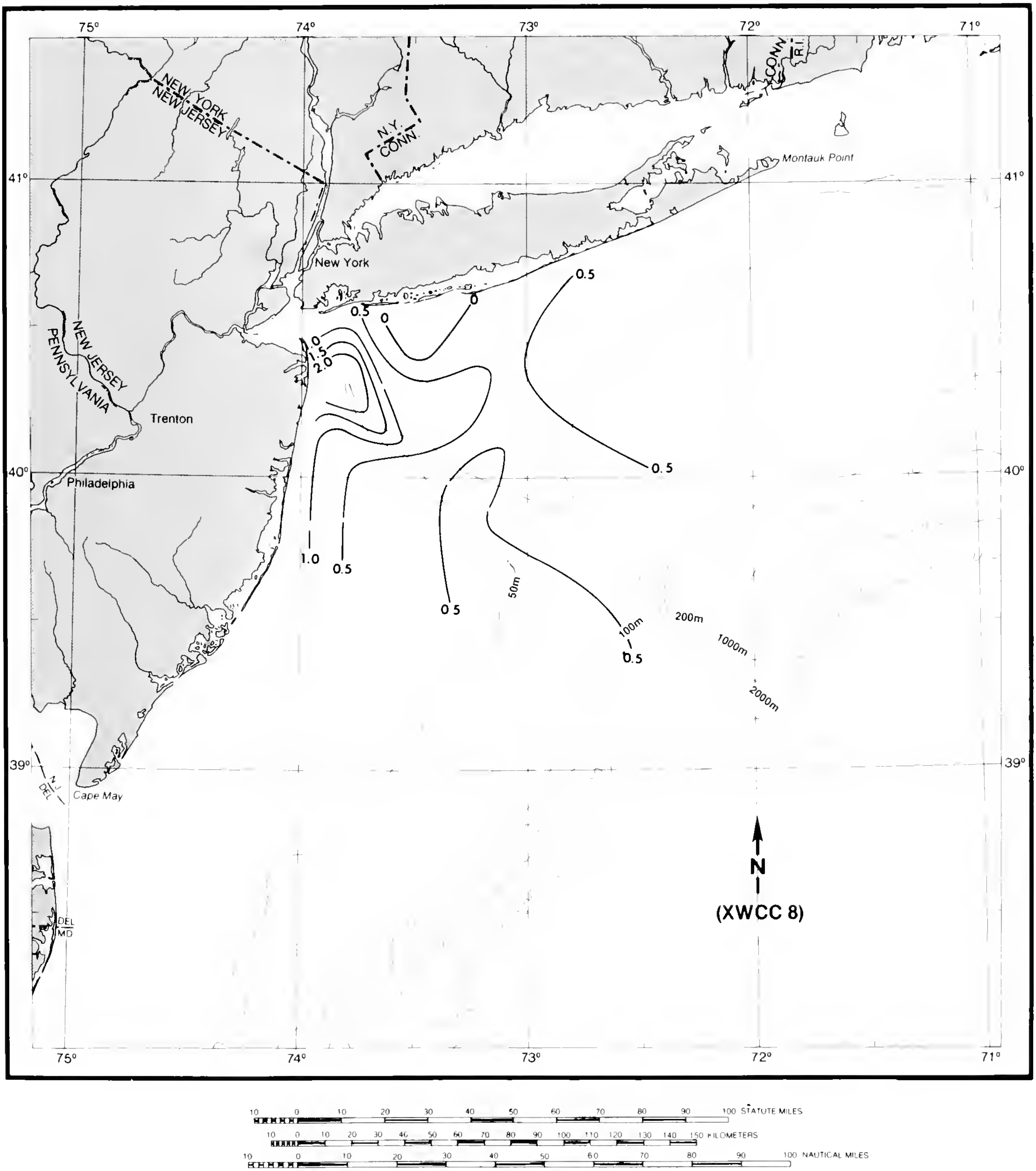

FIGURE 2-8.—April 1976 distribution of pycnocline density-difference ($\Delta\sigma_t$) values. Expanded water-column characterization cruise 8.

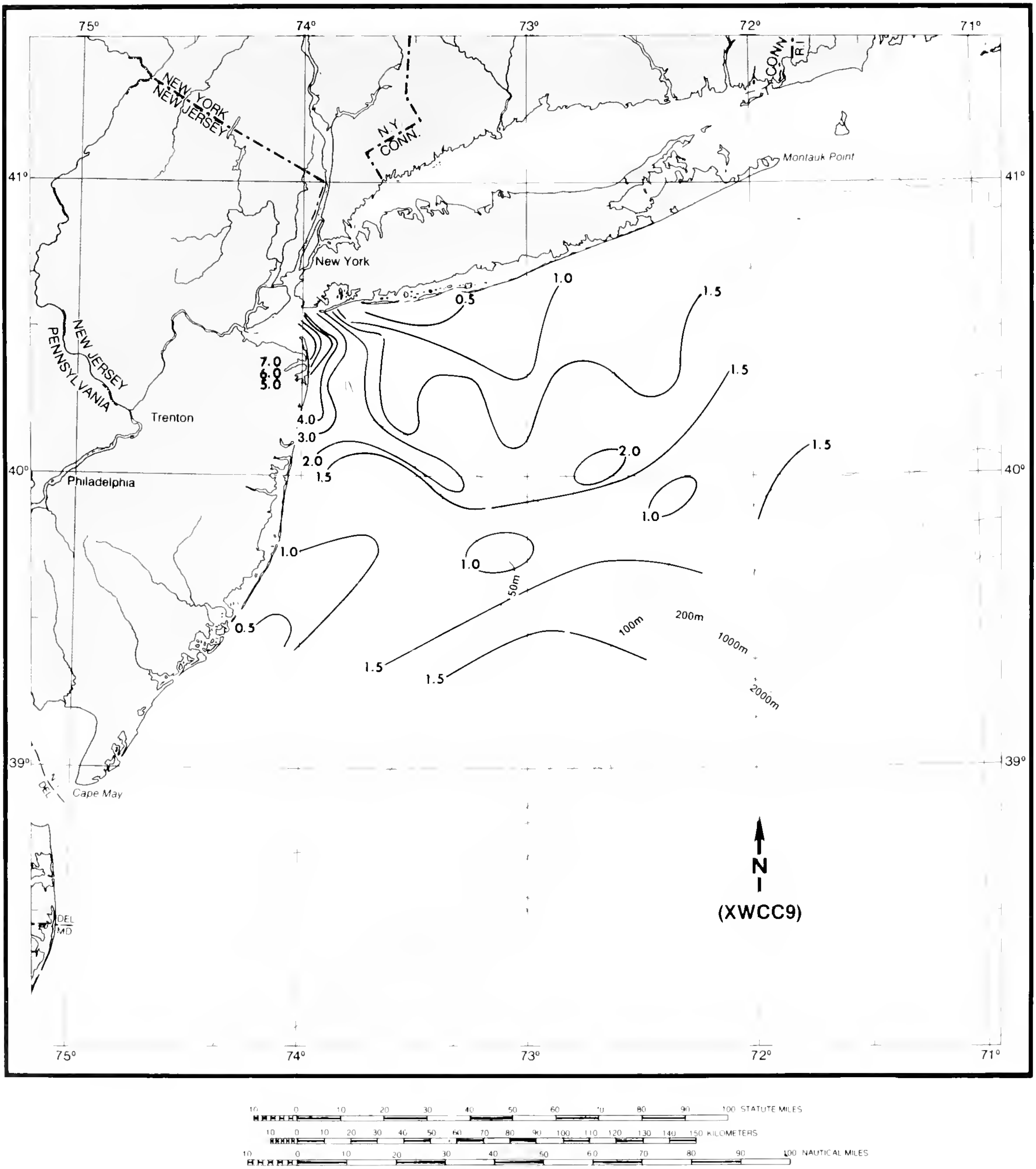

FIGURE 2-9.—May 1976 distribution of pycnocline density-difference ($\Delta\sigma_t$) values. Expanded water-column characterization cruise 9.

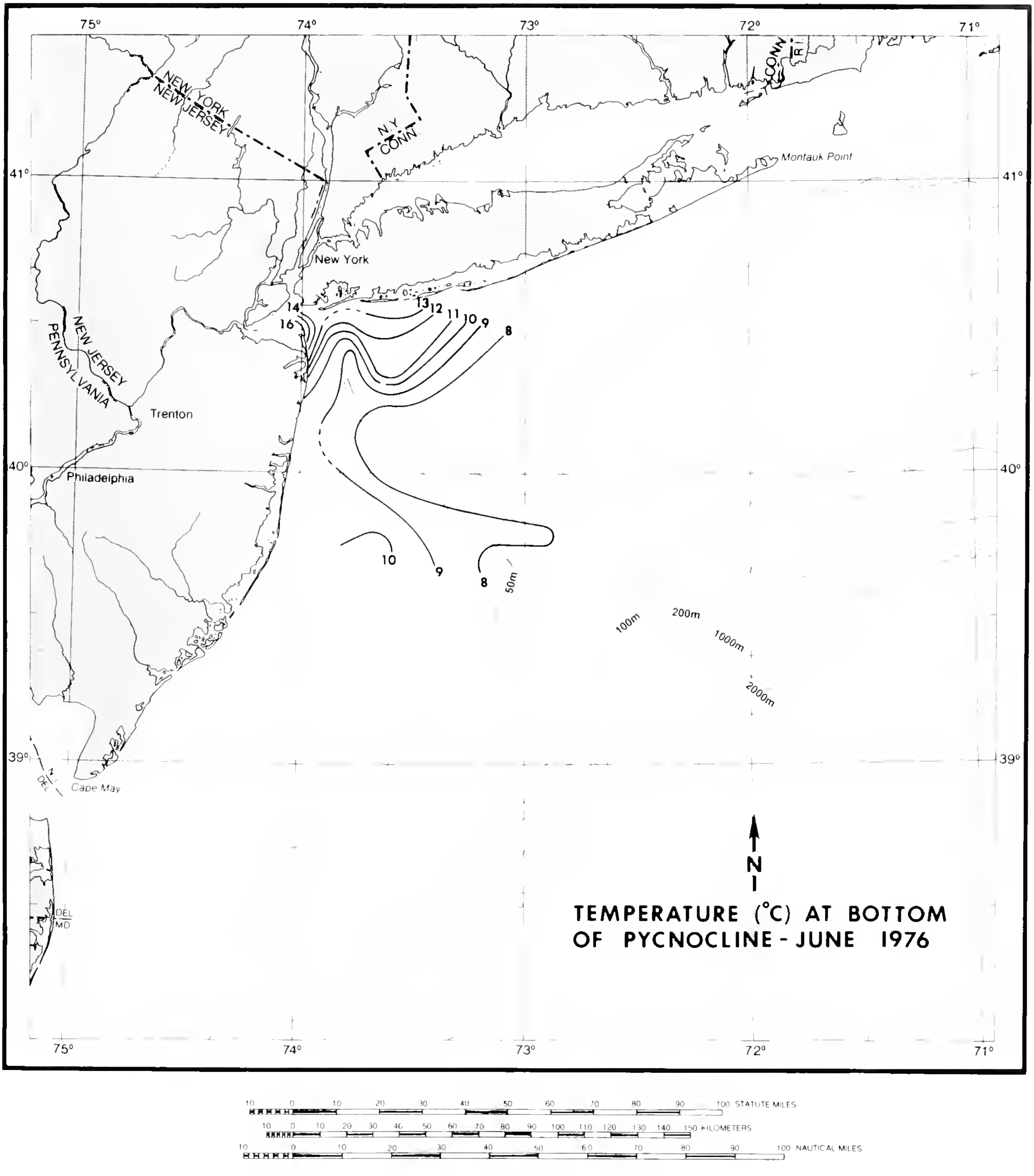

FIGURE 2-10.—June 1976 distribution of temperature (° C) at bottom of pycnocline.

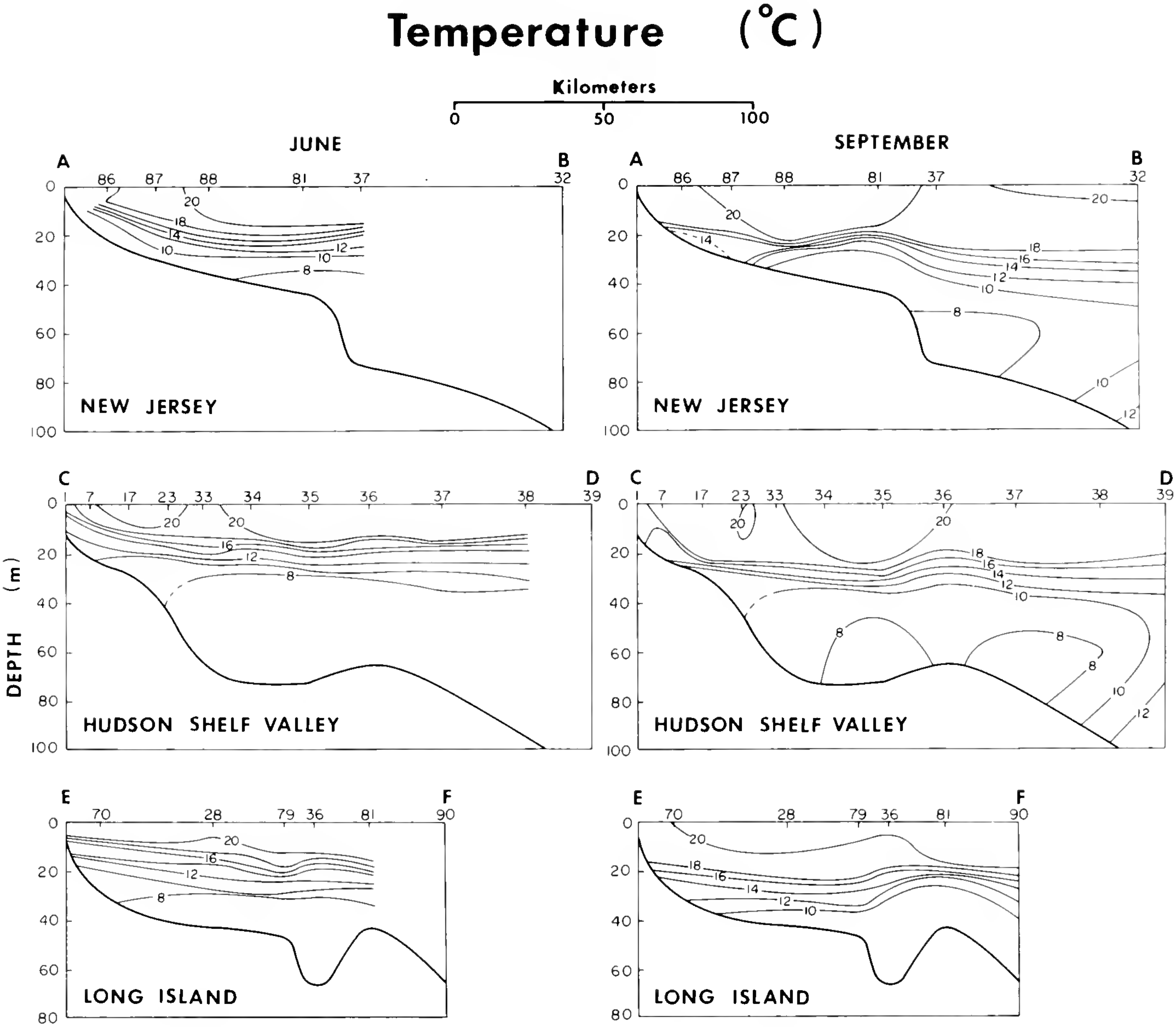

FIGURE 2-11.—June and September 1976 temperature (° C) sections.

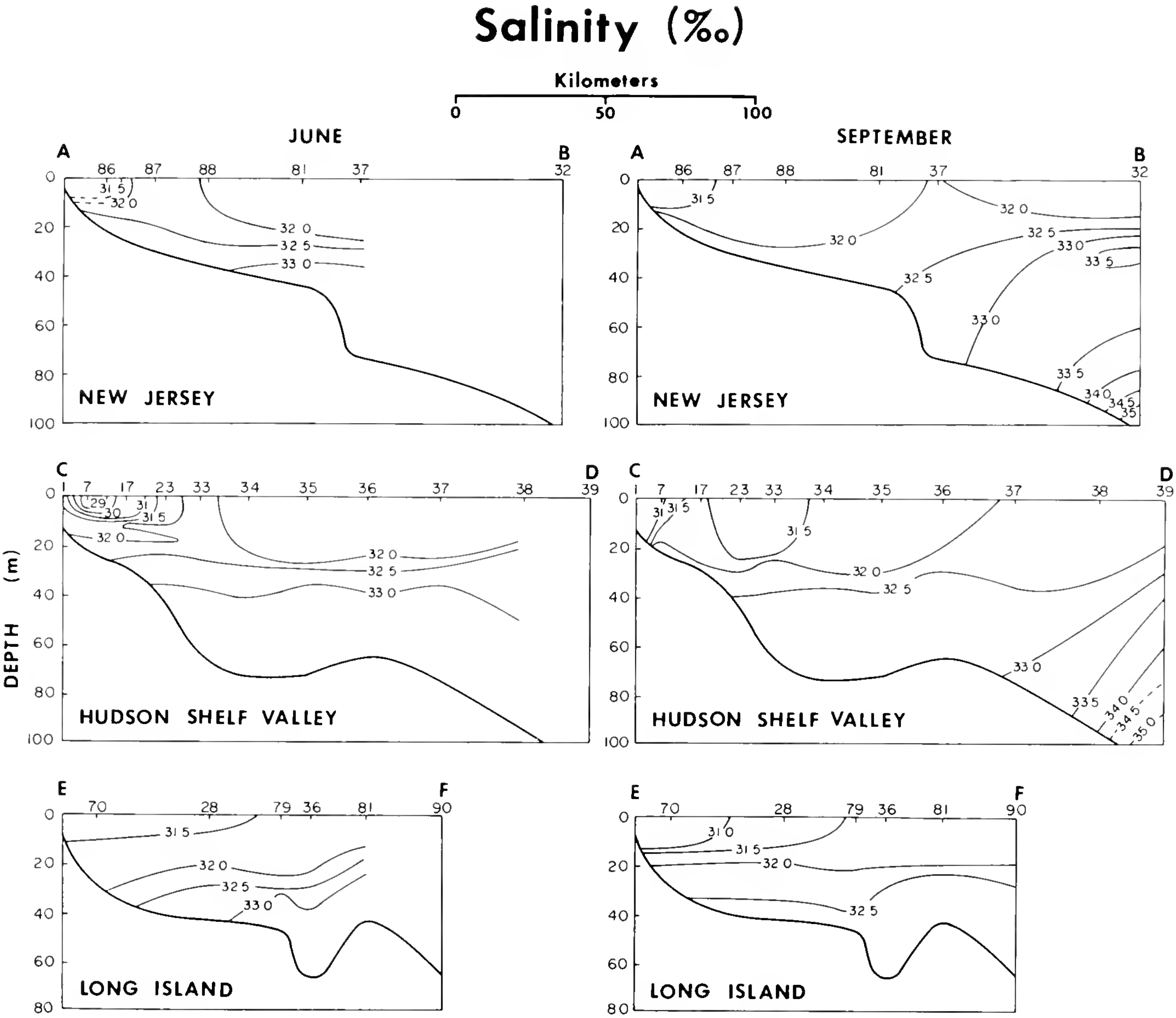

FIGURE 2-12.—June and September 1976 salinity (‰) sections.

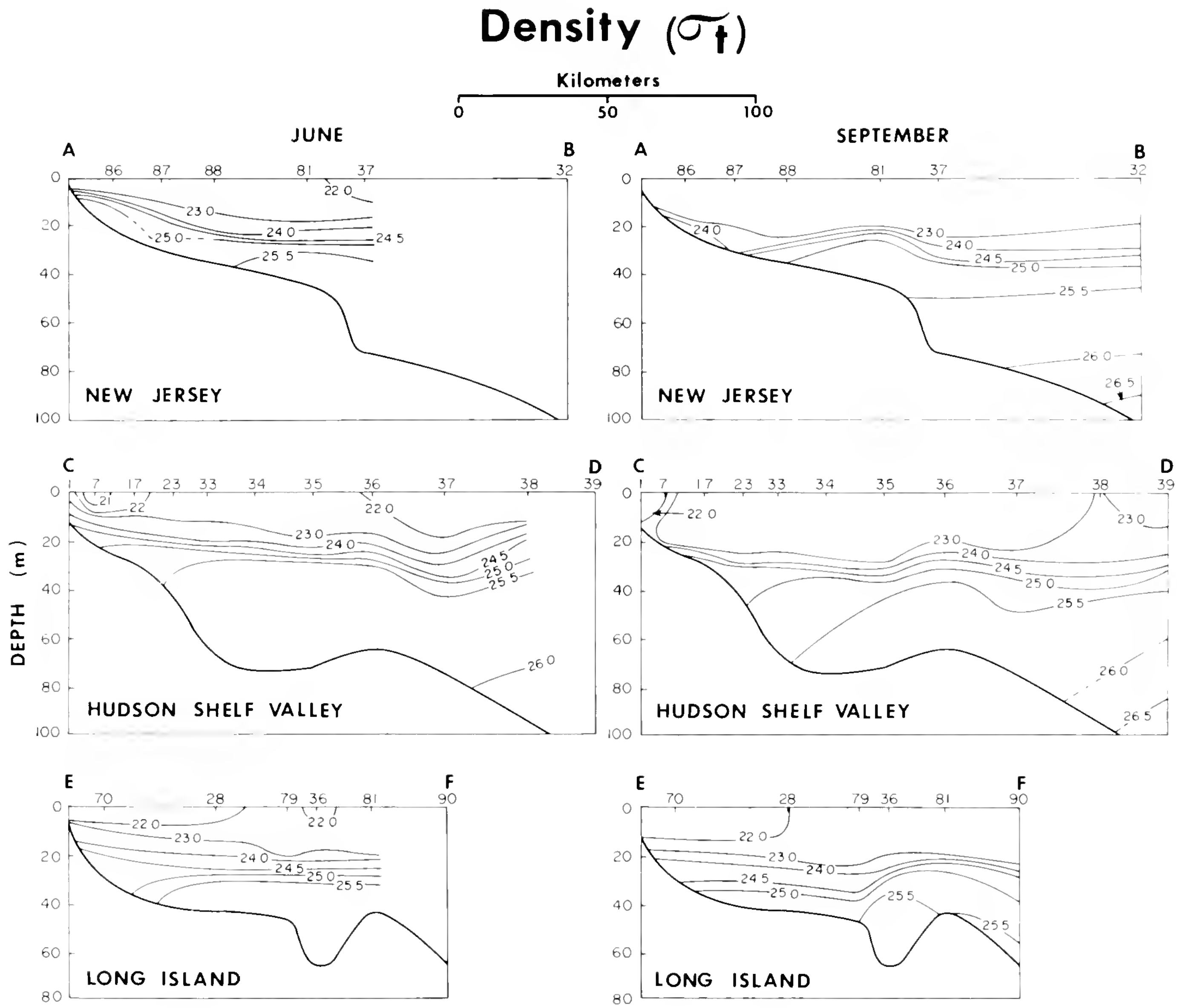

FIGURE 2-13.—June and September 1976 density ($\sigma_t$) sections.

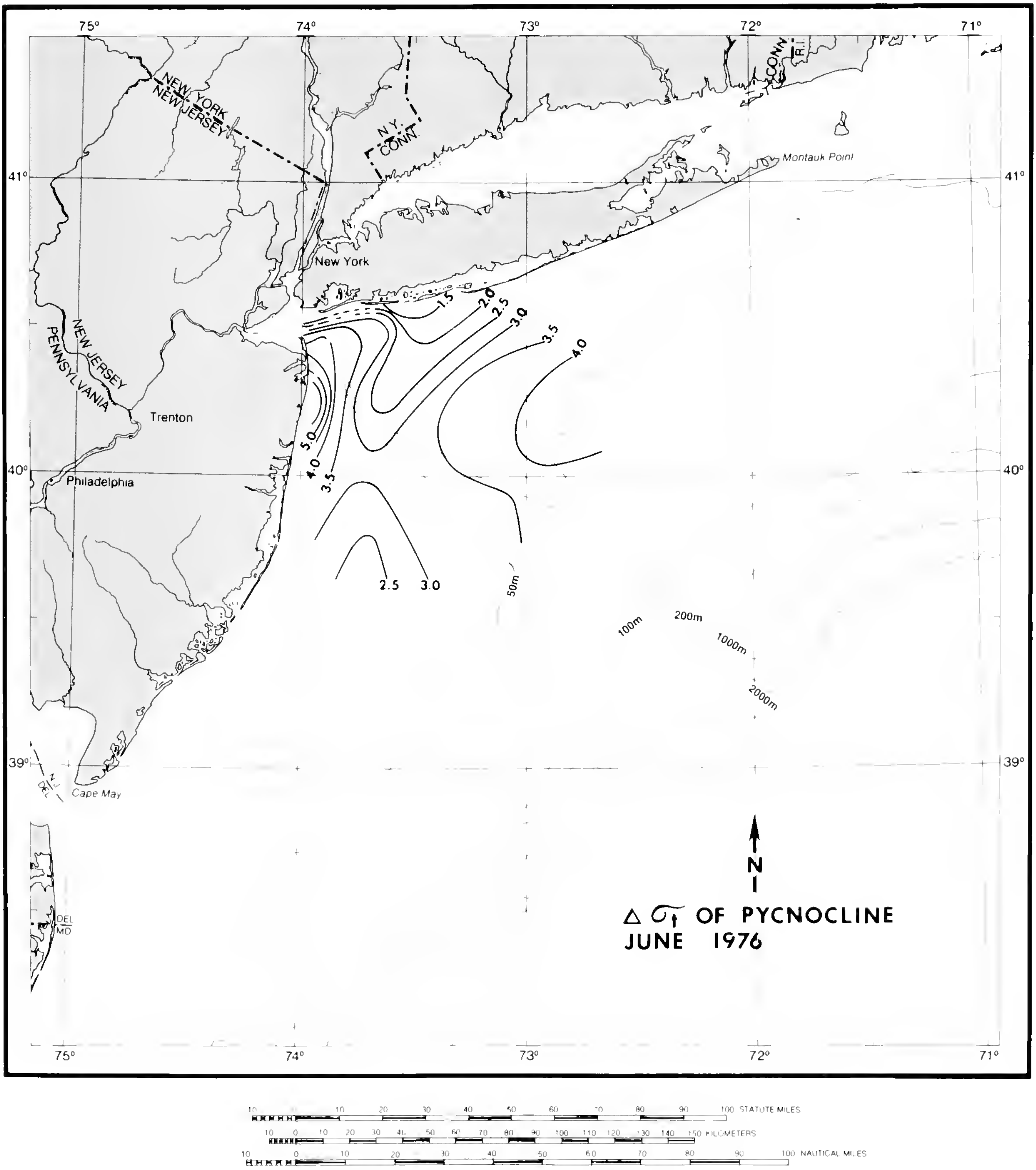

FIGURE 2–14 —June 1976 distribution of pycnocline density-difference ($\Delta\sigma_t$) values

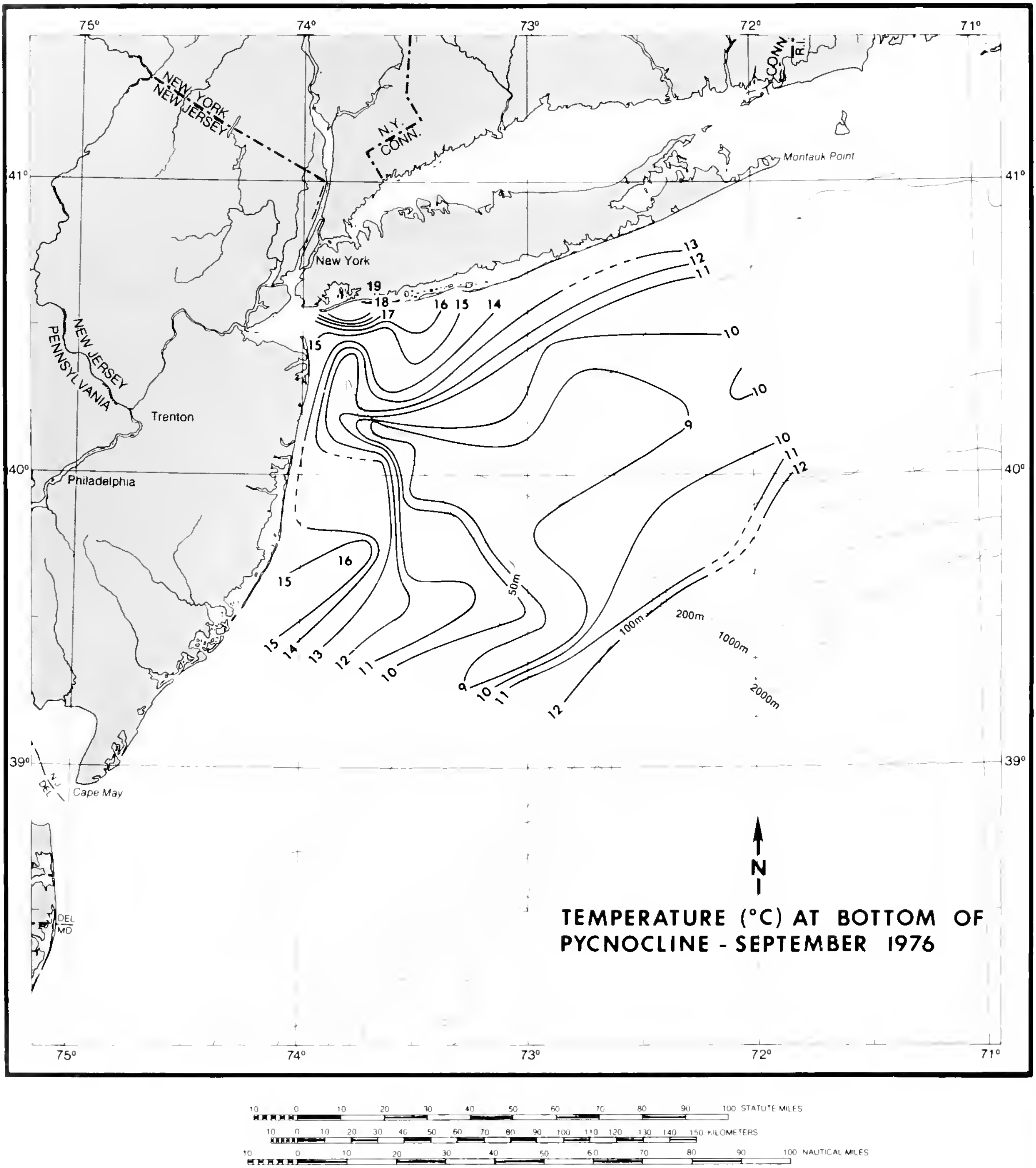

FIGURE 2-15.—September 1976 distribution of temperature (° C) at bottom of pycnocline.

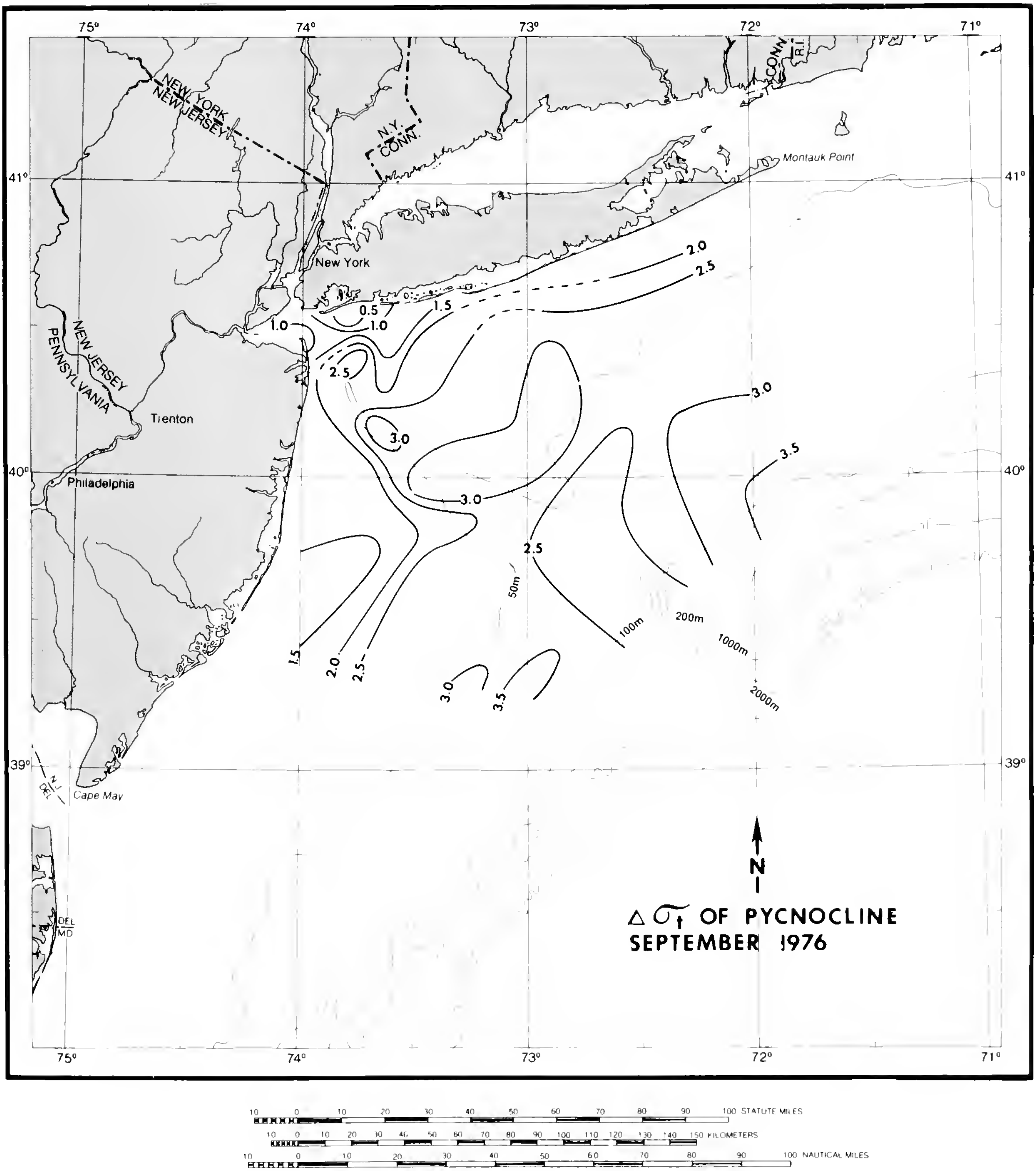

FIGURE 2-16.—September 1976 distribution of pycnocline density-difference ($\Delta\sigma_t$) values.

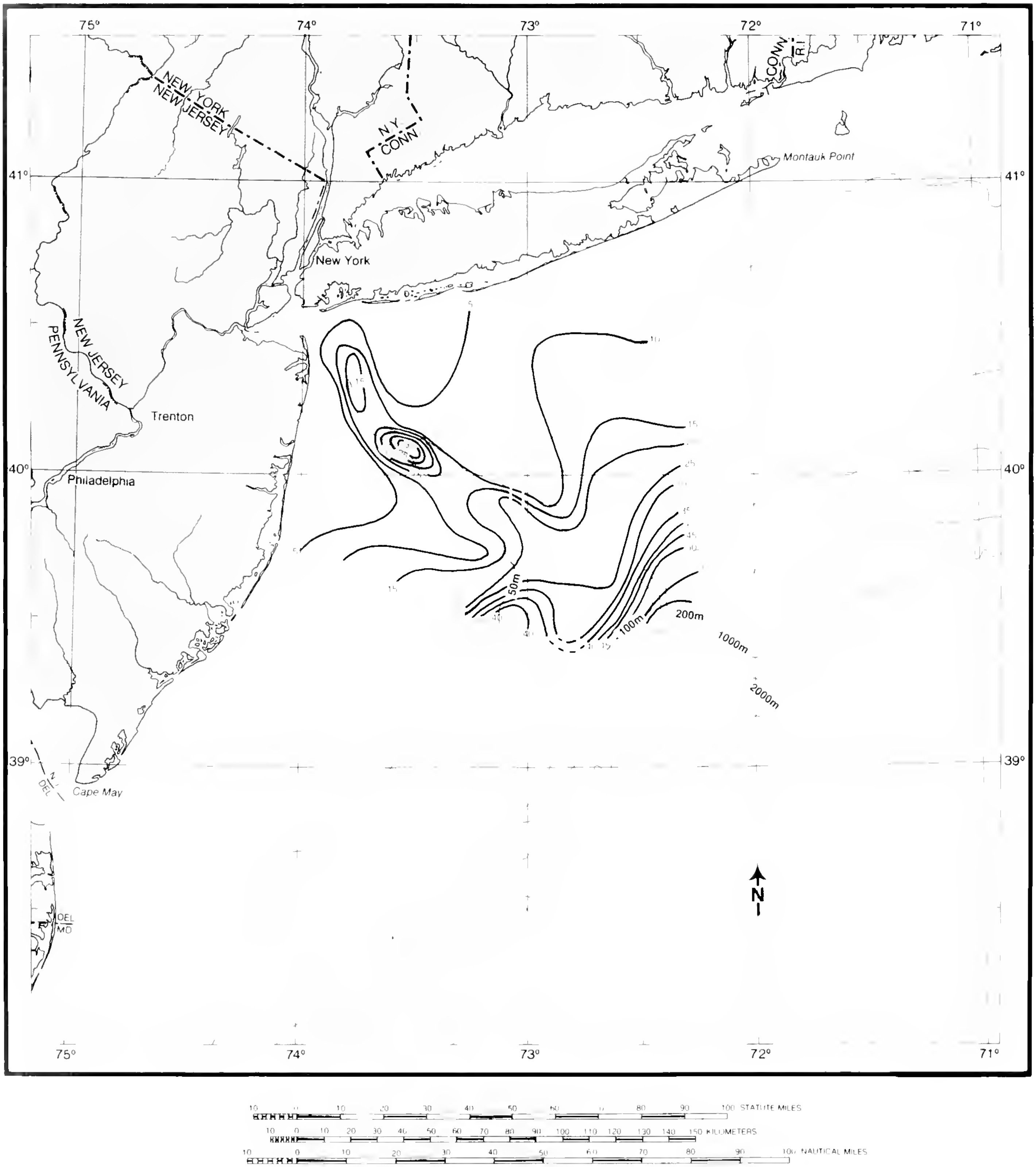

FIGURE 2-17.—April 1976 distribution of bottom-of-pycnocline distance (m) above sea-floor values.

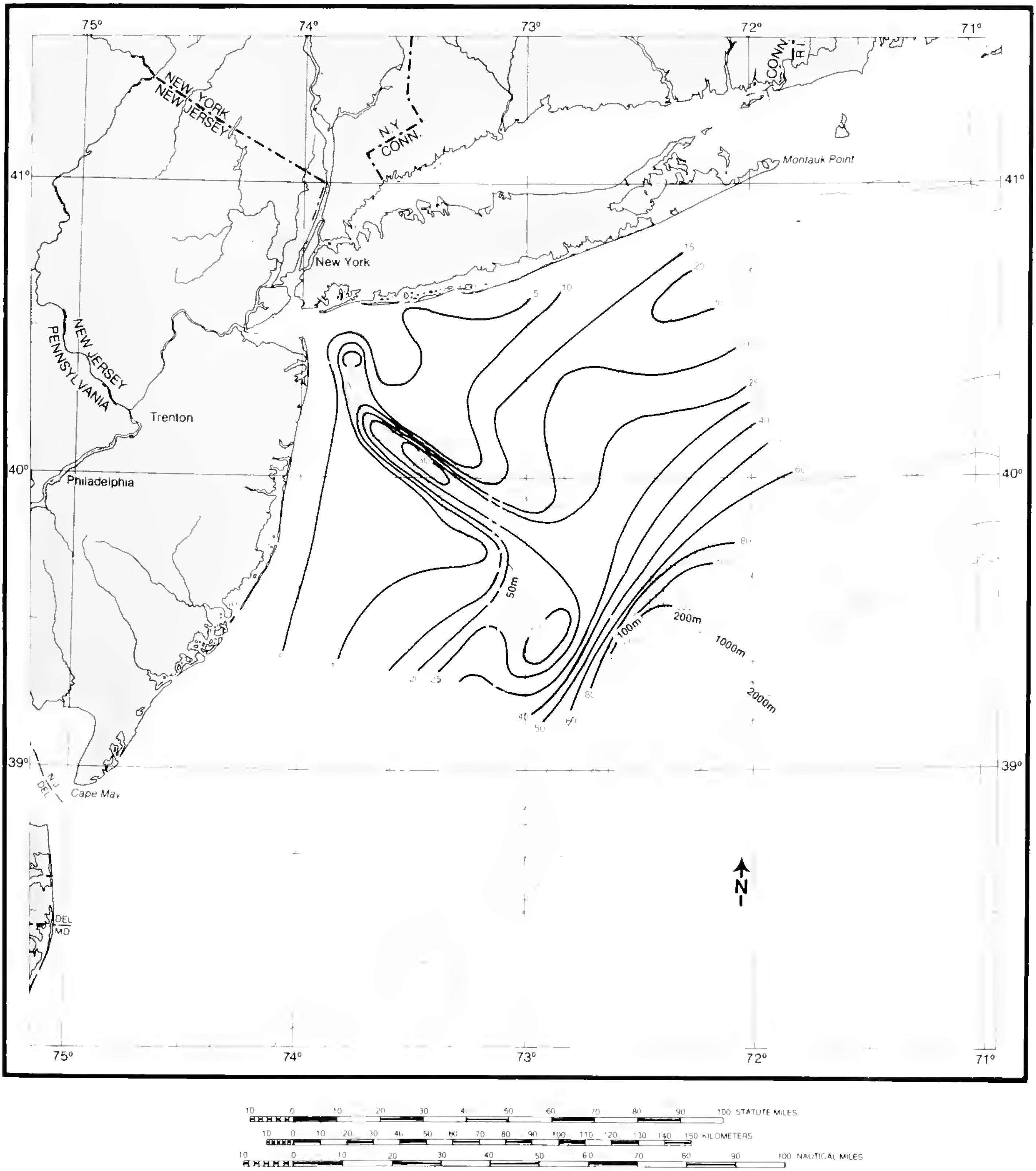

FIGURE 2-18.—May 1976 distribution of bottom-of-pycnocline distance (m) above sea-floor values.

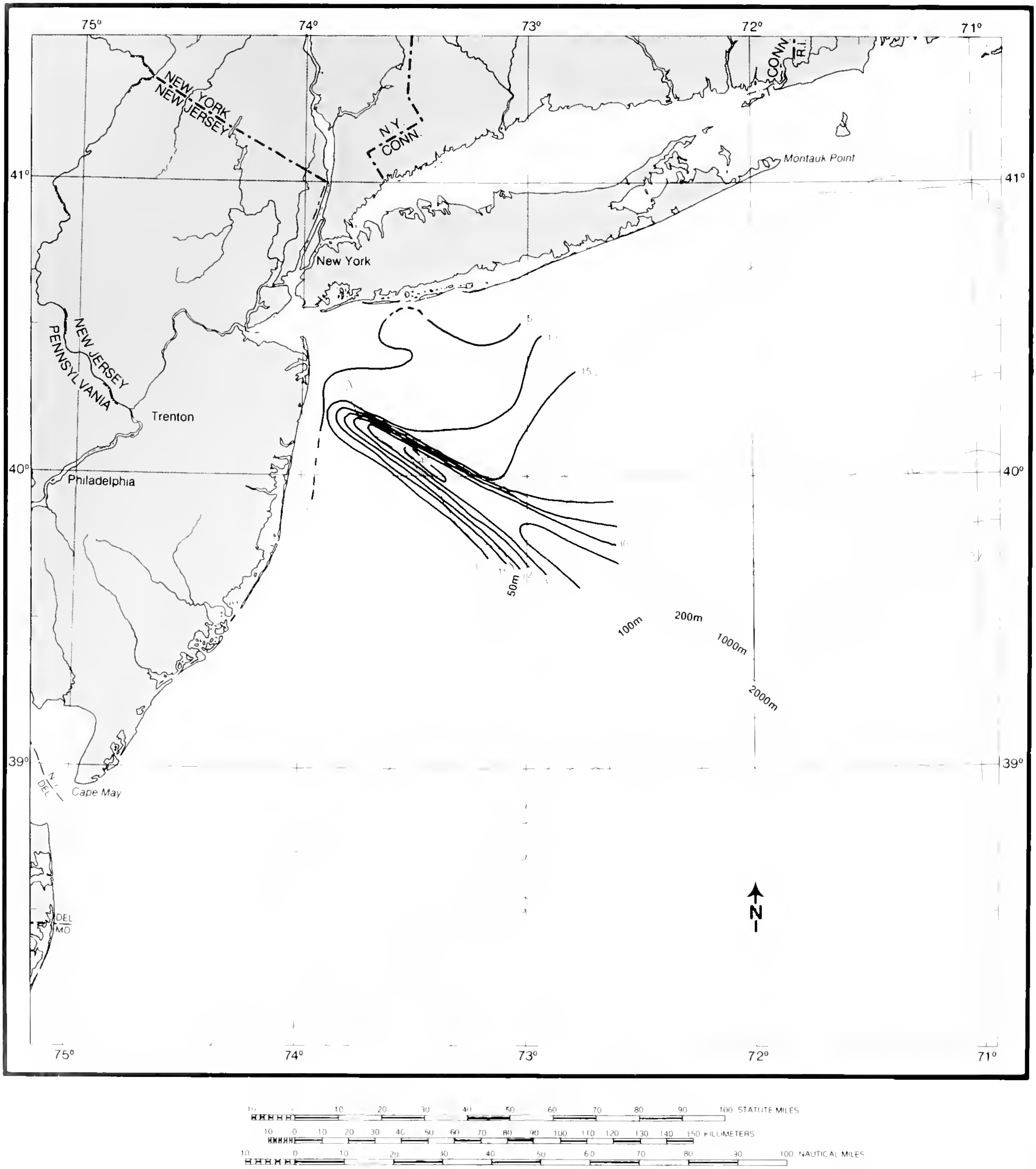

FIGURE 2-19.—June 1976 distribution of bottom-of-pycnocline distance (m) above sea-floor values.

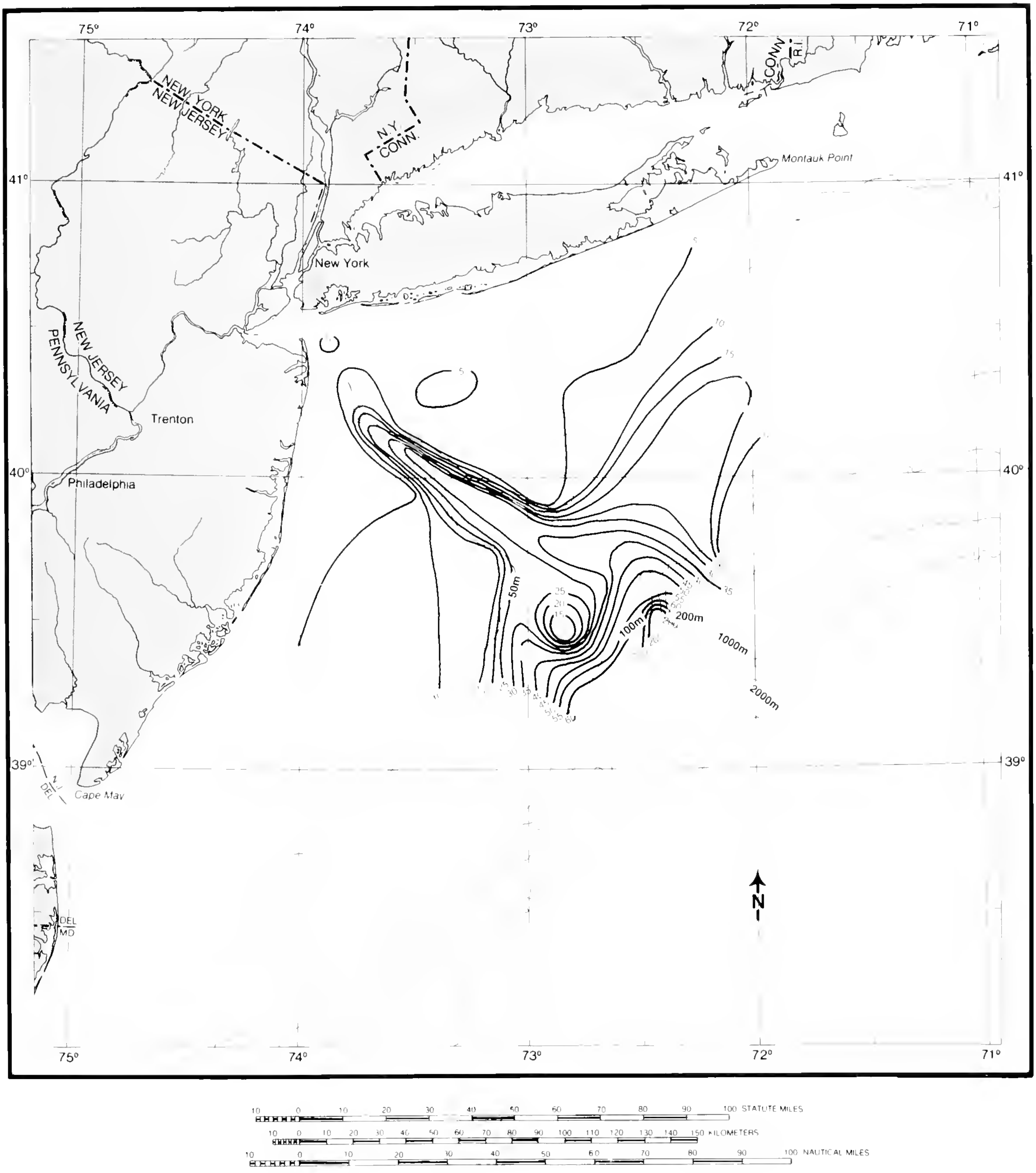

FIGURE 2-20.—September 1976 distribution of bottom-of-pycnocline distance (m) above sea-floor values.

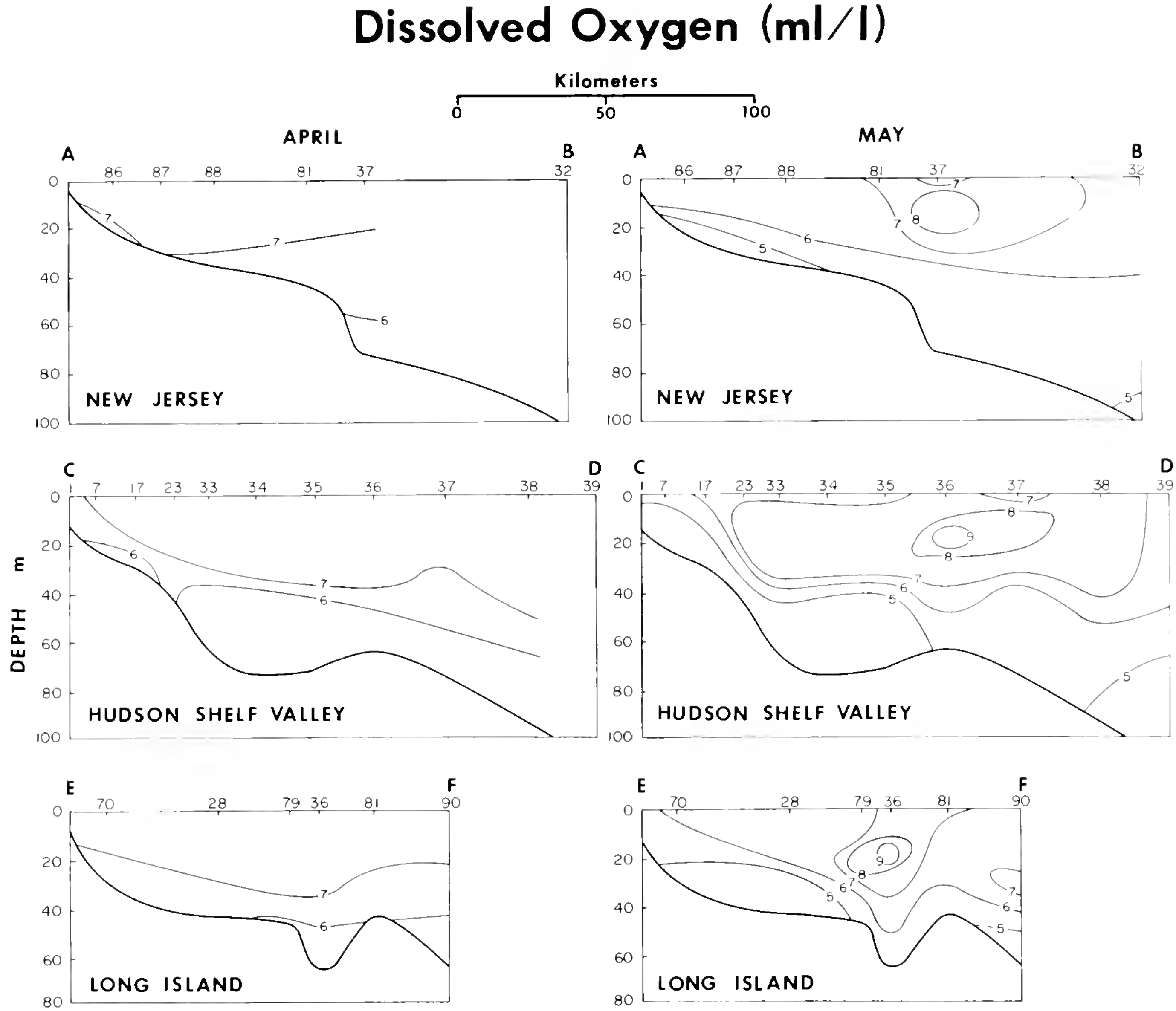

FIGURE 2-21.—April and May 1976 dissolved oxygen (ml/l) sections.

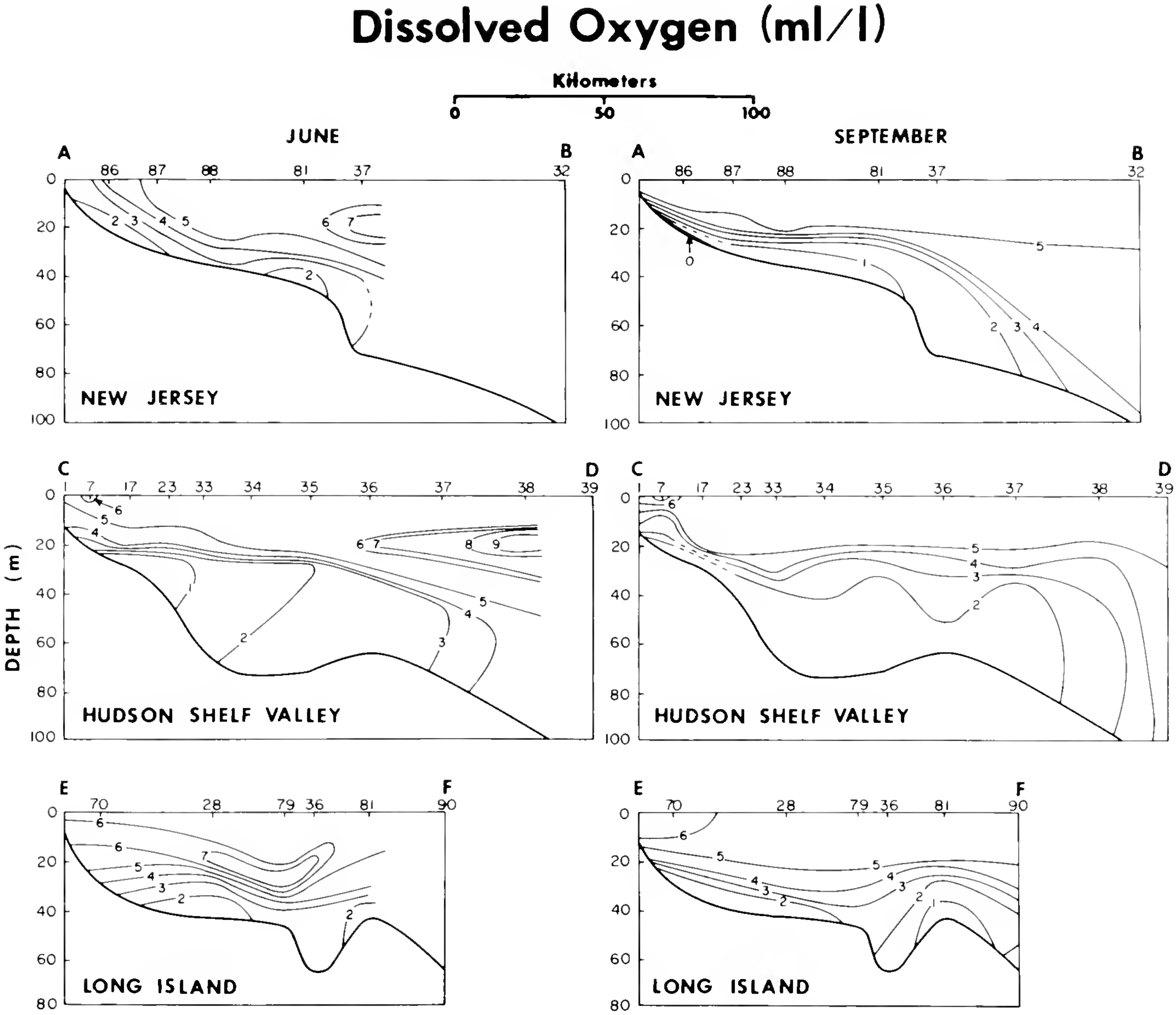

FIGURE 2–22.—June and September 1976 dissolved oxygen (ml/l) sections.

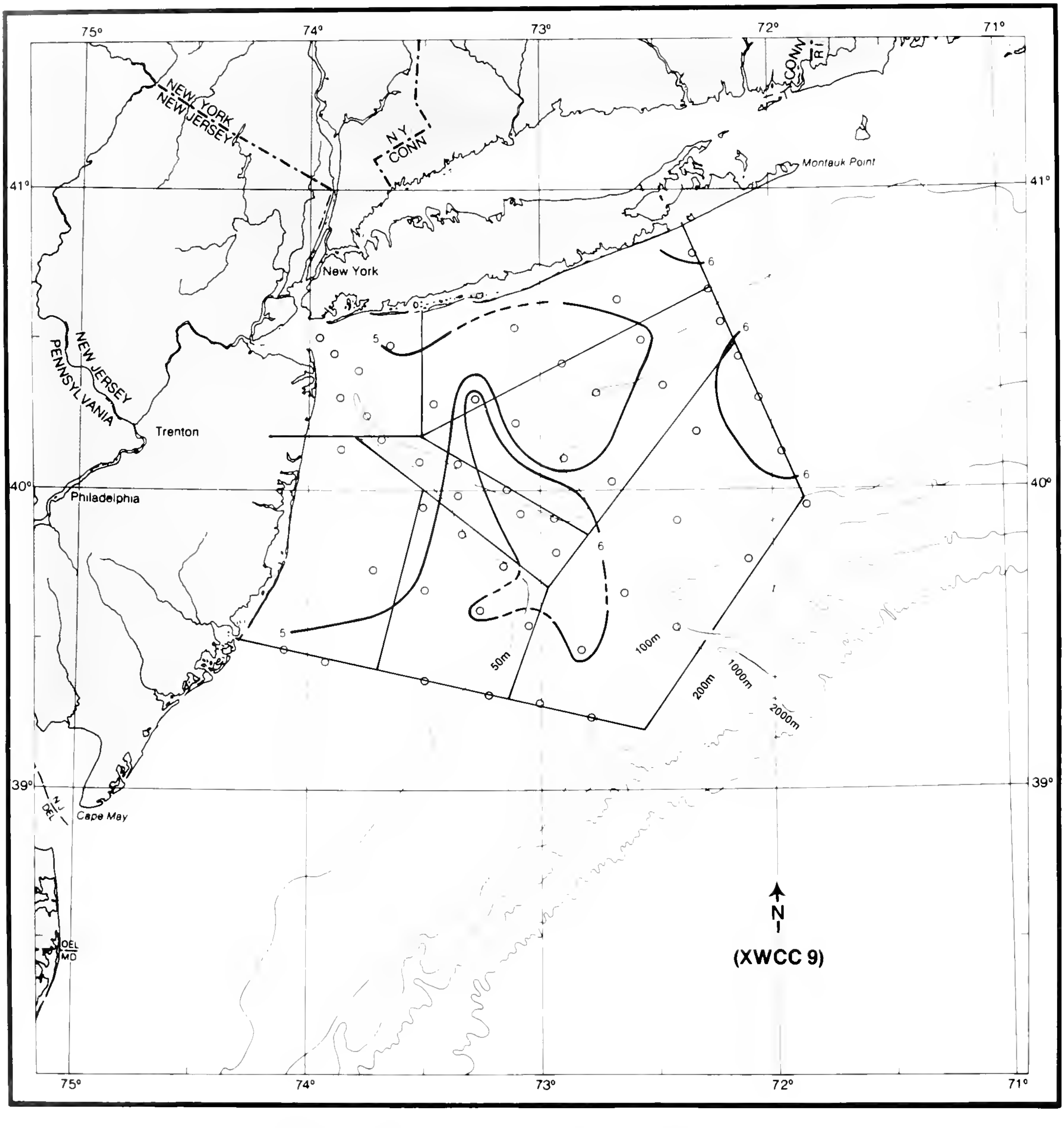

FIGURE 2-23.—May 1976 distribution of average dissolved oxygen concentration (ml/l) below pycnocline by segments of the Bight. Expanded water-column characterization cruise 9.

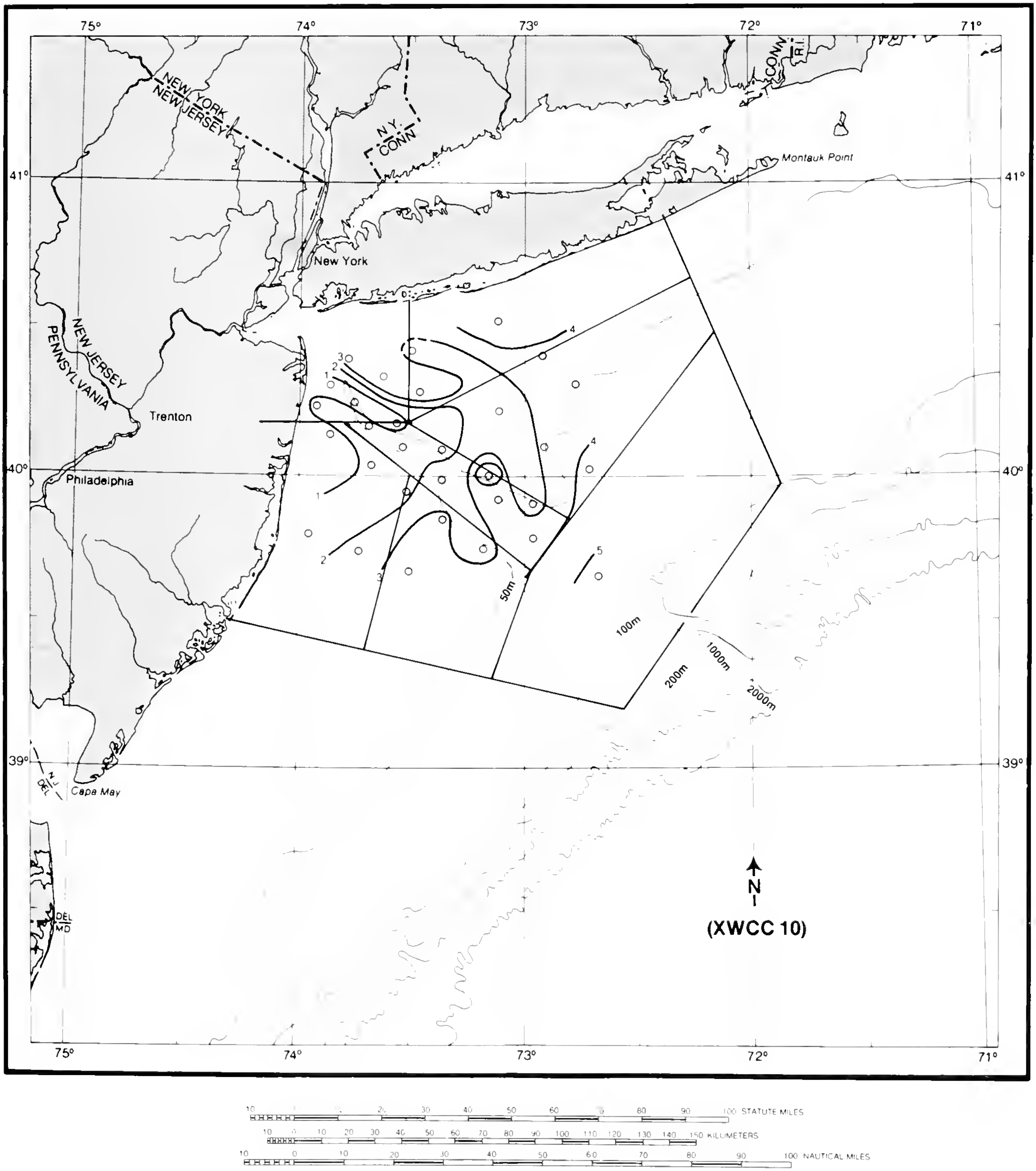

FIGURE 2-24.—June 1976 distribution of average dissolved oxygen concentration (ml l) below pycnocline by segments of the Bight. Expanded water-column characterization cruise 10

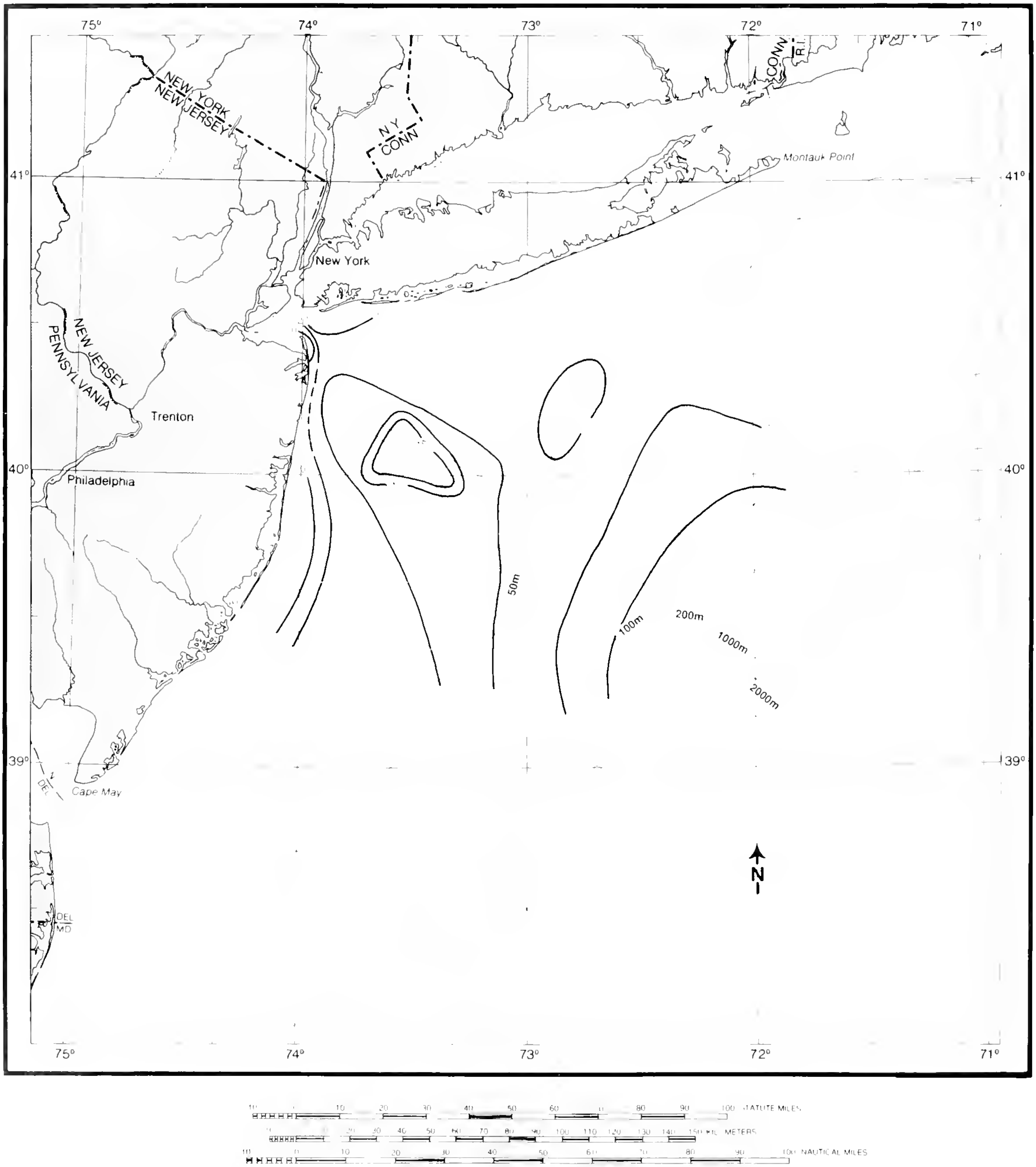

FIGURE 2-25.—May 1976 distribution of main dissolved-oxygen-minimum distance (m) above sea floor.

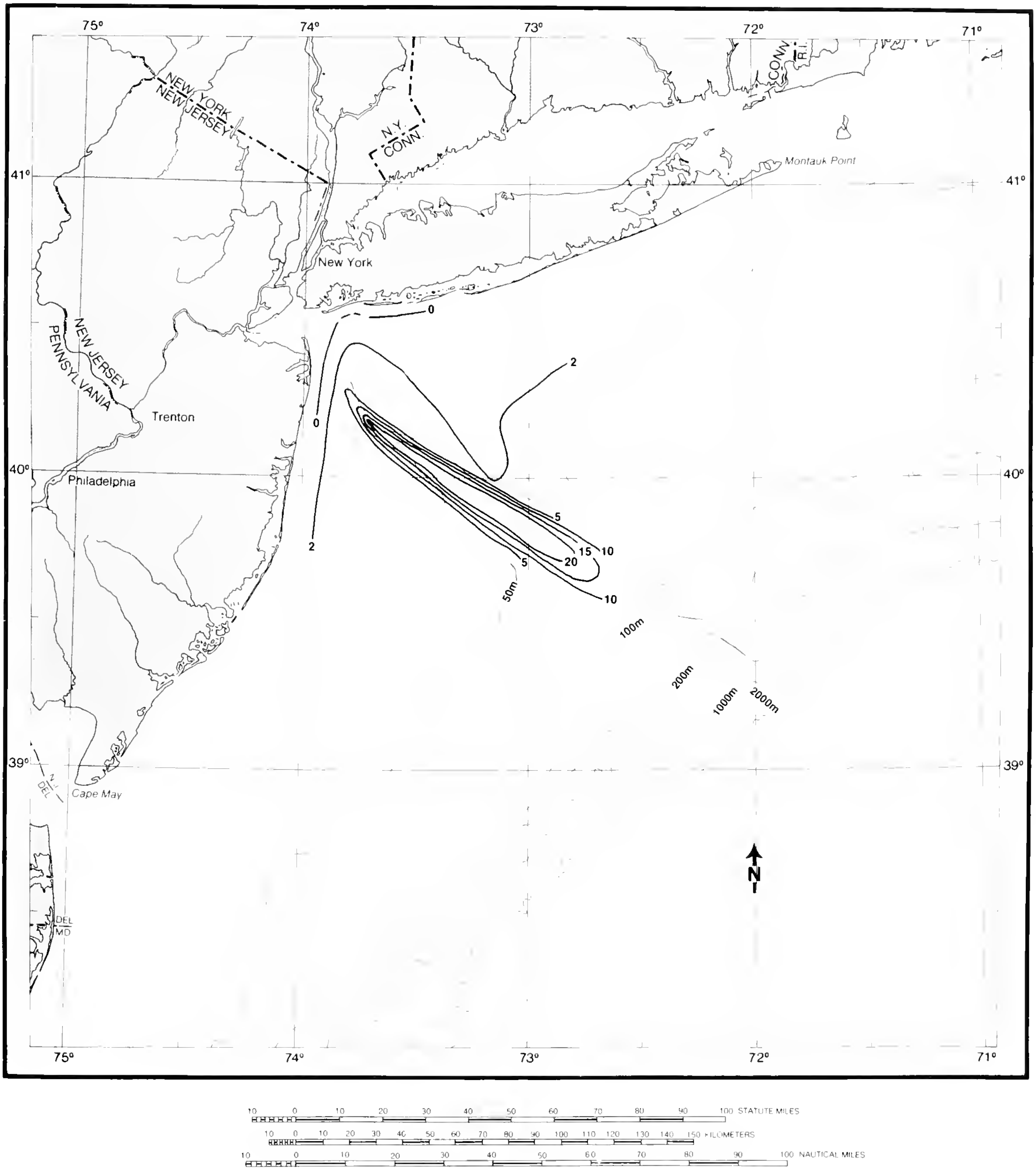

FIGURE 2–26.—June 1976 distribution of main dissolved-oxygen-minimum distance (m) above sea floor.

Valley. In May, the minimum grounded only along the New Jersey coast, but in June it also grounded along Long Island (figs. 2–25 and 2–26). In May it was closer to the bottom off New Jersey than off Long Island but the reverse was true in June.

## HURRICANE BELLE

The seasonal progression of stratification in New York Bight was interrupted on August 10 by the northward passage of hurricane Belle through the area. Belle had 26- to 30-m/s winds and a forward speed of 10 to 30 m/s during this period (NOAA 1977). Immediately preceding (August 8) and following (August 11) the hurricane, Sandy Hook Laboratory personnel made XBT observations at three stations along 39° 30′N latitude off Beach Haven Inlet, N.J., in the vicinity of XWCC stations 40 and 41 (fig. 2–1). The three sites were occupied again on August 16. Bottom oxygen values were determined on all stations, so an evaluation of return to prehurricane conditions can be made.

The XBT traces for the three sites are shown in figure 2–27. Before hurricane Belle, surface temperatures were between 22° and 23° C. Bottom temperatures were near 11° C. A very strong thermocline existed from a depth of 5 m at the inshore and offshore stations to a depth of 12 m at the middle station. After hurricane Belle, on August 11, surface temperatures had been lowered to between 18° and 19.5° C; bottom temperatures had been raised 6° C at the inshore station, 4° C at the middle station, but only 2° C at the station farthest offshore. The thermocline was markedly reduced at the inshore station, less so at the middle station, but was still relatively strong at the offshore station.

Five days later, on August 16, surface waters had warmed by 1.5° to 3.5° C, to over 21° C at all three sites. Greater warming was evident at the middle station. Bottom waters had cooled about 1.4° C, and a strong thermocline was beginning to be reestablished. Though bottom temperatures were nearly the same at all three sites before the hurricane, they exhibited a negative, offshore gradient of 2° to 3° C between adjacent sites at the two reoccupations following the hurricane. The colder bottom waters could only result from water being advected to these sites from an outside source, probably from offshore because the coldest bottom water was at the station farthest offshore. Bottom oxygen measurements for the three XBT stations showed an increase from zero or near zero before the hurricane to 2.0 to 3.5 ml/l immediately after. Measurements were again zero or near zero 6 days later.

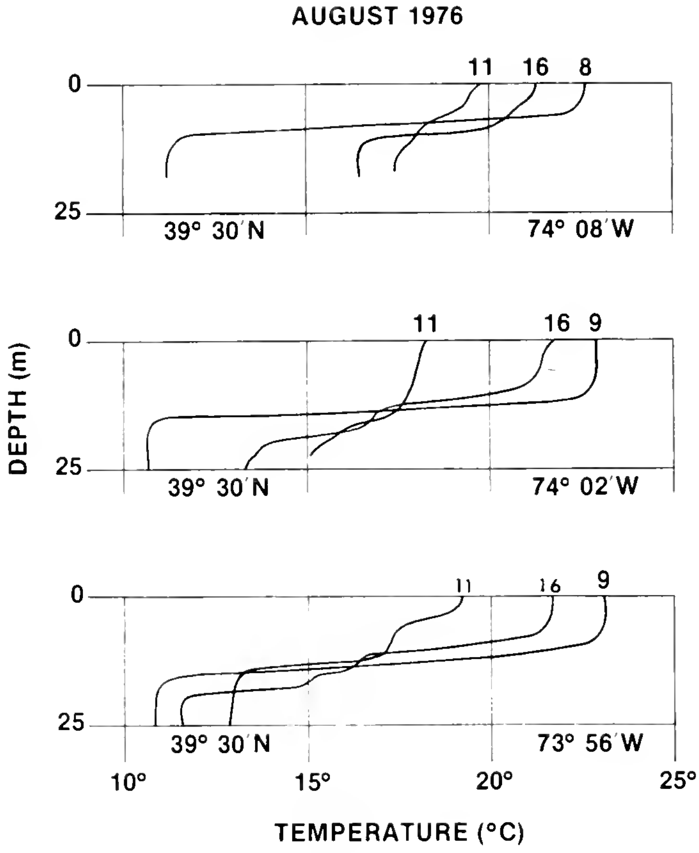

FIGURE 2–27.—Effect of hurricane Belle on temperature structure. XBT station locations: shoreward (top), intermediate (middle), and seaward (bottom) stations. Dates of observations: August 8 and 9 (before), August 11 (immediately after), and August 16 (6 days later)

## BOTTOM ENVIRONMENT IN SEPTEMBER

The *Researcher* September 11–17 stations, and the *Albatross IV* August 24 to September 9 stations in the same area and southward along the New Jersey shelf to Cape May, provide complete and relatively detailed data for the area of oxygen depletion.

Bottom-water temperatures (fig. 2–28) were variable. The coldest water was observed in the Hudson Shelf Valley and in a band along the outer shelf. The offshore band has been named the "cold pool" (Bigelow 1933; Beardsley et al. 1976). Bottom waters generally were warmer off New Jersey than off Long Island. They were warmest off the Hudson-Raritan estuary and extended eastward a short distance along the Long Island shore. The salinity pattern (fig. 2–29) was much more regular. Relatively fresh water was observed off the estuary and along the coasts. The resulting density distribution also was very regular. Lowest density values were off the western Long Island shore, but bottom waters had lower densities on the New Jersey shelf than on the Long Island shelf. Values of D.O. (fig. 2–30) associated with these distributions were almost as irregular as the temperature, but show a pattern consistent with that reported previously (Steimle 1977). Two regions had oxygen concentrations less than

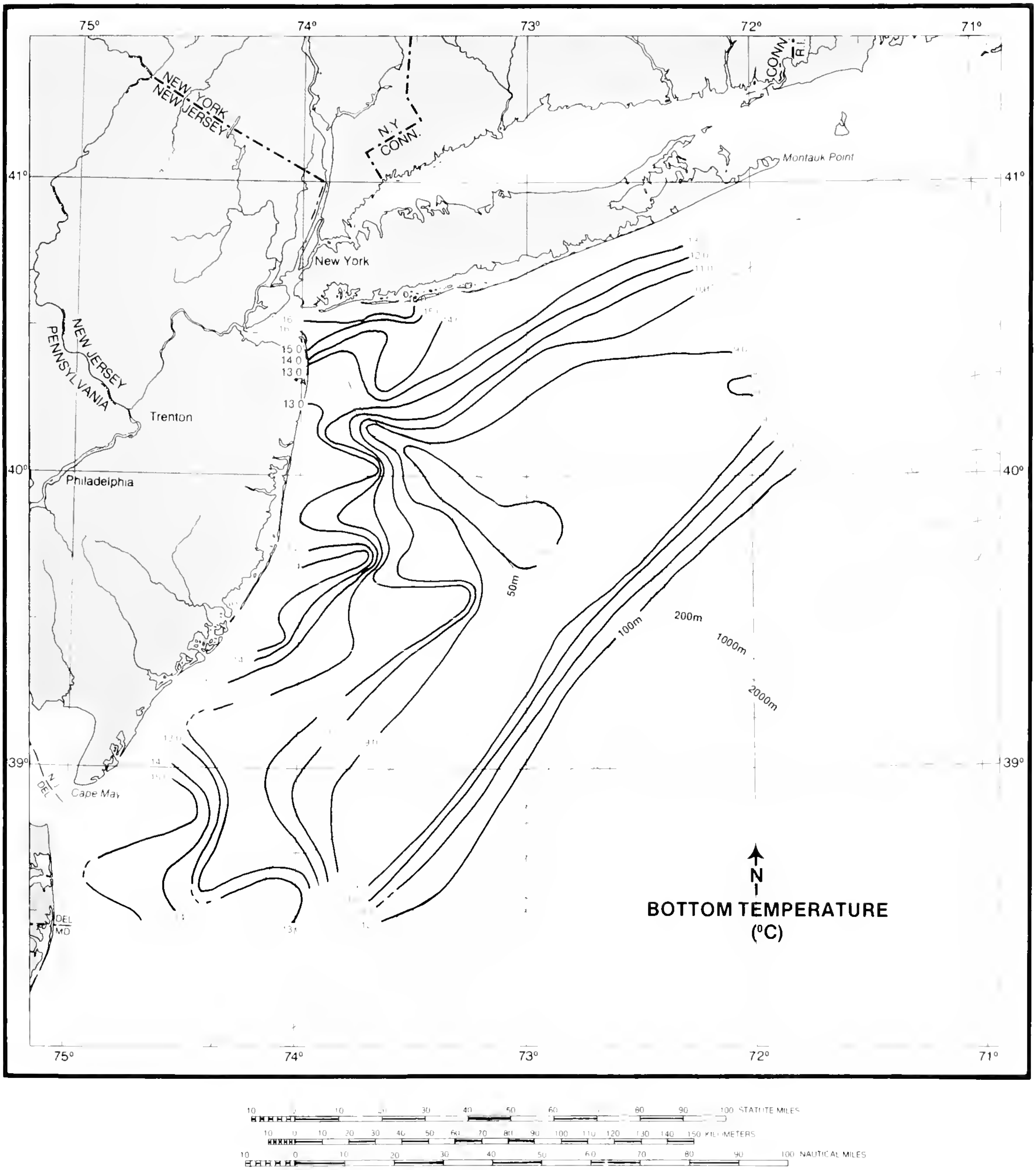

FIGURE 2-28.—August-September 1976 distribution of bottom temperature (° C).

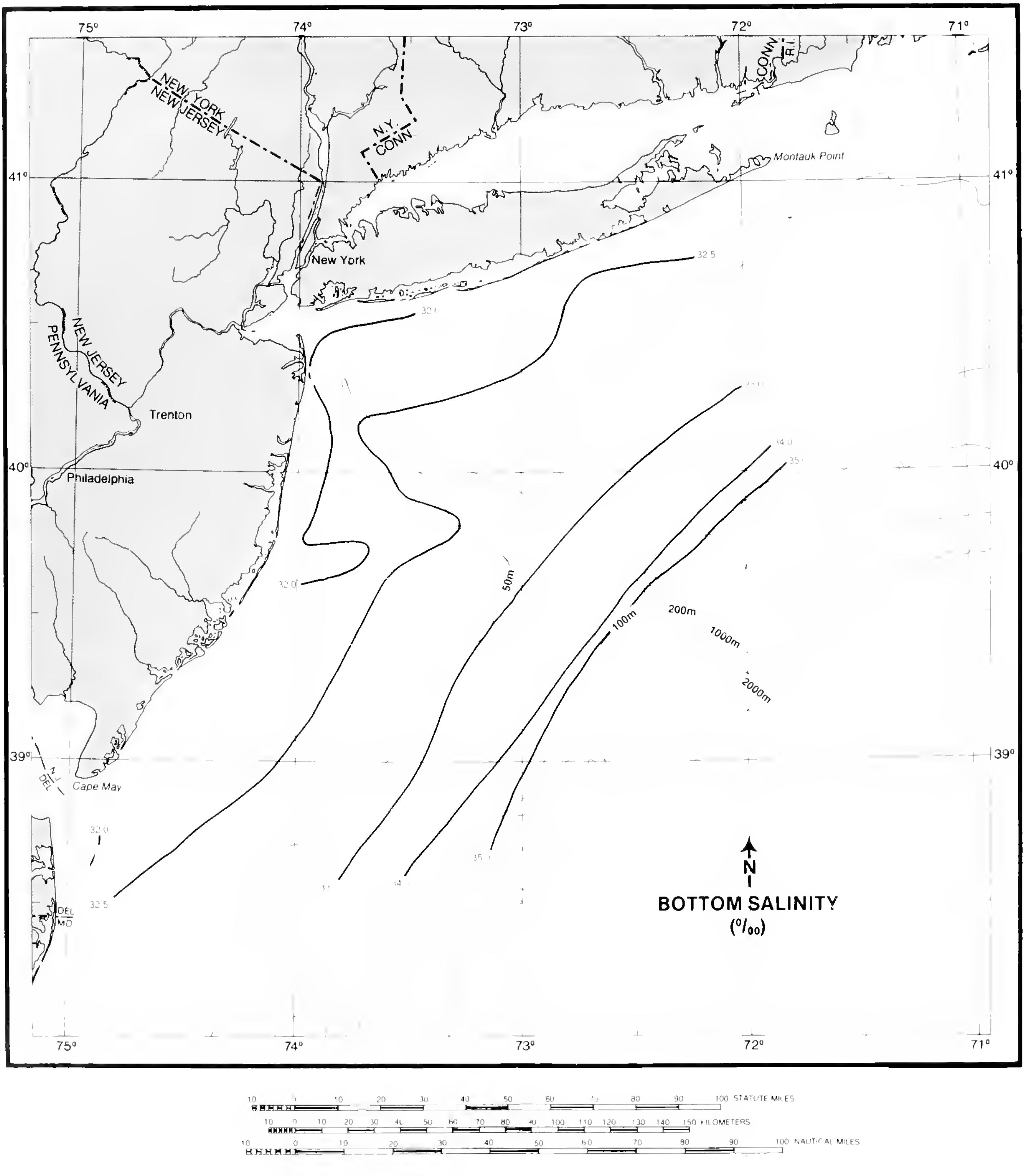

FIGURE 2-29.—August-September 1976 distribution of bottom-salinity (‰).

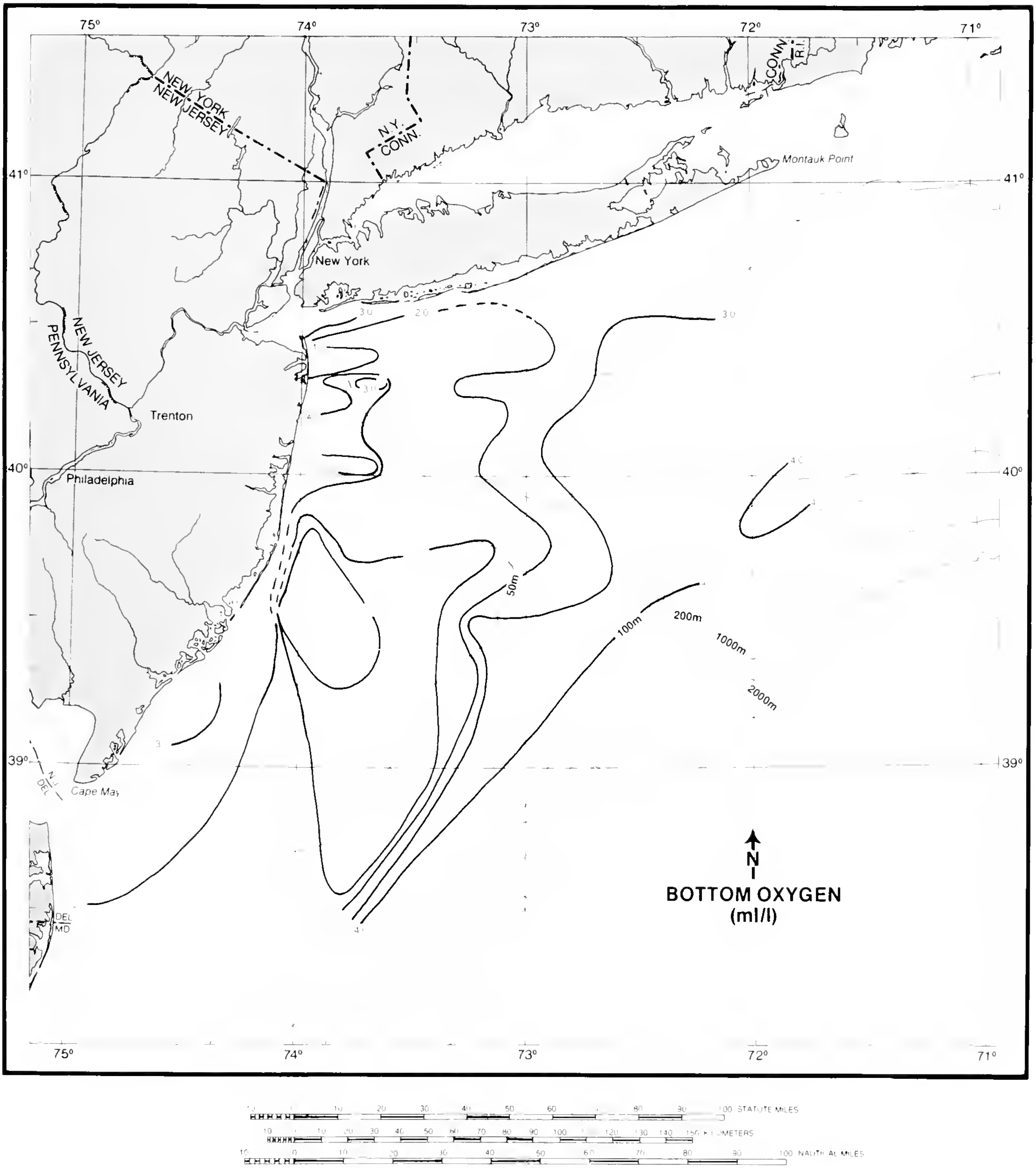

FIGURE 2-30.—August-September 1976 distribution of bottom dissolved oxygen (ml/l).

1 ml/l—a large area off the central New Jersey coast and a smaller area off northern New Jersey where the oxygen deficiency was first reported. These were separated by an area of relatively high but variable oxygen content.

## SUMMARY

Study of the oceanic conditions and events, and their progression in the New York Bight during 1976, indicates the presence of warmer-than-normal bottom waters early in the year. This is in accord with the findings of Hazelworth and Cummings (ch. 5), and suggests a larger amount of offshore water in the Bight than usual. There may be a connection between this presence of offshore water and the large concentration of *Ceratium tripos* in the Middle Atlantic Bight in 1976. (See chapter 9, part 1.) By June, however, surface and bottom waters were nearly normal.

The distribution of properties in the Hudson Shelf Valley and off New Jersey in May, June, and September, and at the hurricane Belle XBT and bottom-oxygen stations, suggests an onshore movement of water beneath the pycnocline. This agrees with the sluggish onshore set found in the current meter records by Mayer and others (ch. 7). The thickness of the subpycnocline layer is about 4 m less in May and June off New Jersey than off Long Island, though the bottom of the pycnocline is at a shallower depth off New Jersey. This difference in thickness was less in September. In both localities bottom water was effectively isolated from the surface by a relatively strong pycnocline. This pycnocline did not appear to be significantly stronger than normal, particularly early in the year.

The occurrence of bottom water that was 2.5° C warmer than normal in April and 3° to 4° C colder than normal in the latter half of the season indicates advection of bottom water into the region. If the continental shelf were the source of this water, then it must have been subjected to anomalous conditions upstream when it was at the surface. Hurricane Belle had some effect on the water column down to at least 25 m.

## ACKNOWLEDGMENTS

The authors are grateful to Thomas Azarovitz for the hurricane Belle XBT and bottom oxygen data; to D. V. Hansen and H. B. Stewart, Jr., for suggestions and review; and to the officers and crew of the NOAA ships *Albatross IV*, *George B. Kelez*, and *Researcher* for their long and diligent hours.

## REFERENCES

Beardsley, R. C., Boicourt, W. C., and Hansen, D. V., 1976. Physical oceanography of the Middle Atlantic Bight. *Am. Soc. Limnol. Oceanogr. Spec. Symp.* 2:20–34.

Bigelow, H. B., 1933. Studies of the waters on the continental shelf, Cape Cod to Chesapeake Bay. 1. The cycle of temperatures, *Papers in Physical Oceanography and Meteorology* 2(4), Massachusetts Institute of Technology and Woods Hole Oceanographic Institution, 135 pp.

Bowman, M. J., and Wunderlich, L. D., 1977. Hydrographic Properties, *MESA New York Bight Atlas Monogr.* 1, New York Sea Grant Institute, Albany, N.Y., 78 pp.

Hazelworth, J. B., Cummings, S. R., Starr, R. B., and Berberian, G. A., 1977a. MESA New York Bight Project expanded water column characterization cruise (XWCC 8) NOAA ship *George B. Kelez*, April 1976, *NOAA Data Rep.* ERL MESA-27, Marine Ecosystems Analysis Program Office, Environmental Research Laboratories, Boulder, Colo., 108 pp.

Hazelworth, J. B., Cummings, S. R., Minton, S. M., and Berberian, G.A., 1977b. MESA New York Bight Project expanded water column characterization cruise (XWCC 11) NOAA ship *Researcher*, September 1976, *NOAA Data Rep.* ERL MESA-29, Marine Ecosystems Analysis Program Office, Environmental Research Laboratories, Boulder, Colo., 189 pp.

Hazelworth, J. B., Starr, R. B., Cummings, S. R., and Berberian, G. A., 1978. MESA New York Bight Project expanded water column characterization cruise (XWCC 9) NOAA ship *George B. Kelez*, May 1976, *NOAA Data Rep.* ERL MESA-31, Marine Ecosystems Analysis Program, Environmental Research Laboratories, Boulder, Colo., 184 pp.

National Oceanic and Atmospheric Administration, 1977. Marine Weather Review, Smooth Log, North Atlantic Weather, July and August 1976, *Mariners Weather Log*, 21(1):25–31, Environmental Data and Information Service, Washington, D.C.

Starr, R. B., Hazelworth, J. B., Cummings, S. R., and Berberian, G. A., 1977. MESA New York Bight Project expanded water column characterization cruise (XWCC 10) NOAA ship *George B. Kelez*, 28 June-1 July 1976, *NOAA Data Rep.* ERL MESA-28, Marine Ecosystems Analysis Program, Environmental Research Laboratories, Boulder, Colo., 91 pp.

Steimle, F. W., 1977. Appendix III under Physical/Chemical Oceanography, *in* Oxygen depletion and associated environmental disturbances in the Middle Atlantic Bight in 1976, *Northeast Fisheries Center Tech. Ser. Rep.* No. 3, National Marine Fisheries Service, Sandy Hook Laboratory, Highlands, N.J., pp. 41–64.

## Oxygen Depletion and Associated Benthic Mortalities in New York Bight, 1976

# Chapter 3. Atmospheric Conditions and Comparison With Past Records

*Henry F. Diaz*[1]

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## INTRODUCTION

During the first half of 1976, atmospheric conditions along the Middle Atlantic coast departed substantially from the climatological norm. Following a cold January associated with a moderately amplified trough pattern in the westerlies over eastern North America (Wagner 1976a), the mean circulation at 700 millibars (mb) over the eastern United States reverted to a generally fast zonal flow in February (Dickson 1976a). This pattern prevailed through March (Taubensee 1976a). The pattern of 700-mb heights provides a measure of the air circulation at low levels. Negative height anomalies indicate relatively cold conditions prevailing whereas positive departures from the mean height indicate relatively warm conditions. At 40° N latitude the height anomaly of the mean 700-mb surface along the U.S. east coast changed from about −20 m in January to around +45 m in February and +50 m in March.

These departures in February and March were reflected in anomalous pressure and circulation patterns (more typical of spring conditions) that limited the transport of cold air from Canada to the United States. As a result, warm maritime air masses predominated over most of the country, causing extreme warm conditions over the eastern two-thirds of the United States during these months.

The April circulation pattern was close to normal, although mean temperatures in the eastern United States remained 1° to 2° C above the climatological mean (Wagner 1976b). The monthly mean pattern, however, masks the very large change that occurred between the first and second halves of the month. In the New England area mean 700-mb heights increased by more than 100 m and record cold weather during the first half of April was replaced by record warm weather in the second half.

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During May and June strong sea-level pressure rises were observed over the Atlantic Ocean (Dickson 1976b; Taubensee 1976b), which resulted in an increase in the speed and persistence of southerly winds over the Bight.

Atmospheric forcing is one of the dominant influences driving the New York Bight circulation and exchange processes (Mooers et al. 1976) and thus affects the marine ecosystem. Long-term changes in atmospheric circulation patterns can have a pronounced effect on the strength and persistence of this forcing. Dickson and Namias (1976) demonstrated how different circulation regimes affect the baroclinicity or cyclogenetic potential along the U.S. east coast, reducing or increasing the number and vigor of disturbances. To provide some measure of the relative strength of this forcing during the few months preceding the onset of the 1976 anoxia, the number of storm centers entering the Bight area bounded by 38° – 42° N and 70°–75° W was tabulated for February through June, 1950–76 (fig. 3–1), based on extratropical cyclone track charts (NOAA 1950–76). Minimum storm activity occurred in 1976. Although the average number of storms crossing this area during the 5 months is about 15, only 6 storms were recorded in 1976, and only a single storm was recorded in each of the months of February and March.

The magnitude and persistence of these anomalous weather patterns during the few months preceding the period of bottom-water anoxia suggested a possible connection to the observed disruption of the marine environment in the Bight. Sea-surface temperature is considered a relatively good indicator of the degree of stratification, however, with regard to its early onset, other factors may be important in determining the vertical density profile. For example, the temperature of the bottom layers, which are influenced by antecedent winter conditions, affects the surface of bottom temperature contrast. Another important element is the salinity of the surface waters. During the spring of 1976, low surface salinity contributed to early stratification.

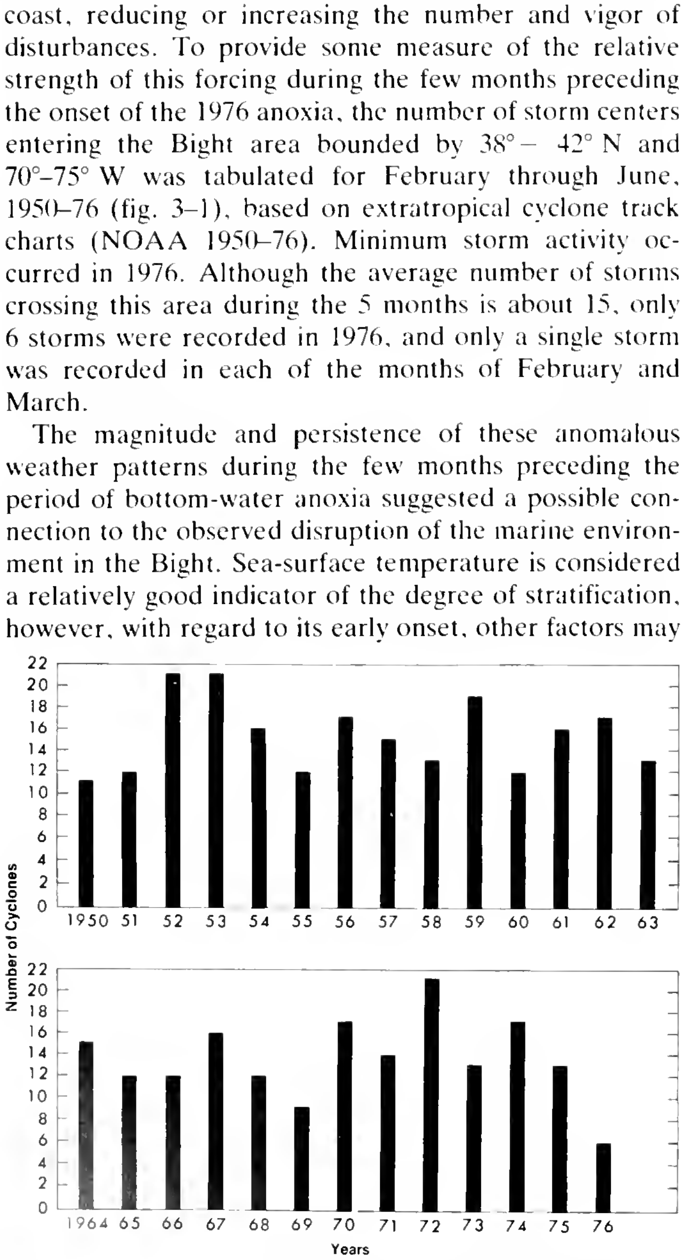


FIGURE 3–1.—Number of extratropical cyclones entering New York Bight area (38°–42° N, 70°–75° W), February-June 1950–76. (NOAA 1950–76 data.)

The surface wind field provides a measure of the large-scale circulation in the Bight. Anomalous winds, by modifying the normal circulation and exchange (vertical mixing) processes of Bight waters, could have aided in the development and maintenance of oxygen depletion. Because surface wind stress represents a primary driving force for oceanic motions, intensified or persistent upwelling/onwelling in the Bight could have been an important factor in the development of a phytoplankton bloom along the New Jersey coast.

## SEA-SURFACE TEMPERATURE

Sea-surface temperature data were extracted from three principal digital files at the National Climatic Center (NCC): the New York Bight Atlas file (1949–73); the Tape Data Family-11 (TDF-11) file, 1870–1973; and the Global Weather Central Telecommunications file (1973–76). In addition, the National Weather Service's monthly publication, *Gulfstream*, which contains monthly means of sea-surface temperature by 1° squares, was used for the period 1971–76 whenever the number of sea-surface temperature observations exceeded those in NCC files.

Sea-surface temperatures were analyzed for a 2°-square area (39°–41° N, 72°–74° W) comprising most of the New York Bight region (fig. 3–2). This is the area used by Lettau et al. (1976) for the *MESA New York Bight Atlas Monograph* 7 on "Marine Climatology," and for which the tape data file covering the years 1949 to 1973 was created. To determine whether surface waters throughout the Bight were unusually warm during the 1976 months preceding the oxygen-depletion event, sea-surface temperature means for the months of February, March, and April—for the long-term records of 1876–1976 in the northwest marine area and 1896–1976 in the southwest marine area—were plotted as departures from the 1949–73 reference period mean (fig. 3–3). The northwest and southwest 1°-square marine areas of figure 3–2 include the greater portion of the zone of oxygen deficiency identified in chapter 1.

A value was plotted only when four or more observations were available for a given year/month. Values derived from fewer than 20 observations, which also fell beyond ±3 standard deviations from the reference mean, were rejected. These limits were arbitrarily chosen to prevent undue biases either from too little data or from the

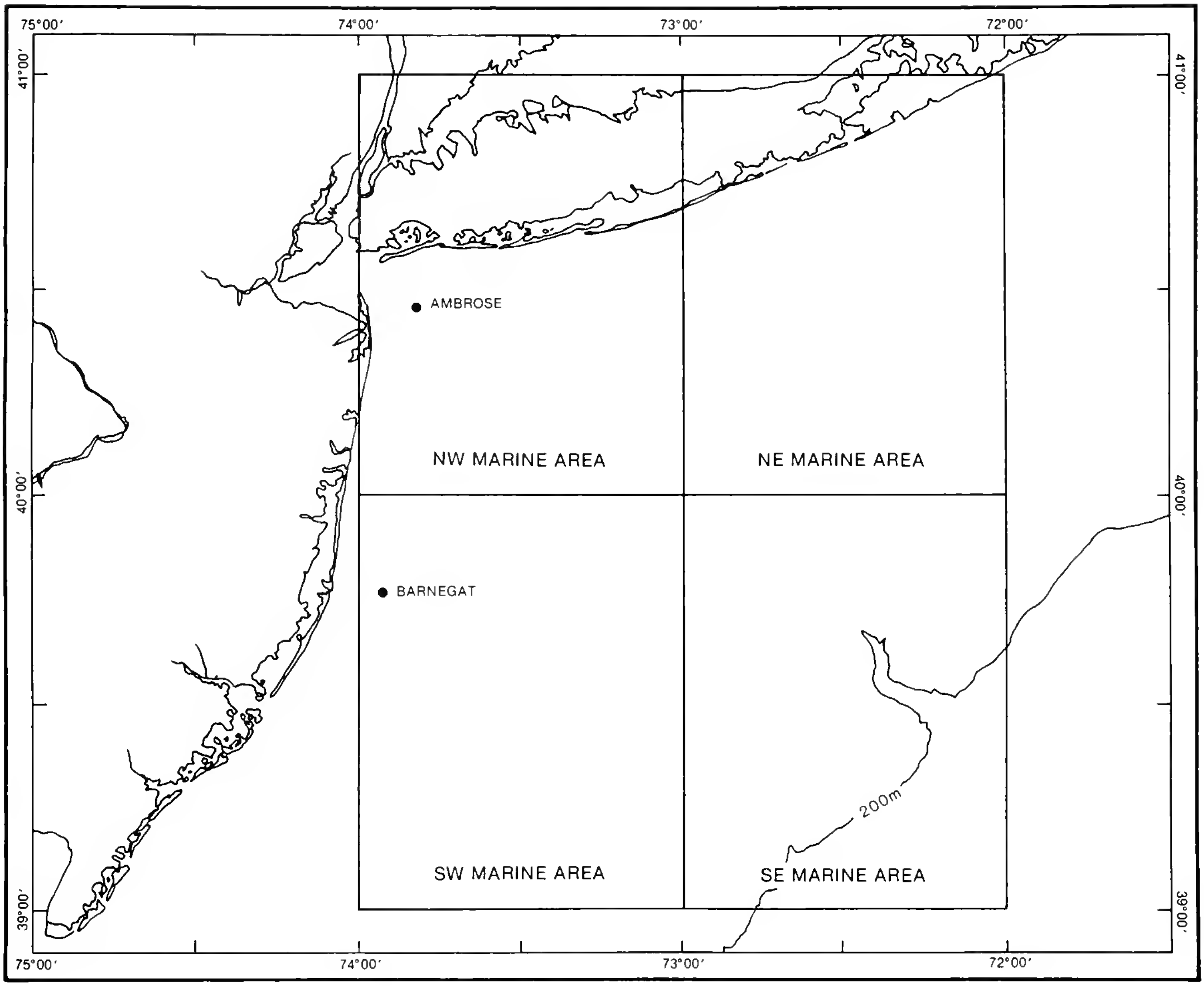


FIGURE 3-2.—New York Bight 2°-square area for which sea-surface temperature data were analyzed

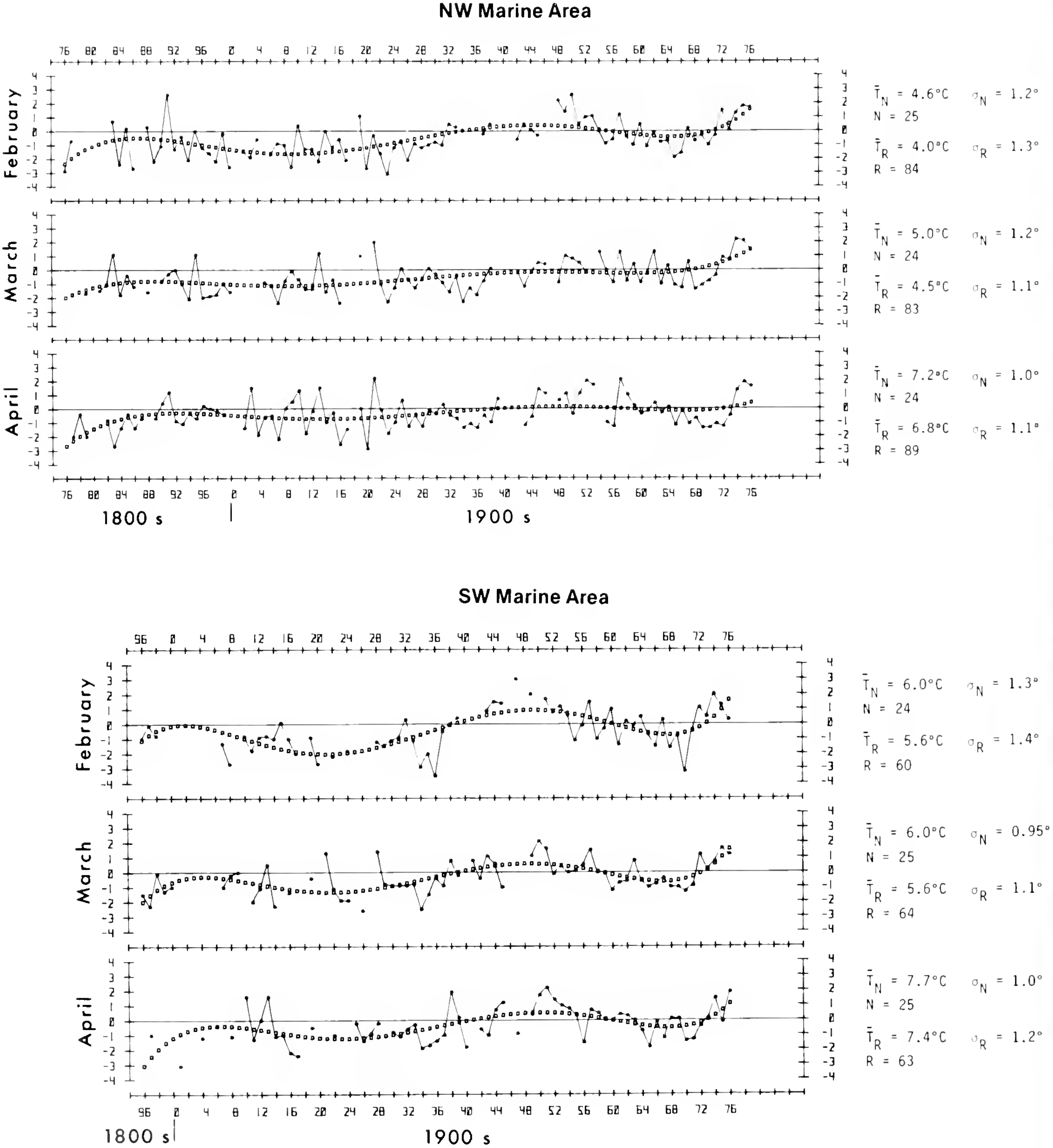


FIGURE 3-3.—Departure of February, March, and April New York Bight mean sea-surface temperatures from 1949–73 reference-period mean and long-term trend. The squares of the long-term trend line represent smooth (fifth-order polynomial least-squares fit) values. Numbers on right are mean and standard deviation for reference period ($\overline{T}_N$ and $\sigma_N$) and long-term record ($\overline{T}_R$ and $\sigma_R$).

presence of spurious values in a relatively small sample. A smoothed line was then computed by fitting a 5th-order polynomial to each set of data using the least-square method. This degree was chosen to resolve as many long-term fluctuations as the computer and available software permitted.

The 1876–1976 mean for the northwest area is about 0.5° C cooler than the mean for the 1949–73 reference period, but the standard deviation is essentially the same. The 1896–1976 mean for the southwest area is about 0.4° C lower than the 1949–73 mean. Some cyclical behavior is apparent in the values for both areas, with the amplitude of the oscillation being more pronounced in February than in April. The temperature record for the two areas shows generally good coherence. About 1970, there is a strong warming trend in both sets of data, amounting to about 2° C. Namias and Dickson (1976) have shown that this warming extended into the Atlantic over a broad zone.

The record of mean monthly air temperatures for February and March at New York City's Central Park for 1876 to 1976 is presented for comparison (fig. 3–4). The mean temperature for February 1976 was 4.4° C, a value exceeded only once (4.5° C in February 1954) during the previous 100 years. Although March 1976 was not so near to a record as February, the mean of 6.9° C was exceeded only eight times in the previous 100 years. Thus it represents a substantial positive departure from the long-term mean. Furthermore, when the averages for February and March are combined, the resulting 2-month average for 1976 is the second warmest in 100 years, being exceeded only by February-March 1945. The records for sea-surface temperatures in New York Bight and air temperatures in Central Park correlate well, particularly when their smoothed (best 5th-order fit) curves are compared, as might be expected.

The sea-surface temperatures (fig. 3–3) during late winter and early spring of 1976 in the western sector of the Bight were among the highest recorded over a long period of years. Because of this, it was thought that some correlation could be established between the abnormally high late winter and early spring sea-surface temperatures and the unusually low oxygen concentrations subsequently observed. However, relatively high sea-surface temperatures also occurred during the several years before 1976, and in the early 1950s and late 1940s, without the kind of large-scale ecosystem disruption observed in summer 1976. Although fishkills were documented less extensively before the 1976 event, those recorded in the area were limited in extent. (See chapter 1.)

Thus, it seems likely that other factors besides higher sea-surface temperatures acted to produce the anoxia. The simultaneous occurrence of anomalous wind conditions in the Bight appears to have been one such factor. The minimum cyclonic activity between February and June 1976 may have contributed directly to the early development of stratification by significantly reducing vertical mixing and contributing to shallow, intense stratification in the water column (Elsberry and Garwood 1978). Although 1974 and 1975 sea-surface temperatures were similarly warm, more than twice as many storm systems crossed the Bight in those years as did in 1976 (fig. 3–1).

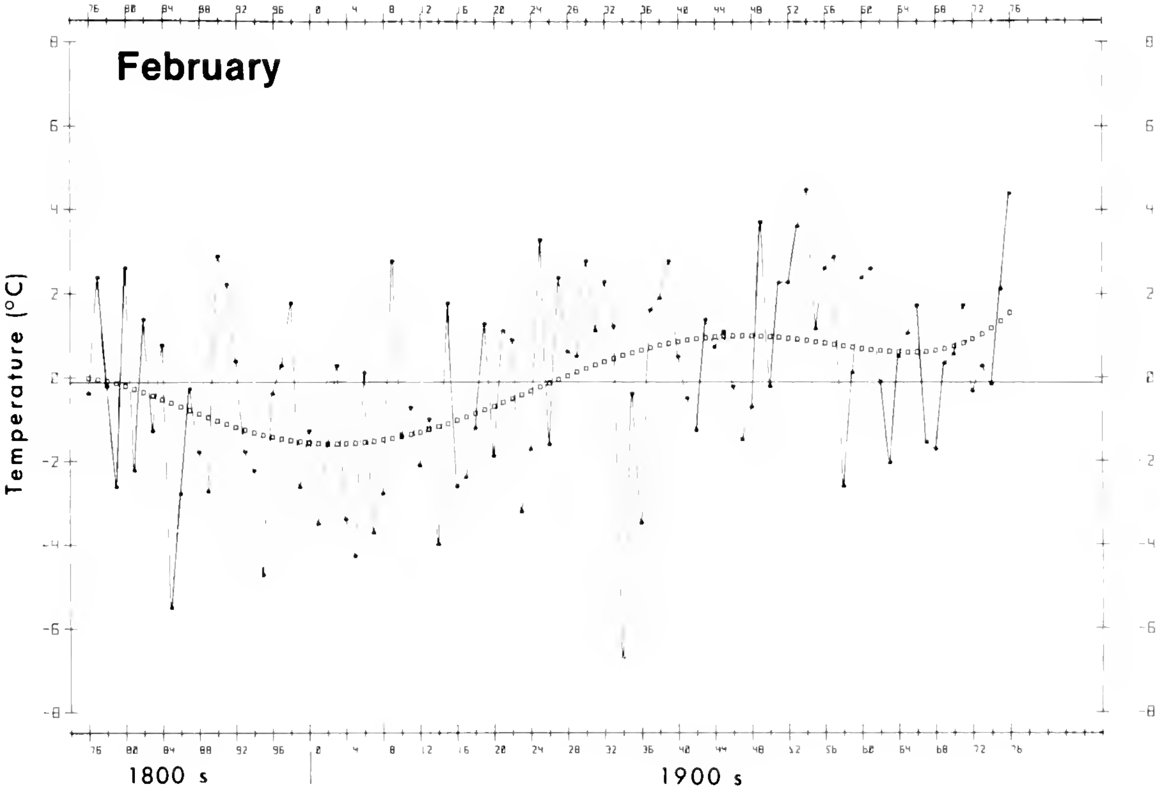
## SURFACE WIND FIELD

The surface wind field analysis included observations at four land stations (Atlantic City, Newark, John F. Kennedy International Airport, and Westhampton Beach, L.I.), two stations at lights (Ambrose and Barnegat), and two environmental buoys (EB34 and EB41) (fig. 3–5). These data are contained in Local Climatological Data (LCD) summaries, original observation forms on file at NCC, and computer products based on data received from the National Data Buoy Office and routinely archived at the National Climatic Center. The observations for February through August 1976 were averaged by 10-day segments for each station and plotted as a time series of mean resultant wind vectors for the four stations at sea and Westhampton Beach (fig. 3–6). The 10-day interval was chosen to account, as much as possible, for within-month variations in wind regime while minimizing the number of computations required. Ten days also is roughly equivalent to the mean time interval between the passage of cyclonic disturbances in the New York Bight area during the spring months. The wind vectors were subjectively analyzed to give mean flow patterns for each 10-day segment over the 7 months. From these the mean direction and speed at each of six grid points (identified in fig. 3–5), plus Westhampton Beach, were used to compute the mean surface wind stress for each month February through June, using the bulk aerodynamic formula

$$\vec{\tau} = \bar{\rho} C_D |\mathbf{V}| \mathbf{V}, \qquad (1)$$

where $\mathbf{V}$ is the 10-day mean vector wind, $\bar{\rho}$ is the mean air density ($1.26 \times 10^{-3}$ g/cm$^3$) calculated from the average surface air pressure and temperature field over the Bight and $C_D$ is the drag coefficient. A value of $2.6 \times 10^{-3}$ for $C_D$ was used; this relatively large value for the drag coefficient was adopted primarily to compensate for the smoothing inherent in the use of time-and space-averaged winds (see Bakun 1973). The stress vectors for each 10-day interval at each grid point were averaged to produce monthly mean values for February through June. These in turn were spatially averaged to obtain an estimate by month of the magnitude and direction of the surface wind stress over the Bight.

In figure 3–7, surface wind patterns for February through August 1976 are compared with the long-term



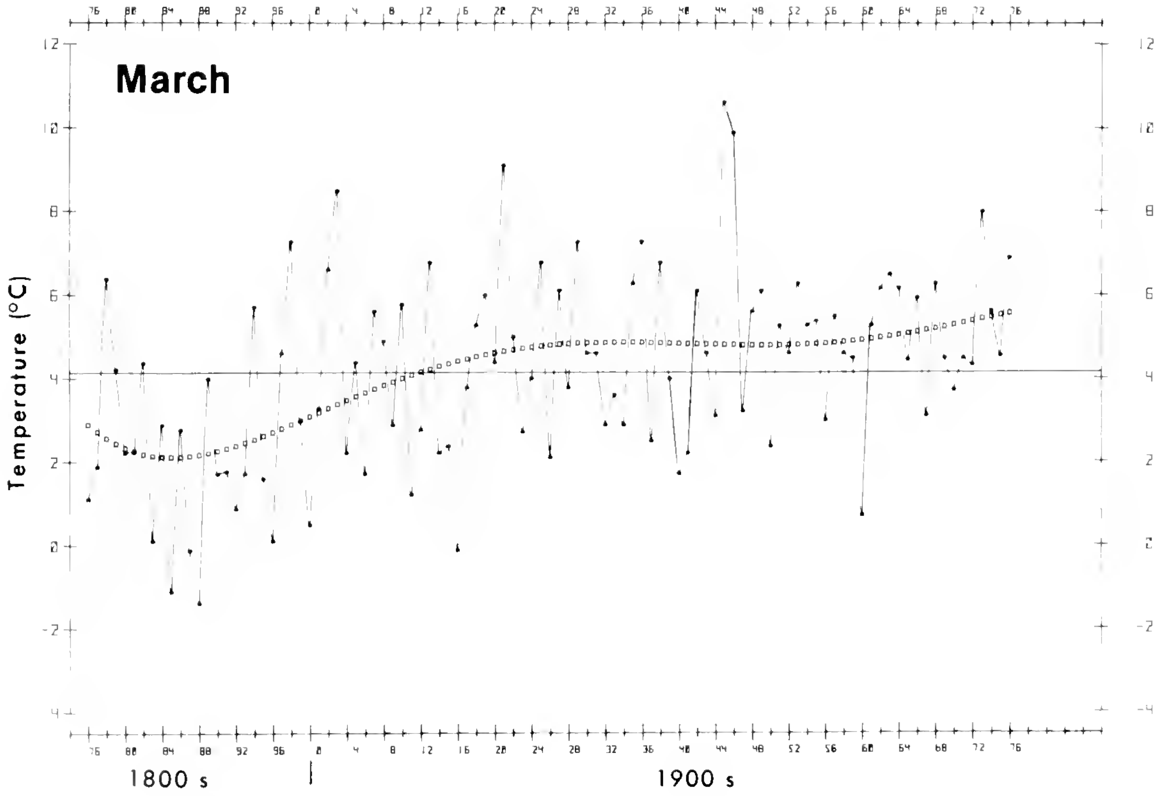


FIGURE 3-4.—Departure of February and March Central Park Observatory (New York City) mean air temperatures from the long-term mean and long-term trend

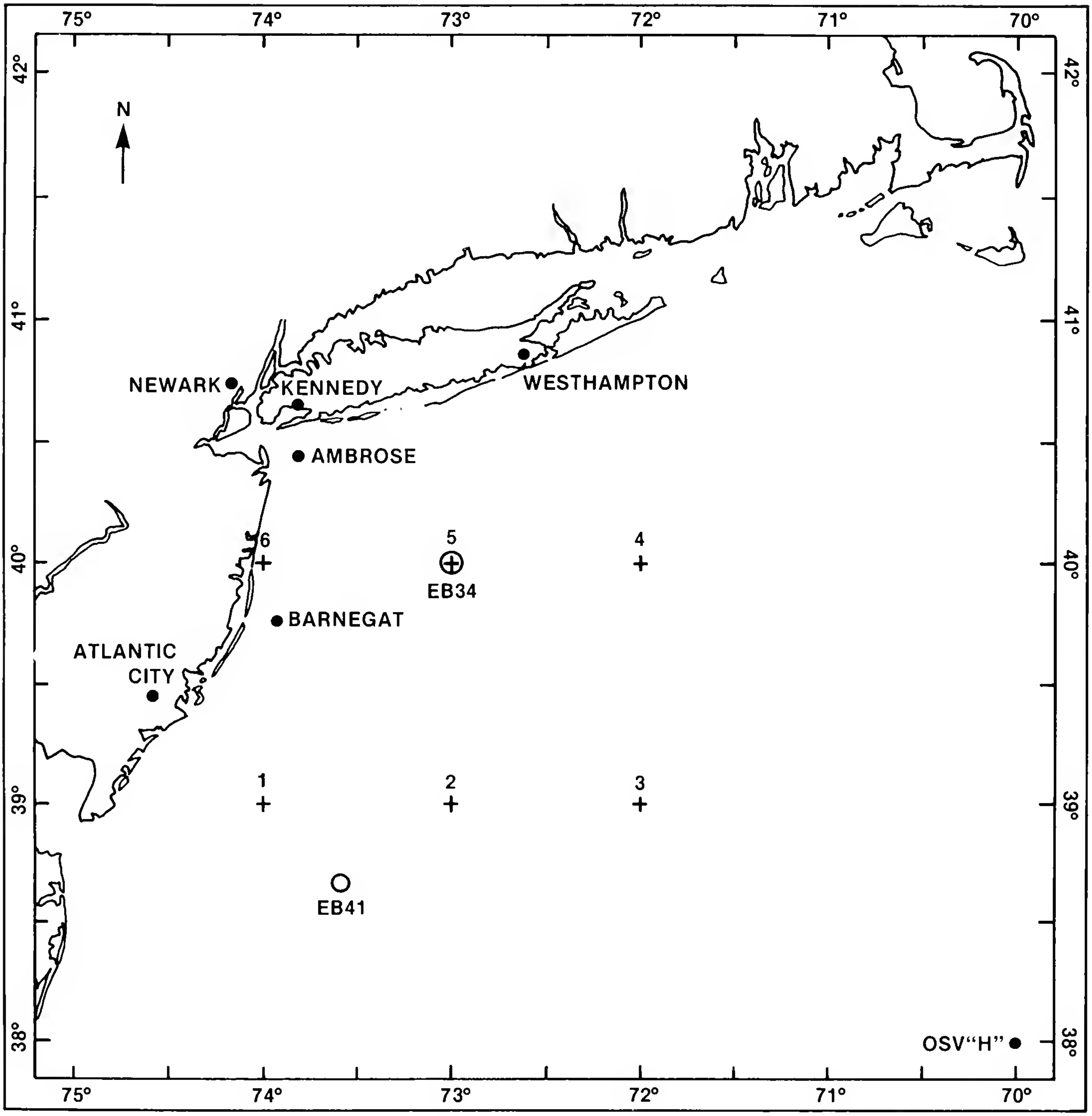


FIGURE 3-5.—Surface wind field observation stations (circles) and six grid points for which mean surface wind stress was computed.

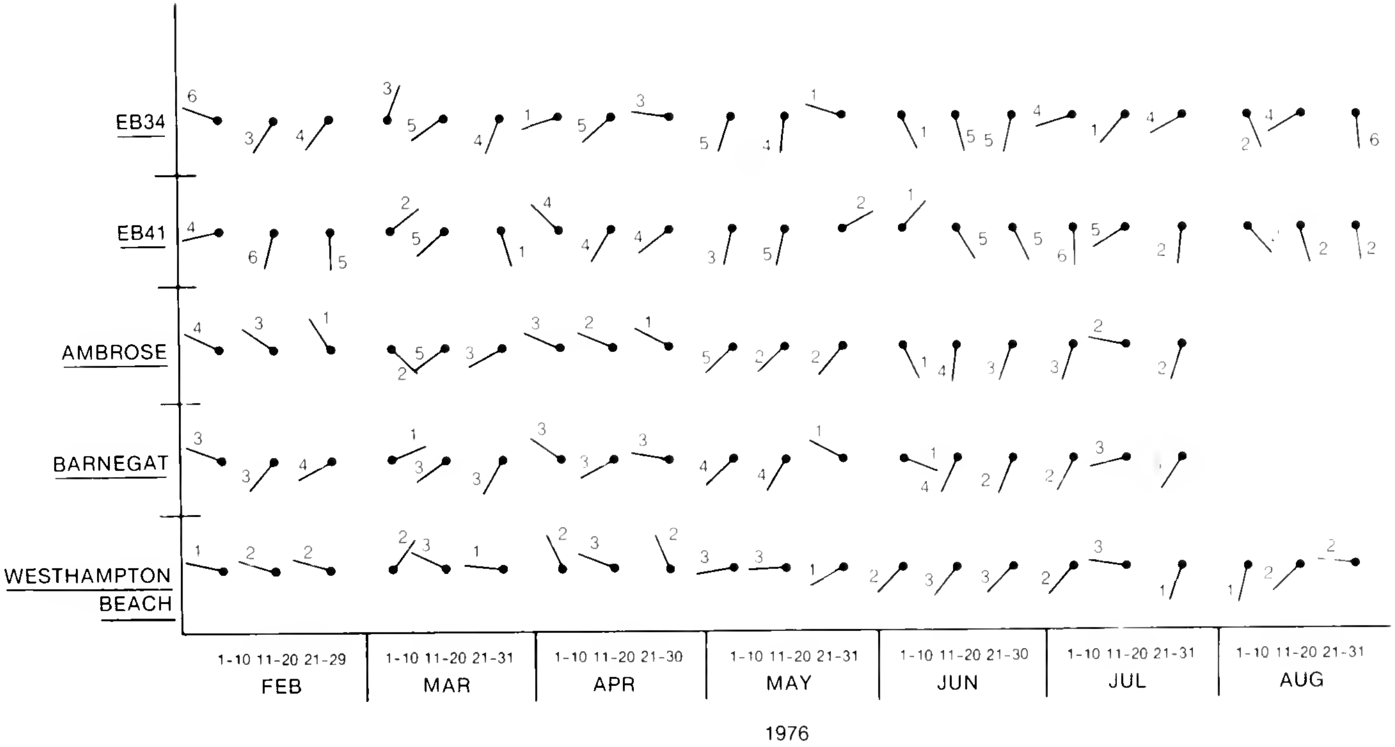


FIGURE 3–6.—Mean resultant wind vectors by 10-day segments for February through August 1976. Wind blows toward dot; number indicates speed in m/s.

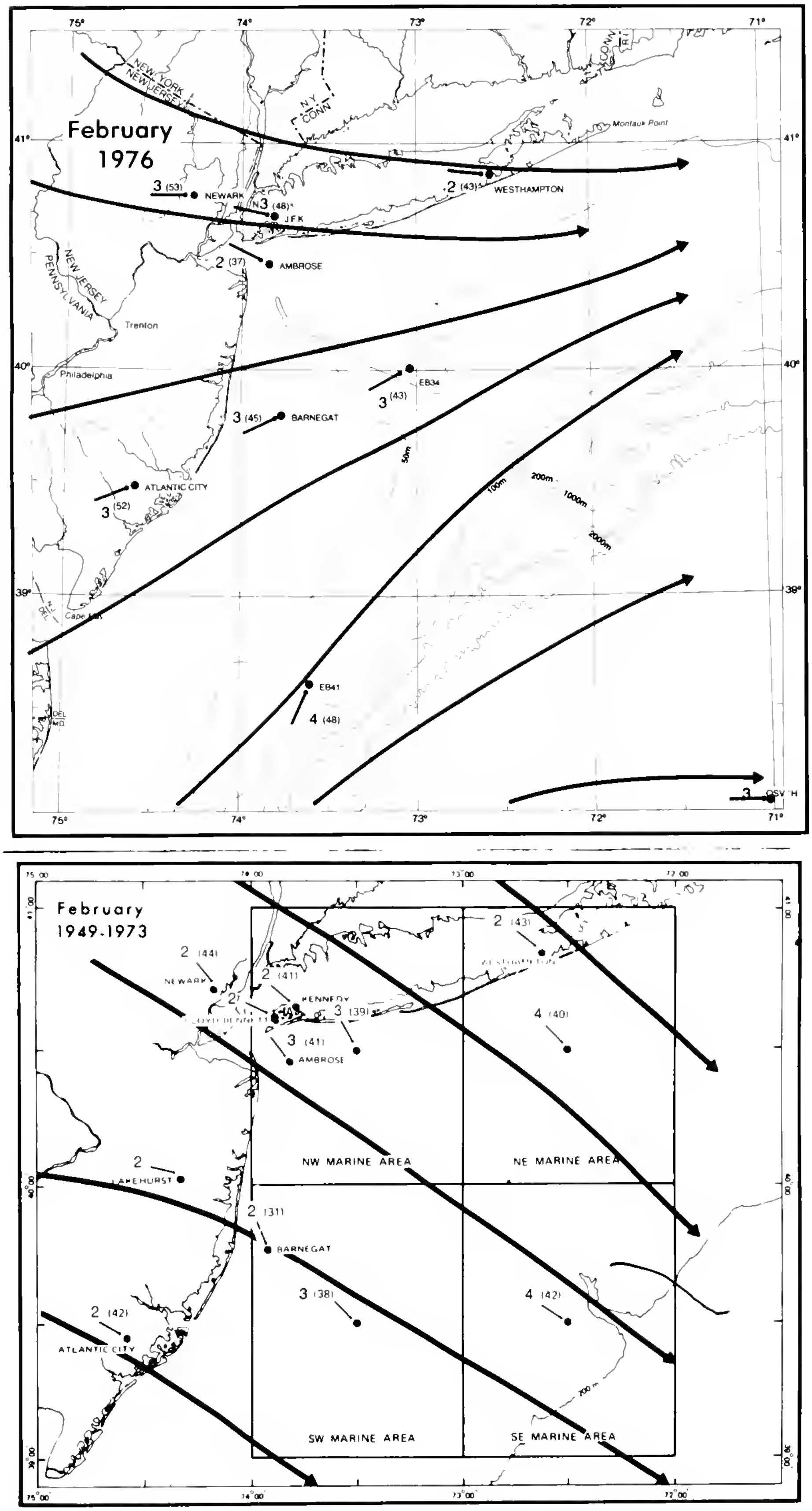


FIGURE 3–7.—Monthly mean surface wind patterns and resultant wind flow, February-August, 1976 and 1949–73 (speed in m/s; constancy in % in parentheses next to vector magnitude)

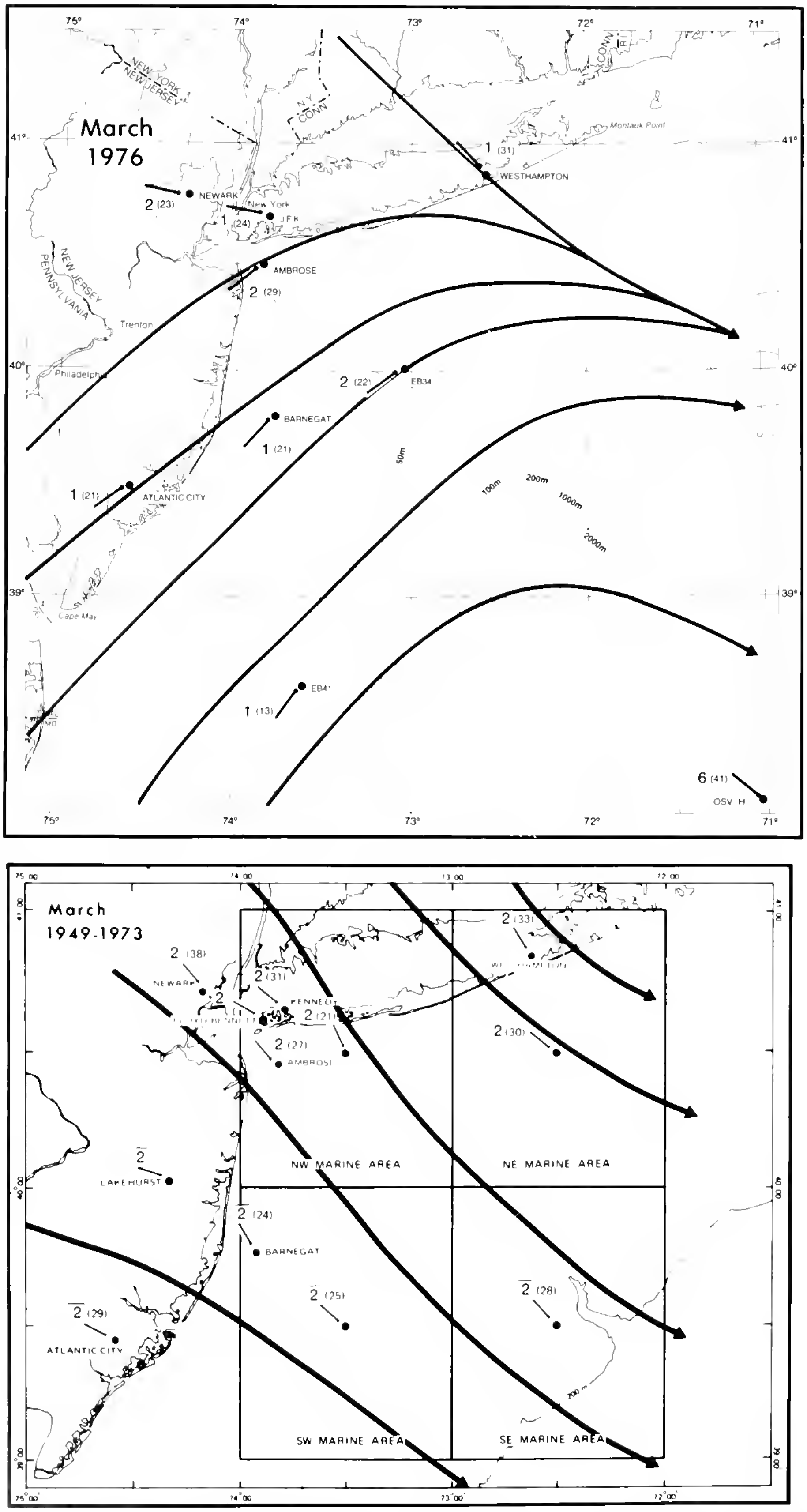


FIGURE 3-7.—Monthly mean surface wind patterns and resultant wind flow, February-August, 1976 and 1949-73 (speed in m/s; constancy in % in parentheses next to vector magnitude)—continued.

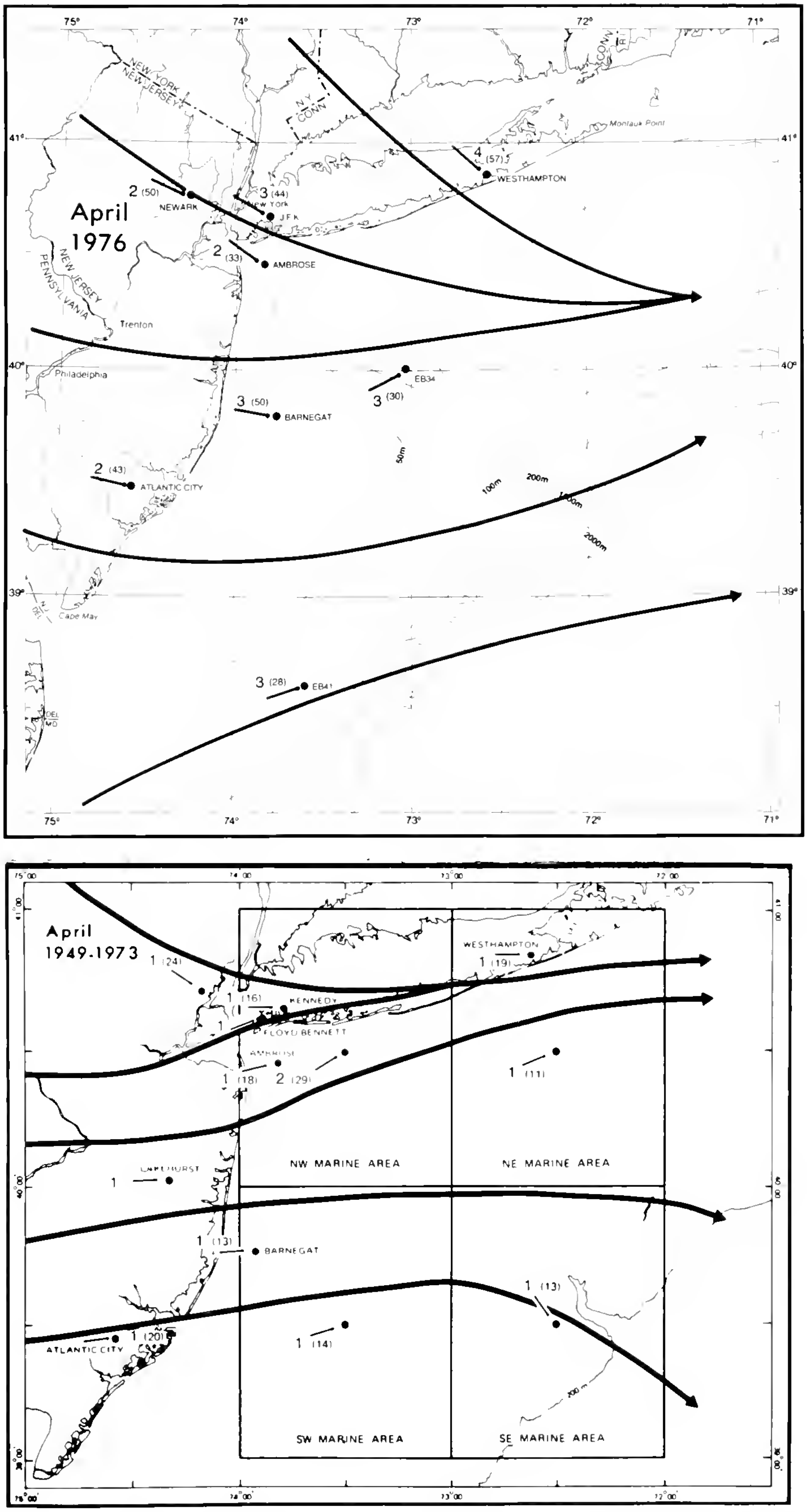


FIGURE 3–7.—Monthly mean surface wind patterns and resultant wind flow, February-August, 1976 and 1949–73 (speed in m/s; constancy in % in parentheses next to vector magnitude)—continued.

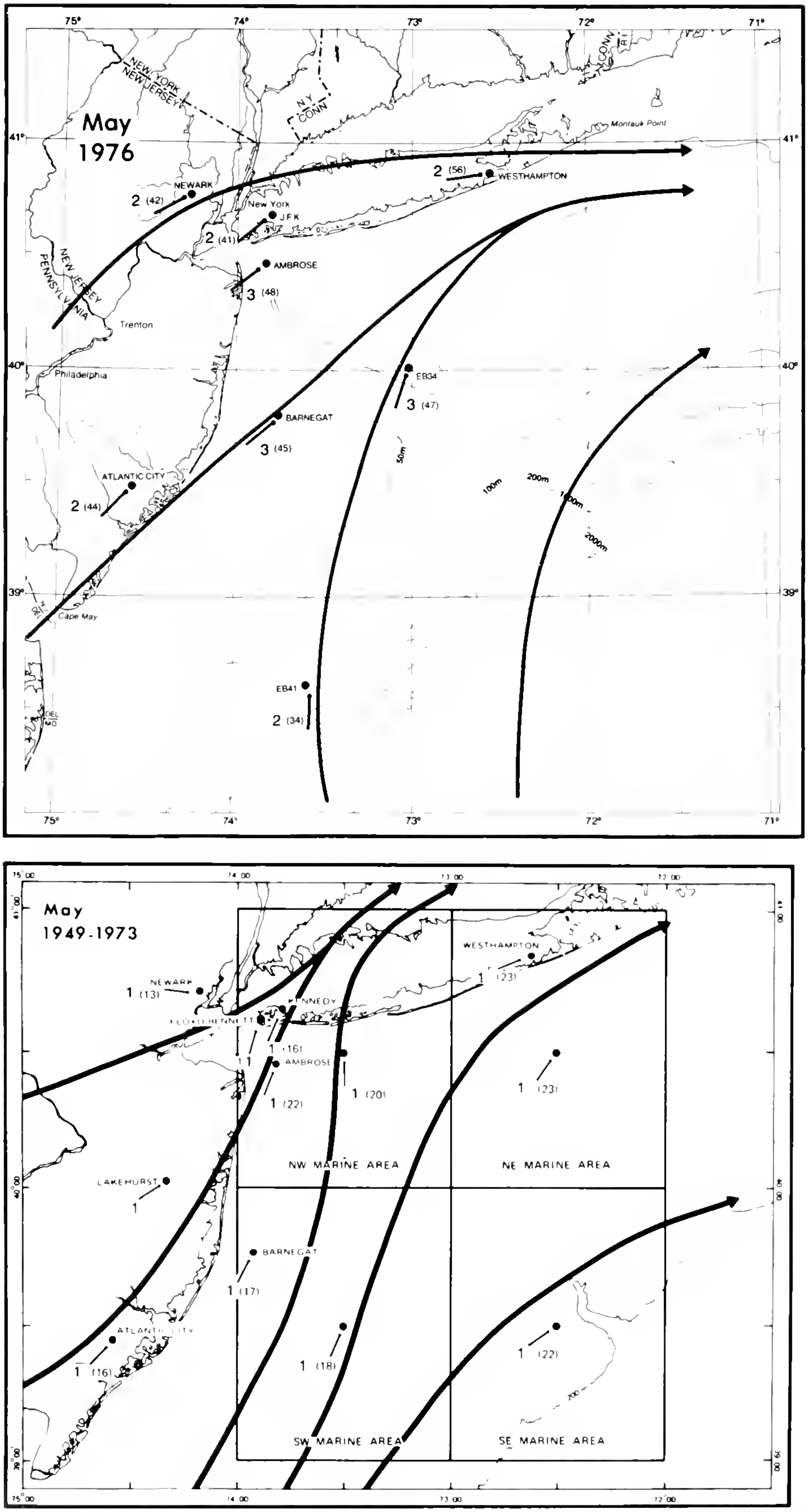


FIGURE 3–7.—Monthly mean surface wind patterns and resultant wind flow, February-August, 1976 and 1949–73 (speed in m/s; constancy in % in parentheses next to vector magnitude)—continued.

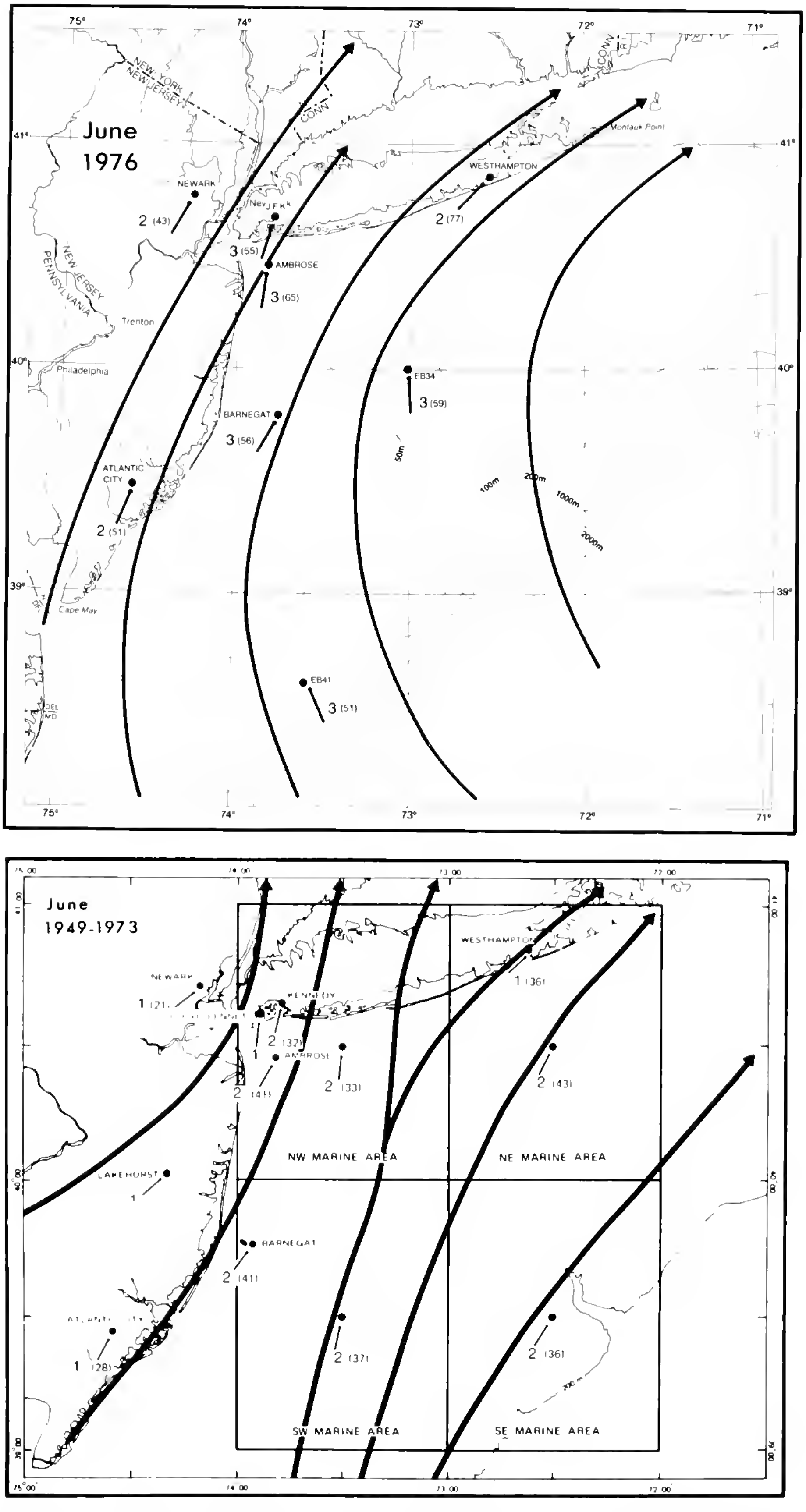


FIGURE 3–7.—Monthly mean surface wind patterns and resultant wind flow, February-August, 1976 and 1949–73 (speed in m/s; constancy in % in parentheses next to vector magnitude)—continued.

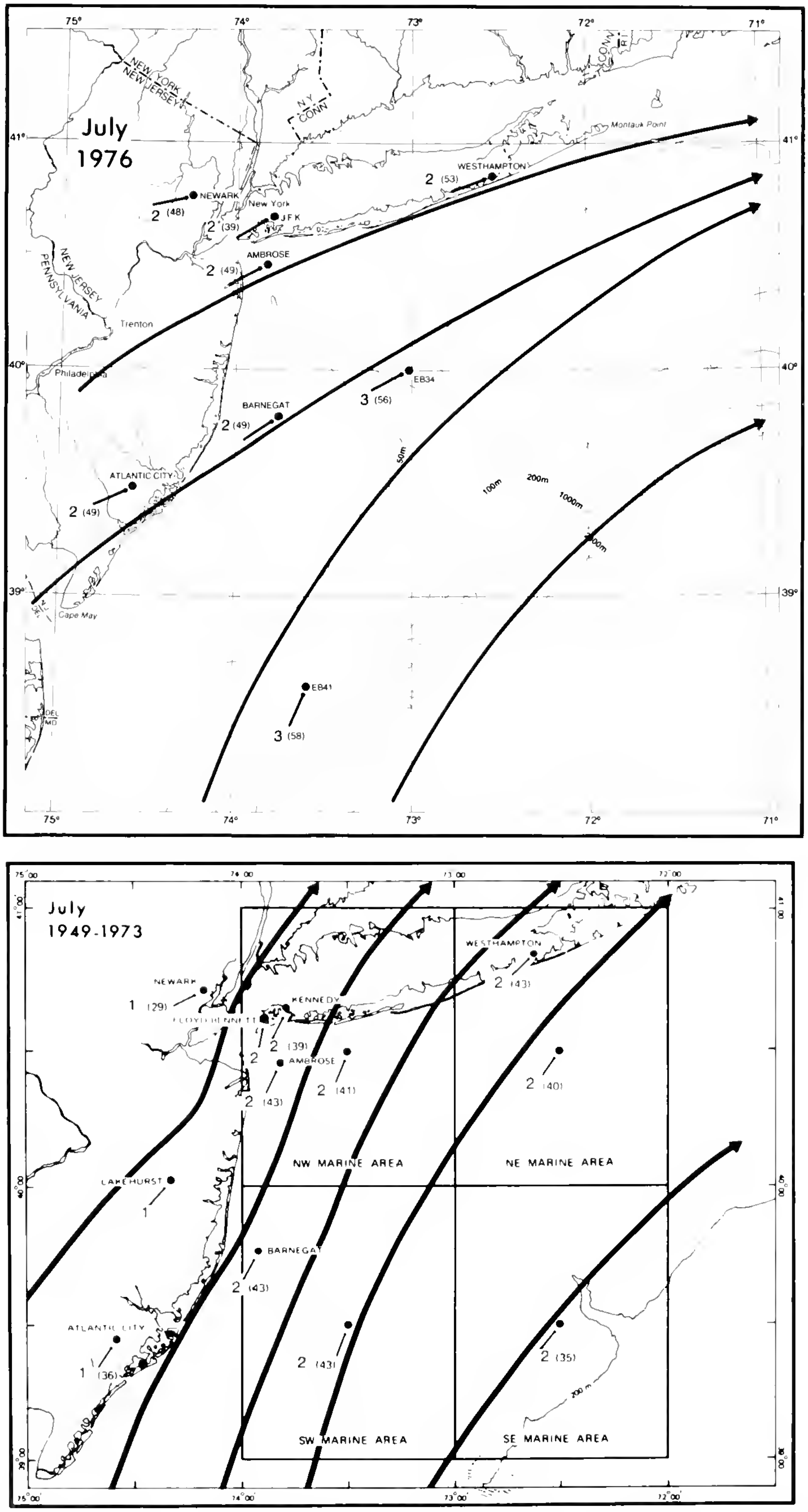


FIGURE 3–7.—Monthly mean surface wind patterns and resultant wind flow, February-August, 1976 and 1949–73 (speed in m/s; constancy in % in parentheses next to vector magnitude)—continued.

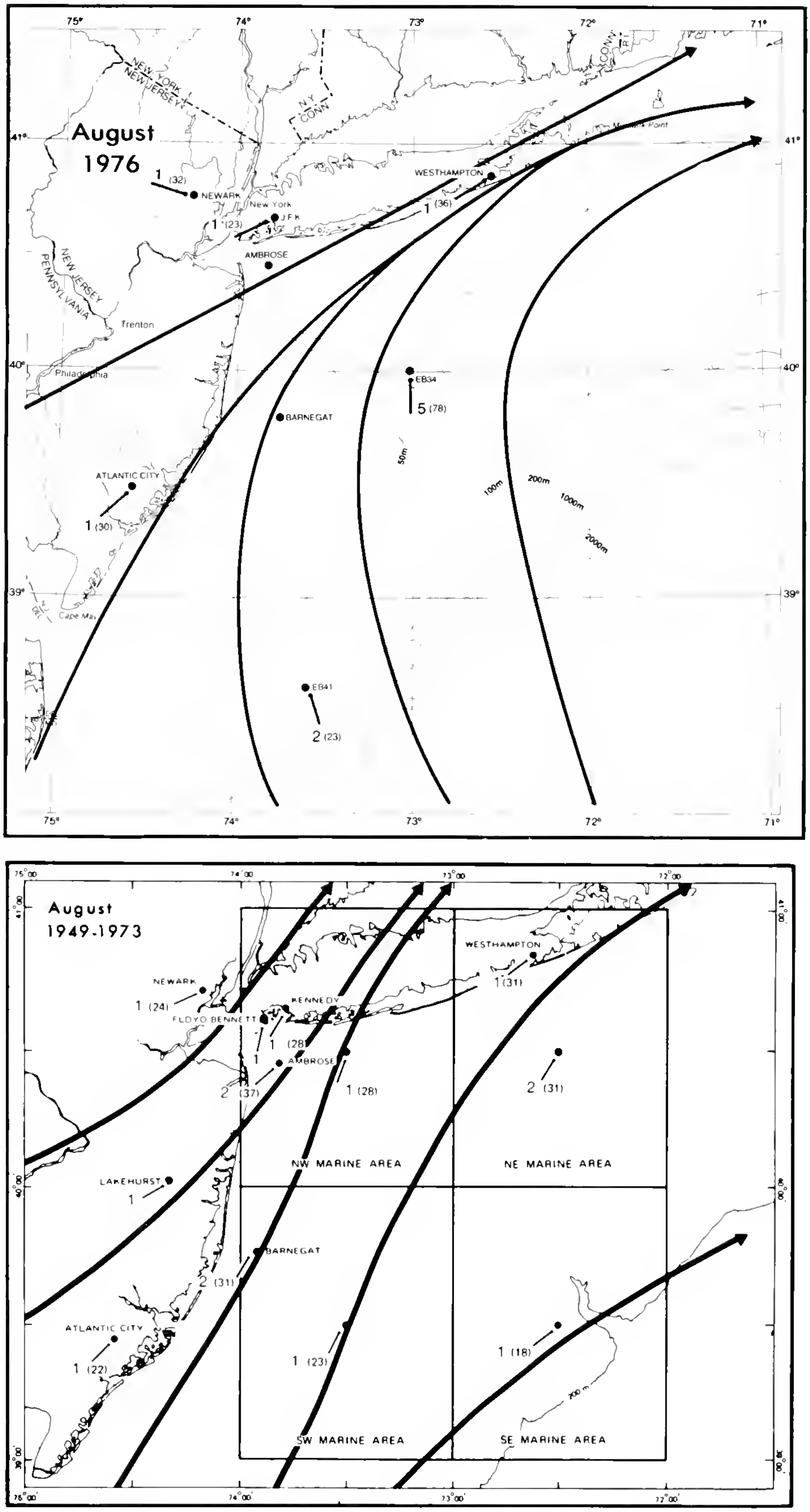


FIGURE 3–7.—Monthly mean surface wind patterns and resultant wind flow, February-August, 1976 and 1949–73 (speed in m/s; constancy in % in parentheses next to vector magnitude)—continued.

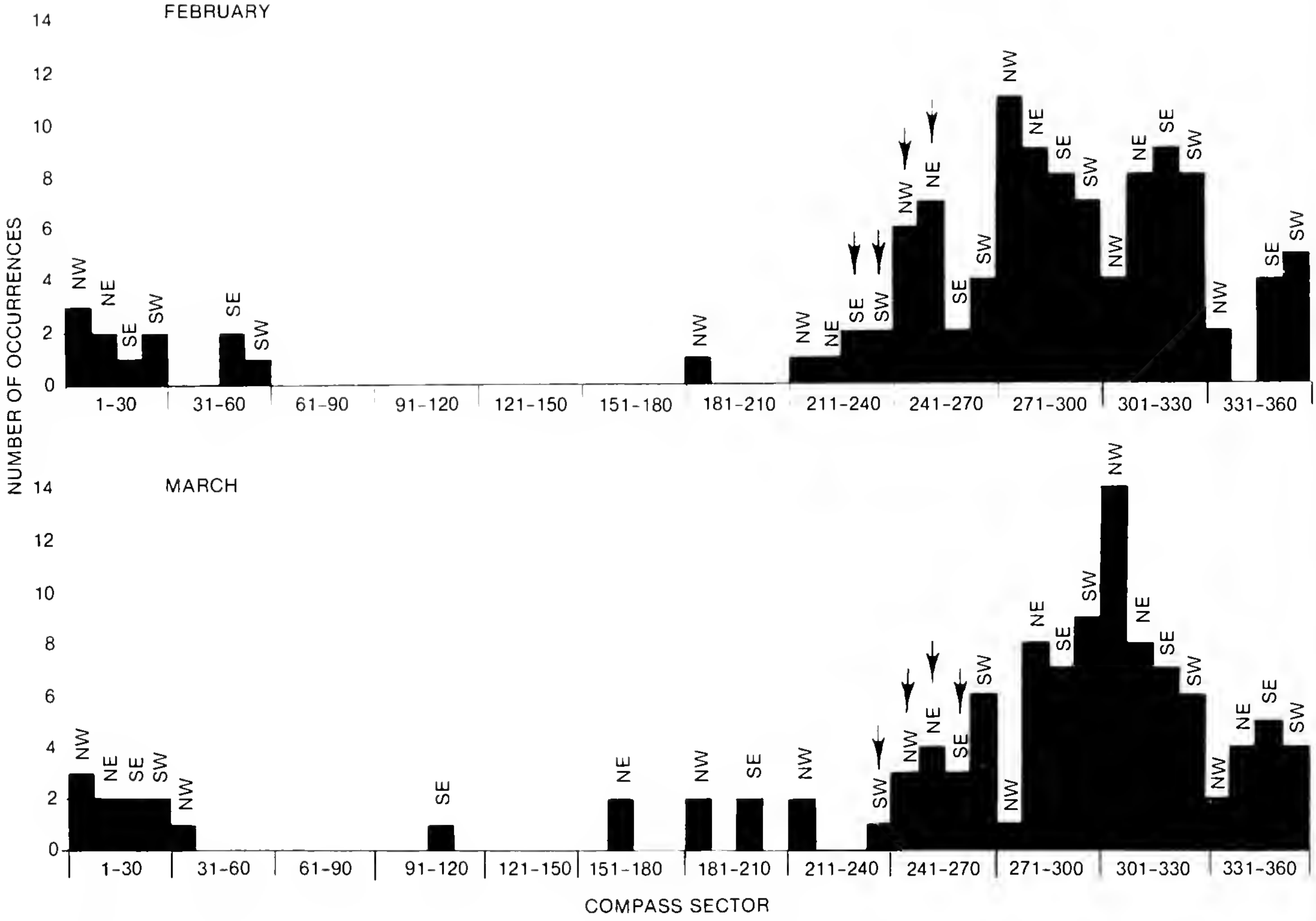


FIGURE 3-8.—Resultant mean wind directions over New York Bight marine areas by 30° compass sectors, February-June, 1949–76 (arrows indicate prevailing directions in 1976).

mean wind-flow patterns for the seven months. During February and March, the climatological resultant flow is from the northwest because the area is normally influenced by repeated polar outbreaks. April is a transition month between the northerly regime of winter and the southerly regime of summer, with winds weakly predominant from the west. Prevailing winds from May through August are from the south and southwest, but in May the wind constancy is considerably less than in June, as the region is influenced by a greater number of disturbances from the west. The constancy is defined as the ratio,

$$|\mathbf{V}_R|/\bar{U}$$

where $\mathbf{V}_R$ is the mean vector wind and $\bar{U}$ is the scalar mean wind speed. In contrast to climatology, the winds for February and March 1976 have a net southerly component south of about 40.5° N, and February exhibits unusually large constancy values. The flow patterns for the other months are closer to the mean, but May and June exhibit substantially higher directional persistence. It should be noted that the surface winds during June agree well with conditions necessary to wash floatable material along the Long Island south shore beaches (Swanson et al. 1978).

To further quantify the uniqueness of the wind patterns during 1976, the frequency distribution of resultant monthly wind vectors by 30° sectors for each of the four marine areas was tabulated. The results (fig. 3–8) show the number of years, beginning in 1949, that the prevailing winds for each month, February through June, "blew" from a given direction.

Thus, during February (including 1976) resultant wind direction from 241°–270° occurred about six times or nearly 21 percent of the time in the northern two areas and in the southern two areas from 211°–240° two times, or less than 10 percent of the time. During March, re-

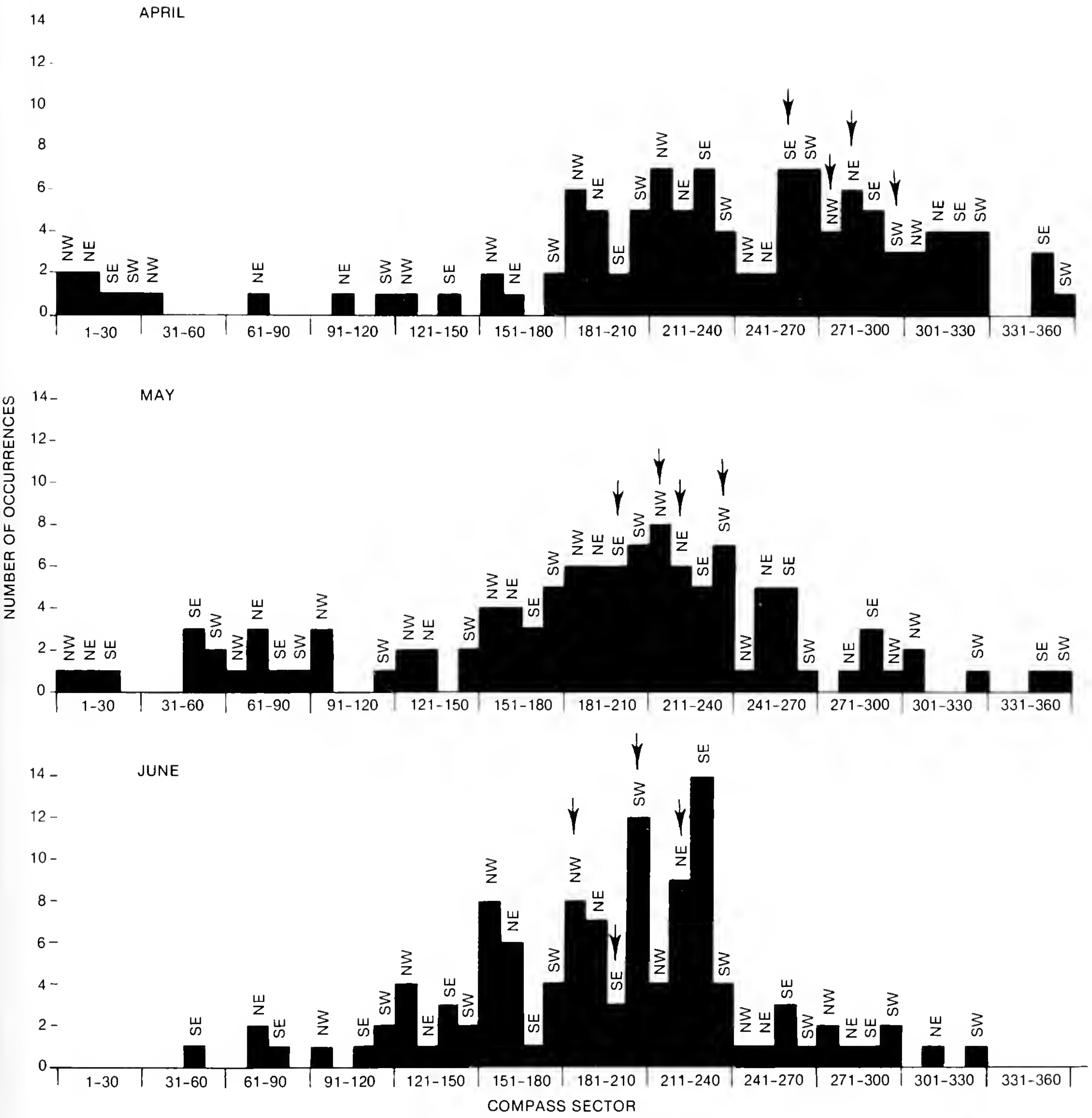


FIGURE 3-8.—Resultant mean wind directions over New York Bight marine areas by 30° compass sectors, February-June, 1949-76 (arrows indicate prevailing directions in 1976)—continued.

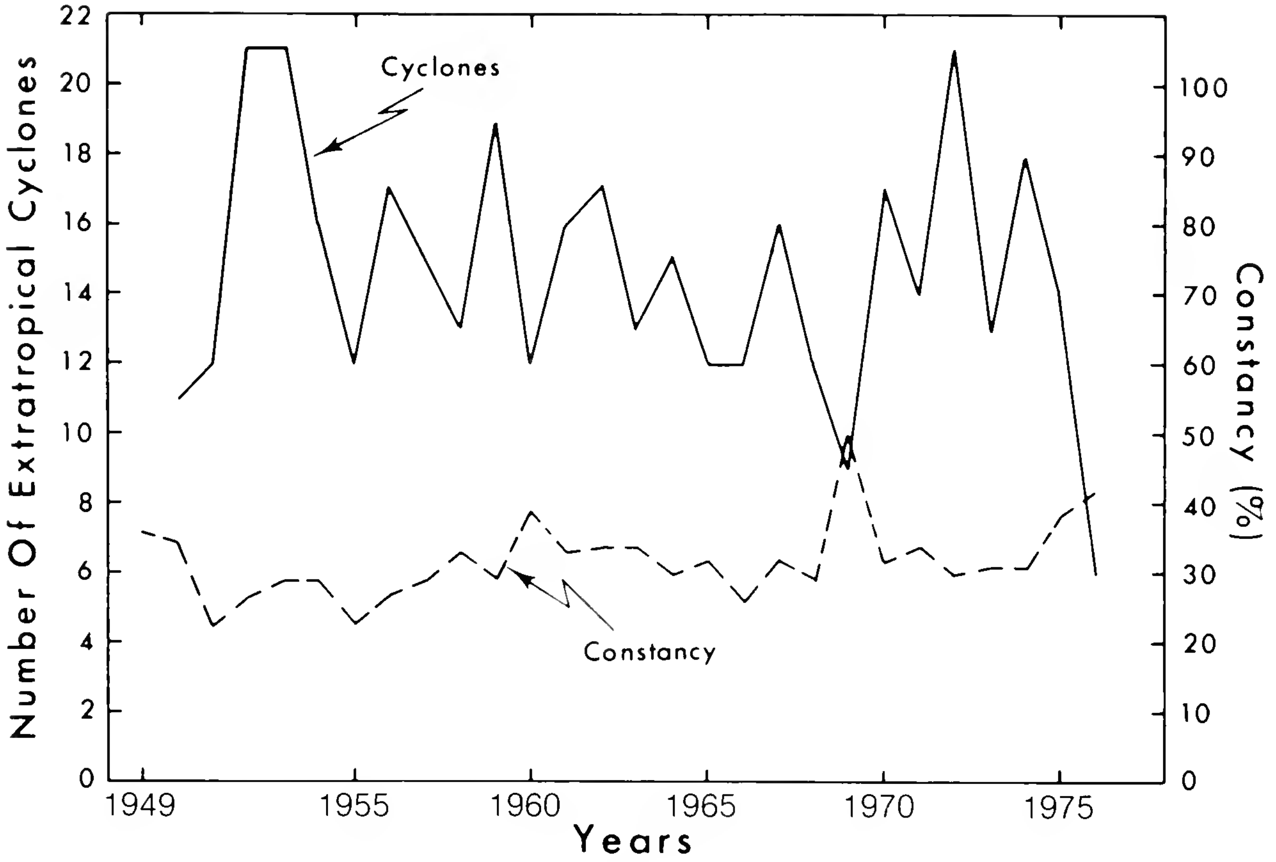


FIGURE 3-9.—Average wind constancy and number of extratropical cyclone centers crossing New York Bight, February-June 1949-76.

sultant winds from 241°-270° occurred about three times or slightly over 10 percent in the northern marine areas, one time from 211°-240° (less than 5% of the time) in the southwest area, and three times (a little over 10%) in the southeast area. These figures indicate that the surface wind flow during February-March was somewhat more anomalous over the Southern Bight. April had a more even distribution from all sectors, consistent with the low wind constancies in figure 3-7. Wind patterns during May and June were close to the climatological norm. The most unusual character of the wind field during these months is its above-normal persistence.

The relative absence of cyclonic activity between February and June 1976 should be reflectd in low wind variability as expressed by a higher constancy ratio. The highest average constancy over this period coincided with the two minima in cyclonic activity over the Bight (in 1969 and 1976) during the 27-year period of record (fig. 3-9). Although constancy is a measure of the vector variance of wind and hence of its directional persistence, scalar variance gives a better measure of turbulence associated with wind. The choice of the 27-year (1949-75) record at John F. Kennedy International Airport (fig. 3-10) as an indicator of the larger scale behavior of the wind field offshore is a reasonable one, since, as may be seen in figure 3-7, changes in wind constancy during 1976 were mirrored by similar changes over the Bight. The wind variance in February and March 1976 was considerably below the long-term mean, as expected. During May, however, the variance was the highest since 1955, showing a substantial increase over 1975. April and June did not have marked differences from their respective means.

Regardless of the particular response time of a water body to changes in atmospheric forcing, it might be expected that in the New York Bight area major features in the wind field, such as its constancy, averaged over a month's time would in turn be reflected in the mean Bight circulation features. The wind data in figure 3-10 correlate well with current meter measurements (see chapter 7), which show a higher total current variance in the Bight during May 1976 than during 1975. The currents also have periods of northeastward flow in accordance with the higher wind constancies (sustained southwesterly winds) in May (fig. 3-7).

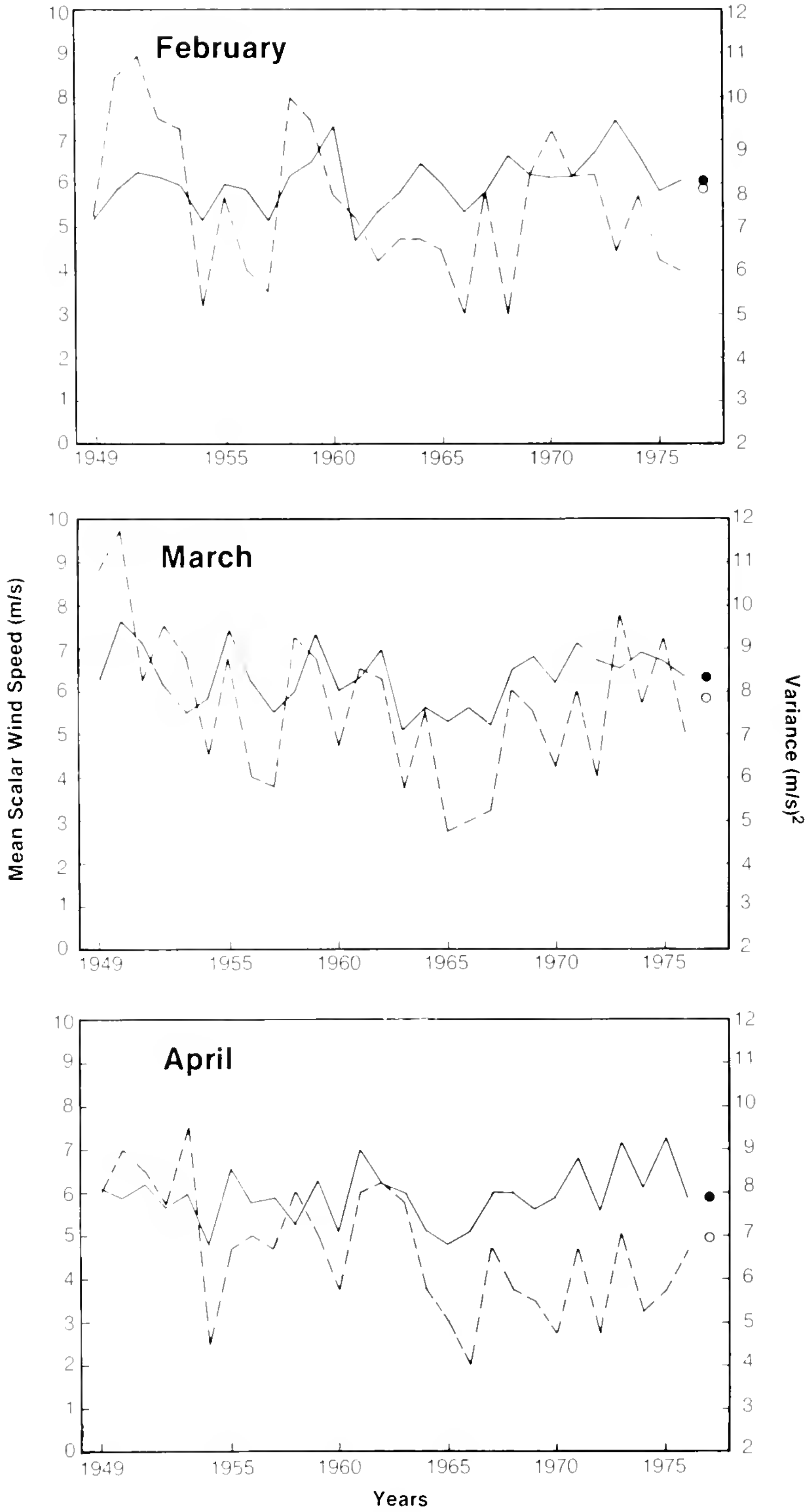


FIGURE 3–10.—Time profile of monthly average wind speed in m/s (solid line) and scalar wind variance in (m/s)$^2$ (dashed line) at John F. Kennedy International Airport, computed from 3-hourly observations, 1949–76. Solid and open circles indicate means values for solid and dashed lines, respectively.

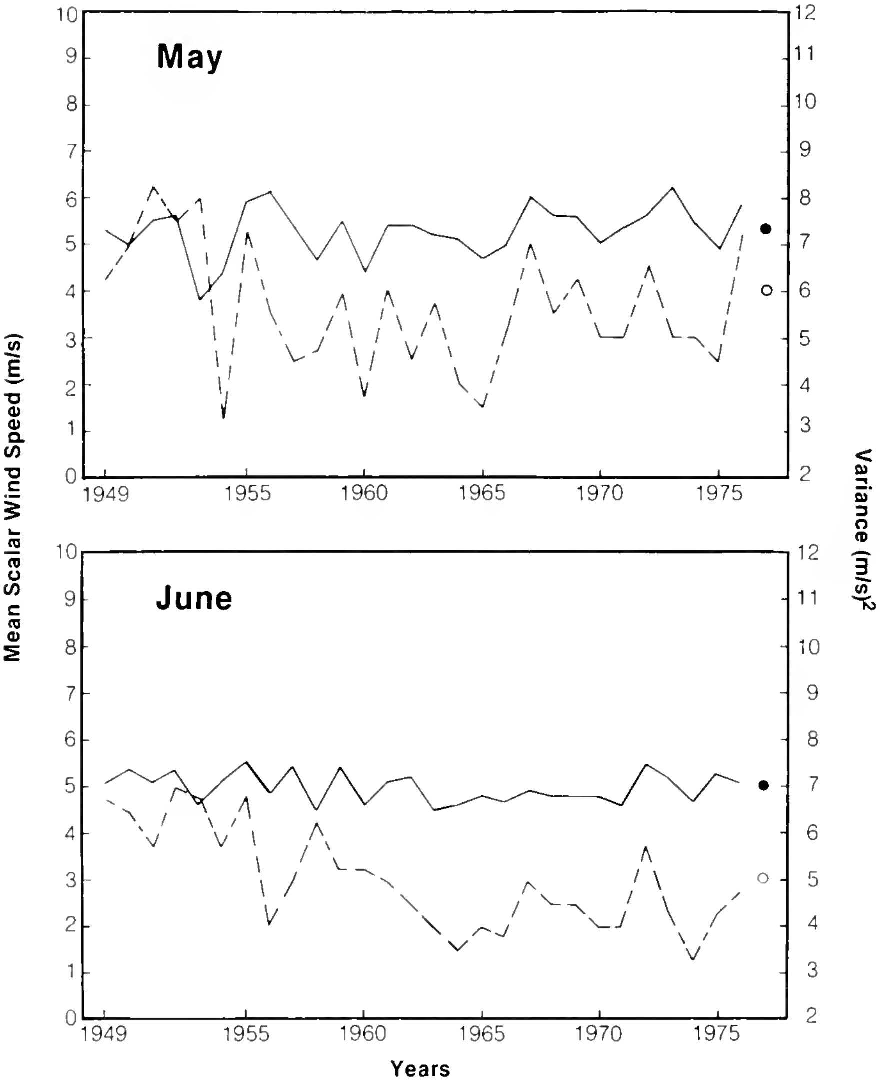


FIGURE 3–10.—Time profile of monthly average wind speed in m/s (solid line) and scalar wind variance in $(m/s)^2$ (dashed line) at John F. Kennedy International Airport, computed from 3-hourly observations, 1949–76—continued.

## WIND STRESS AND VERTICAL MOTION

Using the method described earlier, the average monthly wind stress over the Bight for February-June is presented in figure 3–11. The average monthly surface wind stress vector had a component towards the north for all months February through June, consistent with the resultant wind flow analyses of figure 3–7. Whether a mean northward component of flow at the surface and offshore surface Ekman transport were set up in the Bight 2 to 3 months earlier than usual is not known. However, the results suggest the possibility of some anomalous circulation features during these months.

There are two mechanisms for wind-driven upwelling. One operates in the open ocean, independent of coastal boundaries. It involves the open ocean divergence of the surface Ekman transport, which depends upon the curl of the wind stress and the change in the Coriolis parameter with latitude, and it applies to mid-shelf and outer-shelf regions. The other operates in coastal regions, and depends upon the existence of coastal boundaries. It involves the coastal divergence of the surface Ekman transport, which depends upon the orientation of coastal boundaries relative to the wind stress vector, and it applies to inner-shelf regions. The effects of both mechanisms have been evaluated for the bight and are discussed below.

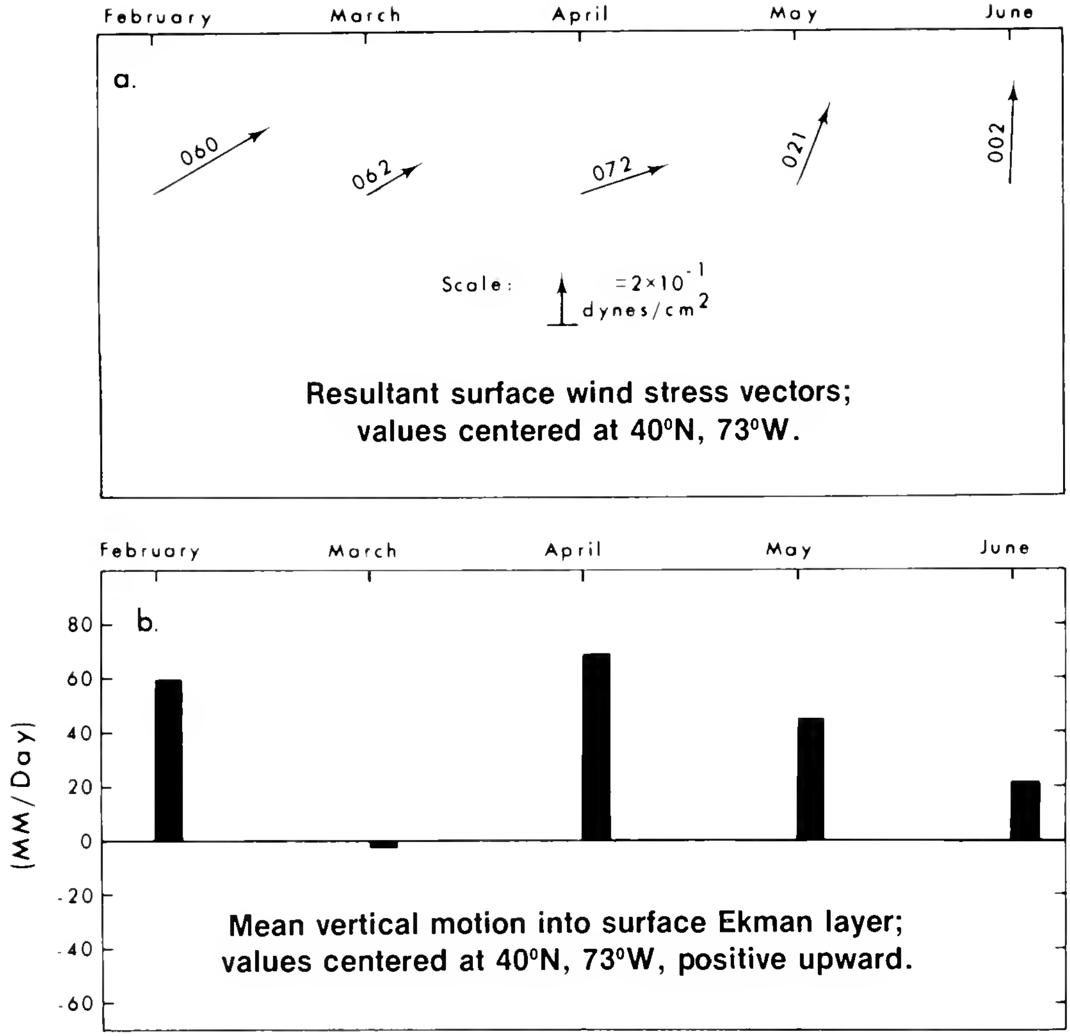


FIGURE 3-11.—Variation of monthly (a) mean surface wind stress over New York Bight (computed by using 10-day wind vector averages) and (b) mean vertical motion at bottom of surface Ekman layer, February-June 1976.

An estimate of the mean vertical motion through the bottom of the surface Ekman layer was calculated from the linearized steady state vorticity equation (see McLellan 1965) and is given by

$$W = \frac{1}{\rho_w f}\left(\frac{\partial \tau_y}{\partial_x} - \frac{\partial \tau_x}{\partial_y}\right) + \frac{\beta \tau_x}{f} \qquad (2)$$

where $\tau_x$ and $\tau_y$ are, respectively, the zonal and meridional components of the stress vector, $\rho_w$ is the water density, $f$ is the Coriolis parameter, and $\beta$ is the change in $f$ with latitude.

Except for March, the vertical motion induced by the curl of the wind stress is positive. This suggests that ("open-ocean") upwelling may have been prevalent in the Bight throughout the analysis period.

A more appropriate indicator of the vertical motion field for the inner shelf is the upwelling index of Ekman mass transport given by:

$$M_{EK}^{(x)} = \tau_y/f \qquad (3)$$

$$M_{EK}^{(y)} = -\tau_x/f \qquad (4)$$

where $\tau_y$, $\tau_x$ and $f$ are defined above. Figure 3-12 shows that the integrated mass transport in the surface mixed layer had a strong offshore component from February to June. The sustained cross-isobath flow implies that onwelling of deeper water onto the continental shelf off New Jersey may have been anomalously strong and established 2 to 3 months sooner than normal.

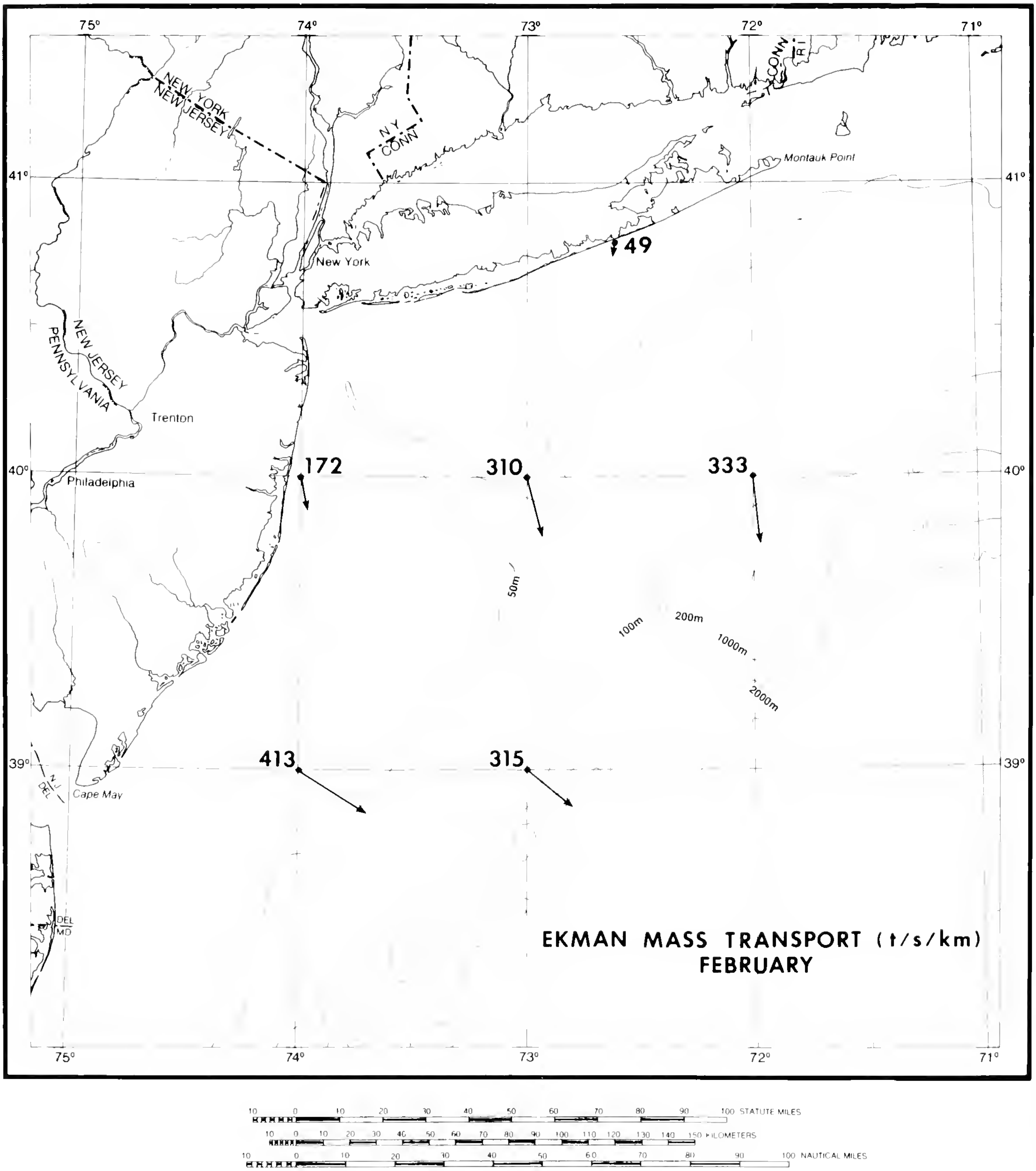


FIGURE 3–12.—Estimated monthly average Ekman mass transport (t/s/km), computed from 10-day averages of wind velocity, February-June 1976.

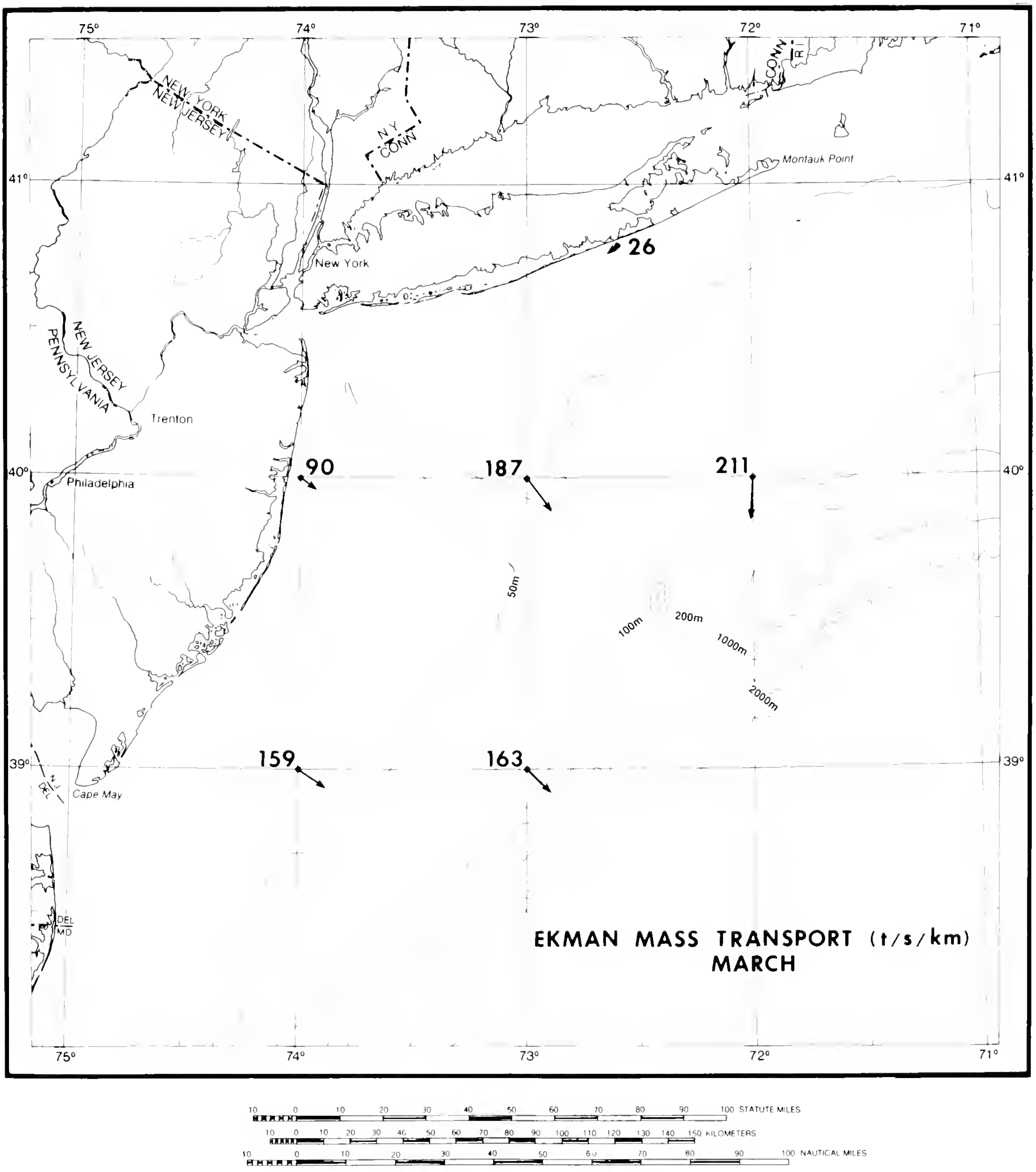


FIGURE 3–12.—Estimated monthly average Ekman mass transport (t/s/km), computed from 10-day averages of wind velocity, February-June 1976—continued.

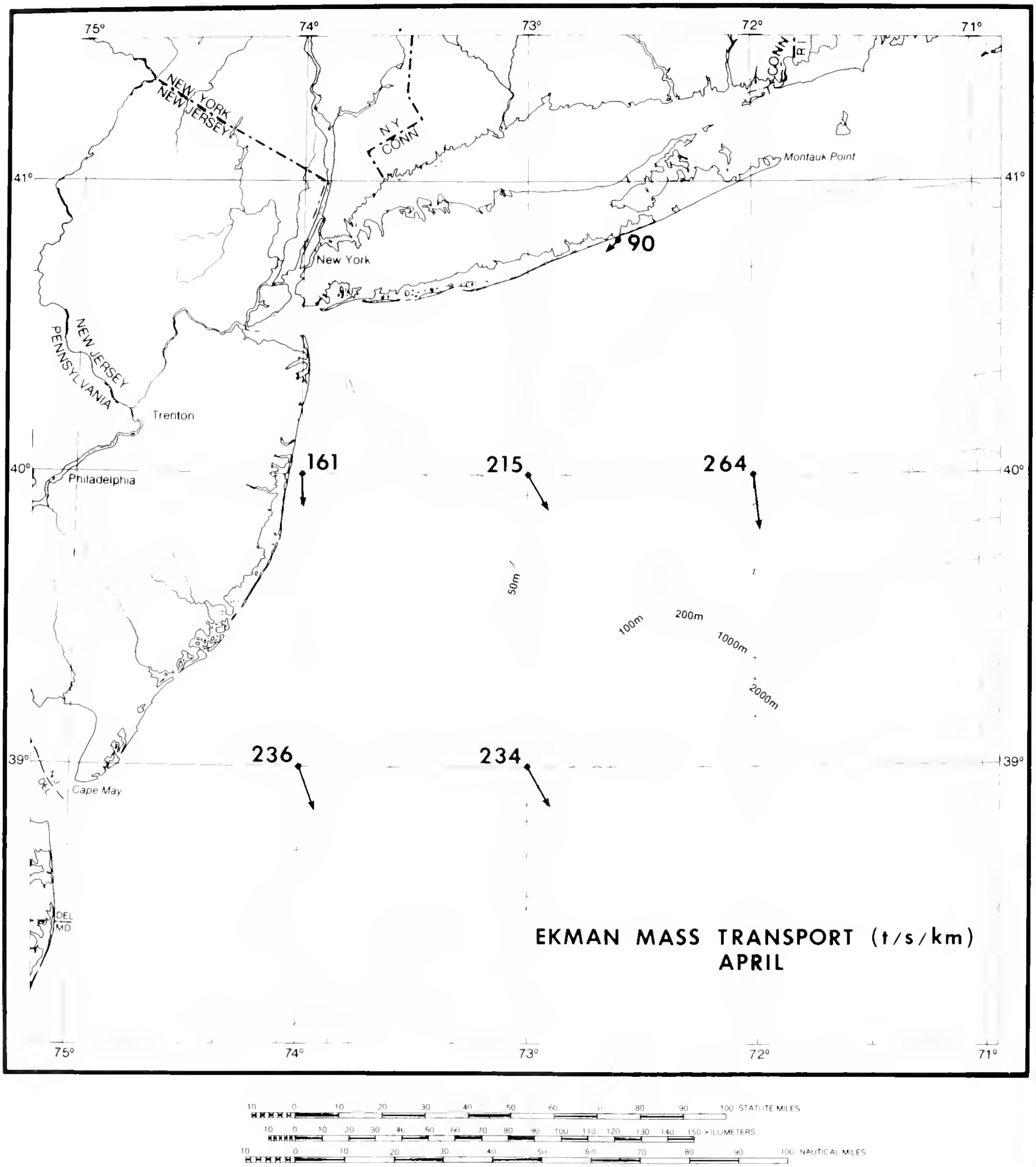


FIGURE 3-12.—Estimated monthly average Ekman mass transport (t/s/km), computed from 10-day averages of wind velocity, February-June 1976—continued.

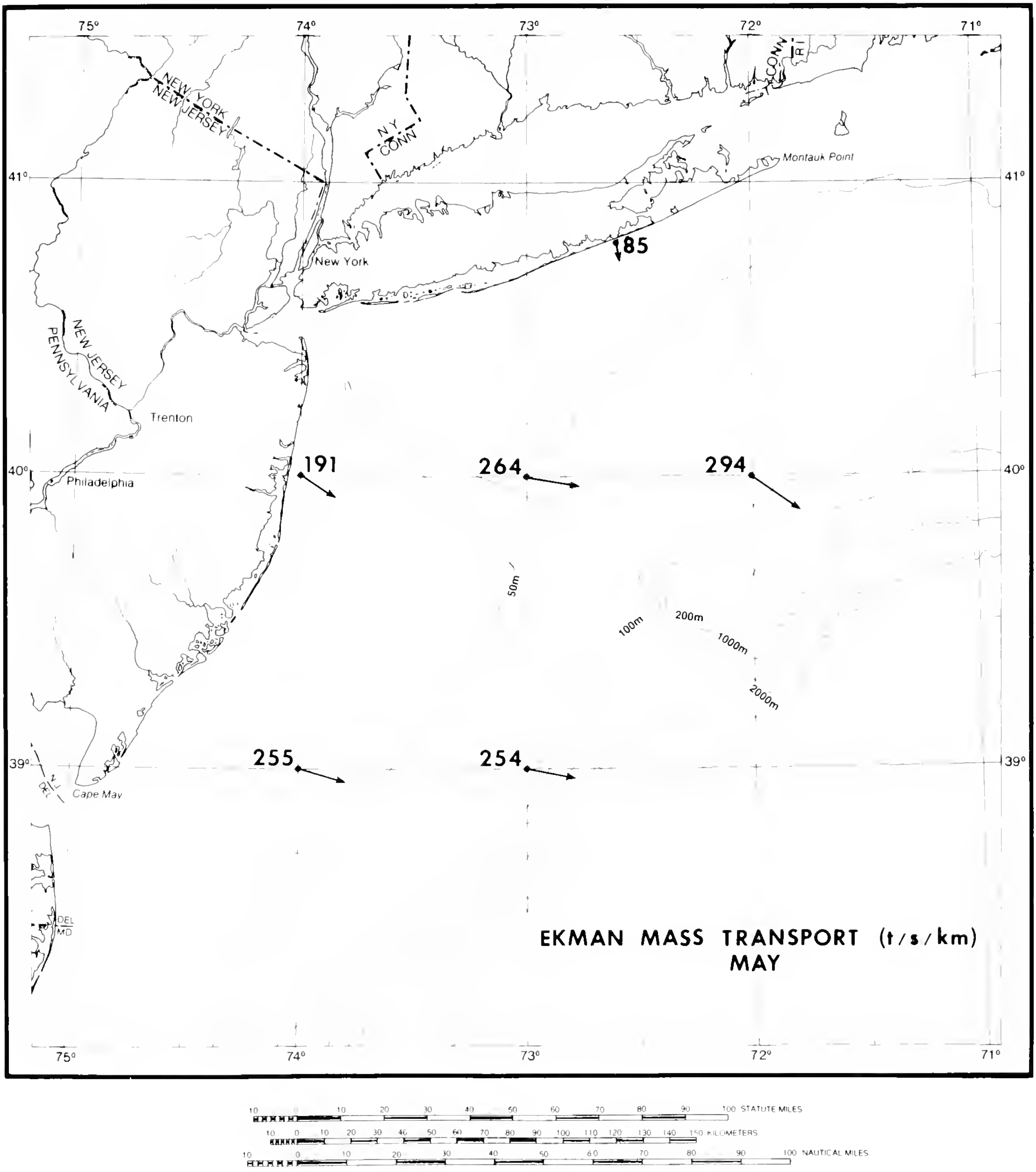


FIGURE 3-12.—Estimated monthly average Ekman mass transport (t/s/km), computed from 10-day averages of wind velocity, February-June 1976—continued.

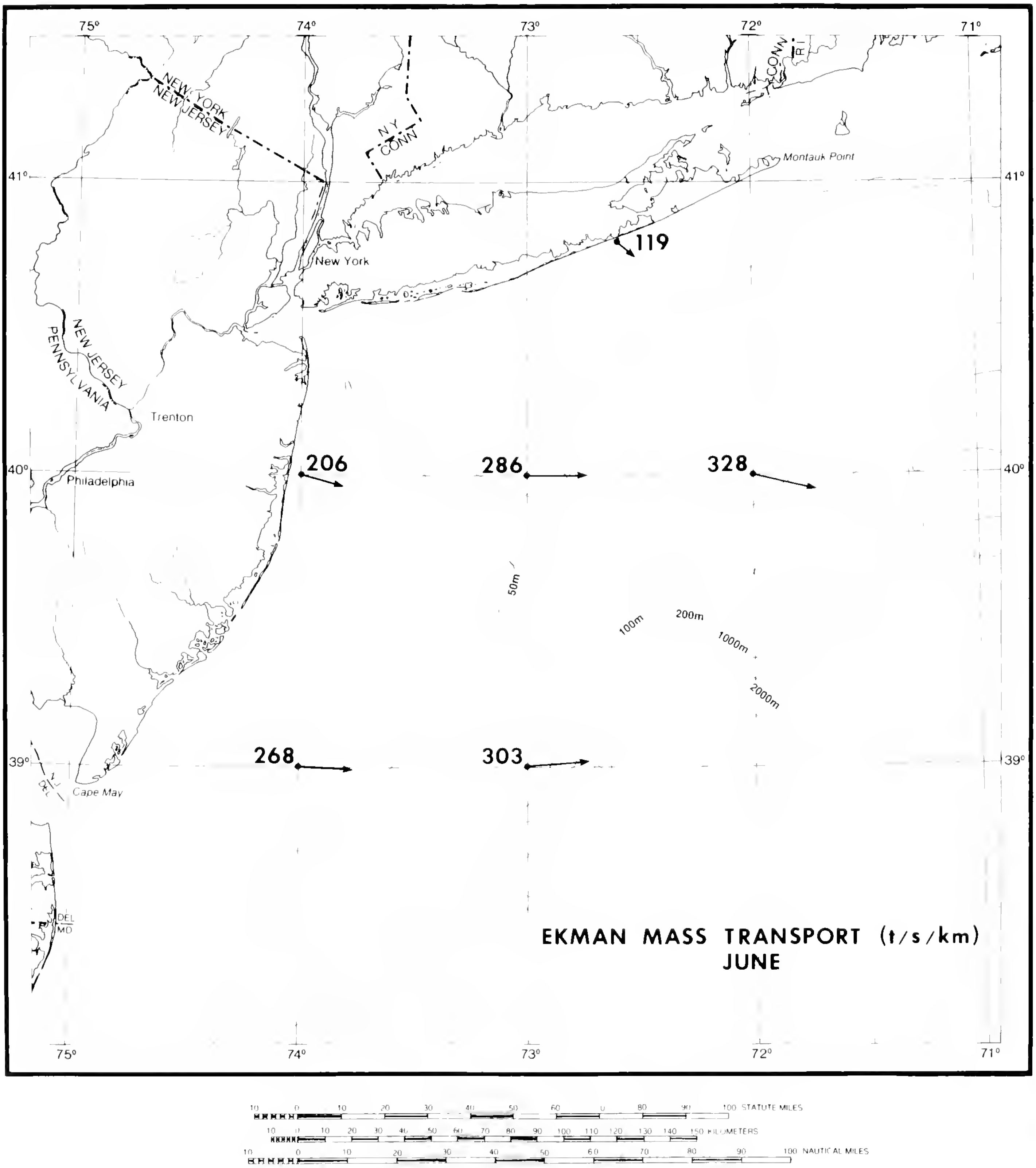


FIGURE 3-12.—Estimated monthly average Ekman mass transport (t/s/km), computed from 10-day averages of wind velocity, February-June 1976—continued.

## CONCLUSIONS

Some of the relevant atmospheric forcing fields affecting the surface environment in New York Bight were examined for February through August 1976, the period before and during the oxygen-depletion event. The same kinds of physical conditions in the historical record were compared to identify possible similarities.

Three salient points relating to atmospheric conditions emerged. First, sea-surface temperatures throughout the Bight were relatively high early in the year when compared with the record for the past 100 years, but there were other similar occurrences in the record. Also, February and March air temperatures over the northeast were near their warmest levels in the past century. The usually warm temperatures may have aided in the early development and subsequent strengthening of stratification of Bight waters. Second, the monthly surface wind patterns showed persistent south to southwesterly flow during the entire period, blowing with above-normal constancy during May and June. Steady wind conditions could have had a pronounced effect on Bight circulation and exchange processes. The general atmospheric circulation patterns over eastern North America departed considerably from the norm during the February through June months. This resulted in a minimum of storm activity over the Bight, and presumably less mixing of the water column, compared with the record for the past 25 years. And third, vertical motion calculations using both open-ocean and coastal upwelling estimates indicate that upwelling/onwelling may have been prevalent during most of the analysis period.

## ACKNOWLEDGEMENTS

This work was sponsored by NOAA's Environmental Data and Information Service through its National Climatic Center, Asheville, N.C. Special thanks are given to Vernell Woldu, for her valuable assistance, and to N. Lawrence Nicodemus, Nathaniel Guttman, Richard Whiting, and the staff of the Applied Climatology Branch.

### *List of Symbols*

$\vec{\tau}$ = Wind stress vector, units of dynes/cm$^2$
$\bar{\rho}$ = Mean density of air, units of grams/cm$^3$ (g/cm$^3$)
$\rho_w$ = Water density, units of grams/cm$^3$ (g/cm$^3$)
$f$ = Coriolis parameter, units of seconds $^{-1}$ (s$^{-1}$)
$\beta$ = The change of $f$ with latitude, units of cm$^{-1}$s$^{-1}$
$\tau_x$ = East-west component of wind stress (positive eastward), units of dynes/cm$^2$
$\tau_y$ = North-south component of wind stress (positive northward), units of dynes/cm$^2$
$W$ = Vertical motion through the bottom of surface Ekman layer, units of mm/day
$C_D$ = Nondimensional drag coefficient
$\mathbf{V}$ = Wind velocity vector, units of cm/s
$\mathbf{V}_R$ = Mean vector wind, units of m/s
$\bar{U}$ = Mean scalar wind, units of m/s
$M^{(x)}_{EK}$ = Ekman mass transport in the east-west direction, units of metric tons/second/kilometer (t/s/km)
$M^{(y)}_{EK}$ = Ekman mass transport in the north-south direction, units of metric tons/second/kilometer (t/s/km)

## REFERENCES

Bakun, A., 1973. Coastal upwelling indicies, west coast of North America, 1946–71, *NOAA Tech. Rep.* NMFS SSRF–671, National Marine Fisheries Service, Washington, D.C., 103 pp.

Dickson, R. R., 1976a. Weather and circulation of February 1976, *Mon. Wea. Rev.* 104:660–665.

Dickson, R. R., 1976b. Weather and circulation of May 1976, *Mon. Wea. Rev.* 104:1084–1089.

Dickson, R. R., and Namias, J., 1976. North American influences on the circulation and climate of the North Atlantic sector, *Mon. Wea. Rev.* 104:1255–1265.

Elsberry, R. L., and Garwood, R. W., Jr., 1978. Sea-surface temperature anomaly generation in relation to atmospheric storms, *Bull. Amer. Meteor. Soc.* 59:786–789.

Lettau, B., Brower, W. A., Jr., and Quayle, R. G., 1976. Marine Climatology, *MESA New York Bight Atlas Monogr.* 7, New York Sea Grant Institute, Albany, N.Y., 240 pp.

McLellan, H. J., 1965. *Elements of Physical Oceanography*, Pergamon Press, Inc., Oxford, England, pp. 82–87.

Mooers, C. N. K., Fernamdez-Partagas, J., and Price, J. F., 1976. Meteorological forcing fields of the New York Bight, *Univ. Miami Tech. Rep.* UM-RSMAS, TR76–8, 151 pp.

Namias, J., and Dickson, R. R., 1976. Atmospheric climatology and its effect on sea-surface temperature, *in* The Environment of the United States Living Marine Resources, 1974, U.S. Department of Commerce *MARMAP Contrib.* No. 104, pp. 3–1 to 3–12.

National Oceanic and Atmospheric Administration, 1950–76, Climatological Data, National Summary, for February-June 1950–76, National Climatic Center, Asheville, N.C.

Swanson, R. L., Stanford, H. M., O'Connor, J. S., Chanesman, S., Parker, C. A., Eisen, P. A., and Mayer, G. F., 1978. June 1976 pollution of Long Island ocean beaches, *J. Environ. Engineer. Div. ASCE* vol. 104, no. EE6, Proc. Paper 14238, pp. 1067–1085.

Taubensee, R. E., 1976a. Weather and circulation of March 1976, *Mon. Wea. Rev.* 104:809–814.

Taubensee, R. E., 1976b. Weather and circulation of June 1976, *Mon. Weo. Rev.* 104:1200–1205.

Wagner, A. J., 1976a. Weather and circulation of January 1976, *Mon. Wea. Rev.* 104:491–498.

Wagner, A. J., 1976b. Weather and circulation of April 1976, *Mon. Wea. Rev.* 104:975–982.

# Oxygen Depletion and Associated Benthic Mortalities in New York Bight, 1976

# Chapter 4. Chemical Factors

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*Adriana Y. Cantillo, George A. Berberian, Joan M. Parker, and Philip G. Hanson*[1]
*James P. Thomas and Jay E. O'Reilly*[4]

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## INTRODUCTION

In this chapter we discuss the chemistry associated with what has been termed the 1976 anoxic event in New York Bight in light of what is known about anoxic conditions in the ocean. We also look at how the chemistry of Bight waters in 1976 differed from other years for which data exist.

When an ocean system like New York Bight moves toward anoxia, chemical events can be described in this general way (Richards 1965; Deuser 1975; Dugdale et al. 1977):

1. Once the system is isolated or overloaded with an oxygen demand, respiration and oxidation of organic matter deplete the dissolved oxygen (D.O.) available.

2. When all or nearly all the D.O. has been utilized, the next source of energy for oxidation of organic matter is nitrate ($NO_3^-$). As the nitrate is utilized, and chemically reduced, concentrations of nitrite ($NO_2^-$) and ammonium ($NH_4^+$) increase. There is some evidence that this reduction should continue to nitrous oxide ($N_2O$) and to elemental nitrogen ($N_2$).

3. When oxygen, nitrate, and nitrite have been consumed, the system uses dissolved sulfate ($SO_4^=$) as its source of oxidative energy, and sulfate is reduced to sulfide ($S^=$), which occurs in the system as hydrogen sulfide ($H_2S$). Since hydrogen sulfide is very toxic, a good deal of sudden mortalities can be expected at this stage.

4. As oxygen, nitrate, nitrite, and sulfate are depleted, the system's oxidizing capability drops, and the environment becomes a reducing one; that is, instead of being an electron sink, the system becomes an electron source. As a result, the oxidation states of numerous dissolved species, notably metals, are changed. This, combined with

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the addition of sulfide to the system, affects solubility behavior. For example, in a normal ocean system, the oxidation state of iron is three, so iron would exist as ferric, $FE^{+3}$ (Fe/III/). However, at the pH of seawater, ferric hydroxide, $Fe(OH)_3$, is so insoluble that iron is immediately removed from the dissolved phase and either precipitates or exists as a colloidal suspension. The formation of ferric hydroxide may also scavenge manganese from seawater (manganese in normal seawater has an oxidation state of four). In anoxic systems, however, iron is reduced to ferrous, $Fe^{+2}$ (Fe/II) and manganese to manganous, $Mn^{+2}$ (Mn/II/). Since chemical species formed by the +2 oxidation states of these metals are more soluble (e.g., rhodochrosite) than those of higher states, the amounts of these metals in the dissolved phase are markedly increased in anoxic waters.

5. Once chemical species that can provide energy for oxidation of organic matter are depleted, the amount of dissolved and particulate organic material should increase as long as sources for the material are present (such as surface productivity). There is evidence that this does occur, but it has not been demonstrated in all situations.

Most of the above effects were noted during 1976 in New York Bight. In fact, it is interesting that the system responded so rapidly to the changing chemical environment at that time.

## 1976 DISTRIBUTION OF OXYGEN COMPARED TO OTHER YEARS

During winter months, New York Bight waters are well mixed and ventilated, with adequate D.O. throughout. As density stratification develops in spring (ch. 2 and 5), oxygen levels below the pycnocline begin to decrease. Smith et al. (1974) described this process for the New York Bight, which they term an outwelling area, and attributed the depletion to three factors:

1. Vertical density isolation restricting ventilation of deep waters;
2. Increased carbon inputs in the warm season caused by increased productivity in surface waters; and
3. Increased D.O. utilization caused by increased temperature.

Segar and Berberian (1976) reported that oxygen depletion occurs every summer in the bottom water of the Bight Apex. They attributed this depletion to plankton productivity stimulated by nitrogen nutrients in the Hudson River discharge. This conclusion was based on oxygen data collected between April 1974 and March 1975. To what extent was 1976 different?

Available 1976 data on bottom oxygen in New York Bight were compared with the historical data base for other years to determine the extent to which oxygen depletion occurred, and whether this depletion was more severe than previously observed. The data base was compiled from National Oceanographic Data Center (NODC) and NODC/MESA data files, and from cooperating investigators (table 4–1).

Data coverage in space and time was less than ideal. Data were heavily concentrated in the Bight Apex, and an order of magnitude more data were available for the years since 1973 than in all other years combined (fig. 4–1). The earliest year for which data are available is 1932. Figure 1–9 in chapter 1 shows the area for which the data base was set up as well as areal segments (boxes) chosen for individual data display.

Available data were first visually inspected for obvious errors and to ensure uniformity of units; they were then placed in a uniform format on a master computer tape. Data on the tape were screened to make sure they were below 10 m, below any existing thermocline, and within 10 m of the bottom (table 4–2). This ensured that only bottom layer samples that were minimally affected by surface mixing would be considered. A sample was tested for a sample depth equal to or greater than 10 m. If temperature was available, samples which did not have a temperature equal to or less than that chosen to represent the bottom of the thermocline were discarded. If no temperature was available but a sample depth was, a test was applied for the depth of bottom of the thermocline. If no temperature or sample depth was available the point was also discarded. Samples with depths not within 10 m of the recorded bathymetric depth were discarded. Samples with no bathymetric or sample depth were discarded unless the sample had been taken with a bottom-tripping bottle.

The results of this screening process are demonstrated in figure 4–2 and summarized in table 4–3. Roughly 50 percent of the overall data did not survive our screening tests. Coverage is particularly poor for years other than 1976 in segments M1, M2, and M3, that is, off the southern New Jersey coast.

In figure 4–3 each area segment has two data plots. One shows the screened bottom oxgyen points for all years except 1976 plotted at ml $O_2$/l versus Julian day (J.D.), and the other shows only 1976 screened data.

We consider oxygen-depleted bottom water to be 2.0 ml/l or less. All species of finfish tested by Azarovitz et al. (ch. 13) avoid waters of 2.1 ml/l. Thurberg and Goodlet (ch. 11, pt. 2) show extensive surf clam mortalities at oxygen levels slightly below 2.0 ml/l. In all segments, except M1, M2, and M3 (where there are essentially no non-1976 data to compare) and L3 (which is well offshore), 1976 was an anomalous year with regard to the extent of oxygen depletion during the stratified season. Low bottom oxygen values either occurred earlier and lasted longer in

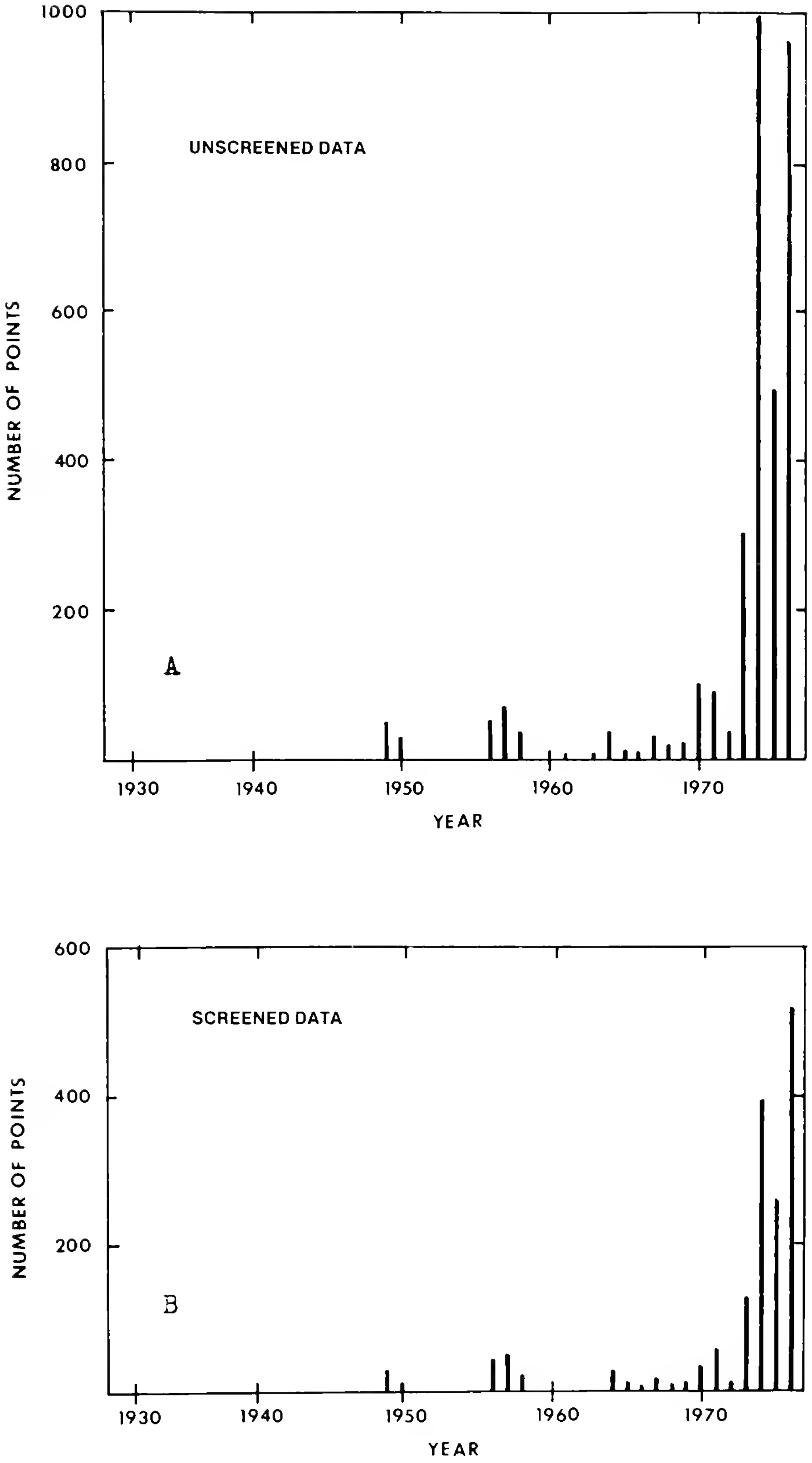


FIGURE 4-1.—Inventory of bottom dissolved oxygen data for New York Bight, 1930–76. A, unscreened data; B, screened data

TABLE 4.1—*Sources for data base*

Amos, A. F., 1976. The New York Bight and Hudson Canyon in October 1974: Hydrography, nephelometry, bottom photography, currents. *Vema* cruise 32 Leg 1 data. Prepared for U.S. Energy Research and Development Administration under Contract No. E(11–1)–2185 by Lamont-Doherty Geological Observatory, Columbia University, Palisades, N.Y., 192 pp.

Atlantic Oceanographic and Meteorological Laboratory, Ocean Chemistry Laboratory, Miami, Fla., Unpublished data of expanded water column characterization cruises (XWCC) 1–11, Nov. 1974-Sept. 1976.

Atlantic Oceanographic and Meteorological Laboratory, Physical Oceanography Laboratory, Miami, Fla., Unpublished data of the cruise of the NOAA ship *Ferrel* (F–5), Nov. 26–29, 1973.

Cape May County Municipal Utilities Authority. Data collected as part of a study by Pandullo Quirk Associates, Wayne, N.J. (in preparation).

Charnell, R. E., Darnell, M. E., Berberian, G. A., Kolitz, B. L., and Hazelworth, J. B., 1976. New York Bight Project, water column characterization cruises 1 and 2 of the NOAA ship *Researcher*, March 4–15, May 5–14, 1974. *NOAA Data Report*, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Washington, D.C.

City College of New York, Biology Department, New York, N.Y. Cruises of the RV *Commonwealth* Numbers 1–12, Sept. 1973-Aug. 1974. Data retrieved from NODC/MESA Data Base. Accession No. 76–1894.

Cox, G. Y. (sr. ed.), 1976. Environmental survey of a proposed alternate dumpsite in the outer New York Bight, Performed for U.S. Environmental Protection Agency by Raytheon Company, Oceanographic and Environmental Services, Portsmouth, R.I.

EG&G, Environmental Consultants, Waltham, Mass., 1977. Marine chemistry measurements in New Jersey coastal waters near 39° 28′ N latitude and 74° 15′ W longitude on January 13, 1976. Letter report prepared for Public Service Electric and Gas Company, Newark, N.J.

EG&G, Environmental Consultants, Waltham, Mass., 1975. Summary of oceanographic observations in New Jersey coastal waters near 39° 28′ N latitude and 74° 15′ W longitude during the period May 1973 through April 1974. Letter report prepared for Public Service Electric and Gas Company, Newark, N.J.

EG&G, Environmental Consultants, Waltham, Mass., 1975. Water quality measurements in New Jersey coastal waters near 39° 28′ N latitude and 74° 15′ W longitude on January 22, 1975. Letter report prepared for Public Service Electric and Gas Company, Newark, N.J.

EG&G Environmental Consultants, Waltham, Mass., 1975. Water quality measurements in New Jersey coastal waters near 39° 28′ N latitude and 74° 15′ W longitude on February 27, 1975. Letter report prepared for Public Service Electric and Gas Company, Newark, N.J.

EG&G, Environmental Consultants, Waltham, Mass., 1975. Water quality measurements in New Jersey coastal waters near 39° 28′ N latitude and 74° 15′ W longitude on December 12, 1974. Letter report prepared for Public Service Electric and Gas Company, Newark, N.J.

EG&G, Environmental Consultants, Waltham, Mass., 1974. Water quality measurements in New Jersey coastal waters near 39° 28′N latitude and 74° 15′ W longitude during March 1974. Letter report prepared for Public Service Electric and Gas Company, Newark, N.J.

EG&G, Environmental Consultants, Waltham, Mass., 1974. Water quality measurements in New Jersey coastal waters near 39° 28′ N latitude and 74° 15′ W longitude on June 12 and 27, 1974. Letter report prepared for Public Service Electric and Gas Company, Newark, N.J.

EG&G, Environmental Consultants, Waltham, Mass., 1974. Water quality measurements in New Jersey coastal waters near 39° 28′ N latitude and 74° 15′ W longitude on July 11 and 25, 1974. Letter report prepared for Public Service Electric and Gas Company, Newark, N.J.

Grumman Ecosystems Corporation, Bethpage, N.Y., and Lawler, Matusky and Skelly, Engineers, 1975. Oceanographic studies to assess the environmental implication of offshore siting of electric generation facilities, New York field studies—1973–1974. Prepared for the New York State Energy Research and Development Authority. Available NTIS FB 250384.

Himchak, P. J., 1977. Ocean sampling related to the algae bloom and subsequent offshore fishkill during the summer of 1976, summation of dissolved oxygen monitoring, New Jersey Division of Fish, Game, and Shellfisheries. Marine Fisheries Section, Nacote Creek Research Station.

Interstate Sanitation Commission Boat Survey Data, Interstate Sanitation Commission, New York, N.Y.

Malone, T. C., 1976. Phytoplankton productivity in the Apex of the New York Bight: September 1973-August 1974, *NOAA Tech. Mem.* ERL MESA–5, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Washington, D.C. 100 pp.

Marine Sciences Research Center, S.U.N.Y., Stony Brook, N.Y. Cruises of RV *Micmac* (MESA 01, MESA 02, MESA 03, MESA 04, MESA 05) from Nov. 5, 1973-June 6, 1974. Data retrieved from NODC Data Base, Accession No. 75–0931.

Nassau County Department of Health, Mineola, N.Y., 1971. Atlantic Ocean (East) water quality survey results, 1971.

Nassau County Department of Health, Mineola, N.Y., 1972. Atlantic Ocean (East) water quality survey results, 1972.

Nassau County Department of Health, Mineola, N.Y., 1973. Atlantic Ocean (East) water quality survey results, 1973.

Nassau County Department of Health, Mineola, N.Y., 1974. Atlantic Ocean (East) water quality survey results, 1974.

Nassau County Department of Health, Mineola, N.Y., 1971. Atlantic Ocean (West) water quality survey results, 1971.

Nassau County Department of Health, Mineola, N.Y., 1972. Atlantic Ocean (West) water quality survey resutls, 1972.

Nassau County Department of Health, Mineola, N.Y., 1973. Atlantic Ocean (West) water quality survey results, 1973.

Nassau County Department of Health, Mineola, N.Y., 1974. Atlantic Ocean (West) water quality survey results, 1974.

Nassau County Department of Health, Mineola, N.Y., 1975. Nassau County ocean surface water quality report, 1975 Report Year.

Nassau County Department of Health, Mineola, N.Y. Nassau County surface water sampling data chemical results, Atlantic Ocean West and East, computer printout of data.

Nassau County Department of Health, Mineola, N.Y., 1970. Atlantic Ocean West water quality survey results, 1970.

Nassau County Department of Health, Mineola, N.Y., 1970. Atlantic Ocean East water quality survey results, 1970.

Nassau County, New York, 1976. Report of a study conducted by the Bureau of Water Pollution Control of the Nassau County Department of Health, Mineola, N.Y. Report on the Impact of Ocean

TABLE 4.1—*Sources for data base—continued*

Sludge Disposal on the Nearshore Water and Sediment Quality, 53 pp.

NODC Worldwide Data Base. Data retrieved in November 1976 Sandy Hook Laboratory, Highlands, N.J., Middle Atlantic Coastal Fisheries Center. Historical Corps of Engineers Study 1968–1971, data collected from the *Albatross IV*, *Oregon II*, *Delaware II* and various smaller vessels; 8/2/73 to 8/6/73, 10/19/73 to 10/26/73, 1/22/74 to 1/30/74, 3/22/74 to 4/4/74, and 8/26/74 to 9/6/74, plus various other dates 1968–1972. Data retrieved from NODC/MESA Data Base. Accession No 76–1310.

Sandy Hook Laboratory, Highlands, N.J., National Marine Fisheries Service. MESA Primary Productivity Study in Raritan—lower Hudson estuary, cruises of the RV *Rorqual* from Nov. 12, 1973-June 4, 1975. Data retrieved from NODC/MESA Data Base. Accession No. 76–1435.

Sandy Hook Laboratory, Highlands, N.J., National Marine Fisheries Service, Middle Atlantic Coastal Fisheries Center. Cruises of the RV *Oregon II* and RV *Delaware II* (07401, D7409, D7416, D7502 and D7512) from March 22, 1974-Aug. 23, 1975. Data retrieved from NODC/MESA Data Base, Accession No. 76–1469.

Sandy Hook Laboratory, Highlands, N.J., National Marine Fisheries Service. Oxygen data tape brought to AOML by F. Steimle, March 1976.

Smith, K. L., Rowe, G. T., and Clifford, C. H., 1974. Sediment oxygen demand in an outwelling and upwelling Area *Tethys* 6:223–230.

U.S. Environmental Protection Agency. Data reported in various sources, often duplicating each other. Major sources are:

(1) STORET Environmental Data Base, retrieval data Nov. 29, 1976.

(2) Ocean Disposal in the New York Bight, Technical Briefing Report No. 2, USEPA, Region II, April 1975. (Caution: There are errors in the way data are presented in these technical reports.)

(3) Data sent by Hal Stanford via memorandum dated Sept. 28, 1976, called "EPA Data Relative to Fish Kill Problem."

Vaccaro, R. F., Grice, G. D., Rowe, G. T., and Wiebe, P. H., 1972. Acid-iron waste disposal and the summer distribution of standing crops in the New York Bight *Water Res.* 6(3):231–256.

Virginia Institute of Marine Science (VIMS). Data collected under Contract 08550–CT5–42 between VIMS and the Bureau of Land Management as part of the Mid-Atlantic Biological-Chemical Benchmark Program.

Whitledge, T. E., and Wold, E. (eds.), 1978. Preliminary data report I: Atlantic coastal experiment 1 (ACE–1), March 26,—April 9, 1975. Oceanographic Sciences Division, Brookhaven National Laboratory, Upton, N.Y. Informal Report (Limited Distribution) #24098.

Woods Hole Oceanographic Institution, Woods Hole, Mass., 1961. Biological, chemical, and radiochemical studies of marine plankton. Appendix C to Reference No. 61–6: Report submitted to the U.S. Atomic Energy Commission under contract at (30–1)–1918 (unpubl. ms.), *Crawford* Cruise 13, July 10–12, 1957.

TABLE 4–2.—*Screening criteria applied to dissolved oxygen data to test whether samples were below thermocline and in bottom water*

| Month | Jan. | Feb. | Mar. | Apr. | May | June | July | Aug. | Sept. | Oct. | Nov. | Dec. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Julian day (J.D.) at end of month | 31 | 59 | 90 | 120 | 151 | 181 | 212 | 243 | 273 | 304 | 334 | 365 |
| Temperature (°C) at bottom of thermocline* | ** | ** | ** | 8.0 | 9.1 | 10.2 | 11.3 | 12.4 | 13.5 | 14.5 | 14 | ** |
| Depth (m) to bottom of thermocline* | ** | ** | ** | 20 | 20 | 20 | 30 | 30 | 30 | 30 | 20 | ** |
| Maximum displacement from bottom | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 | 10 |

*Algorithm used for temperature for April through October is: $T = 0.035(\text{J.D.}) + 4.4$. Temperatures and depths for the bottom of the thermocline are those used in chapter 5.

**Thermocline nonexistent, use within 10 m of bottom screening criteria only.

TABLE 4–3.—*Screening of dissolved oxygen data for New York Bight bottom water—1932–75 and 1976 data base*[1]

| Area segment[2] | A | J1 | J2 | M1 | M2 | M3 | L1 | L2 | L3 | H |
|---|---|---|---|---|---|---|---|---|---|---|
| Total points available | 1,887 | 127 | 160 | 334 | 115 | 46 | 173 | 139 | 249 | 133 |
| Total points after screening | 751 | 105 | 137 | 80 | 80 | 38 | 95 | 122 | 184 | 121 |
| Total 1976 points available | 184 | 48 | 73 | 318 | 106 | 39 | 54 | 39 | 57 | 39 |
| 1976 points available after screening | 77 | 45 | 62 | 71 | 73 | 37 | 31 | 35 | 48 | 35 |
| Total non-1976 points after screening | 674 | 60 | 75 | 9 | 7 | 1 | 64 | 87 | 136 | 86 |

[1] Compiled by NOAA Atlantic Oceanographic and Meteorological Laboratories.

[2] Limits of area segments are shown in figure 1–9 of chapter 1.

1976 than in any of the previous years represented in the data base (segment A), or the lowest bottom oxygen records for the entire data base were observed in 1976. The latter is particularly true for segments J1, J2, L1, L2, and H where no, or infrequent, bottom oxygen values below 2.0 ml/l were observed prior to 1976. However, in each of these segments, numerous values between 0.0 and 2.0 ml/l were observed between J.D. 200 and 270 (July 27 and October 5) in 1976. It is also clear that the 1976 depletion was less severe off Long Island (segments L1, L2) than in the Apex (segment A) and off New Jersey (segments J1, J2, M1, M2). Off New Jersey and in the Apex numerous values of bottom oxygen were less than 2.0 ml/l as early as J.D. 200; however, the only values less than 2.0 ml/l off Long Island were observed about J.D. 270 (XWCC cruise 11) and only one of these was less than 1.0 ml/l.

Figure 4–3 also gives some idea of the spreading rate of the 1976 oxygen depletion; segments A, J1, J2, M1, and M2 have bottom data for the entire year. Assuming that if, and when, low bottom oxygens existed they would have been detected, we can establish the following approximate dates that bottom oxygen levels became critical, that is, less than 2.0 ml/l:

| | |
|---|---|
| New York Bight Apex (segment A) | mid-June |
| Northern New Jersey coast, nearshore (segment J1) | mid-June |
| Northern New Jersey coast, offshore (segment J2) | mid-June |
| Southern New Jersey coast, nearshore (segment M1) | early August |
| Southern New Jersey coast, offshore (segment M2) | mid-August |

This time sequence is essentially the same as that presented in other reports (IDOE Workshop Proceedings 1976; Interagency Workshops 1976); however, whether this was simply a discovery sequence of low oxygen occurrence or a real spreading of the phenomenon has been questioned. Because the data distribution shown here covers the entire year, we can say with some confidence that this is indeed an occurrence sequence rather than a discovery sequence.

Table 4–4 shows how many zero oxygen values (representing total anoxia) for 1976 actually show up in the data base. Only five such values occur outside segment M1. Of the 17 in segment M1, only three were shown to be below the thermocline as defined by the above criteria. Though we use "anoxic" and anoxia" here, the phenomenon is better described as a severe oxygen depletion.

Figure 4–3 also shows the theoretical oxygen solubility changes in each segment as a result of temperature changes in bottom water and linear least-squares fits to D.O. versus Julian-day plots wherever sufficient data exist.

TABLE 4–4.—*Screening of 1976 zero oxygen values for New York Bight*

| Area segment[a] | Total number of zero values observed | Number of zero values in screening |
|---|---|---|
| A | 0[b] | 0[b] |
| L2 | 0 | 0 |
| L2 | 0 | 0 |
| L3 | 0 | 0 |
| M3 | 0 | 0 |
| M2 | 1 | 0 |
| M1 | 17 | 14[c] |
| J1 | 1 | 0 |
| J2 | 3 | 0 |
| H | 0 | 0 |

[a] Limits of area segments shown in figure 1–9 of chapter 1.

[b] One non-1976 zero value in area segment A.

[c] All 14 points are from one data source—a 1977 report by P. J. Himchak of New Jersey Division of Fish, Game, and Shellfisheries, Marine Fisheries Section, Nacote Creek Research Station. All 14 samples are for late July or August, list no bathymetric depth, and fail either the temperature or depth test for being below the thermocline. Sample depths vary from 12 to 29 m.

The oxygen solubility is the theoretical solubility (i.e., maximum concentration) at 1 atmosphere pressure and was calculated on the basis of mean bottom temperatures (table 4–5) for each month in 1974, 1975, and 1976 as determined from data presented in chapter 5. Since the effect of salinity on oxygen solubility is small, we assumed a mean salinity for Bight bottom waters of 32.75‰ for the solubility calculation. Note that temperature changes in the bottom water are a result of advection and mixing with warmer or colder waters. The solubility curve should not be viewed as a loss in oxygen as bottom water became warmer but rather a change in the maximum theoretical amount of oxygen that the bottom water could contain. As seen in figure 4–3, changes in oxygen solubility resulting from temperature changes have a minimal effect on depletion of oxygen in the bottom water. Changes in theoretical maximum oxygen concentration due to temperature changes were about 1 ml/l, whereas observed depletions due to all causes ranged from 4 to 8 ml/l.

Lines for linear least-squares fits in figure 4–3 were drawn for the time intervals noted only when the conditions listed in the figure explanation were fulfilled. These severely limiting conditions prevented drawing many of the lines. Attempts to use more intervals to better define changes in depletion rates with time failed because of poor data distribution. These lines represent *depletion* rates not *utilization* rates. The latter are discussed in chapter 8.

An attempt was made to compare 1976 depletion rates (J.D. 100 to 200) in each segment to mean depletion rates for all other years, but this was difficult (table 4–6). Only

TABLE 4-5.—*Temperatures used to compute mean oxygen solubility in New York Bight bottom water—1974, 1975, and 1976*

| Month | | Jan | Feb | Mar | Apr | May | June | July | Aug | Sept. | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Mean Julian day of month | | 15 | 46 | 74 | 106 | 135 | 166 | 196 | 227 | 258 | 288 | 319 | 349 |
| Station 23[1] (A, J1, H) | $\bar{T}$°C: | 7.0 | 6.0 | 5.5 | 6.3 | 7.7 | 8.7 | 9.7 | 12.7 | 12.7 | 12.0 | 13.0 | 12.0 |
| Station 69[1] (L1, L2) | $\bar{T}$°C | 7.0 | 6.0 | 6.0 | 5.5 | 7.0 | 7.0 | 7.5 | 8.5 | 12.0 | 15.0 | 12.0 | 11.0 |
| Station 49 or 88[1] (J2, M1, M2) | $\bar{T}$°C | 7.0 | 7.0 | 6.0 | 7.0 | 7.5 | 8.5 | 9.5 | 11.0 | 12.5 | 14.0 | 12.0 | 11.0 |
| Station 38[1] (L3, M3) | $\bar{T}$°C | 7.0 | 7.0 | 8.0 | 8.5 | 7.5 | 8.0 | 8.0 | 8.5 | 9.0 | 11.0 | 13.0 | 13.0 |

[1] Station from which indicated mean temperature (°C) of bottom water was used to compute mean oxygen solubility for area segments indicated in parentheses. Station locations are given in chapter 5. Limits of area segments are shown in figure 1-9 of chapter 1.

TABLE 4-6.—*Oxygen depletion rates calculated from linear regression of least-squares fits—time interval Julian day 100 to 200*

| Area segment[1] | 1976 | | | Non-1976 | | |
|---|---|---|---|---|---|---|
| | Rate (ml/l/d) | $R^2$ | $R^2$ for $P<0.05$ | Rate (ml/l/d) | $R^2$ | $R^2$ for $P<0.05$ |
| A | −0.053 | 0.89 | 0.35 | −0.017 | 0.38 | 0.13 |
| J1 | −0.054 | 0.91 | 0.50 | +0.004 | 0.07 | 0.46 |
| J2 | −0.058 | 0.94 | 0.46 | −0.012 | 0.19 | 0.41 |
| M1 | −0.047 | 0.91 | 0.42 | — | — | — |
| M2 | — | — | — | — | — | — |
| M3 | — | — | — | — | — | — |
| L7 | −0.033 | 0.85 | 0.51 | +0.011 | 0.18 | 0.40 |
| L2 | −0.039 | 0.98 | 0.55 | −0.010 | 0.21 | 0.40 |
| L3 | — | — | — | −0.014 | 0.29 | 0.33 |
| H | −0.048 | 0.97 | 0.47 | −0.003 | 0.09 | 0.36 |

[1] Limits of area are shown in figure 1-9 of chapter 1.

[2] R is the correlation coefficient for the plot of dissolved oxygen versus Julian day for the interval J.D. 100 to 200. A perfect correlation would have R equal to 1.0 and a probability (P) of 0 that the correlation occurred by chance. The columns "R for $P<0.05$" give the correlation coefficient necessary to statistically state that the correlation occurred by chance is $<0.05$.

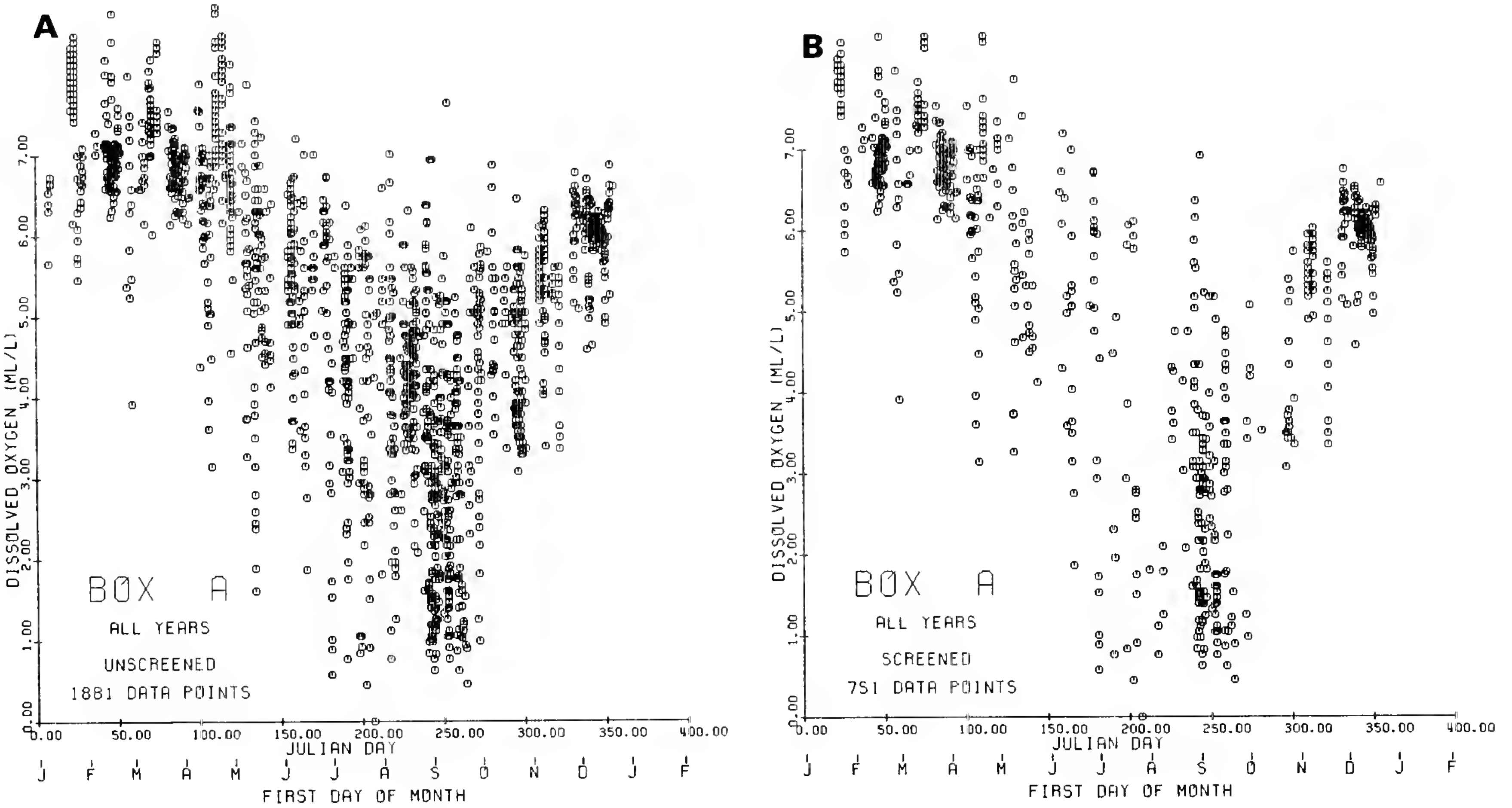


FIGURE 4-2.—Unscreened (A) and screened (B) values of bottom dissolved oxygen observed in New York Bight Apex (area segment A), 1930–76, by time of year values were observed.

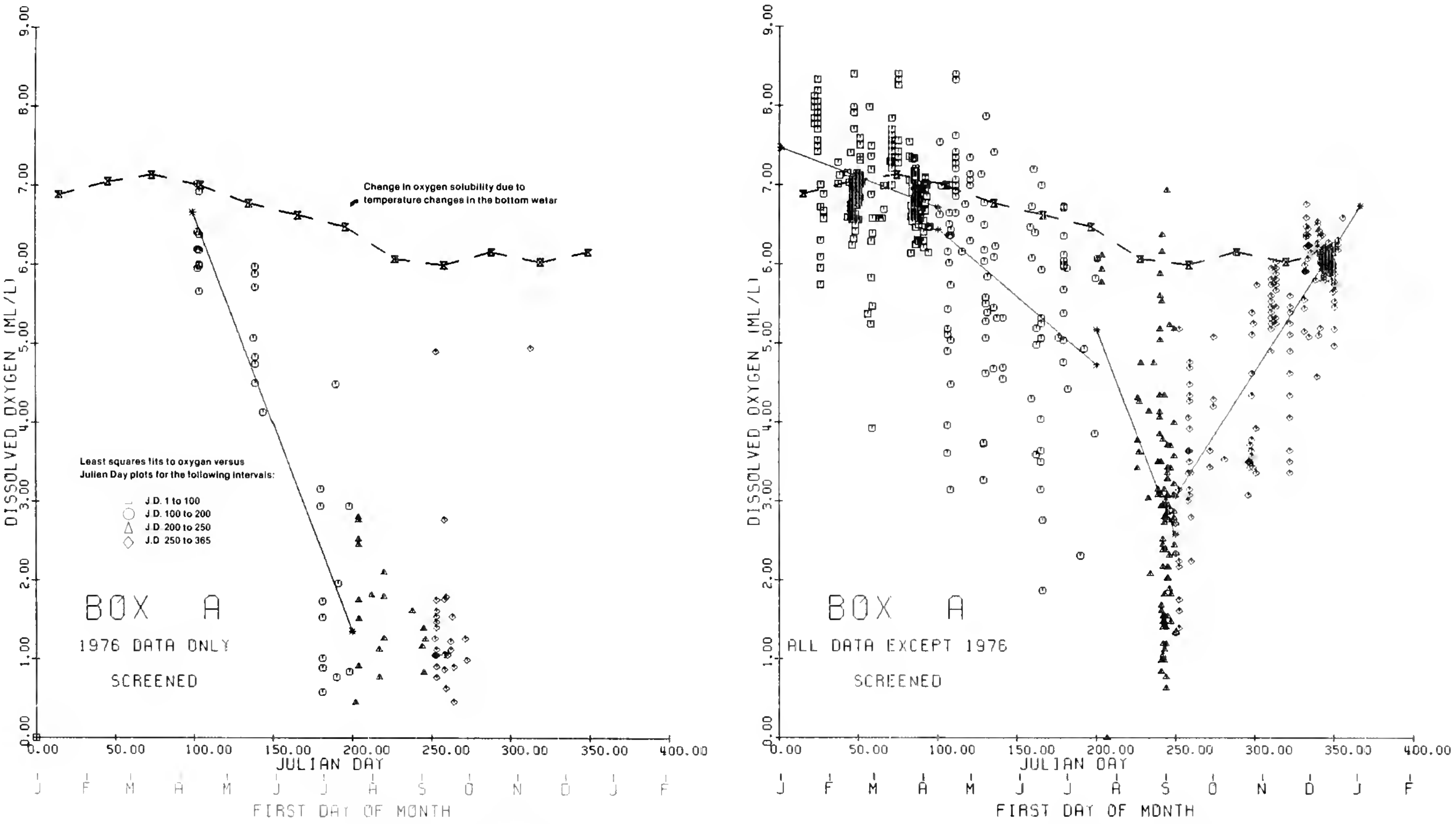


FIGURE 4-3.—Screened values of bottom dissolved oxygen by 1976 and non-1976 periods of observation for segments of New York Bight (indicated by box number); time of observations in Julian days; trends of oxygen depletion and recovery (solid lines); and oxygen solubility—capacity of water to hold dissolved oxygen (dashed line at top). Explanation: Solid lines showing trend of oxygen depletion and recovery were plotted for selected intervals—Julian days 1 to 100 (square points), 100 to 200 (circles), 200 to 250 (triangles), and 250 to 365 (diamonds). These lines were plotted when: 10 or more data points were available for the interval, there were at least two points in each third of the interval; and the correlation coefficient for the linear regression analysis of least-squares fit was significant at the P = 0.05 level. Dashed lines showing trend of oxygen solubility were calculated on the basis of bottom-water temperature changes.

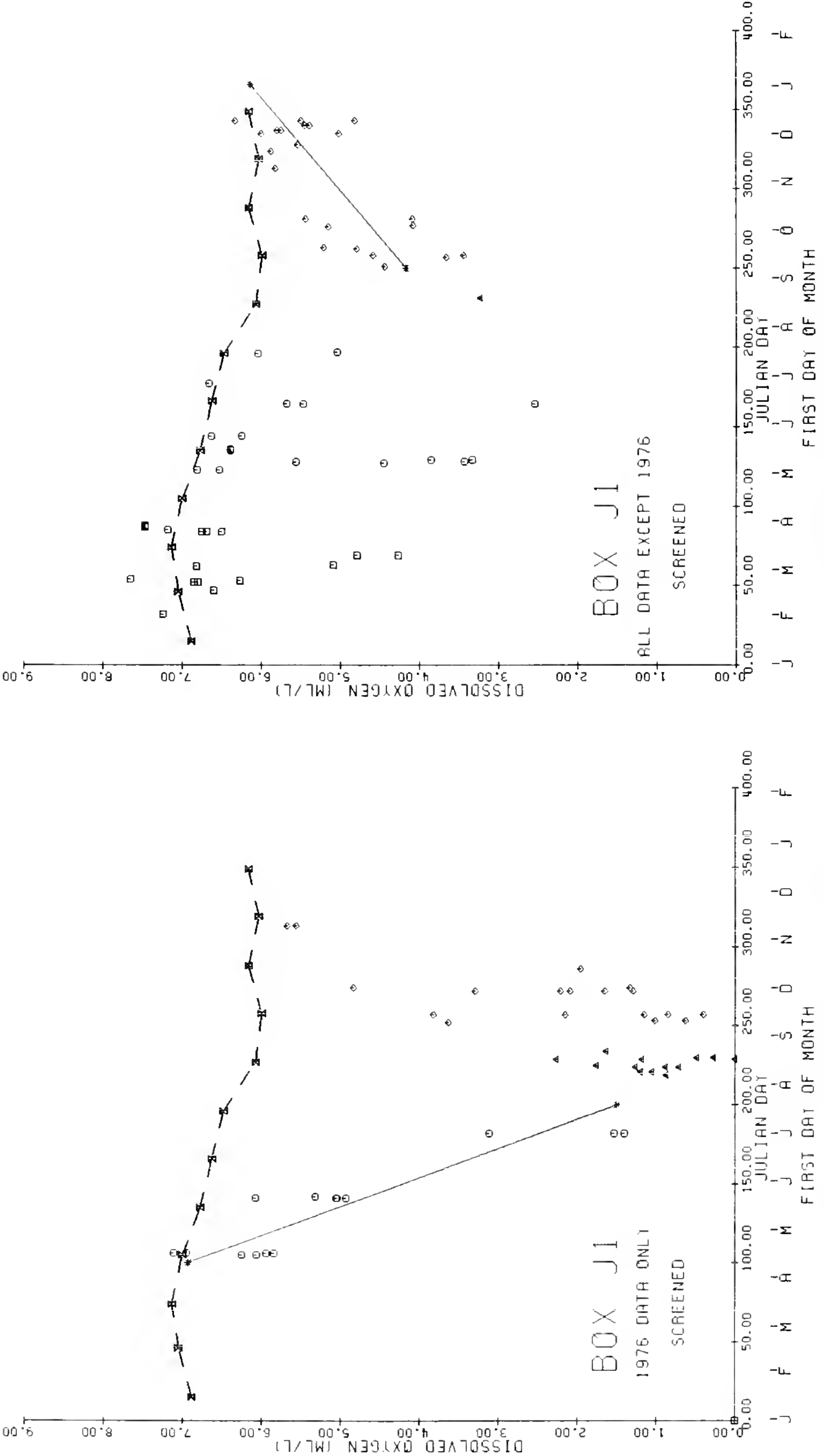


FIGURE 4-3.—Screened values of bottom dissolved oxygen by 1976 and non-1976 periods of observation for segments of New York Bight—continued

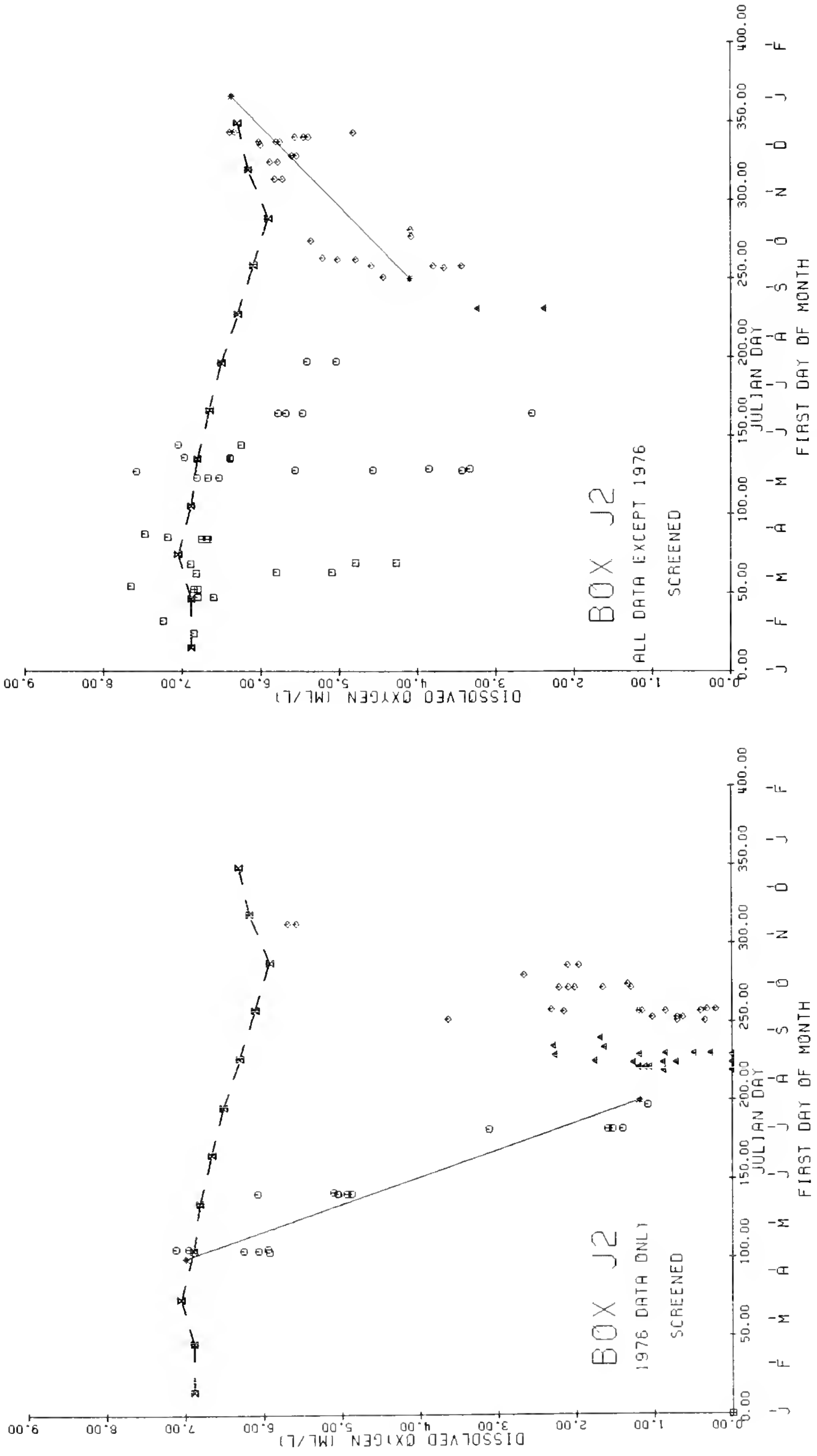


FIGURE 4-3.—Screened values of bottom dissolved oxygen by 1976 and non-1976 periods of observation for segments of New York Bight—continued.

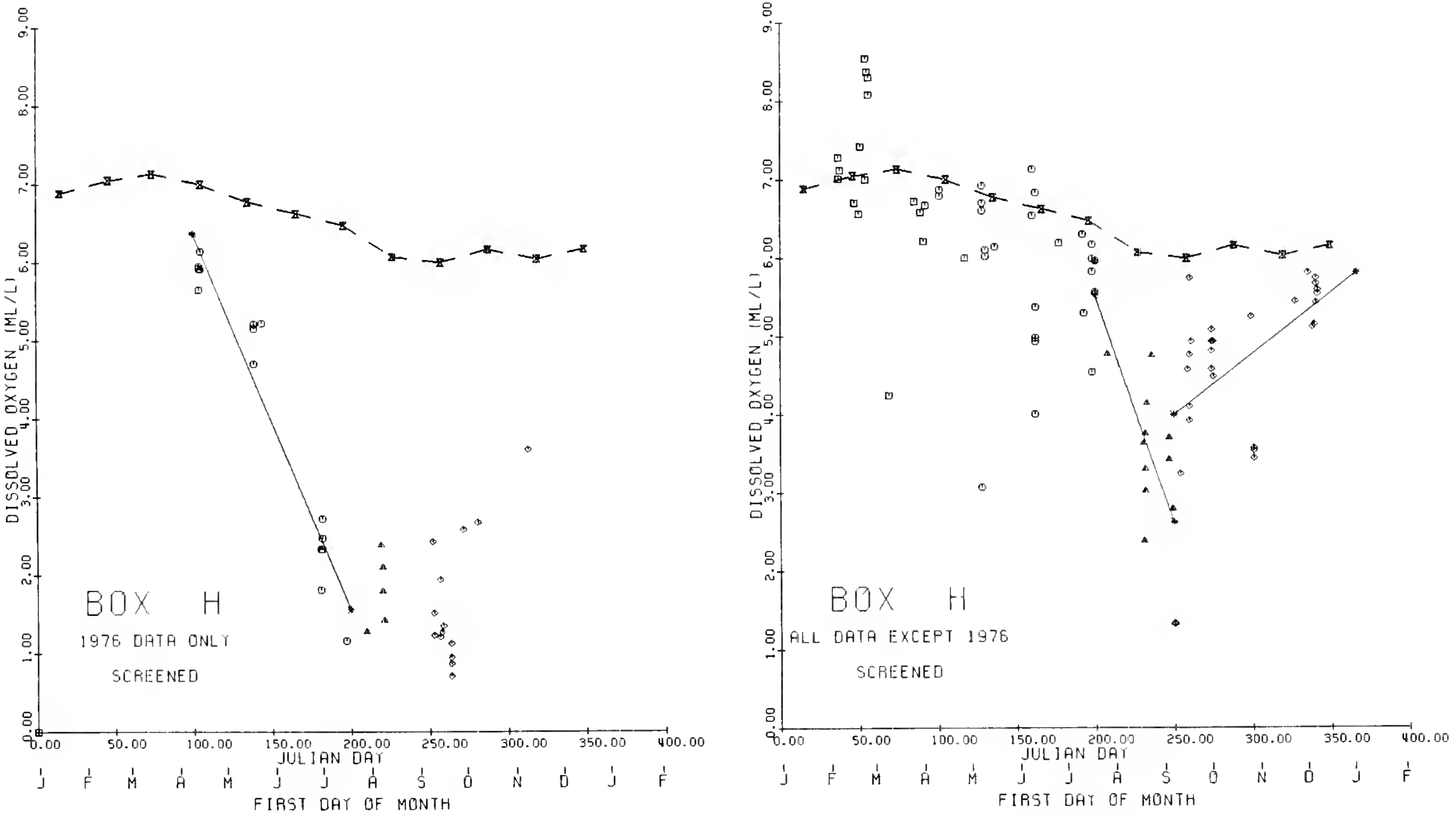


FIGURE 4–3.—Screened values of bottom dissolved oxygen by 1976 and non-1976 periods of observation for segments of New York Bight—continued.

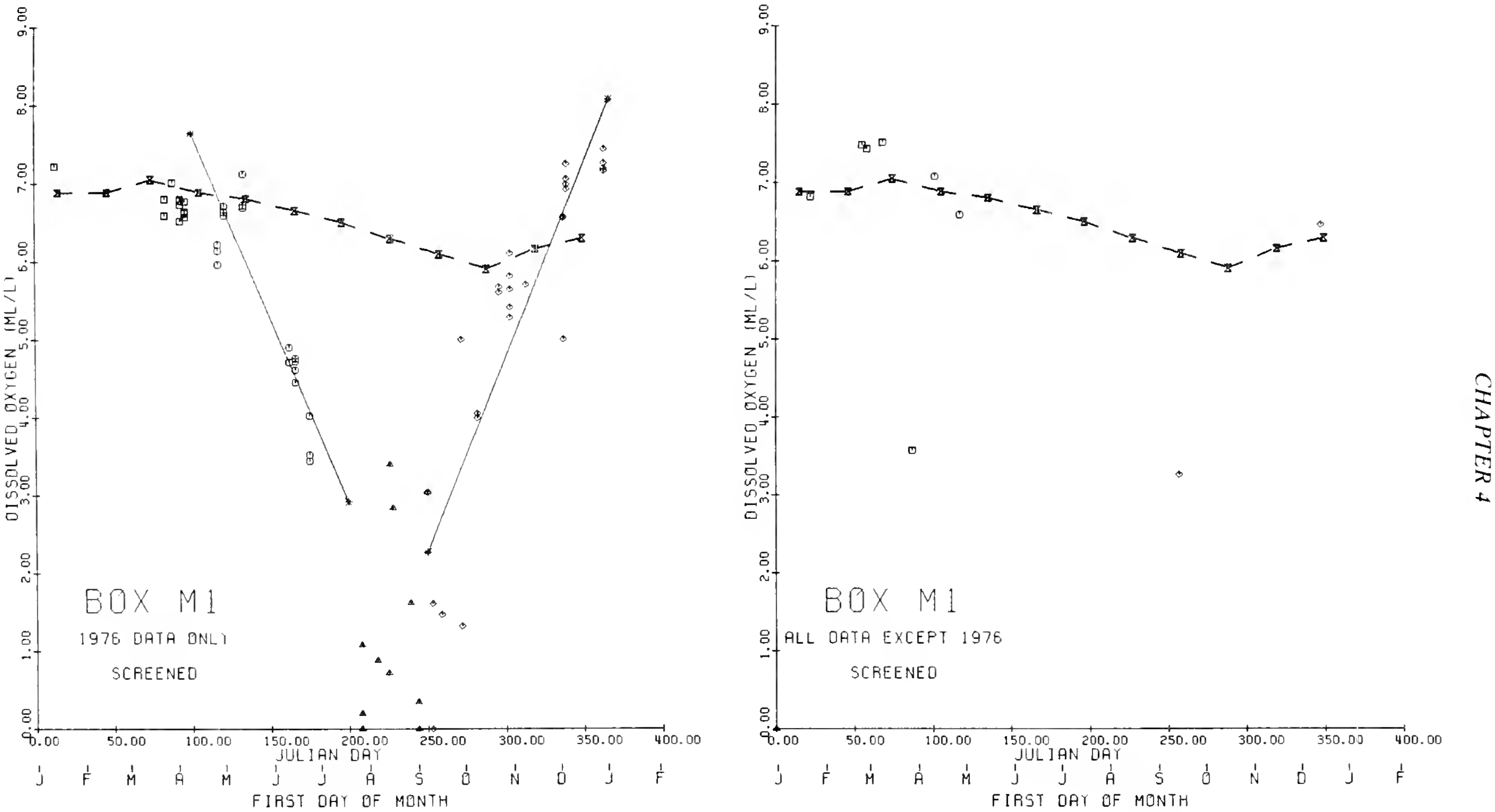


FIGURE 4–3.—Screened values of bottom dissolved oxygen by 1976 and non-1976 periods of observation for segments of New York Bight—continued.

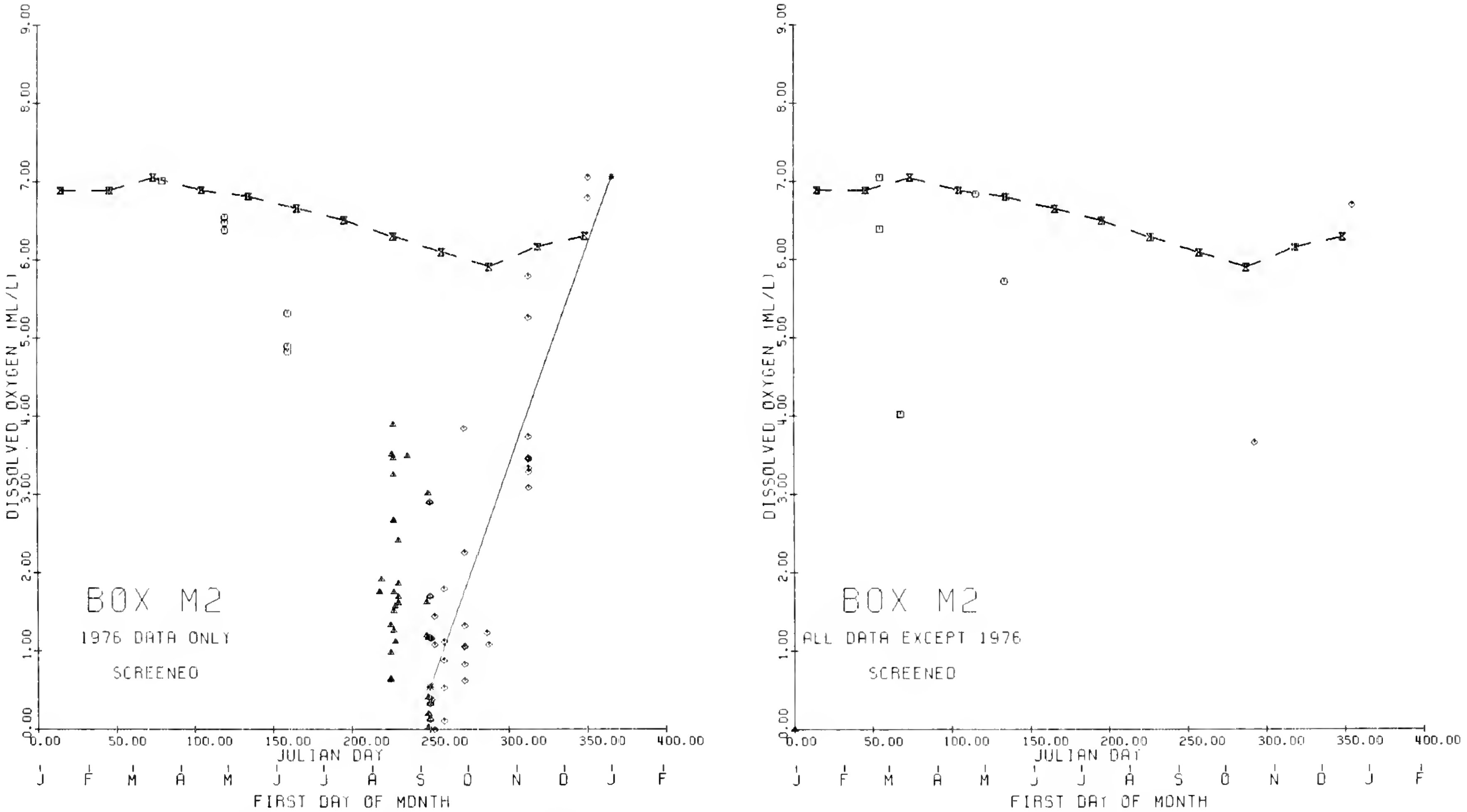


FIGURE 4-3.—Screened values of bottom dissolved oxygen by 1976 and non-1976 periods of observation for segments of New York Bight—continued

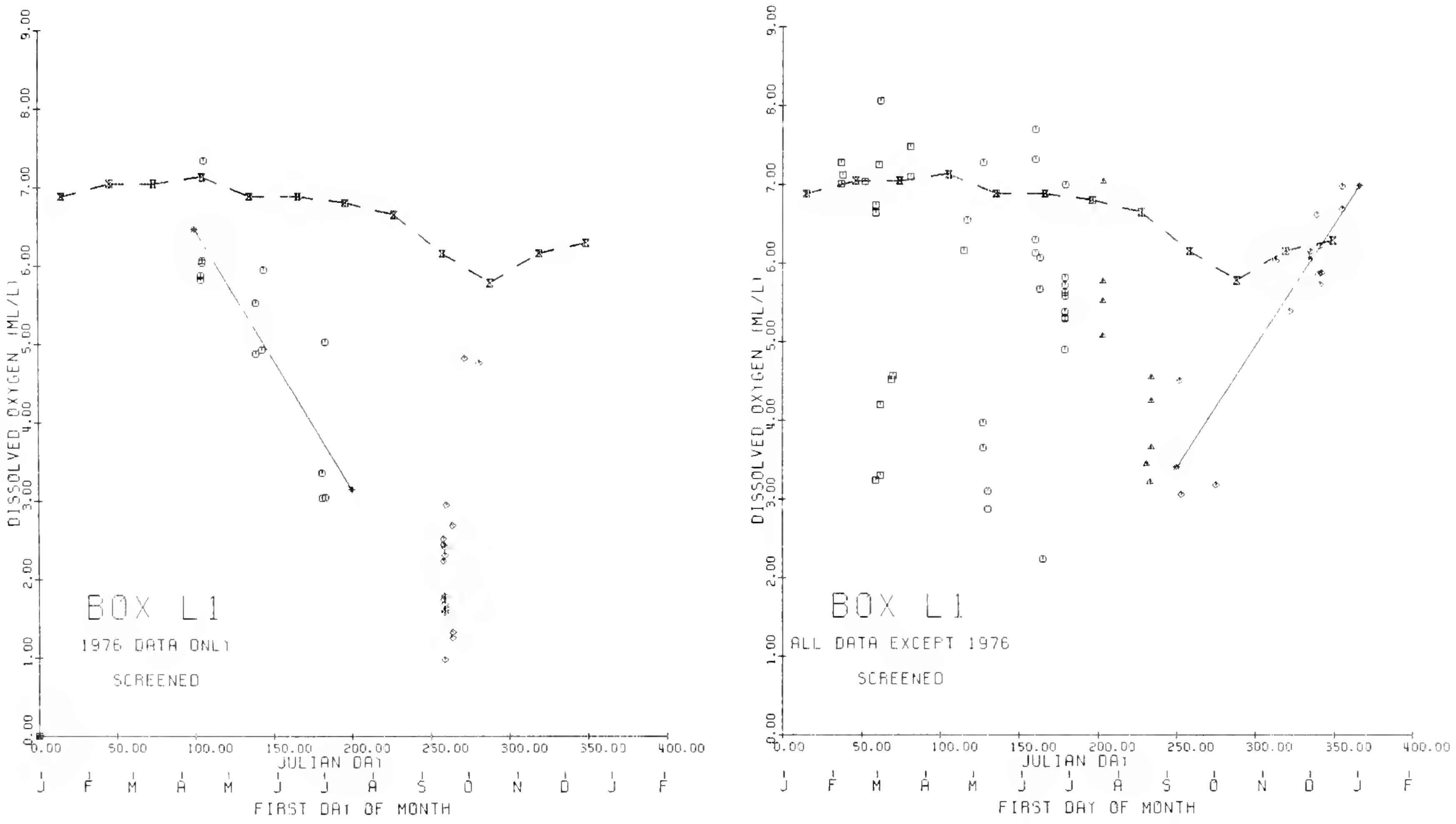


FIGURE 4-3 —Screened values of bottom dissolved oxygen by 1976 and non-1976 periods of observation for segments of New York Bight—continued.

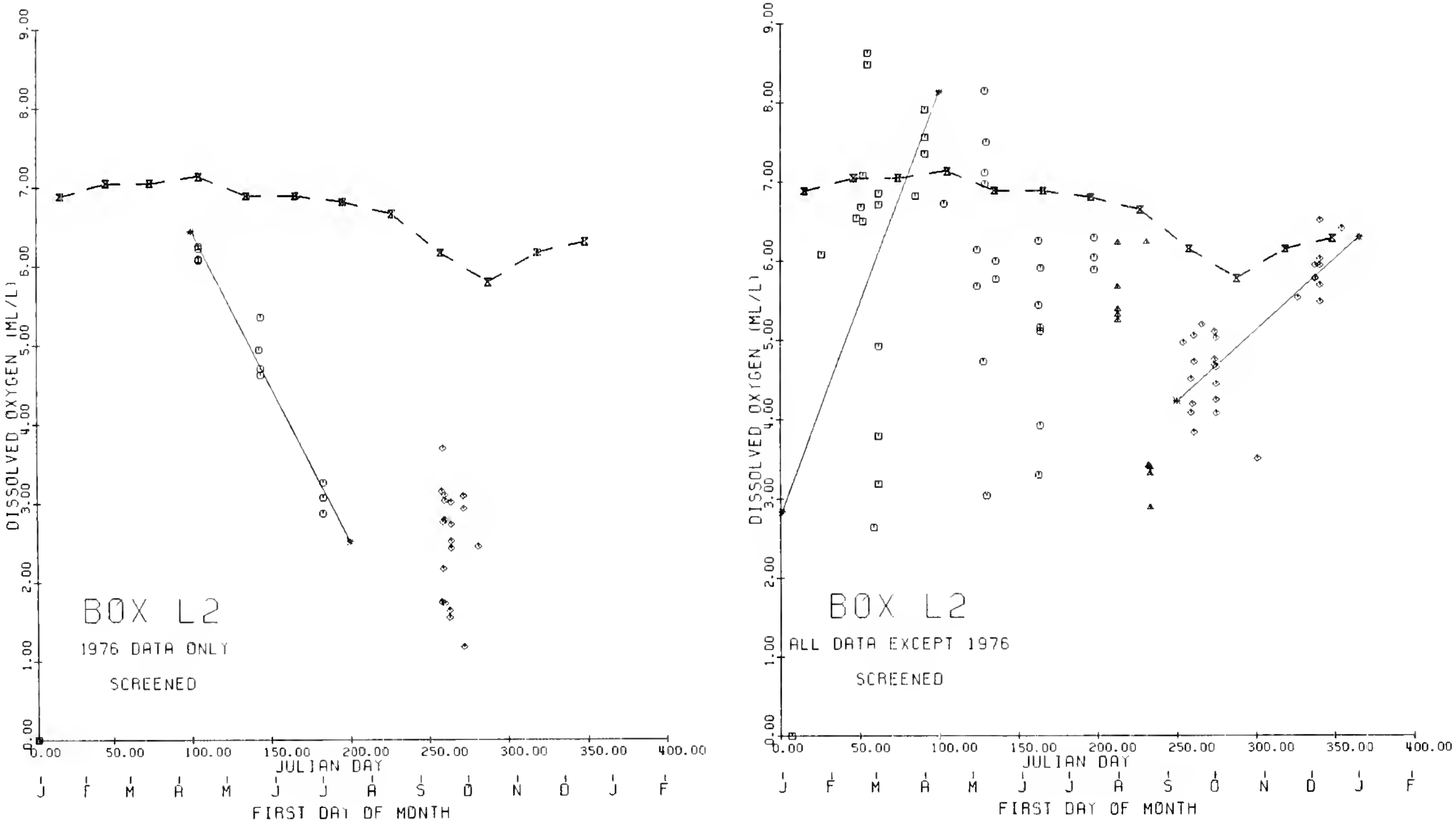


FIGURE 4-3.—Screened values of bottom dissolved oxygen by 1976 and non-1976 periods of observation for segments of New York Bight—continued.

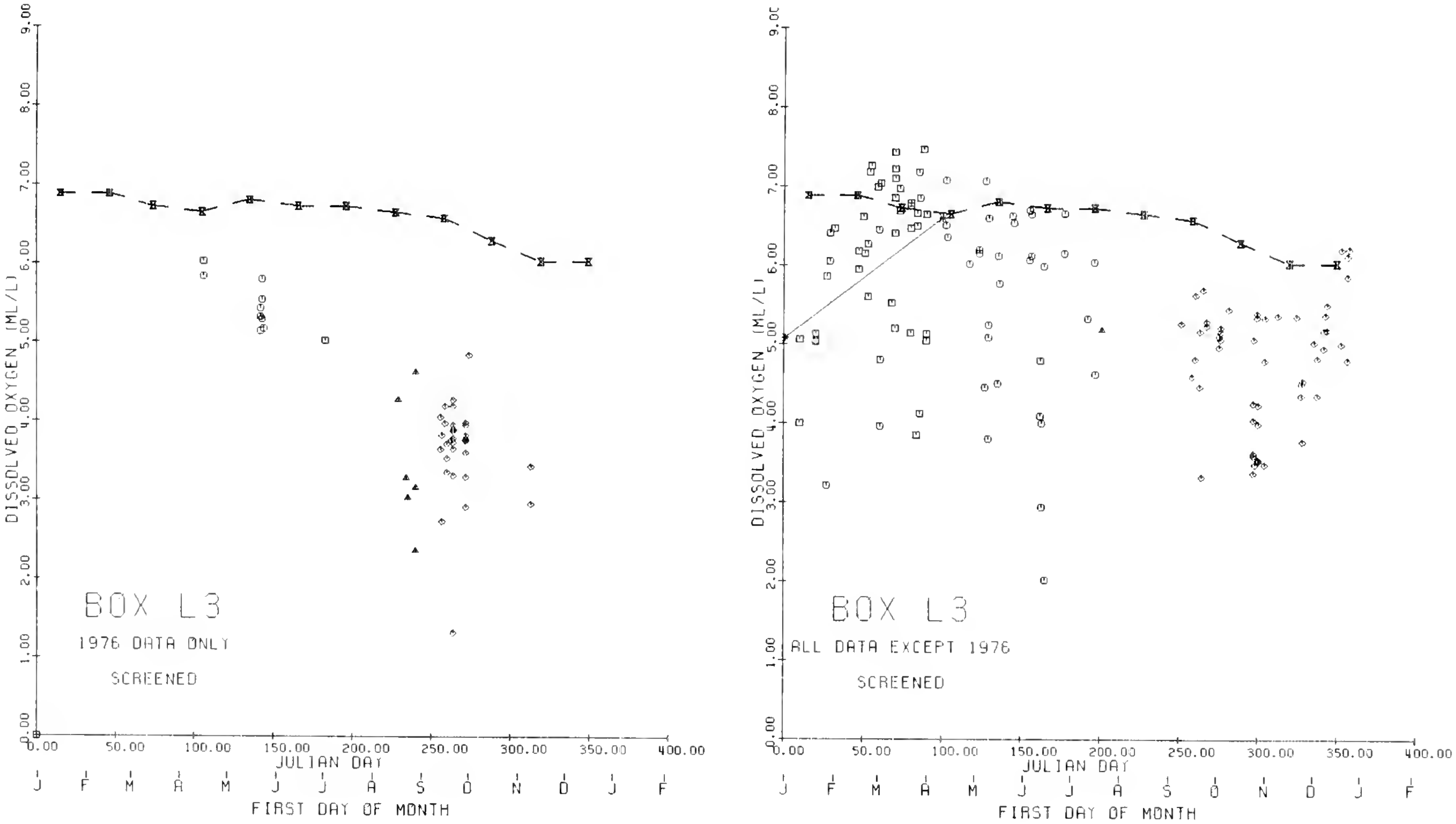
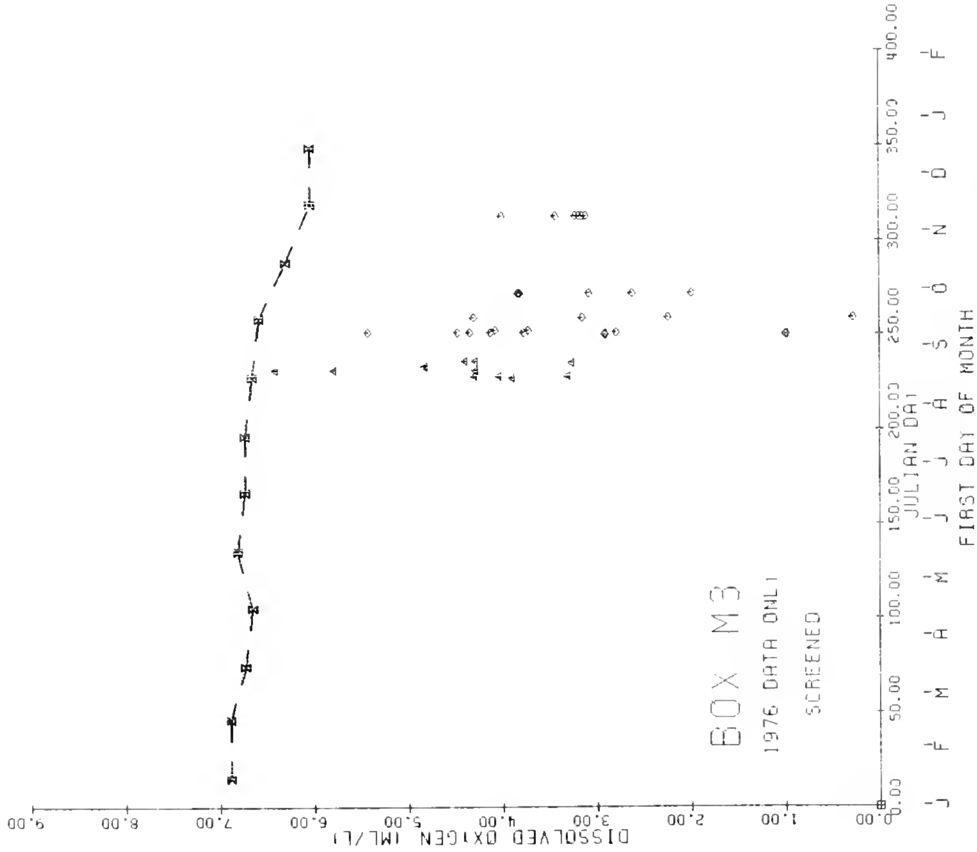


FIGURE 4–3.—Screened values of bottom dissolved oxygen by 1976 and non-1976 periods of observation for segments of New York Bight—continued.



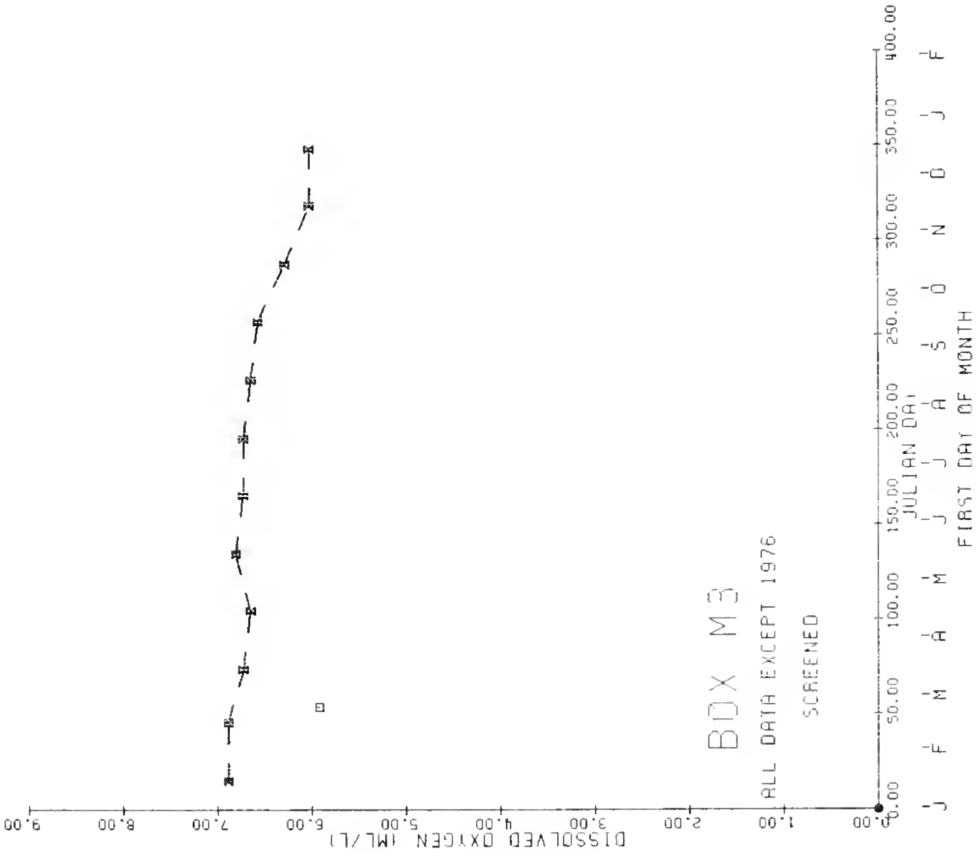


FIGURE 4-3.—Screened values of bottom dissolved oxygen by 1976 and non-1976 periods of observation for segments of New York Bight—continued

in segment A is the data distribution good enough for the non-1976 years to fulfill conditions for drawing a regression line. Depletion rates listed for 1976 all appear statistically significant ($P<0.05$) and are up to 10 times more rapid than non-1976 mean values; however, except for segment A, none of the non-1976 rates have correlation coefficients high enough to be considered significant at the $P<0.05$ level.

The 1976 depletion rates shown in table 4–6 for 1976 compare very well with those determined by Han et al. (ch. 8). Note that the actual oxygen utilization rates, which consider advection, are about double the depletion rates (chapter 8, table 8–2).

Recovery rates (J.D. 250 to 365) also are more rapid in 1976, but we consider this a natural result of the 1976 oxygen deficiency; that is, once stratification was broken up, equilibrium with the atmosphere was rapid, and recovery rates in the depleted system were high.

## NUTRIENT DISTRIBUTION

Nutrient distributions control productivity and its subsequent input of oxidizable carbon, thus reducing oxygen concentrations in bottom waters. The distribution of nutrients in time and space in New York Bight has been examined in some detail during the last 3 or 4 years by several agencies and institutions. However, only late in 1976 did specific studies focus on the low oxygen condition which existed during that summer. The MESA New York Bight Project sponsored a series of extended water-column characterization (XWCC) cruises throughout 1975 and during 1976. The following is a comparison of data from the early XWCC cruise with data collected by MESA and Brookhaven National Laboratory (BNL) during the severe oxygen-depletion event.

All nutrient data reported here resulted from analysis of frozen or fresh samples, using Technicon AutoAnalyzer systems. Atlantic Oceanographic and Meteorological Laboratories (AOML) analyzed samples using standard Technicon techniques described in their manuals. These methods were checked against accepted methods of analysis (Strickland and Parsons 1968; Fanning and Pilson 1973). The results of this comparison are available in an AOML data report (Berberian and Barcelona 1978). Methods used by BNL are given in Walsh et al. (1977).

Nutrient samples collected in most of the studies were frozen for later analysis in the laboratory because laboratory space aboard research vessels and analytical equipment availability were limited. Exceptions were the AOML cruise in September 1976 and BNL's Atlantic Coastal Ecosystem (ACE) cruises where nutrients were run aboard ship. Some changes can be expected from frozen samples, but previous studies have shown that the mean change between fresh and frozen samples is only about 10 percent (Thayer 1970) for orthophosphate, dissolved silicon, nitrate, and nitrite. Changes in ammonium concentrations between fresh and frozen samples are sometimes very large and contamination is a problem, so ammonium was determined only in samples analyzed at sea. On the September 1976 cruise, samples were drawn in triplicate. One aliquot was analyzed aboard ship for nitrate plus nitrite. The other two aliquots were frozen and later analyzed at BNL and AOML to check whether or not differences occurred as a result of such storage. Those run fresh had a mean difference of -0.05 µg-at/l for BNL frozen samples (table 4–7). AOML frozen samples were generally lower than the BNL frozen samples, with a mean difference of about 1.0 µg-at/l. Since bottom samples analyzed by the two laboratories showed essentially the same differences, it was concluded that differences are not related to the concentration of nitrogen but resulted from a systematic difference in handling and analysis. As a result, the values shown in the figure of this paper may have a <1 µg-at/l difference between data sets and this should be considered when making comparisons.

AOML's nitrate samples with concentrations of 0.5 µg-at/l or less were recorded as zero on the figures herein, since AOML considers that the detection limit for the

TABLE 4–7.—*Comparison of concentrations of nitrate plus nitrite measured in fresh or frozen samples on XWCC cruise 11, September 1976*

| Sample description[1] | Concentration differences between[2] | Number of samples | Mean of differences | Standard deviation | Range of differences |
|---|---|---|---|---|---|
| | | | µg-at/l | µg-at N/l | |
| All samples | A-B | 162 | −0.05 | 0.64 | −5.83 to 1.61 |
| All samples | A-C | 177 | 1.08 | 1.71 | −2.30 to 9.82 |
| All samples | B-C | 83 | 0.96 | 1 16 | −2.16 to 4.83 |
| Bottom samples | A-B | 27 | −0.15 | 0.61 | −1.76 to 0.95 |
| Bottom samples | A-C | 22 | 1.09 | 1.34 | −1.11 to 5.00 |
| Bottom samples | B-C | 23 | 1.05 | −1.35 | −2.16 to 4.83 |

[1] Compared samples are from same water sampling bottles and were either run fresh or were frozen in polyethylene bottles.

[2] A = fresh samples run by BNL. B = frozen samples run by BNL. C = frozen samples run by AOML.

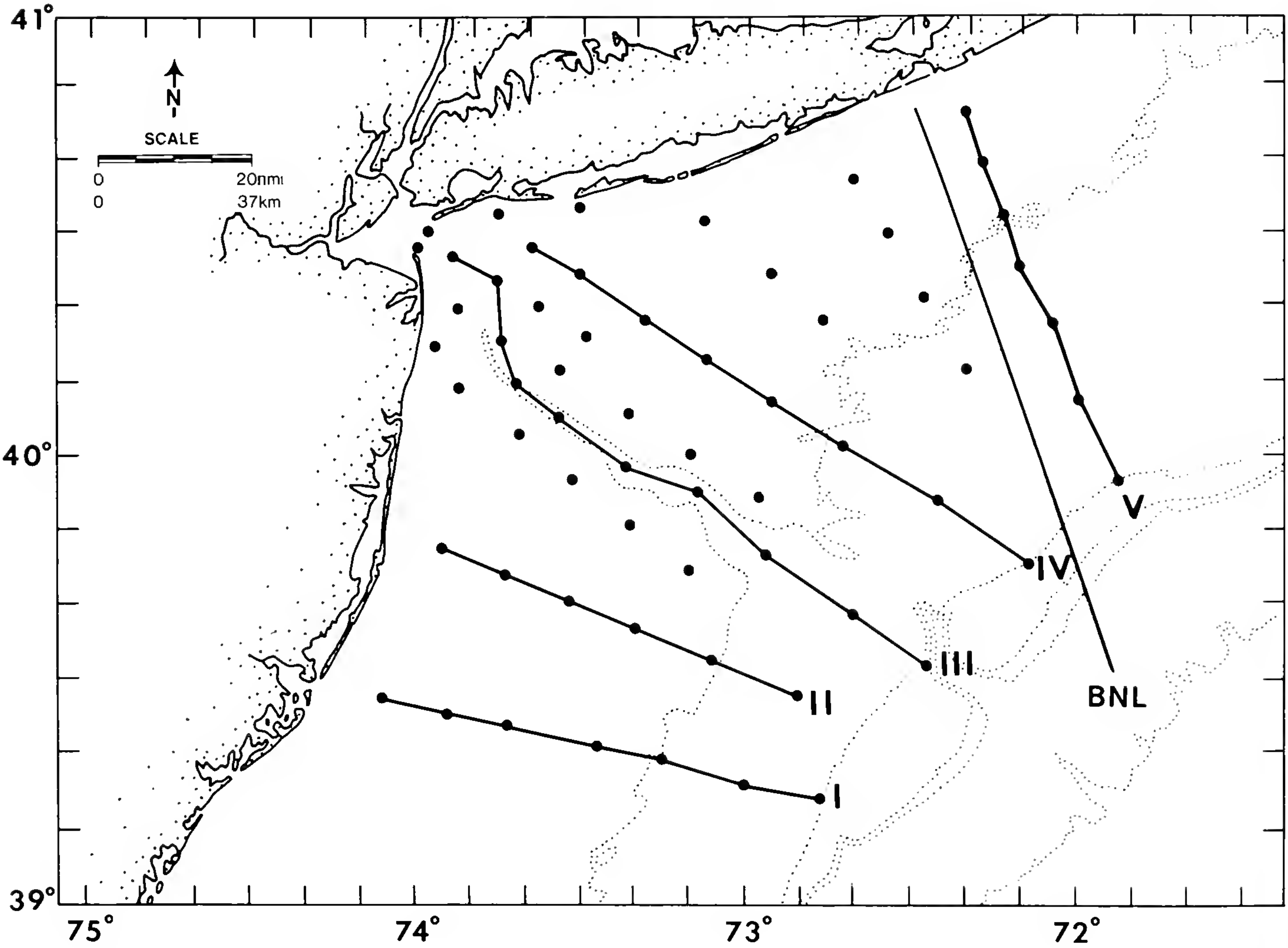


FIGURE 4–4.—NOAA AOML extended water-column characterization (XWCC) cruise transects I–V of 1975 and 1976 and Brookhaven National Laboratory (BNL) transect during oxygen-depletion event of 1976.

analyses performed. This is not considered in table 4–7 or in the above discussion.

The nutrient samples collected during the XWCC cruises over 1975 and 1976 (at nearly monthly intervals) and during several ACE cruises established a large data base for the area impacted by low oxygen concentrations in summer 1976. Nitrogen is emphasized in the results and discussion because (1) nitrogen compounds are closely coupled with oxygen during periods of denitrification (the biological reduction of nitrate, $NO_3^-$, and nitrite, $NO_2^-$, to nitrogen or nitrous oxide, $N_2O$), which occur to some degree in areas where hydrogen sulfide is generated (Redfield et al. 1963), and (2) nitrogen has been shown to be the nutrient that limits phytoplankton production in the Bight (Ryther and Dunstan 1971). This latter observation has been confirmed by samples collected in recent $^{15}N$ uptake studies (Conway and Whitledge, personal communication), where orthophosphate concentrations greater than 0.5 μg-at/l were still available even when nitrogen was depleted. Two-thirds of this nitrogen uptake by phytoplankton was ammonium and the remaining one-third was nitrate.

### Nitrate

Possible correlations between low oxygen and nitrate distribution were examined over two similar offshore transects (I and II in fig. 4–4) off the New Jersey coast where the oxygen deficiency was most pronounced. It was assumed that 1975 was a nearly normal year; at least no critical oxygen deficiencies were observed, although "normal" depletion did occur in the bottom waters during the stratified season. Late winter and early spring conditions of February/March 1975 (fig. 4–5) indicate that nitrate concentrations of 1 to 2 μg-at/l were present in the near-

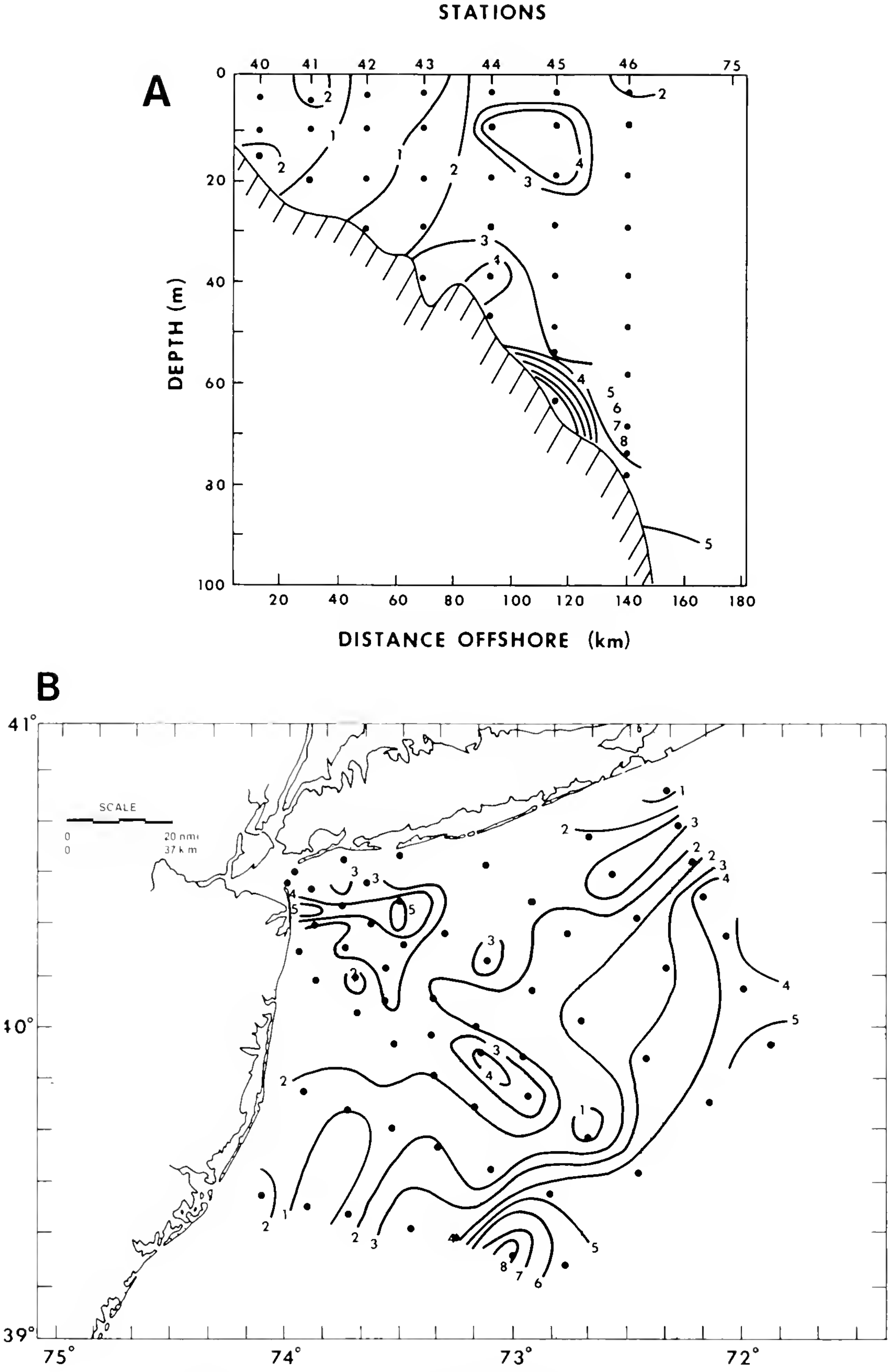


FIGURE 4–5A.—Nitrate concentrations for late winter 1975. XWCC cruise 2 transect I (A) and bottom (B) nitrate in µg-at/l (Feb. 22—Mar. 5, 1975).

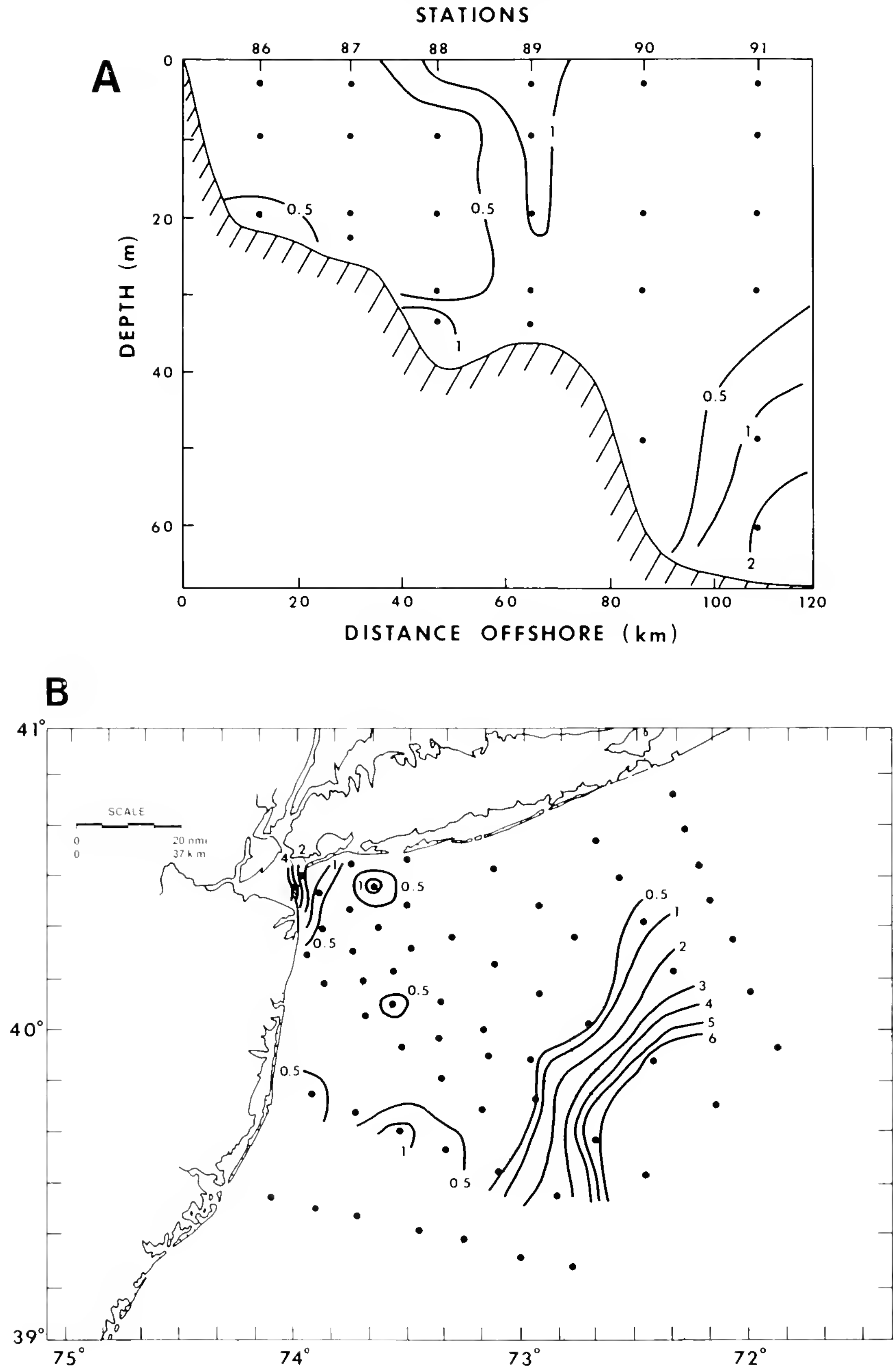


FIGURE 4-5B.—Nitrate concentrations for spring 1976 XWCC cruise 8 transect II (A) and bottom (B) nitrate in µg-at/l (Apr. 12–16, 1976).

shore region, with no values lower than 0.5 μg-at/l. At mid-shelf, values up to 8 μg-at/l at 65 m depth were measured. The bottom nitrate concentrations were above 4 μg-at/l on the outer shelf region, and some nitrate was probably introduced to the Bight Apex by Hudson-Raritan river runoff.

In spring 1976 off New Jersey (fig. 4–5), bottom nitrate concentrations were slightly lower than in early spring 1975. Concentrations at the inshore stations dropped to less than 0.5 μg-at/l, probably as a result of the spring phytoplankton bloom. Concentrations at the deeper offshore stations also declined. April 1976 bottom nitrate concentrations were high at the shelf edge off Long Island and corresponded closely to deep values observed in March 1975 off New Jersey (fig. 4–5).

The BNL transects taken in April 1975 (fig. 4–4) and April-May 1976 show interesting differences between the 2 years (fig. 4–6). Inshore concentrations were markedly lower in 1976; nitrate values *integrated* over the euphotic zone were as low as 2.2 μg-at/m$^2$ (Conway and Whitledge, personal communication). The nitrate gradient at the shelf break was smaller in 1976 than in 1975 and deeper source waters off the shelf contained 3 μg-at/l less nitrate. This lower concentration in the deep water persisted over 2 weeks and could represent a deficiency in the 1976 source water. If so, any cross-shelf movement of this water would have brought less nitrate to the midshelf and inshore regions in 1976.

A late spring sampling off New Jersey in May 1975 showed little or no nitrate inshore of the 60-m isobath (fig. 4–7). However, the deep water, which probably acted as a nitrate source, had concentrations similar to those observed in February-March 1975, indicating a general nitrate depletion on the shelf—most pronounced off New Jersey and less apparent off Long Island (area of transect V on fig. 4–4). A similar sampling in May 1976 found slightly higher nitrate near the bottom of the euphotic zone off New Jersey, but no value was greater than 1 μg-at/l (fig. 4–7). The May 1976 bottom nitrate concentrations were negligible over the entire shelf. Note that the shelf break nitrate concentrations shown for May 1975 and May 1976 are similar; this weakens the evidence for depletion of nitrate in the 1976 "source" water.

A 1975 summer section off New Jersey (fig. 4–8) showed nitrate values similar to those seen in May of that year. Data for about the same place and time in 1976 are limited, even though they were taken about the same time that the initial anoxic conditions arose; however, data collected at that time for that section are all below the detection limit of 0.5 μg-at/l and are not shown in the figure. For the 1976 cruise also, all bottom nitrate values except those off the shelf were less than the detection limit. Apparently, bottom nitrate concentrations inside the shelf break were an order of magnitude less in 1976 than in 1975—possibly a result of reduced transport of nitrate across the shelf break or a result of denitrification.

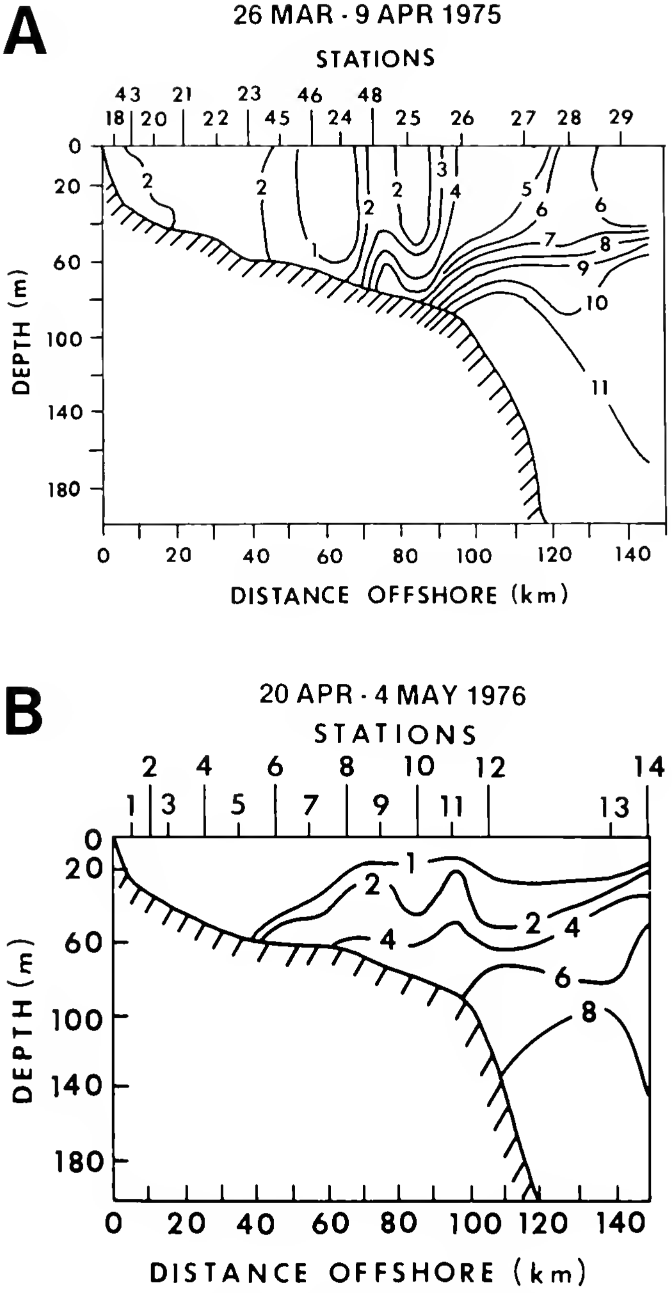


FIGURE 4–6.—Nitrate concentrations for spring 1975 (A) and spring 1976 (B) BNL cross-shelf transect values in μg-at/l.

Late summer sections off New Jersey for 1975 and 1976 (fig. 4–9) both show the effects of bottom shoreward transport of nitrate-rich water. At this time in 1976, oxygen-deficient water was still located off some areas of the New Jersey coast. The bottom nitrate concentration increased 8 or 9 μg-at/l off Long Island during both years, but some

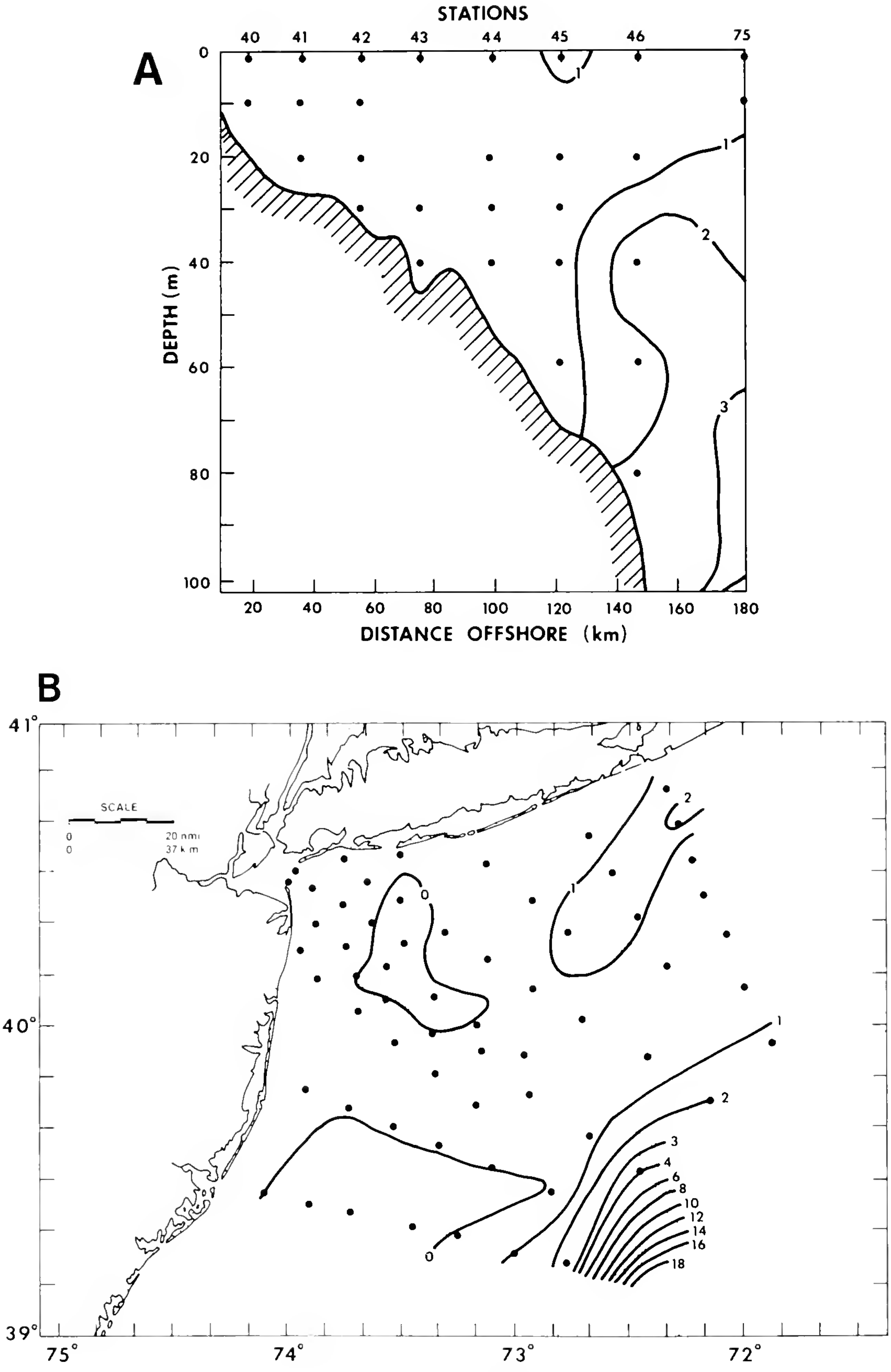


FIGURE 4-7A.—Nitrate concentrations during May 1975. XWCC cruise 4 transect I (A) and bottom (B) nitrate in µg-at/l (May 3–10, 1975).

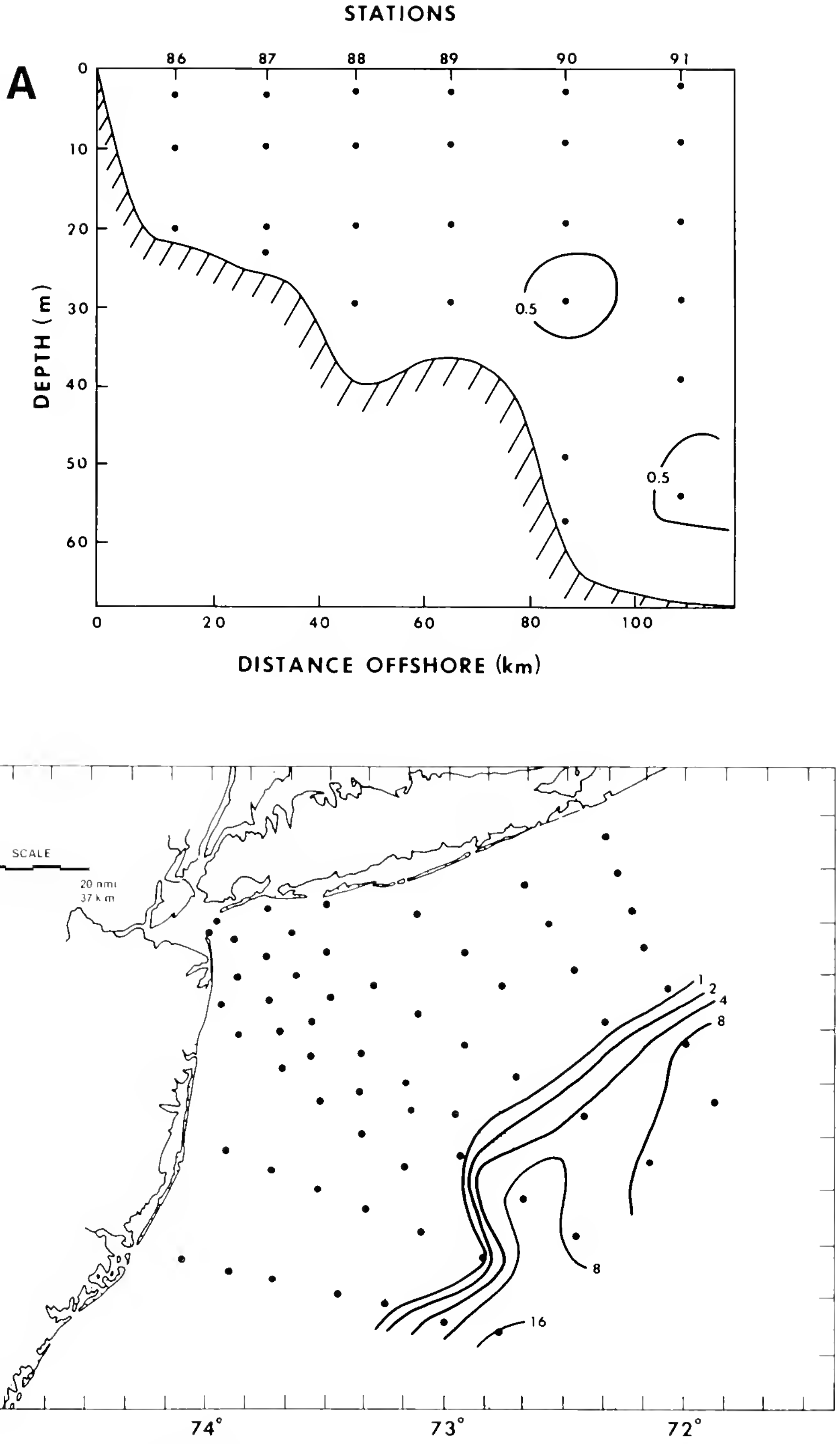


FIGURE 4–7B.—Nitrate concentrations during May 1976. XWCC cruise 9 transect II (A) and bottom (B) nitrate in μg-at/l (May 17–24, 1976).

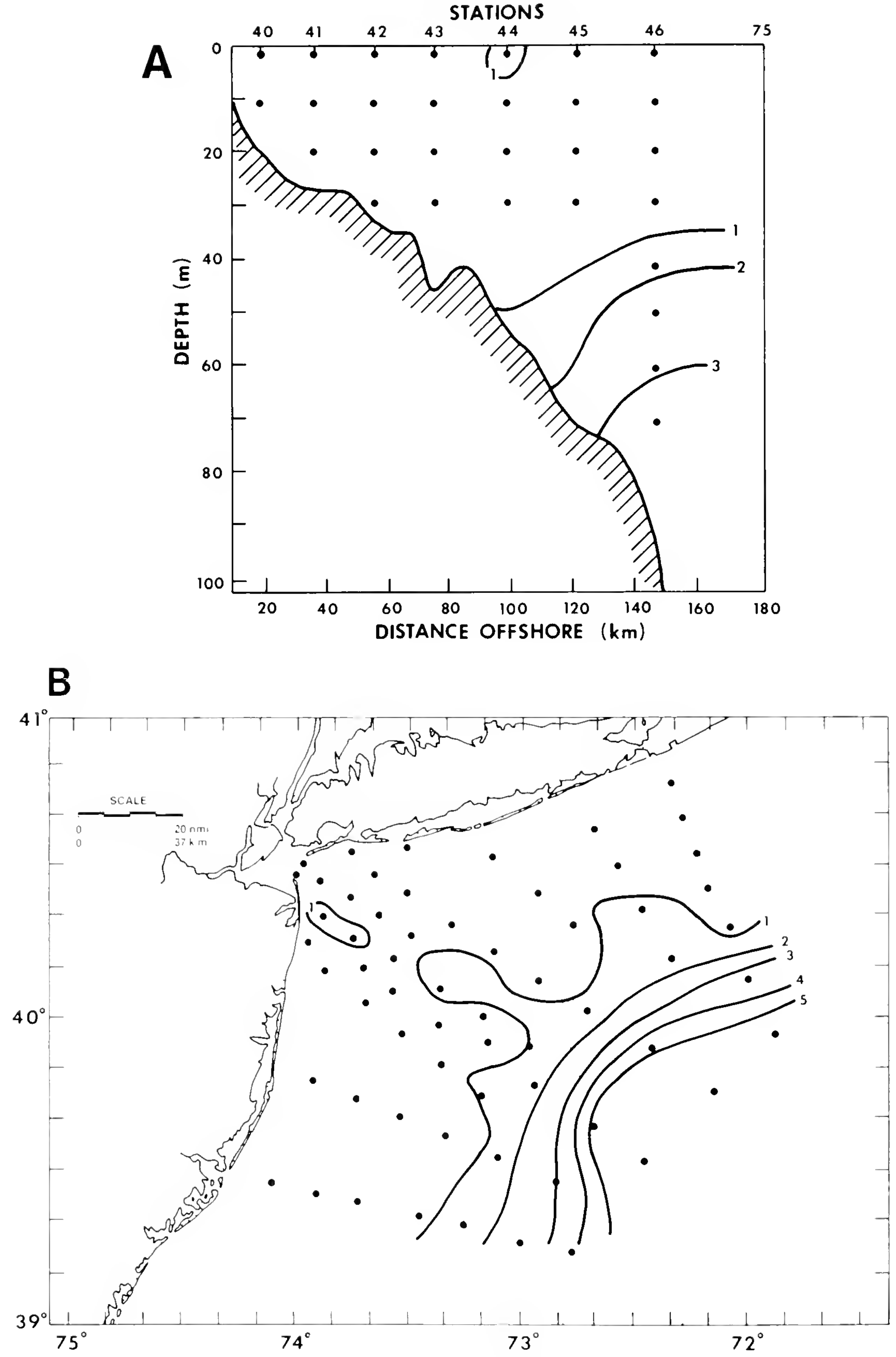


FIGURE 4–8A.—Nitrate concentrations during June 1975. XWCC cruise 5 transect I (A) and bottom (B) nitrate in μg-at/l (June 8–15, 1975).

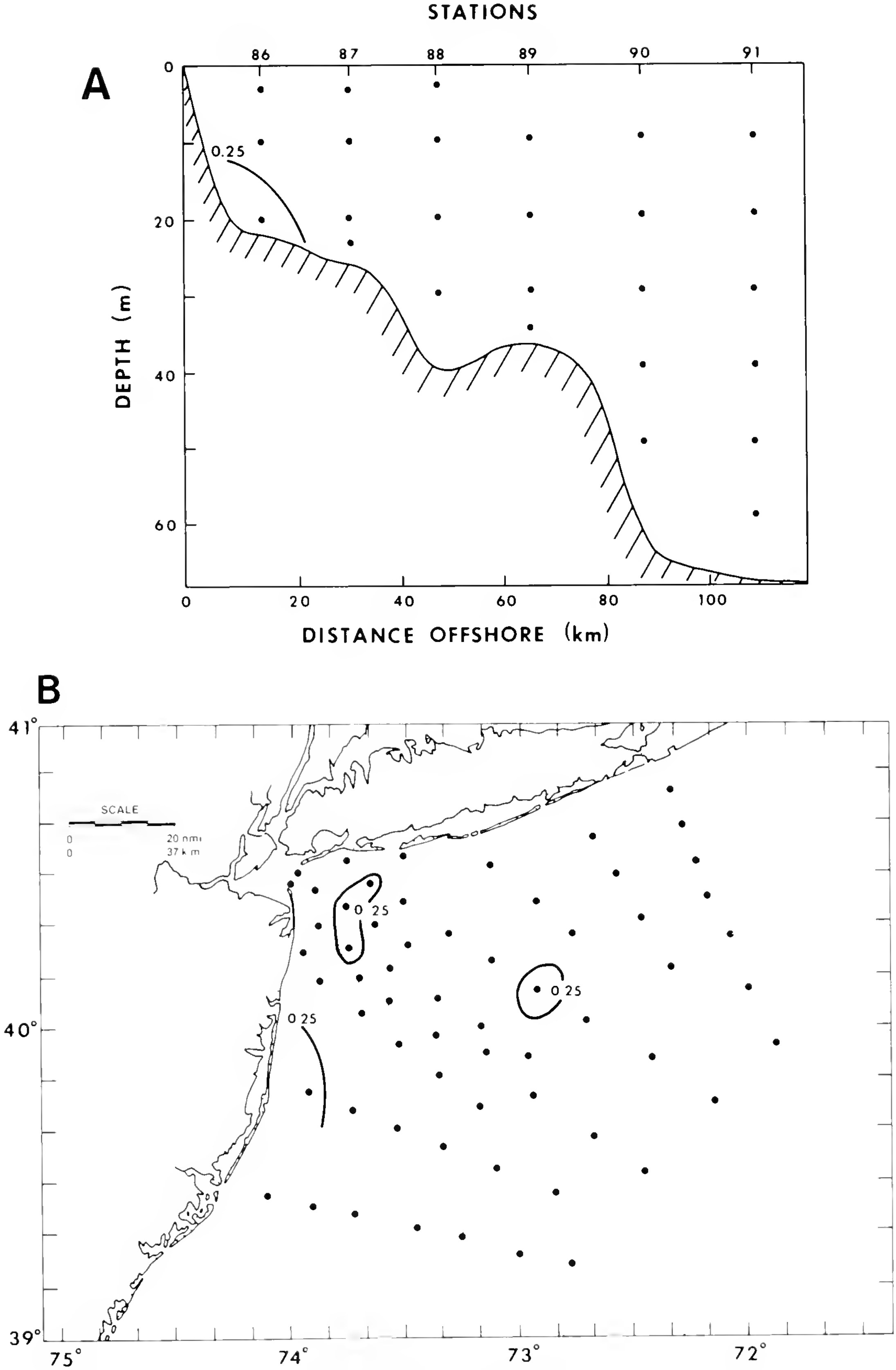


FIGURE 4-8B —Nitrate concentrations during June 1976 XWCC cruise 10 transect II (A) and bottom (B) nitrate in μg-at/l (June 28—July 1, 1976)

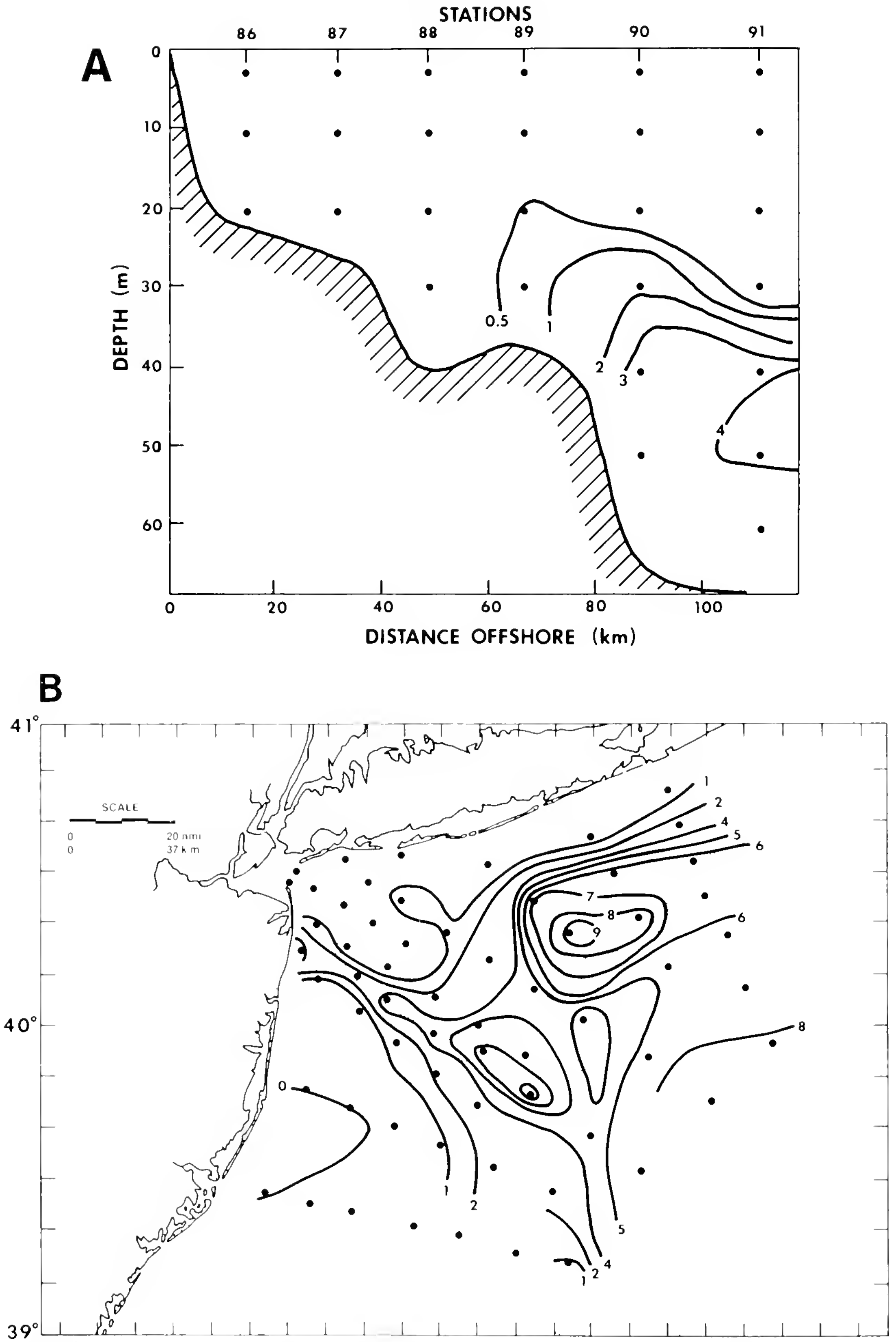


FIGURE 4–9A.—Nitrate concentrations during autumn 1975. XWCC cruise 6 transect 1 (A) and bottom (B) nitrate in μg-at/l (Sept. 29—Oct. 4, 1975).

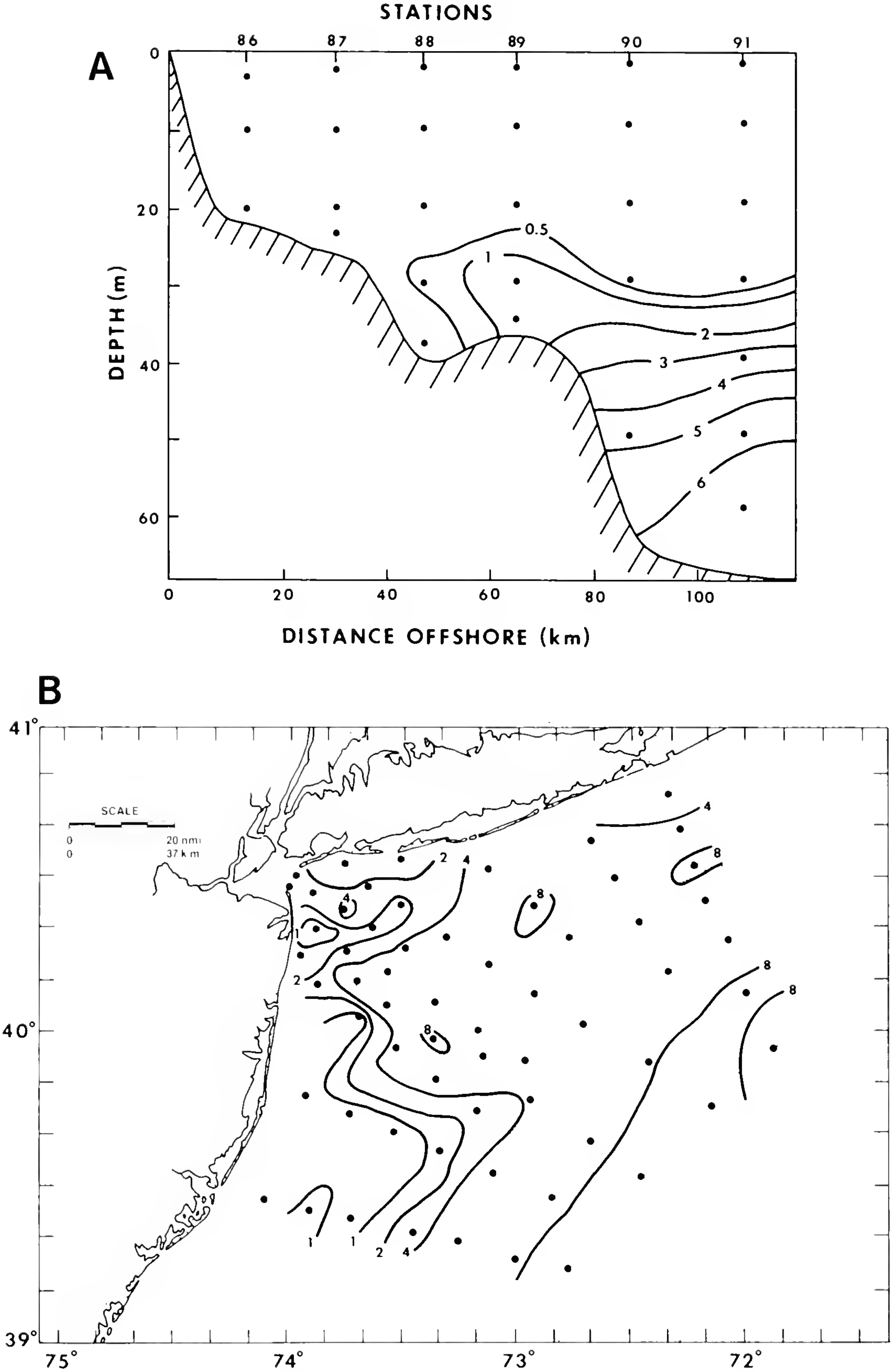


FIGURE 4–9B.—Nitrate concentrations during autumn 1976. XWCC cruise 11 transect II (A) and bottom (B) nitrate in µg-at/l (Sept. 11–17, 1976).

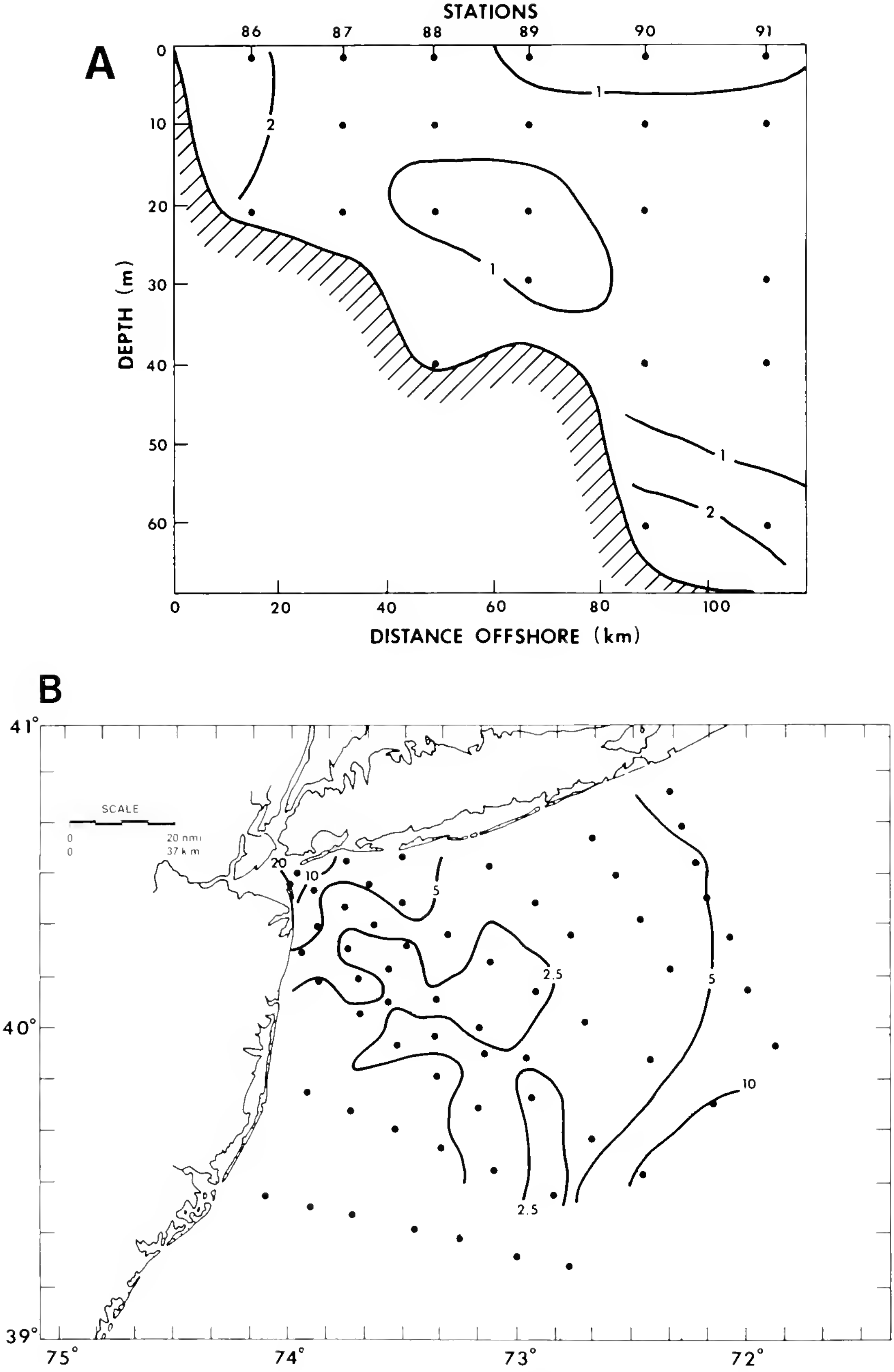


FIGURE 4-10 —Nitrate concentrations December 1975. XWCC cruise 7 transect II (A) and bottom (B) nitrate in μg-at/l (Dec. 3-8, 1975).

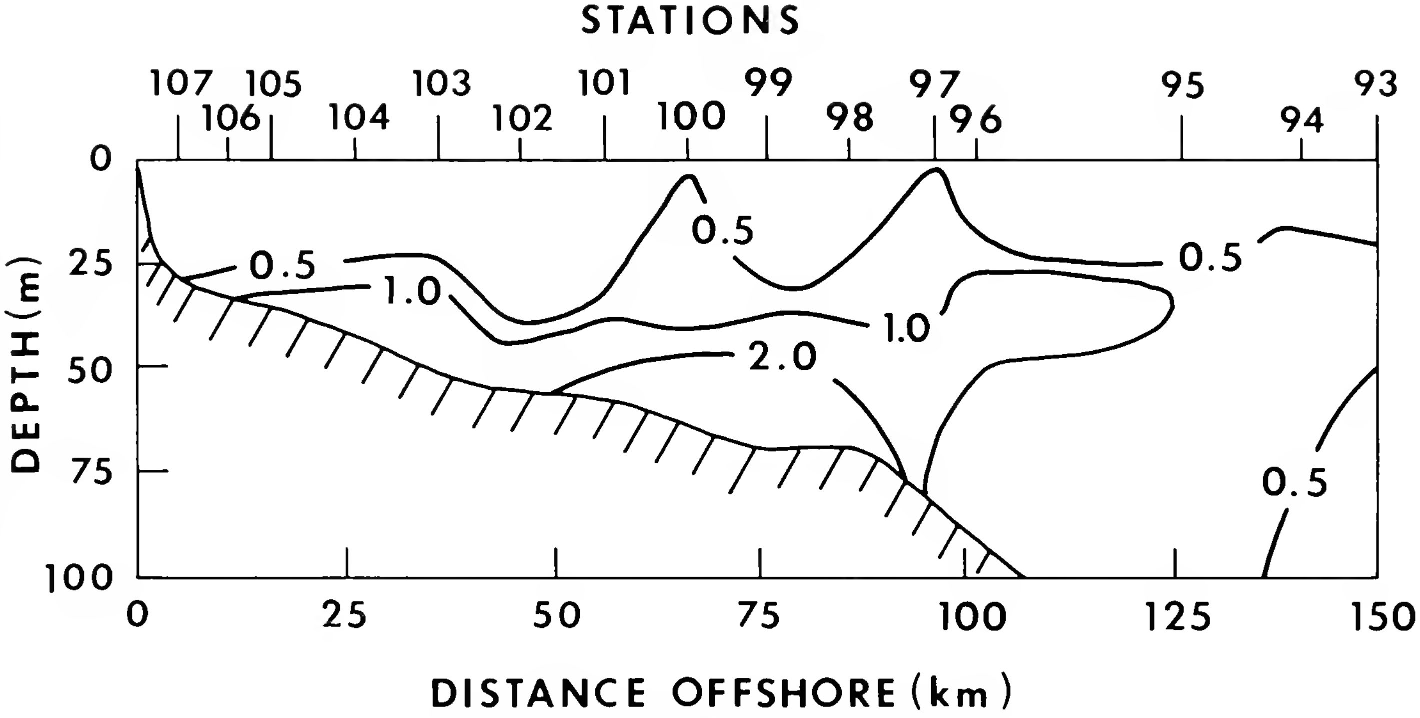


FIGURE 4–11.—Ammonium concentrations April 20 to May 4, 1976. BNL cross-shelf transect values in μg-at/l

regions of the New Jersey shelf received little input (fig. 4–9). The extent of high bottom nitrate concentrations was larger in 1976 than in the previous year, but low oxygen was still observed simultaneously off New Jersey.

Winter 1975–76 nitrate concentrations were larger than 2 μg-at/l nearshore, and there was some possible input from the Hudson-Raritan runoff (fig. 4–10). Concentrations greater than 0.5 μg-at/l were present everywhere over the shelf, and bottom concentrations were 2 to 5 μg-at nitrate/l. Hudson River stations contained more than 20 μg-at/l, and thus elevated nitrate concentrations in the Apex.

### Ammonium

Ammonium concentrations were measured in fewer samples than nitrate because they were measured only when analyses were performed aboard ship. This severely limits our ability to present an overall picture of nitrogen nutrient distributions in 1975 and 1976. The 1976 spring distribution (fig. 4–11) along the BNL transect (fig. 4–4) off the Long Island coast was almost uniform across the shelf and ranged from 0.5 to 2.0 μg-at/l.

In early autumn 1976, during the last part of the severe oxygen depletion, ammonium levels were measured along five transects (fig. 4–12). The transects off New Jersey contained very high values near the bottom, especially in transects I and II where values were greater than 20 μg-at/l. These high bottom concentrations were found in samples that also had little or no oxygen present.

Transects off the Long Island coast showed lower ammonium values, with a maximum of about 2 μg-at/l. Ammonium concentrations (fig. 4–13) show high values near the bottom, centered where the oxygen depletion was present in the New Jersey shelf. This correlation between low oxygen and high ammonium is shown more clearly in figure 4–14, where bottom ammonium values are plotted against D.O. levels. Below oxygen values of 2.0 ml/l, the ammonium levels increase almost exponentially as the oxygen values declined to zero. Surface ammonium concentrations in figure 4–13 show no unusual pattern, with typical values 0.5 to 2.0 μg-at/l. Figure 4–13 also shows evidence of a source of ammonium from Hudson-Raritan discharge.

### Nitrite

Figure 4–14 shows nitrite concentrations plotted against D.O. in September 1976. Where the oxygen concentration was below 3.0 ml/l, the $NO_2^-$ concentration showed a definite increase, reaching a maximum at about 1.6 ml/l oxygen. Below 1.6 ml/l of oxygen, the nitrite concentration dropped off again as the $NO_2^-$ was apparently reduced to $NH_4^+$, as demonstrated in the bottom ammonium plot.

An expected relationship between oxygen and nitrate concentrations (fig. 4–14) is not so well defined as for ammonium and nitrite. The combination of biological use, advection, and nitrification in oxygenated waters evidently produces a highly variable pattern of nitrate and oxygen distribution in which equilibrium conditions may not pre-

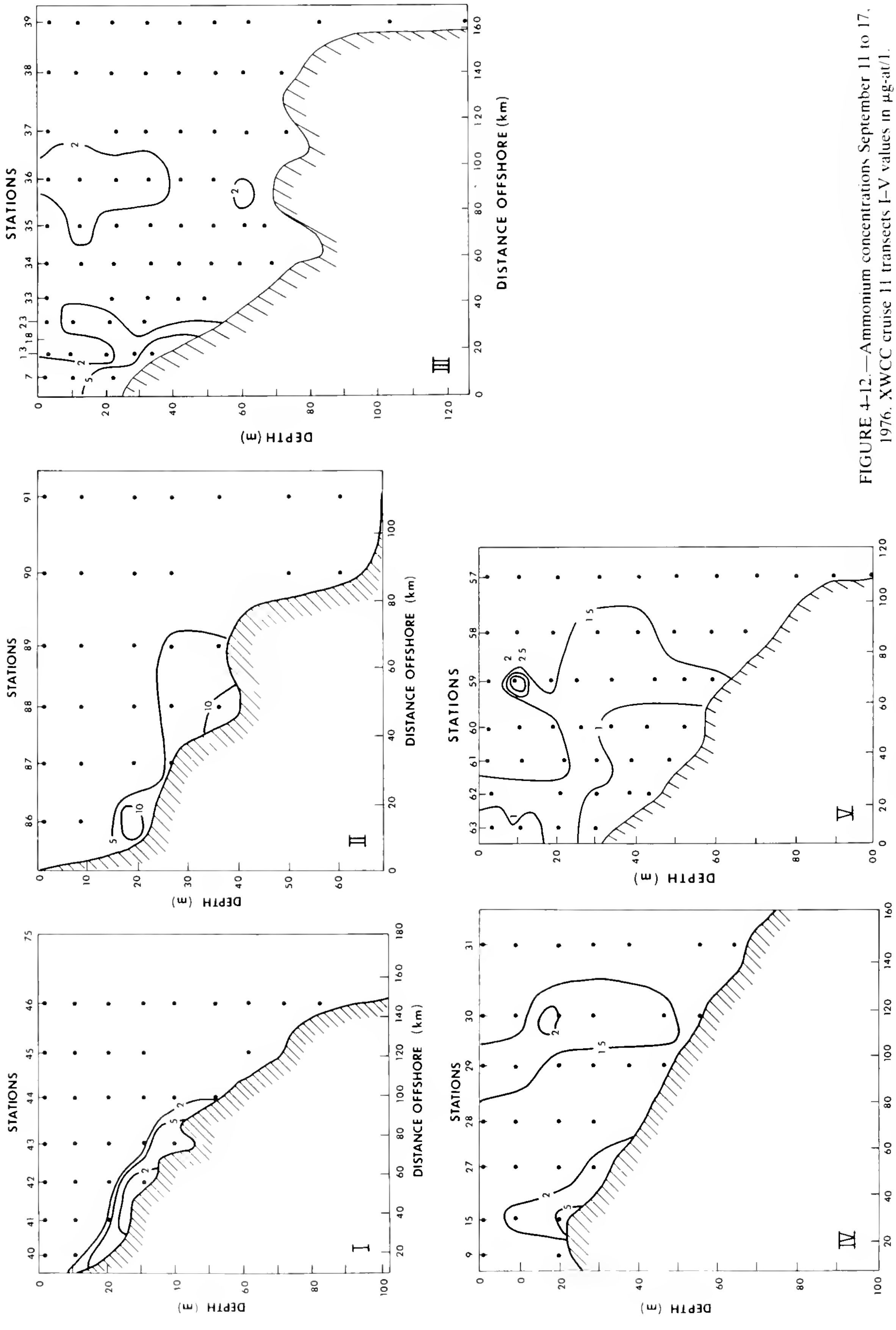


FIGURE 4-12.—Ammonium concentrations September 11 to 17, 1976, XWCC cruise 11 transects I–V values in µg-at/l.

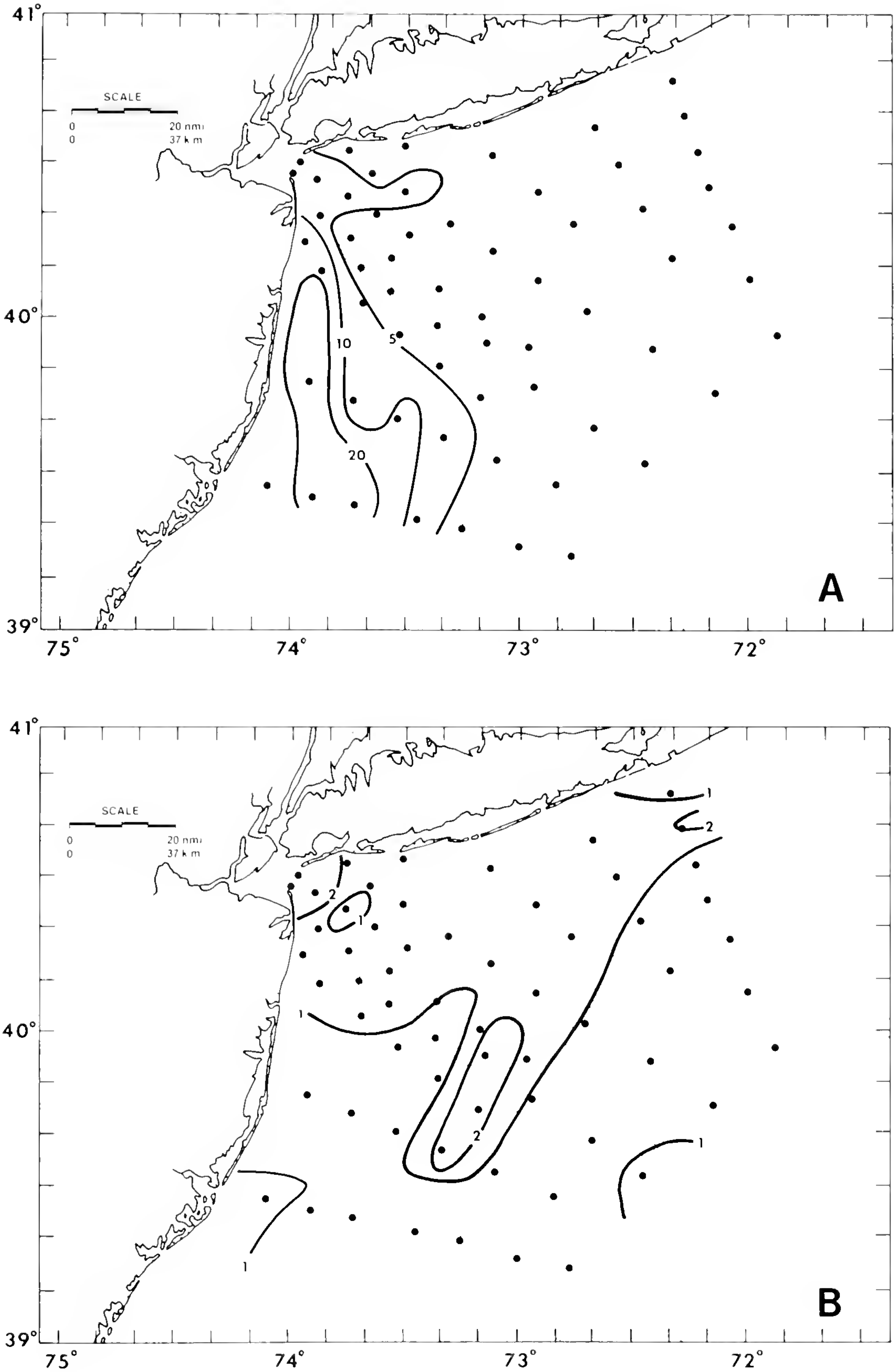


FIGURE 4–13.—Ammonium concentrations of bottom (A) and surface (B) waters September 11 to 17, 1976. XWCC cruise 11 values in μg-at/l.

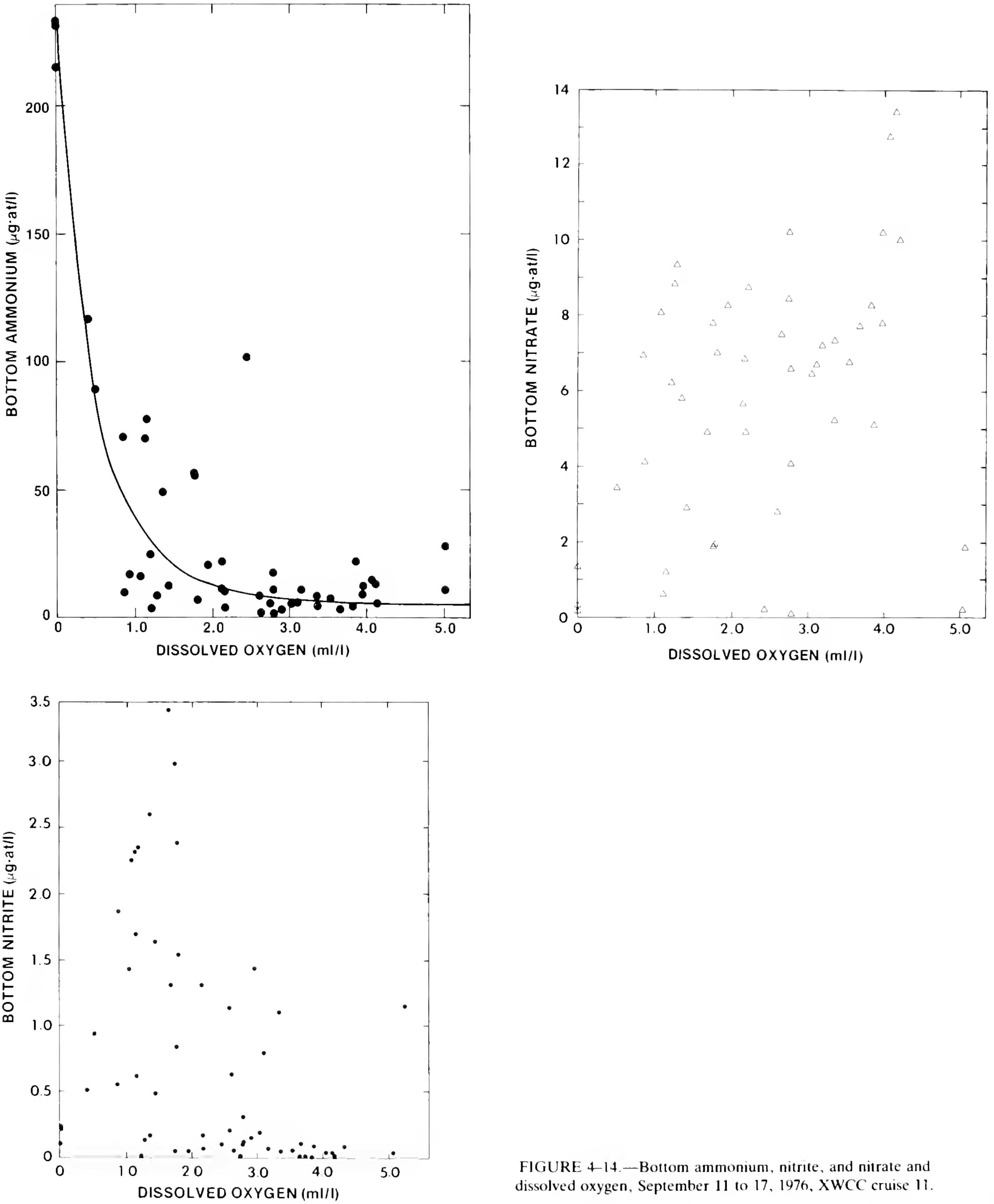


FIGURE 4-14.—Bottom ammonium, nitrite, and nitrate and dissolved oxygen, September 11 to 17, 1976, XWCC cruise 11.

vail. Data quality was responsible for only a minor part of this observed variation. However, at low oxygen concentrations (<1.0 ml/l), where ammonium levels were very high, the few measured nitrate values were low.

**Comparison of 1975 and 1976 nutrient distribution**

There are no apparent causal factors to be found in the nutrient distribution itself that explain the low oxygen concentrations in New York Bight in the summer of 1976. However, the nutrient data exclude several possibilities, such as larger than normal nutrient inputs from the Hudson River estuary or greatly prolonged or reduced rates of transport of offshore water to the inner shelf region. The outstanding differences in nutrient distributions between 1976 and 1975 are: smaller amounts of nutrients at the shelf break in spring 1976; lower nitrate concentrations over the entire shelf in July 1976 (when the oxygen depletion developed); and extraordinarily larger concentrations of ammonium and sulfide in the region of the 1976 low oxygen concentrations. Taken singly, these observations are not powerful clues to the cause of the oxygen deficiency, but, taken together, they may be significant.

If the source for water brought onto the shelf by upwelling or other physical processes in 1976 had a deficit of at least 3 μg-at $NO^-$/l, the resulting smaller concentrations of nitrate available on the shelf would favor development of phytoplankton such as *Ceratium tripos*, which can function at lower light and nutrient levels. This might have contributed to *Ceratium*'s domination of the phytoplankton community (ch. 9, pt. 1). The uptake of ammonium accounted for 66 percent of nitrogen uptake in stations collected across the shelf (Conway and Whitledge, personal communication). This probably also favors production of dinoflagellates such as *Ceratium* because of their affinity for ammonium-rich environments.

The very low nitrate concentrations over the entire shelf in July 1976 (even in bottom waters) probably resulted from renewal processes being slower than usual compared to biological uptake rates. The extraordinarily large concentrations of ammonium measured off New Jersey in 1976 are an order of magnitude larger than pristine oceanic concentrations. Large ammonium concentrations have been measured as high as 150 μg-at/l off marine sewage outfalls (Whitledge, unpublished data), 500 to 1,200 μg-at/l in the New York Bight sewage sludge dumpsite (Duedall et al. 1975; Duedall et al. 1977), and somewhat lower in anoxic areas like the Black Sea and Lake Nitinat (Richards et al. 1965).

The distribution of ammonium off New Jersey suggests its origin is other than Hudson-Raritan discharge. This agrees with the limited range of estuarine influence from the Hudson River found for nutrients (Segar and Berberian 1976) and trace metals (Segar and Cantillo 1976). The possibility of heavy organic loading, which decomposes to produce the observed ammonium concentrations, is not great since the gradient for dissolved organic carbon in the Hudson-Raritan discharge is small (fig. 4–15).

The wide area where ammonium concentrations were greater than 5 μg-at/l is probably where denitrification processes occurred or where ammonium was not being oxidized to nitrate. These high ammonium concentrations were located where undetectable or minute quantities of oxygen were measured (ch. 2) and in the general locations where hydrogen sulfide was found.

Off Long Island, the near-bottom concentrations of ammonium were sometimes as high as 3 μg-at/l in the BNL transect (BNL, unpublished data), and these elevated concentrations occurred several meters above the bottom. Whether these concentrations originated in the sediments or in an organic layer of decomposing phytoplankton at the sediment interface is not known. The highest concentrations of sulfide (equivalent to 56.2 μg-at/l) correspond well with amounts predicted from empirical relationships in anoxic environments where the ratio ammonium:sulfide was equal to 0.319 (Richards et al. 1965).

## DISSOLVED AND PARTICULATE ORGANIC LOADING

Depletion of D.O. in isolated bottom waters results mostly from oxidation of organic matter. The nutrients discussed above are important to the production of this organic matter, but understanding the distribution of the organic matter itself is important to any comprehension of the causes of depletion. The limited information pertinent to the summer of 1976 is discussed below.

During late August and early September 1976, samples for particulate organic carbon (POC) and dissolved organic carbon (DOC) were collected during a National Marine Fisheries Service (NMFS) cruise (fig. 4–16). POC samples were analyzed using a Coleman carbon analyzer. DOC samples were analyzed by the Marine Chemistry Laboratory of the University of Delaware, using a modification (Sharp 1973) of the method of Menzel and Vacarro (1964). This method is inaccurate compared to high temperature combustion methodology (up to 25% lower in deep ocean samples where more refractory carbon compounds are found), but in relatively shallow coastal waters the error is probably minimal (Sharp 1973).

Ideally, interpretation of these data would include comparison to other measurements in coastal environments; however, little such information exists. Additional unpublished data from the University of Delaware, designated NOAA Salt Marsh, and TransX, were utilized. The DOC analytical methods used for these samples were the same as for the NMFS samples, but POC analyses were performed with a modified CHN analyzer (Sharp 1974).

The 1976 NMFS cruise organic carbon data given in table 4–8 are summarized in table 4–9 by grouping all

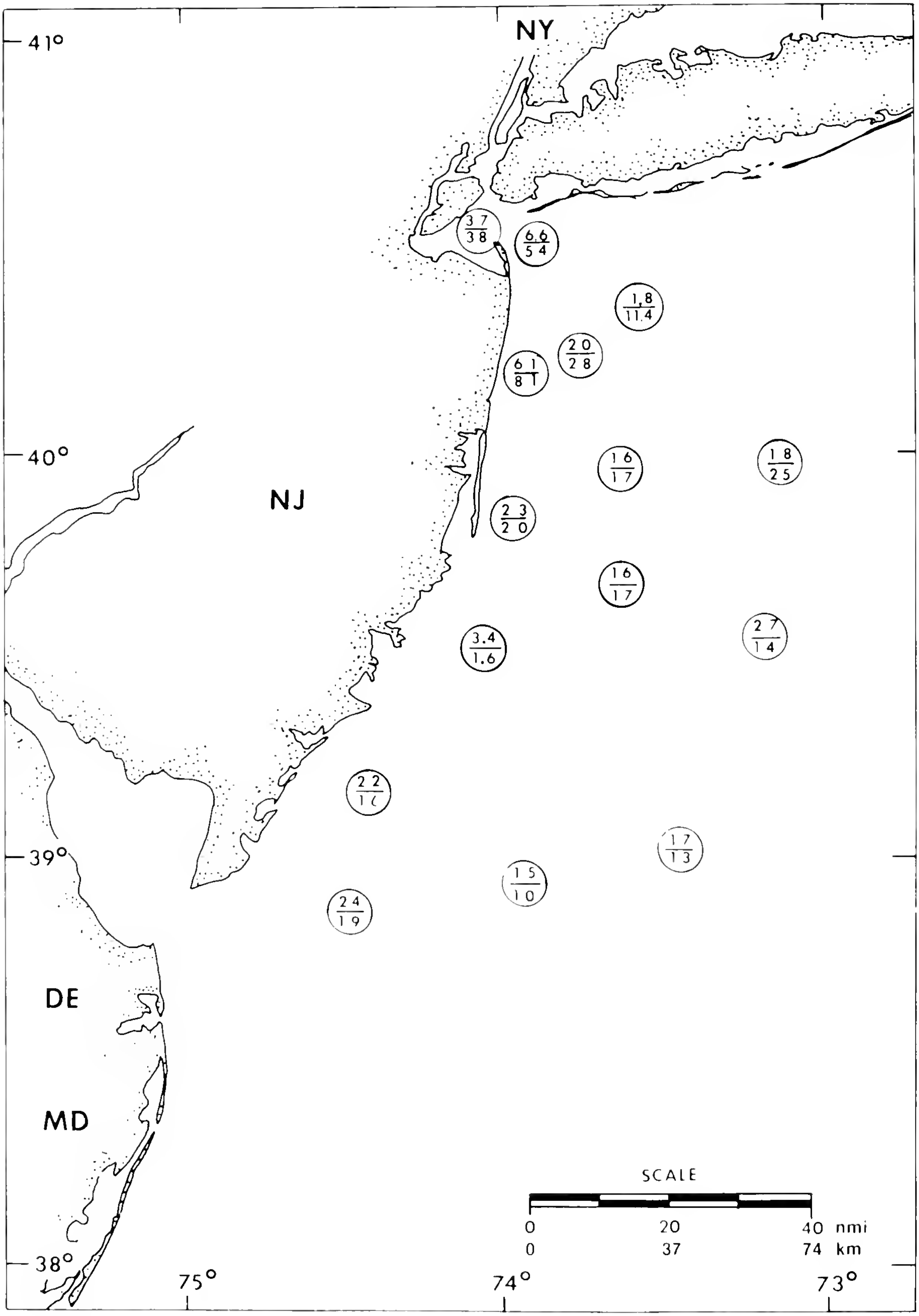


FIGURE 4–15.—Average values for dissolved organic carbon in shallow (photic zone) and deep samples; top and bottom units, respectively, in μg-C/l

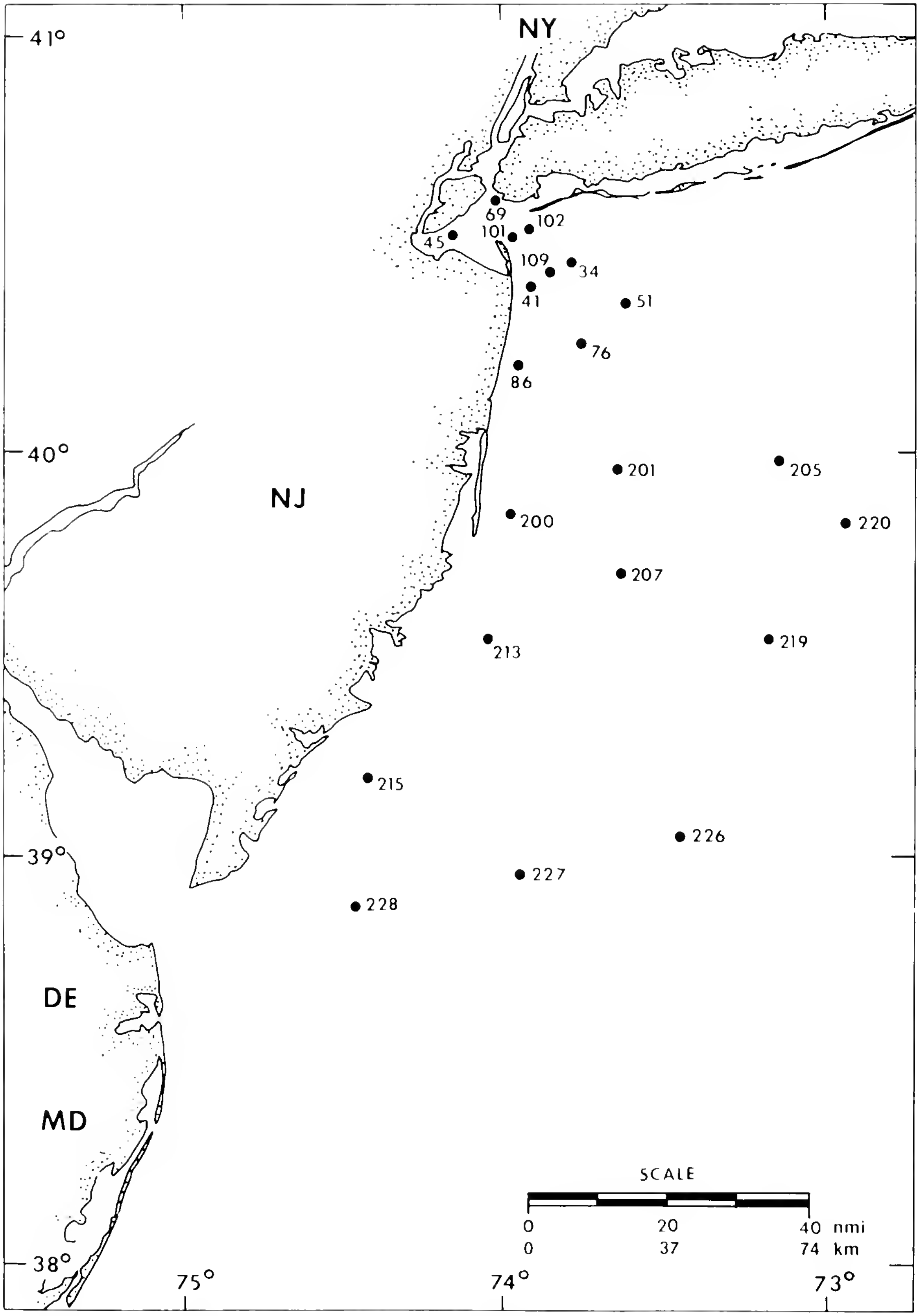


FIGURE 4–16.—Station locations for National Marine Fisheries Service August-September 1976 cruise.

TABLE 4–8.—*Organic carbon data for August-September 1976*

| Station[1] | Sample depth | Dissolved organic carbon | Particulate organic carbon | Total organic carbon | POC: Total |
|---|---|---|---|---|---|
| No. | m | mg/l | mg/l | mg/l | Percent |
| 34 | 1.0 | 5.34 | 0.373 | 5.71 | 6.5 |
| | 4.0 | 6.53 | .646 | 7.18 | 9.0 |
| | 6.0 | 5.13 | .872 | 6.00 | 14.5 |
| | 10.0 | 4.08 | .366 | 4 45 | 8.2 |
| | 18.0 | 5.68 | .314 | 5.99 | 5.2 |
| | 26.0 | 5.01 | .287 | 5.30 | 5.4 |
| | 36.0 | 3.75 | .414 | 4.16 | 9.9 |
| 41 | 1.0 | 5.78 | .361 | 6.14 | 5.9 |
| | 2.0 | 3.90 | .388 | 4.29 | 9.0 |
| | 4.0 | 5.90 | .328 | 6.23 | 5.3 |
| | 6.0 | 5.44 | .164 | 5.60 | 2.9 |
| | 9.0 | 7.77 | .154 | 7.92 | 1.9 |
| | 15.0 | 5.35 | .417 | 5 77 | 7.2 |
| | 20.0 | 6.26 | .552 | 6.81 | 8 1 |
| 45 | 1.0 | 3.32 | —— | —— | —— |
| | 3.0 | 9.24 | —— | —— | —— |
| | 6.0 | 8.45 | —— | —— | —— |
| | | | .859 avg. | | 11.9 avg. |
| 51 | 1.0 | 2.97 | .273 | 1.78 | 15 3 |
| | 2.0 | 1.66 | —— | —— | —— |
| | 3.0 | 2.14 | —— | —— | —— |
| | 11.0 | 1.02 | —— | —— | —— |
| | 14.0 | 13.37 | —— | —— | —— |
| | 17.0 | 11.97 | —— | —— | —— |
| | 23.0 | 2.62 | —— | —— | —— |
| 69 | 1.0 | 1.67 | 1.210 | 2.88 | 42.0 |
| | 3.0 | 3.11 | 1.398 | 4.51 | 31.0 |
| | 4.0 | 4.09 | 1.256 | 5.35 | 23.5 |
| | 5.0 | 7.39 | 1.460 | 8.85 | 16 5 |
| | 8.0 | 3.04 | .637 | 3.68 | 17.3 |
| | 11.0 | 4.80 | .323 | 5.12 | 6.3 |
| 76 | 1.0 | 1.95 | .187 | 2.14 | 8.8 |
| | 5.0 | 2.06 | .196 | 2.26 | 8.7 |
| | 10.0 | 2.27 | .204 | 2.47 | 8.2 |
| | 16.0 | 1.89 | .275 | 2.17 | 12.7 |
| | 23.0 | 1.64 | .226 | 1.87 | 12.1 |
| | 30.0 | 4.88 | .119 | 5.00 | 2.4 |
| | 40.0 | 2.17 | .178 | 2.39 | 7.5 |
| | 50.0 | 1.28 | .152 | 1.43 | 10.6 |
| 86 | 1.0 | 6.57 | .011 | —— | —— |
| | 4.0 | 6.09 | .218 | 6 31 | 3.5 |
| | 8.0 | 7.58 | .298 | 7.88 | 3.8 |
| | 12.0 | 4.12 | .352 | 4 47 | 7.9 |
| | 18.0 | 8.06 | .852 | 8 91 | 9 6 |
| 101 | 1.0 | 4.11 | .601 | 4 71 | 12.8 |
| | 3.0 | 2.40 | .491 | 2.89 | 17.0 |
| | 5.0 | 3.59 | .519 | 4 11 | 12.6 |
| | 8.0 | 1.94 | .512 | 2.45 | 20.9 |
| | 11.0 | 3.80 | .764 | 4 56 | 16.7 |
| 102 | 1.0 | 1.87 | .590 | 2.46 | 24.0 |
| | 3.0 | 1.77 | .380 | 2 15 | 17.7 |
| | 5.0 | 1.76 | .480 | 2.24 | 21.4 |
| | 7.0 | 1.91 | .491 | 2.40 | 20.4 |
| | 9.0 | 2.39 | .438 | 2.83 | 15.5 |
| | 13.0 | 1.82 | .351 | 2.17 | 16.2 |
| 109 | 1.0 | 8.50 | .204 | 8.70 | 2.3 |
| | 4.0 | 10.21 | .348 | 10.56 | 3.3 |
| | 7.0 | 9.49 | .251 | 9.74 | 2.6 |
| | 12.0 | 2.20 | .328 | 2.53 | 13.0 |
| | 14.0 | 6.25 | .300 | 6.50 | 4.6 |
| | 21.0 | 9.13 | .321 | 9.45 | 3.4 |
| 200 | 1.0 | 3.42 | .126 | 3.55 | 3.6 |
| | 4.0 | 1.87 | .082 | 1.95 | 4.2 |
| | 11.0 | 1.70 | .349 | 2.05 | 17.0 |
| | 14.0 | 1.95 | .133 | 2.08 | 6.4 |
| | 17.0 | 2.06 | .846 | 2.91 | 29.1 |
| | 21.0 | 2.04 | 1.149 | 3.19 | 36.0 |
| 201 | 1.0 | 1.62 | .328 | 1.95 | 16.8 |
| | 3.0 | —— | .345 | —— | —— |
| | 8.0 | 1.63 | .468 | 2.10 | 22.3 |
| | 18.0 | 1.58 | .142 | 1.72 | 8.2 |
| | 23.0 | 1.79 | .194 | 1.98 | 9.8 |
| | 28.0 | 1.55 | .874 | 2.42 | 36.1 |
| | 33.0 | 1.86 | .250 | 2.11 | 11.8 |
| 205 | 1.0 | 1 93 | .273 | 2 20 | 12.4 |
| | 6.0 | 1.74 | .161 | 1.90 | 8.5 |
| | 14.0 | 1.89 | .371 | 2 26 | 16.4 |
| | 21.0 | 1 61 | .330 | 1.94 | 17.0 |
| | 30.0 | 1.38 | .293 | 1.67 | 17.5 |
| | 46.0 | —— | .093 | —— | —— |
| | 62.0 | 3.67 | .318 | 3.99 | 8.0 |
| | 80.0 | 1.31 | .369 | 1.68 | 22.0 |
| 207 | 1.0 | 1.72 | —— | —— | —— |
| | 5.0 | 1.58 | —— | —— | —— |
| | 20.0 | 1.56 | —— | —— | —— |
| | 26.0 | 1.61 | —— | —— | —— |
| | 31.0 | 1.87 | —— | —— | —— |
| | | | .269 avg. | | 13.9 avg. |
| 213 | 1.0 | 5.33 | .116 | 5.45 | 2.1 |
| | 4.0 | 4.25 | .178 | 4.42 | 3.8 |
| | 9.0 | 1.52 | .150 | .167 | 9.0 |
| | 15.0 | 2.66 | .191 | 2.85 | 7.0 |
| | 18.0 | 1.67 | 999 | 2.67 | 37.4 |
| | 21.0 | 1.57 | .993 | 2.56 | 38.7 |
| 215 | 1.0 | 2.66 | .205 | 2.87 | 7.2 |
| | 4.0 | 2.40 | .152 | 2.55 | 6.0 |
| | 7.0 | 1.51 | .149 | 1.66 | 9.0 |
| | 14 0 | 2.18 | .266 | 2.45 | 10.9 |
| | 17.0 | 1.75 | .315 | 2.07 | 15.2 |
| | 20.0 | 1.45 | .382 | 1.83 | 20.9 |
| 219 | 1.0 | 4.91 | .123 | 5.03 | 2.4 |
| | 5.0 | 2.58 | .150 | 2.73 | 5.5 |
| | 11.0 | 1.60 | .153 | 1 75 | 8.7 |
| | 19.0 | 1.65 | .314 | 1.96 | 16.0 |
| | 25.0 | 1.21 | .314 | 1.52 | 20.6 |
| | 29.0 | 1.30 | .273 | 1.57 | 17.4 |
| | 34.0 | 1.40 | .191 | 1.59 | 12.0 |
| | 41.0 | 1.52 | .491 | 2.01 | 24.4 |
| 226 | 1.0 | 1.69 | .127 | 1.82 | 7.0 |
| | 6.0 | 1.56 | .128 | 1.69 | 7.6 |

TABLE 4–8.—*Organic carbon data for August-September 1976—continued*

| Station[1] | Sample depth | Dissolved organic carbon | Particulate organic carbon | Total organic carbon | POC: Total |
|---|---|---|---|---|---|
| No. | m | mg/l | mg/l | mg/l | Percent |
| | 18.0 | 4.06 | 150 | 4.21 | 3.6 |
| | 26.0 | 1.97 | .104 | 2.07 | 5.0 |
| | 40.0 | 2.09 | .273 | 2.36 | 11.6 |
| | 47.0 | 1.00 | .273 | 1.27 | 21.4 |
| | 54.0 | 1.65 | .328 | 1.98 | 16.6 |
| 227 | 1.0 | 1.27 | .055 | 1.33 | 4.2 |
| | 8.0 | 1.70 | .133 | 1.83 | 7.3 |
| | 16.0 | 1.50 | .083 | 1.58 | 5.2 |
| | 28.0 | 1.39 | .243 | 1.63 | 14.9 |
| | 36.0 | 1.31 | .139 | 1.45 | 9.6 |
| | 40.0 | 1.05 | .145 | 1.20 | 12.1 |
| 228 | 1.0 | 2.26 | .314 | 2.57 | 12.2 |
| | 4.0 | 1.49 | .067 | 1.56 | 4.3 |
| | 6.0 | 3.40 | .044 | 3.44 | 1.3 |
| | 11.0 | 2.49 | .059 | 2.55 | 2.3 |
| | 16.0 | 1.27 | .358 | 1.63 | 22.0 |
| | 22.0 | 2.52 | .271 | 2.79 | 9.7 |

[1] Station locations are shown in figure 4–16.

samples from the Hudson River mouth and Raritan Bay as one, all those from stations 34, 41, 51, 76, 86, and 109 as the Apex, and stations 200 to 228 as the outer Bight. These August-September 1976 values are compared in table 4–9 to other data, including March, April, June, and July 1977 data from the southern portion of New York Bight, which covers samples from between NMFS stations 213 and 219 south to about 38° 20′N. The NMFS cruise and the last three TransX cruises were made when the water was well stratified with a summer thermocline so that bottom waters were distinctly different from surface waters. Surface and deepwater values were averaged for an overall picture and comparison. Monthly or 2-month averages are also listed for a salt marsh at the mouth of Delaware Bay (Canary Creek). It is obvious from table 4–9 that DOC values for the Apex are exceptionally high. As a general reference, average DOC values for typical estuarine and typical oceanic environments are respectively 2.90 and 0.80 mgC/l (Sharp 1975). The average of 4.41 mgC/l for the Delaware marsh is higher than normal estuarine values, partly because it represents output from a shallow, tidal emergent marsh. The Hudson-Raritan estuary values probably are not extraordinary, and the outer Bight values seem a little high but understandable when compared to the other coastal values given in the table. A striking feature is that the Apex values are considerably higher than those in the estuary. In contrast, POC values do not appear to be exceptional; typical estuarine and oceanic particulate values are respectively about 2,000 and 150 μg C/l (Sharp 1975).

August-September DOC data can be summarized in another way. The samples in the photic zone are averaged

TABLE 4–9.—*Comparison of organic carbon averages*

| Study | Area | Time | | Dissolved organic carbon | Particulate organic carbon | Total organic carbon | POC: Total |
|---|---|---|---|---|---|---|---|
| | | Month | Year | mg/l | mg/l | mg/l | Percent |
| NMFS | Hudson-Raritan | Aug.-Sept. | 1976 | 3.78 | 0.76 | 4.54 | 16.7 |
| NMFS | Bight Apex | Aug.-Sept. | 1976 | 5.31 | 0.31 | 5.62 | 5.5 |
| NMFS | Outer New York Bight | Aug.-Sept. | 1976 | 2.00 | 0.26 | 2.26 | 11.6 |
| TransX Cruise | lower mid-Atlantic shelf | March | 1977 | 1.34 | 0.28 | 1.62 | 17.2 |
| TransX Cruise | lower mid-Atlantic shelf | April | 1977 | 1.21 | 0.17 | 1.38 | 12.1 |
| TransX Cruise | lower mid-Atlantic shelf | June | 1977 | 1.22 | 0.13 | 1.35 | 9.9 |
| TransX Cruise | lower mid-Atlantic shelf | July | 1977 | 1.20 | 0.20 | 1.40 | 14.3 |
| NOAA Salt Marsh | Delaware Marsh | Jan.-Feb. | 1975 | 4.24 | 1.41 | 5.65 | 25.0 |
| Do. | do. | Mar.-Apr. | 1975 | 3.61 | 1.77 | 5.38 | 33.0 |
| Do. | do. | May-June | 1975 | 5.64 | 1.98 | 7.62 | 26.0 |
| Do. | do. | July | 1975 | 8.96 | 2.37 | 11.33 | 20.9 |
| Do. | do. | August | 1975 | 4.90 | — | — | — |
| Do. | do. | Sept.-Oct. | 1975 | 3.68 | 2.05 | 5.73 | 35.8 |
| Do. | do. | Nov.-Dec. | 1975 | 3.43 | 2.77 | 6.20 | 44.7 |
| Do. | do. | Feb. | 1976 | 3.71 | 2.11 | 5.82 | 32.2 |
| Do. | do. | April | 1976 | 5.32 | 1.84 | 7.16 | 25.7 |
| Do. | do. | May | 1976 | 3.46 | 1.72 | 5.18 | 33.2 |
| Do. | do. | June | 1976 | 3.96 | 1.87 | 5.83 | 32.1 |
| Do. | do. | July | 1976 | 6.36 | 2.90 | 9.26 | 31.3 |
| Do. | do. | Aug. | 1976 | 5.04 | 2.34 | 7.38 | 31.7 |
| Do. | do. | Sept.-Oct. | 1976 | 4.09 | 2.83 | 6.92 | 40.9 |
| Do. | do. | Nov.-Dec. | 1976 | 2.84 | 2.57 | 5.41 | 47.5 |

as shallow and those below as deep (the summer thermocline usually is close to the bottom of the photic zone). This is done in figure 4–15, with stations 34, 41, and 109 grouped and stations 45, 69, 101, and 102 grouped. Again, there is striking evidence of higher DOC in the Bight Apex than in the estuary. Also striking is the extraordinarily high value for the deep water at station 51 (this station is nearer to the acid dumpsite than to the sewage sludge dumpsite). There is a rather consistent offshore trend of decreasing DOC which needs explanation.

One reason for the very high values in the Apex may be sludge dumping. That possibility has been explored and shown to be unlikely (Segar and Berberian 1976; Sharp 1976). Segar and Berberian suggest that the high oxygen demand in this area is the result of high productivity supported by nutrients from the estuarine outflow. Another cause of high nutrients that would also explain the decrease of DOC in an offshore trend comes from a mathematical model (Riley 1967). According to Riley, the higher productivity in a shallow coastal region as compared to farther offshore is a result of faster exchange between surface and bottom waters. This, when coupled with upwelling, can give a continuous and rapid supply of nutrients to the phytoplankton. Resulting higher productivity would ultimately give rise to more organic matter in the water, which soon resides in the DOC pool. Similarly, Han et al. (ch. 8) show greater upward vertical flux for water in the Apex than in adjacent segments. (See their fig. 8–12.) The strong flow of water to the north in June (ch. 7) could also contribute to the concentration in the Apex.

Another explanation of the offshore carbon trend is organic input from salt marshes. There are marshes all along the New Jersey coast, and the NOAA Salt Marsh data show output of DOC and POC throughout the year (F.C. Daiber, personal communication). Since a consistent data set is available for 1975 and 1976, it is possible to see whether the marsh output of organic carbon was exceptional in the second year. The NOAA Salt Marsh data for the lower Delaware Bay are considered representative of salt marshes along the New Jersey and Long Island coasts. A more thorough analysis of actual fluxes is being prepared (V. A. Lotrich, personal communication); the values to be considered here are averages of ambient concentrations taken over tidal cycles. Values are given in table 4–9 and are plotted in figure 4–17. As can

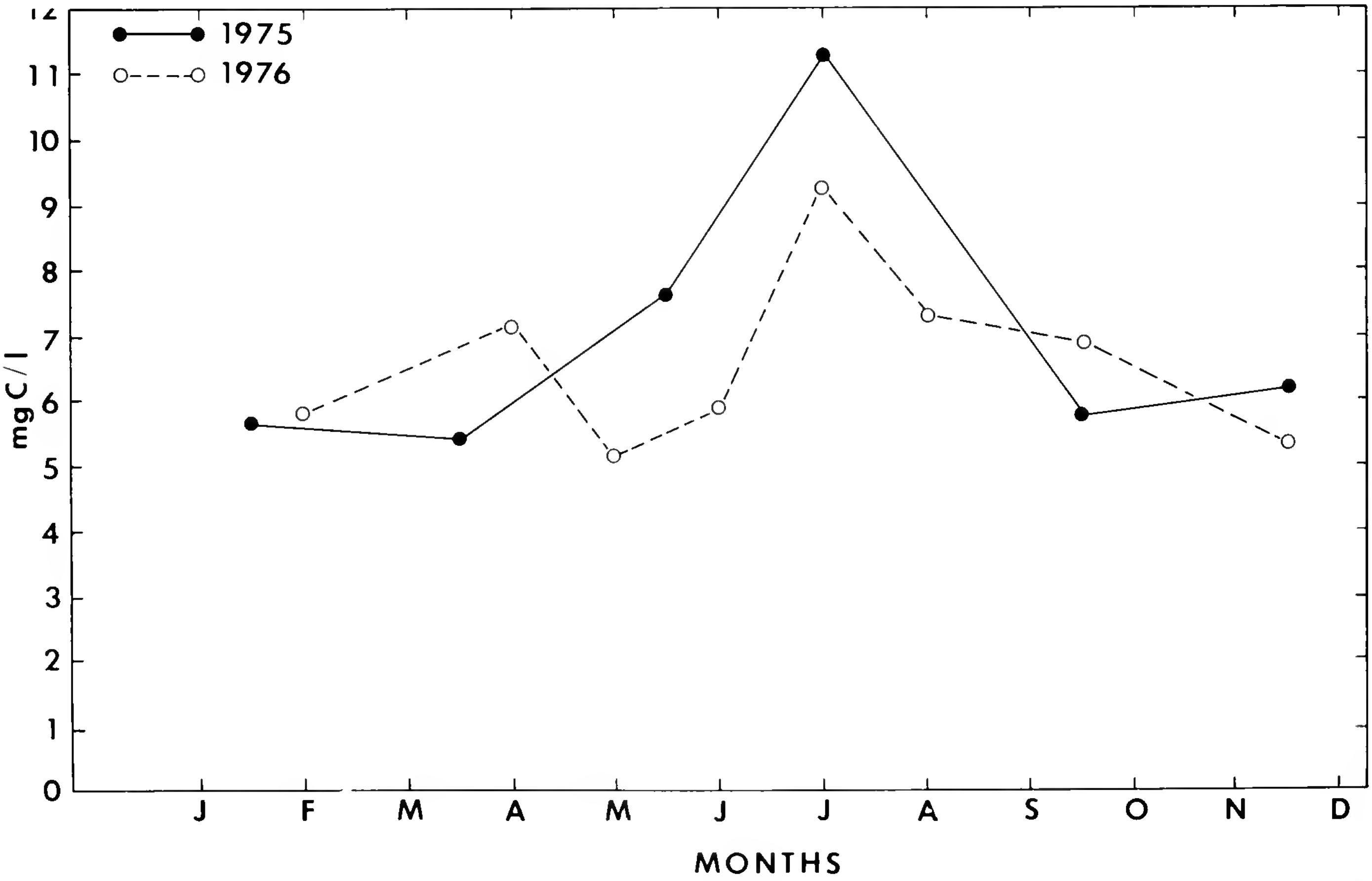


FIGURE 4–17.—Total organic carbon (dissolved and particulate) in waters of a salt marsh on lower Delaware Bay in 1975 and 1976. (NOAA Salt Marsh data).

be seen, the organic carbon in marsh water in 1976 generally was equal to or lower than 1975, so there is no evidence of exceptional marsh output for 1976 unless flow rates out of the marshes were exceptional in 1976 as compared to 1975.

The impact of this organic carbon on oxygen distribution in the Bight should be considered. A somewhat simplified stoichiometric relationship for primary productivity and organic breakdown has been established (Redfield et al. 1963), and can be written:

$$[(CH_2O_{106}\ (NH_3)_{16}\ H_3PO_4] + 138\ O_2 \rightleftarrows 106\ CO_2 + 16\ HNO_3 + H_3PO_4 + 122\ H_2O,$$

where the term in brackets represents an average chemical composition for marine phytoplankton. It is the product of analysis of elements in plankton and of nutrients in seawater and was intended as an average picture for the oceanic environment. If a semienclosed coastal system can be considered in equilibrium, these same ratios can hold. Analysis of TransX data (Sharp et al. 1979) indicates that sometimes Middle Atlantic coastal bottom waters do show the predicted molar ratios of fluxes of phosphate, D.O., and organic carbon. Therefore, it is possible to evaluate the impact of the measured organic carbon on bottom water D.O., using the idealized ratio of 138 moles of oxygen to 106 moles of carbon. We can postulate the D.O. for a starting point by using the concentration that would be in equilibrium with the atmosphere if there were no biological oxygen utilization. Bottom water salinity in the New York shelf region is about 32.75‰, and the temperature is about 9.6° C. The salinity is the average from chapters 2 and 5; temperature is an average of June through September for all segments from table 4–5. Using oxygen saturation tables (e.g., Riley and Skirrow 1975), this would give an oxygen content of 6.57 ml/l. With stoichiometric equivalence, this amount of oxygen would be used by respirational consumption of 0.225 millimoles C/l or 2.70 mg C/l.

Of course, all organic matter in the water will not be easily broken down by rapid heterotrophic activity. However, organic content greatly in excess of 2.70 mg C/l may suggest sufficient labile (oxidizable) material to pose a serious oxygen demand that, without oxygen replenishment, could hypothetically lead to oxygen depletion. For this consideration, total organic carbon (TOC) should be treated as the cause of the potential oxygen demand, and particulate matter may be less important than dissolved material; Duedall et al. (1977) showed that bacterial oxidation of dissolved organic matter in sewage sludge occurs before oxidation of particulate matter. This opinion is also based upon the observation that particulates usually make up only 10 to 15 percent of the total organic matter (table 4–8) and upon the suspicion that the particulates are not a long-term (months) feature of the water column. The water column, not the benthic interface, has been shown to be responsible for the majority of the oxygen demand on an areal basis (Thomas et al. 1976). If an average oceanic DOC value is taken as 0.80 mg C/l (Sharp 1975) and is viewed as the upper limit of refractory carbon in an oceanic environment, then anything greater than 0.8 can be considered labile. By adding 0.80 and 2.70, we get 3.50 mg C/l as an amount sufficient to provide a 100-percent oxygen demand and leave the residual refractory oceanic value. From table 4–8, we can see that many of the samples in the Bight Apex have potential oxygen demands sufficient to cause anoxia if the organic degradation were rapid in comparison to oxygen replenishment. More startling is that all the averaged bottom water values (fig. 4–15) for the Apex have sufficient DOC to deplete the oxygen present if no oxygen renewal occurs. The bottom waters of the Bight are not physically stagnant and the general circulation is southwestward (Bumpus 1973; ch. 7). However, this circulation also develops gyres and areas of very sluggish circulation (ch. 8). Thus, unless a source of oxygen-rich, organic-poor water is postulated, we would expect the water in this region to continue to pose a large oxygen demand until the autumnal breakdown of the thermocline.

Therefore, from examination of the data acquired during August-September 1976, it is concluded that DOC (1) was not exceptional in the Hudson-Raritan estuary; (2) was possibly higher than normal (compared to other coastal areas) in the lower portion of New York Bight; and (3) was extraordinarily high in the Apex. There is no way of knowing whether the high Apex values are unusual as compared to other years. If they are, they could have resulted from the combined effects of the large *Ceratium* bloom in summer 1976 and the estuarine circulation of the Apex. POC did not show exceptional values in these areas. In the Apex, the organic carbon values are more than sufficient to give a potential oxygen demand that could totally deplete the D.O. in the bottom waters.

## CHEMICAL RESPONSES

In 1976 oxygen demand loading in the bottom waters of the Bight depleted D.O. levels to near anoxic or anoxic conditions over an area roughly equal to segments A, J1, J2, M1, and part of M2. We will now examine how the Bight chemistry changed as a result of this depletion by briefly discussing it in the light of other chemical events associated with anoxic development.

Evidence for nitrate reduction is presented above in the discussion of nutrients where plots of $NH_4^+$, $NO_2^-$, and $NO_3^-$ versus D.O. are shown for cruise XWCC–11 (fig. 4–14). Although there is no clear evidence that $NO_3^-$ was removed from the system as oxygen declined, the peak

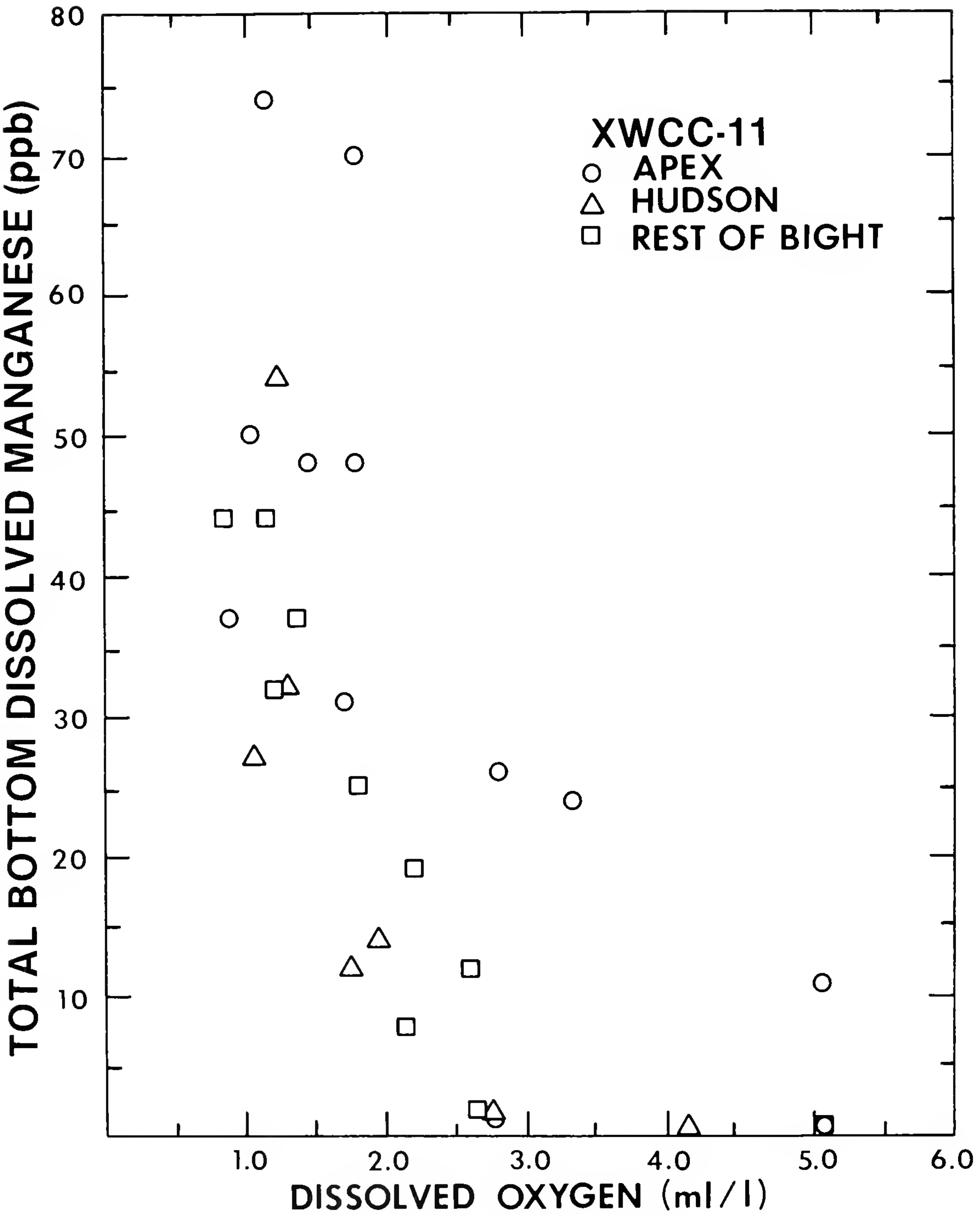


FIGURE 4–18.—Dissolved manganese and dissolved oxygen concentrations in bottom samples September 1976, XWCC cruise 11.

in $NO_2^-$ concentration at about 1.6 ml/l oxygen, and an exponential increase in $NH_4^+$ concentrations below 2.0 ml/l, are evidence that reduction of $NO_3^-$ to $NO_2^-$ and then to $NH_4^+$ occurred. Whether or not reduction to elemental nitrogen or $N_2O$ took place cannot be determined from the data available.

There is ample evidence that $SO_4^=$ reduction occurred throughout the oxygen-depleted area (Steimle 1976). Hydrogen sulfide was detected up to 15 m from the bottom in the oxygen-depleted area but not above the thermocline. Sulfide levels were high and reached 1.76 mg/l (Draxler and Byrne, personal communication). The $H_2S$ was also evident in apparent upwelling of anoxic bottom water along portions of the central New Jersey coast and was probably partially responsible for the high mortalities of benthic organisms.

Segar and Cantillo (1976) have shown that in the Apex, bottom dissolved manganese concentrations ranged from 1.0 ppb to as high as 40 ppb; the highest values were associated with bottom water near the Hudson-Raritan discharge. Dissolved iron concentrations ranged from 2.0 ppb to 40 ppb, with one sample of 92 ppb in June 1974, near the acid waste dumpsite.

If the oxygen depletion was sufficient to reduce Mn(IV) to Mn(II), and Fe(III) to Fe(II), in areas where sulfide was present, we should have seen an increase in dissolved manganese and iron concentrations. Where oxygen was depleted the manganese concentration increased almost exponentially to very high values (fig. 4–18). We assume this must be due to reduction of manganese to $Mn^{+2}$ and the higher solubility of species formed by this oxidation state.

An attempt to show the same effect for iron is given in figure 4–19; however, here the picture is not so clear. Even in low oxygen areas, values for dissolved iron were about the same as those in earlier years (Segar and Cantillo 1976). Any increase in dissolved manganese and iron over the short time scale represented by the 1976 anoxic event probably results from dissolution of these metals from suspended particulate matter. A 2-month period probably is not long enough for appreciable amounts of these metals to diffuse out of the bottom sediments. Betzer (personal communication) pointed out that if this is so, manganese should appear in the dissolved phase before iron since it is more concentrated in the weak acid soluble phase of the particulate matter whereas iron is more concentrated in the refractory phase. This, then, may explain why XWCC–11 data showed no increase in dissolved iron in low oxygen areas. If the deficiency in oxygen had continued for some time, the iron concentration would have increased as did manganese.

Thus, the chemical responses in New York Bight in summer 1976 were very similar to those noted in other anoxic areas of the ocean.

## SUMMARY

Dissolved oxygen in bottom waters of the New York Bight shelf (especially in the Apex and off the New Jersey coast) was severely depleted in 1976 compared to other years for which there are data. Although D.O. depletion is an annual occurrence during the warm season (that is, when the density stratification is strong), it occurred earlier in 1976 and was more severe. In certain areas, D.O. values were zero or near zero.

Other than this severe oxygen depletion, no clear chemical differences were detected in the water column between 1976 and other years represented by the data base. Apparently, there was no exceptional nutrient input to stimulate productivity. In fact, there is some evidence that fewer nutrients may have been available at the shelf break in 1976. If this is true, it might have affected the types of organisms found in shelf waters; that is, it could have favored production of organisms such as *Ceratium tripos*. Also, there is no *chemical* evidence of exceptional inputs of organic carbon either as POC or DOC although there is strong biological evidence for a very dense plankton bloom *(Ceratium tripos)*, which certainly contributed to the organic loading. The high DOC levels present in the Bight had the capacity to cause the depletion observed.

Clearly something *was* different in 1976, and perhaps this "something" was a natural occurrence. Since an adequate existing data base covers only a short time span (post-1970) and lacks many essential variables, we cannot ascertain what this was. It is significant that extraordinary DOC values exist in the Bight, especially in the Apex. Our limited data do not allow a comparison of 1976 DOC levels with those of previous years nor do they allow much insight into the chemical or physical nature or variations in space and time of the organic matter that is lumped into the category of DOC. More information on organic matter perhaps could provide insights into future events of a similar nature.

The observed chemical responses of Bight seawater to the oxygen depletion were as expected, based on our knowledge of other low oxygen or anoxic areas in the ocean. When oxygen was depleted, nitrate was reduced to nitrite and then ammonium, sulfate was reduced to sulfide, and the solubility of certain metals changed as the reducing environment developed and caused changes in their oxidation states.

## ACKNOWLEDGMENTS

Data from NOAA Salt Marsh samples for organic matter were provided by Franklin R. Daiber of the University of Delaware. Data from TransX cruises are from a study by J. H. Sharp, University of Delaware, supported in part by NSF Grant OCE 76–82571.

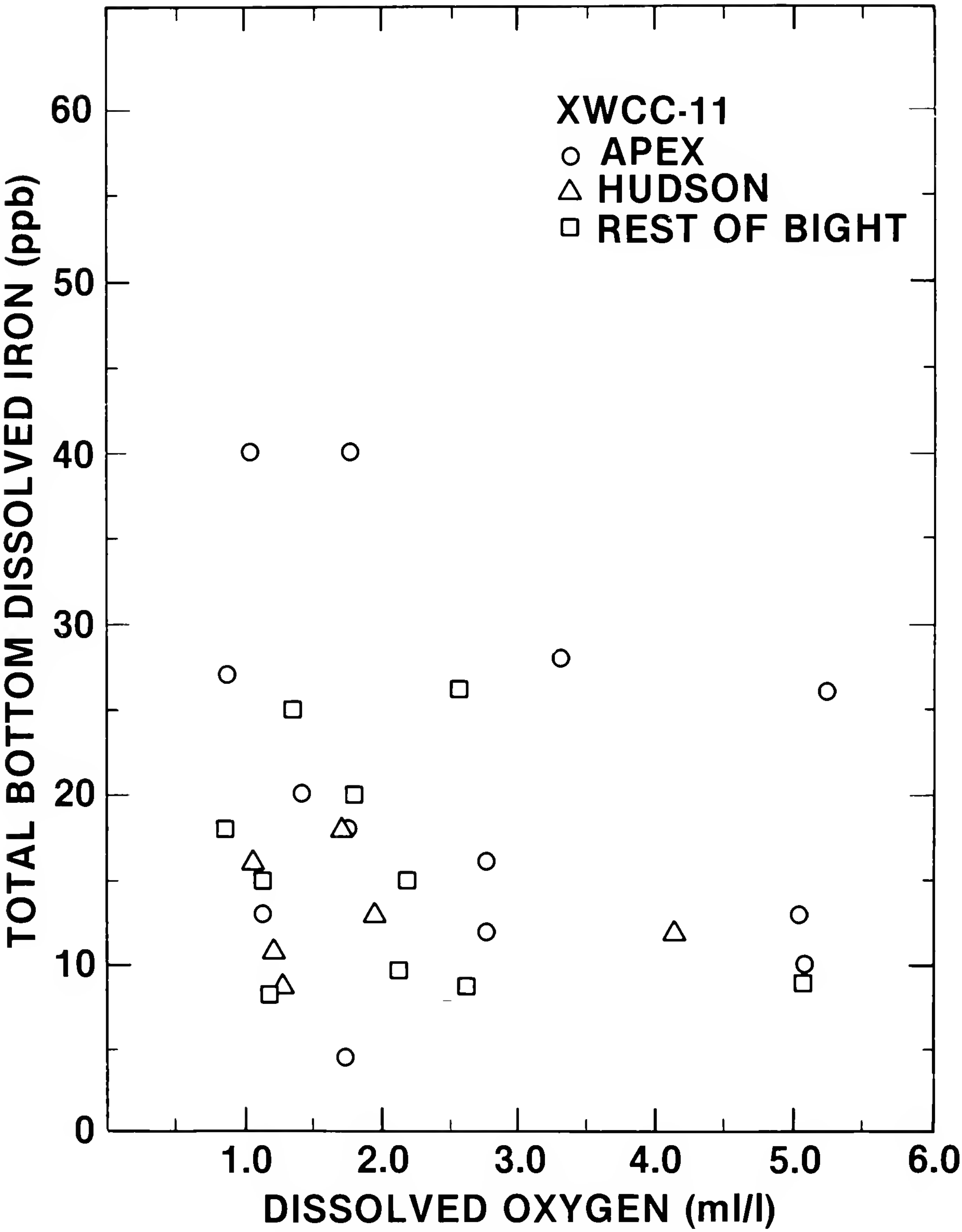


FIGURE 4–19.—Dissolved iron and dissolved oxygen concentrations in bottom samples September 1976, XWCC cruise 11.

# REFERENCES

Berberian, G. A., and Barcelona, M. J., 1979. Comparison of manual and automated methods of inorganic micronutrient analyses, *NOAA Tech. Mem.* ERL AOML–40.

Bumpus, D. F., 1973. A description of the circulation on the continental shelf of the east coast of the United States, *Progress in Oceanography* 6:111–157, Pergamon Press.

Deuser, W. B., 1975. Reducing environments, in J. P. Riley and G. Skirrow (eds.), *Chemical Oceanography*, 2d ed., vol. 3, Academic Press, New York, pp. 1–37.

Duedall, I. W., Bowman, M. J.,and O'Connors, H. B., 1975. Sewage sludge and ammonium concentrations in the New York Bight Apex, *Estuar. Coastal Mar. Sci.* 3:457–463.

Duedall, I. W., O'Connors, H. B., Oakley, S.A., and Stanford, H. M., 1977. Short-term water column perturbations due to sewage sludge dumping in the New York Bight Apex, *J. Water Pollut. Control Fed.*

Dugdale, R. C., Goering, J. J., Barber, R. T., Smith, R. L., and Packard, T. T., 1977. Denitrification and hydrogen sulfide in the Peru upwelling region during 1976, *Deep-Sea Res.* 24:601–608.

Fanning, K.A., and Pilson, M. E. Q., 1973. On the spectrophotomatic determination of dissolved silica in natural waters, *Anal. Chem.* 45, 136 pp.

IDOE Workshop on Anoxia on the Middle Atlantic Shelf During the Summer of 1976, October 15 and 16, 1976, in Washington, D.C., J. H. Sharp (ed.).

Menzel, D. W., and Vaccaro, R. F., 1964. The measurement of dissolved organic and particulate carbon in seawater, *Limnol. Oceanogr.* 9:138–142.

National Marine Fisheries Service, 1977. Oxygen depletion and associated environmental disturbances in the Middle Atlantic Bight in 1976, *Northeast Fisheries Center Tech. Ser. Rep.* No. 3, Sandy Hook Laboratory, Highlands, N.J., 471 pp.

Redfield, A. C., Ketchum, B. H., and Richards, F. A., 1963. The influence of organisms on the composition of seawater, in M. N. Hill (ed.), *The Sea*, vol. 2, Interscience (New York), pp. 2–77.

Richards, F. A., 1965. Anoxic basins and fjords, in J. P. Riley and G Skirrow, (eds.), *Chemical Oceanography*, vol. 1, Academic Press, New York, pp. 611–645.

Richards, F. A., Cline, J. D., Breonokow, W. W., and Atkinson, L. P., 1965. Some consequence of the decomposition of organic matter in Lake Nitinat, an anoxic fjord, *Limnol. Oceanogr.* 10 (suppl.): R185–R201.

Riley, G. A., 1967. Mathematical model of nutrient conditions in coastal waters, *Bull. Bingham Oceanogr. Coll.* 19:72–80.

Riley, J. P., and Skirrow, G. (eds.), 1975. *Chemical Oceanography*, 2d, ed., Academic Press, New York, Appendix, Table 6.

Ryther, J. H., and Dunstan, W. M., 1971. Nitrogen, phosphorus, and eutrophication in the coastal environment, *Science* 171:1008–1013.

Segar, D.A., and Berberian, G. A., 1976. Oxygen depletion in the New York Bight Apex: Causes and consequences, in M. G. Gross (ed.), Middle Atlantic Continental Shelf and the New York Bight, *Amer. Soc. Limnol. Oceanogr. Spec. Symp.* 2:220–239.

Segar, D. A., and Cantillo, A. Y., 1976. Trace metals in the New York Bight, in M. G. Gross (ed.), Middle Atlantic Continental Shelf and the New York Bight, *Amer. Soc. Limnol. Oceanogr. Spec. Symp.* 2:171–198.

Sharp, J. H., 1973. Total organic carbon in seawater, comparisons of measurements using persulfate oxidation and high temperature combustion, *Mar. Chem.* 1:211–229.

Sharp, J. H., 1974. Improved analysis for "particulate" organic carbon and nitrogen from seawater, *Limnol. Oceanogr.* 19:984–989.

Sharp, J. H., 1975. Gross analyses of organic matter in seawater: Why, how, and from where, in T. M. Church (ed.), Marine Chemistry in the Coastal Environment, *ACS Symposium Series* 18, Amer. Chem. Soc., pp. 682–696.

Sharp, J. H., 1976. A general box model approach, in J. H. Sharp (ed.), Anoxia on the Middle Atlantic Shelf During the Summer of 1976, National Science Foundation Workshop Report, pp. 63–70.

Sharp, J. H., Church, T. M., and Culberson, C. H., 1979. Biochemical dynamics in Middle Atlantic coastal waters (in preparation).

Smith, K. L., Jr., Rowe, G. T., and Clifford, C. H., 1974. Sediment oxygen demand in an outwelling and upwelling area, *Tethys* 6:223–230.

Steimle, F., 1976. A summary of the fish kill—anoxia phenomenon off New Jersey and its impact on resource species, in J. H. Sharp (ed.), IDOE Workshop on Anoxia on the Middle Atlantic Shelf During the Summer of 1976.

Strickland, J. D. H., and Parsons, T. R., 1968. A practical handbook of seawater analysis, *Bull. Fish. Res. Board Can.* 167, 311 pp.

Thayer, G. W., 1970. Comparison of two storage methods for analysis of nitrogen and phosphorous fractions in estuarine water, *Chesapeake Sci.* 11:155–158.

Thomas, J. P., Phoel, W. C., Steimle, F. W., O'Reilly, J. E., and Evans, C. A., 1976. Seabed oxygen consumption in the New York Bight Apex, in M. G. Gross (ed.), Middle Atlantic Continental Shelf and New York Bight, *Amer. Soc. Limnol. Oceanogr. Spec. Symp.* 2:354–269.

Walsh, J. J., Whitledge, T. E., Kelley, J. C., Hurtsman, S. A., and Pillsbury, R. D., 1977. Further transition states of the Baja California upwelling ecosystem, *Limnol. Oceanogr.* 22:264–280.

**Oxygen Depletion and Associated Benthic Mortalities in New York Bight, 1976**

# Chapter 5. Physical Conditions Compared With Previous Years

*John B. Hazelworth and Shailer R. Cummings*[1]

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135 ACKNOWLEDGMENTS

## INTRODUCTION

Dissolved oxygen content of water in New York Bight has an annual cycle. In general, it reaches its well-mixed maximum during the winter, then gradually decreases during spring, dropping to its minimum during summer. The minimum is considerably lower at the bottom than at the surface. In the autumn, cold air and storms cool surface water, break down the thermocline, introduce oxygen into the water, and cause mixing to greater depths. The oxygen content in the water increases until it again reaches its maximum during winter. The causes of the autumnal oxygen increases are physical and fairly well understood. The processes causing the spring and summer oxygen decline, however, are not as well understood. Apparently, atmospheric, biological, and chemical processes combine with physical processes to bring about the oxygen decrease.

To compare 1976 physical conditions with those of previous years, physical data were obtained from several sources:

1. Seven MESA expanded water-column characterization (XWCC) cruises in 1975, four XWCC cruises in 1976, and nine water-column characterizion (WCC) cruises in 1974, all by NOAA's Atlantic Oceanographic and Meteorological Laboratories (AOML);
2. Monthly mean sea-surface temperatures, compiled by NOAA National Marine Fisheries Service's (NMFS) Atlantic Environmental Group (AEG) from ship reports, and from data provided by NOAA Environmental Data and Information Service's National Climatic Center (NCC);
3. Oceanographic data from Lamont-Doherty Geological Observatory of Columbia University;
4. Oceanographic data from NMFS laboratories at Sandy Hook, N.J., and Woods Hole, Mass.;
5. Oceanographic data from Virginia Institute of Marine Science (VIMS); and

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6. Monthly mean sea-surface temperature at tide stations at Atlantic City, N.J., from NOAA's National Ocean Survey.

Since environmental conditions in New York Bight were extensively documented by XWCC cruises in 1975 and 1976, the primary comparisons were between these 2 years—1976, a year of anoxic conditions, and 1975, a year without anoxic conditions. Four XWCC stations—23, 38, 69, and 88 (station locations shown in fig. 2–1 of chapter 2)—were chosen for comparison, because they were considered representative of the Bight Apex, Hudson Shelf Valley, Long Island shelf, and New Jersey shelf regions, respectively.

## DENSITY (sigma-*t*)

Physical properties in all four areas could be compared in 1975 and 1976, the only 2 years during which all XWCC stations were occupied. Station 23 was occupied several times during 1974, providing a long record. Depth vs. time plots of temperature, salinity, and density or sigma-*t* ($\sigma_t$) were drawn for 1975 and 1976 for each station. Similar plots were drawn for 1974 for station 23. Figure 5–1 shows the $\sigma_t$ plots for station 88.

From the plots, a gross indication of the strength of the density gradient was computed, using surface-to-bottom differences of interpolated (midpoint of month) $\sigma_t$ divided by depth. Ratios of these monthly values were obtained for comparisons between years. Averages within years and stations were then computed from the monthly $\sigma_t$ gradients (table 5–1). Monthly $\sigma_t$ gradients less than 0.01 were excluded to eliminate the influence of nonstratified conditions on the mean.

The mean of the 1976/1975 ratios was about the same for all stations, varying between 1.3 and 1.6, indicating that the $\sigma_t$ gradient was uniformly stronger during 1976. In contrast, at station 23 the mean ratio between 1976 and 1974 was 1.0, indicating the strength of the pycnocline was comparable in those years. A month-by-month comparison of 1976/1975 ratios indicates $\sigma_t$ gradients were similar at all stations during July, August, and September, but were significantly greater in 1976 during April, May, and June, with the exception of June at station 88. During April 1975, isopycnic or nearly isopycnic conditions were observed. In April 1976, stratification was apparent at all stations and was most intense at station 23. Stratification was developed by May 1975, apparently about 2 to 4 weeks later than during 1976. Maximum stratification was reached sometime during the summer, varying in time from area to area. Maximum occurred during June or July in 1976, but not until July or August in 1975. After reaching a maximum, the gradient gradually decreased through September.

TABLE 5–1.—*Sigma-t gradients ($\Delta\sigma_t/m$)*

| Station<br>Year | Mar. | Apr. | May | June | July | Aug. | Sept. | Mean |
|---|---|---|---|---|---|---|---|---|
| **Station 38** | | | | | | | | |
| 1975 | | 0.005 | 0.010 | 0.030 | 0.035 | 0.037 | 0.037 | 0.026 |
| 1976 | | 0.007 | 0.029 | 0.040 | 0.053 | 0.040 | 0.039 | 0.035 |
| Ratio | | | | | | | | |
| 75/76 | | 1.4* | 2.9 | 1.3 | 1.5 | 1.1 | 1.1 | 1.6 |
| **Station 23** | | | | | | | | |
| 1974 | | 0.059 | 0.075 | 0.072 | 0.132 | 0.092 | 0.074 | 0.084 |
| 1975 | | 0.003 | 0.020 | 0.078 | 0.110 | 0.112 | 0.076 | 0.067 |
| 1976 | | 0.046 | 0.059 | 0.092 | 0.100 | 0.088 | 0.069 | 0.076 |
| Ratios | | | | | | | | |
| 75/76 | | 15.3* | 3.0 | 1.2 | 0.9 | 0.8 | 0.9 | 1.4 |
| 76/74 | | 0.8* | 0.8 | 1.3 | 0.8 | 1.0 | 0.9 | 1.0 |
| 74/75 | | 19.7* | 3.8 | 0.9 | 1.2 | 0.8 | 1.0 | 1.5 |
| **Station 69** | | | | | | | | |
| 1975 | | 0.011 | 0.020 | 0.070 | 0.101 | 0.100 | 0.068 | 0.062 |
| 1976 | | 0.027 | 0.040 | 0.104 | 0.098 | 0.089 | 0.079 | 0.073 |
| Ratio | | | | | | | | |
| 76/75 | | 2.4* | 2.0 | 1.5 | 1.0 | 0.9 | 1.2 | 1.3 |
| **Station 88** | | | | | | | | |
| 1975 | 0.005 | 0.000 | 0.017 | 0.077 | 0.101 | 0.101 | 0.068 | 0.062 |
| 1976 | 0.026 | 0.015 | 0.050 | 0.071 | 0.107 | 0.119 | 0.066 | 0.071 |
| Ratio | | | | | | | | |
| 76/75 | 5.2* | —* | 2.9 | 0.9 | 1.1 | 1.2 | 1.0 | 1.4 |

*Value not used in the computation of the mean of the monthly ratios.

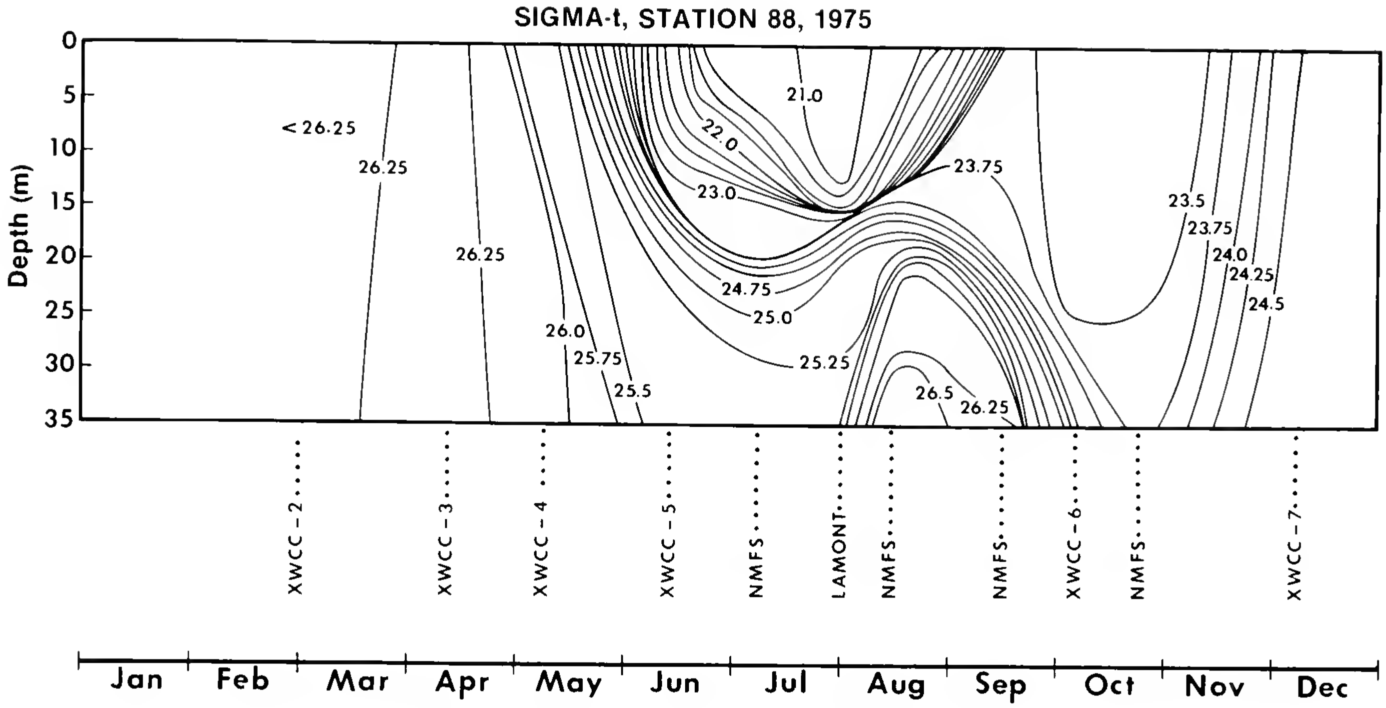

FIGURE 5–1A.—Sigma-*t* vs. time at station 88 in 1975.

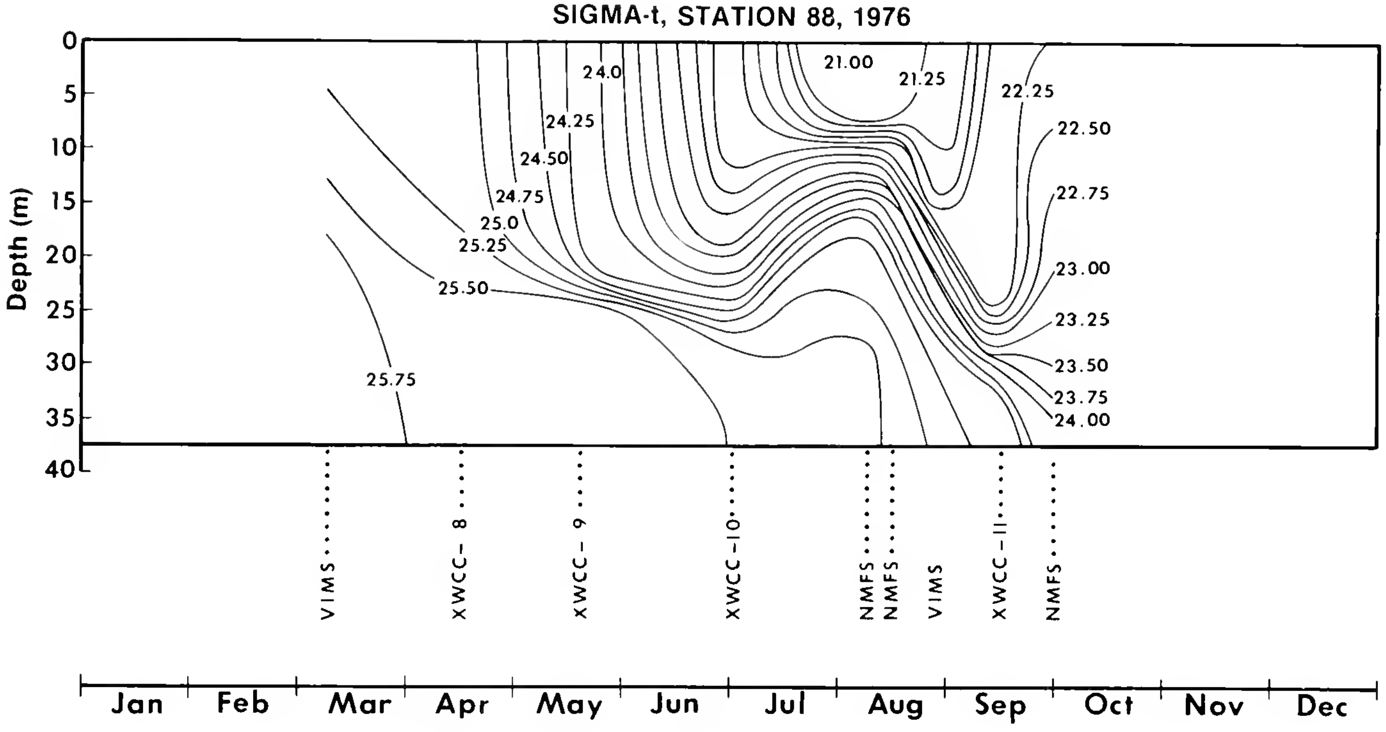

FIGURE 5–1B.—Sigma-*t* vs. time at station 88 in 1976.

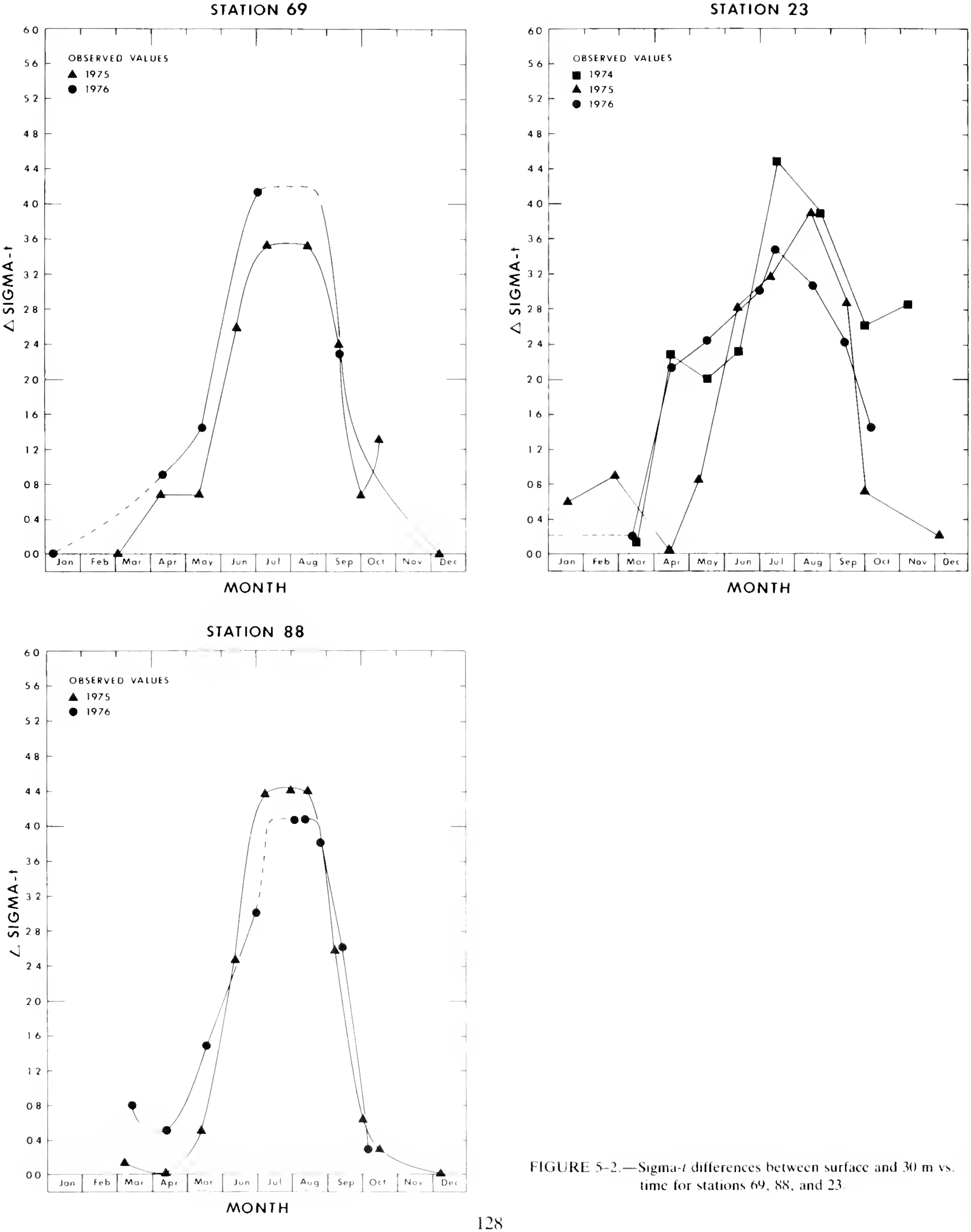

FIGURE 5-2.—Sigma-*t* differences between surface and 30 m vs. time for stations 69, 88, and 23.

Density differences at station 88 (fig. 5–2) were significantly greater during 1976 for March, April, and May, but were slightly less during the summer months. At station 23 the differences between April and May were similar in 1974 and 1976, but were considerably greater than for the corresponding time in 1975. At station 69 the stratification was more strongly developed in 1976 than 1975 until the autumnal breakdown.

## TEMPERATURE

During the first half of 1976, the monthly mean air temperature had a number of anomalous features. According to Diaz (ch. 3), January was somewhat colder than normal, whereas extreme warm air temperatures prevailed during February and March. During April the mean air temperature remained about 1° to 2° C above normal, but the monthly mean temperature masked a large change in April. Record cold weather prevailed during the first half of April, followed by record warmth in the second half. We can conclude that average air temperatures over New York Bight during the first 4 months of 1976 were only slightly above normal—record cold periods partially offset record warm periods.

Monthly mean sea-surface temperatures for the Bight Apex and Long Island area for 1975 and 1976 were compared with historical mean temperatures (fig. 5–3). The monthly mean sea-surface temperatures for February, March, and April 1976 exceeded the long-term mean and, qualitatively at least, correlate with the corresponding mean monthly air temperatures. Monthly sea-surface temperature anomalies (departure from 1949–76 mean) for 1974, 1975, and 1976 are compared in figure 5–4. They indicate that the mean monthly sea-surface temperatures for the January-April period were 1° to 2° C above normal for all 3 years. During the winters, temperatures decreased until February (fig. 5–3), when the mean monthly temperature was minimum. A spring warming trend was recorded for March. An above-normal sea-surface temperature continued through spring and summer during all 3 years. In May and June 1975 temperature increases exceeded the more normal conditions as reflected in May and June in 1976.

Temperature variations with depth were plotted as a time series for station 88 (fig. 5–5). Temperature data from moored current meters (stations LT2 and LT4) supplemented the temporal data from cruises. (See chapter 7, fig. 7–7.) During March 1975 and 1976 the water was nearly isothermal, varying between 5° and 6° C. The March warming trend did not result in significant thermal structure until mid-April in 1976 and in late April 1975. By mid-April 1976, the mean surface temperature was 1.7° C warmer and the mean bottom temperature 1.2° C warmer than during the corresponding period in 1975. During May and June this differential continued. The thermocline during the summer months remained strong and at a near-constant depth. Surface and bottom temperatures in July and August were about the same for the 2 years. By September of both years (fig. 5–5) the temperature had begun to decrease, with a corresponding gradual deepening of the thermocline. By the first of October 1976, the surface temperature was about 3° C higher and the bottom temperature was about 1° C higher than at the corresponding time in 1975.

From the moored-meter temperature data (fig. 5–5), the bottom temperature minimum for the 1975–76 winter varied between 4° and 5° C and was maintained from January 23 to February 21, 1976, at which time the temperature began to increase. From about February 26, bottom temperature data were recorded for both 1975 and 1976. From that date until April 10, the bottom temperature was about the same for both years. After April 10, 1976, warming increased at a much greater rate than during the corresponding period of 1975. The moored-meter temperature data indicated the record warmth lasted until April 26.

The temperature difference curves in figure 5–6 were constructed using interpolated values from figure 5–5 and a similar figure for station 69 (not shown). April and May had a slightly greater surface-to-bottom temperature differential in 1976 than in 1975. In summer 1975 and 1976 the temperature differential between surface and bottom waters was greater at station 69 than at station 88.

## SALINITY

Salinity stratification was very prominent at all stations during April 1976, in contrast to the same period in 1975 when stratification was slight. During March, stratification was considerably greater in 1976 than in 1975 at station 88 (fig. 5–7). At station 23, however (fig. 5–7), stratification was quite low during March 1974 and 1976. The greatest contrast between years was in April in the Bight Apex (station 23). There, salinity stratification was significantly greater during April-May 1974 and 1976 than during the same period in 1975. At station 88 stratification was considerably greater in 1976 during March, April, and May than in 1975. At station 69 during April 1976 stratification was greater than April 1975 (fig. 5–7). During March and May, stratification was about the same for the 2 years. During the summer, stratification appeared to be greater during 1975 at stations 23 and 88 than in 1976.

Armstrong (ch. 6) compared monthly discharge rates for the Delaware and Hudson rivers for 1976 with long-term means and extremes. The discharge rate usually reached a maximum in April when it was significantly

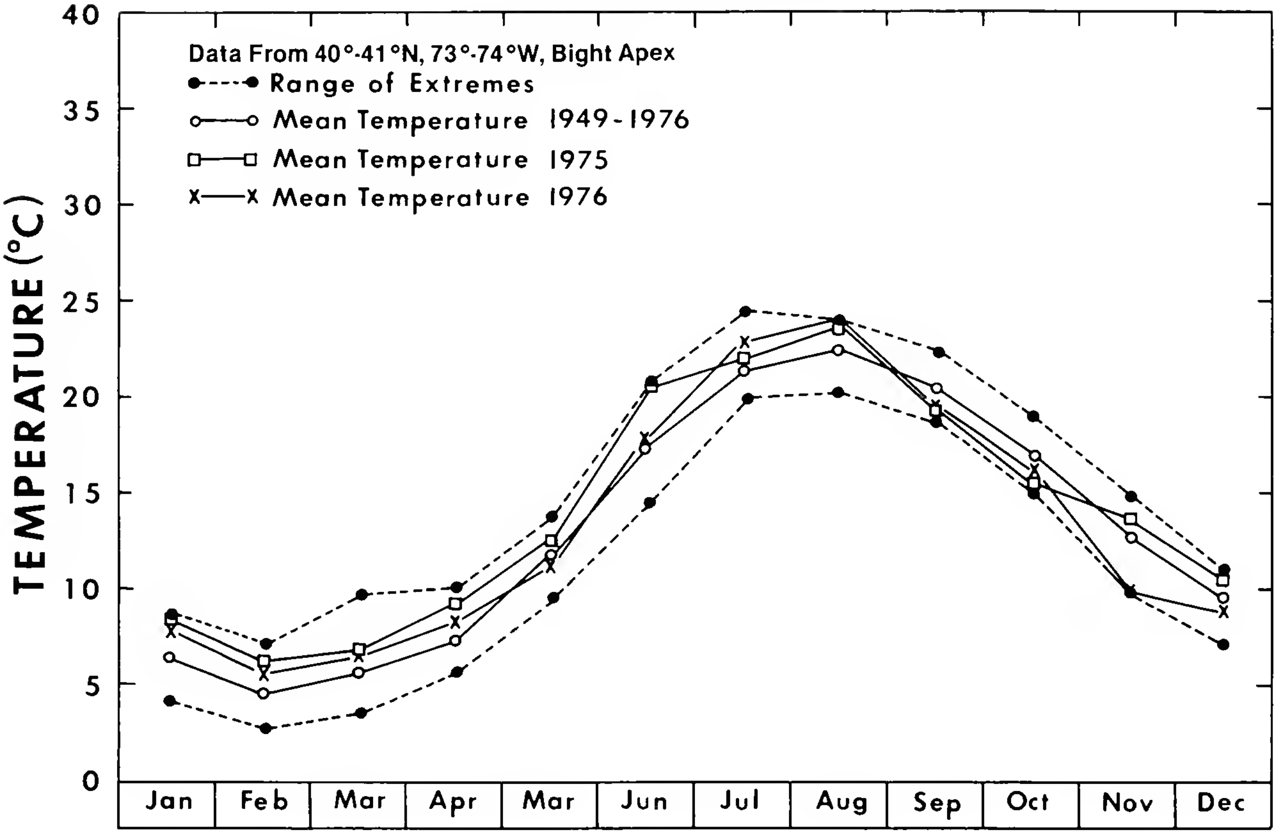

FIGURE 5–3.—Comparison of monthly mean sea-surface temperature for 1975 and 1976 with range of historical values.

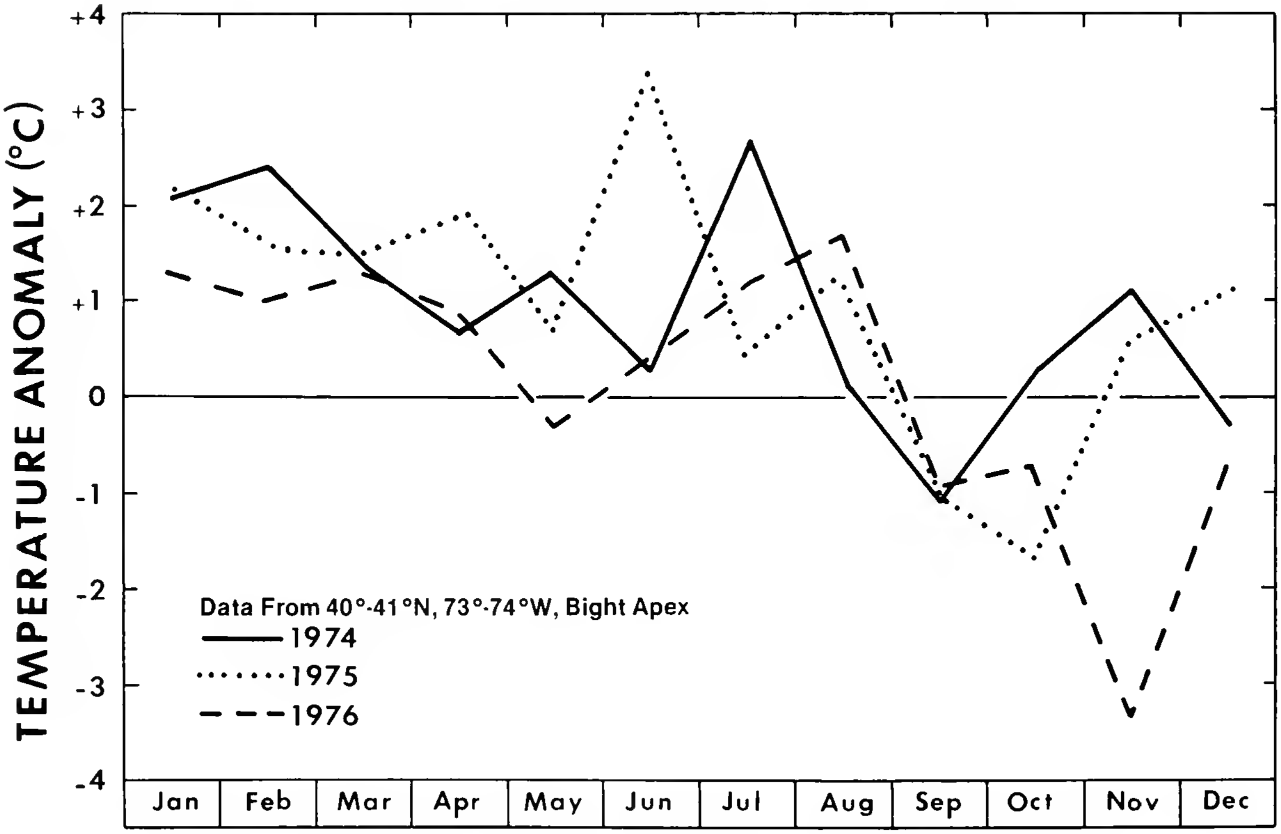

FIGURE 5–4.—Comparison of monthly sea-surface temperature anomalies for 1974, 1975, and 1976.

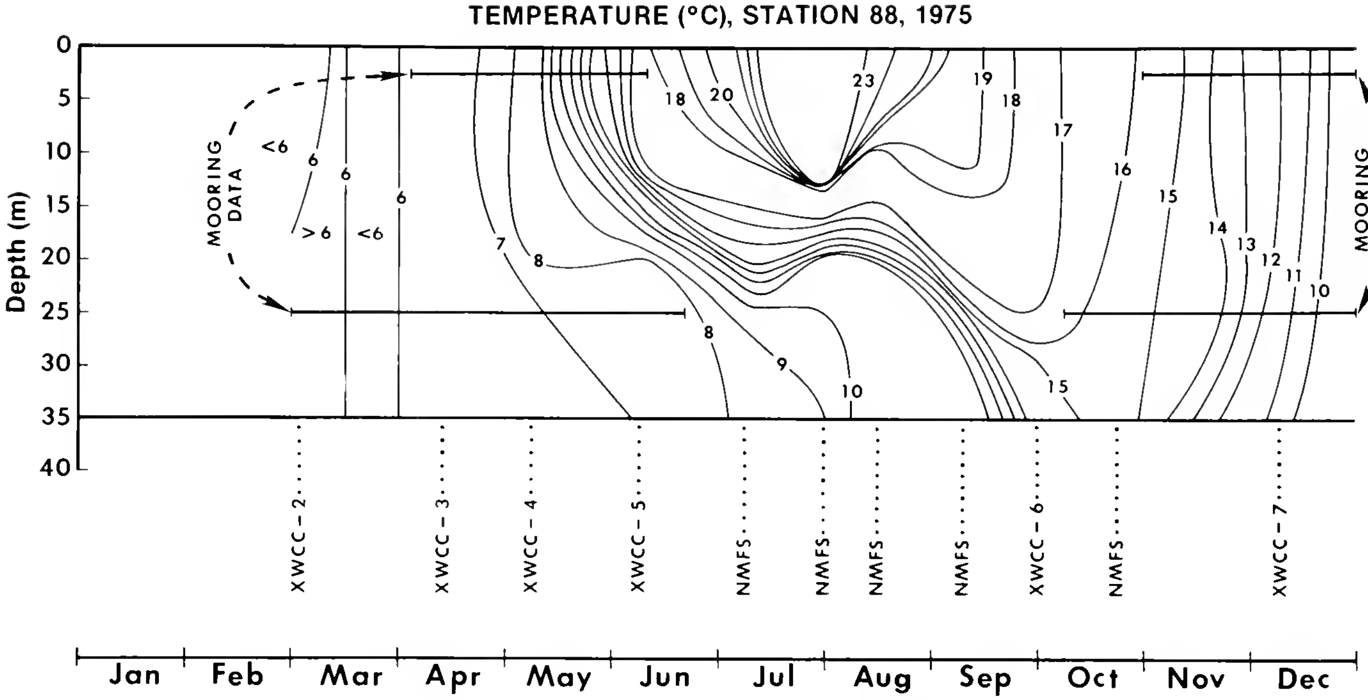

FIGURE 5-5A.—Temperature vs. time, station 88 in 1975.

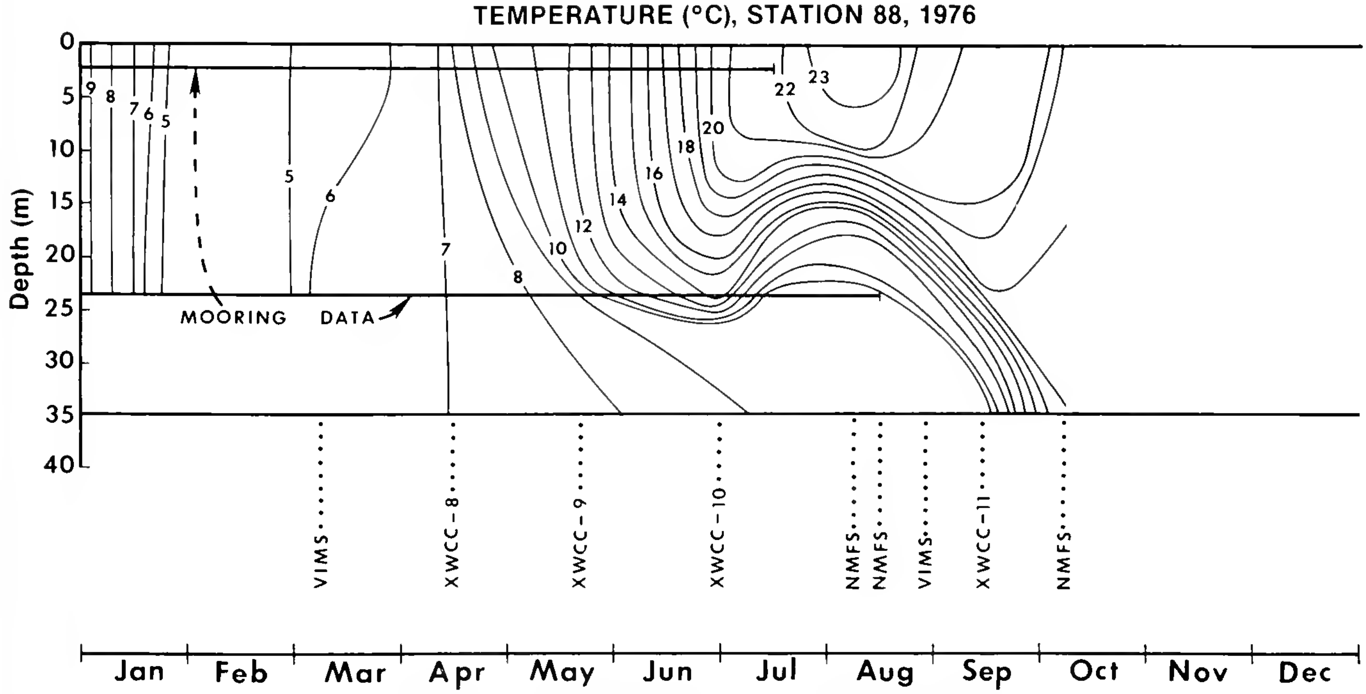

FIGURE 5-5B.—Temperature vs. time, station 88 in 1976.

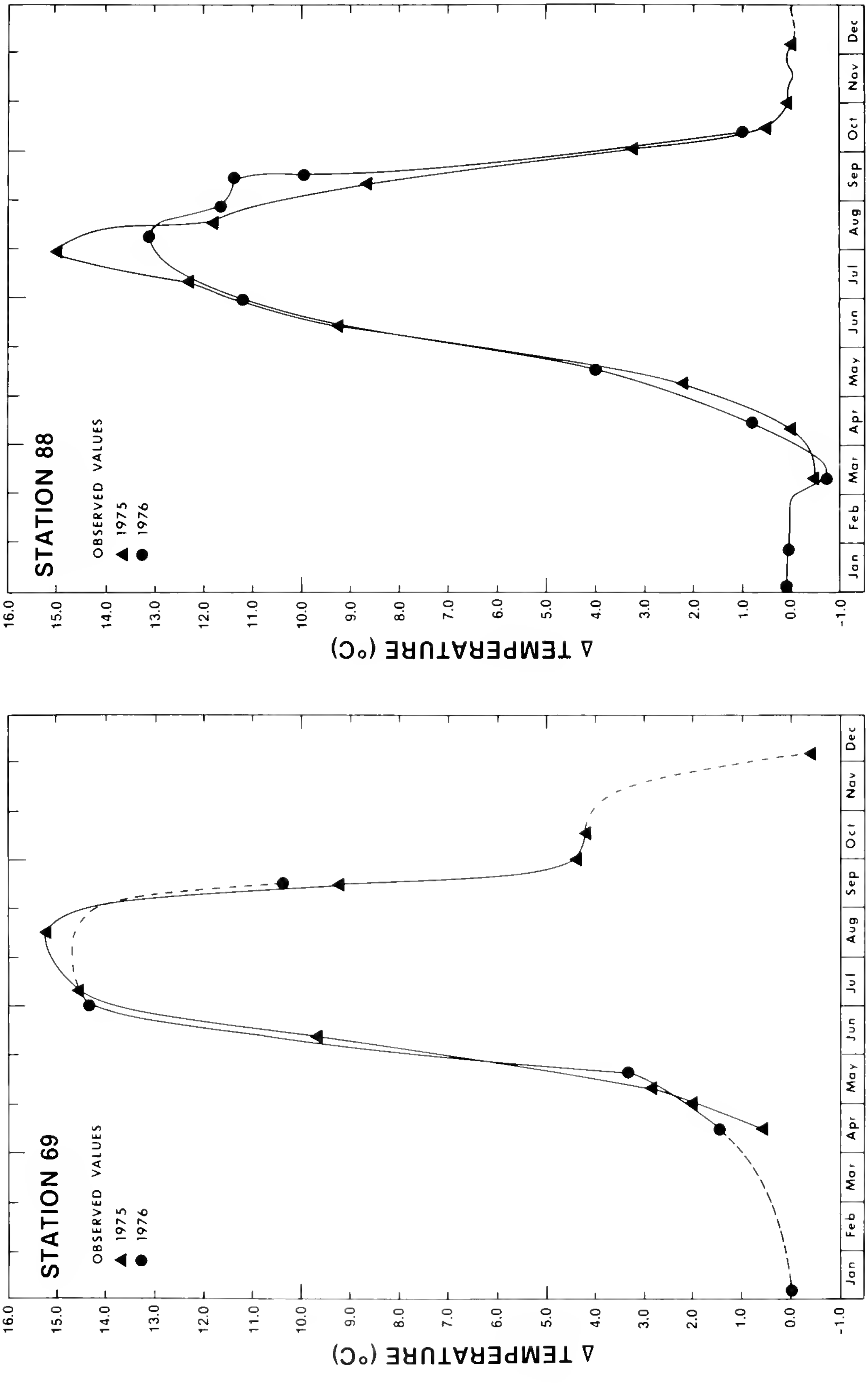

FIGURE 5-6.—Temperature differences between surface and bottom vs. time, stations 69 and 88.

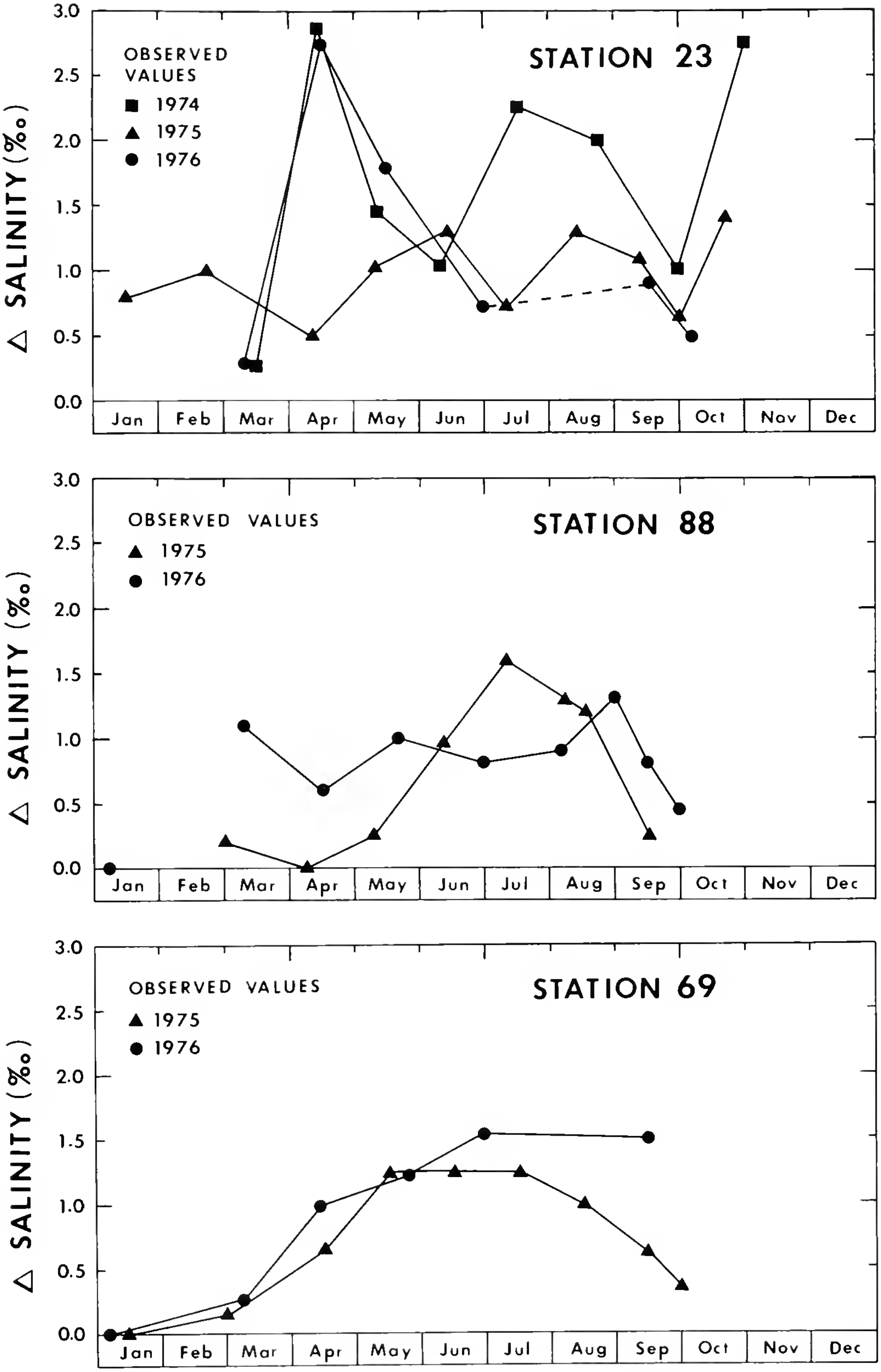

FIGURE 5-7.—Salinity difference between surface and bottom vs. time, stations 23, 88, and 69

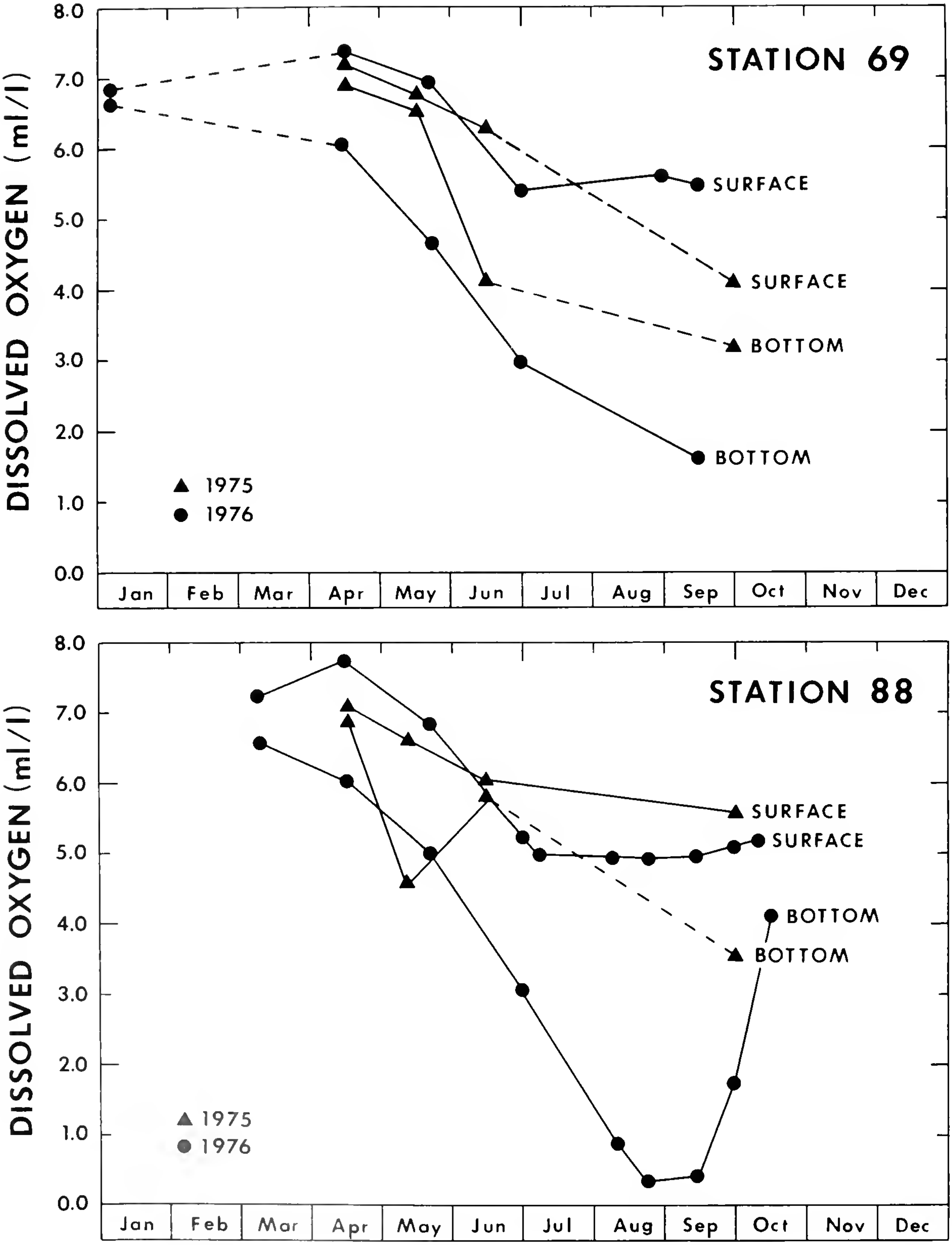

FIGURE 5–8.—Surface and bottom dissolved oxygen vs. time, stations 69 and 88.

greater than any other month. However, in 1976, an abnormally high discharge rate was recorded during February, and was largely sustained into May. Thus, near-surface waters, especially at station 23, should show unusually low salinity with correspondingly greater stratification. This is in part corroborated by the April high-density ratio (1976/1975) value of 15 at station 23 (table 1). The April and May 1976 salinity differences (fig. 5–7) are relatively higher than in 1975, implying that the discharge of the Hudson River was either greater or more confined to the Bight Apex during 1976.

## DISSOLVED OXYGEN

In April 1976 surface oxygen values were higher and bottom oxygen values lower than in April 1975 (fig. 5–8). Consequently, oxygen stratification was pronounced by April 1976, but a well-mixed condition existed in April 1975. Stratification development was not apparent until June or July 1975.

As summer progressed, surface oxygen decreased in both years, but generally continued over 100 percent saturation. The only exception was at station 88, where surface oxygen values fell slightly below 100 percent saturation during July, August, and September 1975.

As summer advanced in both years, bottom oxygen values decreased at rapid rates, but the 1976 rate was considerably greater. (See chapter 4.)

## SUMMARY

Seasonal density stratification began about 1 month earlier in 1976 than in 1975 (April vs. May), because of early seasonal heating (thermal stratification) and, more importantly, strong and sustained river discharge (salinity stratification). Subsequently, the rate of bottom replenishment of dissolved oxygen from the sea surface was less than that of 1975.

## ACKNOWLEDGMENTS

Adriana Cantillo and Dennis Mayer of ERL/AOML and Steacy Hicks of NOS provided necessary data. The following individuals contributed data sets used in the analysis: Tom Azarovitz of NMFS, Woods Hole; Art Kendall, Frank Steimle, and W. G. Smith of NMFS, Sandy Hook; Frank Aikman of Lamont-Doherty Geological Observatory; and E. P. Ruzecki of Virginia Institute of Marine Science. D. V. Hansen made helpful suggestions. The officers and crew of NOAA ships *George B. Kelez* and *Researcher* devoted long and diligent hours in acquiring data.

# Chapter 6. Bottom Oxygen and Stratification in 1976 and Previous Years

*Reed S. Armstrong*[1]

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## INTRODUCTION

The areal extent of the 1976 anoxic condition implies that broad-scale, climatic events may have contributed to the depletion of dissolved oxygen (D.O.). Although the area of depleted oxygen extended widely over the continental shelf off New Jersey, it apparently did not develop to the north, off Long Island, nor to the south, off the Delmarva Peninsula. Therefore, if unusual climatic conditions did contribute to the anoxia and resulting benthic mortalities, then other distinct differences among these three regions of the Middle Atlantic Bight should be apparent.

To examine the impact that climatic events in the marine environment may have had on the generation of anoxic conditions, historical and climatological data were compiled for comparison with conditions observed in 1976. Included were monthly mean air and sea-surface temperature records and oceanographic data from the National Climatic Center (NCC), National Oceanographic Data Center (NODC), National Ocean Survey (NOS), and National Weather Service (NWS) of the National Oceanic and Atmospheric Administration (NOAA), and river discharge records from the U.S. Geological Survey. Data from oceanographic stations occupied in the area in 1976 were provided by NOAA National Marine Fisheries Service's (NMFS) Sandy Hook Laboratory, and NOAA Environmental Research Laboratories' Atlantic Oceanographic and Meteorological Laboratories (AOML).

## CLIMATOLOGICAL CONDITIONS

Springtime conditions in 1976 began developing 1 to 2 months earlier than normal (ch. 3). Monthly mean air

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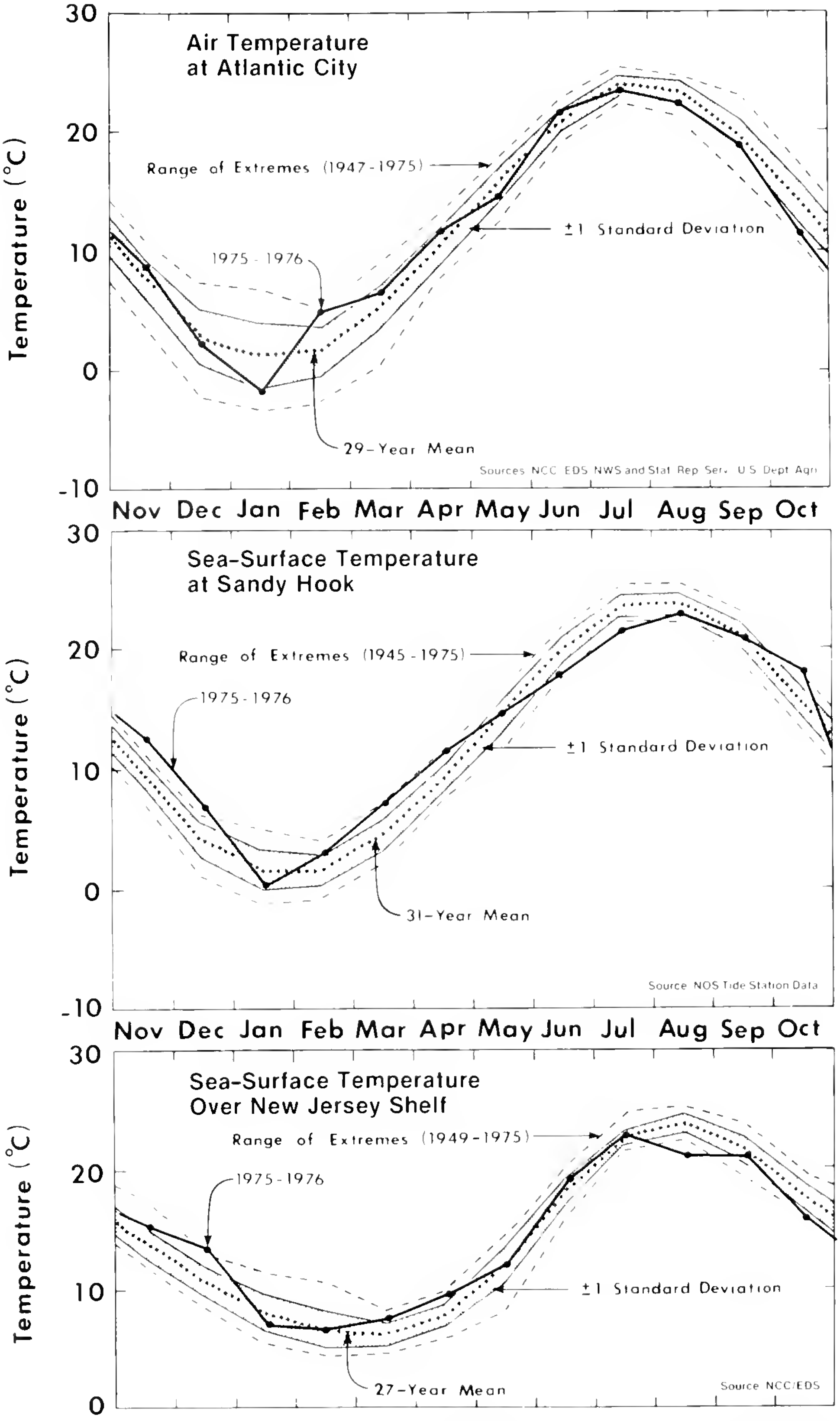


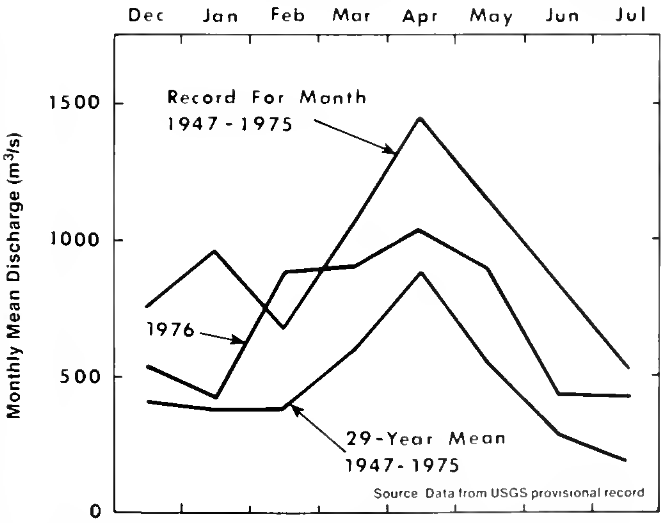
FIGURE 6-1.—Monthly mean air and sea-surface temperatures for New Jersey shelf, 1975-76 and historical record.

temperature records at Atlantic City showed that in 1976 one of the coldest Januarys was followed by one of the warmest Februarys of the 30-year record. Sea-surface temperatures also followed this general trend (fig. 6–1). Although air and sea-surface temperatures in the spring were unusually warm, they were not unique.

Perhaps more significant for hydrographic conditions than early warming was that the normal spring increase in river discharge in 1976 began about 2 months early. Monthly mean discharge for February 1976 in the Hudson River was greater than for any February of the preceding 29 years (fig. 6–2). The discharge rate in February was comparable to the normal peak discharge that typically occurs in April.

A comparison of historical data and monthly mean discharge rates in 1976 indicated a record high discharge in February into Long Island Sound (48 years of record: 1929–76) and the second highest of record for the Delaware River (36 years of record: 1941–76). On the Delaware River, the monthly mean discharge in February 1976 (760 $m^3/s$) was greater than the long-term monthly mean for the peak discharge month (616 $m^3/s$ in April). The February 1976 discharge rate into Long Island Sound (1,651 $m^3/s$) was almost as large as the average value for peak-month discharge (1,866 $m^3/s$ in April). In their description of the seasonal cycle of hydrographic conditions in the New York Bight Apex, Bowman and Wunderlich (1976) noted the close connection between the time of decrease in surface salinities and the usual March-April increase in discharge from the Hudson River. Therefore, an early river discharge of magnitude comparable to the normal spring peak value would have led to a 2-month earlier than normal freshening of surface waters over at least the Bight Apex.

The results of these unusual climatic events during the first months of 1976 would probably have caused 1) destruction of any remaining stratification in the shelf waters during the strong cooling in January, and 2) a 1- to 2-month earlier than normal reestablishment of stratification, resulting from the early decrease of surface salinities due to the early occurrence of spring discharge. Chapters 2 and 5 indicate that early warming had minimal effect on density structure. In principal, early warming should have worked in unison with river discharge and minimal storm activity to promote early stratification, since the salinity layering would not have been destroyed by overturning from the continued decline in surface water temperatures that is typical for that time of year. Indications of the early onset of thermal stratification in 1976 are described and compared with historical data in chapter 5.



Source Data from USGS provisional record

FIGURE 6–2.—Monthly mean discharge of Hudson River at Green Island, N.Y., in 1976 and long-term means and extremes.

## OXYGEN CYCLE AND STRATIFICATION

The annual cycle of D.O. in bottom waters over the continental shelf off New Jersey is shown in figure 6–3. For this analysis the D.O. measurement at the greatest sampling depth in excess of 20 m for each station with bottom depths greater than 20 m and less than 60 m was used; values were compiled by cruises. These depth criteria were used to limit the analysis to shelf waters below the pycnocline during spring and summer, or comparable depths in months when the waters are unstratified. For each cruise, the bottom-water oxygen observations were averaged and plotted in figure 6–3, along with the range of values on the average date of station occupation, regardless of year. Data were used from 28 cruises (82 stations) between 1932 and 1973. Observations were available in all months. Hand-smoothed curves were drawn through the values to derive a mean annual trend. Representative maximum and minimum curves were drawn to depict the normal range of conditions.

Stratification data were developed from temperature and salinity observations for the same stations used in the analysis of D.O. For each station, surface $\sigma_t$ values were subtracted from $\sigma_t$ values at the deepest observation level (corresponding to the subpycnocline or bottom water D.O. measurement). These differences were compiled into cruise averages and ranges and plotted in figure 6–3 along with the normal annual trend and ranges derived from the distribution of the data.

For comparison with the "normal" annual cycles of bottom oxygen concentrations and stratification, observations collected in December 1975 and during 1976 were compiled similarly to the historical data (fig. 6–3). Chapters 2 and 5 describe these data more fully. The stratification data acquired by the NMFS Sandy Hook Laboratory in March 1976 had no oxygen observations. Those observations made in August after the passage of hurricane

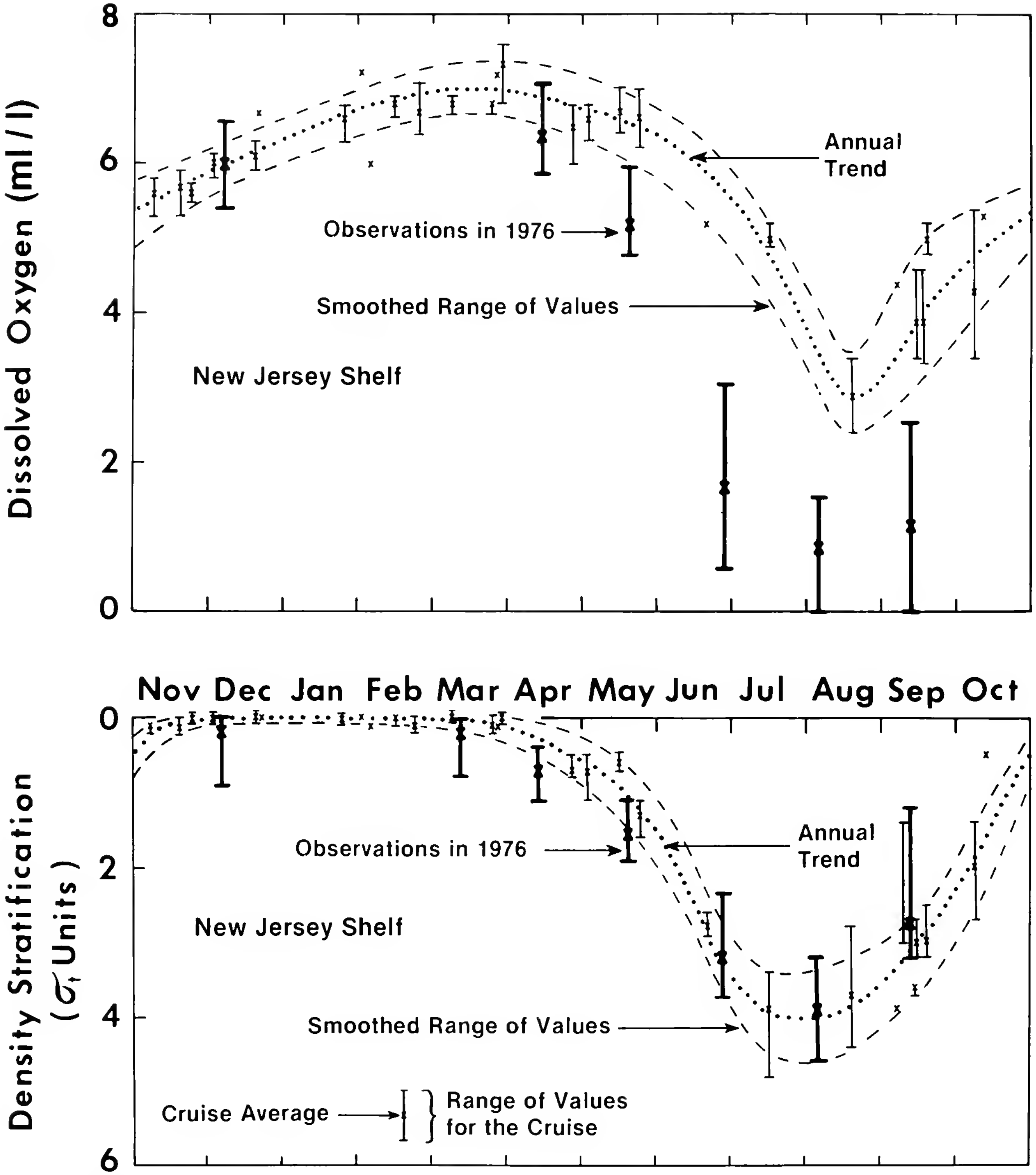


FIGURE 6–3.—Dissolved oxygen levels in bottom waters (>20 m) and vertical density stratification (surface-subpycnocline $\sigma_t$ difference) of New Jersey-Cape May shelf waters, 1976 and historical record. Historical data from EDIS/NODC and WHOI (1961 publ.); 1975-76 cruise data from NMFS/SHL and ERL/AOML.

Belle were excluded because of uncertainties about the storm's effects on the normal cycle of D.O.

Parallel patterns in the normal annual cycles of stratification and D.O. in the bottom waters off New Jersey (fig. 6–3) imply a direct relation between the two. During autumn, surface cooling in shelf waters causes overturning and vertical mixing. This diminishes the stratification and replenishes oxygen in the bottom waters. By December and continuing through March, shelf waters are essentially unstratified and bottom waters are saturated with D.O. Further increases in bottom D.O. during winter result from increased oxygen solubility of the water brought about by decreasing water temperature. Bottom D.O. increases to the annual average maximum of about 7.0 ml/l in March.

Initiation of stratification normally begins during April when surface water density declines, because of warming (fig. 6–1), and river discharge increases (fig. 6–2). With the onset of stratification, vertical replenishment of oxygen into the bottom water becomes limited. Within the normal ranges and cycles of water circulation and biological activity, utilization exceeds replenishment, resulting in a decrease in oxygen concentration. Based on the historical data of figure 6–3, the annual minimum D.O. value occurs in August, averaging about 2.9 ml/l. In September, when surface cooling begins to destroy stratification, replenishment exceeds utilization and oxygen concentrations increase.

To depict the correspondence between increase in strength of stratification and D.O. decline, monthly values of both were derived from the annual trend curves of historical data in figure 6–3. For each 1-month period from mid-March through mid-August (spanning the interval of developing stratification and of declining D.O.), monthly means of the strength of stratification were computed. Against these were plotted the amount that D.O. declined during the corresponding 1-month periods; the data points were connected by a hand-smoothed curve to give monthly rates of oxygen decline as a function of stratification (fig. 6–4). To provide some estimate of the range of conditions around the average trend curves, similar monthly computations were made from the smoothed ranges of values in figure 6–3, assuming that the high D.O. values correspond to weakest stratification and low oxygen to strongest stratification in a given month. Again, smooth curves were drawn through the data points.

As stratification increases the rate of oxygen decline increases (fig. 6–4) as would be expected, since enhanced stratification acts to further isolate bottom waters from replenishment. Basically, the relationships in figure 6–4 represent the imbalance in replenishment and use of D.O. which, on the replenishment side, is strongly affected by stratification. The reason for the change in slope of these curves at greater stratification values (at about 3.5 $\sigma_t$ units for the average curve) is unclear, but probably is associated with seasonal changes in the structure of the pyc-

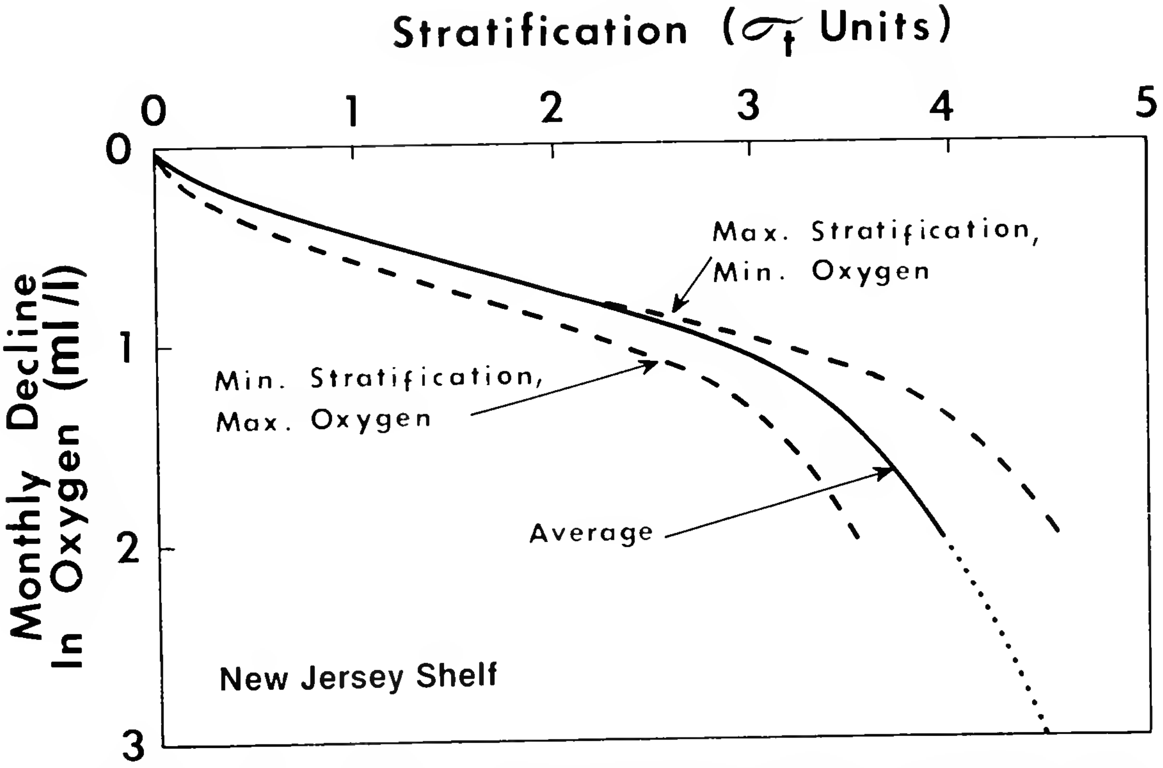


FIGURE 6–4.—Relation between strength of stratification and decline in dissolved oxygen in bottom waters (>20 m) of New Jersey-Cape May shelf.

nocline, in circulation that could affect horizontal advection of oxygen, or in the use of oxygen brought about by variations in biological oxygen demand. (See chapter 9, part 1.)

## STRATIFICATION AND DISSOLVED OXYGEN IN 1976

A comparison of D.O. observations made off New Jersey during cruises in December 1975 through September 1976 and historical data (fig. 6–3) shows that bottom oxygen concentrations were typical in December. However, D.O. concentrations in near-bottom waters were below normal by April, and progressively declined until late in the summer. The sharp drop in air and surface water temperatures in December-January probably destroyed the slight stratification that was present in December 1975 (fig. 6–3). In March, April, and May, the early increase in river discharge, and reduced storm activity, probably led to greater than normal stratification. Stratification was typical in June and into August, before the passage of hurricane Belle. Stations occupied by the NMFS Sandy Hook Laboratory immediately after the hurricane indicated a distinct decrease in stratification, particularly at shallower stations, but with less impact in deeper water, as discussed in chapter 2. In September 1976, stratification had weakened and values were typical for that time of year, except at one station with particularly weak stratification.

Using the values of stratification observed in 1976 (fig. 6–3), the curves of figure 6–4 can be used to model the cycle of bottom D.O. decline that could have been expected from the strength of stratification alone during that year. For the modeling, the intense cooling of surface waters in January 1976 was assumed to have destroyed the stratification remaining from December, leaving the waters unstratified by mid-January. Beginning with no stratification in mid-January, the cruise-averaged values of stratification strength observed in 1976 were connected to define the average cycle during the season of stratification. Similar cycles were drawn connecting each of the minimum and maximum points, all beginning with the value of zero in mid-January. From these three cycles, monthly mean values were derived for each monthly interval from mid-January to mid-August. Monthly rates of decrease in D.O. were determined from the appropriate curves of figure 6–4.

D.O. concentrations in the bottom waters off New Jersey were assumed to increase from December 1975 conditions (ranging from 5.4 to 6.6 ml/l, 6.0 average) at the normal rate for that time of year until mid-January. As-

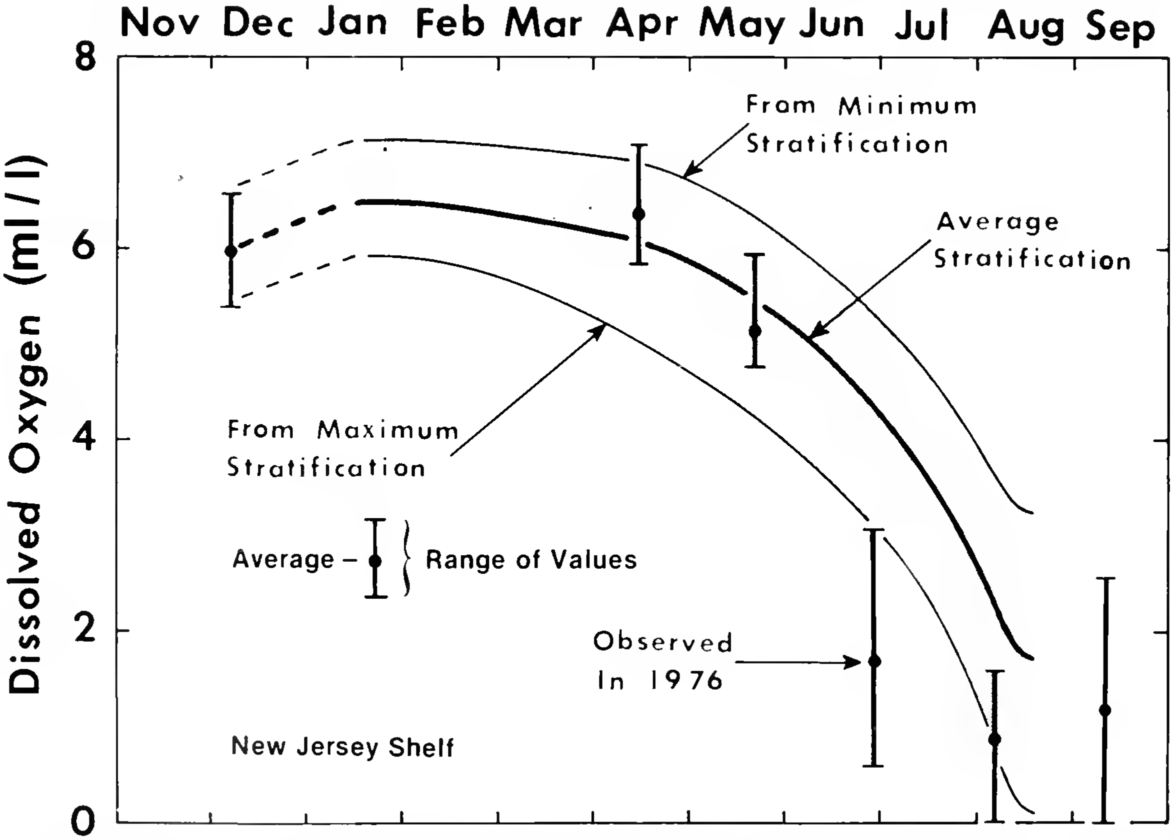


FIGURE 6–5.—Dissolved oxygen content of bottom waters (>20 m) of New Jersey-Cape May shelf as predicted from stratification model and as observed in 1976.

suming that stratification began 2 months earlier than normal in 1976 (February rather than April), the annual maximum oxygen concentrations would have occurred in mid-January (ranging from 5.9 to 7.1 ml/l and averaging 6.5 ml/l). If these January values of oxygen were then allowed to decrease at rates obtained from the relationship established in figure 6–4 (average curve), then the cycle of D.O. for 1976 can be estimated from stratification, along with the range of predicted conditions (fig. 6–5). Based on this model, minimum average concentrations in August would have been 1.75 ml/l, ranging from 0.15 to 3.30 ml/l, which is well below the normal annual minimum (2.9 ml/l).

For comparison with the 1976 D.O. cycle as predicted from stratification, the cruise averages and ranges of D.O. concentrations are also shown in figure 6–5. It can be seen that stratification may account for the April and May D.O. concentrations, but, by the end of June and continuing through summer, actual conditions were much more severe than could have been anticipated from strength of stratification alone. Particularly during June, other factors must have affected the utilization-replenishment balance—for example, the flow reversals in the bottom waters (ch. 7) and the increase in biological oxygen demand that resulted from the congregation, respiration, and decomposition of *Ceratium* in the subpycnocline waters. (See chapter 9, part 2.)

## REGIONAL ASPECTS

Anoxic conditions and the resulting mortalities in 1976 were apparently limited to the shelf waters off the New Jersey—Cape May area and did not develop in waters of adjacent shelf regions to the northeast or south. To construct hypotheses for the cause of the geographic extent of anoxic conditions, data archived at NODC and observations by the Woods Hole Oceanographic Institution (1961) were examined for annual cycles of water-column stratification and bottom-water D.O. concentrations in adjacent shelf areas. Using the methods employed in developing figure 6–3 for the New Jersey—Cape May shelf waters, historical values were compiled into cruise averages and ranges for the Long Island shelf region (areas L1 and L2 in fig. 1–9 of chapter 1). The values were plotted on the average date of station occupations, regardless of year, and annual trend curves and smoothed ranges of values were drawn (fig. 6–6). The compilation involved 40 cruises (123 stations) made in 1932–75, with observations available in all months.

Off Long Island, bottom D.O. concentrations normally are maximum in March (averaging about 7.0 ml/l), decrease in spring and summer to the annual average minimum in August of about 3.9 ml/l, and begin to increase in September. The annual cycle of D.O. parallels the cycle of density stratification. Although the annual cycles of bottom D.O. concentrations in the two areas were quite similar, oxygen decline off Long Island proceeded slightly more rapidly in April and May than off New Jersey, but less rapidly during summer, resulting in an average annual minimum about 1.0 ml/l greater than off New Jersey.

AOML cruises in December 1975 and in April, May, June, and September 1976 surveyed the waters off Long Island. A NMFS Sandy Hook Laboratory cruise in March 1976 provided data for computing stratification, but D.O. measurements were not made. AOML data, processed with the same depth limitations as used with the historical data, are shown for comparison as cruise averages and ranges (fig. 6–6). As off New Jersey, oxygen values were near normal in December, somewhat below normal in April, and distinctly below historical conditions in May, June, and September. Values in May through September were not as low as off New Jersey, but were almost as anomalous. Averages for the stations occupied in each area indicated that, at the end of June 1976, bottom D.O. concentrations were 2.6 ml/l below the normal annual trend curve off Long Island and 3.8 ml/l below normal off New Jersey for that time of year.

Comparison of historical data and stratification values from the cruise data of 1975–76 shows the same general pattern off Long Island (fig. 6–6) as off New Jersey. Indications of early stratification are apparent, with a return to normal for May through September.

From the historical annual trend and range curves of figure 6–6, monthly rates of decrease in bottom D.O. concentration and monthly mean stratification values were determined. Following the same methods used for figure 6–4 for the New Jersey waters, figure 6–7 was developed to show the correspondence between stratification and rate of oxygen decline for bottom waters on the continental shelf off Long Island. Figures 6–4 and 6–7 show the same tendencies. For stratification values greater than about one $\sigma_t$ unit, however, the rates of oxygen decline per month (for comparable strength of stratification) are about one-third greater for New Jersey waters than for Long Island waters.

Using the stratification data from observations made in the cruises of December 1975 through September 1976, monthly mean averages and ranges were computed, assuming that 1) all stratification was destroyed by the strong cooling of January, and 2) stratification became established over most of the area in February 1976. From these monthly means of stratification, rates of decrease in bottom D.O. were determined from the appropriate curves in figure 6–7. In developing an estimate of the oxygen cycle as a function of stratification for 1976, it was assumed that the observed values in December 1975 increased at the normal (historical) rate until mid-January, yielding at that time an average concentration of 6.4 ml/l (range 5.9 to 6.8 ml/l). To develop the curves in figure 6–8, a counterpart to figure 6–5, these values were then allowed to

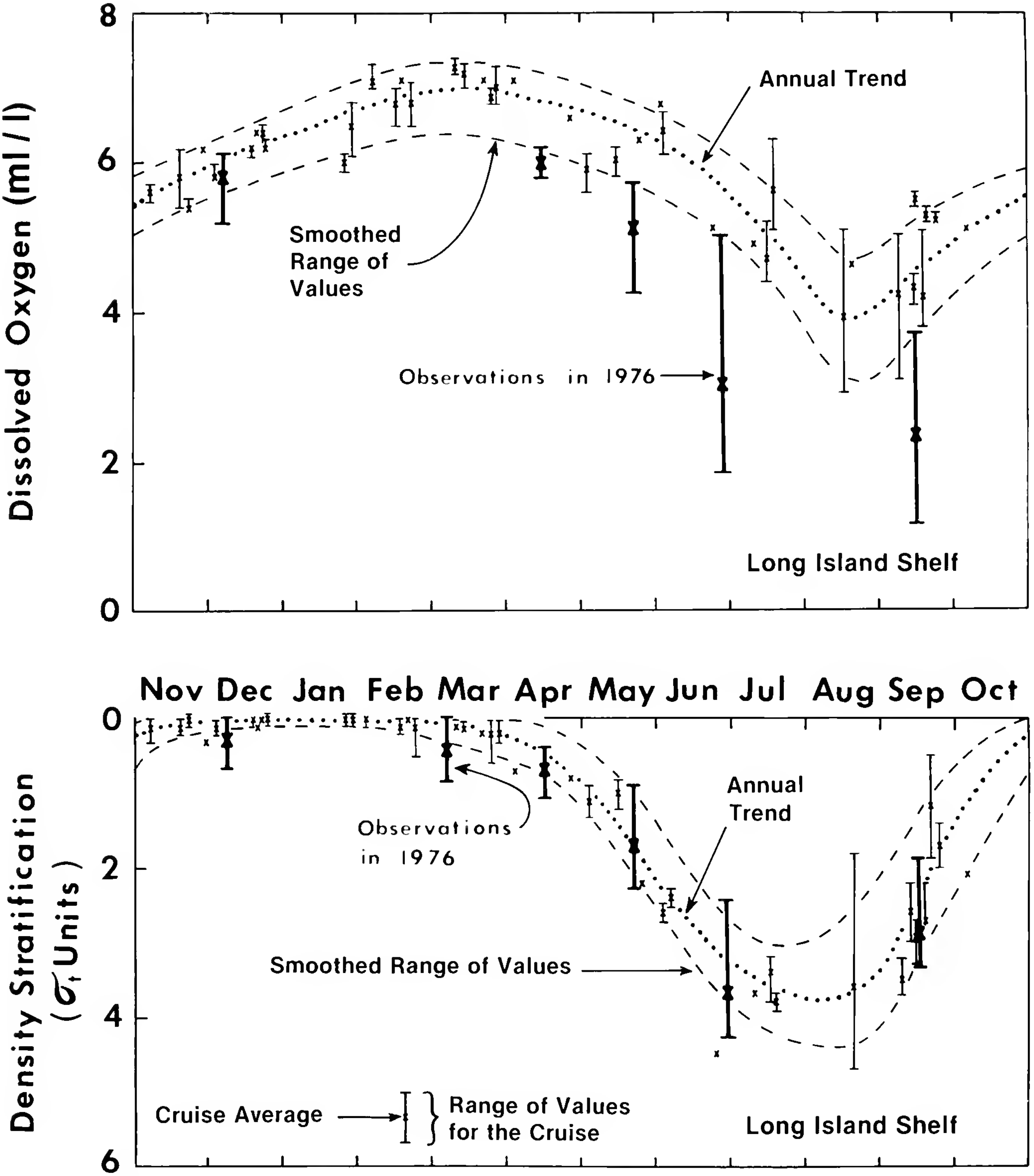


FIGURE 6–6.—Dissolved oxygen levels in bottom waters (>20 m) and vertical density stratification surface-subpycnocline $\sigma_t$ difference) of Long Island shelf waters, 1976 and historical record. Historical data from EDIS/NODC and WHOI (1961 publ.); 1975–76 cruise data from NMFS/SHL and ERL/AOML.

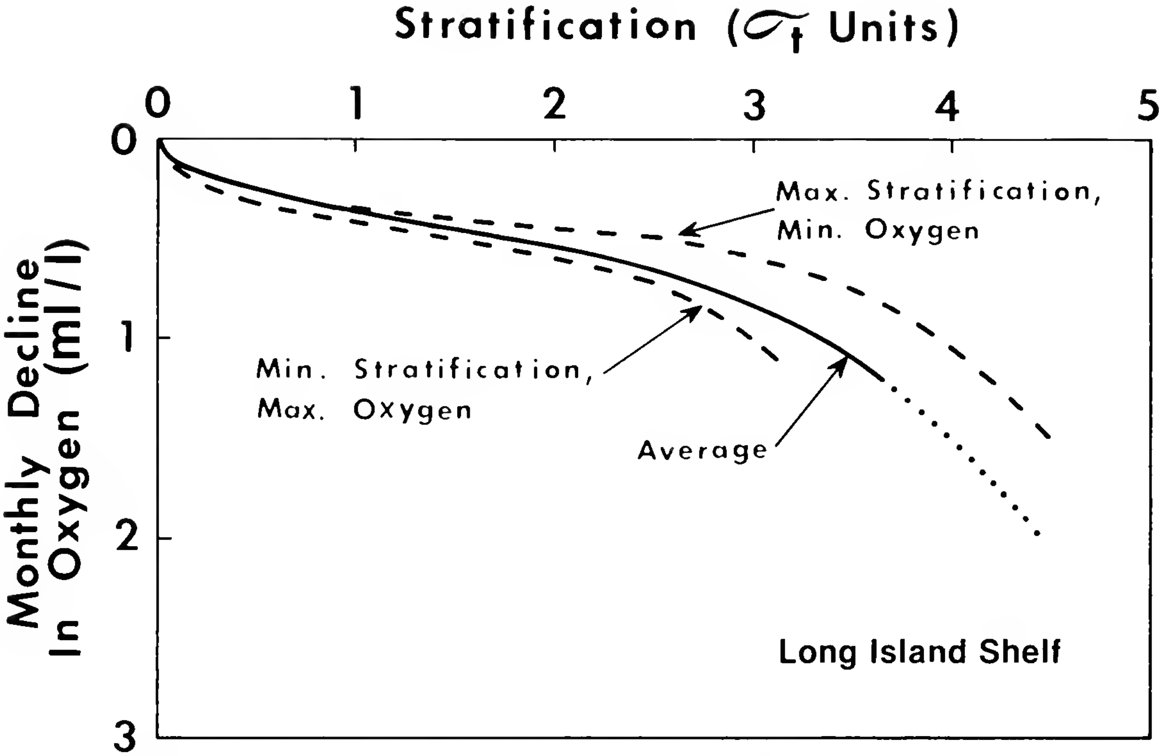


FIGURE 6-7.—Relation between strength of stratification and decline in dissolved oxygen in bottom waters (>20 m) of Long Island shelf.

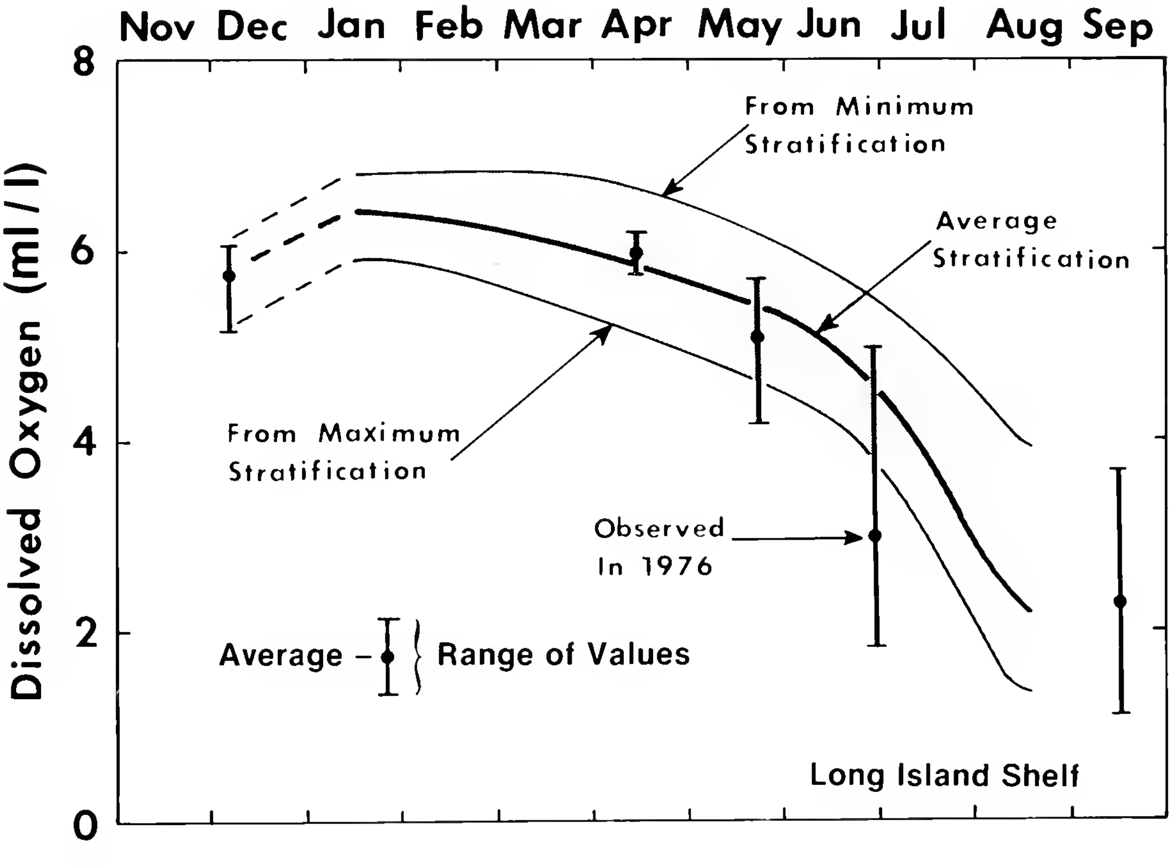


FIGURE 6-8.—Dissolved oxygen content of bottom waters (>20 m) of Long Island shelf as predicted from stratification model and as observed in 1976.

decrease until mid-August at the rates defined by the observed strength of stratification. Also shown in figure 6–8 are the cruise averages and ranges of values observed during 1976. The estimated average minimum, in August, was 2.30 ml/l (range 1.40 to 3.95 ml/l).

The comparison in figure 6–8 of predicted bottom D.O. concentrations for the waters off Long Island with conditions observed in 1976 indicates that the stratification-dependent oxygen model accounts fairly well for the observed conditions in April and May. By the end of June, bottom D.O. concentrations were below the model values, but not as much as in the waters of the New Jersey—Cape May area (fig. 6–5). As with the waters off New Jersey, one or more additional circumstances must have developed in the Long Island waters, particularly in June, to affect the replenishment-utilization ratio in such a way that the oxygen decline was more rapid. But the impact on the D.O. concentrations was not as intense for waters off Long Island as off New Jersey.

South of New Jersey, over the continental shelf of the Delmarva Peninsula, no anoxia was reported in 1976. Presumably the early warming and early occurrence of spring river discharge would also have influenced these waters. Historical observations in the NODC archives for that area were too sparse to demonstrate an annual cycle of bottom oxygen, and data were not available for describing developing conditions during 1976. Presumably, bottom D.O. concentrations off the Delmarva Peninsula normally follow an annual cycle similar to those off New Jersey and Long Island, but do not normally decrease to concentrations as low as off New Jersey.

Possibly the differences in the annual cycle of bottom D.O. concentration between the New Jersey—Cape May areas and Long Island, and presumably the Delmarva Peninsula, are the result of bathymetric differences. Stearns (1969) noted that on the New Jersey side of the Hudson Shelf Valley, gravel deposits have caused the continental shelf waters off northern New Jersey to be about 5 fm (9 m) shoaler than on the Long Island side of the valley. He pointed out that the effect of the gravel deposits is apparent in bathymetric charts: the 20- to 30-fm (37 to 55 m) isobaths are farther off New Jersey than off Long Island.

To depict bathymetric differences of the continental shelf off Long Island, New Jersey, and the Delmarva Peninsula, average depth profiles were made for the three regions (fig. 6–9). The profiles were constructed from the bottom topography maps of Uchupi (1968) by computing the average distance offshore to selected isobaths contoured on the maps (20, 40, 60, 80, 100, 140, and 200 m). In general, the continental shelf off New Jersey is shoaler than the shelf off Long Island and wider than the shelf off the Delmarva Peninsula. Figure 6–9 shows that the depth of the shelf is about 20 m less off New Jersey than off Long Island.

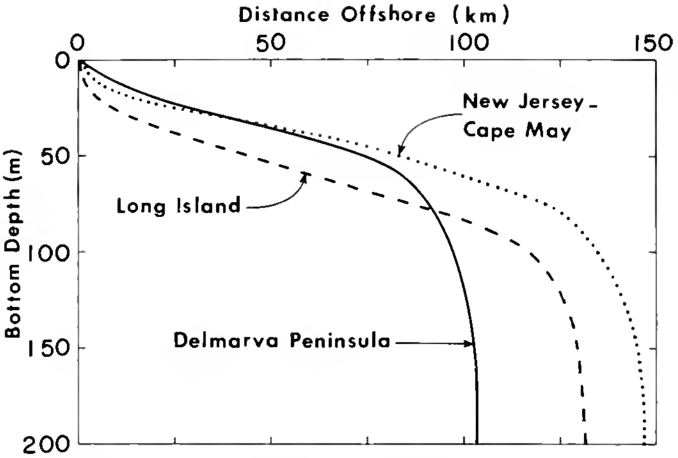


FIGURE 6–9.—Average bottom depth profiles across selected areas of continental shelf in Middle Atlantic Bight.

To explore how the difference in water depth in the Long Island and New Jersey areas might affect seasonal oxygen declines, the data displayed in figure 2–18 of chapter 2 were examined for differences in thickness of bottom water (pycnocline bottom to ocean bottom) for the two areas. The May cruise was chosen because it was made during stratified conditions and provided more extensive coverage than either the April or June surveys. Area averages of the thickness of subpycnocline or bottom waters from the coasts to the 60-m isobath were calculated for each of the two shelf regions. Average thicknesses were 13 m for the Long Island shelf and 9 m for the New Jersey shelf, reflecting the greater depth to the bottom off Long Island.

With the greater volume of water that would tend to be isolated in the subpycnocline layer during the months of stratification off Long Island, and realizing that maximum oxygen concentrations are typically about the same in both regions, then there would be a volume of about 44 percent more oxygen available in the bottom waters off Long Island than off New Jersey. In the most simplistic case (where there is no advection and presuming that the biological oxygen demand per unit area is the same in both shelf regions) the lesser volume of oxygen available in the thin layer of bottom water off New Jersey would be diminished to lower concentrations. From the historical, annual trends of figures 6–3 and 6–6, D.O. values in the bottom waters off Long Island normally decrease a total of 3.1 ml/l (from the annual maximum in March of 7.0 ml/l to the August minimum of 3.9 ml/l), and in bottom waters off New Jersey decrease about 4.1 ml/l (from a maximum in March of 7.0 ml/l to a minimum in August of 2.9 ml/l). That is, bottom D.O. concentrations normally decrease about one-third more off New Jersey than off Long Island.

In a comparison of the averaged bathymetric profiles of the Delmarva Peninsula and the continental shelf off

New Jersey (fig. 6–9), the most striking feature is that the New Jersey shelf is about 40 km, or 44 percent, wider than the Delmarva shelf, as measured from the coast to the 100-m isobath. Although no comparative evidence apparently exists, it would seem as though the narrower shelf off the Delmarva Peninsula would promote greater across-shelf exchange, which may tend to diminish any isolating effect of stratification development. The results from recovered seabed drifters (Bumpus 1973) indicate slightly higher drift speeds and distinctly lower recovery rates for the bottom waters off Delmarva as compared to the New Jersey shelf. One interpretation of these results would be that the flushing rate of the bottom waters off the Delmarva Peninsula is greater, which might tend to maintain a higher rate of oxygen replenishment.

## PREVIOUS BENTHIC MORTALITIES

Three previous episodes of benthic mortalities have been reported in the same area as the 1976 anoxia: September through early October 1968, October 1971, and August 1974 (ch. 1). None of these earlier mortalities was as extensive or enduring as in 1976. Low D.O. concentrations in bottom waters off New Jersey were reported with each occurrence.

In comparing conditions during earlier mortalities and what occurred in 1976, indexes associated with unusual stratification were the only factors for which sufficient historical records exist. To determine whether conditions similar to 1976 occurred in the earlier cases of anoxia, and at other times, climatological records of sea-surface temperature from shore stations and discharge rates for the Hudson River at Green Island were examined for the 30-year period 1947–76. During this period, high discharge (arbitrarily defined as greater than 150 percent of the monthly mean) occurred five times in January (1949, 1950, 1952, 1973, and 1974) and four times in February (1949, 1951, 1954, and 1976). Shore station temperature records for Sandy Hook and Atlantic City, N.J., indicated early warming of the water (monthly mean for February warmer than for January) 12 times at Sandy Hook and 9 times at Atlantic City. Early warming was reported at Sandy Hook in 1970 and 1971, but at Atlantic City observations were not made those years. Early warming and high discharge coincided in 1949, 1952, 1954, 1974, and 1976. Therefore, these 5 years are considered potential times when anoxic conditions might have developed during summer in the shelf waters off New Jersey as the result of early onset of stratification. For the 30-year record, the greatest warming and discharge recorded in February were in 1976. Included in the list of potential years of early onset of stratification is 1974, one of the times of reported mortalities. The 1968 and 1971 instances are not included.

The 1974 and 1976 mortalities were during summer, but the 1968 and 1971 mortalities were during autumn. The implication is that very low D.O. can result from an early spring or a late autumn; either would tend to lengthen the stratification period.

The effect of a prolonged summer (late onset of cooling) can be derived from the relation between strength of stratification and monthly rate of D.O. decline as shown by the annual cycles of bottom D.O. and stratification (fig. 6–3). During summer, stratification usually is about 4.0 $\sigma_t$ units, which corresponds to an average, monthly rate of oxygen decline of about 2.0 ml/l. Typically, the average annual minimum oxygen is about 2.9 ml/l in August. If the usual breakdown of stratification by surface cooling is delayed a month (October rather than September) then minimum bottom D.O. concentrations off New Jersey would be expected in September at an average concentration of about 0.9 ml/l.

In examining conditions that might indicate the late arrival of autumn, surface temperatures were considered the only significant factor, because river discharge in summer and autumn is typically small. In the 30-year record for the Hudson River (1947–76) the discharge for August is less than the monthly means for December, January, and February, and the September discharge was as great or greater than the monthly means for December through February only once—1975. Sea-surface temperature records for Atlantic City (1947–76) show that August was typically the warmest month and September was warmer than August only seven times—in 1948, 1957, 1959, 1965, 1966, 1968, and 1971. Of these years the highest rate of September warming was in 1968 and the second highest in 1971. These are the years of autumn mortalities. There were no instances of early-spring and late-autumn conditions occurring in the same year.

Included in the NODC historical data for bottom D.O. concentration (fig. 6–3) were some values in February and June 1968 and March 1971. At these times, bottom D.O. values were above or equal to the average trend values, implying that the low D.O. reported with the mortalities did not result from early onset of stratification.

## SUMMARY

Based on historical oceanographic data, the D.O. content of bottom waters over the New Jersey-Cape May and Long Island continental shelves typically declines during spring and summer, reaching minimum values in August. The seasonal decline in D.O. closely parallels the development of density stratification, and the rate at which D.O. declines seems to correspond with the strength of stratification. Stratification tends to isolate bottom waters from vertical replenishment until September, at which time cooling of the surface and mixing begins to destroy the vertical structure. This results in increased replenishment of bottom D.O. Continued cooling and overturning through autumn and winter typically cause a steady increase in oxygen values to the annual maximum in March. The influence of stratification on rates of oxygen decline may be greater off New Jersey than in adjacent regions because of bathymetric differences. However, this assessment does not take into account any effects on D.O. concentrations that might result from unusual advective and biologic processes. Comparison with the normal cycle of bottom D.O. indicates that concentrations were already below normal by April in 1976 throughout the New York Bight.

In 1976, the early occurrence of increased river discharge accompanied by early warming led to the early development of stratification; above-normal stratification persisted through May. The early onset of stratification in 1976 would have contributed to the occurrence of abnormally low bottom D.O. in the New York Bight in three different ways:

1. If D.O. concentrations increased as per the normal trend into January 1976 (as indicated from observations made in December 1975), then with a 2-month earlier than normal onset of stratification, maximum concentrations for the year would have been in January at about 6.5 ml/l, which is 0.5 ml/l less than the usual March maximum of 7.0 ml/l. Given normal conditions through the rest of the year, the D.O. values in 1976 could have been somewhat below normal each month until autumn.

2. Normally, the season of strengthening stratification and declining D.O. lasts about 5 months (April-August). In 1976, this season was apparently lengthened as much as 2 months, because of the early onset of stratification. This means that 1976 had 7 months in which utilization of oxygen would have exceeded replenishment.

3. From March through May 1976, and probably beginning as early as February, stratification was stronger than normal and about typical for June through August. As a result, the decline in D.O. would have been greater than normal during as many as 4 months in 1976 and at typical rates during summer. Thus the cycle of bottom D.O. concentration would have proceeded at values below normal for as long as February through August.

Historical observations, stratification values, and bottom D.O. decline rates were used to develop a graphic model. The model was then used to estimate the cycle of bottom D.O. concentration for 1976. These estimates were compared with 1976 observations and indicated that stratification, with the early arrival of spring conditions, accounted for the below-normal D.O. values in April and May. The model-derived estimate further implied that D.O. would have become almost totally depleted over the New Jersey shelf in August. But D.O. measurements in the area during June indicate that concentrations fell much more rapidly than estimated, because of stratification alone. Similarly, model-derived estimates for Long Island shelf waters indicated that below-normal concentrations should have developed there in 1976, but not at such low values as off New Jersey. Also, in June, Long Island D.O. concentrations fell more rapidly than predicted from the model.

Because stratification alone failed to explain the full magnitude of the oxygen depletion, there must be other contributory factors. Possibly the dramatic decline in bottom D.O. during June resulted from excessive demand from the presence of the large mass of *Ceratium* and, perhaps, from factors associated with the circulation.

Since instances of anoxia-related mortalities have been reported during previous years in the New Jersey shelf waters, historical records of sea-surface temperature and of river discharge were examined for indications that the season of stratified conditions may have been longer than normal in these years. For the 30 years of records examined conditions that could have caused a lengthening of the time the waters were stratified occurred 12 times, or 40 percent of the time. Of these potential cases, five resulted from the early arrival of spring and seven from the late arrival of autumn. Anoxic conditions and mortalities were reported for the four most recent occurrences. This history of fairly frequent instances when stratification-related, depressed D.O. conditions may have developed implies that future recurrences of anoxia should be expected.

## ACKNOWLEDGMENTS

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## REFERENCES

Bowman, M. J., and Wunderlich, L.D., 1976. Distribution of hydrographic properties in the New York Bight Apex, *Amer. Soc. Limnol. Oceanogr. Spec. Symp.* 2:58–68.

Bumpus, D. F., 1973. A description of the circulation on the Bcontinental shelf of the east coast of the United States, Progress in Oceanography 6:111–157, Pergamon Press.

Stearns, Franklin, 1969. Bathymetric maps and geomorphology of the Middle Atlantic Continental Shelf, *Fish. Bull.* 68:37–66.

Uchupi, Elazar, 1968. Atlantic continental shelf and slope of the United States: Physiography, *U.S. Geol. Survey Professional Paper* 529–C, 30 pp.

Woods Hole Oceanographic Institution, 1961. Biological, chemical, and radiochemical studies of marine plankton, reduced data report, Appendix C to *WHOI Ref.* No. 61–6, (unpublished manuscript).

## Oxygen Depletion and Associated Benthic Mortalities in New York Bight, 1976

# Chapter 7. Water Movement on the New Jersey Shelf, 1975 and 1976

*D. A. Mayer, D. V. Hansen, and S. M. Minton*[1]

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## INTRODUCTION

Current meter moorings were maintained at several sites in the New York Bight during the late winter and spring of 1975 and from autumn 1975 throughout 1976. The strength and variation on various time scales of currents observed on the continental shelf off New Jersey and Long Island, N.Y., were investigated to determine the differences between the 2 years. These differences may help explain why anoxic conditions developed in New Jersey near-bottom waters during summer 1976, but did not develop in summer 1975.

Seven taut-wire moorings (with Aanderaa current meters and tethered surface spar buoys) were selected for analysis from those deployed during the 1975 and 1976 MESA current surveys (fig. 7–1, table 7–1). On the New Jersey shelf, three stations (P11, 49, and LT2) were established in shallow water (about 30 m), and two (P12 and LT3) were in deeper water (60–70 m) near the shelf break. Off Long Island, two stations (P31 and LT4) were established near shore in 49 m of water. Because low dissolved oxygen (D.O.) concentrations were observed near the bottom, this analysis focuses on near-bottom motions. Weather data also were obtained from John F. Kennedy International Airport (JFK) and from two meteorological data buoys, EB34 and EB41 (fig. 7–1).

## DATA PROCESSING

Only the highest quality data were retained for analysis. Raw current-meter data (sampling intervals were mostly 30 minutes, some were 20-minute intervals) were scrupulously edited. These were then 3-hour low-pass filtered and resampled hourly, resulting in a more manageable

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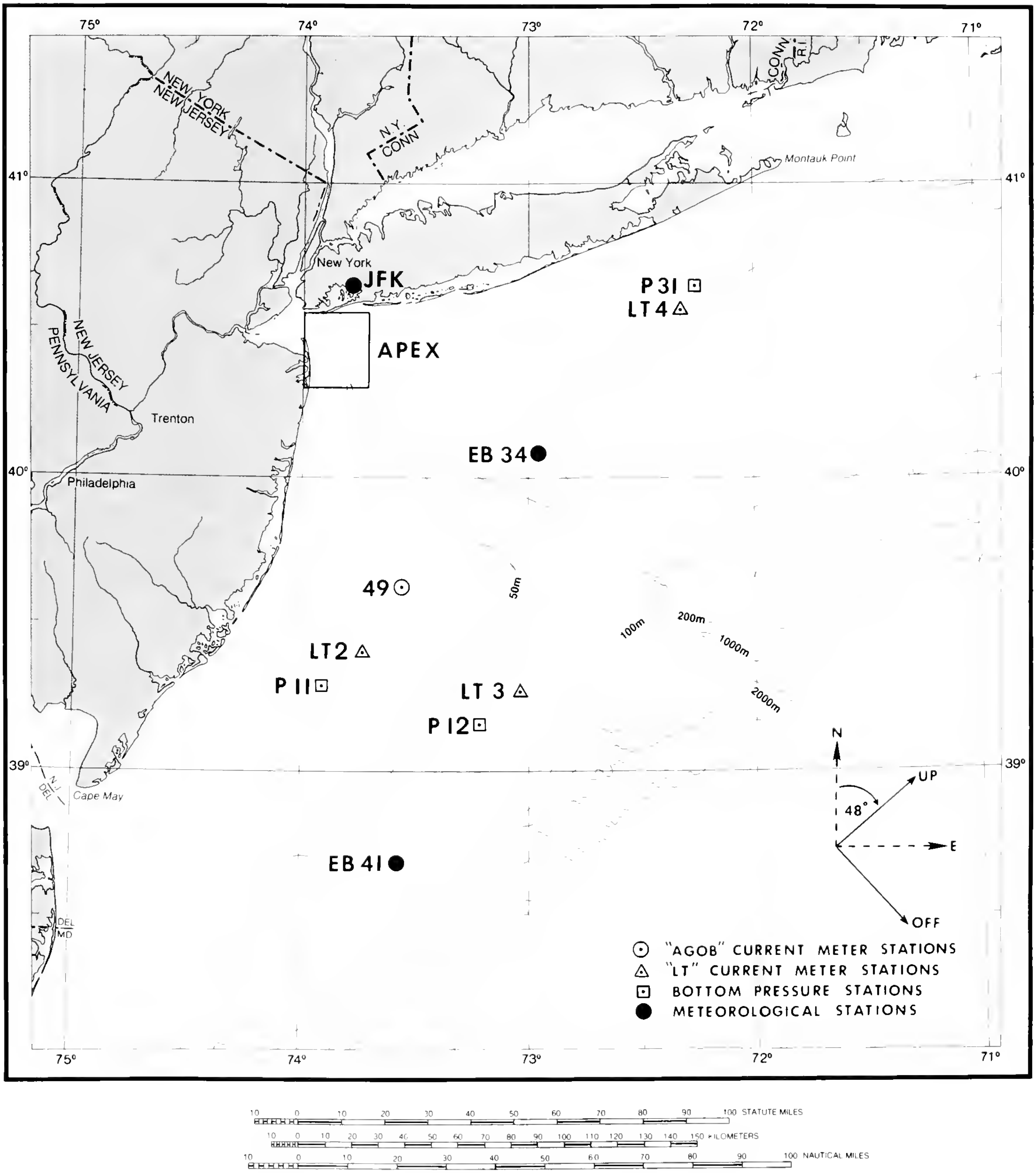

FIGURE 7-1.—Location of environmental buoys and current meter stations in New York Bight, 1975 and 1976.

Table 7–1.—*New York Bight 1975–76 current-meter and wind-observation stations and characteristics*

| Station | Water depth | Distance from bottom | Distance from surface | Location[1] | | Years |
|---|---|---|---|---|---|---|
| | | | | Latitude | Longitude | |
| | m | m | m | ° | ° | |
| New Jersey shelf | | | | | | |
| P11 | 33 | 5 | 28 | 39 16.6 | 73 55.3 | 1975 |
| 49S | 35 | 32 | 3 | 39 37.9 | 73 34.2 | 1975 |
| 49B | | 8 | 27 | | | |
| LT2S | 32 | 29 | 3 | 39 23.8 | 73 42.9 | 1975–76 |
| LT2B | | 9 | 23 | | | |
| New Jersey shelf break | | | | | | |
| P12 | 62 | 5 | 57 | 39 08.9 | 73 13.4 | 1975 |
| LT3D | 70 | 11 | 59 | 39 15.7 | 73 01.6 | 1976 |
| Long Island shelf | | | | | | |
| P31 | 47 | 5 | 42 | 49 39.3 | 73 14.6 | 1975 |
| LT4S | 49 | 46 | 3 | 40 33.6 | 72 18.6 | 1975–76 |
| LT4B | | 8 | 41 | | | |
| LT4C | | 1 | 48 | | | |
| Meteorological stations | | | | | | |
| JFK | | | 6 | 40 39 | 73 47 | 1975–76 |
| EB34 | | | 5 | 40 05 | 72 58 | 1976 |
| EB41 | | | 5 | 38 42 | 73 36 | 1975 |

[1] Station locations are shown on figure 7–1.

number of data points. Ortman (1978) described the methods and editing criteria used. Raw weather data were used with sampling intervals of 1 hour for the EB stations and 3 hours for JFK. Water motion statistics were computed for appropriate time scales, and progressive vector diagrams (PVDs) were plotted for these same time scales. For the statistics and the plots of velocity components, the coordinate system was rotated 48° clockwise so that the north component transformed into the upshelf (toward Cape Cod) component and the east component transformed into the offshelf (toward Bermuda) component. This rotation provides an approximation to the orientation of the bathymetry off both Long Island and New Jersey. Small-scale topographic variability prohibits conclusive statements about cross-shelf flow where the crossing angle is small.

Because the PVD presentation is extensively used in the arguments that follow, it is useful to review what a PVD portrays. For a series of velocity measurements, a PVD is a virtual displacement diagram derived by integrating the velocity in time to yield a representation of water movement past the current meter. It is virtual displacement in the sense that a drogue at that depth would move along this displacement diagram (PVD) only if all water adjacent to the point of measurement (the current meter mooring) were moving in exactly the same way. The flow field would then be spatially homogeneous. This is not the case, because water particles distant from the current meter may have moved into a different flow field, which, if current meter measurements were available, would produce a different displacement diagram. The PVD does, however, yield valuable information about the cumulative displacement of water particles past the point of measurement. A PVD is a useful tool for visualization of the average and slowly varying components of flow.

## TIME SCALES

The basic question addressed here is whether weakened or otherwise altered circulation during 1976 may have contributed to development of anoxic conditions by reducing advection of D.O. into the region or by concentrating oxygen-demanding material. This question does not have a simple answer within the confines of the data. As will be shown, the net movement over several weeks was indeed less during spring and summer 1976 than during spring 1975. Over shorter periods, however, the measured currents usually were more energetic. This is revealed in the larger variance statistics in 1976 for corresponding months in the 2 years. Spectrum analyses show the increased variance to be distributed over a broad band of time scales, covering periods from at least 0.5 to 6 days. The measured tidal currents were greater in 1976 than in 1975, which is more likely to be due to uncertainty of measurement than true secular variation. Although there are undoubtedly measurement uncertainties in both years, the general trends are believed to be real. Increased variance at all frequencies, including tidal, can result from high-frequency mooring motion, usually induced by surface waves. The moorings (49 and LT2) used off New Jersey during 1975 and 1976 were almost identical, and the weather differences seem insufficient to account for the differences in variance across all frequencies. The mooring sites were about 27 km apart; the LT2 mooring site (1976) is about 4 m shoaler than station 49. Some amplification of tidal currents is expected in shoaler water. In addition, the slightly stronger stratification occurring in 1976 (ch. 5) may have enabled internal gravity waves to be excited over a wider band of frequencies and more vigorous internal tides to have been generated. Perhaps more important, the LT2 bottom meter, being somewhat nearer to the surface (23 compared to 27 m), may have introduced more error into measurements in 1976.

Interpreting these data to address the cause of development of anoxic conditions implies selection of a time scale pertinent to the problem. For small (1–10 km) pollution problems, the relatively rapidly varying currents would be most important, and 1976 would likely be shown by our data to be a relatively favorable year for pollutant dispersal. Considerations of the oxygen demand on a static environment (Segar and Berberian 1976) or of the observed time and space scales of the D.O. distribution in the New York Bight (ch. 2 and 5) suggest that 30 days, or even a sequence of 30-day intervals, is appropriate for this problem. Hence, the data are presented in 30-day blocks. The vector mean flow over these intervals is probably the property of greatest significance here, but we also discuss the total current variance or horizontal kinetic energy to demonstrate the point about variability made above.

## TEMPORAL VARIATION OF CURRENTS

Extremely low D.O. concentrations were not observed in 1975. Data from stations P11 and 49 in the region where very low D.O. concentrations were observed in summer 1976 are available for periods up to 90 days, starting from Julian day (J.D.) 65 in 1975. This spans the period of development of the pycnocline during spring (ch. 5). Results from meters located below or in the bottom of the pycnocline during this time are summarized in PVD format (fig. 7–2). These PVDs reveal irregular intervals of weaker or stronger flow, but they also show net monthly displacements of 100 to 120 km to the southwest and south at both stations (P11 and 49B). These data are part of the same data set used by Beardsley et al. (1976) and Hansen (1977) and are consistent in speed and direction with other data acquired at that time from other parts of the shelf. They also generally agree with drift bottle results acquired over several years (Bumpus 1973). Bumpus also summarized results from deployment of seabed drifters over several years. Results from drifter studies necessarily are biased toward shoreward movement, and Bumpus' (1973) summary typically indicates a region of diffluence in the most critical area off New Jersey during the summer. Regional patterns of confluence or diffluence are not well determined from such data, however.

In addition, the near-bottom direct current meter measurements treated are 8 to 9 m above the bottom, and only up to 90 days of record are available for analysis. However, a considerable amount (nearly 12,000 hours) of data are available from the LTM site (Mayer et al. 1979) 4 to 8 m above the bottom, although in water about 15 m deeper and upshelf from the Hudson Shelf Valley. From almost 18 months of these data, it has been estimated that the average or normal flow at this level above the bottom is 1 to 1.5 cm/s toward 220° T. Well within the bottom boundary layer (1 m above the bottom), the picture is not as clear, because current velocities are less than 1 cm/s (with only about 6 months of data available) making it difficult to reasonably estimate either speed or direction. With this limited data set, addition or deletion of several weeks of data can reverse the direction of the mean, so it is not meaningful to compare in detail our current meter data (up to 90 days in 1975) with Bumpus' seabed drifter results.

The simple mean circulation described above is greatly complicated by events (mostly of meteorologic origin), some of which persist for as long as 3 months (Mayer et al. 1979). Most events, however, lie within the 3- to 10-day frequency band associated with energetic weather systems. These events are manifest in the many observed upshelf velocities generated by an upshelf component of wind stress. A conceptual model follows: "Upshelf winds cause offshore flow in the upper part of the water column, which presumably causes a drop of coastal sea level, providing a pressure gradient that drives a quasi-geostrophic upshelf flow of deeper water" (Mayer et al. 1979).

By now it should be clear how variable the circulation is on the Middle Atlantic shelf and how difficult it is to make definitive statements about the mean or normal circulation. With regard to the background material consisting of a limited (90 days or less) current meter data set from 1975, we can say that it is consistent with what is believed known about "normal" circulation in the Middle Atlantic Bight.

A longer series of current meter observations in the New York Bight, including station LT2 off New Jersey, was obtained from October 1975 through summer 1976. Ten months of continuous record from a current meter located below the pycnocline during the stratified season was available for the analysis of anoxic conditions off New Jersey. Figure 7–3 shows results from essentially the same level as the 1975 data in figure 7–2 for corresponding time periods. In October 1975 the displacement was about twice that observed during the preceding spring, but slowed dramatically and reversed direction for about a month in November. During the subsequent several months the

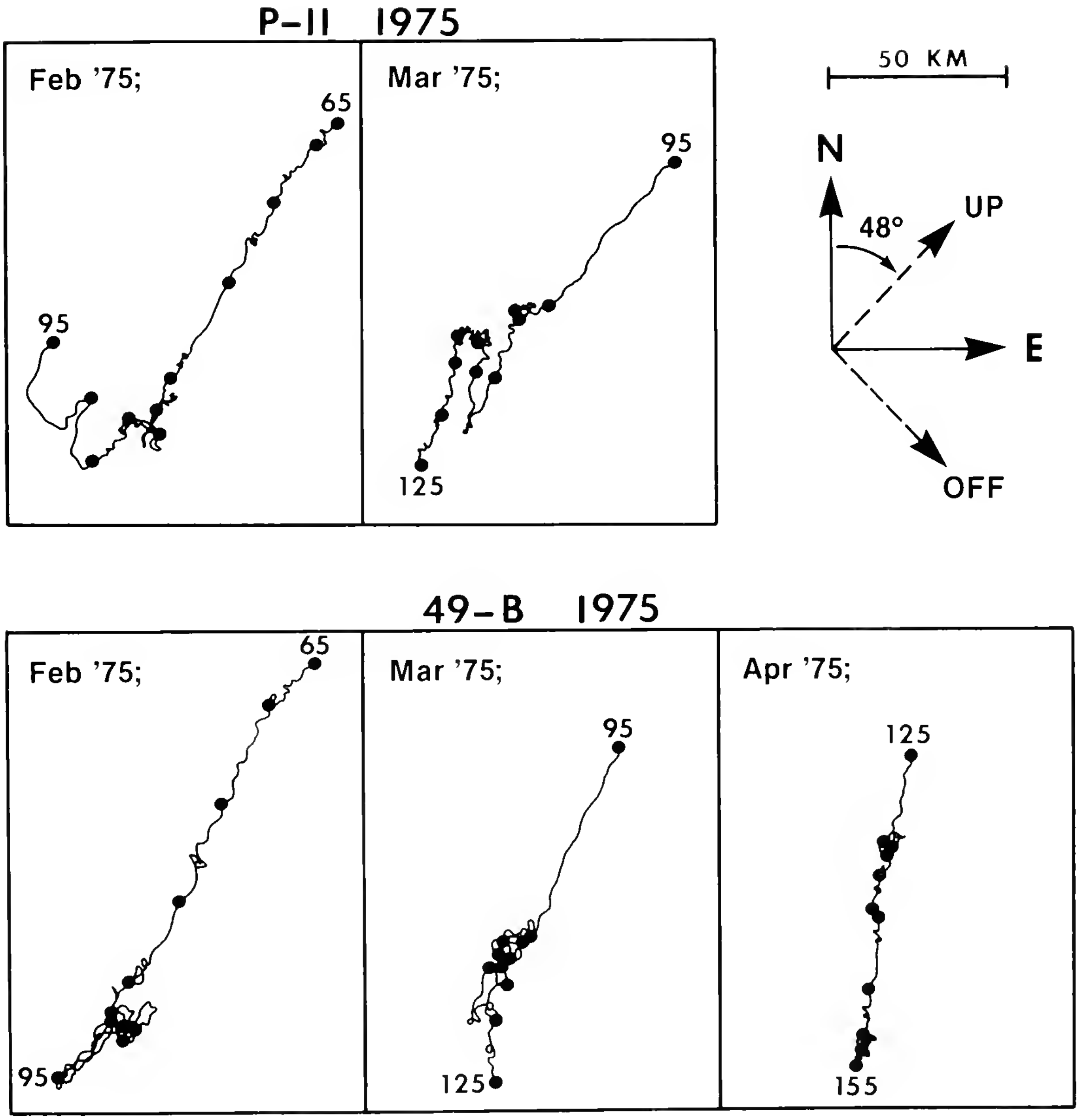

FIGURE 7-2.—Progressive vector diagrams of currents for stations P11 and 49, February-March and February-April 1975, showing computed displacement (in km) of water by 3-day intervals (dots) within period of observation designated in Julian days.

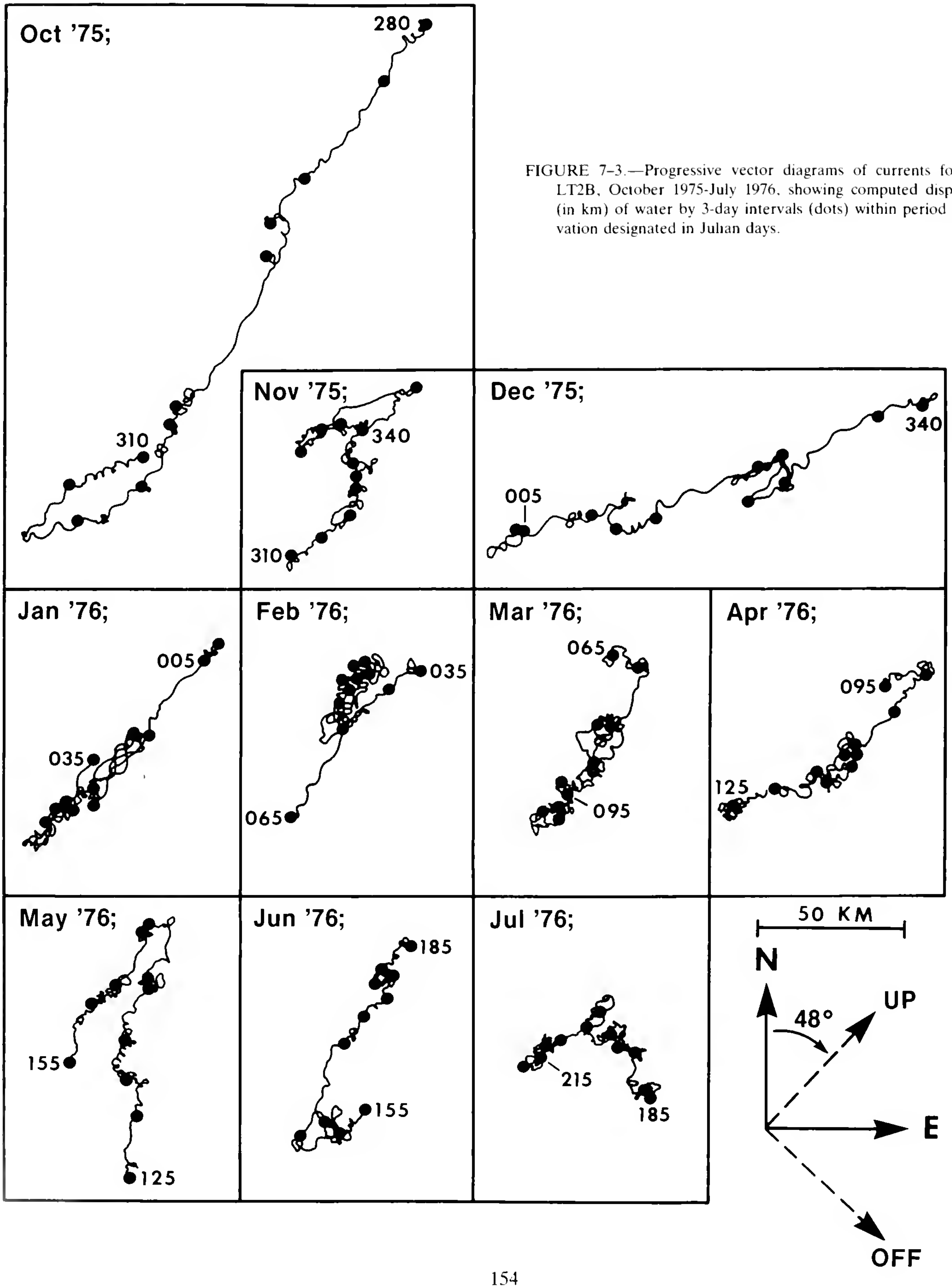

FIGURE 7–3.—Progressive vector diagrams of currents for station LT2B, October 1975-July 1976, showing computed displacement (in km) of water by 3-day intervals (dots) within period of observation designated in Julian days.

TABLE 7–2.—*New York Bight 1975–76 current data time-series subsets*[1]

| Meter no. and location | Start time (J.D.)[2] for subset no. | 280 | 310 | 340 | 5 | 35 | 65 | 95 | 125 | 155 | 185 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | Full series |
| **Nearshore stations** | | | | | | | | | | | | |
| New Jersey | | | | | | | | | | | | |
| 1975 | 49S | ... | ... | ... | ... | ... | ... | −6.1 | −3.3 | | | |
| | | | | | | | | 1.3 | 0.7 | | | |
| | | | | | | | | 342 | 388 | | | |
| | 49B | ... | ... | ... | ... | ... | −4.3 | −3.4 | −2.7 | | | |
| | | | | | | | 1.5 | 1.8 | 2.1 | | | |
| | | | | | | | 308 | 224 | 128 | | | |
| 1975–76 | LT2S | ... | −1.2 | −8.1 | −2.2 | −5.1 | −0.5 | −4.4 | | | | |
| | | | 3.0 | 3.1 | 1.4 | 3.2 | 4.1 | 3.9 | | | | |
| | | | 424 | 426 | 436 | 413 | 407 | 383 | | | | |
| | LT2B | −6.6 | 1.8 | −5.1 | −1.9 | −2.6 | −1.6 | −2.6 | 0.5 | 1.9 | −0.8 | −1.6 |
| | | 1.8 | −0.6 | −2.3 | −0.0 | 0.3 | 0.8 | −0.2 | −1.7 | −1.2 | −1.4 | −0.4 |
| | | 377 | 305 | 383 | 434 | 368 | 301 | 436 | 303 | 221 | 234 | 346 |
| Long Island | | | | | | | | | | | | |
| 1975 | P31 | ... | ... | ... | ... | ... | 0.1 | −0.0 | | | | |
| | | | | | | | −2.0 | −1.8 | | | | |
| | | | | | | | 141 | 90 | | | | |
| 1975–76 | LT4S | ... | ... | ... | ... | ... | ... | −6.0 | 3.9 | 4.9 | 2.3 | |
| | | | | | | | | −0.1 | 1.8 | 5.6 | 4.9 | |
| | | | | | | | | 381 | 329 | 344 | 314 | |
| | LT4B | −5.3 | −0.3 | −1.6 | 3.0 | −2.4 | −2.1 | −2.5 | −2.5 | −2.7 | −3.9 | −2.1 |
| | | −1.4 | 0.2 | −3.2 | −2.7 | −0.9 | −1.3 | −0.9 | −0.3 | −0.2 | −0.9 | −1.1 |
| | | 301 | 307 | 344 | 405 | 393 | 216 | 257 | 198 | 183 | 125 | 278 |
| | | | | | | | | | J.D.<br>115 | | | |
| **Shelf-break stations** | | | | | | | | | | | | |
| 1975 | P12 | ... | ... | ... | ... | ... | ... | ... | −6.3 | | | |
| | | | | | | | | | 32. | | | |
| | | | | | | | | | 112 | | | |
| 1976 | LT3D | ... | ... | ... | ... | ... | ... | ... | −1.1 | | | |
| | | | | | | | | | −0.3 | | | |
| | | | | | | | | | 211 | | | |

[1] Numbers for each subset are: top, upshelf component in cm/s; middle, offshelf component in cm/s; bottom, total variance ($\sigma_T^2$).

[2] Julian day calendar: 1975, days 1–365; 1976, days 1–166 (one added to each day beginning March 1 to account for leap year).

currents were generally similar to those observed in spring 1975, but at somewhat lower net speeds, except for December, typically 50 to 70 km per month. During May and June the flow maintained, or slightly increased, speed, but became more variable in direction, reversing the "normal" southwestward pattern. In July the flow continued to be variable in direction and also diminished in speed. The net displacement during July was less than 40 km to the west northwest. During the first 2 weeks of August (not shown) net water movement virtually ceased. The net displacement observed during the 3 months between May 4 and August 2, 1976, was about 120 km towards 340° T.

Statistics of each 30-day segment are arranged for easy comparison in figure 7–4 and table 7–2. These consist of the vector mean (represented in table 7–2 as upshelf and offshelf components) and the total variance ($\sigma_T^2$). The uncertainty in determination of the monthly mean values due to the relatively large variance is less than 1 cm/s. The substantial difference between the average flows of corresponding months during spring 1975 and 1976, followed by a prolonged period (90 days) of onshore flow below the thermocline off New Jersey, is especially evident in figure 7–4.

Flushing of the New Jersey coastal region is undoubtedly important for the ecological health of the marine environment. The principal difference that might have affected the flushing of the area and the development of anoxic conditions in 1976 was the reduction of speed and reversal (alongshore component directed upshelf) of direction of the water movement in the bottom layer off New Jersey, compared to spring 1975.

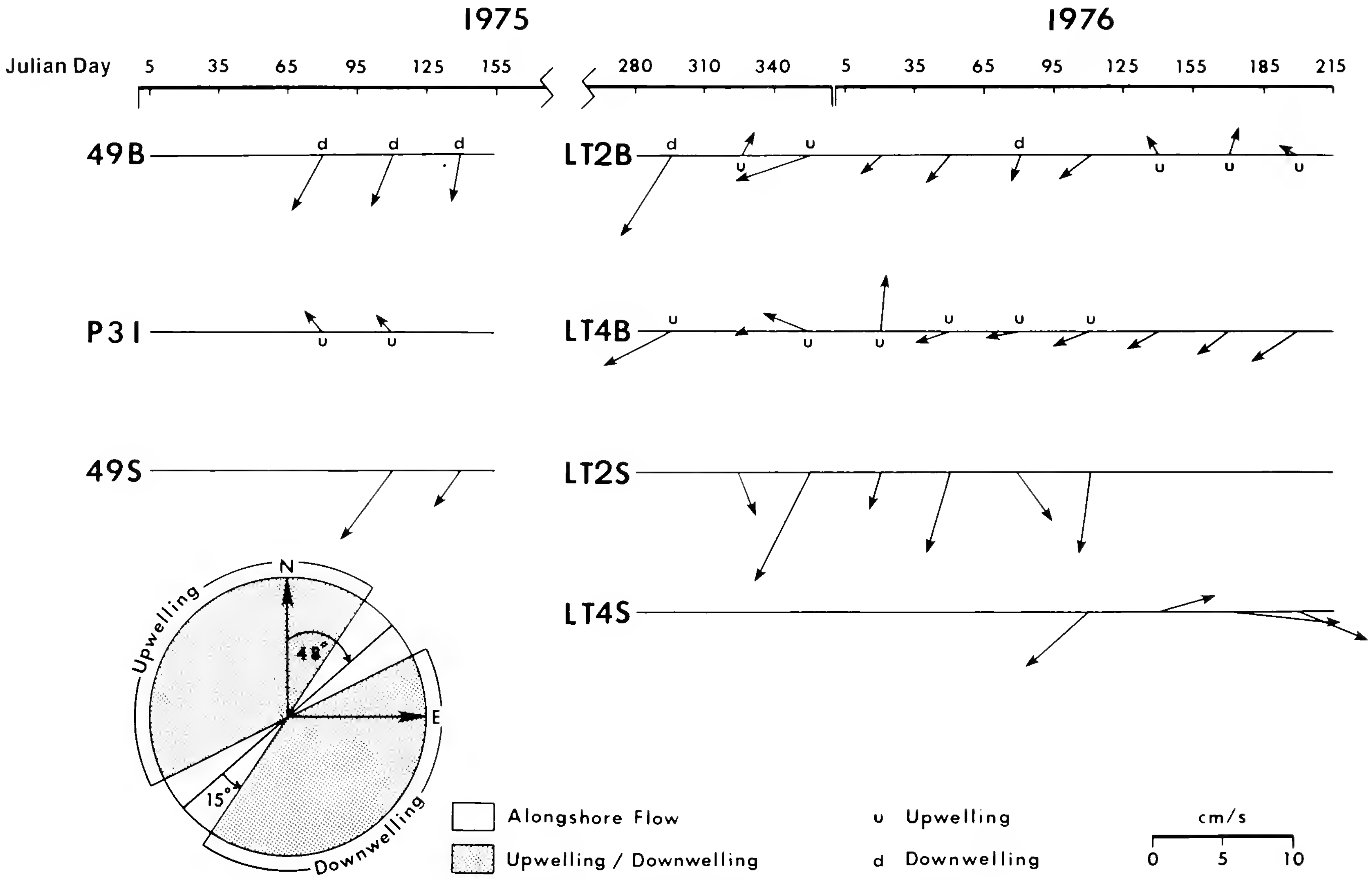

FIGURE 7-4.—Stick plots of 30-day means of currents observed in 1975 and 1976.

## REGIONAL VARIATION OF CURRENTS

Another question associated with the development of anoxia is its apparent confinement to approximately the inner half of the continental shelf off New Jersey. Current meter observations made off Long Island (stations P31 and LT4) during the same times as those off New Jersey, and some shorter records from observations near the shelf-break off New Jersey (stations P12 and LT3), were studied to determine whether the interannual current variation observed in the region of anoxia was experienced throughout the entire New York Bight. Anoxic conditions were not observed at either site during 1976.

Data from LT3 and P12 were available for only 1 month (J.D. 115–145 in April and May) common to both 1975 and 1976 (table 7–2). In 1975, the flow at station P12 was toward the southwest as elsewhere on the shelf, and at substantial speed. The 30-day displacement was over 200 km. In 1976, at station LT3D, the flow was to the southwest, as normally expected over the shelf, at a time when the flow closer inshore was reversed. The speeds at LT3D were about one sixth those of the previous year, even at a level farther (11 vs. 5 m) from the influence of bottom friction. The total variance at P12 is only about half that at LT3D, but this may be due to closer proximity of the current meter to the bottom on station P12 and to the fact that the subsurface float on this mooring was much farther below the surface.

The best data for comparing conditions off Long Island with those in the anoxic area off New Jersey during 1975 are data from the bottom station, P31 (fig. 7–4). These data are inconsistent with most other data acquired at this time (Beardsley et al. 1976; Hansen 1977) in that the observed flow was weakly to the northwest, generally upslope across the continental shelf. This measurement also was relatively close to the bottom (5 m) and consequently may have been perturbed by local bathymetry, although no likely cause appears on the best available bathymetric charts. When observations in this area were resumed in October 1975, a relatively strong southwestward flow was observed off both Long Island and New Jersey. In November, off New Jersey a northeastward flow (LT2) was observed while off Long Island (LT4) there was a period of essentially no net flow; which was followed in December and January by northwest and northward flows that were not observed off New Jersey. This 3-month midwinter perturbation of the normal southwestward flow over the shelf is of the same time and amplitude scales as that observed coincident with the development of anoxia off New Jersey, but anoxic conditions are not expected during the unstratified conditions of winter. From February through July the flow off Long Island was steadily to the southwest at speeds of 55 km/mo (2 cm/s) or more. The monthly means off Long Island do not indicate the slowing and reversal of flow that occurred off New Jersey during the summer. The July 1976 flow off Long Island is in fact slightly stronger than in the months immediately preceding.

## UPWELLING

A possible aspect of the circulation that can contribute to development of anoxic conditions is upwelling, or shoreward and upward flow of water from below the pycnocline offshore. This water may tend to be somewhat higher in nutrients than typically found in coastal bottom waters.

It is frequently not possible to discern in local current measurements the occurrence of upwelling, because the alongshore component of flow is much larger than the cross-shelf flow and the local orientation of the shelf bathymetry is insufficiently defined. It is apparent in figure 7–2 that the flow is generally parallel to the bathymetry (48°-228° T) much of the time. When the flow crosses the nominal isobath by more than 15° (ratio of components 1:4) for significant periods we believe meaningful statements can be made about local onshelf flow or upwelling. This crossing angle is about three times greater than our uncertainty in determining the shelf direction. Such situations are identified in figure 7–4. Indication of net upwelling is seen off both Long Island and New Jersey. Off New Jersey it is associated primarily with the flow perturbation of summer 1976. In the 13 months of observations available (stations 49B and LT2B), upwelling and downwelling occurred five times each in the monthly means; shelf-parallel flow occurred in three monthly means. Off Long Island, upwelling occurred in 8 of the 12 monthly means available (stations P31 and LT4B), but occurred most strongly in connection with the midwinter current perturbation. The information on the monthly mean near-surface currents included in table 7–2 and figure 7–4, considered jointly with either the currents below the pycnocline or the winds observed at JFK, demonstrate only that the surface currents off Long Island were strongly influenced by local winds.

## LOCAL METEOROLOGICAL EFFECTS

Recent studies (e.g., Beardsley et al. 1976) show that a large fraction of the kinetic energy in water movements in nearshore coastal waters is correlated with local winds. Because there are indications of anomalous atmospheric conditions during winter and spring 1976 (ch. 3), it is appropriate to review here the winds that influenced circulation in the New York Bight during these seasons of 1975 and 1976. For this purpose we obtained wind obser-

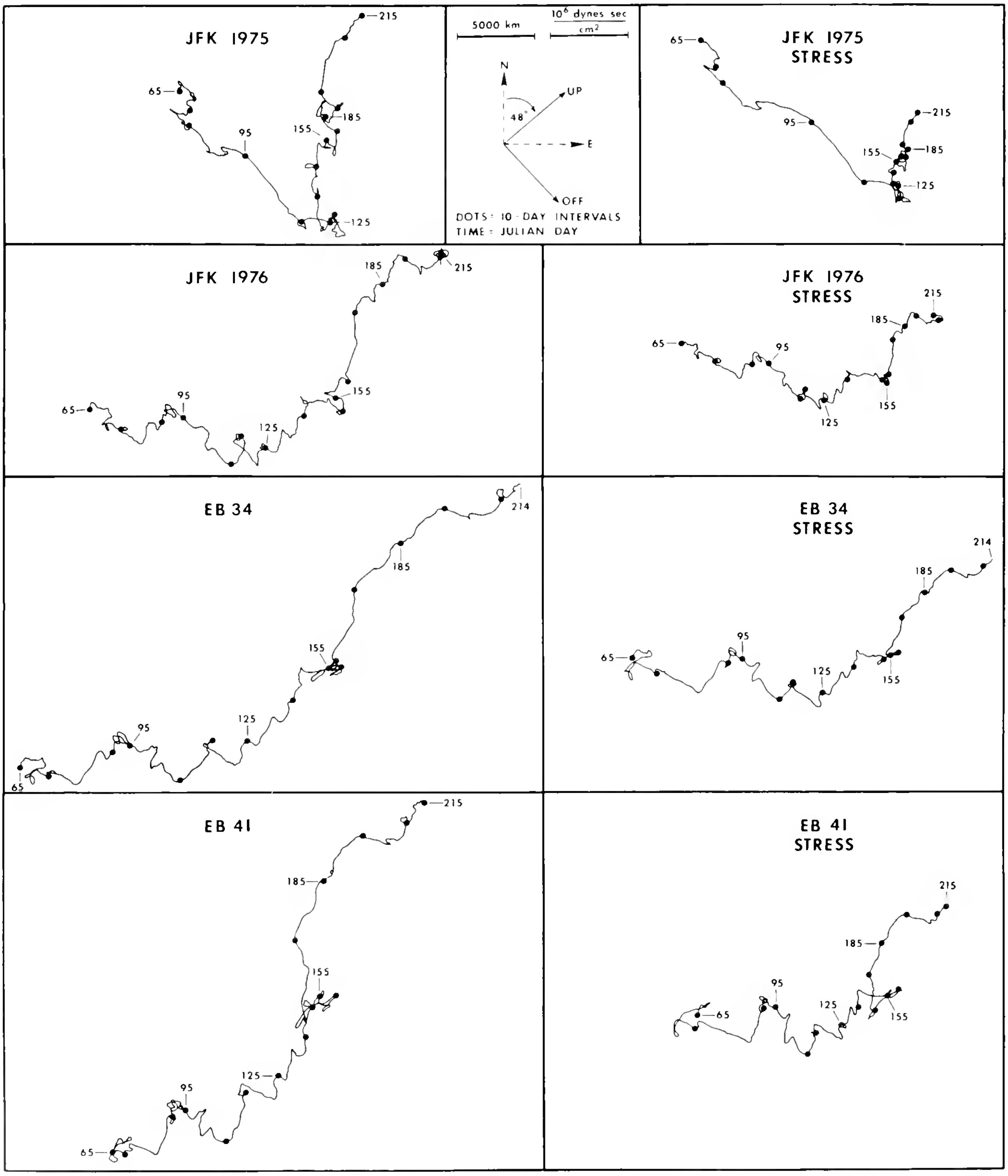

FIGURE 7-5.—Progressive vector diagrams of wind and stress at JFK Airport from March through July, 1975 and 1976, and at environmental buoys EB34 and EB41 in 1976.

vations at JFK and the two environmental buoys (EB34 and EB41). These are shown in PVD format for both velocity components and stress (figure 7–5). Time series of stress were computed according to Wu (1969). The stress data for both 1975 and 1976 clearly show the transition in early May (J.D. 120–125) from the generally northwesterly winds characteristic of winter to the more southwesterly winds of summer (southerly at JFK in 1975). In late winter and early spring 1976, the winds at JFK were slightly weaker and more westerly than during the previous year. Data obtained from EB34 and EB41 show that the winds were more westerly in the southern reaches of the Bight.

A relatively normal transition to summer conditions occurred about the first of May 1976 at JFK and EB34, but about 2 weeks earlier at EB41. A period of slightly greater than normal wind speed of unusual persistence from the south and southwest occurred during much of June. This period of persistent winds evidently caused a large amount of floatable material to wash ashore on Long Island (Swanson et al. 1977). Although these winds were clearly much stronger and steadier than those of June 1975, they were not dramatically different from those of July 1975. In July 1976 the winds again weakened and were more southwesterly. The major difference in low-frequency wind behavior between 1975 and 1976 seems to be that in 1976 there was a greater tendency for winds to have a westerly component in late winter and early spring and a long period during June 1976 when the winds were persistently from the southwest, in opposition to the normal flow of water.

Early in the morning of August 10, 1976, hurricane Belle passed through the New York Bight (figure 7–6). Though unrelated to the genesis of anoxia in the Bight, this event is of interest in connection with possible advective renewal of oxygen-depleted waters or increased vertical mixing (ch. 2), either of which may be expected to alleviate low D.O. conditions. Figure 7–6 shows the currents observed over the few days spanning the passage of the hurricane at stations LT2 and LT4. Prior to the hurricane, the normal semidaily tidal currents are most noticeable, especially at station LT2. These rotary tidal currents have speeds of 15 to 20 cm/s and produce no net displacement over a complete tidal cycle. The hurricane's time of arrival and speed of passage were such that its effects appear to be almost in phase with the tidal currents, approximately doubling their speed for about one cycle (one-half day). The sequence of enhanced flows is offshelf (SE), downshelf (SW), onshelf (NW), and upshelf (NE). Unlike the tidal currents, which are almost in phase at these two stations, the storm-induced disturbance at station LT2 occurred before that at LT4 by about 4 hours, about equal to the time it took for the hurricane to pass through the Bight. Following this is a period of weaker, but significant, residual flow upshelf at both stations, perhaps caused by the southerly winds following the hurricane. This upshelf flow is a continuation of the anomalous trend observed earlier at LT2 and may therefore have contributed to continuation rather than alleviation of anoxic conditions.

The current meters also sample and record temperature. Long temperature series from stations 49 and LT2 are used in chapter 5 so are not discussed extensively here. Some data, however, are of interest in connection with vertical mixing of D.O. and other constituents in the water column. At the time of the hurricane, because temperatures and dissolved oxygen are correlated (ch. 2), temperature can serve as an indicator for vertical transfer of D.O. Figure 7–7 shows temperature observations made concurrently with the current observations in figure 7–6.

Before the passage of the hurricane, the temperatures at station LT2A, 13 m below the surface but above the thermocline, were above the maximum range of the sensor and therefore were not plotted in figure 7–7. During the storm the temperature dropped abruptly into the working temperature range of the thermistor or sensor. The temperature continued to drop more slowly during the subsequent 2 days. At meter LT2B, the temperature increased about 8° C, fluctuated over several degrees in about 4 hours, then after about half a day fell to less than 2° C above its initial value. Our interpretation is that the large transient temperature increase primarily reflects downwelling and offshelf flow followed by upwelling and onshelf flow of water described earlier at this level. The relatively small residual temperature change (2° C) is probably indicative of vertical mixing that can be expected to provide only a modest resupply of oxygen to the region below the pycnocline.

More complete information about the vertical structure of temperature changes is available from station LT4. Four hours after the temperature increase at LT2B, a temperature rise of about 4° C occurred at 21 m depth at LT4A and persisted for several days. Near-surface temperatures (LT4S) rapidly decreased more than 8° C at about the same time as the final rapid temperature drop at LT2B. Subsequently, the temperatures at the 3- and 21-m depths were only slightly different and increased at about the same rate during the following days. This combination of responses suggests vertical mixing to a depth of more than 20 m and possibly upwelling and offshore flow of surface water. It is not clear why the changes observed at the 13-m depth at station LT2 were so much less than those observed in the upper 20 m at LT4. These differences probably cannot be explained by local mixing processes alone. More to the point regarding mixing across the pycnocline, aside from a transient 3° C increase for only about 4 hours at 8 m above the bottom and a 1° C increase spanning about 1½ days at both 8 m and 1 m above the

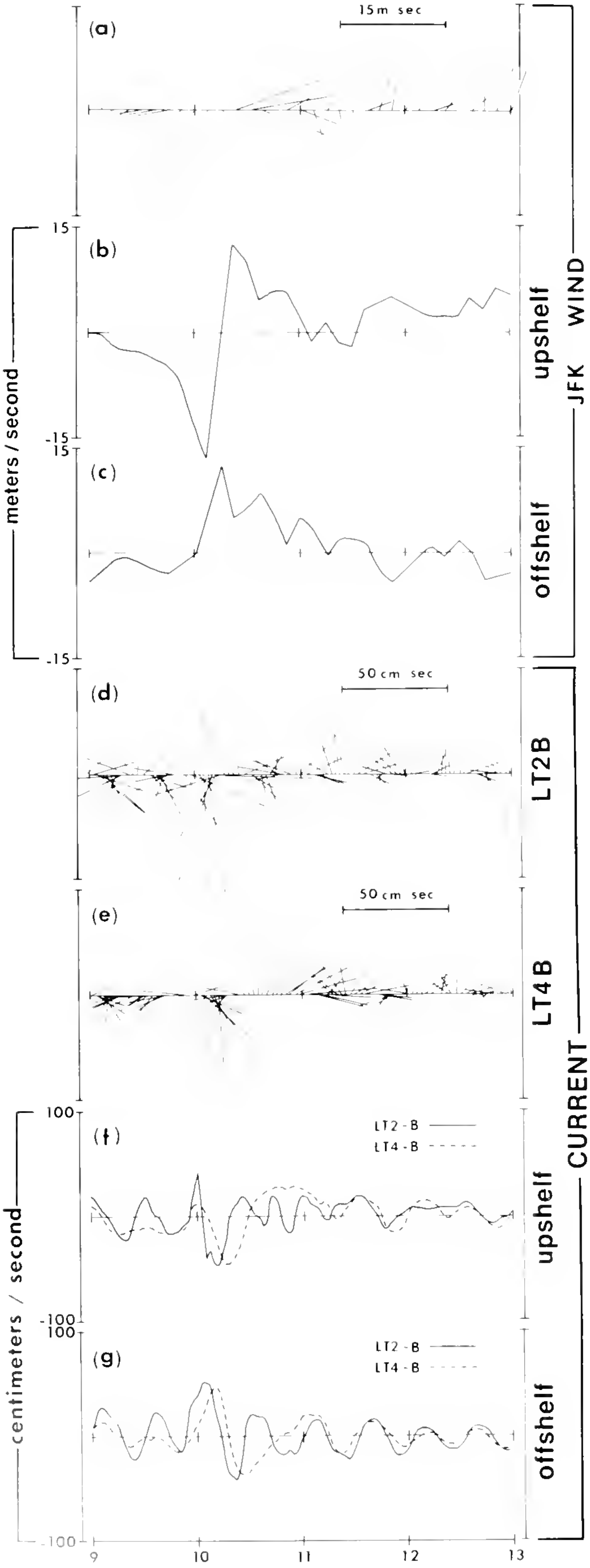

FIGURE 7-6.—Stick plots and rotated (48°) components of winds and currents during passage of hurricane Belle, August 9-13, 1976.

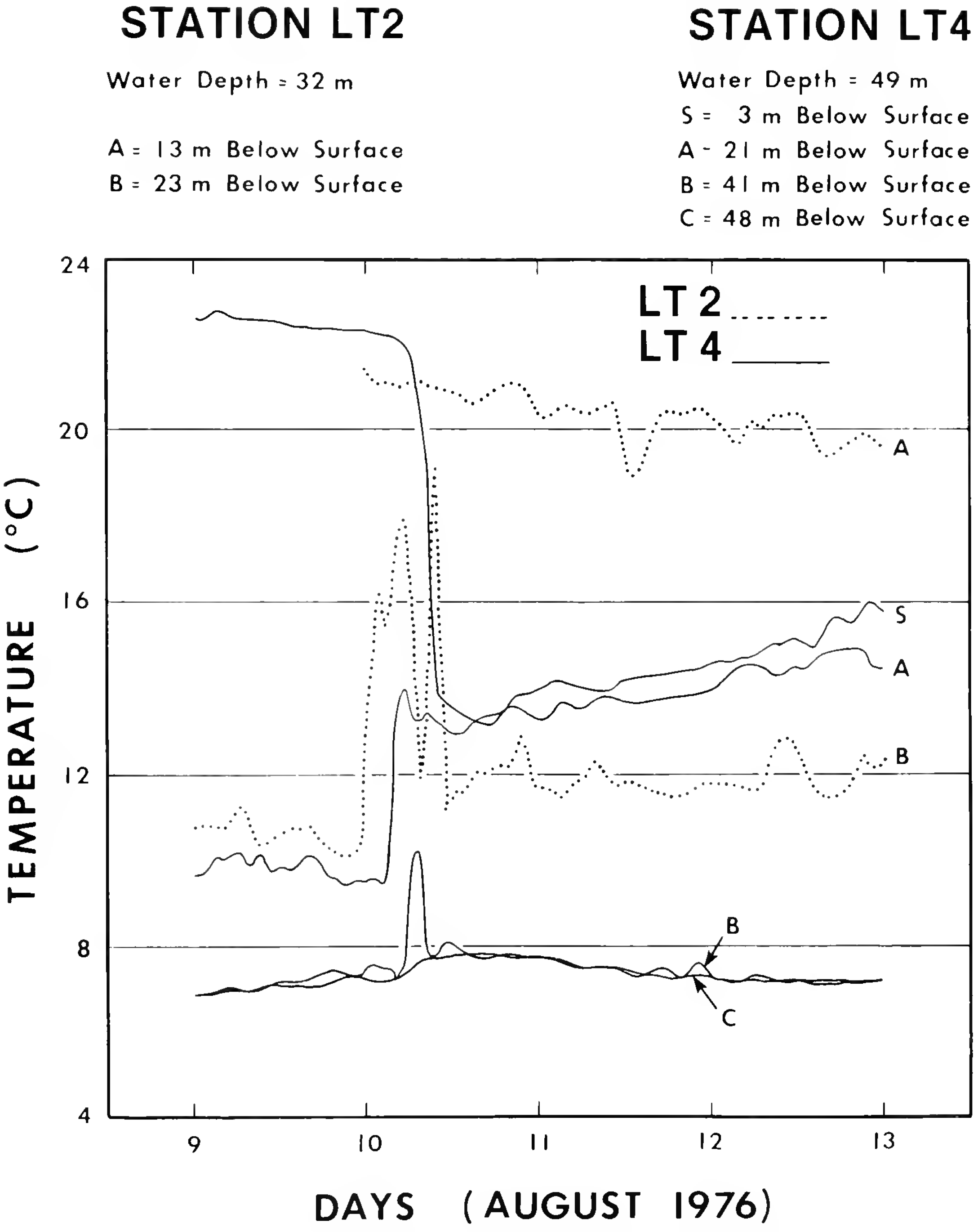

FIGURE 7–7.—Seawater temperature data from stations LT2 and LT4 during passage of hurricane Belle, August 9-13, 1976.

bottom at station LT4, there was little temperature response below the thermocline to suggest mixing of D.O. across the pycnocline.

We conclude that despite strong winds and surface waves hurricane Belle was too small and passed too rapidly to have had a lasting effect on either the advection or vertical mixing processes in the Bight.

## SUMMARY

Our principal objective was to explore the differences between currents observed in 1975 and in 1976 as a possible cause of, or contribution to, the important differences in D.O. concentrations observed during these 2 years. Insufficient flushing of the coastal waters could be an important factor in the depletion of the D.O. reservoir. A distinct difference was observed in the flow beneath the pycnocline in the area of anoxia off New Jersey. The weakened flow and reversal of direction in 1976 altered the usual pattern of material transports in the Bight. Much is still unknown about mechanisms of shelf circulation and its variability, but one major influence certainly was the period of southerly and southwesterly winds from about J.D. 125–215 (early May through early August). Although these winds were not particularly unusual on any given day, their direction was persistently opposite the normal southwestward flow of shelf waters, and their cumulative effect over more than 2 months must have been considerable. Similar reversals of surface currents off New Jersey in summer were reported during the 1960s (Bumpus 1969). Bumpus primarily attributed these reversals to the low river discharge at the time. Anoxia or mass mortalities were not associated with these events.

A likely reason that the southwesterly winds evoked so little response in water below the pycnocline off Long Island is that the water is about half again as deep off Long Island as off New Jersey. The pressure gradient response to wind stress in shallow water is expected to be nearly inversely proportional to depth, hence the shoaler waters off New Jersey are expected to be more responsive to local winds. Another possible cause of the weaker perturbation of the current off Long Island is the spatial pattern observed in the wind stress (ch. 3). Wind stress was generally parallel to the shelf contours off New Jersey, but crossed the coast at a considerable angle off Long Island. Csanady (1976) explained that the alongshore component of wind stress is more important than the cross-shelf component in its influence on currents.

During the period of observations, upwelling occurred primarily in association with the current perturbation off New Jersey, but not off Long Island. Before this time, however, upwelling occurred consistently off Long Island and may have contributed indirectly to the low D.O.'s observed by advection of nutrients into the region. Notable here (clearer in ch. 8) is that during late spring and early summer 1976, circulation below the thermocline was favorable off New Jersey but not off Long Island for concentration of *Ceratium tripos* by the mechanism described in chapter 9, part 1. The average onshelf flow (nearly 1.5 cm/s) observed off New Jersey during the 2 months before initial discovery of the benthic mortalities corresponds to a virtual displacement of about one-third the total shelf width per month. This is enough to have swept a large amount of these organisms from the outer shelf onto the inner shelf off New Jersey.

We infer from the relatively minor response of water below the pycnocline, first, that even though hurricane Belle's winds were intense, its rapid rate of passage was such that its impact on vertical mixing below the thermocline in the Bight was not especially significant. To the extent that wind-induced mixing may result in asymmetric, upward, turbulent entrainment of water across the thermocline, rather than symmetrical vertical mixing, then very little downward flux of oxygen into the bottom water would occur under even more extreme conditions than those of hurricane Belle. Second, we infer that reduced vertical mixing as a result of anomalously low summer wind speeds is not a likely cause of the low D.O. concentration observed during some years. In the New York Bight every summer the density stratification is sufficiently strong that normal or even greater than normal wind-induced mixing cannot effectively transfer D.O. across the pycnocline. This implies that, once the summer stratification has become established, the only physical mechanism for oxygen renewal is by advection or by mixing along isopycnal surfaces that typically slope upward in the offshelf direction, but at very small angles. There is, of course, a period of time in spring and again in autumn when establishment or destruction of the pycnocline is critically dependent upon the occurrence and timing of atmospheric events.

## ACKNOWLEDGMENTS

The officers and crew of the NOAA ships *Researcher* and *George B. Kelez*, are largely responsible for the current meter data used herein. D. Ortman, N. Larsen, and K. Callery also assisted in this work.

## REFERENCES

Beardsley, R. L., Boicourt, W. C., and Hansen, D. V., 1976. Physical oceanography of the Middle Atlantic Bight. *Amer. Soc. Limnol. Oceanogr. Spec. Symp.* 2:20–34.

Bumpus, D. F., 1969. Reversals in the surface drift in the Middle Atlantic Bight area. *Deep-Sea Res.* 16 (suppl.):17–23.

Bumpus, D. F., 1973. A description of the circulation on the continental shelf of the east coast of the United States, *Progress in Oceanography* 6:111–157, Pergamon Press.

Csanady, G. T., 1976. Mean circulation in shallow seas, *J. Geophys. Res.* 81(30):5389–5399.

Hansen, D. V., 1977. Circulation, *MESA New York Bight Atlas Monogr.* 3, New York Sea Grant Institute, Albany, N.Y., 23 pp.

Mayer, D. A., Hansen, D. V., and Ortman, D. A., 1979. Long-term current and temperature observations on the Middle Atlantic shelf, *J. Geophys. Res.* 84, No. C4:1776–1792.

Ortman, D., 1978. Current meter data processing and quality control methods, *MESA Tech. Rep.* ERL, NOAA Environmental Research Laboratories, Boulder, Colo.

Segar, D. A., and Berberian, G. A., 1976. Oxygen depletion in the New York Bight Apex: Causes and consequences, *Amer. Soc. Limnol. Oceanogr. Spec. Symp.* 2:220–239.

Swanson, R. L., Hansler, G. M., and Morotta, J., 1977. Long Island Beach pollution: June 1976, *MESA Spec. Rep.*, NOAA Environmental Research Laboratories, Boulder, Colo.

Wu, J., 1969. Wind stress and surface roughness at air-sea interface, *J. Geophys. Res.* 74(2):444–445.

## Oxygen Depletion and Associated Benthic Mortalities in New York Bight, 1976

# Chapter 8. Diagnostic Model of Water and Oxygen Transport

*G. Han, D. V. Hansen, and A. Cantillo*[1]

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## INTRODUCTION

To thoroughly analyze the 1976 oxygen depletion in New York Bight, the transport of oxygen through the area by currents must be carefully considered. Here the time-averaged water and oxygen fluxes through certain segments of the Bight during the period of anoxia development in May and June 1976 are calculated. Segment boundaries and station locations are shown in figure 8–1.

A simple mass transport model is employed to analyze the oxygen balance, using observations of density, oxygen, and current velocity fields to estimate the various terms. Our major contribution here is an estimate of the water fluxes,utilizing a vorticity balance diagnostic model of the steady-state circulation field from May 18 to June 29, 1976. This time interval was selected because suitable data were available and because the dissolved oxygen (D.O.) concentration was decreasing rapidly, but anoxia had not yet developed. Thus, the role of oxygen and water fluxes in the development of the anoxic condition can be compared to the observed changes of D.O. with time. This will result in the estimate of the net oxygen utilization rates in each segment and the evaluation of the role of water transports on the net utilization rates.

Segar and Berberian (1976) calculated oxygen utilization rates in the Bight Apex. Studies have also been done on the utilization of other dissolved constituents, such as nutrients (Garside et al. 1976).

Previous studies have been hampered by poor knowledge of water transports. Investigators have been forced to resort to arbitrarily chosen and vaguely defined volumes and flushing times to complete their analyses. Because chemical reactions frequently depend on concentrations, and most problems involve finding concentrations that

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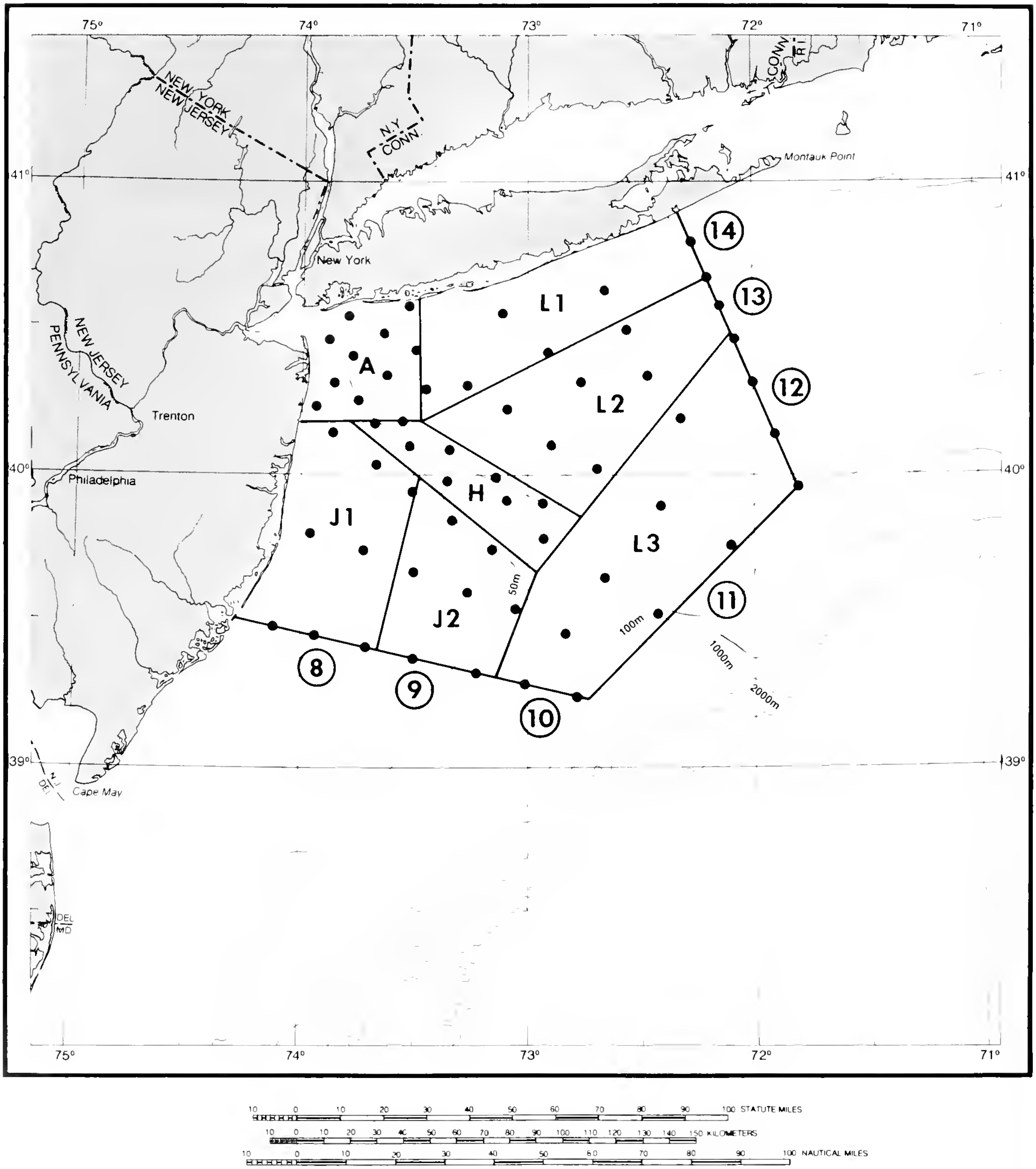

FIGURE 8-1.—New York Bight station locations, segment numbers, and boundary designations for diagnostic model of water and oxygen transport

result from the loading of an area, the determination of mixing volumes and transport rates is critical. Cases of point loadings are difficult to approach because we must know the details of advection and diffusion processes on smaller time and space scales than is usually possible. In addition, large concentration gradients complicate computation procedures and introduce errors in the results. When a substance is well distributed over a region, diffusion processes can be neglected by averaging over a large volume. Then simpler models of mass flow rates can be assumed and longer time and space scales can be used, which are usually a better match to the scales of observations.

Previous studies of transport in the Bight followed salt balance methods initiated by Ketchum et al. (1951). Their studies of the distribution of physical properties produced estimates of flushing (residence) times based upon dilution of seawater by the Hudson River outflow. Estimates of this sort may be valid for the Apex, where salinities are often low enough to make an accurate calculation. When considering the larger area of the continental shelf, however, the alongshore component of circulation, which usually parallels the contours of the salinity distributions, produces far greater flushing in a small area of the shelf than a dilution ratio calculation would indicate.

## MODEL DESCRIPTION

### Theory and Averaging Schemes

The basis for transport modeling is the conservation of material equation

$$Dc/Dt = \Sigma s \tag{1}$$

where $c$ is the concentration of the material, $\Sigma s$ is the sum of sources and sinks, and $D/Dt$ is the total or material derivative. Molecular diffusion effects are ignored here.

When working in a Lagrangian coordinate system (following a parcel of water), eq. (1) describes the balance between the time rate of change and the net production ($\Sigma s > 0$) or net utilization ($\Sigma s < 0$) of the constituent. This strategy is used in laboratory experiments and sometimes attempted in field studies. In most field studies, however, measurements are made in an Eulerian coordinate system at fixed points in space so that material is advected past the points of observation. In this system the material derivative must be expanded and eq. (1) is written as

$$\partial c/\partial t + \nabla \cdot (\mathbf{u}c) = \Sigma s \tag{2}$$

where $\partial c/\partial t$ is the locally observed rate of change of concentration, $\mathbf{u} = (u, v, w)$ is the velocity vector, and $\nabla = \partial/\partial x, \partial/\partial y, \partial/\partial z)$ is the divergence operator. The equivalent relationship for conservation of water mass is

$$\partial \rho/\partial t + \nabla \cdot (\mathbf{u}c) = 0. \tag{3}$$

Equation (2) shows that the material derivative is composed of the local time rate of change of $c$ and the divergence of the flux of $c$; it is the sum of these which balances the sum of production and utilization. All these quantities are evaluated at a fixed position.

Since we cannot accurately estimate these gradients on infinitesimal time and space scales, we must approximate the derivatives so that the observed time and space gradients are consistently treated. When observations in time are made at a spacing of $T$ days, the resolution in space must be of the order of $L = UT$, where $L$, $T$, $U$ are the characteristic length, time, and velocity. Thus, if $T$ is of the order of 10 days and $U$ is 5 cm/s or 5 km/d then $L$ must be of the order of 50 km. If the temporal rates of certain processes are inferred from observations at time interval $T$, then $L$ is the smallest length scale that can be resolved.

One way to approximate spatial gradients is to smooth the data over a selected volume segment. Transports between segments are then treated as advective fluxes. Diffusion effects are introduced by assuming that each volume is well mixed. Any material entering the volume is "instantaneously" mixed over time $T$ throughout the volume. The effective diffusion thus introduced contributes to the transport on scales smaller than those resolved.

Because New York Bight waters were strongly stratified during the period of this study, we will average over an upper layer and over a lower layer, separated at the pycnocline. Vertical diffusion between layers is neglected because the strong stratification implies inhibited vertical mixing; vertical advective fluxes are included.

If observations are available at two discrete times, $t = t_1$ and $t = t_2$, we must decide how to approximate the time derivative. We know the concentrations at $t_1$ and $t_2$, but there is no way of knowing $\partial c/\partial t\,|_{t\,=\,t_1}$. If we approximate $\partial c/\partial t$ by $\Delta c/\Delta t$ where $\Delta c = (c_2 - c_1)$ and $\Delta t = (t_2 - t_1)$, then we should use concentration and velocity data interpolated to $t = (t_1 + t_2)/2$.

After performing appropriate volume and time averages, the discrete version of eq. (2) becomes

$$\frac{\Delta VC}{\Delta t} + \Sigma QC + Q_v C = \Sigma s, \tag{4}$$

and assuming constant density eq. (3) becomes

$$\frac{\Delta V}{\Delta t} + \Sigma Q + Q_v = 0, \tag{5}$$

where the capitalized letters are now volume averaged quantities and $Q$ is the outward horizontal volume flux, $Q_v$ the vertical flux, $\Sigma QC$ the sum of divergence of concentration flux around the boundaries of each segment, and $V$ the segment volume. Assuming incompressibility, water density has been taken equal to a constant density, $\rho_o$, in eq. (5). To estimate these fluxes, we will use a diagnostic model of shelf circulation. Once the advective terms of eq. (4) are known, the time rate of change of concentration term can be related to the source and sink term.

### Diagnostic Model

Computing water transport on the shelf requires spatial resolution of a velocity field greater than is normally available from current meter observations alone. Calculation of the velocity field requires understanding the dynamics of shelf circulation; that is, understanding how water moves in response to the imposed forces, as well as having adequate measurements of all the various forcing and indicator fields.

One major forcing field is wind stress. Only a portion of water transport on the shelf, however, is in the frictional layer driven directly by wind. Simple Ekman theory explains how a wind stress along a coastline will transport surface water perpendicular to the coast, resulting in a cross-shelf gradient in surface elevation. The response to this force is a geostrophic velocity along the shelf. Horizontal density gradients and bottom friction will modify the vertical profile of horizontal velocity, but it is mainly the forcing by seasurface elevation gradients (set up by the wind stress) that determines the gross characteristics of the flow.

At present we cannot calculate the barotropic component of flow from wind data alone. Winds acting on different sections of the Middle Atlantic Bight produce varied responses, particularly at a bend in the coastline, such as in the New York Bight. A "prognostic" dynamic model should be able to calculate flow directions, given wind stress, river discharge, bottom topography, and other boundary conditions. Such a model would probably have to include the entire Middle Atlantic Bight and be able to approximate many processes we now understand only poorly.

A more limited approach, but one that can yield the required flow field, is to construct a "diagnostic" model as is done here. The model is a steady-state representation of the flow for which it is assumed that the structure of the density field is known and is not being changed by the velocity field. The general flow condition must be known from current measurements at appropriate points to calculate boundary conditions which strongly influence the flow. This type of modeling might alternatively be considered a formalism for interpolating or synthesizing over the field of available data. The result is tightly bound to the observed data. Wind stress does not enter the formulation explicitly but is reflected in the boundary conditions, calculated from current velocity data for the open boundaries and from a no-flux condition for the solid boundaries. Only the curl of the wind stress enters the model, and this is much less important than the other terms for the cases considered.

The model addresses a condition which is not truly steady state but is actually a time average over a certain period. The period should be long enough to span any storm events but short enough to allow the approximation of an unchanging density field. The diagnostic model concept is supported by recent work of Csanady (1976), who hypothesized that short-term storms generate flows which tend to organize the density field into patterns such that the time-average flows can be analyzed from the density patterns with a simple linearized equation of motion. Thus, a reasonable averaging period is of the order of 5 to 30 days.

The fundamental physical problem reduces to solving a differential equation for the shape of the sea surface. The model equation is:

$$\rho_o g J\,(\zeta,H) + gJ(\alpha,H) + \mathbf{k}\cdot(\nabla\times\vec{\tau}_w) + \gamma g\rho_o\left\{\frac{\nabla^2\alpha}{\rho_o} + \nabla^2\zeta\right\} = 0, \qquad (6)$$

where $\zeta$ is the elevation of the sea surface, $H$ bottom depth, $\vec{\tau}_w$ surface wind stress, $\gamma$ linear bottom friction parameter taken as 1600 cm following Csanady (1976), $\rho_o$ reference density, $\mathbf{k}$ unit vector in the vertical direction, $g$ gravitational acceleration, $\alpha = \int_{-H}^{0} \rho\, dz$, where $z$ is the vertical coordinate, zero at the surface and positive upward, and

$$J(\xi,\eta) = \left(\frac{\partial\xi}{\partial x}\frac{\partial\eta}{\partial y} - \frac{\partial\xi}{\partial y}\frac{\partial\eta}{\partial x}\right)$$

A complete description of this equation is not possible here. Alternative forms of the model have been developed and described by Hsueh et al. (1976) and by Galt (1975). Galt's vorticity equation, used here, results from the linearized equations of motion on a rotating Earth and is derived by summing the transports in the surface Ekman layer, the geostrophic interior, and the bottom Ekman layer, and then imposing the continuity condition that the divergence of the transport must be zero. This is an extension of the classical geostrophic current calculation to include frictional layers at the sea surface and over a sloping bottom. The diagnostic variable, $\zeta$, is used as the surface boundary condition for a calculation of the geostrophic velocity profile. The equivalent condition in the deep ocean is the assumption of a depth of no motion. The terms in eq. (6) are interpreted consecutively as: barotropic-geostrophic, baroclinic-geostrophic, wind stress curl, and bottom friction components.

To aid in visualizing the equations, consider a simplified system with constant density, no wind stress curl, and no bottom friction. Then only the barotropic term remains and eq. (6) becomes

$$J(\zeta, H) = 0. \tag{7}$$

A property of the operator, $J$, or the Jacobian, is that it is zero whenever one variable in the argument list is a function of the other variable. Equation (7) is satisfied if the surface elevation contours parallel the depth contours. Thus, in this simplified case, the geostrophic velocity field at all depths is described by the $\zeta$ contours as streamlines. This flow is, of course, everywhere parallel to the bottom contours as well.

Once eq. (6) is solved for the $\zeta$ field, the geostrophic velocity profile can be calculated at any depth $z = 0$ to $z = -H$ by

$$\mathbf{u} = \mathbf{k} \times \frac{g}{f} \left\{ \nabla\zeta - \frac{z}{H} \frac{\nabla\alpha}{\rho_o} \right\} \tag{8}$$

where $f$ is the Coriolis parameter. The current profiles derived from eq. (8) are somewhat simplified in that the vertical shear associated with the density gradients is assumed uniform. The complete velocity profile can be formed by superimposing the proper profiles for a surface and bottom Ekman layer.

## MODEL APPLICATION AND RESULTS

### Water Fluxes

Results from the diagnostic model are used to calculate the water flux in the layer below the pycnocline. To apply the diagnostic model, the data required are depth ($H$), vertically integrated density ($\alpha$), wind stress field ($\vec{\tau}_w$), and appropriate boundary conditions. To calculate the boundary conditions on $\zeta$, current meter data are needed on the two cross-shelf boundaries.

Model equation (6) is solved for the surface elevation field using a finite element technique, developed by Galt (1975), on a grid shown in figure 8–2, where each triangle vertex is an STD station location. Values of $H$, $\alpha$, and $\vec{\tau}_w$ are specified at these vertices. The station grid and density data were used from MESA cruise XWCC–9 (May 17–24, 1976). Several stations were added near the Hudson Shelf Valley to better approximate the sharp depth gradients. Values of $\alpha$ were smoothly interpolated to these new stations. Figures 8–3 and 8–4 show the depth and $\alpha$ fields used in the calculations. Wind stress was calculated from EB34 wind velocity data; EB34 is located at midshelf just northeast of Hudson Shelf Valley (ch. 7, fig. 7–1). Wind stress was taken as constant over the domain (grid).

Current meter records from the MESA 1976 survey were averaged over four separate time periods spanning May 18 to June 29, 1976. The four periods were selected so that wind and current conditions were relatively uniform over each interval. The averaged currents and wind stresses are shown in figure 8–5.

To solve the model equation, the surface elevation field must be specified around the entire boundary because (6) is an elliptic equation. By calculating $\nabla\zeta$ between each boundary point, $\zeta$ is then calculated relative to the northeast corner elevation, fixed arbitrarily at 10 cm because only $\nabla\zeta$ enters into the calculation. There are three types of boundaries: 1) solid boundaries on the New Jersey and Long Island coasts for which no-flux condition is imposed; 2) cross-shelf open boundaries for which elevations are calculated from velocity data on those boundaries; and 3) shelf-break open boundary for which the elevations are interpolated between the seaward points on the cross-shelf boundaries.

In calculating the cross-shelf elevation profile, data are used from the deepest current meter on each array that is not a bottom-mounted meter. These meters, located approximately 8 m above the bottom, are used because we are attempting to model the lower layer velocities and wish to avoid the influence of bottom friction. The two velocity data points on each boundary, as shown in figure 8–5, are used to first construct a smooth profile across the shelf of velocity perpendicular to the boundaries. Then the geostrophic velocity profile (eq. 8) is used to solve for $\nabla\zeta$ along the boundary. This procedure produces values of $\zeta$ along the solid and northeastern open boundary, but on the southern open boundary only the values of $\nabla\zeta$ are known. The final $\zeta$ field is determined by evaluating several solutions of eq. (6) with varying slopes on the shelf-break boundary until a smooth flow at the southern boundary is produced. This procedure is equivalent to fine-tuning by adjusting the imposed alongshore pressure gradient. However, the nature of the equations causes the northeastern cross-shelf boundary (the major inflow boundary of the circulation) to have the greatest influence on the flow because topographic vorticity waves propagate alongshelf from that boundary. The nature of the equations is such that changing $\zeta$ on the southern boundary influences the flow only in a narrow zone adjacent to that boundary.

Once the $\zeta$ field is found from the solution of eq. (6), the velocity profile and then the transport in the lower layer are calculated by integrating eq. (8) from the pycnocline depth to the bottom and adding the transport in the bottom Ekman layer. The lower layer transport, T becomes

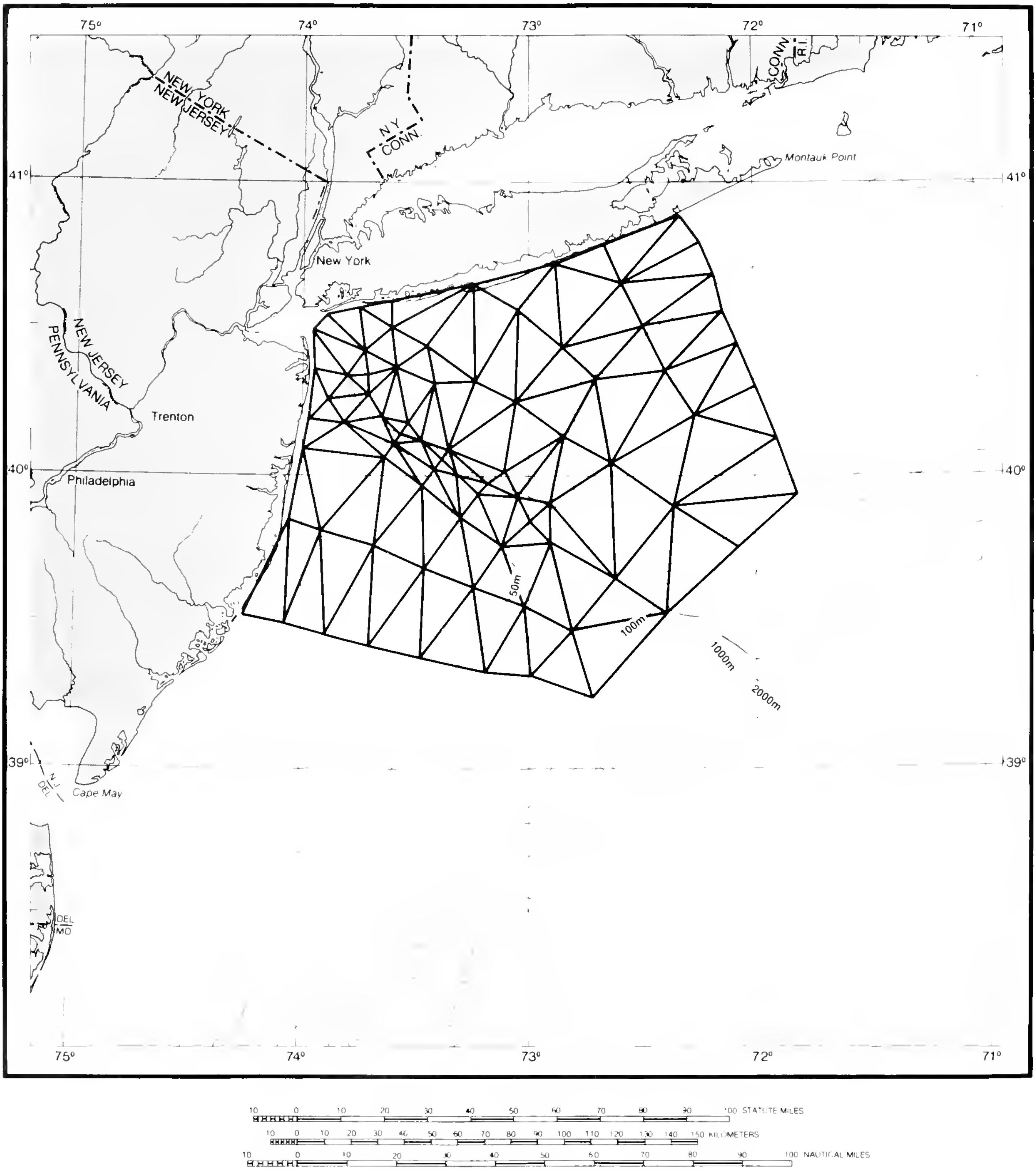

FIGURE 8-2.—Finite element triangular grid.

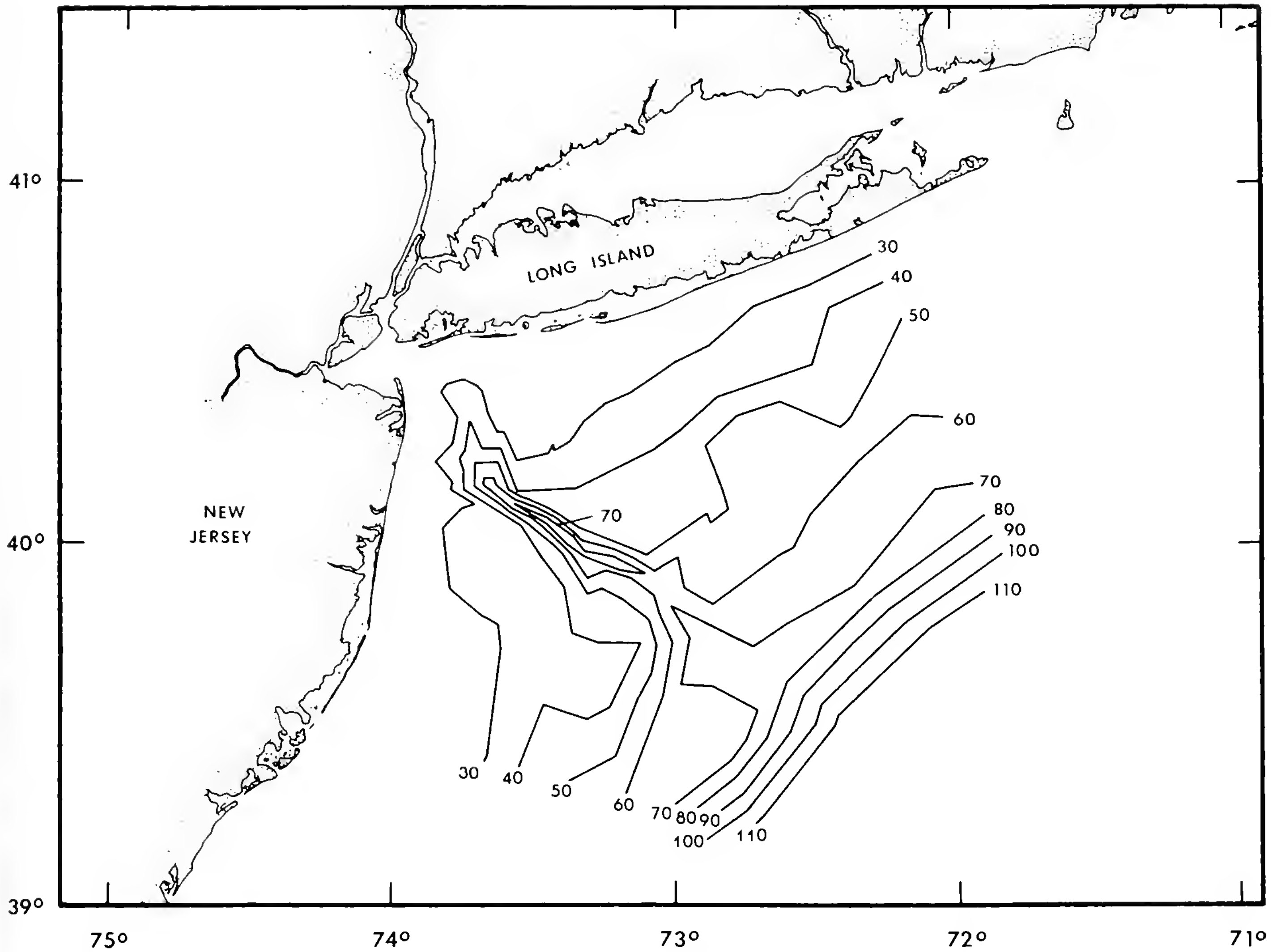

FIGURE 8–3.—Input field of total depth (m).

$$\mathbf{T} = \mathbf{k} \times \frac{g}{f}\left[\nabla\zeta(H-d) - \frac{\nabla\alpha}{H\rho_o}\left(\frac{d^2-H^2}{2}\right)\right] + \mathbf{T}_B \quad (9)$$

where the pycnocline is at $z = -d$ and where $\mathbf{T}_B$ is the transport in the bottom Ekman layer, which is expressed as

$$\begin{aligned}\mathbf{T}_B = \frac{\gamma g}{f}\Bigg\{&\Bigg[\left(\frac{\partial\zeta}{\partial x}\cos\delta - \frac{\partial\zeta}{\partial y}\sin\delta\right)\\ &+ \frac{1}{\rho_o}\left(\frac{\partial\alpha}{\partial x}\cos\delta - \frac{\partial\alpha}{\partial y}\sin\delta\right)\Bigg]\mathbf{i}\\ &+ \Bigg[\left(\frac{\partial\zeta}{\partial x}\sin\delta + \frac{\partial\zeta}{\partial y}\cos\delta\right)\\ &+ \frac{1}{\rho_o}\left(\frac{\partial\alpha}{\partial x}\sin\delta + \frac{\partial\alpha}{\partial y}\cos\delta\right)\Bigg]\mathbf{j}\Bigg\}\end{aligned}$$

where $\delta$ is the veering angle between the bottom velocity and the bottom stress taken as 10°, consistent with the theoretical results of Smith and Long (1976).

The pycnocline depth was found from vertical density profiles taken during MESA cruise XWCC–9 by averaging the depths of the top and the bottom of the pycnocline. The thickness of the lower layer $(H - d)$ and the pycnocline depth $(d)$ during XWCC–9 are shown in figure 8–6.

Each time period for averaged currents (fig. 8–5) was diagnosed separately. An example of the solution for $\zeta$ is shown for the first interval (May 18–23) in figure 8–7. From eq. (8), the velocity pattern at 8 m above the bottom is displayed in figure 8–8, along with the superimposed observed velocities. Transports in the lower layers were calculated from eq. (9) and are shown in figure 8–9. The transports are easier to interpret in schematic form, so the

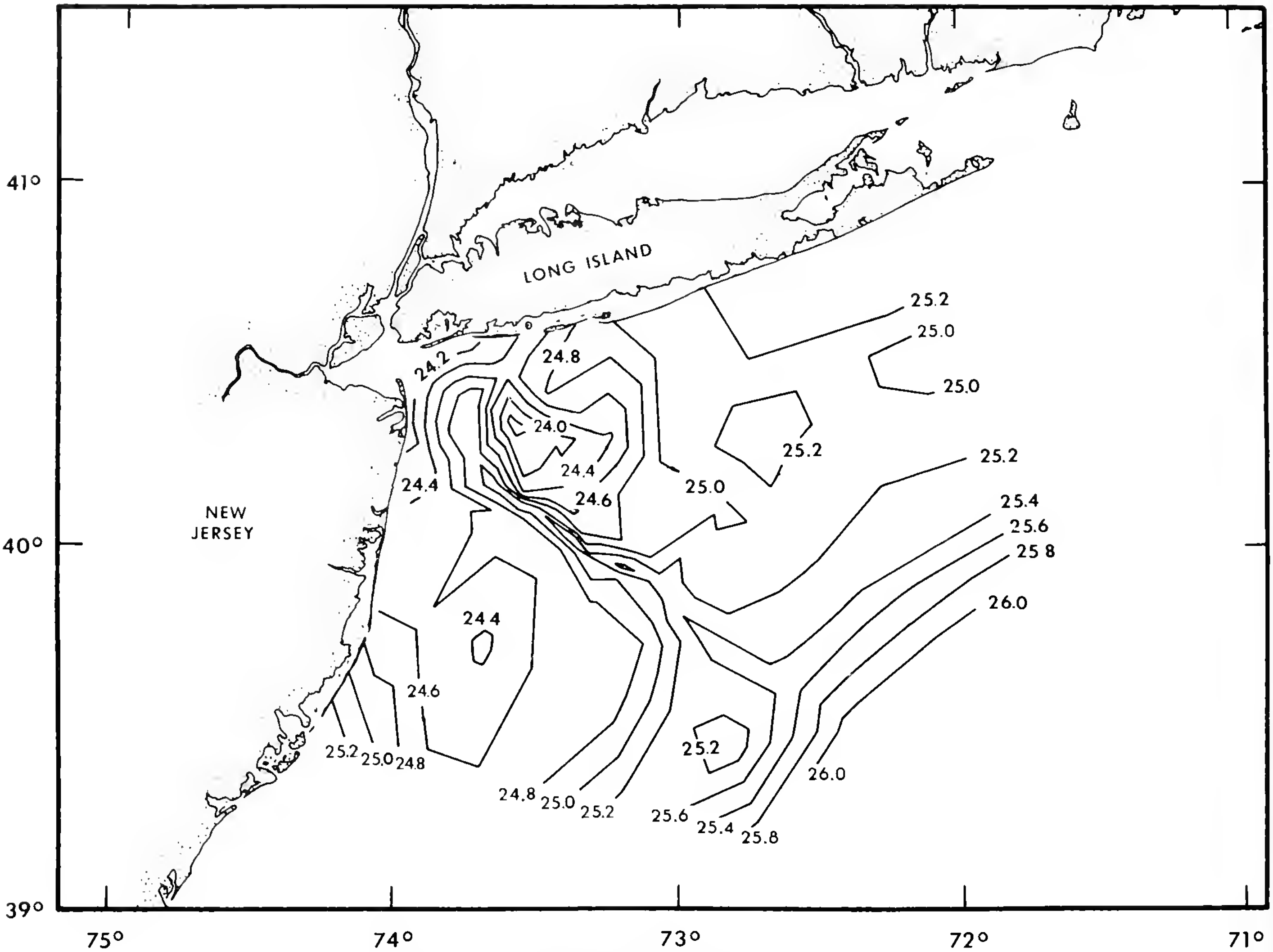

FIGURE 8–4.—Input field of α expressed as $(\alpha/H\text{-}1)10^3$. Density (sigma-$t$ units).

results for each interval are presented in figure 8–10. The average transport over the entire interval (fig. 8–11) was calculated by weighting each pattern in proportion to the duration it represents. The horizontal fluxes through each segment boundary were computed by multiplying the length of the boundary transect in each triangle by the transport component through the transect and summing over the triangles making up the transect. The vertical flux, $Q_v$, in each segment was calculated to satisfy the continuity relationship (eq. 5). The term $\Delta V/\Delta t$ in eq. (5) was estimated from the change in volume between XWCC–9 and XWCC–10. It was found to be an order of magnitude smaller than the other terms and was ignored in eq. (5) and in eq. (4). Hudson River discharge was also ignored because the magnitude of even the largest monthly average flow is an order of magnitude smaller than the fluxes in the Apex segment and would not contribute significantly to the water balance.

### Oxygen Transport

Dissolved oxygen (D.O.) data for application in eq. (4) were acquired on MESA cruises XWCC–9 and XWCC–10. The patterns of D.O. concentration are shown in chapter 2. Volume-averaged concentrations were calculated by first finding the average concentration in the upper and lower layer at each STD station. Then the thickness of each layer (fig. 8–6) multiplied by the average concentration and weighted by an area factor, taken as 1.0 for interior points and 0.5 for points on the segment boundary.

These were summed for each segment, divided by the sum of the weights, and multiplied by the segment surface area to yield the oxygen mass in each layer of each segment. The same process was repeated with the layer thickness alone to give the volume in each layer of each segment. Table 8–1 contains the values of surface area, volume, and D.O. for each segment. Because no data

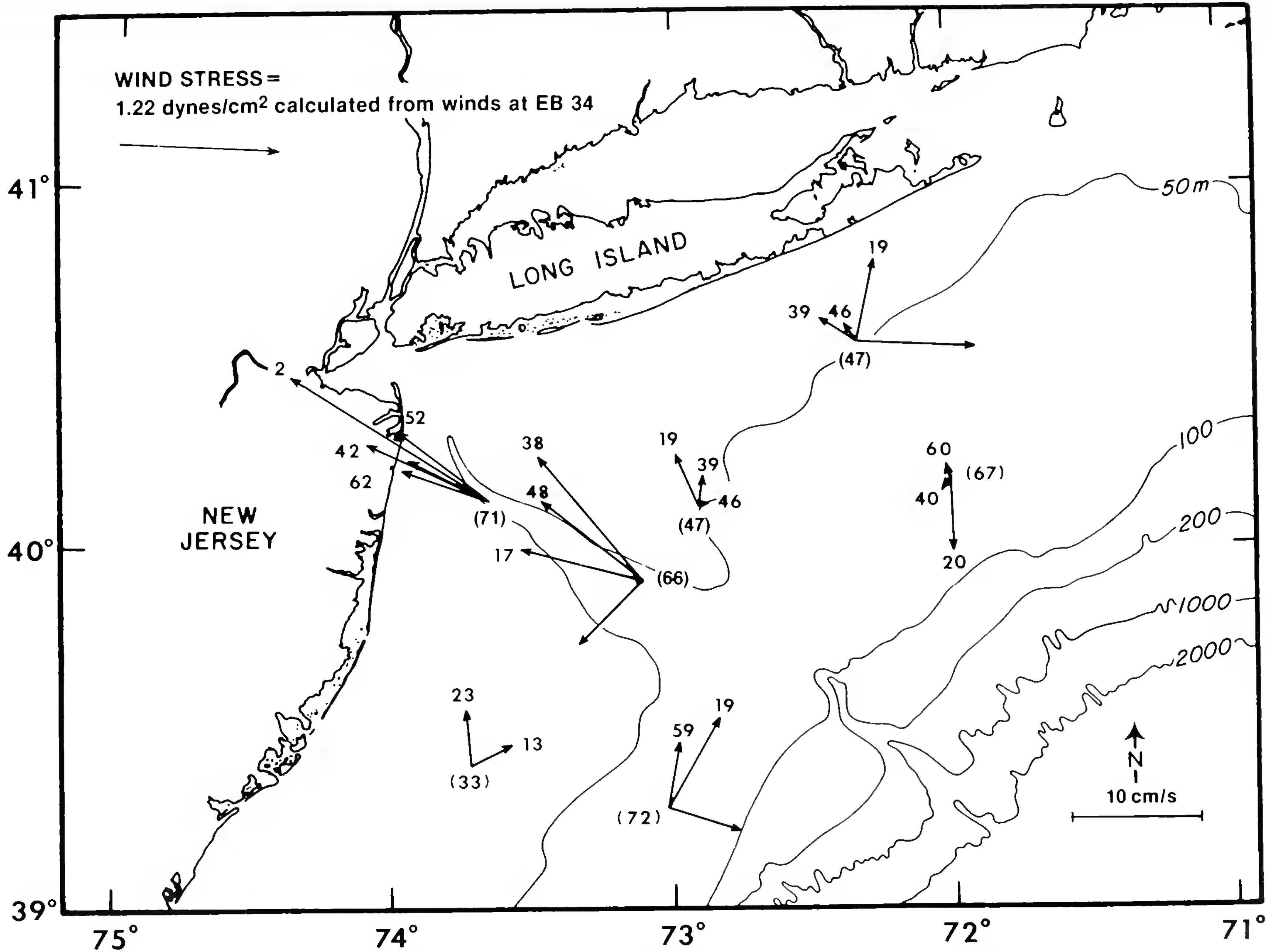

FIGURE 8–5A.—Average current velocity in New York Bight, May 18-23, 1976. Number at end of arrow indicates depth (m) of measurement; number in parentheses indicates total depth (m)

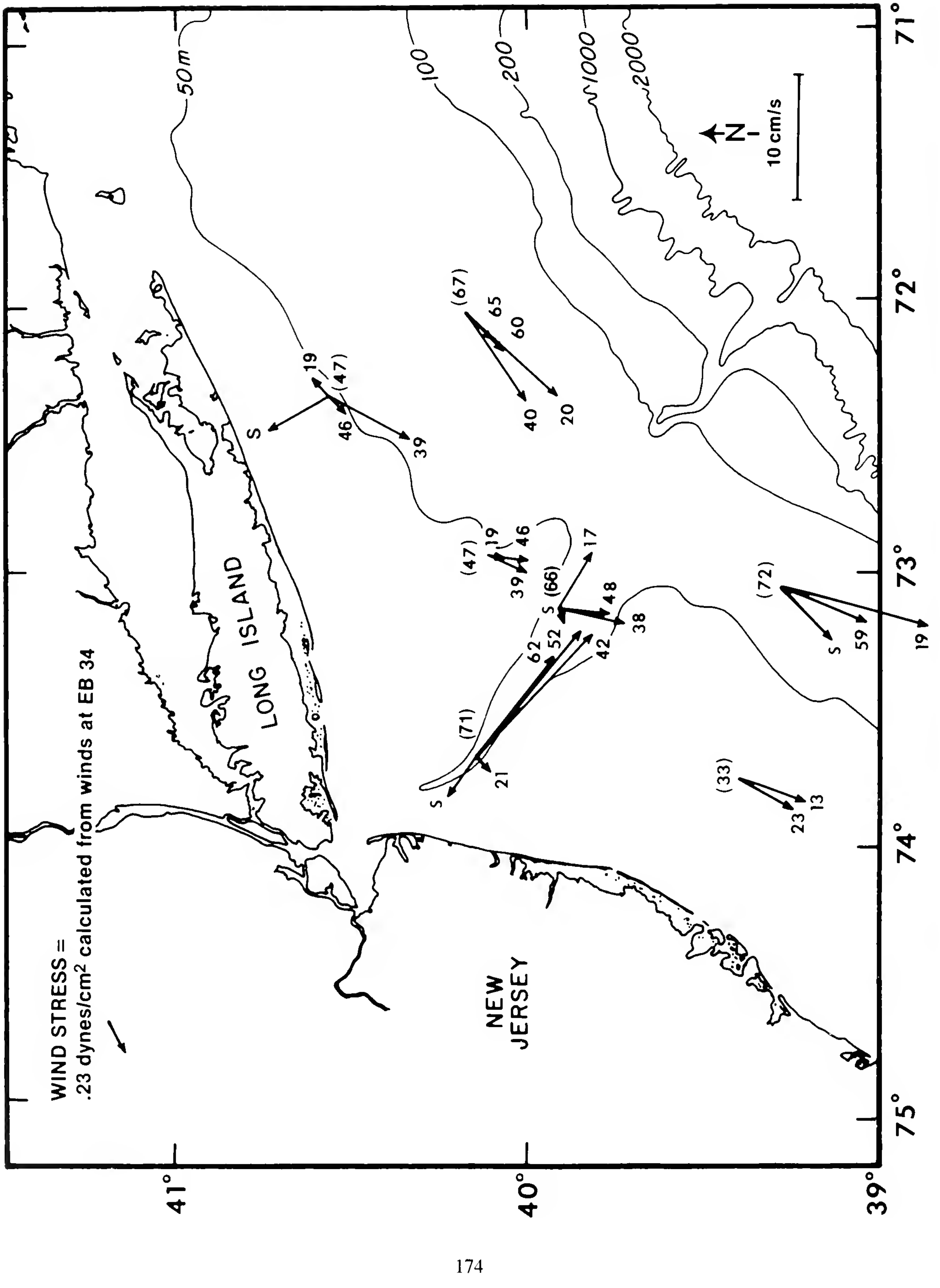

FIGURE 8-5B.—Average current velocity in New York Bight, May 23-June 3, 1976.

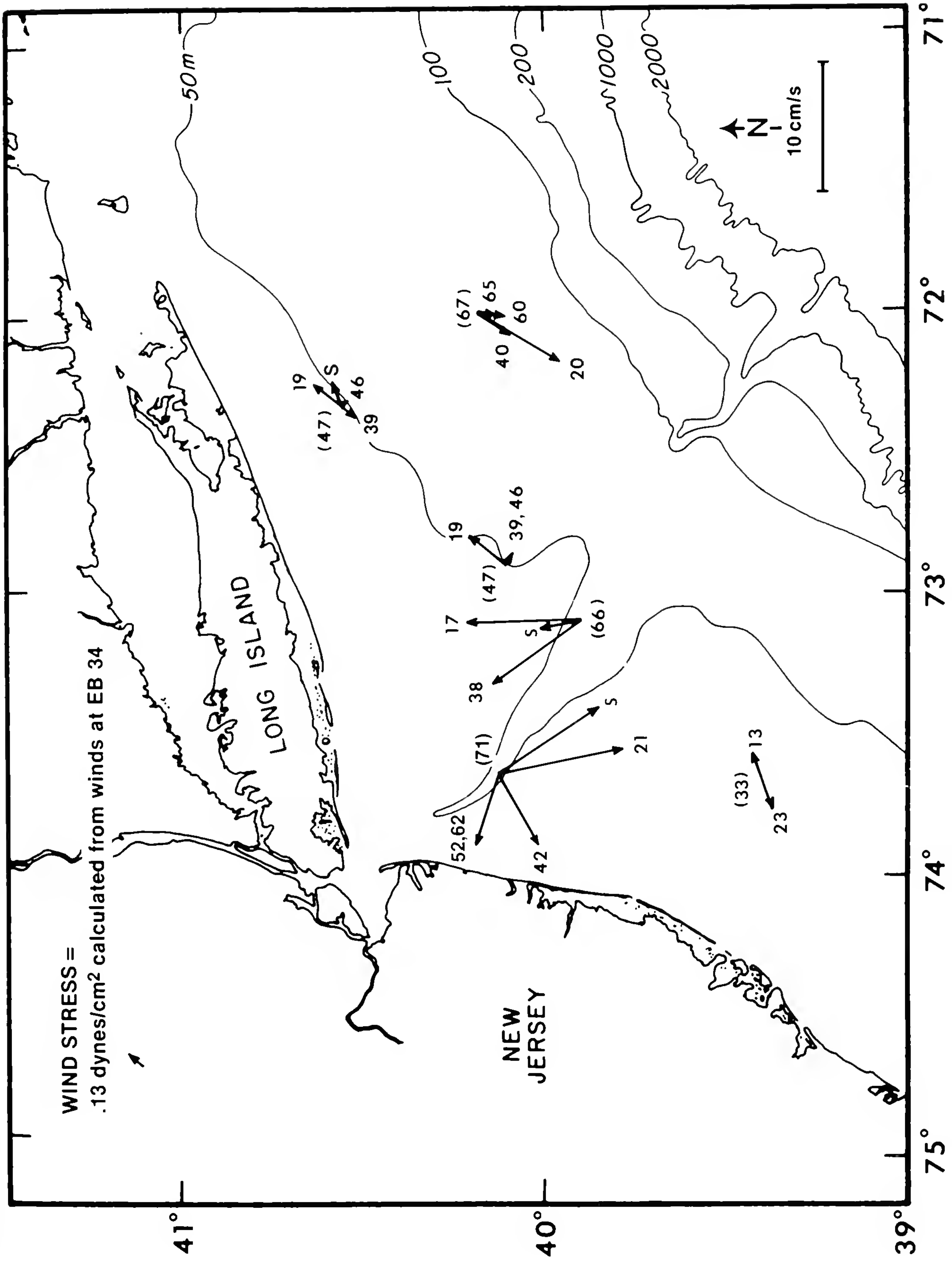

FIGURE 8-5C.—Average current velocity in New York Bight, June 3-13, 1976

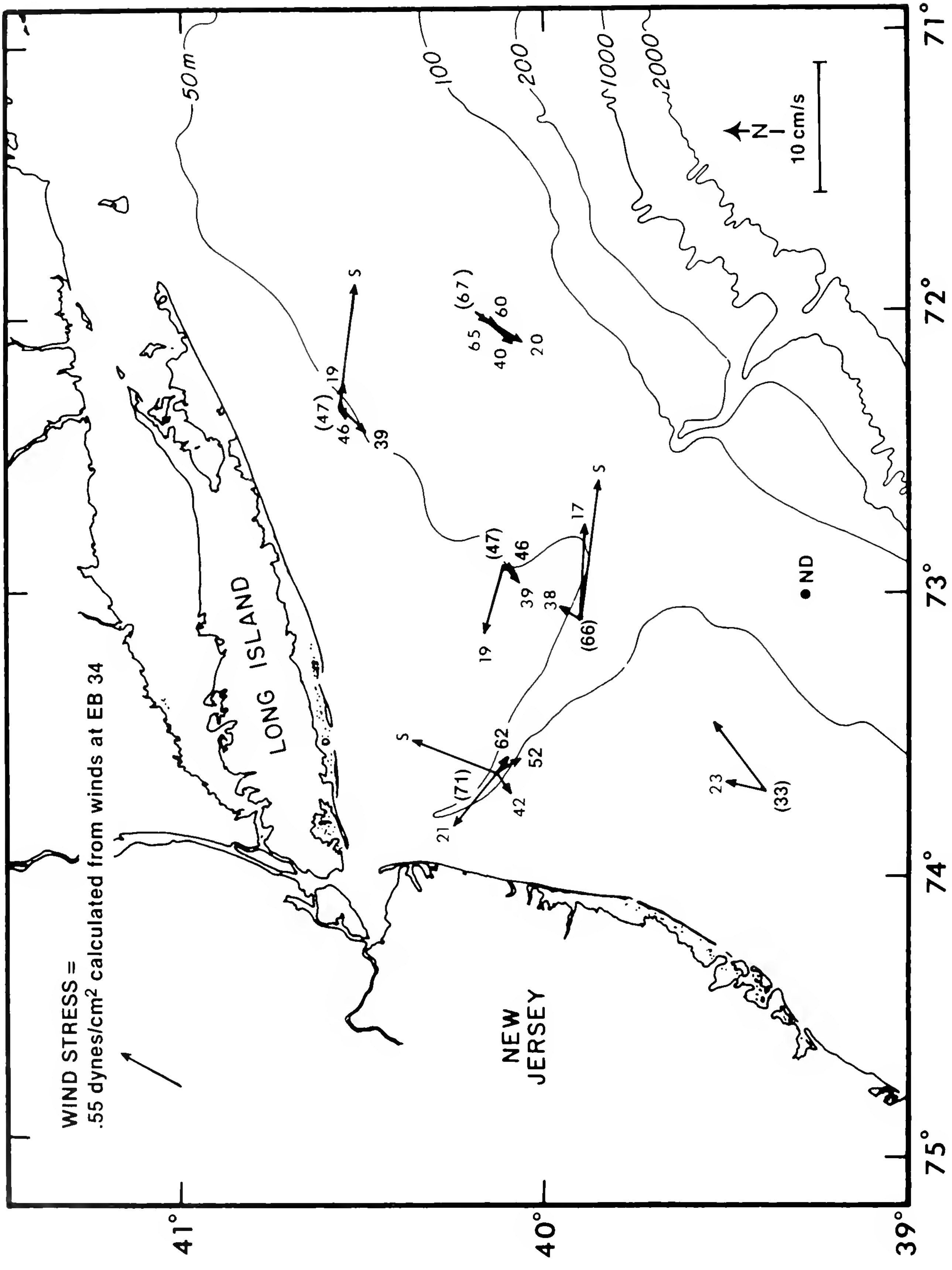

FIGURE 8–5D.—Average current velocity in New York Bight, June 13-29, 1976.

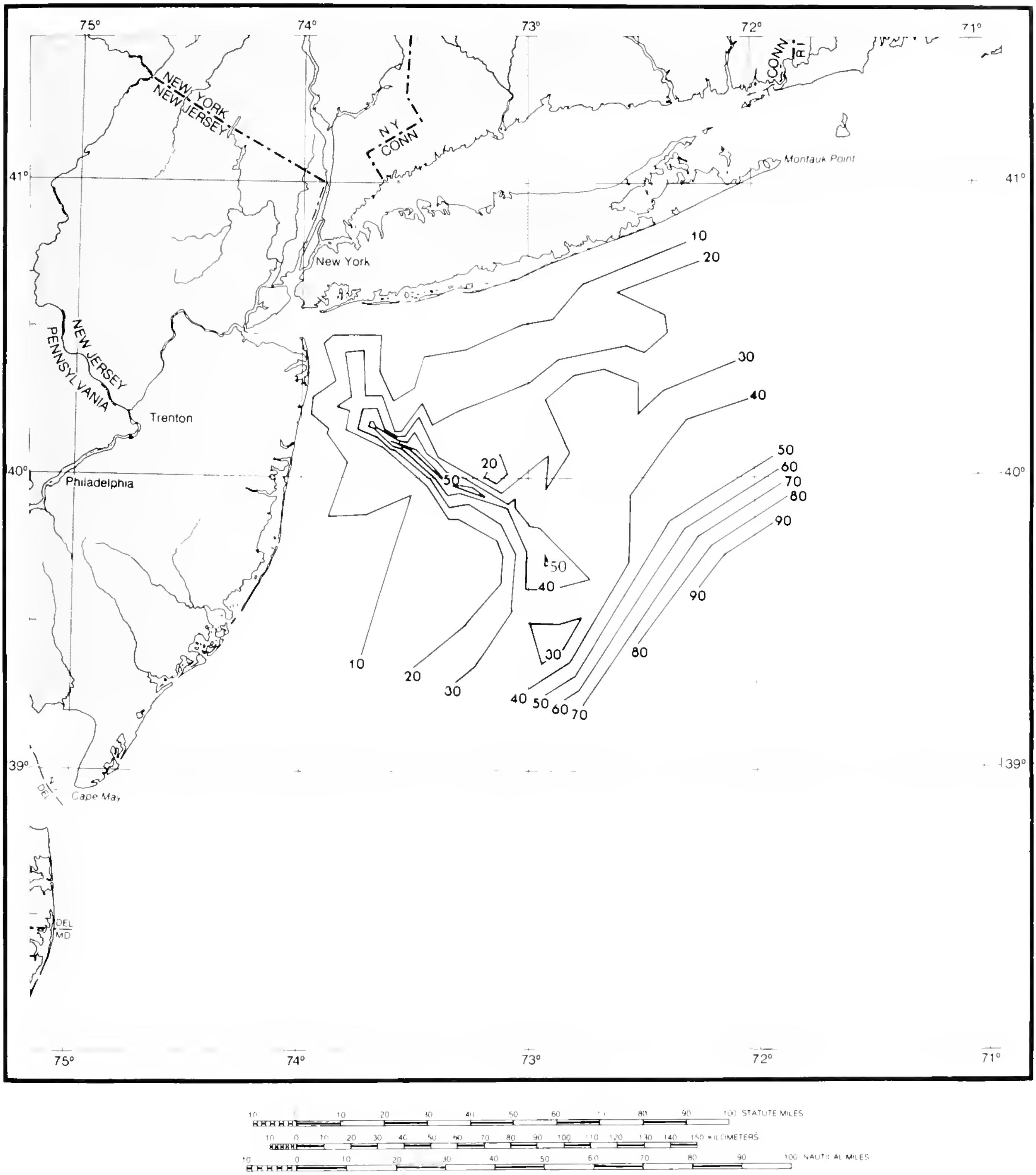

FIGURE 8-6A.—Thickness (m) of lower layer

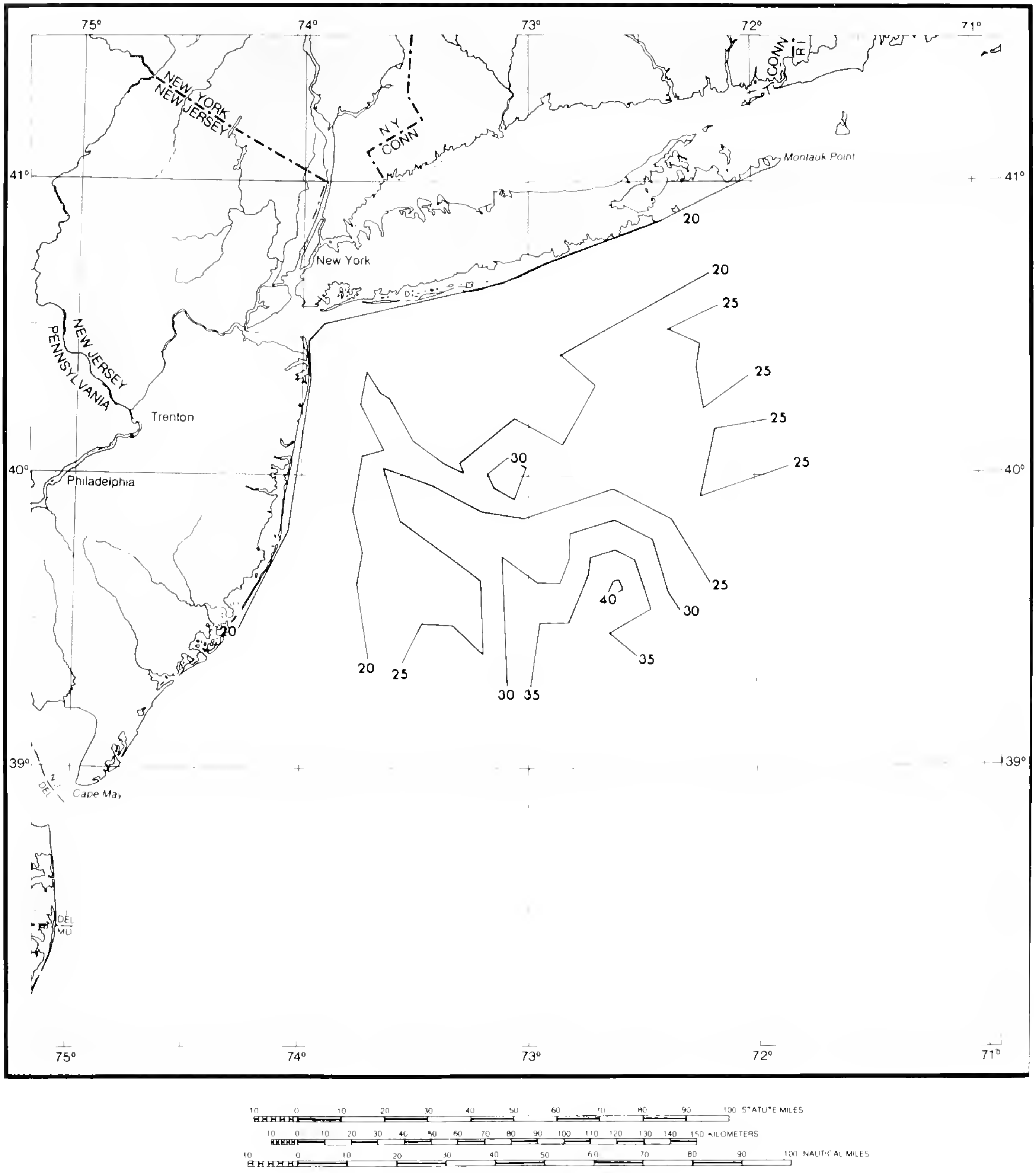

FIGURE 8-6B.—Depth (m) of pycnocline.

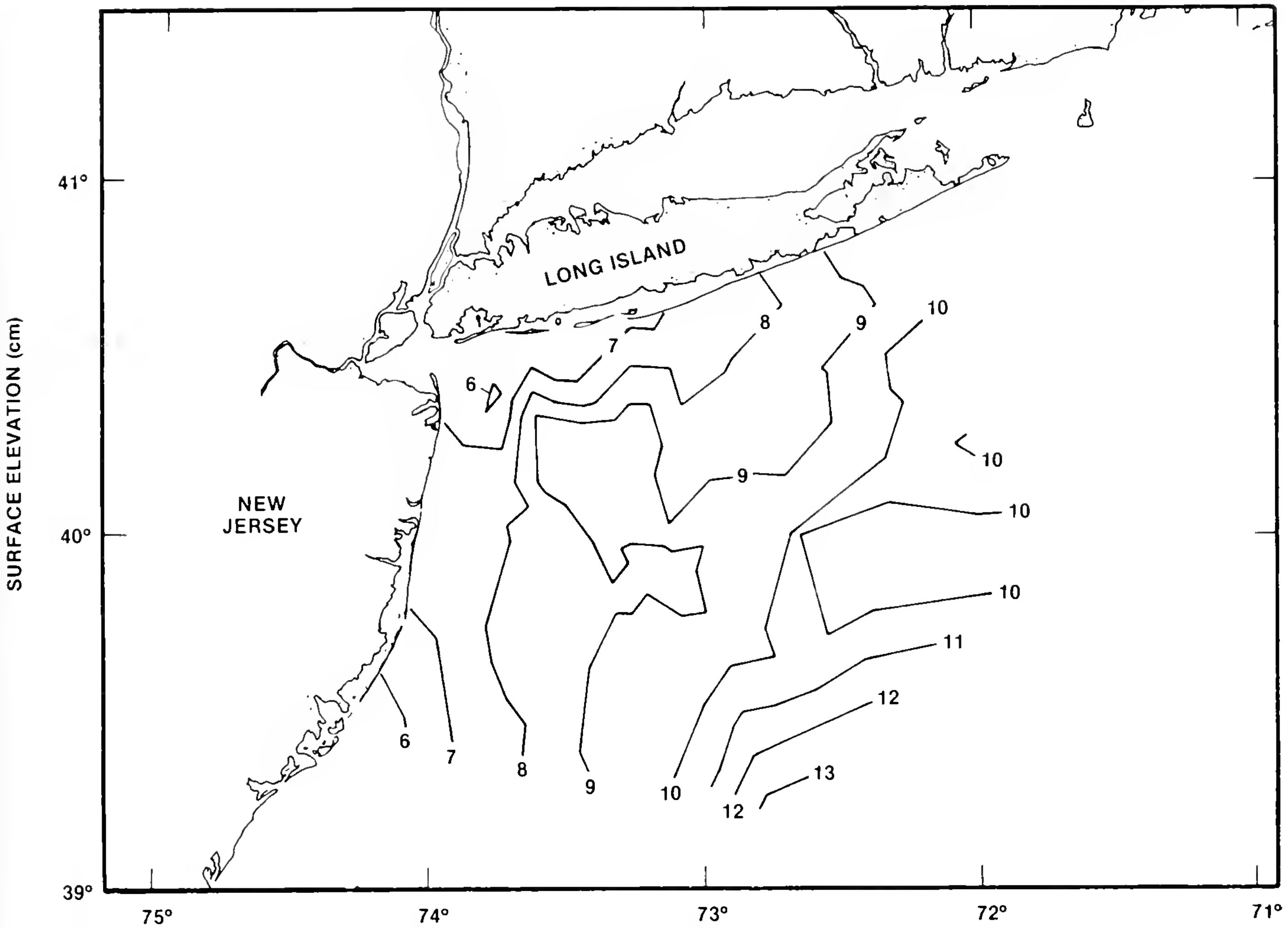

FIGURE 8–7.—Solution of model for $\zeta$, surface elevation (cm), May 18-23, 1976.

were available to find values of D.O. for regions outside the boundaries, these were approximated by vertically averaging D.O. at stations on the outside boundaries. Oxygen concentration data were not available for XWCC–10 at the northeastern and southern boundaries of the region. To compute the volume-averaged concentrations for XWCC–10, all data available in each segment were utilized. The boundary concentrations for XWCC–10 were calculated by using the same ratio between the boundary and adjacent segment concentrations as was observed on XWCC–9.

Oxygen fluxes were found for each segment boundary during the four separate intervals. The oxygen fluxes were calculated by multiplying the water flux through each segment boundary (fig. 8–11) by the oxygen being transported. The oxygen concentrations were different for each interval because they were linearly interpolated in time between the values for XWCC–9 and XWCC–10 (table 8–1) fluxes. The oxygen fluxes at each boundary were then averaged, in a manner similar to the water fluxes, to produce an average over the entire 42-day interval (fig. 8–12).

The first two terms in eq. (4) were calculated for each segment from the volume of the segment and the time rate of change on D.O. between XWCC–9 and XWCC–10 (table 8–1) and the divergence of the oxygen fluxes from the values in figure 8–12. The net utilization rate was calculated using eq. (4). Values of all terms in eq. (4) are listed in table 8–2. The residual term, $s$, is a net utilization rate incorporating all sources of oxygen other than advective fluxes, such as phytoplankton production and vertical diffusion, minus any utilization of oxygen, such as respiration of any ogranism and bacterial decay.

## DISCUSSION

Use of the diagnostic model is limited both in concept and input data to representation of circulation patterns

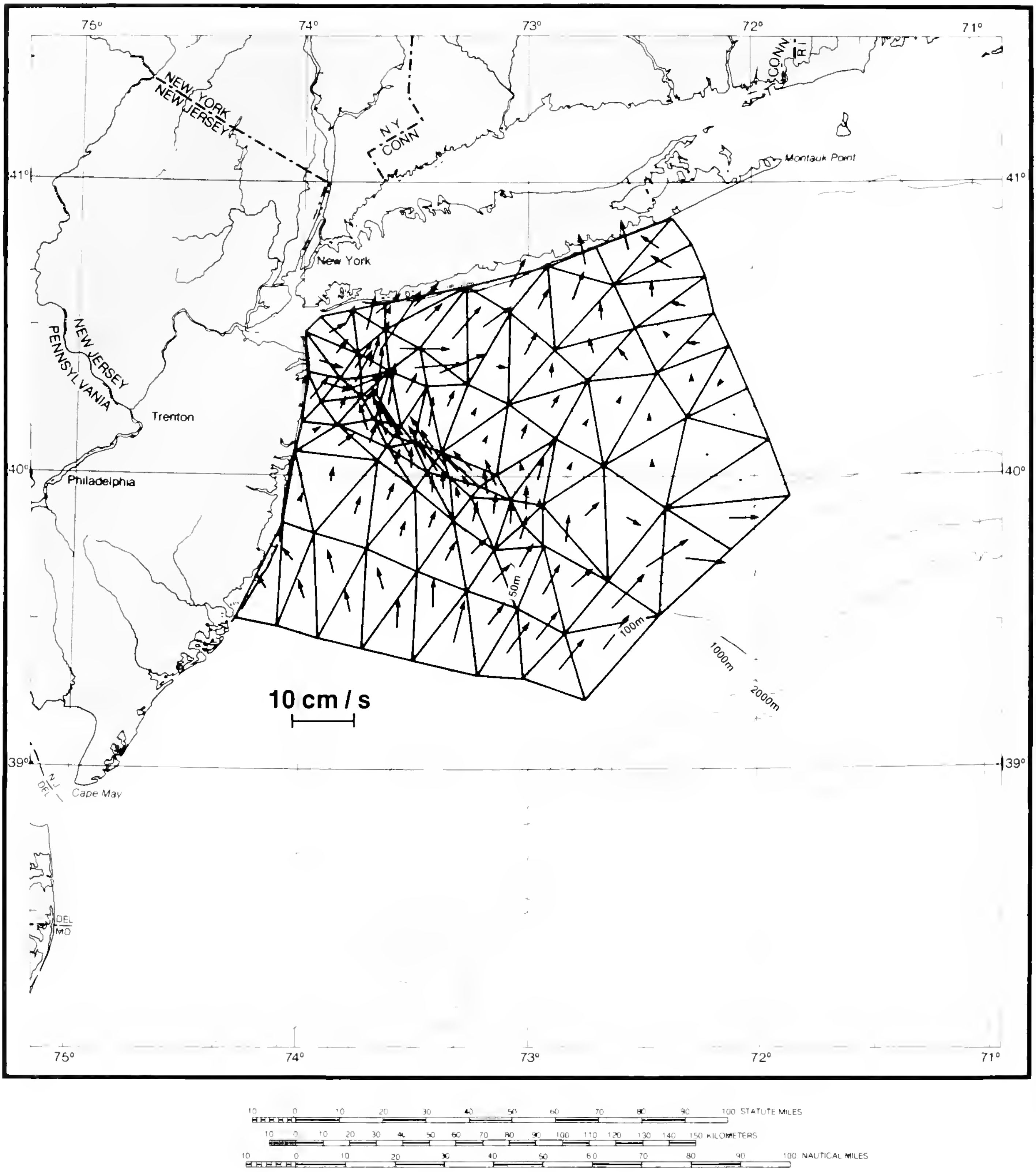

FIGURE 8-8.—Average velocity, 8 m above bottom, May 18-May 23, 1976, modeled and observed.

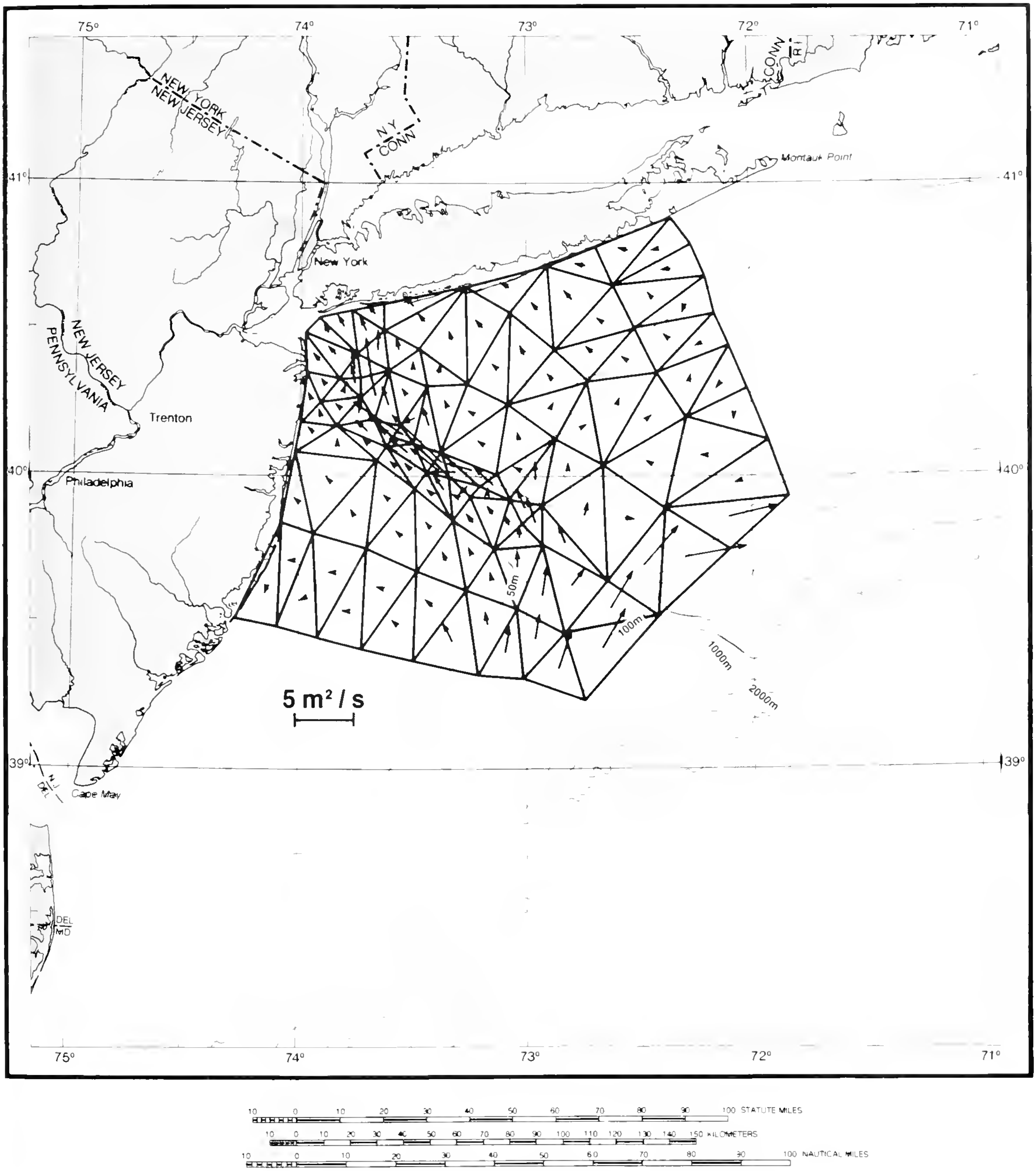

FIGURE 8-9 —Transport in bottom layer below pycnocline for May 18-23, 1976

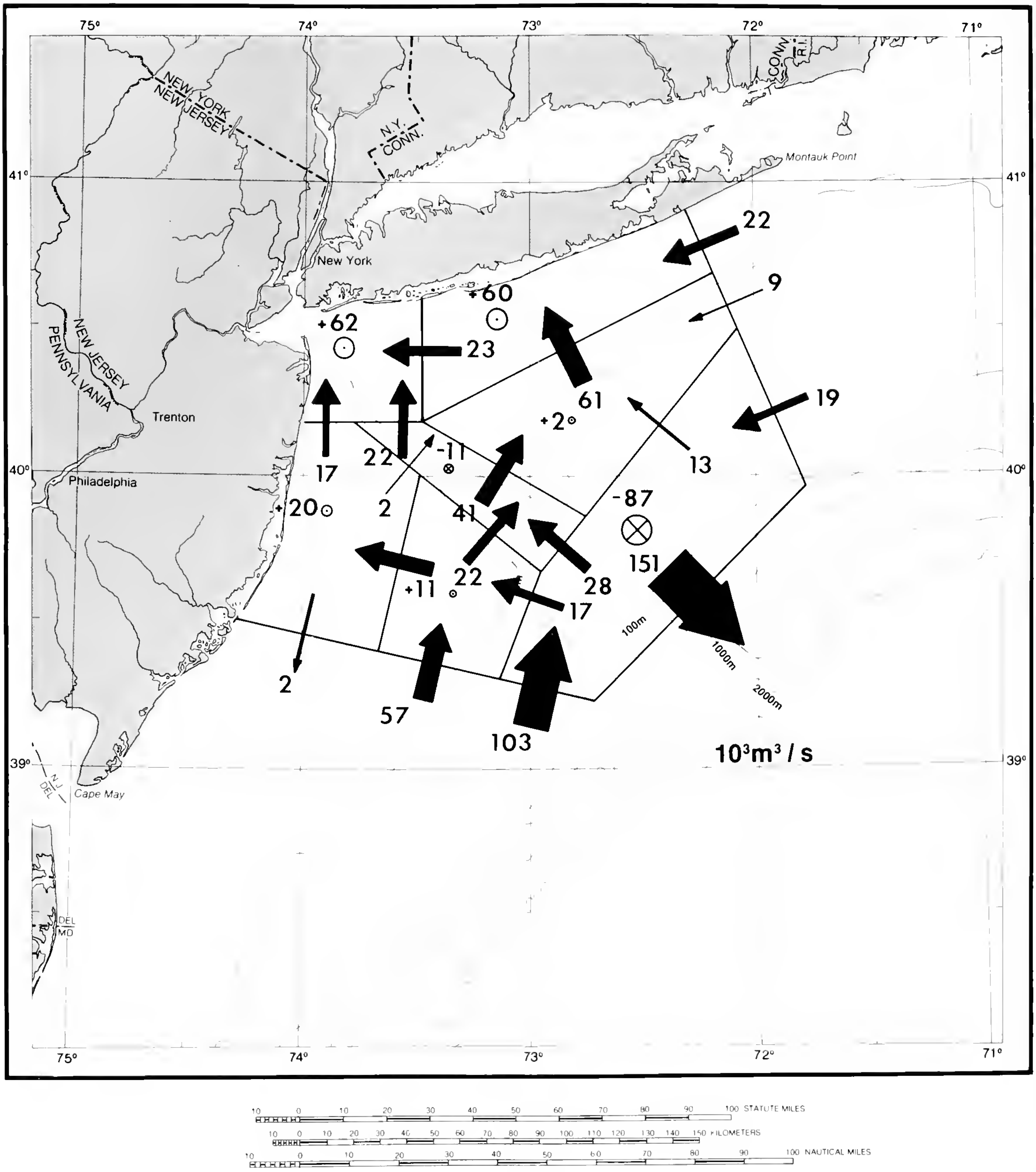

FIGURE 8–10A.—Schematic of water transport below pycnocline for May 18-23, 1976.

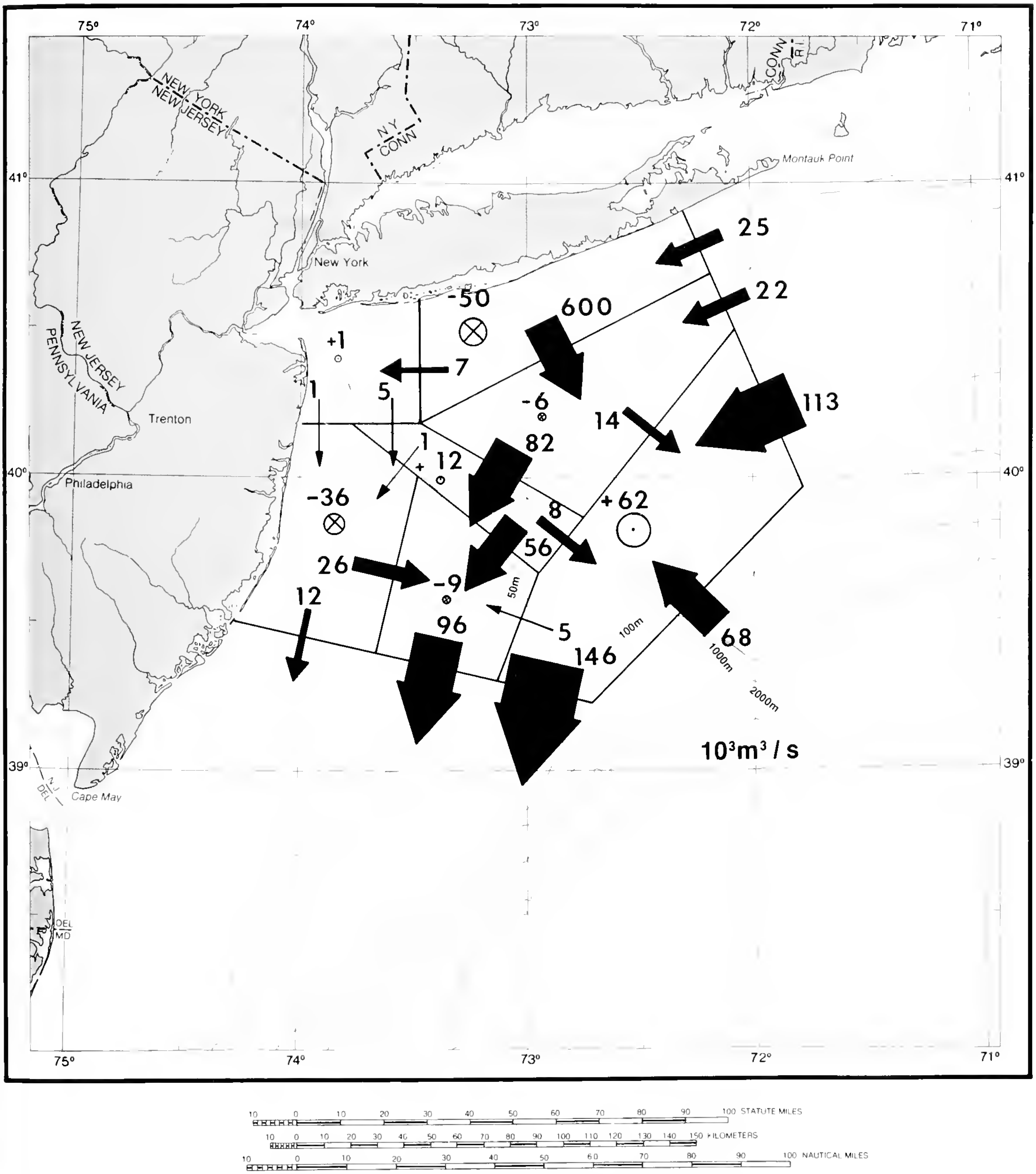

FIGURE 8-10B.—Schematic of water transport below pycnocline for May 23-June 3, 1976.

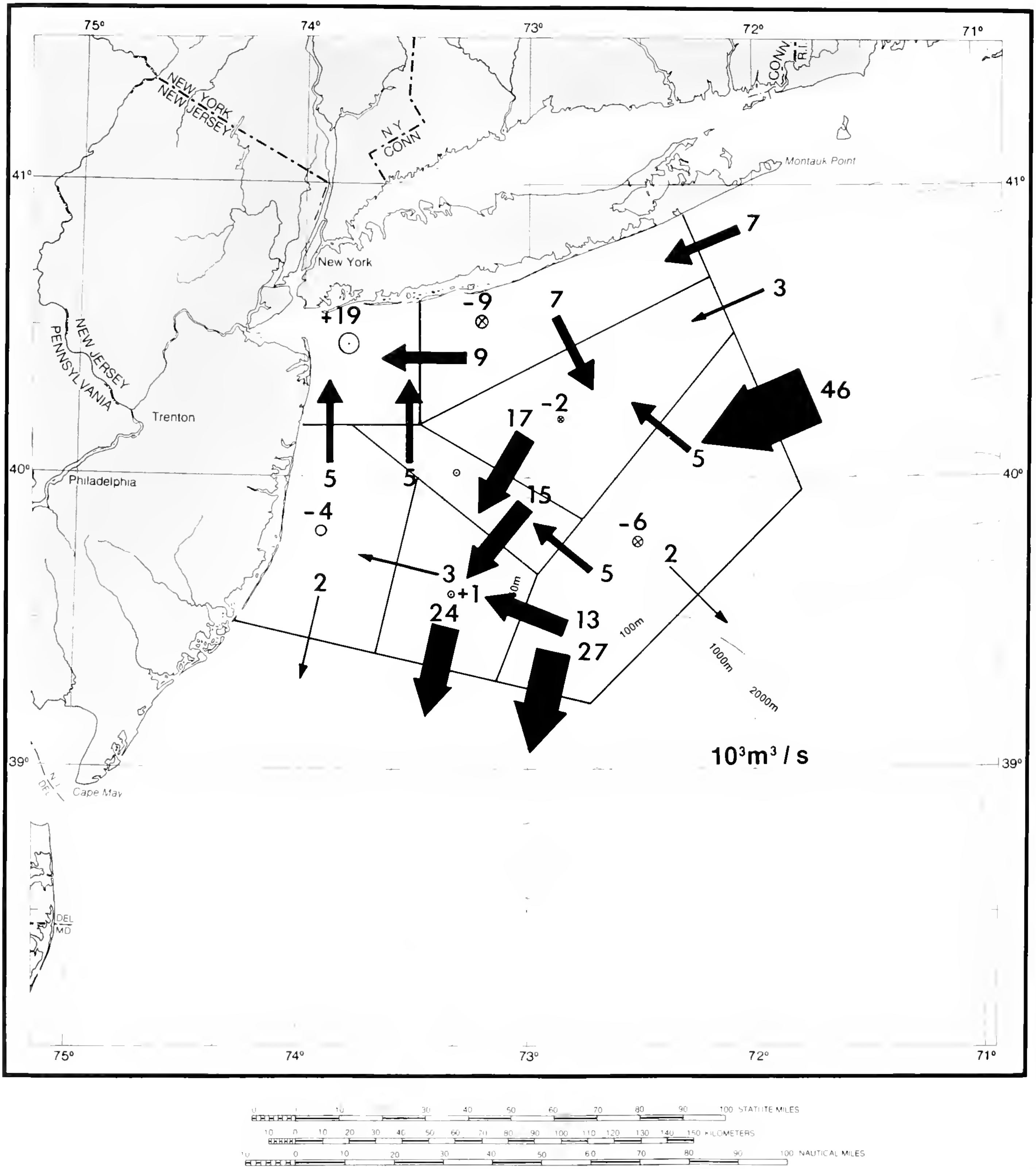

FIGURE 8-10C.—Schematic of water transport below pycnocline for June 3-13, 1976

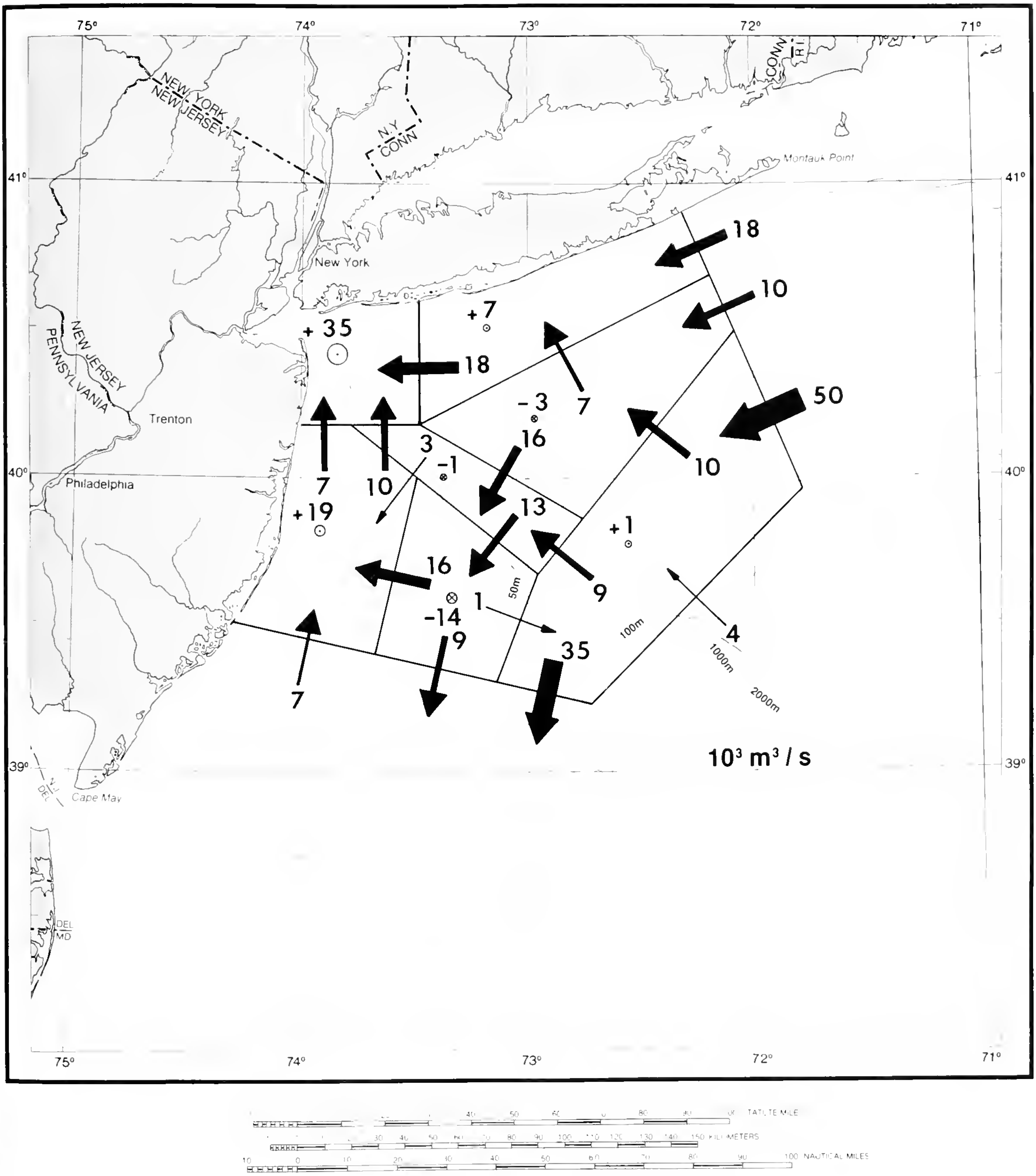

FIGURE 8-10D —Schematic of water transport below pycnocline for June 13-29, 1976

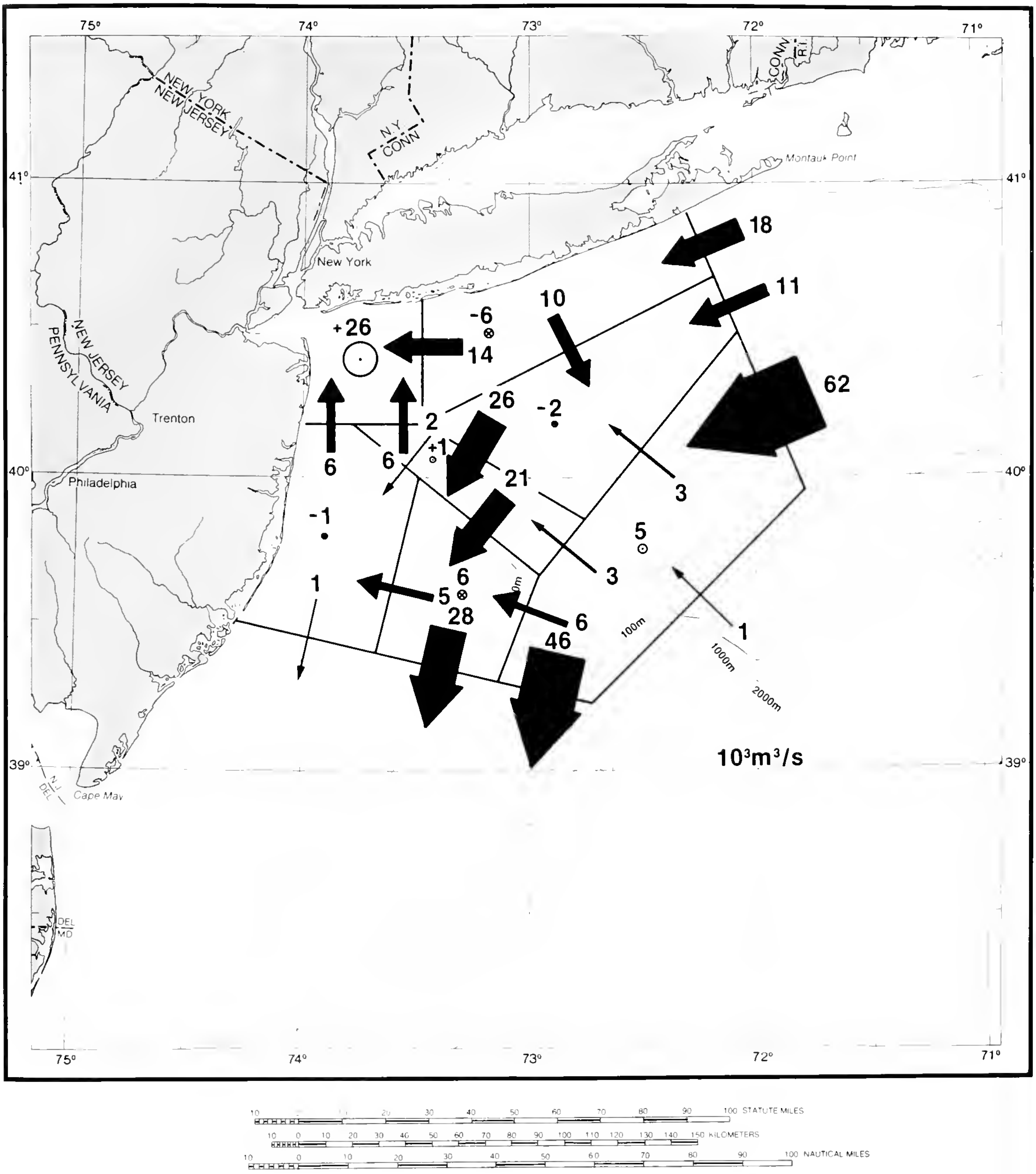

FIGURE 8–11.—Average water transport below pycnocline in New York Bight, May 18-June 29, 1976.

TABLE 8–1.—*Surface area, volume, and average dissolved oxygen concentrations in New York Bight, 1976*

| Segment[1] of Bight | L1 | L2 | L3 | A | H | J1 | J2 |
|---|---|---|---|---|---|---|---|
| Surface area (km$^2$) | 3905 | 4320 | 6490 | 1780 | 1440 | 3510 | 2760 |
| Volume (km$^3$): | | | | | | | |
| Upper layer | 67.9 | 93.3 | 191 | 28.1 | 33.7 | 69.8 | 75.6 |
| Lower layer | 63.3 | 119 | 347 | 31.3 | 56.2 | 34.7 | 47.7 |
| Averaged dissolved oxygen (ml/l): | | | | | | | |
| XWCC–9 (May 17–24): | | | | | | | |
| Upper layer | 6.85 | 6.94 | 7.16 | 6.38 | 7.37 | 6.63 | 6.80 |
| Lower layer | 5.41 | 5.23 | 5.74 | 5.52 | 6.02 | 5.17 | 5.41 |
| XWCC–10 (June 28 to July 1): | | | | | | | |
| Upper layer | 5.75 | 6.01 | 6.90 | 5.34 | 5.47 | 4.65 | 5.59 |
| Lower layer | 4.56 | 3.73 | 5.35 | 1.95 | 3.23 | 1.33 | 2.60 |
| Boundary dissolved oxygen (ml/l): | | | | | | | |
| Boundary designators[1] | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
| XWCC–9: | | | | | | | |
| Lower layer | 5.11 | 5.58 | 5.34 | 5.67 | 6.14 | 5.81 | 5.83 |
| XWCC–10: | | | | | | | |
| Lower layer | 1.31 | 2.68 | 4.99 | 5.00 | 5.72 | 4.14 | 4.91 |

[1] Segment numbers and boundary designators refer to figure 8–1.

averaged over selected time intervals such as shown in figure 8–8 . These patterns are consistent with the current velocities shown in figure 8–5 and are based upon both these current data and the density data described more extensively in chapters 2 and 7. The diagnosed currents are evaluated at much greater spatial resolution than can be obtained from current meters only. However, it is difficult to demonstrate the veracity of the model in as much detail as it portrays. Because of the nature of the available oxygen data, as discussed previously, transports are in fact more useful than detailed velocity structure in application to the anoxia problem. Thus, the major results from the circulation model are presented instead as transports in the lower layer through the various boundaries of the several segments of New York Bight. These are shown in figure 8–10.

Transport below the thermocline during the interval diagnosed is consistently to the southwest, into the Bight, all across the shelf off eastern Long Island. Off southern New Jersey, transport is predominantly southward, out of the Bight, over the outer shelf, and is directed weakly southward over the inner shelf on the average, but the transport undergoes large reversals over the interval.

The lower layer flow in the Hudson Shelf Valley is predominantly shoreward into the Apex. In the Apex segment, the diagnosed horizontal transport from all adjacent segments is into the Apex, causing the mass balance to be maintained by an estuarine-like upward flow through the pycnocline. Exchange with the estuary has been ignored because the required upwelling flux is more than 30 times the Hudson River discharge. A small but perhaps significant fraction of this upwelling probably occurs by horizontal transport into, and upwelling within, the estuary. Neglect of this detail does not invalidate the model for the present analysis. The implied vertical flow rate across the thermocline in the Apex segment is about 1.3 m/d, and the outer shelf segment has upwelling across the pycnocline of the order of 0.1 m/d. Diaz (chap. 3) used monthly mean wind values to compute the mean vertical motion in New York Bight during May and June as upward at about 0.04 and 0.02 m/d, respectively. The upwelling velocity, as determined with the diagnostic model but averaged over all the Bight as defined for the model, is upward at about 0.06 m/d. The discrepancy between these results can probably be attributed to the limit of accuracy in the diagnositc model and to the fact that Diaz's com-

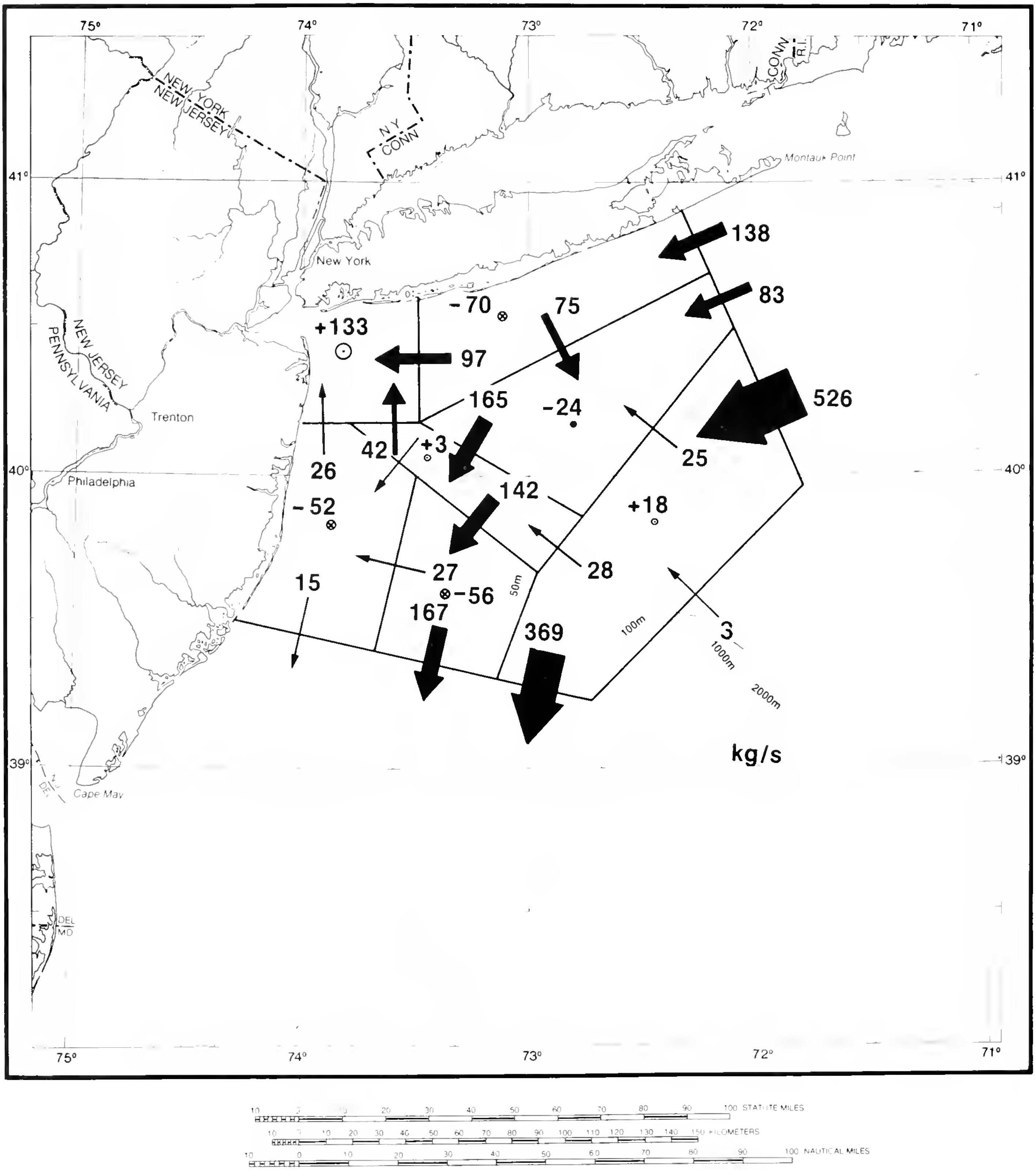

FIGURE 8-12 —Average oxygen transport below pycnocline in New York Bight, May 18-June 29, 1976.

TABLE 8–2.—*Water and oxygen transport characteristics in New York Bight, May 18 to June 29, 1976*

| Segment of Bight[1] | L1 | L2 | L3 | A | I1 | J1 | J2 |
|---|---|---|---|---|---|---|---|
| Net advective input of water, $Q_{in}$ ($10^3 m^3/s$) | 24 | 26 | 63 | 26 | 29 | 7 | 33 |
| Water flushing time, $V/Q_{in}$ (d) | 31 | 53 | 64 | 14 | 23 | 58 | 17 |
| Change in oxygen concentration with time, $\Delta C/\Delta t$ ($10^{-3}$ ml/l/d) | −20 | −36 | −9 | −85 | −66 | −91 | −67 |
| Divergence of oxygen flux, $(\Sigma QC + Q_VC)/V$($10^{-3}$ ml/l/d) | −33 | −21 | −7 | −62 | 2 | −80 | −67 |
| Net oxygen utilization rate, $\Sigma S/V$ ($10^{-3}$ ml/l/d) | −53 | −57 | −16 | −148 | −64 | −172 | −134 |
| Oxygen ventilation time, $CV/\Sigma(QC)_{in}d^{-1}$ | 25 | 43 | 60 | 12 | 22 | 24 | 13 |

[1] Segment numbers refer to figure 8–1.

putations are based on simple Ekman divergency ("Ekman suction") upwelling appropriate to the open ocean rather than on coastal Ekman divergency appropriate to the coastal ocean.

An objective estimate of the advective flushing time of the several segments of the Bight emerges from these calculations; that is, the ratio of the volume of each segment to the flux into or out of the segment as determined by the diagnostic model for the conditions observed below the thermocline during spring and early summer 1976, $V/Q_{in}$. As seen in table 8–2, these flushing times within the bottom layer varied from about 2 weeks to 2 months. The most rapid flushing occurred in the Apex; the slowest occurred off the New Jersey coast and in the outer segments off Long Island. A comparison with table 8–1 shows a general correlation between flushing time and individual segment size; this is to be expected because current speeds are generally similar throughout the Bight. Also, the ratio of an appropriate dimension of a segment to the speed of the mean flow provides a first-order estimate of the advective flushing time. The corresponding flushing time for the entire Bight was of the order of 75 days. Such calculations are limited in that there is no assurance that water "flushed" from the Bight, or any part of it, does not return later. On the other hand, it also does not take into account the flushing effect of motions that occur on time scales much shorter than 10 days. Even in this year of extreme oxygen depletion, there were flows between the various segments in the Bight, and between the Bight and surrounding waters, which exchange these waters on time scales that are short compared to the seasonal cycle of thermal stratification.

The oxygen flux calculations indicate a net advection of oxygen into the Bight as a whole, and into each segment defined for this analysis, except for the Hudson Shelf Valley. All segments characterized by upwelling had a net input of oxygen by horizontal advection. Those characterized by downwelling had a net loss of D.O. by horizontal advection, which was more than compensated by the downwelling of water with high D.O.

The results of the primary objectives of these calculations are summarized in table 8–2. Interpretation of these results requires an appreciation of how the values were obtained. We began with observations of the rate of decrease in time of oxygen in the various segments. If there was no net transport of oxygen into or out of the segment, then the net utilization of oxygen would be the observed time rate of change of concentration. However, if there was some net advective flux of oxygen, say into a segment, then the net utilization rate, $\Sigma S$, in the segment is equal to the sum of the change of oxygen content in the segment, $V\Delta C/\Delta t$, and that advected into the segment, $\Sigma QC + Q_VC$. To put the utilization rates into perspective, we calculated the utilization rate per unit volume, $\Sigma S/V$, for easy comparison with the observed time rate of change of concentration, $\Delta C/\Delta t$, and for comparison of effective ratios between sections.

It is readily seen in table 8–2 that in the inner and mid-shelf segments the actual utilization rate is approximately twice as large as would be inferred from the observed change of concentration alone. Furthermore, the utilization rate found for the seriously impacted areas in the Apex and the inner shelf off New Jersey is about 3 times greater than for other regions of the inner and middle shelf and more than 10 times higher than that found over the outer shelf. Segar and Berberian (1976) estimated the oxygen consumption rate during summer 1974 as $10^7$ kg $O_2$/d for water below 10 m depth in the Bight Apex. By dividing the appropriate volume (26 $km^3$), this is equal to a utilization rate of $0.27 \times 10^{-3}$ ml/l/d. Their estimate is some 55 percent greater than our values for the Apex, and 2 to 17 times greater than the other values from over the shelf. Although Segar and Berberian's rate is not greatly more than our maximum value, the unusual circumstances surrounding our 1976 data suggest that the rate calculated by Segar and Berberian is an overestimate, probably because much of the primary productivity contributing dominantly to their calculation is in fact advected out of the area rather than simply sinking through the thermocline.

Another time scale of interest is an analog for oxygen of the advective flushing time for water. That is the ratio of the oxygen storage in a segment to the advective input of oxygen, $CV/\Sigma(CQ)_{in}$, which we will call the ventilation time. This ratio is a measure of the flow-thru rate of oxygen. Short ventilation times indicate that the availability of oxygen by advective flow-thru is large relative to ambient oxygen storage. Ventilation times defined in this way exhibit the same general features as the water flushing time, but typically are 15 to 60 percent shorter, except in the outer shelf segment and the shelf valley where they are nearly equal. The implication of these results is that advection is more effective in supplying oxygen to the Bight than it is for simple renewal of water. These results are due, in part, to the reduced oxygen concentration values that occur regularly in the inner Bight during summer relative to higher oxygen concentrations existing elsewhere available for transport to that region.

An analysis of the errors in the calculation must be made to determine the significance of the results. Standard error of the means can be calculated for the D.O. concentrations, but the errors in volume, $V$, and transport, $Q$, cannot be calculated from the available results. If the error in volume and transport is assumed to be 10 percent, it is the dominant error in calculation. The values of the net utilization rates are greater than one standard error of the rates for all the segments except L.3. The values of $\Sigma S$ for segments A and J1 are 4.0 and 4.8 times the standard errors in $\Sigma S$, respectively. If the assumed errors in $Q$ are increased to 20 percent of their magnitude, then the standard errors in $\Sigma S$ are still less than $\Sigma S$ for the segments of critical interest—A, J1, J2, and L2. It would be necessary to assume errors of 50 percent in $Q$ to make the errors in $\Sigma S$ greater than the magnitude of $\Sigma S$ in segment J1. Thus, the important results of the calculations can be taken as meaningful even if the errors in approximating the transports are large.

A drawback of diagnostic modeling is that it cannot forecast how details of the circulation would change under different wind or other forcing conditions. The model can be used to describe and analyze only conditions for which at least some current velocity data are available.

The density field is held stationary over the entire 42-day interval because only one complete set of density observations was available. This introduces errors in the transport calculation in equations (8) and (9), but the near-bottom velocity field is unchanged. Comparisons of observed and modeled velocities and the effect of the density field on model accuracy will be the subject of a further study. The results of our model are probably more accurate than a prognostic model, since the calculation is based upon a large amount of observed data.

Another shortcoming of the method as presently used is that it is applicable to only the steady or most slowly changing components of the flow. Therefore, diffusion of oxygen by higher-frequency movements such as tidal currents and storm-driven transient flows is not included in the diagnosis. This effect arises from simultaneous variation of flow speed and oxygen concentration, the basic mechanism of turbulent transport, within the four time periods that were diagnosed and averaged. In defense of the present application, incorporation of a gradient diffusion mechanism of any sort into the model would indicate additional oxygen flux into the oxygen-deficient regions, thus strengthening the major conclusion of the investigation. In fact, the respiration rate calculated by Malone et al., using an independent approach (ch. 9, pt. 1), indicates that the sum of observed D.O. change and advective import are of approximately the correct magnitude to supply the oxygen utilization; hence, diffusive flux of oxygen seems to be relatively unimportant.

The circulation pattern, both in the Bight Apex over 31 days of the study and all along the inner New Jersey shelf over 21 days of the study, shows convergent flow in the lower layer and upwelling through the pycnocline. Though the upper layer model results are not shown, the upper layer flow was offshore as is seen in the current meter data (fig. 8–5a, b, and d). The cause of the convergence in the Apex is the unusual flow pattern shown in figures 8–5a and d, where the nearshore flows in the lower layer off New Jersey and Long Island are both directed toward the Apex. Away from the Apex, the bottom Ekman layer transport, which is directed to the left of the alongshore flow, creates a strong convergence off New Jersey. This pattern of shoreward flow and convergence in the bottom waters, compensated by divergent seaward flow in the upper waters is kinematically similar to the circulation commonly observed in coastal plain estuaries. Festa and Hansen (1978) showed that particulate materials characterized by a suitable particle sinking velocity will tend to be concentrated by a flow field of this type, irrespective of whether they are introduced from the river or from the ocean. It is one of the causative mechanisms for the turbidity maximum that has long been known to occur in coastal plain estuaries. We expect that under the influence of the circulation observed in the New York Bight in the late spring of 1976, oxidizable particulate materials originating in the Hudson Estuary, *or elsewhere throughout the Bight,* will have been concentrated in the Apex and along the inner shelf off New Jersey.

*Ceratium tripos* are ideally suited to couple to this convergent pattern, as suggested in chapter 9, part 1, since they are capable of vertical motility and choose to remain below the pycnocline. Organisms which are transported into the convergent areas do not move through the pycnocline into the divergent area above. This leads to a concentration of organisms in the lower layer of the convergent areas off New Jersey and in the Apex.

## CONCLUSION

The first conclusion to be drawn from the use of the diagnostic model is that even during May and June 1976, the replacement time of water in New York Bight was relatively short compared to the general seasonal cycle of property changes for the Bight as a whole and for the inshore segments of principal interest. A second conclusion is that oxygen depletion in the critical region during the May-June period was due to oxygen utilization about 3 times greater than in other regions of the inner shelf and nearly 10 times greater than that occurring over the outer shelf, rather than simply being due to the length of stratified season, stagnation, or advection of low-oxygen water. The most critically affected regions, in fact, had a relative advective oxygen input substantially greater than other areas.

The key problem in examining the anoxia episode is explaining the high consumption rates that occurred off New Jersey during spring and summer 1976. Numerous causes have been suggested, including ocean dumping, estuarine discharge, primary production (Segar and Berberian 1976; ch. 10), and an anomalous bloom of dinoflagellate organisms (ch. 9, pt. 2). All these suggestions do not adequately address the questions of why 1976 and why the inner shelf off New Jersey. Although observations obtained and techniques used are deficient for explicit quantitative modeling of carbon/oxygen relationships, or even the distribution of particulate material or *Ceratium tripos* in the Bight, a strong qualitative case can be made from results of the diagnostic circulation model of the Bight, and the model study of particulate material transport by Festa and Hansen (1976), that the 1976 anoxia episode off New Jersey came about in the following way.

For reasons not well understood but probably related to the pattern of surface wind, and quite possibly to the heavy discharge from the Hudson River during early 1976, the circulation in and near the Apex was kinematically equivalent to that commonly occurring in coastal plain estuaries for the entire period from May 18 to June 29. A similar situation existed in the average along the entire inner New Jersey shelf over the last 26 days of the period. Such circulations tend to trap and concentrate suspended particulate matter having a small sinking velocity. This concentration process functions irrespective of where such particulate materials are introduced into the circulation pattern. Hence, particulates from the Hudson River, the dumping activities, and plankton productivity would have concentrated in the Apex and over the inner shelf off New Jersey. This concentration of oxidizable material had an exorbitant biochemical oxygen demand that depleted the oxygen supply in spite of reasonably active ventilation of waters below the thermocline.

If *Ceratium tripos*, which are capable of relatively rapid movement (see chapter 9, part 2), seek a position below the thermocline, this behavior will couple to the circulation just as do inanimate particle distributions. In the case of *Ceratium tripos* the concentration mechanism can be expected to function with particular efficiency because the organism can optimize its vertical movement relative to that of the water. A principal outstanding question is whether *Ceratium tripos* did in fact contribute in a dominant way to the oxygen demand off New Jersey, or whether the concentration of other oxidizable particulates would have led to anoxia even in the absence of *Ceratium tripos*.

Conditions in May and June 1975 have not been diagnosed. But the comparison of current meter data between 1975 and 1976 made in chapter 7 shows that the convergent circulation pattern which fostered inshore concentration of particulates did not exist during spring 1975.

Though we can calculate what occurred in 1976, the comparison of oxygen utilization rates to average rates suffers because we have a poor idea of what the average really is. Changes in both terms of the oxygen mass balance, $(\Sigma QC + Q_V C)$ and $\Sigma S$, contributed to the large decrease in concentrations with time preceding the anoxic episode. A really illuminating result is that an order of magnitude change in these terms is not necessary to produce the observed conditions. Relatively small changes, smaller than a factor of two, can considerably influence the mass balance. The simplicity of the oxygen mass balance equation conceals many feedback loops between the water transport and oxygen production. Decreased transport will, for example, prevent nutrients from reaching an area, thus decreasing plankton growth rates. In the solution to these problems and others, such as nutrient supply, organic loadings, and planktonic growth rates, and the oxygen consumption rates of all these constituents, lie the answers to why the anoxia developed off New Jersey in summer 1976. The oxygen transport is only a piece of the puzzle.

## *List of Symbols*

$c$ = concentration of material
$\Sigma S$ = sum of sources and sinks
$D/Dt$ = total of material derivative
$\partial c/\partial t$ = rate of change of concentration
$\rho$ = density of water
$\rho_o$ = reference (constant) density
$T$ = time interval (days)
$\mathbf{T}$ = transport in bottom layer
$\mathbf{T}_B$ = transport in bottom friction layer
$L$ = length (km)
$t$ = discrete time ($t_1$, $t_2$, etc.)
$Q$ = horizontal volume flux
$Q_v$ = vertical volume flux
$V$ = segment volume
$C$ = volume-averaged concentration quantities
$\Sigma QC$ = divergence of concentration flux around boundaries of each segment
$H$ = bottom depth
$g$ = acceleration of gravity
$\zeta$ = elevation of sea surface
$\vec{\tau}_w$ = surface wind stress
$\gamma$ = linear bottom friction parameter
$z$ = vertical coordinate
$f$ = Coriolis parameter
$\alpha$ = vertically integrated density
$\nabla$ = divergence operator ($\partial/\partial x$, $\partial/\partial y$, $\partial/\partial z$)
$J$ = Jacobian operator
$\mathbf{i}$ = unit vector
$\mathbf{j}$ = unit vector
$\mathbf{k}$ = unit vector in vertical direction
$\mathbf{u}$ = velocity vector ($u$, $v$, $w$)
$\mathbf{U}$ = velocity (cm/s or km/d)

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## REFERENCES

Csanady, G. T., 1976. Mean circulation in shallow seas, *J. Geophys. Res.* 81 (30):5389–5399.

Festa, J. F., and Hansen, D. V., 1976. Turbidity maxima in partially mixed estuaries. A two-dimensional model, *Estuar. Coastal Mar. Sci.* 4:309–323.

Galt, J. A., 1975. Development of a simplified diagnostic model for interpretation of oceanographic data *NOAA Tech. Rep.* ERL–339–PMEL–25, NOAA Environmental Research Laboratories, Boulder, Colo., 46 pp.

Garside, C., Malone, T. C., Roels, O. A., and Sharfstein, B. A., 1976. An evaluation of sewage-derived nutrients and their influence on the Hudson Estuary and New York Bight, *Estuar. Coastal Mar. Sci.* 4:281–289.

Hsueh, Y., Peng, G., and Blumsack, S. L., 1976. A geostrophic calculation of currents over a continental shelf, *Mem. Soc. Royal Sci. Liege* 6(10):315–330.

Ketchum, B. H., Redfield, A. C., and Ayers, J. C., 1951. The oceanography of the New York Bight, *Pap. Phys. Oceanogr. Meteorol.* 12, 46 pp.

Segar, D. A., and Berberian, G. A., 1976. Oxygen depletion in the New York Bight Apex: causes and consequences, *Amer. Soc. Limnol. Oceanogr. Spec. Symp.* 2:220–239.

Smith, J. D., and Long, C. E., 1976. The effect of turning in the bottom boundary layer on continental shelf sediment transport, *Mem. Soc. Royal Sci. Liege* 6(10):369–396.

**Oxygen Depletion and Associated Benthic Mortalities in New York Bight, 1976**

# Chapter 9. Plankton Dynamics and Nutrient Cycling

## Part 1. Water Column Processes

*Thomas C. Malone,*[1] *Wayne Esaias,*[2] *and Paul Falkowski*[3]

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## INTRODUCTION

An extensive bloom of the dinoflagellate *Ceratium tripos* (O. F. Müller) Nitzsch developed throughout the Middle Atlantic Bight (between 36° N, 41° N, and the continental shelf break) from January through July 1976. By late June-early July an oxygen minimum layer (<2.0 ppm) had developed below the thermocline between the 20- and 40-m isobaths off the New Jersey coast from Atlantic City to Sandy Hook. (See chapter 2.) Local anoxic conditions were most widespread east of Barnegat Inlet (39° 45′N) in early July and east of Great Bay (39° 30′N) by late July. Presence of this subthermocline oxygen minimum layer and associated sulfide production apparently resulted in mass mortalities of demersal fishes and benthic invertebrates. (See chapter 12.)

The occurrence of the *C. tripos* bloom and the subsequent development of the oxygen minimum layer led to the hypothesis that *C. tripos* was involved in generating the biological oxygen demand (BOD) required to produce the oxygen minimum. In an effort to clarify the role of *C. tripos,* this paper addresses these questions:

1. What was the areal extent of the bloom and the time course of its development?
2. What were the most likely causes of the bloom and its collapse?
3. What were the effects of the bloom on the distribution of organic matter and dissolved oxygen?

For this discussion, the New York Bight was divided into five regions (fig. 9.1–1): 1) Long Island coastal area, 2) New Jersey coastal area (<20 m deep within 5 km of the coastline), 3) lower Hudson estuary (including Upper and Lower Bays of New York Harbor), 4) the Apex (bounded by 40° 10′N and 73° 30′W), and 5) the outer Bight (south and east of the Apex to the shelf break between Montauk Point and Cape May).

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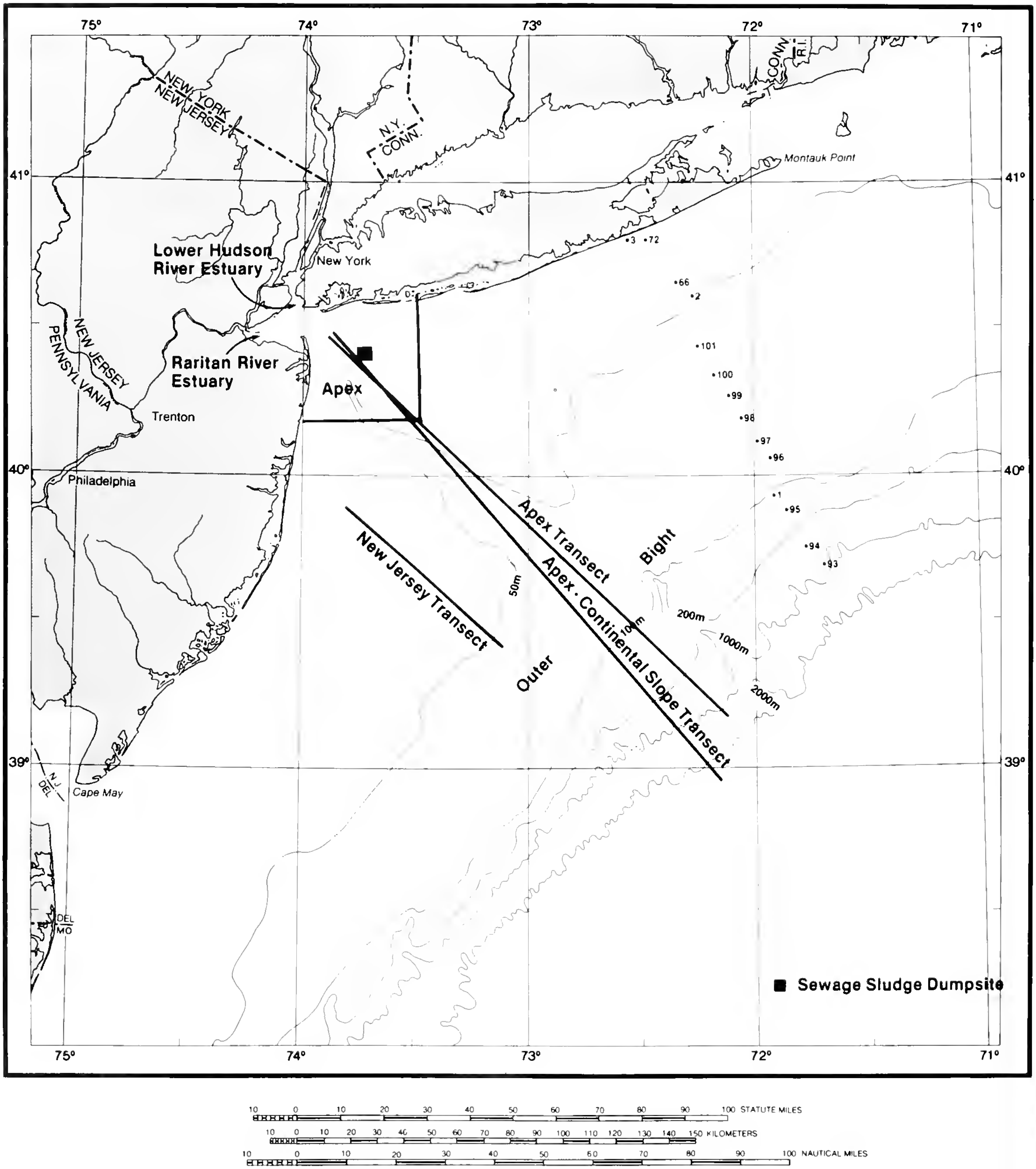


FIGURE 9.1-1.—New York Bight regions, transects, and stations.

## *CHAPTER 9, PART 1*

# PHYTOPLANKTON ECOLOGY

### Productivity

Major studies of phytoplankton productivity include: Ryther and Yentsch (1958), the outer Bight; Mandelli et al. (1970), the Long Island coast; and Malone (1976a, 1976b, 1977a, 1977b), the lower Hudson-Raritan estuary and Bight Apex. The following synthesis is based on these studies and on reviews by Smayda (1976) and Yentsch (1977).

Annual phytoplankton productivity generally decreases with depth and distance from the mouth of the Hudson-Raritan estuarine complex. Phytoplankton productivity in the Apex is about 430 g C/m²/yr, or 70 to 80 percent of the annual input of particulate organic carbon (POC) to the Apex. The remaining inputs are derived primarily from sewage wastes generated by the New York-New Jersey metropolitan population. (See chapter 15.) Phytoplankton productivity in the outer Bight decreases from 160 to 100 g C/m²/yr as water column depth increases from less than 50 m over the continental shelf to 1,000 m over the slope.

An important exception to this general trend is the high phytoplankton biomass and productivity often observed in the region of the shelf break (Fournier et al. 1977). The development of phytoplankton blooms along the shelf break appear to be a consequence of nutrient enrichment and vertical stability provided by a frontal system separating nutrient-poor shelf water from nutrient-rich slope water.

Phytoplankton productivity in the Apex fluctuates between 0.1 and 6.6 g C/m²/d (mean = 1.2 g C/m²/d compared to 0.1 to 1.1 g C/m²/d (mean = 0.4 g C/m²/d) in the outer Bight. Seasonal variations in the outer Bight appear to be characterized by winter-spring blooms. Over the midshelf area (<50 m) of the outer Bight, productivity is 0.5 to 1.0 g C/m²/d from November through April, but is less than 0.5 g C/m²/d the remainder of the year. Offshore (50–150 m), productivity exceeds 0.5 g C/m²/d during March-May.

In contrast, seasonal variations in the Apex are characterized by two bloom periods coinciding with minimum time-dependent changes in surface temperature during February-March (2°-8° C) and June-July (19°-23° C). Chain-forming diatoms (netplankton retained on a 20-µm mesh screen) with mean euphotic zone generation times of 1 to 3 days usually dominate phytoplankton blooms in February-March. During these months the water column (20–30 m deep) is well mixed, the euphotic zone extends to the bottom, and phytoplankton populations are abundant throughout the water column. Maximum biomass occurs during this period. Phytoplankton productivity is generally higher during the June-July bloom period when small green algae (nannoplankton with mean spherical diameters less than 10 µm) growing at mean euphotic zone generation times of 0.5 to 1.5 days dominate phytoplankton blooms. At this time, the water column is well stratified, with the thermocline between 5 and 15 m (5–20 m off the bottom); the euphotic zone is 5 to 15 m deep; and phytoplankton populations are concentrated near the surface, with maximum densities along the New Jersey coast within 20 km of the Hudson-Raritan estuary mouth.

Major inputs of inorganic nutrients (in contrast to regenerated nutrients within the Bight) include estuarine runoff (mainly from the Hudson River) and fluxes onto the shelf in the region of the shelf break. Although observations in the Bight as a whole are lacking in spatial and temporal resolution, they do indicate that phytoplankton biomass tends to be high and decreases slowly away from sites of nutrient input before thermal stratification. As the water column stratifies, the centers of maximum biomass move closer to the nutrient reservoirs that supply the euphotic zone. This leads to narrow zones of high production along the coastline and the shelf break, and to the development of a chlorophyll maximum in the thermocline over the midshelf.

High productivity and the occurrence of two major bloom periods in the Apex reflect the 1) continuous input of nutrient-rich estuarine water (table 9.1–1), 2) effects of thermal stratification and coastal circulation on the distribution of estuarine water, 3) rapid regeneration of nutrients during summer (table 9.1–1), and 4) seasonal variations in grazing pressure, which peaks during late spring and summer. Winter diatom blooms develop, because of low grazing pressure. Apparently, very little diatom production is grazed, and most of the biomass produced sinks to the bottom over an unknown but larger area than the Apex. Thus, winter-spring diatom blooms in the Apex may be a factor in the development of oxygen minima below the pycnocline during summer.

Summer nannoplankton blooms in the Apex are concentrated in the surface layer where they are rapidly

TABLE 9.1–1.—*Seasonal comparison of dissolved nitrogen input by estuarine runoff and uptake by phytoplankton, proportion of phytoplankton demand supplied by runoff, and area required to assimilate the nitrogen input*

| Months | Dissolved nitrogen | | Proportion supplied by runoff | Area required |
|---|---|---|---|---|
| | Input | Uptake[1] | | |
| | —— $10^5$ kg N/d —— | | Percent | km² |
| JFM | 1.6 | 2.2 | 72 | 900 |
| AMJ | 1.6 | 2.7 | 59 | 700 |
| JAS | 1.2 | 2.1 | 57 | 670 |
| OND | 1.6 | 1.5 | 107 | 1350 |

[1] Calculated from primary productivity (Malone 1976a, 1977b) and assuming a C:N assimilation ratio of 7.0 by weight.

grazed and dispersed before significant quantities sink into the bottom layer. Sinking fecal material produced by grazing zooplankton may be a major mechanism by which organic matter of phytoplankton origin reaches the bottom layer during summer.

Rough calculations indicate that the ammonia input to the Apex via regeneration provides 40 to 50 percent of the nitrogen required to support observed levels of phytoplankton productivity in the Apex during spring and summer (table 9.1–1). The importance of ammonia regeneration is especially apparent during summer when phytoplankton productivity is high and dissolved inorganic nitrogen (DIN) concentration is low. Based on observed concentrations of DIN (typically less than 2.0 μg-at/l) and primary productivity (usually greater than 1 g C/m²/d) in the Apex, DIN turnover times in the surface layer ranged from 12 hours to 2 days. Thus, zooplankton grazing, ammonia regeneration, and phytoplankton productivity appear to be closely coupled during the warm summer months when the water column is well stratified.

Vertical mixing and nutrient regeneration are the major mechanisms of euphotic zone enrichment over most of the Bight outside the plume of the Hudson River. Nutrient supplies are more discontinuous than in the plume, and thermal stratification limits rather than enhances the flux of nutrients into the euphotic zone. Consequently, phytoplankton productivity is low throughout the summer and blooms are greatest in magnitude and most frequent during late winter and spring.

## Distribution

The abundance and distribution of phytoplankton was reviewed by Malone (1977c). Phytoplankton cell densities usually range from $10^6$ to $10^9$ cells/l in estuarine and coastal waters compared to $10^4$ to $10^7$ cells/l in the Apex and $10^3$ to $10^5$ cells/l in the outer Bight. Phytoplankton populations are typically dominated by diatoms (cold months) and chlorophytes (warm months) in estuarine and Apex water and by diatoms in the outer Bight.

The diatoms *Skeletonema costatum, Asterionella japonica, Leptocylindrus danicus, Thalassionema nitzschioides,* and *Chaetoceros debilis* are abundant in both estuarine and Bight waters. *Rhizosolenia alata, R. faeroense, Chaetoceros socialis,* and *Nitzschia closterium* usually make up a larger proportion of the diatoms present in the outer Bight than in the Apex. The chlorophyte *Nannochloris atomus* frequently dominates estuarine and Apex phytoplankton during summer. The dinoflagellates *Prorocentrum micans, Peridinium* spp., and *Ceratium* spp. are often abundant during spring, summer, and autumn.

Mandelli et al. (1970) described the species composition of the netplankton along the southern coast of Long Island. Phytoplankton biomass peaked during autumn and late winter. Blooms of *S. costatum* produced both peaks. Diatoms dominated the September-March 1966 period, whereas dinoflagellates were most abundant during the April-August 1966 period. Among the diatoms, *S. costatum, Thalassiosira* sp., *Chaetoceros* sp., and *R. alata* were successively abundant from September through December, and apparently again during February and March. *Peridinium depressum* and *Ceratium massilence* bloomed in April and May, respectively. *Ceratium tripos* was the dominant netplankton from June to August. During March 1967 a succession of species was observed: *S. costatum* dominated during the first week; *Thalassionema nitzschioides, Rhizosolenia* sp., *A. japonica,* and *Nitzschia seriata,* the second week; and *Ceratium tripos, C. macroceros, C. furca,* and *Peridinium depressum,* the last 2 weeks. This alternating pattern of diatom and dinoflagellate abundance appears characteristic of shallow coastal waters off western Long Island.

Recent observations along the New Jersey coast indicate that *C. tripos* was abundant during the summers of 1974 and 1975 (Myra Cohn, personal communication). Cell densities ranged from 40/ml to 740/ml (geometric mean = 133/ml in June 1975 and 222/ml in July 1975). Increases in *C. tripos* cell densities are also typical of Fire Island Inlet on the Long Island coast (Sylvia Weaver, New York University, personal communication). From 1973 to 1975, peaks in cell density (as high as 5/ml) occurred in May and June following slow increases beginning as early as January 1974.

## Biology of *Ceratium tripos*

*Ceratium tripos* (O. F. Müeller) Nitzsch, a large (cell volume 1–10 × $10^5$ μm³) armored dinoflagellate (fig. 9.1–2), is a holoplanktonic, cosmopolitan species commonly found along the east coast of North America from Cape Hatteras to the Gulf of Maine. Based on its distribution and on experimental growth studies (Cleve 1900; Bigelow 1926; Graham 1941; Nordli 1957), *C. tripos* is euryhaline and eurythermal, with a preference for the cooler waters (10°-20° C) and lower salinities (<33‰) of the continental shelf.

The organism seldom occurs in large numbers (greater than 500 cells/l) and may often be overlooked. Maximum concentrations typically range from 1 to 5 × $10^3$ cells/l; peaks reportedly occur during spring and summer.

Two varieties of the species have been described. The larger, *Atlantica* Ostenfeld, is 100 to 170 μm long and has equally well-developed anapical horns. *Baltica* Schutt is smaller (90 to 120 μm long) with unequal anapical horns. *C. tripos* var. *Atlantica* dominated the *Ceratium* population in New York Bight during the 1976 bloom. *C. tripos* var. *Baltica* was more abundant during 1977.

*C. tripos* is photosynthetic, with maximum light-dependent division rates of about 0.3/d (Nordli 1957). As with most other species of *Ceratium,* cell division usually occurs between midnight and sunrise, according to Elbrächter (1973) who reported that *C. tripos* divides at rates of 0.03 to 0.3/d in coastal waters. He also reported dark survival times of 41 days in filtered seawater.

Most species of *Ceratium* are phototactic and probably tend to aggregate at depths where light is optimal. *C. tripos* is usually most abundant near the bottom of the euphotic zone. Hasle (1950) reported light-dependent vertical migrations, but Nordli (1957) did not observe phototaxis in the laboratory.

Large populations of *C. tripos* have been observed below the euphotic zone, but the extent to which this reflects photosynthetic growth at subeuphotic zone light intensities, long dark survival times, or heterotrophic metabolism is unknown. Circumstantial evidence suggests that some ceratia may have the ability to metabolize organic particles (Hofender 1930; Von Stosch 1964; Norris 1969). Falkowski observed inclusions of exogenous origin in ceratia from the Long Island shelf, which suggest phagotrophic assimilation (Plate 1).

The extent to which *C. tripos* is subject to grazing mortality is not well documented. Elbrächter (1973) reported that recently divided ceratia were vulnerable to grazing by isopods and ciliates. However, grazing by copepods (the dominant grazers in New York Bight) appears to be minimal (Chervin, in press; Dagg, Brookhaven National Laboratory, personal communication).

Finally, endoparasites, which inhibit cell division, have been observed in *C. tripos* (Von Arndt 1967; Elbrächter 1973). Consequently, parasitism may be one means by which population size is limited naturally.

## PLANKTON AND BIOLOGICAL OXYGEN DEMAND: JANUARY–SEPTEMBER 1976

### Water-Column Stratification and Dissolved Oxygen

Seasonal variations in water column stratification and dissolved oxygen (D.O.) in bottom water parallel each other off the New Jersey coast. (See chapter 2.) During winter, the water column is well mixed and D.O. concentrations are near saturation (6–8 ml/l). As the water column begins to stratify in April, D.O. concentration in the subpycnocline layer begins to decline so that concentrations are usually 10 to 40 percent of saturation (2–4 ml/l) by July-August. Local anoxic conditions occasionally develop below the thermocline in the Christiaensen Basin (head of Hudson Shelf Valley) adjacent to the sewage sludge dumpsite (fig. 9.1–1) in the Bight Apex (National Marine Fisheries Service 1972). During summer 1976, the oxygen minimum layer was more widespread, existed over a longer period of time, and was characterized by lower oxygen concentrations than generally occur that time of year.

### Time-Course of the *Ceratium* Bloom

*C. tripos* was abundant in the Apex at least as early as February 7, 1976, but did not increase substantially during February (fig. 9.1–3). Cell densities increased steadily from a geometric mean of 5.8 cells/ml to 29 cells/ml by the end of March. The growth rate of 0.06 doublings/d calculated from these changes yields a mean water column cell density of 240/ml by late May, which is within the range of densities reported from the layer of maximum cell density in the Apex at this time (fig. 9.1–3).

A similar pattern was observed at Fire Island Inlet (fig. 9.1–3) where cell density increased from less than 0.1/ml in January to 22/ml by the end of March, a rate of 0.05 doublings/d. The population remained relatively stable through April and May and declined from a maximum of 50/ml in May to less than 0.1/ml by the end of July. This pattern roughly paralleled variations at a station 8 km south of Fire Island Inlet where cell density peaked in May and June and declined rapidly thereafter to near zero in August (fig. 9.1–4).

Mean cell densities along the New Jersey shore peaked near mid-June (fig. 9.1–3). In the New York Harbor region, cell densities were highest in March (29–75/ml), declined to 10/ml by the end of May, and remained constant at 10/ml through mid-July.

Cell densities in the outer Bight increased from 1 to 60/ml (mean = 10/ml) near the end of March to 10 to 400/ml by mid-June (mean = 240/ml). Based on qualitative net phytoplankton samples collected from 10 m with a Hardy continuous plankton recorder (225 by 234 μm mesh), *C. tripos* was present throughout the Bight in January and increased to a maximum in May (fig. 9.1–5). The decrease from May to June was probably a consequence of an aggregation of cells below the thermocline, as discussed later.

### Vertical Distribution

Vertical profiles of temperature, chlorophyll *a*, and *C. tripos* cell density showed little stratification from January through March when netplankton (phytoplankton retained on a 20-μm mesh screen) accounted for more than 80 percent of chlorophyll *a* in the water column. As the water column began to stratify in April, vertical distributions of chlorophyll (figs. 9.1–6 and 9.1–7) and *C. tripos* (fig. 9.1–8) began to show patterns of stratification, which varied systematically across the shelf.

Based on continuous vertical profiles between April 30 and May 5, seaward of the shelf break (stations 93, 94) maximum chlorophyll-*a* concentrations occurred in the upper 25 m and diatoms dominated the phytoplankton (fig. 9.1–6). Across the shelf break (stations 95, 96, 97) a broad maximum between 10 and 35 m was observed, which was dominated by diatoms near the surface and by *C. tripos* at depth. Farther inshore (stations 98, 99, 101,

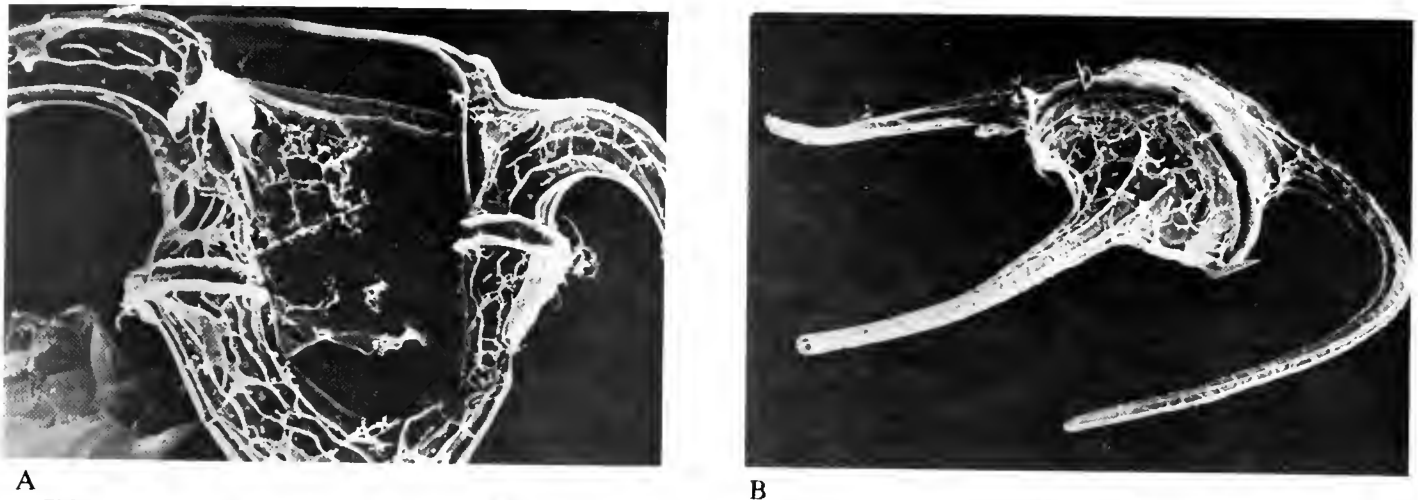


FIGURE 9.1–2.—Scanning electron micrographs of *C. tripos* showing sulcal opening (A) and three dimensional structure (B). Sulcal opening is 33 µm wide and does not appear to be covered by cell wall plates. Original magnification of B is 490×. (Courtesy of M. Ledbetter, Brookhaven National Laboratory.)

66, 72), a strong narrow band maximum developed as diatom populations disappeared. The layer consisted almost entirely of *C. tripos* (>90% of total cells) and was between 0.3 and 3 percent light depths in association with the 10° to 13° C isotherms. The depth of the layer, which was 1 to 3 m thick, decreased gradually from 35 m at station 98 (75 km offshore) to 20 m at station 72 (10 km offshore.) This trend apparently persisted as thermal stratification continued to develop so that by May and June (fig. 9.1–7) most of the *C. tripos* population was concentrated in a thin layer immediately below the thermocline, in association with the 10° C isotherm and between the 0.1 and 10 percent light depths. Because of nannoplankton blooms in the upper 10 m and high concentrations of detritus, the *C. tripos* maximum was below the 1 percent light depth in the Apex and south along the New Jersey coast within 20 km of the shoreline to about Barnegat Inlet (39° 45′N).

### Horizontal Distribution in Maximum Chlorophyll Layer

Areal distributions of *C. tripos* cell density in terms of population size must be interpreted in the context of temporal variations in the vertical distribution of cells. The population was distributed over the upper 30 to 40 m during January-March when the water column was well mixed and was aggregated near the base of the thermocline during April-June when the water column was thermally stratified.

Within the Apex in February and March, population size increased with distance from the mouth of the estuary, especially along the New Jersey coast (fig. 9.1–8). This pattern was closely related to the flow of estuarine water (fig. 9.1–9) so that cell densities were lowest when the proportion of estuarine water was greatest. Conversely, maximum chlorophyll-*a* concentrations (fig. 9.1–10) paralleled the distribution of low-salinity estuarine water, reflecting the rapid response of diatom populations (dominated by *Nitzschia seriata*, with *S. costatum* and *Rhizosolenia* sp. abundant) to nutrient enrichment.

This pattern continued across the shelf along a southeast transect originating in the Apex and extending to the shelf break in late March (fig. 9.1–11). *C. tripos* reached maximum cell density (60/ml) near the shelf break; *Nitzschia seriata* was most abundant in the Apex. Based on these observations and the degree to which *C. tripos* clogged zooplankton nets during March (fig. 9.1–12), high densities of *C. tripos* had developed throughout New York Bight by the end of March; maximum densities occurred in offshore reaches of the outer Bight (midshelf to the shelf break). This inshore-offshore increase in cell density apparently persisted into April (fig. 9.1–5).

As the water column stratified, distribution shifted so that by mid-May an inshore-offshore decrease in abundance was observed; maximum cell densities were located in the Apex near the head of the Hudson Shelf Valley (fig. 9.1–13). Nannoplankton accounted for most of the chlorophyll *a* in the surface layer throughout the Bight except for the center of high chlorophyll *a* (6 µg/l) off Long Island and a very patchy region off New Jersey where a maximum of 10 µg/l was reported. *C. tripos* accounted for more than 85 percent of the chlorophyll *a* at all depths at these two locations. As thermal stratification continued to develop, *C. tripos* distribution shifted to the southeast (fig. 9.1–14) so that by mid-June the center of maximum abundance was in about 60 m of water 80 km east of Seaside Park, N.J. (39°55′N, 73°15′W). Surface chlorophyll-*a* concentrations were low throughout the outer

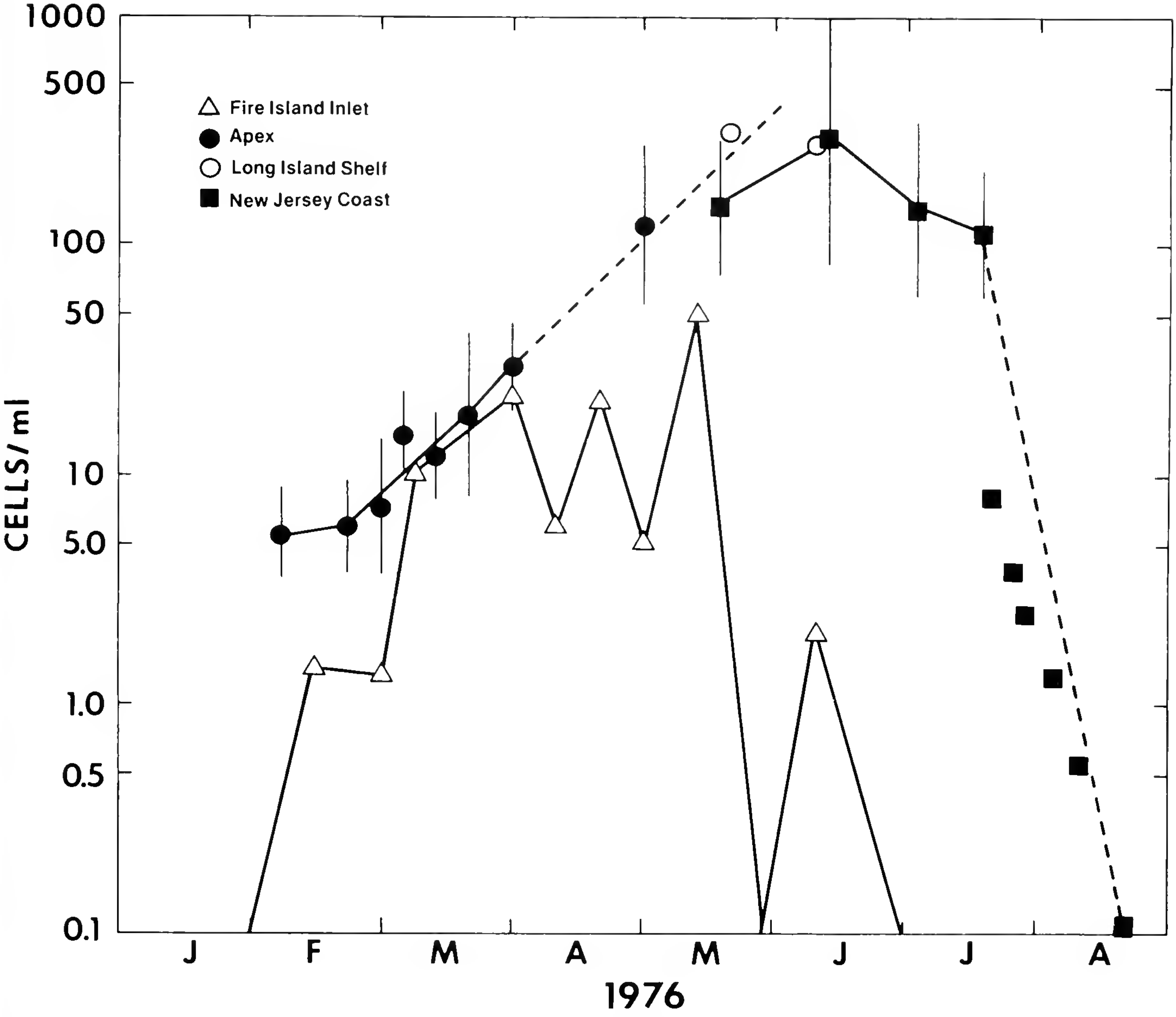


FIGURE 9.1-3.—Temporal variations in *C. tripos* cell density, January to August 1976. (Fire Island data by Sylvia Weaver; New Jersey coast data by Myra Cohn, Paul Hamer, Paul Olsen, and Frank Takacs.)

Bight, but remained high within the Apex owing to the growth of nannoplankton populations (fig. 9.1-14). During May the isopleths of cell density roughly paralleled isobaths off the Long Island and New Jersey coasts. In June this pattern persisted only off the Long Island coast. Off New Jersey, isopleths of cell density were roughly normal to isobaths, and high cell densities intruded closer to the coastline. Consequently, high cell densities were distributed over a larger area of the New Jersey shelf in relatively shallow water (20-40 m). Comparable cell densities over the Long Island shelf were in waters 40 to 60 m deep.

**Growth and Respiration of *Ceratium tripos***

Measurements of photosynthesis in the Apex during February and March and off Long Island in late April-early May 1976 indicate that *C. tripos* was growing at a mean euphotic zone growth rate of 0.04 doublings/d (carbon specific growth; C:Chl = 275), which is in the range of rates reported by Elbrächter (1973). Light-saturated rates were 0.3 to 0.4 doublings/d, in agreement with the cell division rates reported by Nordli (1957). Photosynthetic growth could account for the increase in population size observed before thermal stratification in 1976 (January-March).

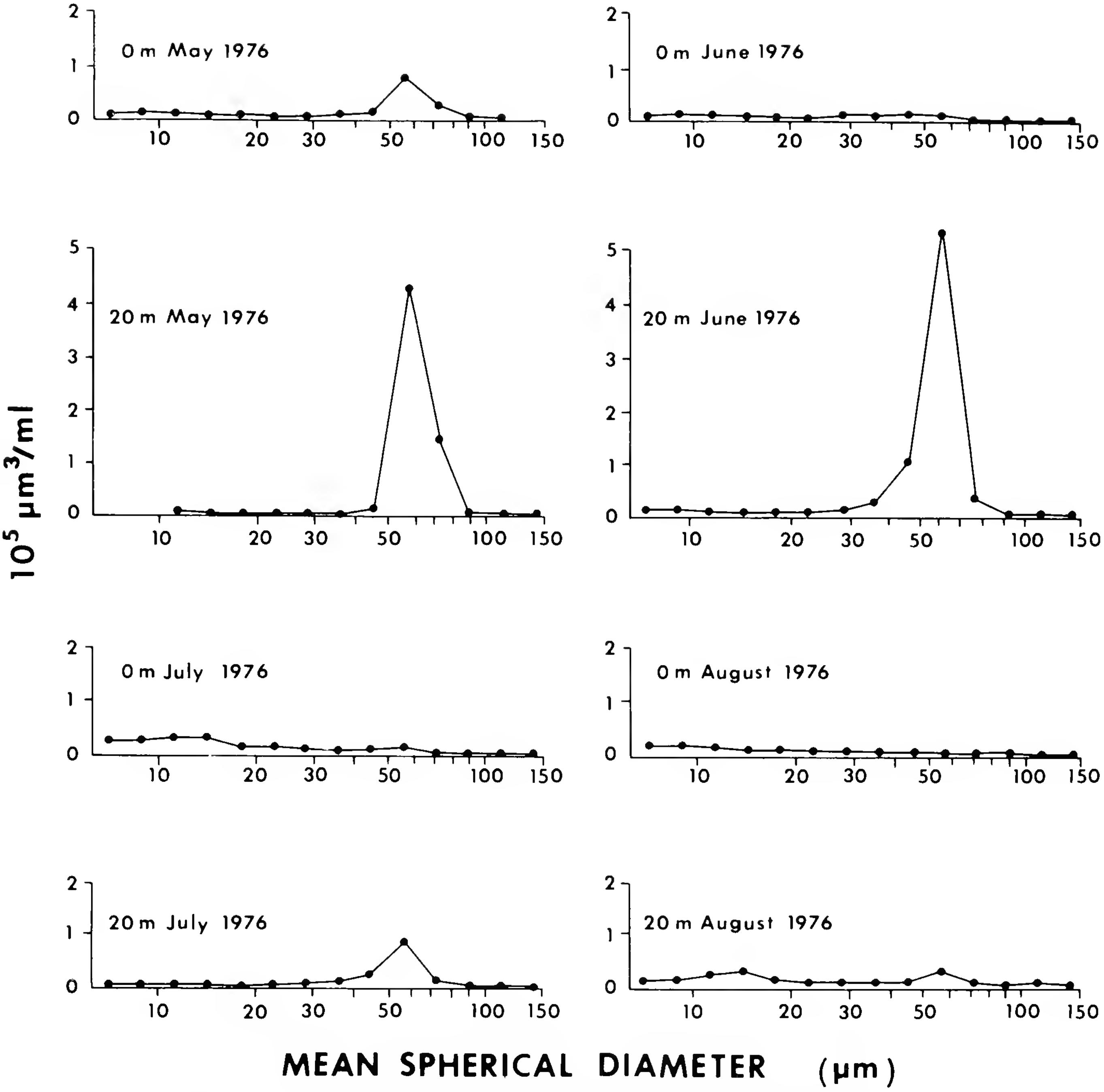


FIGURE 9.1–4.—Particle size frequency distributions from a station 8 km south of Fire Island Inlet, May to August 1976. (Data by Michael Dagg.)

Once the water column stratified, the problem became more complex as euphotic zone nutrients were depleted and the *C. tripos* population aggregated near the base of the thermocline. Although maximum cell densities were observed in June, it is possible that population size did not increase. The population was large enough by the end of March to account for observed cell densities in the maximum layer during June. Changes in cell density could have resulted from concentration of the existing population as well as from the balance between growth and mortality.

*C. tripos* photosynthesizes in the presence of sufficient light. In late April, *C. tripos* growth rates were 0.06 doublings/d averaged over the euphotic zone and 0.02 doublings/d at the 1 percent light depth. Local turbulence disrupted the *C. tripos* layer off Long Island in May (fig.

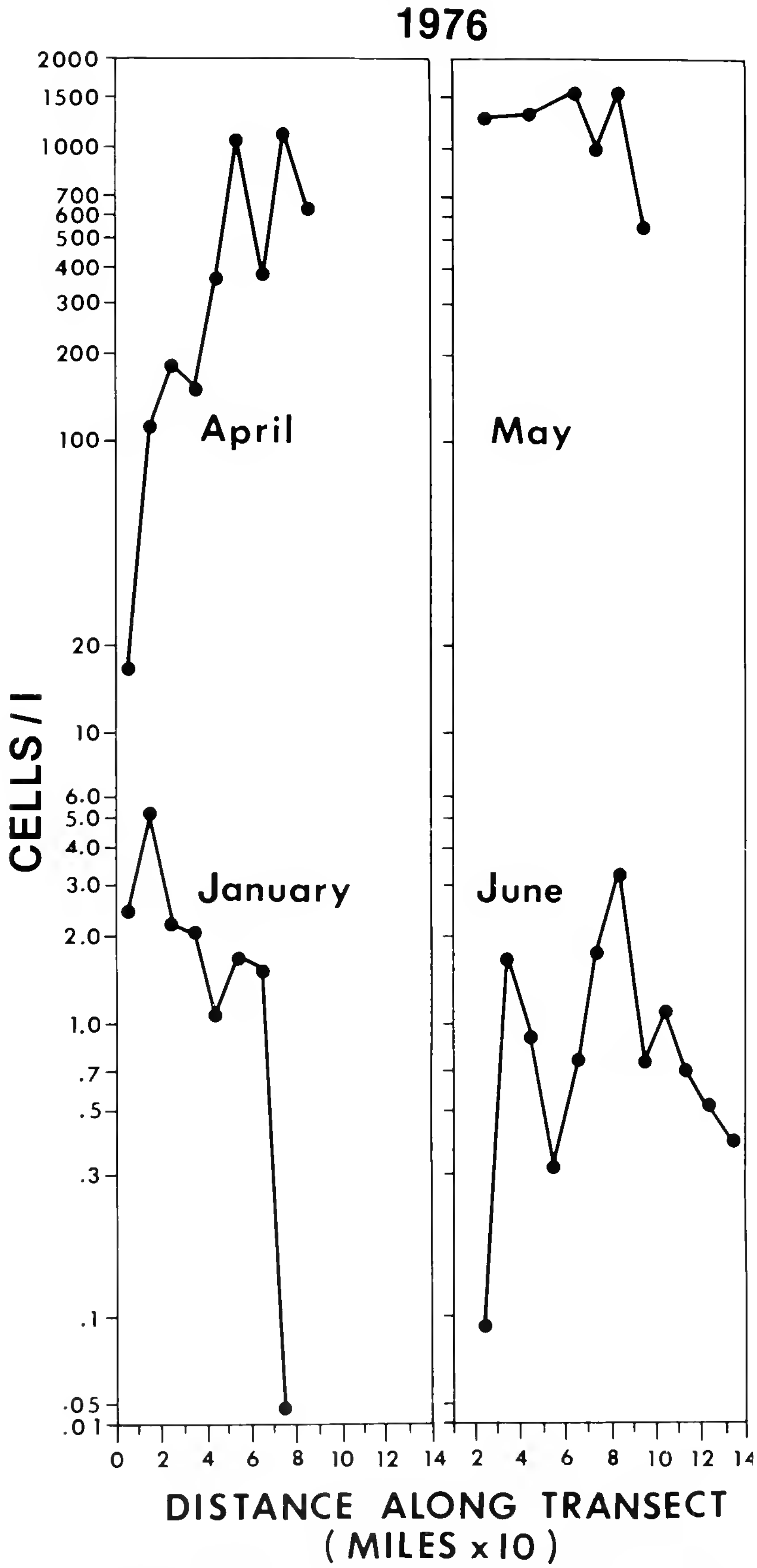


FIGURE 9.1-5—Relative abundance of *C. tripos* along Apex—continental slope transect, January to June 1976. (Data by Daniel Smith and Robert Marrero.)

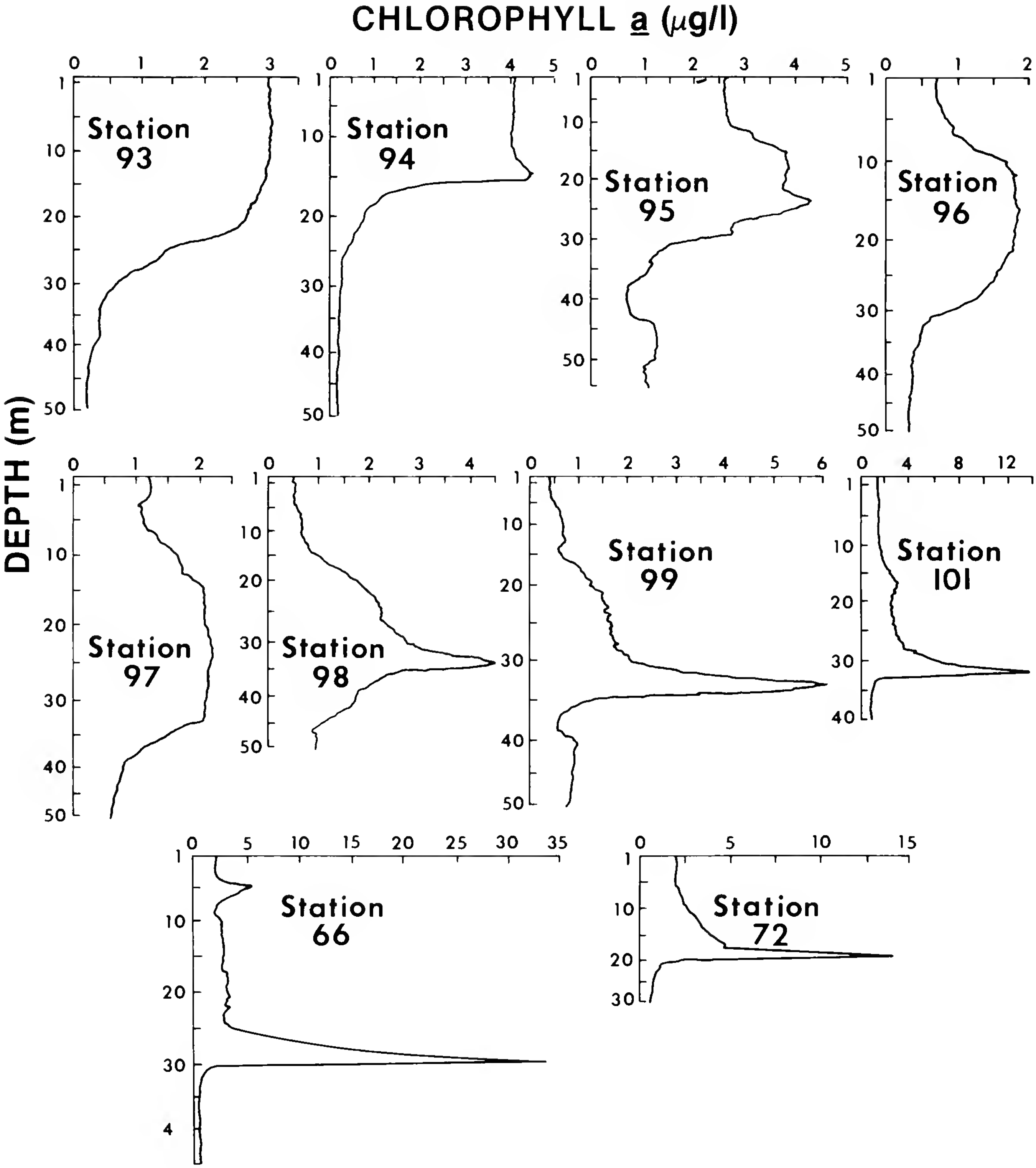


FIGURE 9.1–6.—Vertical profiles of chlorophyll-*a* concentrations from 10 stations shown in figure 9–1, April-June 1976.

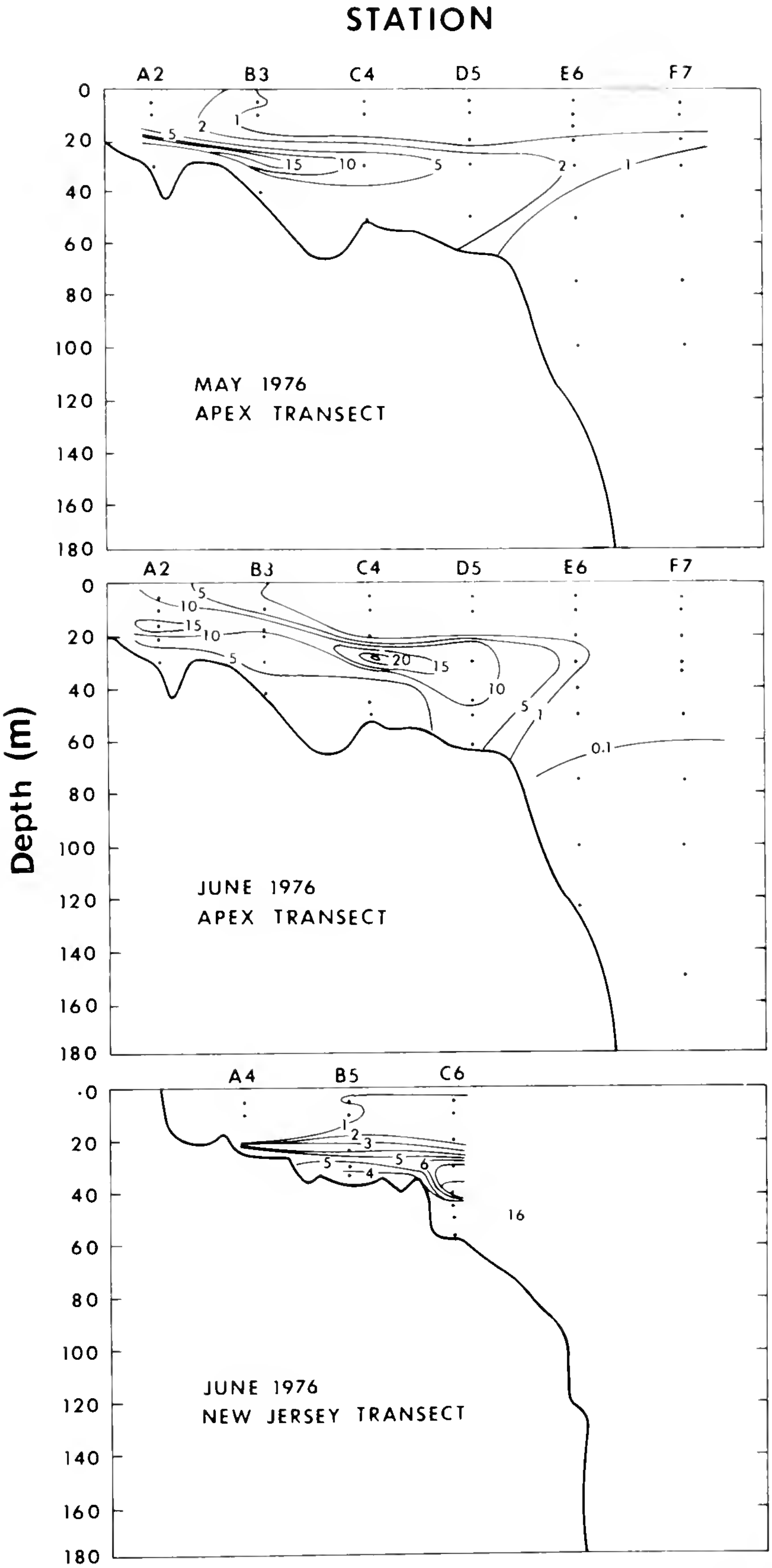


FIGURE 9.1-7.—Distribution of chlorophyll *a* along the Apex and New Jersey transects, May-June 1976

9.1–13), resulting in a uniform distribution of cells across the euphotic zone. Productivity at this station was 3.5 g C/m²/d, giving a mean euphotic zone growth rate of 0.2 doublings/d. A sample from 30 m (1% light depth) in the maximum layer in May had a productivity of 8 mg C/m³/d and a growth rate of 0.04 doublings/d. Thus, cells in the maximum layer in the lower reaches of the euphotic zone were probably growing photosynthetically at very slow rates (20- to 30-day generation times).

Within about 20 km of the New Jersey coast and 80 km of Sandy Hook, the bulk of the *C. tripos* population was below the compensation light depth (compensation intensity = 100–150 μE/m²/d) between the thermocline and the bottom. Two independent estimates of respiration rates (from measured photosynthesis-light curves and from the carbon content of the cells) indicate that *C. tripos* respires about 3 percent of its cell carbon/d at 10° C. Consequently, some form of heterotrophic metabolism or continuous recruitment from offshore photosynthetic populations must have occurred to account for the observed increase in population density after the water column stratified.

### Suspended Particulate Organic Matter and Phytoplankton

Levels of particulate organic carbon (POC) in the Apex water column from September 1973 through November 1975 fluctuated about a mean of 9.8 g C/m² (1 standard deviation = 2.9). The maximum turnover time of this organic matter is 2 to 15 days (annual mean = 8 days) and reflects the fact that particulate organic matter (POM) does not tend to accumulate in the water column under most circumstances.

This rapid turnover of POM was not observed in February and March 1976 (fig. 9.1–15). During this period, POC accumulated in the water column to levels two to three times higher than previously observed. This increase coincided with the initial phases of the *C. tripos* bloom (fig. 9.1–3). *C. tripos* accounted for 25 to 45 percent of suspended POC until the end of March when it accounted for 64 percent. Elimination of the carbon accounted for by *C. tripos* from the suspended POC pool gives water column POC concentrations that reflect the diatom bloom in early March and are in the range of values previously reported (fig. 9.1–15).

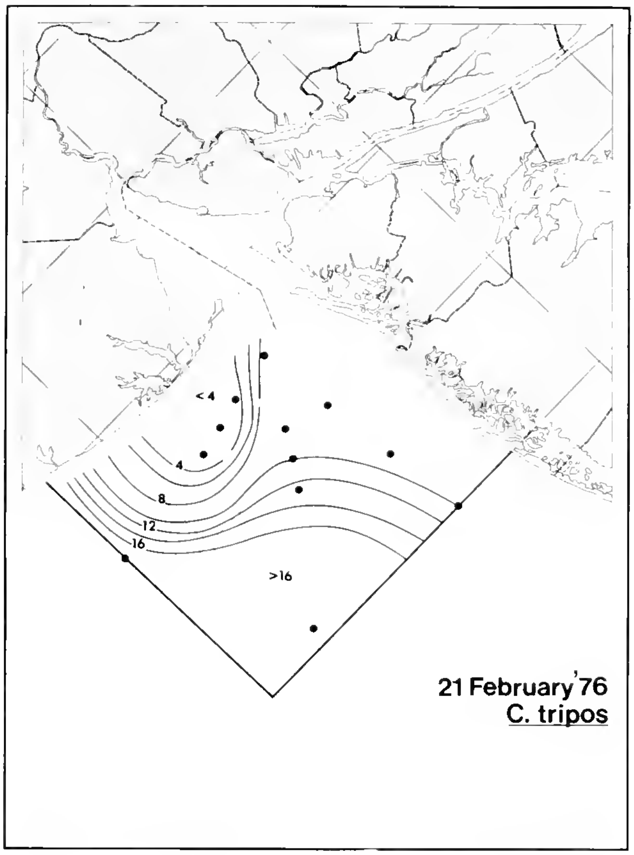
The influence of *C. tripos* on the pool of phytoplankton-C in the Apex was significant (fig. 9.1–16). Before 1976, phytoplankton-C accounted for 15 to 45 percent of suspended POC, with proportions of 35 to 45 percent typical of phytoplankton blooms regardless of time of year and dominant species. During February and March 1976, however, phytoplankton-C increased from 56 to 84 percent of the suspended POC pool. Removal of *C. tripos* brings the proportion of phytoplankton-C back into the range usually observed in the Apex and shows the diatom bloom peaking in early March (fig. 9.1–16). The gradual increase in the biomass of *C. tripos* and the subsequent accumulation of POC in in the water column did not appear to influence the typical development of the winter-spring diatom bloom.

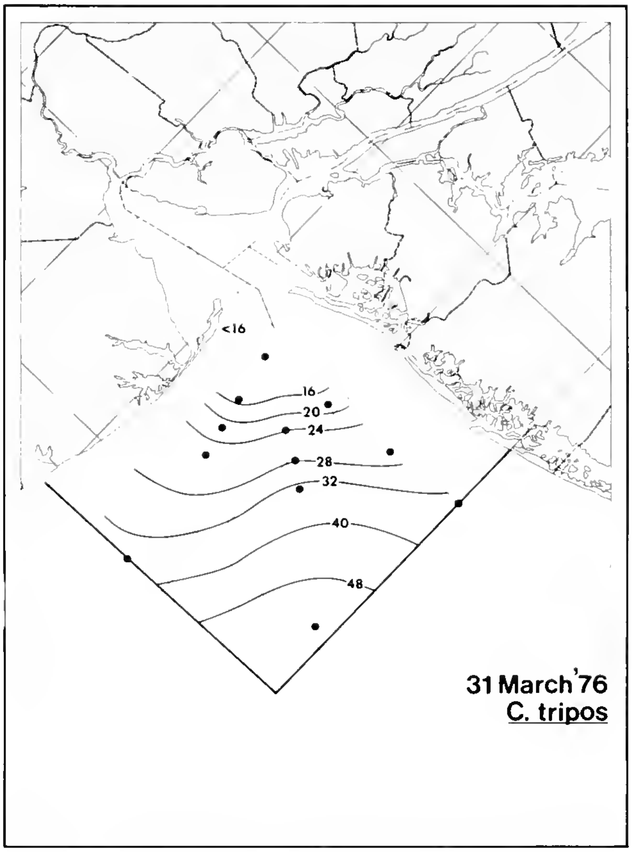
Temporal variations in copepod abundance and grazing rates indicate that very little of the diatom bloom is grazed at temperatures below 10° C (Chervin 1978). Above 10° C selective grazing could become important, because estuarine copepods (the major particle grazers in the Apex) do not eat *C. tripos* (Chervin 1978), and increased copepod grazing pressure during spring is probably a factor in transition from netplankton to nannoplankton-dominated phytoplankton blooms. *C. tripos* appears to be a slow-growing species subject to low predation pressure.

### Accumulation of *Ceratium tripos* off the New Jersey Coast

The temporal and spatial distributions of *C. tripos* in the New York Bight show an increase and a shift in maximum abundance from offshore before stratification to inshore as the water column stratified. The increase in cell density was most pronounced off the New Jersey coast. Two hypotheses, not mutually exclusive, have been suggested to account for these distributions.

The first hypothesis is similar to the accumulation mechanism demonstrated for *Prorocentrum micans* and other dinoflagellates in Chesapeake Bay (Tyler and Seliger 1978). It requires a two-layered circulation pattern with an onshore flow of bottom water and an offshore flow of surface water, organisms that aggregate in the bottom layer, and an ability to survive for extended periods of time at low light levels. A two-layered, thermohaline circulation has been described for New York Bight (Ketchum and Keen 1955; Bumpus 1964), and it has been well-documented in this report that the *C. tripos* population aggregated near the upper boundary of the bottom layer. Possibly, most of the increase in population size occurred before stratification when the population was distributed throughout the euphotic zone and nutrients were plentiful. Once the water column stratified, *C. tripos* aggregated near the base of the thermocline throughout the Bight and the onshore movement of bottom water resulted in a shift in the location of maximum abundance from offshore to inshore. This process took place over 3 months (April-June), and, though we cannot determine whether the observed increase in cell density was a consequence of growth or an aggregation of cells, some form of anabolic metabolism was required to satisfy cellular respiratory demands during this period. Because the *C. tripos* layer was between the 1 and 3 percent light depths over most of the outer Bight more than 20 km from the New Jersey coast, it is likely that the population in this region was





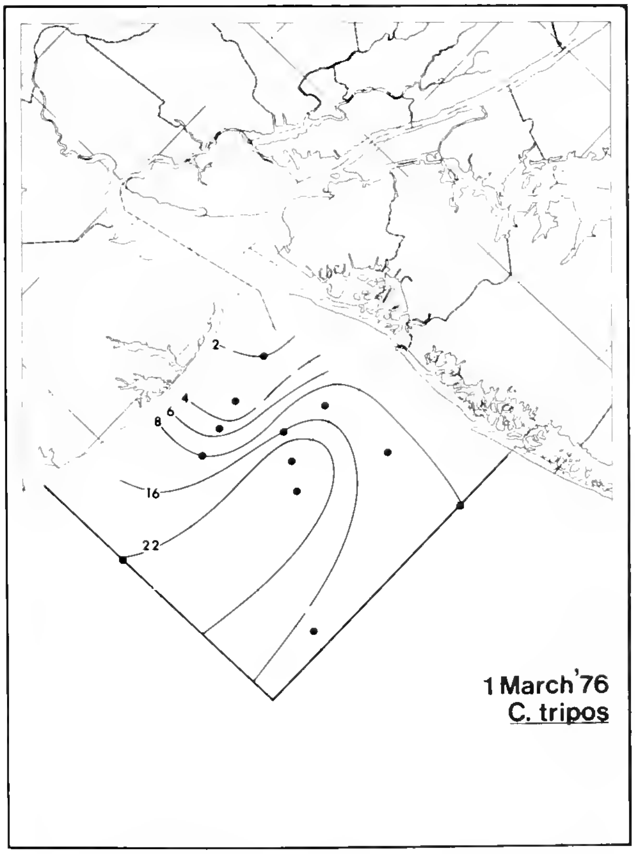
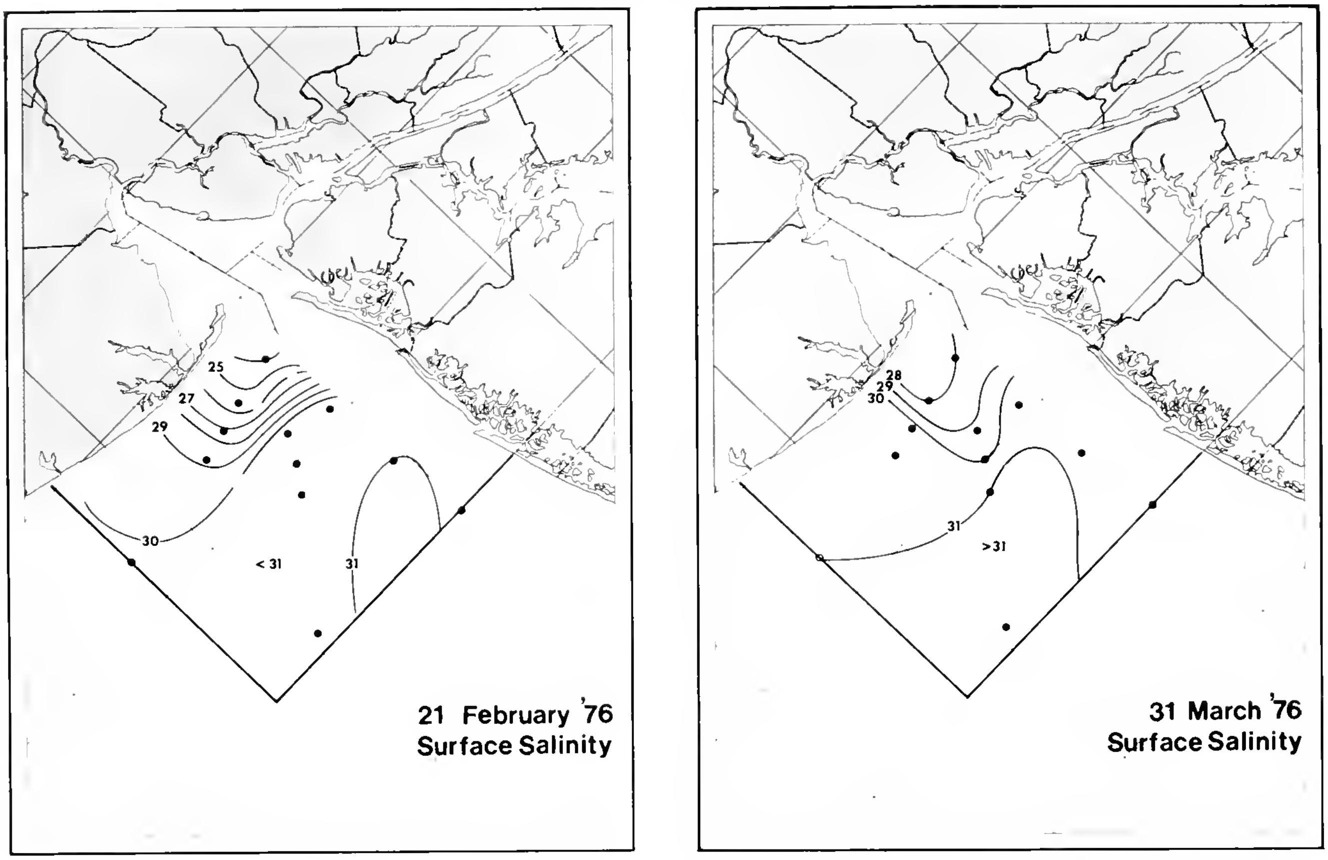


FIGURE 9.1-8.—Distribution of maximum *C. tripos* cell density in the Apex, February-March 1976.



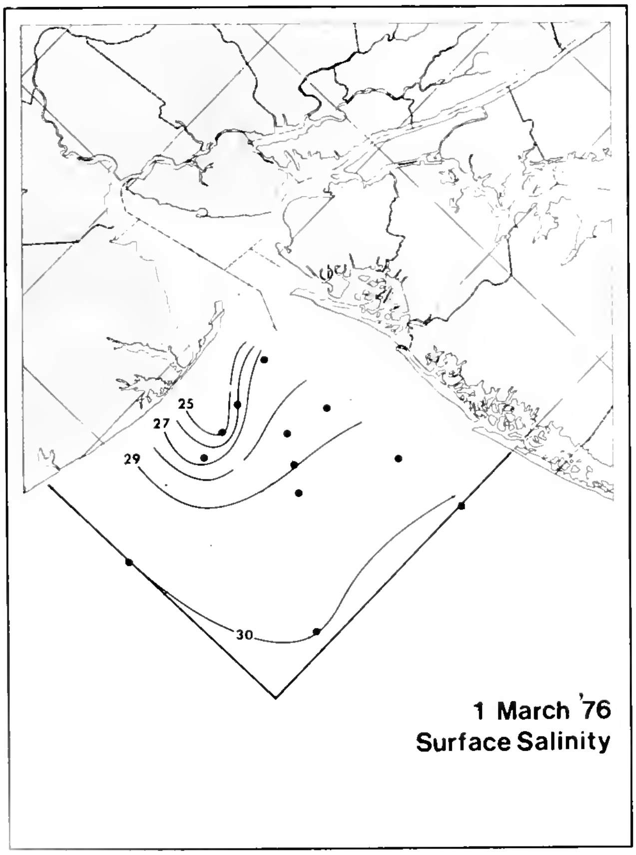
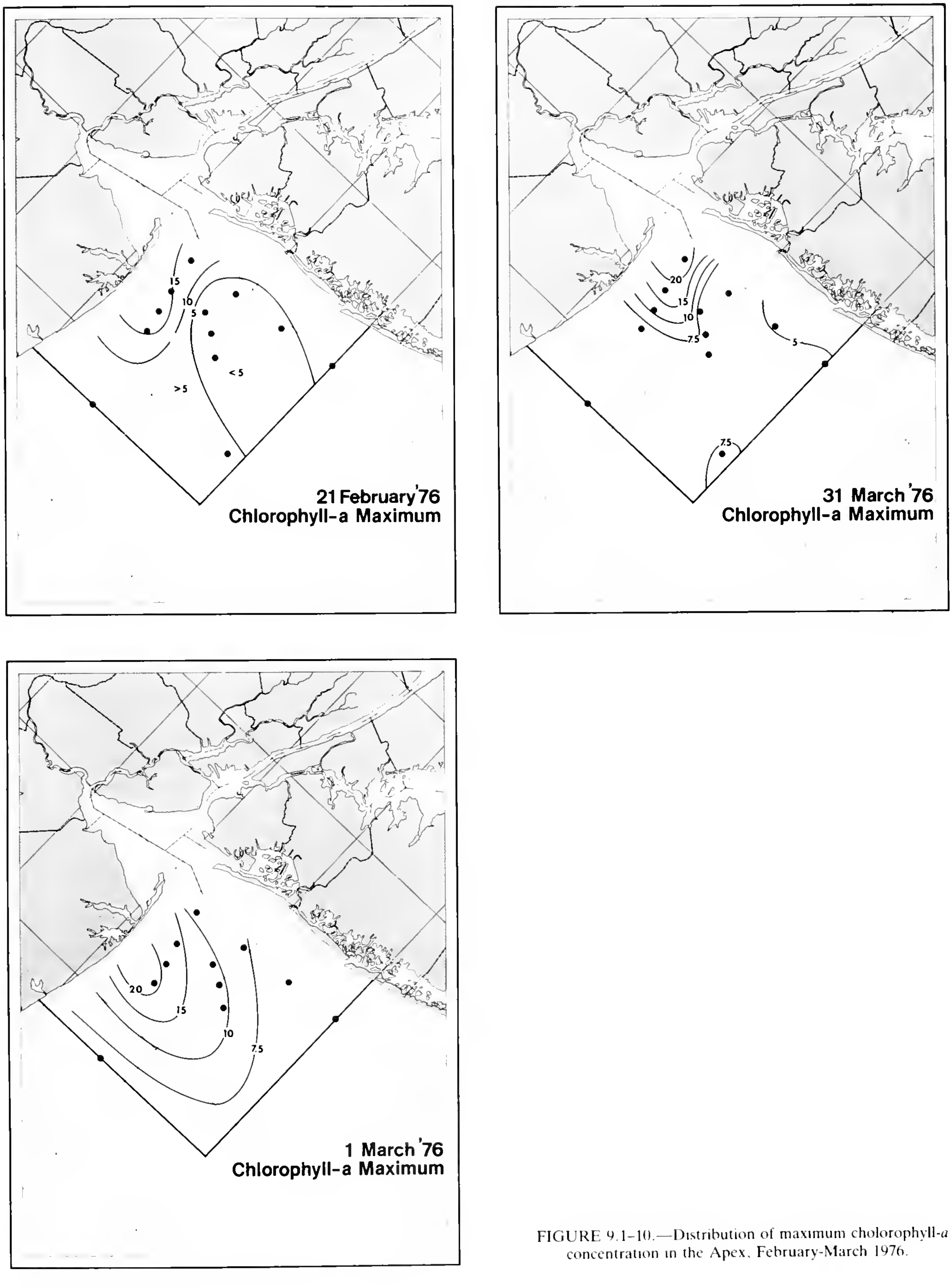


FIGURE 9.1-9.—Distribution of surface salinity in the Apex, February-March 1976.



21 February '76
Chlorophyll-a Maximum

31 March '76
Chlorophyll-a Maximum

1 March '76
Chlorophyll-a Maximum

FIGURE 9.1-10.—Distribution of maximum cholorophyll-*a* concentration in the Apex, February-March 1976.

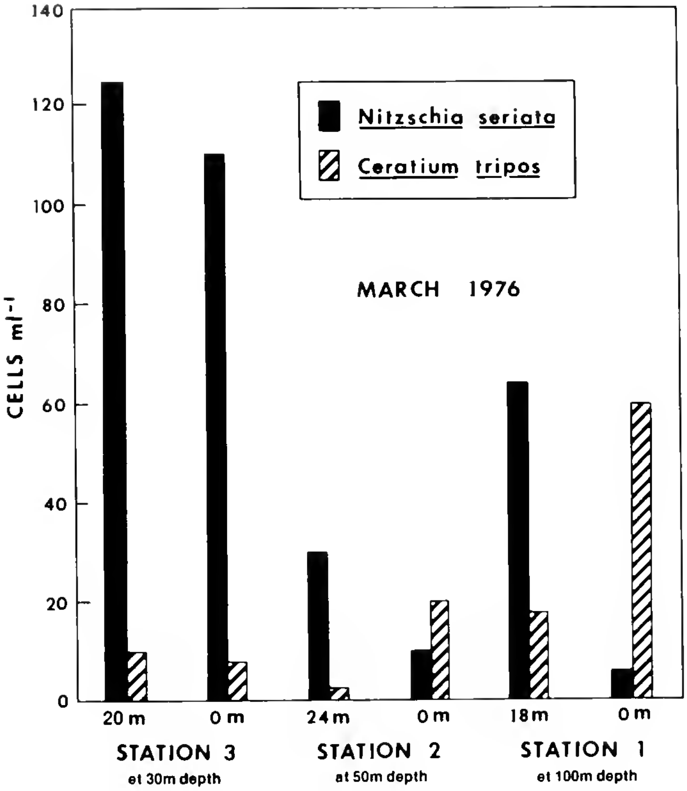


FIGURE 9.1–11.—Histogram of *C. tripos* and *Nitzschia seriata* cell density off Long Island and extending south across the shelf to the shelf break (stations 3, 2, and 1), March 1976.

growing photosynthetically. Within 20 km of the coast, and especially in the region of the Hudson River plume, the *C. tripos* layer was usually below the 1 percent light depth. These observations suggest the hypothesis that coastal populations in the subeuphotic zone were maintained and possibly increased by recruitment of actively growing, photosynthetic populations from farther offshore.

Though some form of shoreward entrainment must have taken place, several objections exist that question the importance of this mechanism.

1. A shoreward flow of bottom water would transport not only *C. tripos* into the region where the oxygen minimum layer was pronounced but also oxygenated water. (See chapter 8, table 8–2.)

2. Estimates of photosynthetic growth rates at the 1 percent light depth were 0.02 to 0.04 doublings/d in both late April and in May. However, the rate of increase of population density from May to June off the New Jersey coast was 0.04 doublings/d. If the coastal population was being maintained by recruitment from offshore populations, the increase in cell density probably reflected an increase in concentration rather than an increase in population size.

3. Nitrate + nitrite concentrations were low throughout the water column across the shelf except in the Apex (fig. 9.1–17). The nitrogen budget for the Apex during May-July 1975 (table 9.1–1) indicates that the nitrogen supply to the euphotic zone and phytoplankton uptake rates are high and closely coupled, and that regenerated ammonia is a major source of nitrogen. Phytoplankton blooms during May and June are usually dominated by small-celled phytoplankters growing at mean euphotic zone rates of 0.5 to 2.0 doublings/d. These blooms are localized in the surface mixed layer (upper 10 m of the water column) and are most pronounced off the New Jersey coast in the plume of the Hudson River. There is no evidence that *C. tripos* influenced the development of these blooms during June 1976, and nannoplankton chlorophyll concentrations in the surface layer were similar to previous years. The nutrients required for nannoplankton growth are derived from estuarine runoff and regeneration above the thermocline (Malone 1976b). Considering the distribution of *C. tripos* and its photosynthetic growth rate, it is unlikely that it was competing (or could compete) with nannoplankton populations for these nutrients. If photoautotrophy was involved in the maintenance or growth of the subthermocline population, nutrient inputs must have been greater than in previous years and must have involved onshore transport of bottom water across the shelf. However, if *C. tripos* is capable of "luxury" nutrient uptake and can store nutrients for weeks or months, the nutrient distributions of May and June might not be a factor. (Luxury consumption of this magnitude has never been reported).

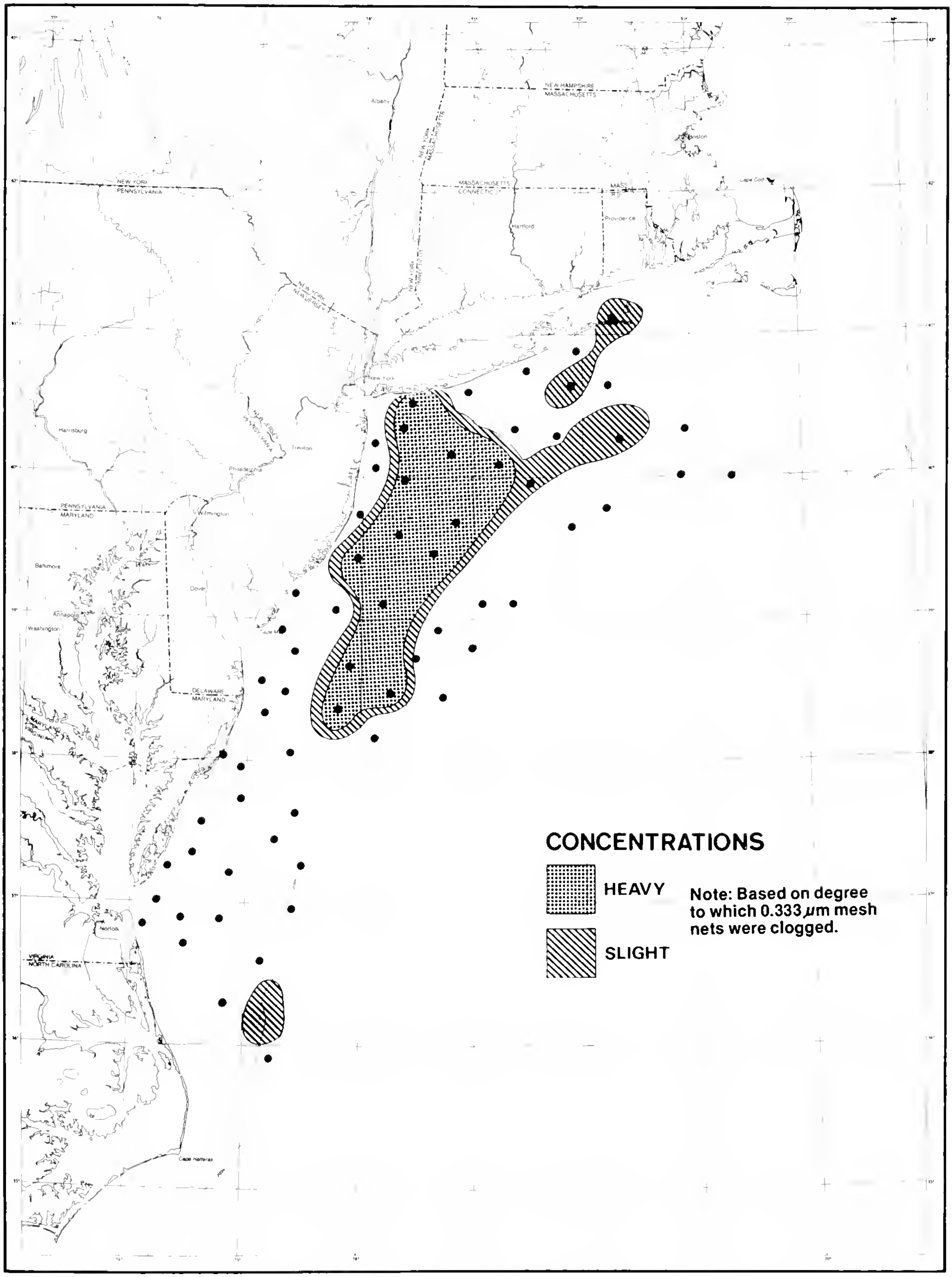
The second hypothesis involves heterotrophic growth (or maintenance) by the *C. tripos* population below the Hudson River plume off the New Jersey coast. This hypothesis is based on circumstantial evidence.

1. Growth of *C. tripos* had no obvious effect on growth of diatom populations during May and June in the Apex. Yet, growth of *C. tripos* during February and March increased the POC content of the water column by a factor of 2 or 3 over previous years.

2. *C. tripos* did not respond (as reflected in distribution of biomass) to estuarine runoff as other photoautotrophic populations did. The observed downstream increase in biomass (in contrast with the distribution of diatoms in February and March and nannoplankton in May and June) would develop if *C. tripos* were feeding phagotrophically on POM of estuarine origin or on phytodetritus.

3. *C. tripos* is euryhaline, with a salinity optimum of 20‰ to 25‰. This suggests that the decline in abundance with decreasing salinity in the Apex was not related to salinity per se.

Since *C. tripos* may have the ability to ingest POM, the observed accumulation of *C. tripos* in the water column may have been a consequence of phagotrophic uptake of



Note: Based on degree to which 0.333 μm mesh nets were clogged.

FIGURE 9.1-12.—Distribution of *C. tripos* during March 1976. (Data from NMFS, Sandy Hook Laboratory.)

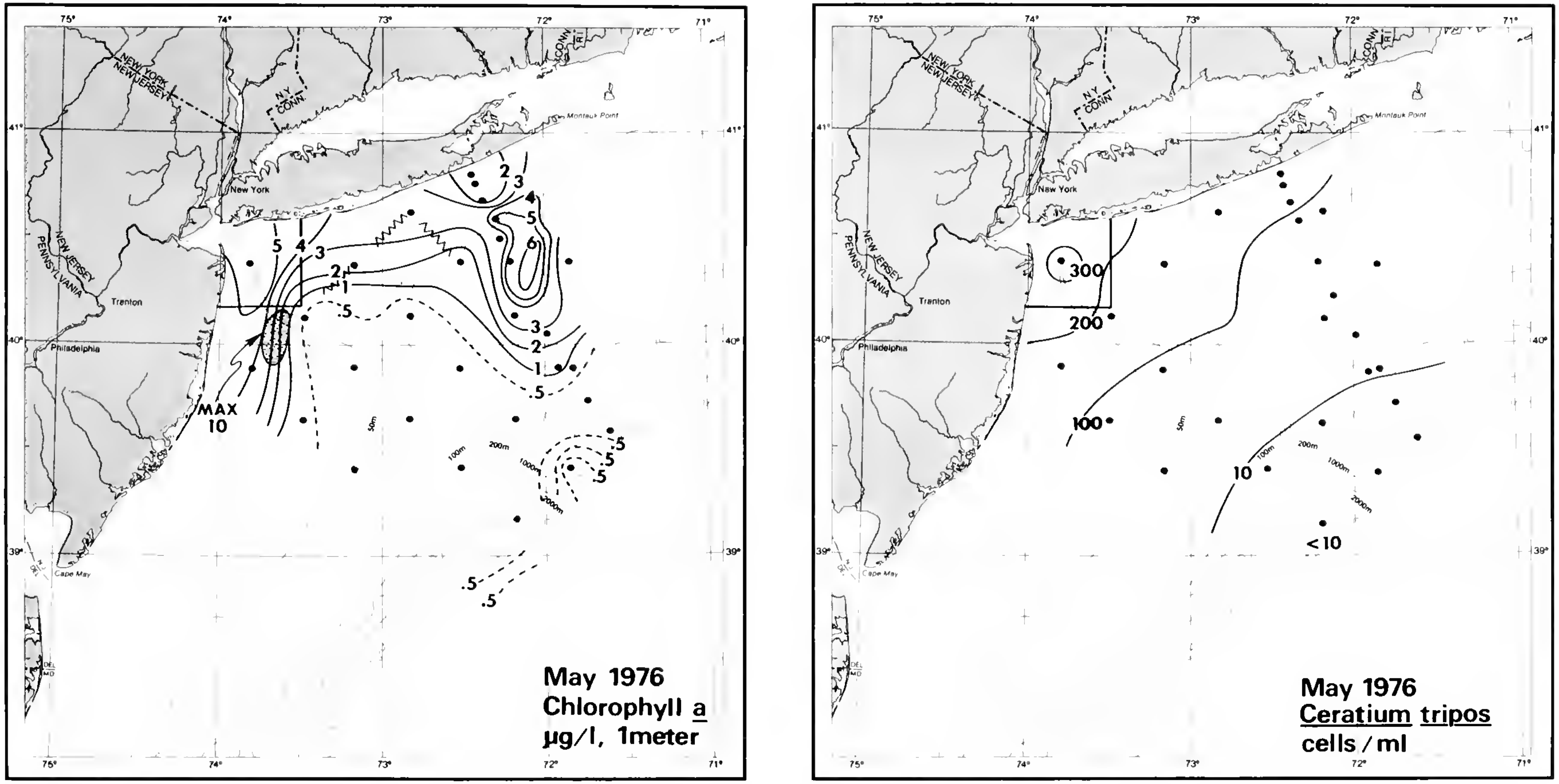


FIGURE 9.1-13.—Distribution of surface chlorophyll *a* (determined by underway fluorescence) and *C. tripos* cell density in the chlorophyll-*a* maximum layer, May 17–24, 1976.

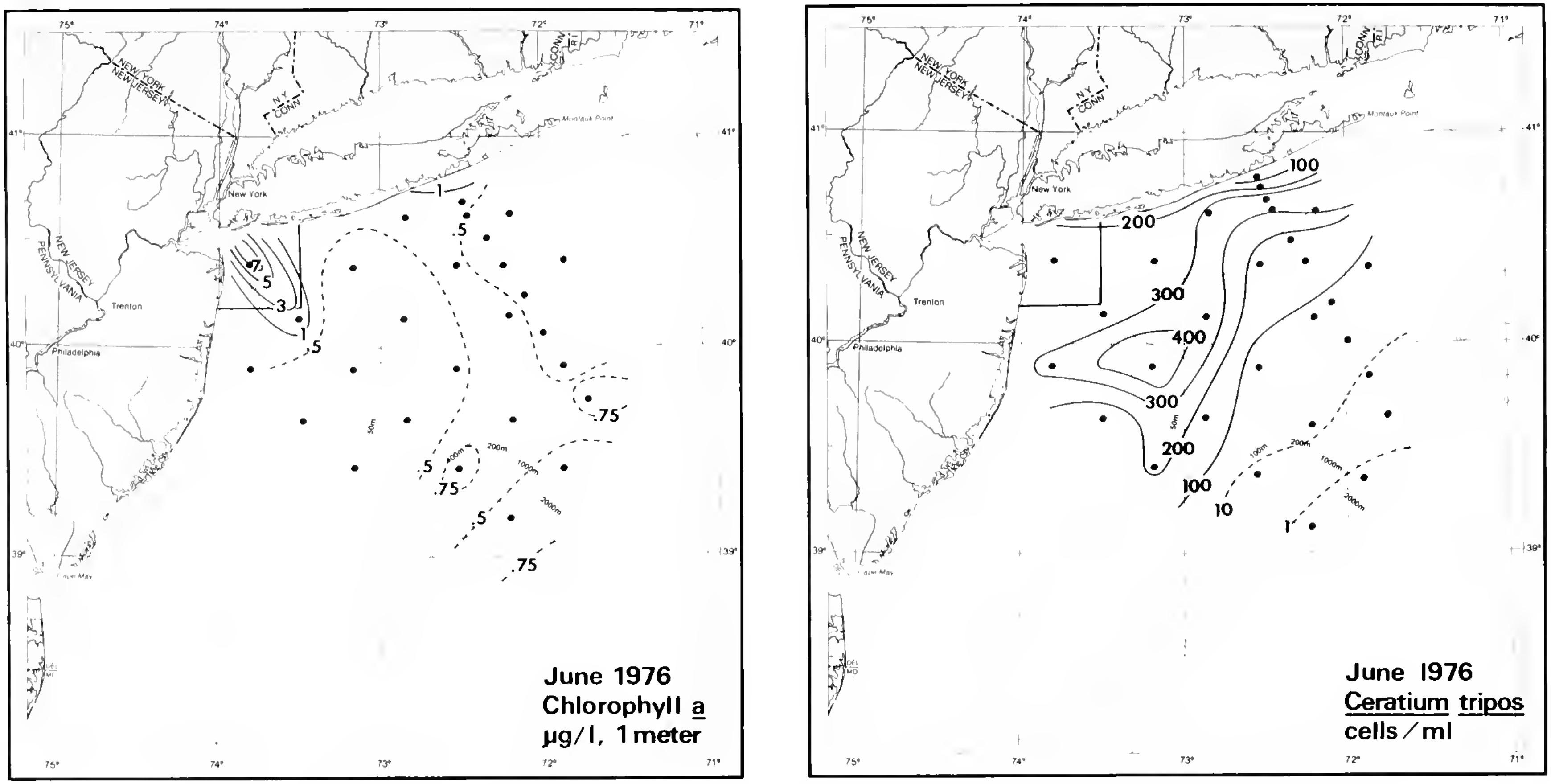


FIGURE 9.1-14.—Distribution of surface chlorophyll *a* (determined by underway fluorescence) and *C. tripos* cell density in the chlorophyll-*a* maximum layer

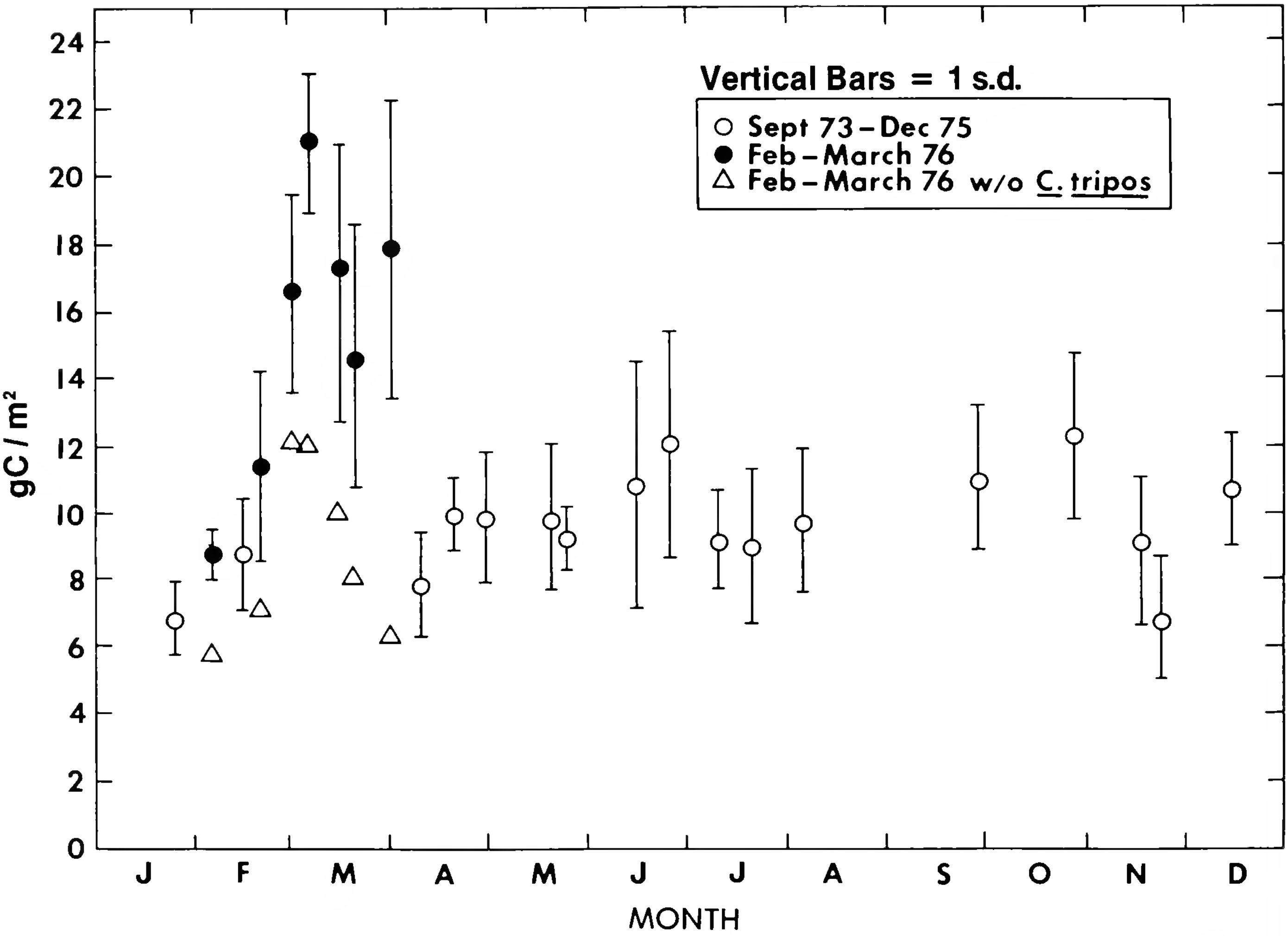


FIGURE 9.1–15.—Temporal variations in mean water column particulate organic carbon content of the Apex, September 1973 to March 1976.

POM that settled to the bottom or washed out of the system in previous years. Aggregation near the bottom of the thermocline would be advantageous in that the population is in a region where POM tends to accumulate as it settles through the water column. By metabolizing POM in the water column, which was previously lost from the system, a substantial increase in water column BOD would be generated without necessarily increasing the input of inorganic nutrients or POM.

Presumably, the bloom's collapse in June and July was a consequence of the exhaustion of nutrient supplies (internal or external) or parasitism. Based on the proportion of *C. tripos*-C in the POC pool of the water column at the end of March (64%), it is possible that as the discharge of the Hudson River began to decline in May and June (fig. 9.1–18) the population off the New Jersey coast suffered mass mortalities due to limited food supplies. Grazing is unlikely, since copepods have been shown not to eat *C. tripos*.

## CONCLUSIONS

Although data were not collected synoptically in time or space, coastal observations correlated well with those in the Apex and outer Bight (figs. 9.1–3, 9.1–5, 9.1–13, and 9.1–14). Temporal variations in *C. tripos* cell density at Fire Island Inlet reflect the early stages of the bloom before stratification, and mean cell densities along the New Jersey shore appeared to reflect at least the latter stages of the bloom during the period of thermal stratification.

The *C. tripos* bloom apparently began throughout the New York Bight in January; maximum cell densities developed in the midshelf to shelf break region in late March before the onset of thermal stratification. The temporal and spatial distributions of cells indicate that the population was increasing most rapidly in the outer Bight during March or that the outer Bight received a larger initial inoculum of cells than the inner Bight. The large area over

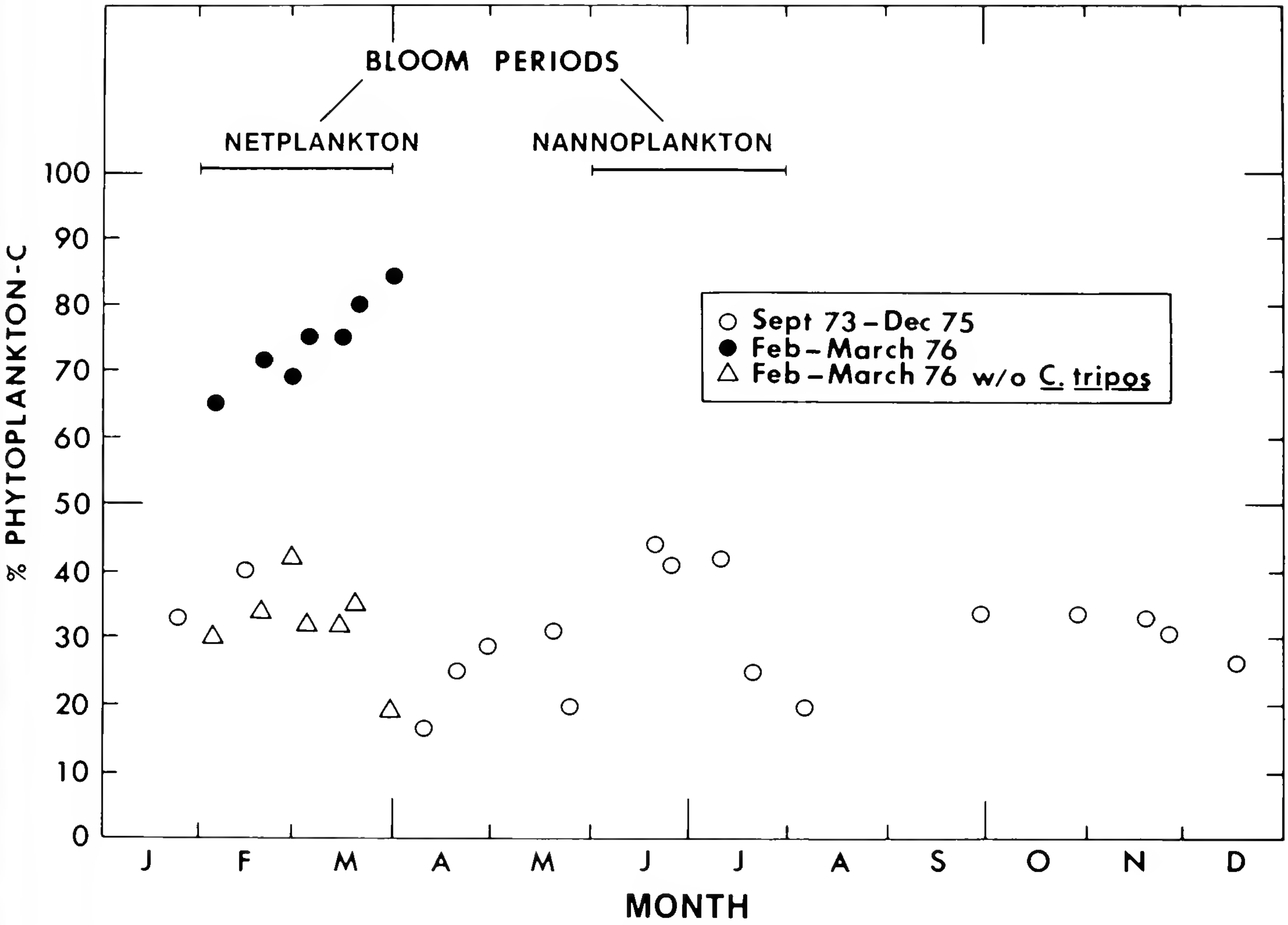


FIGURE 9.1–16.—Temporal variations in the proportion of water column POC accounted for by phytoplankton in the Apex, September 1973 to March 1976.

which the bloom occurred indicates that it did not develop in response to local nutrient enrichment of the coastal zone during the actual period of the bloom. This is supported by the observation that *C. tripos* cell densities were lowest in the Apex where local nutrient enrichment is greatest. The causes of the bloom, whether related to increased growth or decreased mortality rates, must have involved processes operative on spatial scales on the order of the continental shelf and time scales on the order of months to years.

The temporal and spatial development of the bloom during April and May suggest an onshore transport of cells once the population began to aggregate below the thermocline. By mid-June a large population of cells was present below the thermocline in a relatively flat region of the New Jersey shelf between the 20- and 40-m isobaths. Much of this population was below the euphotic zone in a subthermocline layer about 10 m thick. This is in marked contrast to the population off the Long Island coast where the layer of maximum concentration was well off the bottom in a subthermocline layer about 30 m thick. (See chapters 2 and 8.) Maximum population size was probably achieved after March and before July; and population size declined rapidly during July.

There is no evidence that the *C. tripos* bloom influenced the growth of netplankton diatoms or nannoplankton populations. The distribution and abundance of these groups were similar to previous years' observations.

The role of *C. tripos* in the development of the oxygen minimum layer off New Jersey is difficult to evaluate in the absence of data on the time and space distribution of D.O. in the bottom layer and more complete information of the time and space distributions of POC, chlorophyll *a*, and *C. tripos*. The Bight Apex has been subjected to

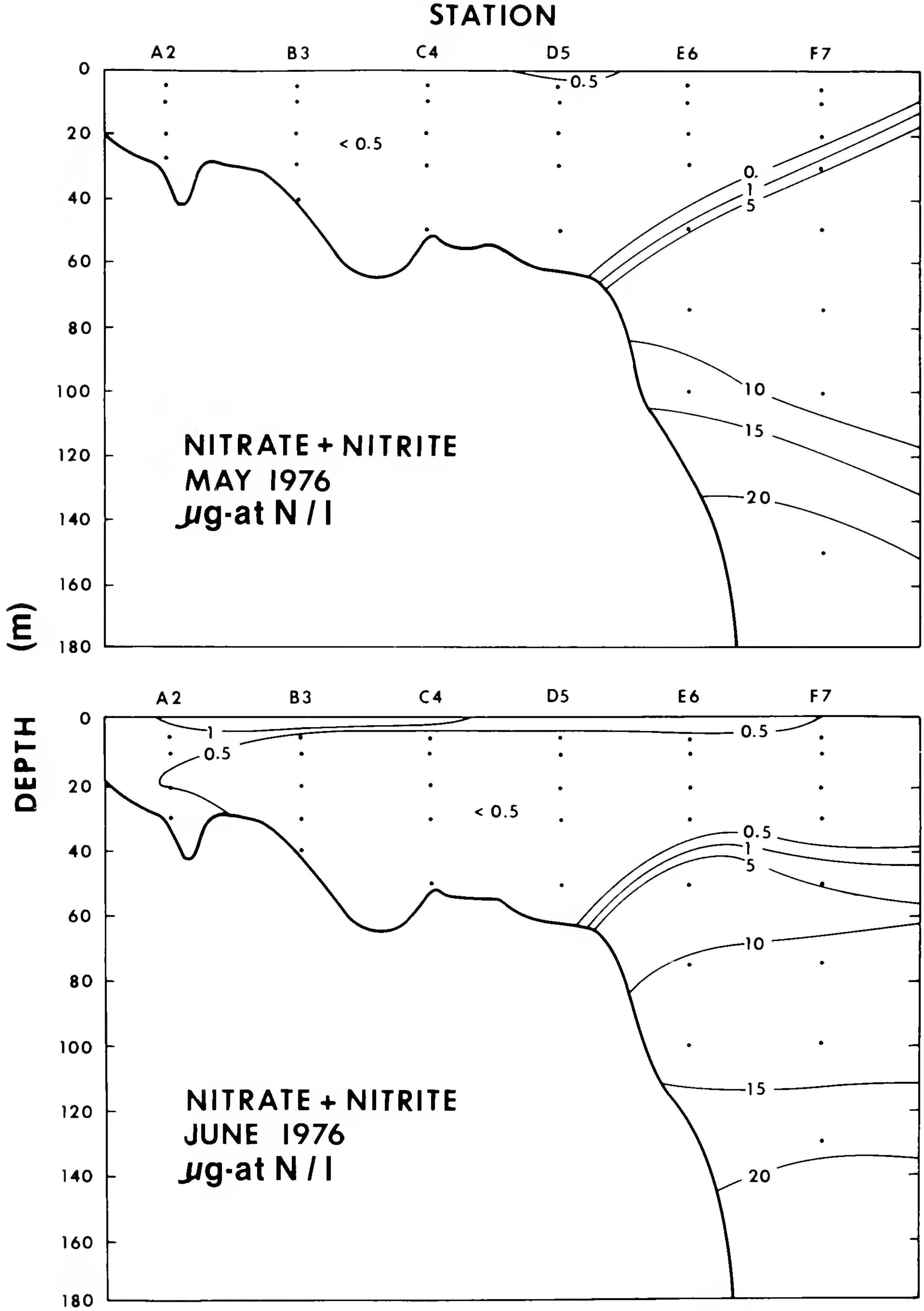


FIGURE 9.1-17.—Distribution of dissolved nitrate + nitrite along the Apex transect, May-June 1976.

considerable organic loading over the past two decades, and the development of oxygen minimum layers and local anoxia have occurred previously during summer (ch. 1).

Based on the effect of *C. tripos* on the content of POC in the water column and on the development of large, subthermocline populations, it is likely that *C. tripos* made a very significant contribution to the oxygen demand required to account for the oxygen minimum layer. In the latter context, a flocculent suspension of organic matter at least 1 cm thick coated the bottom during July between Sandy Hook and Atlantic City from 5 to 50 km offshore. The floc consisted primarily of phytoplankton cells dominated by *C. tripos*. Microscopic examination indicated a steady increase in the decomposition of *C. tripos* cells during July. (See chapter 9, part 2.)

A computer simulation model was used to explore the combined effects of benthic respiration and *C. tripos* respiration on the rate of oxygen depletion below the thermocline. *C. tripos* respiration rates were calculated from the expression $R = aW^b$ (Banse 1976) where $a$ and $b$ are temperature dependent constants and $W$ and $R$ are the weight of the cell in picograms (pg) of carbon and the respiration rate in picograms of carbon/cell/hour, respectively. The carbon content of *C. tripos* was calculated from both CHN analysis and regression of netplankton chlorophyll *a* on netplankton carbon. Values ranged from 20,000 to 30,000 pg/cell; a mean value of 25,000 was chosen for calculating respiration rates. Using $Q_{10} = 2.3$, the carbon specific respiration rate of a single cell was calculated to be 0.003/h at 10° C ($= 1.4 \times 10^{-4}$ μl $O_2$/cell/h). In 1977, *C. tripos* respiration was measured in the field using an oxygen polarographic electrode and an electron transport system assay. The results of these direct measurements suggested a respiration rate of $1.39 \pm 0.17 \times 10^{-4}$ μl $O_2$/cell/h at 10° C, agreeing well with the rate calculated according to the expression given by Banse (1976).

The following information was input:

1. A mean benthic respiration rate of 11 ml $O_2/m^2/h$(1.0 mg-at $O_2/m^2/h$) was calculated from Thomas et al. (1976) for an "average" community in the Bight.
2. Eddy diffusion coefficients of 1.0 $cm^2/s$ across the thermocline and 10 $cm^2/s$ below the thermocline were used.
3. The thermocline was placed 25 m above the bottom. This situation existed off the coast of Long Island, but the thermocline was much closer to the bottom off the coast of New Jersey.
4. The overlying water was nearly saturated with oxygen, starting with 6.72 ml/1(= 0.6 mg-at $O_2$/1).
5. Using data collected on six cruises in New York Bight (Brookhaven National Laboratory data base), the following numbers of cells were placed in the bottom 20 m: (a) 0–5 m (above the bottom) $2 \times 10^7$ cells/$m^3$ (consuming $2.8 \times 10^{-3}$ ml $O_2$/l/h); (b) 5–10 m, $4 \times 10^7$ cells/$m^3$ (consuming $5.6 \times 10^{-3}$ ml $O_2$/l/h); (c) 10–15 m, $6 \times 10^7$ cells/$m^3$ (consuming $8.4 \times 10^{-3}$ ml $O_2$/l/h; (d) 15–20 m, $2 \times 10^8$ cells/$m^3$ (consuming $2.8 \times 10^{-2}$ ml $O_2$/l/h). (Cells from the upper 5 m were excluded because they may be at or above the compensation depth and do not contribute substantially to oxygen depletion.)

The model output indicated that within two months the oxygen concentration in the bottom 5-m layer reaches a steady state concentration that is 45 percent of the initial oxygen concentration. The simulated rate of oxygen depletion below the thermocline is extremely sensitive to changes in eddy diffusivity, and small changes in diffusivity are sufficient to cause simulated anoxia.

These calculations show the potential metabolic influence of *C. tripos*. The water column integrated *C. tripos* respiration rate exceeds the benthic oxygen consumption rate by a factor of 20. Therefore, *C. tripos* biomass is a large potential source of BOD. Oxidation of the *C. tripos* biomass (3,255 mg-at C/$m^2$) within 20 m of the bottom would require 8,463 mg-at $O_2/m^2$ or 71 percent of the initial oxygen content. Thus, the combined effects of respiration and subsequent death and decay of the biomass were more than sufficient to produce anoxia.

The occurrence of an oxygen minimum layer and local anoxic waters off the New Jersey coast in contrast to the Long Island coast may reflect differences in bottom topography, residence time of water in the bottom layer, and turbulent mixing. The shelf within 50 km of the coast is much flatter and shallower off New Jersey than off Long Island. Consequently, the *C. tripos* layer between the 20- and 40-m isobaths off New Jersey was distributed over the bottom surface in a subthermocline water column 5 to 15 m thick, whereas the *C. tripos* maximum off Long Island intersected the bottom along an isobath and was well off the bottom (>30 m) over most of its extent. In addition, high cell densities occurred over larger areas off New Jersey. These observations and the possibility that the residence time of bottom water is longer off New Jersey than off Long Island could explain the development of a more intense and widespread oxygen minimum layer off New Jersey.

Nannoplankton productivity per se was probably not a major factor in the 1976 oxygen depletion even though it normally accounts for most of the input of POM to the region. With the exception of winter-spring diatom blooms, which apparently go ungrazed, there is no evidence that a significant portion of phytoplankton production normally accumulates below the thermocline during summer. The dominance of small-celled phytoplankton (usually less than 10 μm in diameter), vertical chlorophyll-*a* distributions, the importance of ammonia as a nitrogen source for phytoplankton, and the rapid increase in zooplankton grazing pressure during May and June are consistent with

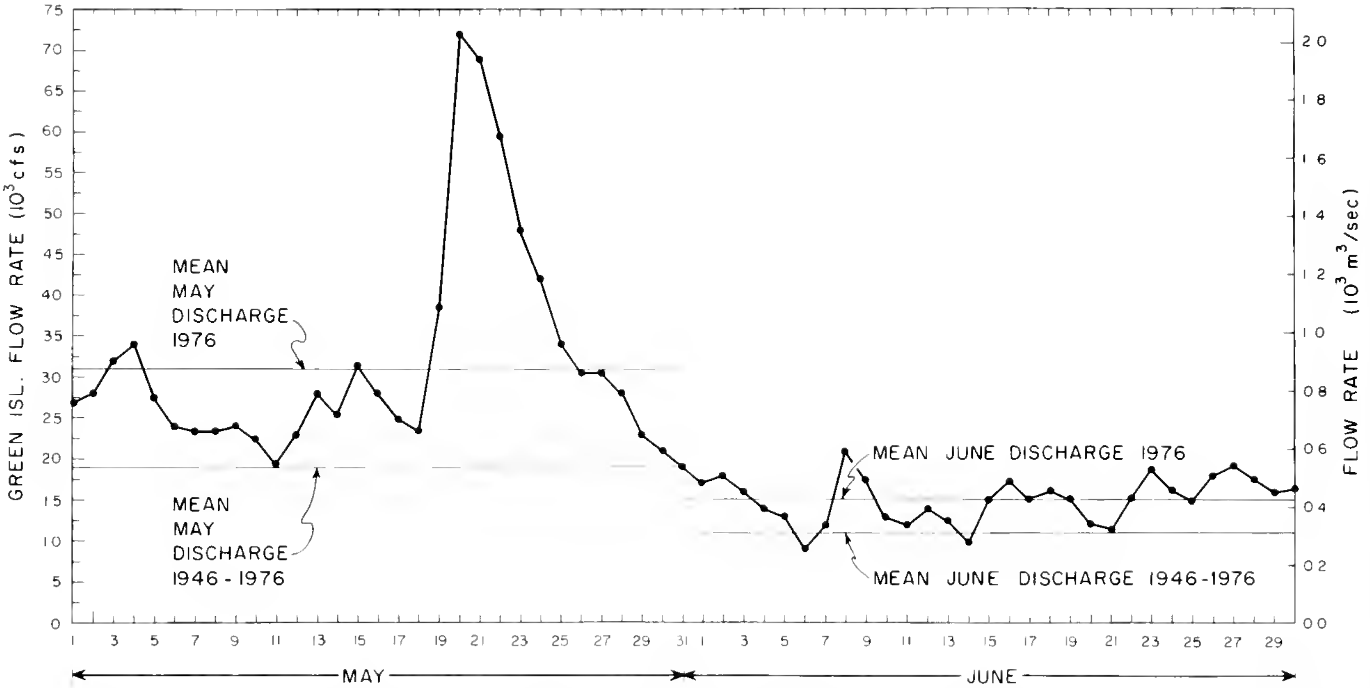


FIGURE 9.1–18.—Freshwater flow of the Hudson River at Green Island during May and June 1976. (C. A. Parker—from U.S.G.S. data.)

the rapid turnover of POC calculated for the Apex in the absence of *C. tripos*. In effect, the *C. tripos* bloom provided a mechanism by which large quantities of POC were accumulated over several months. The change in the relative abundance of phytoplankton species and the effects of this change on the distribution and quantity of POC in the subthermocline water column resulted in exceptionally high BOD in 1976. Unfortunately, we do not understand this type of species succession very well, and the basic question of why the *C. tripos* bloom occurred in the first place remains unanswered.

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## REFERENCES

Banse, K., 1976. Rates of growth, respiration and photosynthesis of unicellular algae as related to cell size—a review, *J. Phycol.* 12:135–140.

Bigelow, H. B., 1926. Plankton of the offshore waters of the Gulf of Maine, *Bull. U.S. Bur. Fish.* 40:1–509.

Bumpus, D. F., 1964. Residual drift along the bottom on the continental shelf in the Middle Atlantic Bight area, *Limnol. Oceanogr.* 10 (suppl.):R50–R53.

Chervin, M. B., 1978. Assimilation of particulate organic carbon by estuarine and coastal copepods, *Mar. Biol.* 49:265–275.

Cleve, P. T., 1900. The seasonal distribution of Atlantic plankton organisms, *Göteborgs Kundl. Vet-och Vitterhets Samhalles Handl.*, 17, 36 pp.

Elbrächter, M., 1973. Population dynamics of *Ceratium* in coastal waters of the Kiel Bay, *Oikos (suppl.)* 15:43–48.

Fournier, R. O., Marra, J., Bohrer, R., and Van Det, M., 1977. Plankton dynamics and nutrient enrichment of the Scotian Shelf, *J. Fish. Res. Board Can.* 34:1004–1018.

Garside, C., and Malone, T. C., 1978. Monthly oxygen and carbon budgets of the New York Bight Apex, *Estuar. Coastal Mar. Sci.* 6:93–104.

Graham, H. W., 1941. An oceanographic study of the dinoflagellate genus *Ceratium*, *Ecol. Monogr.* 11:99–116.

Hasle, G. R., 1950. Phototactic vertical migration in marine dinoflagellates, *Oikos* 2:162–175.

Hofneder, H., 1930. Uber die animalische Ernahurung von *Ceratium hirundinella* O. F. Müller and uber die Rolle des Kernes bei dieser Zellfunktion, *Arch. Protistenkunde* 71:1–32.

Ketchum, G. H., and Keen, D. J., 1955. The accumulation of river water over the continental shelf between Cape Cod and Chesapeake Bay, *Deep-Sea Res.* 3, (suppl.):346–357.

Malone, T. C., 1976a. Phytoplankton productivity in the Apex of the New York Bight: September 1973-August 1974, *NOAA Tech. Memo.* ERL MESA-5, NOAA Environmental Research Laboratories, Boulder, Colo., 100 pp.

Malone, T. C., 1976b. Phytoplankton productivity in the Apex of the New York Bight: Environmental regulation of productivity/chlorophyll *a*, *Amer. Soc. Limnol. Oceanogr. Spec. Symp.* 2:260–272.

Malone, T. C., 1977a. Environmental regulation of phytoplankton productivity in the lower Hudson Estuary, *Estuar. Coastal Mar. Sci.* 5:157–171.

Malone, T. C., 1977b. Light-saturated photosynthesis by phytoplankton size fractions in the New York Bight, *Mar. Biol.* 42:281–292.

Malone, T. C., 1977c. Plankton Systematics and Distribution, *MESA New York Bight Atlas Monogr.* 13, New York Sea Grant Institute, Albany, N.Y., 45 pp.

Mandelli, E. F., Burkholder, P. R., Doheny, T. E., Brody, R., 1970 Studies of primary productivity in coastal waters of southern Long Island, New York, *Mar. Biol.* 7:153–160.

Nordli, E., 1957. Experimental studies on the ecology of *Ceratia*, *Oikos* 8:200–252.

Norris, D. R., 1969. Possible phagtrophic feeding in *Ceratium lunula* Schimper, *Limnol. Oceanogr.* 14:448–449.

Ryther, J. H., and Yentsch, C. S., 1958. Primary production of continental shelf waters off New York, *Limnol. Oceanogr.* 3:327–335.

Smayda, T. J., 1976. Plankton processes in Mid-Atlantic near-shore and shelf waters and energy-related activities, in B. Manowitz (ed.), Effects of Energy-Related Activities on the Atlantic Continental Shelf, BNL Publ. 50484, pp. 70–94.

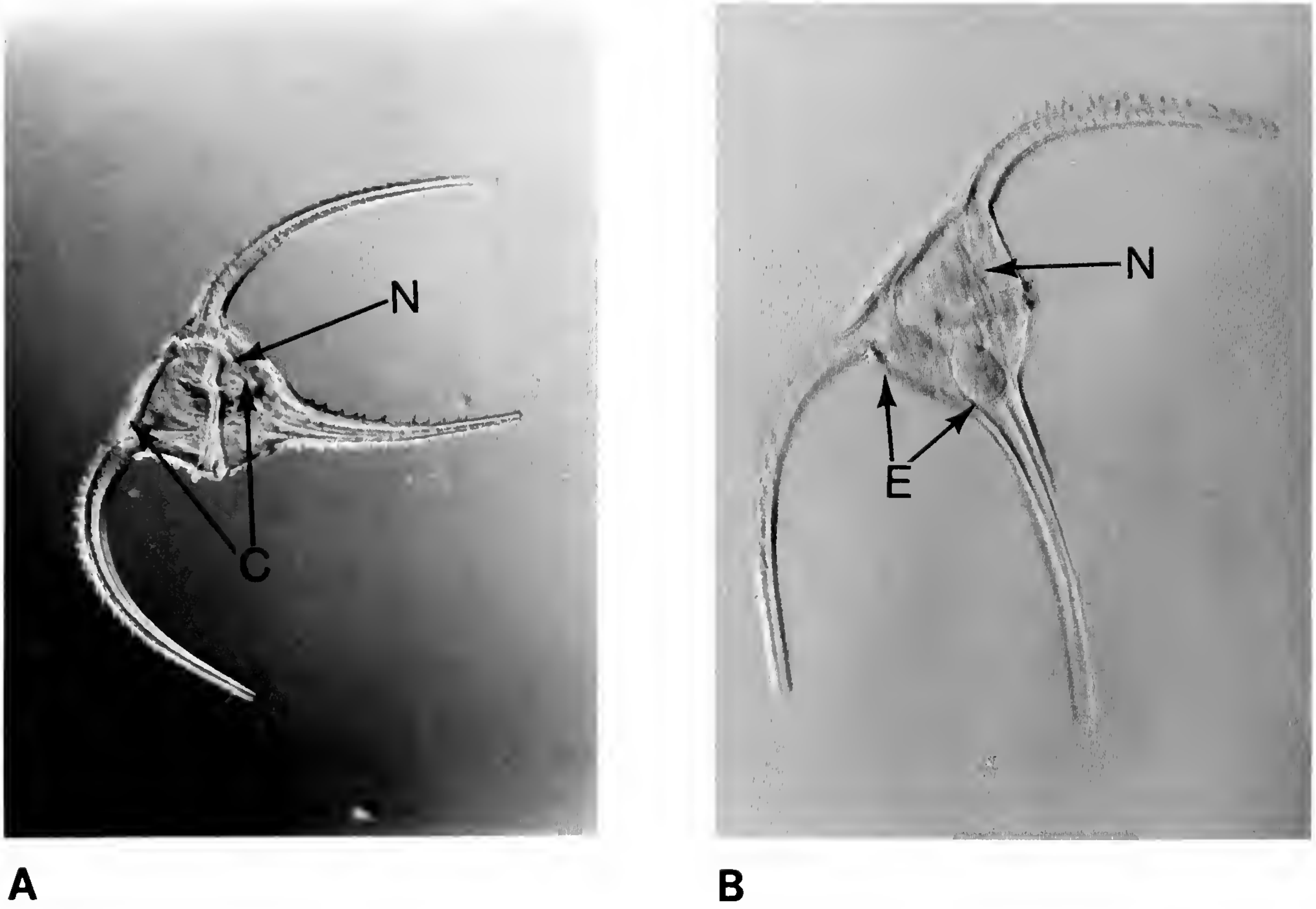
Thomas, J. P., Phoel, W. C., Steimle, F. W., O'Reilly, J. E., and Evans, C. A., 1976. Seabed oxygen consumption in the New York Bight Apex, *Amer. Soc. Limnol. Oceanogr. Spec. Symp.* 2:354–369.

Tyler, M. A., and Seliger, H. H., 1978. Annual subsurface transport of red tide dinoflagellate to its bloom area: Water circulation patterns and organism distributions in the Chesapeake Bay, *Limnol. Oceanogr.* 23:227–246.

Von Arndt, E. A., 1967. Untersuchungen an Populationen von *Ceratium tripos* f. *subsalsum* Ostf. im Gegeiet der Sudkuste der Mechlenburger Bucht, *Wiss. z. Univ. Rostock* 9(10):1199–1206.

Von Stosch, H. A., 1964. Zum Problem der sexuellen Fortflanzung in der Peridiniengattung *Ceratium*, *Helgolander wiss Mieresunters* 10:140–152.

Yentsch, C. S., 1977. Plankton Production, *MESA New York Bight Atlas Monogr.* 12, New York Sea Grant Institute, Albany, N.Y., 25 pp.



CHAPTER 9, PART I, PLATE I.—Nomarski differential interference photomicrographs (A, B) of *Ceratium* stained with acetocarmine. N is cell nucleus; C, chloroplast; and E, nuclear inclusions of extracellular origin. Original magnification of A and B is 250×. (Courtesy of W. Marin and P. Falkowski, Brookhaven National Laboratory.)

**Oxygen Depletion and Associated Benthic Mortalities in New York Bight, 1976**

# Chapter 9. Plankton Dynamics and Nutrient Cycling

## Part 2. Bloom Decomposition

*John B. Mahoney*[1]

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## INTRODUCTION

As discussed in part 1 of this chapter the combined BOD of the respiration of the *Ceratium tripos* population and the cell decomposition during the bloom decline and ultimate collapse would have been sufficient to produce the 1976 oxygen depletion in the New York Bight. This section is concerned with *C. tripos* decomposition.

In early July, when the magnitude of the problem first became evident, divers observed a layer of flocculent material several meters thick at the thermocline and a denser accumulation at least 1 cm thick on the bottom. The floc was present throughout the oxygen-depleted area and persisted during the summer. Examination of initial samples of this material established that it was an aggregate of phytoplankton dominated by *C. tripos*. Signs of decay in this aggregate were obvious. The phytoplankton in the affected area was surveyed during the summer to obtain information on the time sequence and geographical pattern of the decomposition of the *C. tripos* population.

## METHODS

Samples, mostly 1 liter in polyethylene bottles, were collected by divers or taken by water sampler casts. Since viability of the *C. tripos* cells and the activity of other microorganisms and meiofauna were considered important assessments, use of a preservative was avoided whenever possible. Live samples were kept cool until they reached the laboratory where they were refrigerated at 2° C. They were examined within 24 hours. Samples that could not be returned to the laboratory within a day were preserved with Lugol's iodine or buffered Formalin.

Since the phytoplankton in most of the samples was clumped, only qualitative estimates of the relative abun-

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TABLE 9.2-1.—Ceratium tripos *presence in July-August 1976 in areas off New Jersey*
[See explanation of symbols at end of table.]

**A. Sandy Hook-Asbury Park area**

| Date | July 22 | 30 |  | August 4 |  |
|---|---|---|---|---|---|
| Distance from shore (km) | 3.7 | 13 | 20 | 16 | 20 |
| Depth (m): |  |  |  |  |  |
| S | +F(P)<br>++A(P) | * | * | 0 | 0 |
| 4–6 | * | +F<br>+++F | +F<br>++F | * | * |
| 11–12 | * | 0 | +F<br>++A<br>+++A | +A<br>++A | +A<br>++A |
| 17–18 | * | * | * | 0 | +F<br>++F |
| 27 | — | 0 | 0 | * | * |
| 30 | — | — | — | * | 0 |
| 34 | — | — | — | 0 | * |
| 41–44 | — | — | — | 0 | 0 |

**B. Manasquan area**

| Date | July 4 | 9 |  | 15 | 17 | 20 | 24 | August 2 |  |
|---|---|---|---|---|---|---|---|---|---|
| Distance from shore (km) | 11 | 3 | 15 | 6.5 | 5.5 | 1 | 14 | 3.7 | 20 |
| Depth (m): |  |  |  |  |  |  |  |  |  |
| S | * | * | * | * | * | * | * | +F<br>++F | +A<br>++A |
| 8 | * | * | * | * | * | 0 | * | * | +A<br>++A |
| 10 | * | * | * | * | * | * | * | ++F | * |
| 13 | * | * | * | * | * | * | * | 0 | * |
| 15 | * | * | * | * | * | * | +F<br>++F | ++F | * |
| 18 | * | +A<br>++F | * | +A(P)<br>++A(P) | +A(P)<br>++A(P) | — | — | 0 | * |
| 20 | * | — | * | — | — | — | — | — | ++A<br>+++A |
| 22 | +A<br>++A<br>+++F | — | * | — | — | — | — | — | ++A<br>+++A |
| 24 | — | — | +A<br>++F | — | — | — | — | — | * |
| 26 | — | — | — | — | — | — | — | — | ++F |

dance of the component species were made. Counts from four continuous, long-axis transects across a Sedgewick-Rafter cell under low power sufficed for this purpose. The terms "abundant" and "sparse" are used to express the count results. For example, a count of just a few *C. tripos* cells was classed sparse; counts in the neighborhood of 10 cells were classed moderately abundant; and higher counts were classed abundant. A phytoplankter designated dominant was the most numerous species in the sample. Additional examinations, such as for bacterial presence, were made on plain slides under high power. Photomicrographs were made with timed or flash exposure on Panatomic-X film.

## OBSERVATIONS

Because decomposition of the *C. tripos* population seemed to progress from north to south, observations were grouped by general locale. The portion of the affected

TABLE 9.2–1—Ceratium tripos *presence in July-August 1976 in areas off New Jersey—continued*

**C. Barnegat-Atlantic City area**

| Date | July 15 | | 21 | | 30 | | August 16 | |
|---|---|---|---|---|---|---|---|---|
| Distance from shore (km) | 18 | 28 | 37 | 9 | 13 | 20 | 22 | 37 |
| Depth (m): | | | | | | | | |
| S | * | * | * | * | +A<br>++A | 0 | 0 | 0 |
| 10–12 | * | * | * | +F(P)<br>++F | +A<br>++A | ++A | * | ++ |
| 13 | +A<br>++F | * | * | * | * | * | * | * |
| 15–17 | +A<br>++F<br>** | +A<br>++F | * | +F<br>++A | * | * | * | * |
| 19–20 | — | +A<br>++F<br>** | +F<br>++A<br>+++F | — | * | * | * | * |
| 22 | — | — | +F<br>++A<br>+++F<br>** | — | ++F | +A<br>++F | 0 | 0 |

Symbols: *, depth not sampled; 0, not observed; +, *C. tripos* fragments; ++, intact but nonmotile cells; +++, motile cells; A, abundant; F, few; (P), preserved samples; **, deepest samples were 6 m above bottom. Unless otherwise noted the deepest samples were at the bottom.

area between Sandy Hook and Asbury Park, N.J., is the northern sector (ch. 9, pt. 1, fig. 9.1–1). The next sector south lies primarily off Manasquan, N. J. The southernmost sector sampled is that off Barnegat to Atlantic City, N.J. Observations were organized chronologically. Because the laboratory first encountered the oxygen depletion off Manasquan, the earliest sampling was in this area. Later, sampling was expanded both north and south as the extent of the problem became evident. Table 9.2–1 provides a synopsis of the *C. tripos* observations in these notes.

### Sandy Hook—Asbury Park

*C. tripos* and, especially, *Prorocentrum redfieldi* were abundant at the surface, 3.7 km off Monmouth Beach on July 22. The rest of the water column was not sampled. *C. tripos* was sparsely present, surface to bottom, at a location 13 km east of Sandy Hook on July 30. The phytoflagellate, *Olisthodiscus luteus,* was dominant at the surface. Floc was abundant only at the bottom. Much of the bottom floc appeared unstructured, but diatoms, including *Skeletonema costatum, Leptocylindrus danicus* and *Coscinodiscus spp.,* were a major component. Visually, bacteria were relatively minimal in numbers.

Farther offshore, about 20 km off Sandy Hook on July 30, *C. tripos* was sparse at the surface, abundant at mid-depth (11 m), and not present at the bottom. The largest amount of floc was present at the bottom; it was predominantly dark brown to black. Again, diatoms were a major recognizable floc component and bacteria appeared sparse.

At two locations on August 4, 16 km off Monmouth Beach and 20 km off Asbury Park, *C. tripos* was absent at the surface, but abundant at 11 to 12 m along with other flagellates, especially *Dinophysis* spp. and various diatoms and small nonmotile chlorophytes. Except for *C. tripos,* the same phytoplankton, although in lesser abundance, was present at 17 to 18 m; *C. tripos* was present at this depth only at the location farthest offshore. Near and at the bottom (30–44m), *C.tripos* was absent but *O. luteus,* many of the cells live, was numerous along with small nonmotile chlorophytes. Several species of diatoms, chiefly *S. costatum,* were present. Just a few bacteria were seen.

### Mansaquan

The initial phytoplankton samples collected off New Jersey during the anoxia event were obtained on July 4 by a diver, at the bottom, 11 km off Manasquan. These contained a yellowish floc that, microscopically, appeared to be a phytoplankton aggregate. The dominant species, by biomass at least, was *C. tripos. C. fusus* was also present as well as the diatoms, *S. costatum, Coscinodiscus* spp., *Nitzschia seriata, Thalassiosira nordenskioldii, L. danicus,* and others. Most of the *Ceratium* spp. cells were disrupted to various degrees and empty of cytoplasm, although a few live individuals were observed. Numerous bacteria, some motile, were seen in the mass.

On July 9, bottom samples from the same area, about 3 and 15 km, off Manasquan, also contained abundant floc. The general phytoplankton composition of the material was similar to that of the first samples, but further decomposition of the *C. tripos* cells and a change from yellow to predominantly brown was evident. Live *C. tripos* were not seen. Bacteria appeared more abundant; ciliate protozoans were also abundant.

On July 15, *C.tripos* still dominated the phytoplankton on the bottom in locations 6 to 7 km off Manasquan. About twice as many fragmented as intact *C. tripos* cells were seen; *C. tripos* appeared to make up 25 to 50 percent of the floc volume. *Coscinodiscus excentricus* was second in importance. The floc retained the brownish color. Because these samples were treated with preservative, bacterial presence was not estimated.

*C. tripos* was absent in the bottom floc 3.7 km off Manasquan by August 2; however, a few *C. tripos* cells and broken tests were present in the water column. The phytoplankton, from the surface to the bottom, was dominated by *S. costatum* and *L. danicus*, followed by *Ceratium minutum*, *Peridinium trochoideum*, *Dinophysis* spp., and *Prorocentrum micans*. These were all numerous at the surface, but most were in decreased abundance at the other depths. *P. trochoideum* and small nonmotile chlorophytes, however, were also abundant at the bottom. The amount of floc in the water column and on the bottom appeared greatly reduced compared to the amount seen previously. The color of the floc was changed; under the microscope, white and black portions were about equal. Only a few bacteria were seen.

Farther offshore (20 km) on August 2, in definite contrast to the inshore location, all depths except the bottom had abundant intact or fragmented *C. tripos*. At 20 m, there was an increased amount of intact, and for about half the cells, motile *C. tripos*. At 22 m, there were numerous, nearly all vigorously motile, *C. tripos* cells. Apparent bacterial digestion of some of the fragmented *C. tripos* cells was observed. *S. costatum* and small nonmotile chlorophytes were numerically dominant through the water column. *O. luteus* and *P. trochoideum* were abundant at the surface; *O. luteus* was also very abundant at the bottom.

### Barnegat—Atlantic City

Three locations, about 18, 28, and 37 km off Barnegat, N.J., were sampled on July 15. Because divers found the floc to be primarily in the bottom waters, sampling was at 6 and 9 m off the bottom. At the 18- and 28-km stations, samples from both depths contained floc that was yellow or yellow-green with some blackish spots. Many of the *C. tripos* cells were disrupted. Bacteria in chains or as motile individuals were most evident in the samples collected 6 m off the bottom. At the farthest offshore station, decomposition did not appear as advanced. The floc was predominantly yellow. Most *C. tripos* cells were intact; disrupted cells were in large fragments. Some motile *C. tripos* were observed. Again, bacteria were more evident in the lower depth sample.

At 10 m, 5 km off Barnegat on July 21, only a small amount of fine floc particles and a sparse phytoplankton, including just a few *C. tripos*, were present. At 15 m, however, a fairly abundant, by comparison, floc was composed almost entirely of *C. tripos*.

On July 30, 13 km off Barnegat, the surface had a moderate abundance of free, intact *C. tripos* cells. At middepth, around 11 m, *C. tripos* cells, most without cytoplasm, were numerous; broken tests were more numerous than intact ones. The bottom had fewer and more decayed *C. tripos*. The floc was abundant only at the bottom. The floc ranged from yellow to dark brown or black. Much of the material was unstructured; diatoms, especially *S. costatum* and *L. danicus*, composed most of the identifiable phytoplankton; bacteria were moderately abundant.

At 20 km off Barnegat on July 30, *C. tripos* was absent at the surface. At middepth, numerous free, intact *C. tripos* cells dominated the phytoplankton (a mixed group of diatoms and dinoflagellates). At the bottom, a smaller abundance of intact and disrupted *C. tripos* was evident. The floc was most abundant, although moderately so, at the bottom. Various diatoms, especially *S. costatum*, were abundant in the floc. Apparent vigorous swarming of bacteria around partially digested *C. tripos* and fungus dispersed throughout the floc were observed.

*C. tripos* was absent at two locations, about 22 and 37 km, off Barnegat on August 16. *S. costatum* dominated the generally sparse phytoplankton, which also included a mixture of other diatoms, dinoflagellates, and smaller nannoplankton. On the bottom, the diatoms appeared to be in a state of advanced decomposition, judging from the appearance of the cells. Only a small amount of blackish floc was present. At the same time, however, farther to the south, 11 km off Atlantic City, *C. tripos* was moderately abundant at middepth although it was not seen in the rest of the water column. *S. costatum* was numerically dominant at all depths. Floc, yellow to greenish-brown, was abundant at the bottom. Bacteria appeared abundant in the floc.

At locations 18.5 and 93 km off Atlantic City on September 2, the bottom and middepth samples contained only a sparse amount of fine floc, at least 50 percent of which was black. A few diatoms were present, but no *C. tripos*. The phytoplankton was even less abundant in the surface samples; again no *Ceratium* spp. were seen.

### *C. tripos* Decomposition Sequence and the Floc

With the decline of the bloom, the *C. tripos* cells, in senescence or death (figs. 9.2–1, 9.2–2), formed into a

FIGURE 9.2–1.—An intact *Ceratium tripos* cell; a fragment of another individual is adjacent

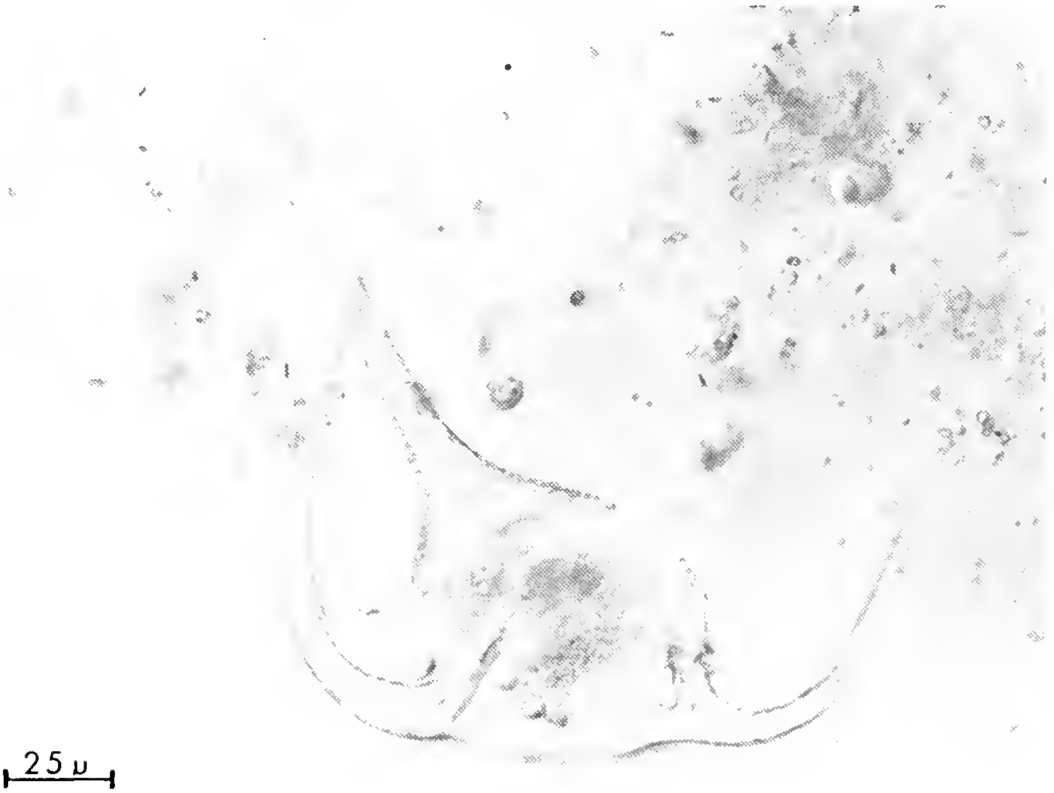

FIGURE 9.2–2.—A newly disrupted *C. tripos* cell

flocculent aggregate. This floc was seen at various times and places during July and August, but, by far, most was at the thermocline (where the *C. tripos* bloom population had previously concentrated) and on the bottom. In the Manasquan area, less than 20 km from shore on July 4, nearly all of the *C. tripos* seen at the bottom were dead and these, broken or fragmented, composed most of the floc biomass (fig. 9.2–3). In the same area, less than a week later, the *C. tripos* dominance had become less clear; increased disruption of the cells was evident and the floc had darkened (fig. 9.2–4). With further decomposition (fig. 9.2–5), the material became even darker and far fewer *C. tripos* fragments were identifiable. By August 2, no *C. tripos* were seen in the inshore bottom floc off Manasquan (fig. 9.2–6). Therefore, in this area, except for refractory constituents, decomposition at the bottom of massive numbers of *C. tripos*, which presumably had begun in June, was complete by late July or early August. Temporal and geographical differences in the *C. tripos* decomposition are discussed in the next section. Figures 9.2–7 and 9.2–8 show microbial decomposition of the *C. tripos*. Figures 9.2–9 and 9.2–10 show one effect of the bloom decomposition: the gill of the mud shrimp, *Axius serratus*, is partially occluded with floc material. A concentration of these animals, dead or dying, was found out of the substrate around 18 km off Barnegat on July 15.

## CONCLUSIONS

*C. tripos* remained a significant portion of the bottom floc in the oxygen-deficient area between Manasquan and Barnegat at least until mid-July. Around the end of July, no *C. tripos* were seen in bottom samples from off Sandy Hook and it had almost disappeared from the bottom floc off Manasquan, but it was still evident in the Barnegat area. The floc from the Manasquan area at this time was about equally black and white under the microscope, but the Barnegat floc retained much of the earlier yellow-brown appearance. By mid-August, the bottom samples from off Barnegat had no *C. tripos* and little floc; what was present appeared generally decayed. Bottom samples from off Atlantic City still contained abundant yellow-brown floc. Vaughan (1977) surveyed the *C. tripos* population in southern New Jersey coastal waters between Great Bay and Cape May from July 21 to its complete disappearance around August 20. The decline of *C. tripos* abundance he observed had a pattern similar to that seen in the more northerly regions, but occurred later. In addition, during late July and the first half of August, Vaughan (personal communication) found *C. tripos* present nearly always, even inshore, as individual, intact cells retaining cytoplasmic contents. Because a preservative was used, he was not able to determine whether the cells were alive when collected. However, the cells were at least not disrupted or aggregated in a detrital mass as they were to the north when the first samples were examined on July 4. The combined observations indicate that the decomposition proceeded earlier or at a more rapid rate in the Sandy Hook—Manasquan area and progressed southward.

Some *C. tripos* concentrations, alive and apparently vigorous, were found around middepth between the middle of July and early August off Sandy Hook, Manasquan, and Barnegat. They were all at stations 20 km or greater from the shore. During the same period, intact but nonmotile cells and fragments of cells, but no live cells, were found at various depths less than 20 km from shore (table 9.2–1). This suggests that *C. tripos* survived better in offshore waters. If so, a possible explanation (ch. 9, pt. 1) is that by May and June, the *C. tripos* population within 20 km of the shoreline between the Bight Apex and Barnegat Inlet was light limited.

Based on microscopic observations, some bacterial presence was associated with aggregates of phytoplankton material in the water column, but it was greatest at or near the bottom where most of the floc was also found. Also, general bacterial presence seemed to be associated with the presence of *C. tripos* (the notable exception was in the August 16 Atlantic City bottom sample in which abundant bacteria but no *C. tripos* were seen). Unmistakable bacterial decomposition of *C. tripos* cells (fig. 9.2–7) was observed several times; fungus attack on *C. tripos* was also seen (fig. 9.2–8). Protozoans and small nematodes were fairly numerous in some samples and may have been feeding on the floc material, although this was not determined. Vigorous activity and clustering around the floc by ciliate protozoans seen in a number of samples did suggest feeding behavior. All these forms probably contributed to the decomposition process. The cell wall of *C. tripos* is cellulosic. In the Gulf of Maine and Georges Bank, Waksman et al. (1933) found extensive populations of bacteria able to use cellulose and hemicelluloses, although cellulose-decomposing marine bacteria were less abundant than species not having this capability. Barghoorn and Linder (cited in Zobell 1945) found several species of marine fungi able to use cellulose. Marine ciliates have been known to feed on bacteria, diatoms, or other protozoa (Lackey 1936).

The presence of numerous *O. luteus* (many individuals apparently in a senescent state) as a floc constituent in locations from Sandy Hook to Sea Girt, N.J., between July 22 and August 4 is interesting. This species bloomed intensely throughout the southern half of Lower New York Bay between June 6 and 13, 1976. Tidal action gradually washed the bloom water to the ocean. If we assume that the *Olisthodiscus* concentrations in the bottom floc originated in the bay, then inshore along the New Jersey

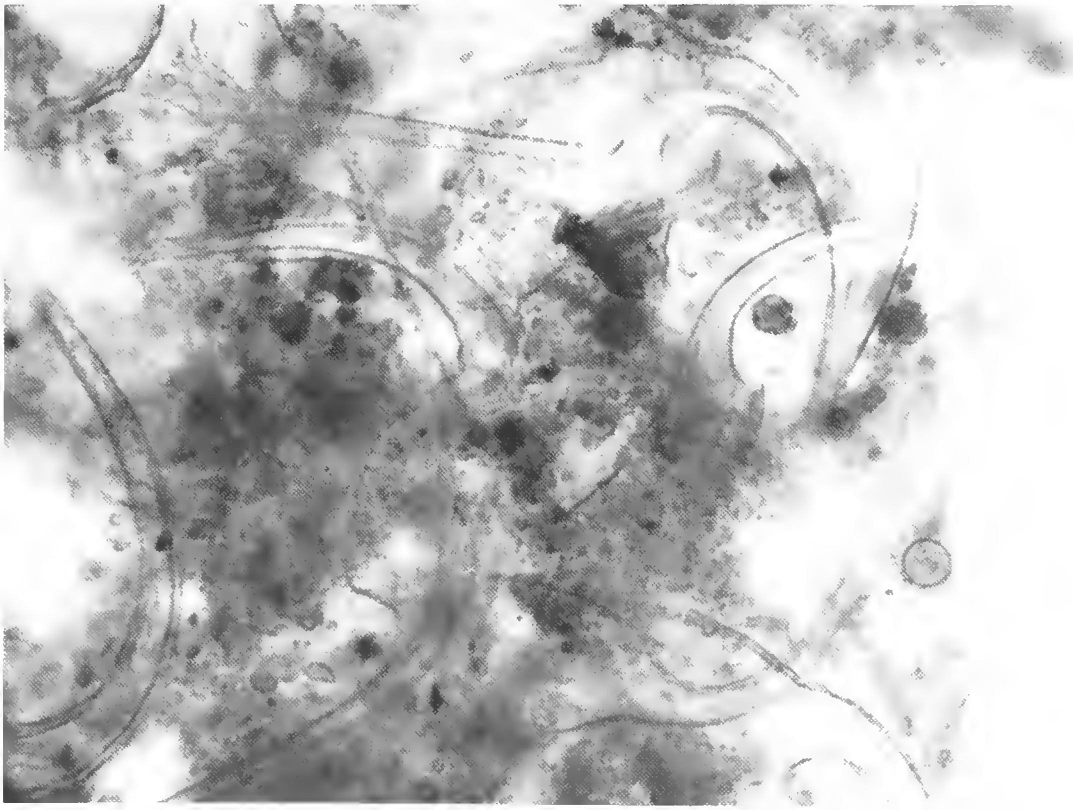

FIGURE 9.2–3.—*C. tripos* is the obvious major component of the aggregate; most of the material is relatively light in color

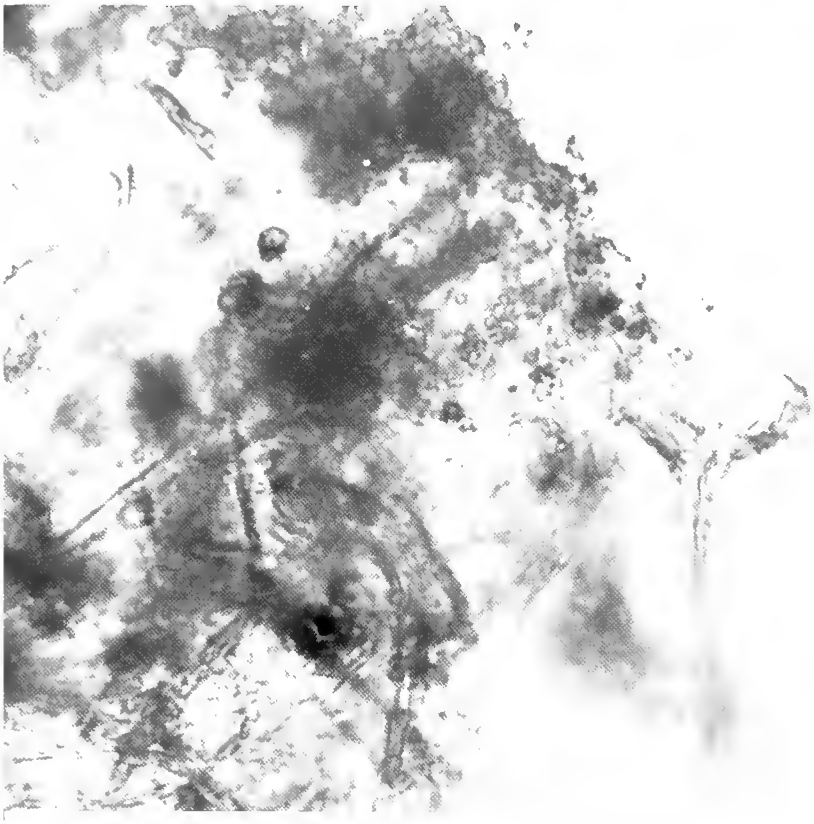

FIGURE 9.2–4.—*C. tripos* is still a major component of this floc, but increased disruption of cell fragments is evident. The floc has darkened in spots.

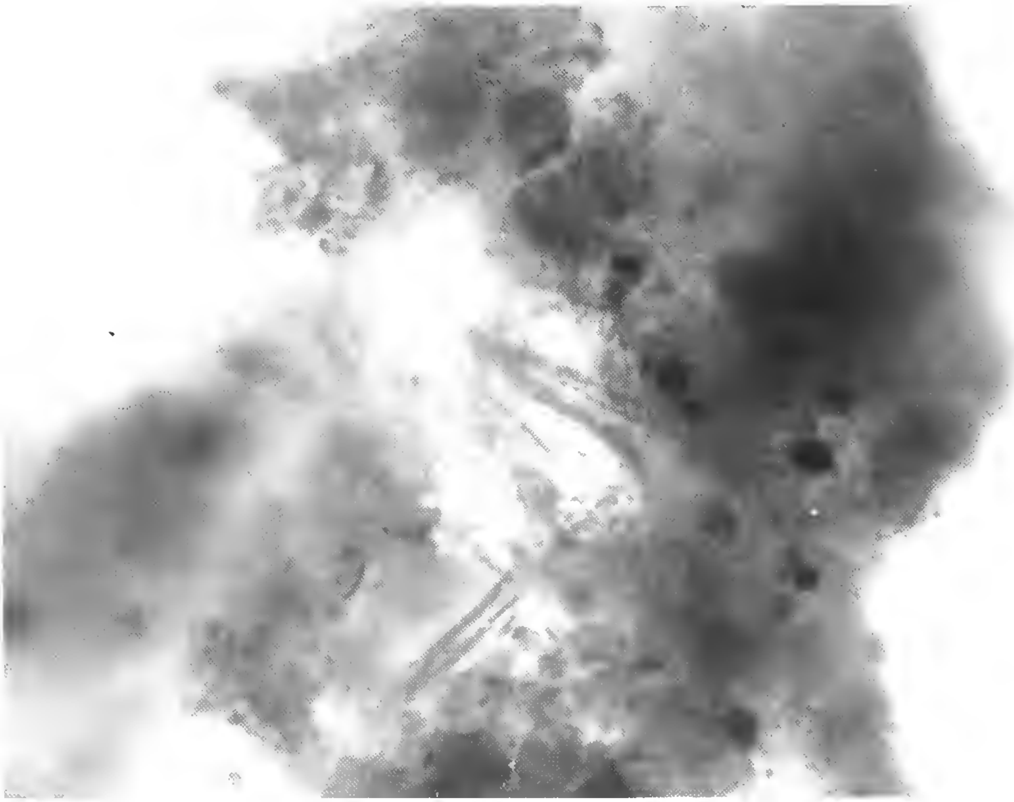

FIGURE 9.2-5.—A few *C. tripos* fragments are identifiable but most of the material appears structureless. Most of the floc is dark.

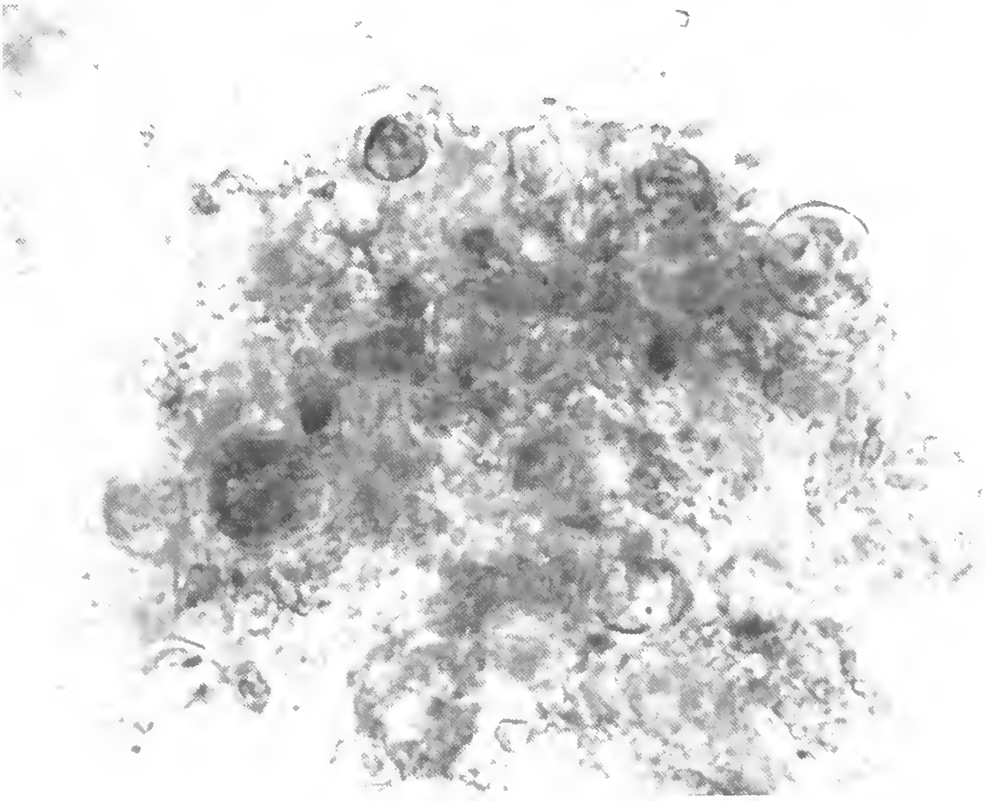

FIGURE 9.2-6.—*C. tripos* is not identifiable in the floc; diatoms are the only evident phytoplankton.

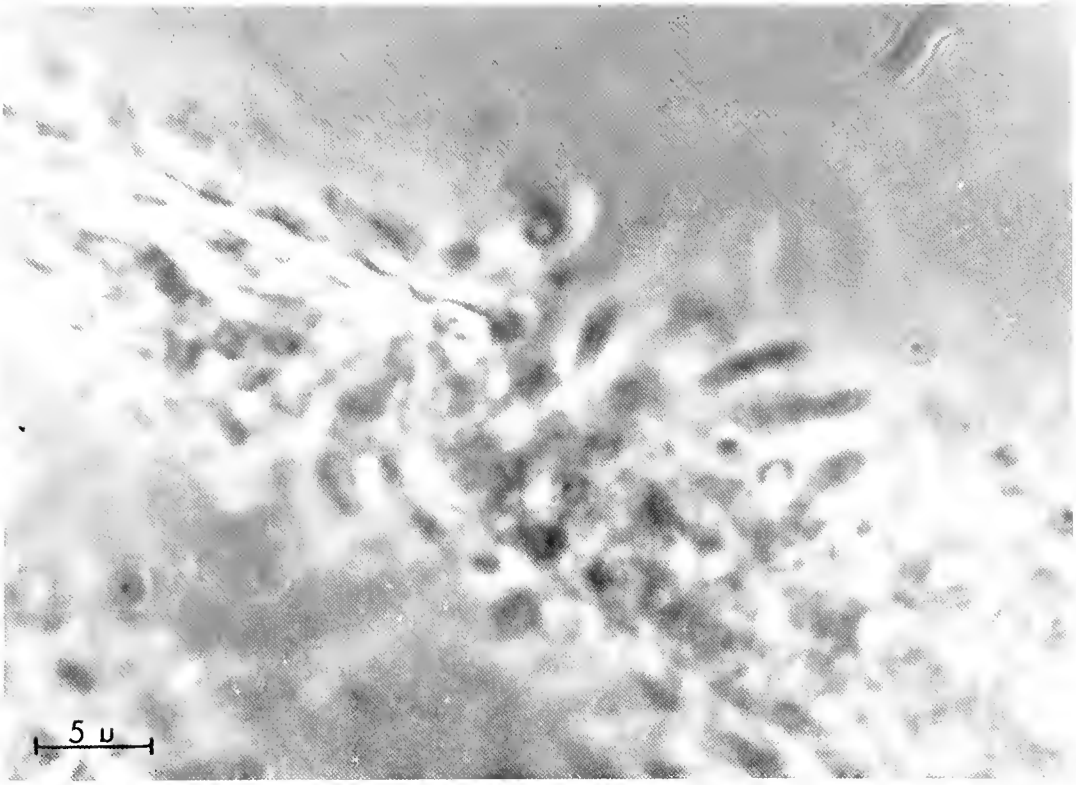

FIGURE 9.2-7.—*C. tripos* horn bristling with motile rod bacteria; area being digested is largely eaten away.

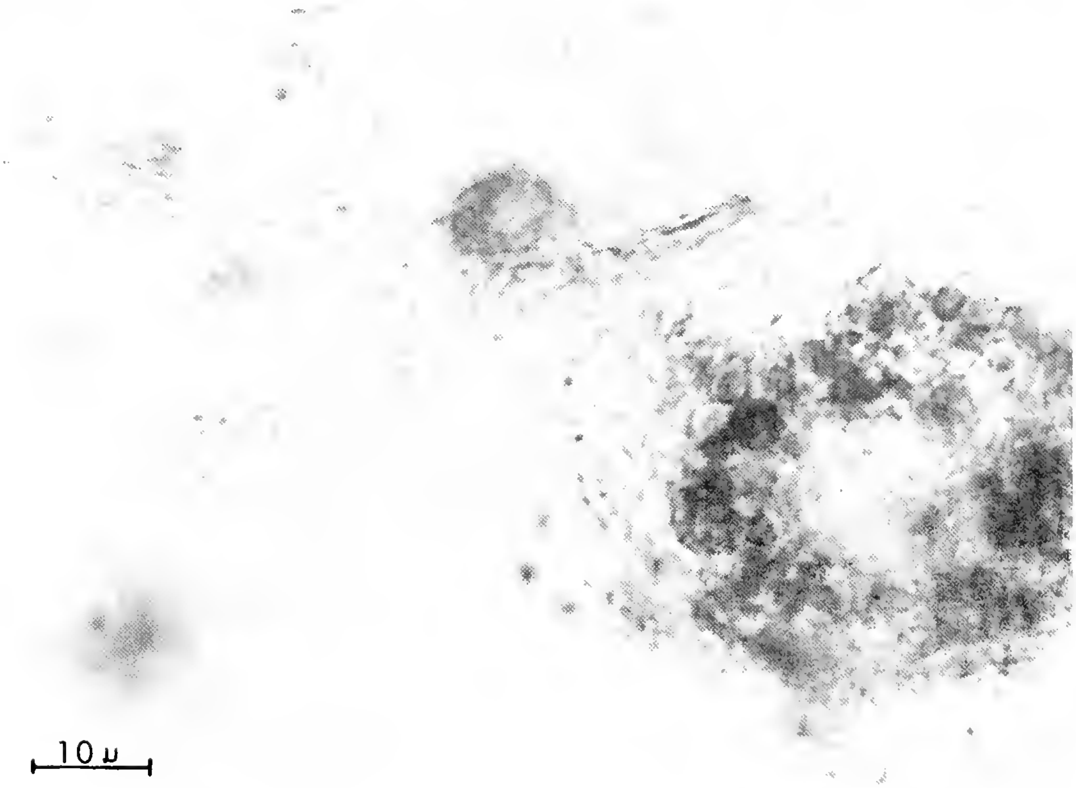

FIGURE 9.2-8.—Fungus dispersion in floc; *C. tripos* cell in decomposition.

FIGURE 9.2-9 —Floc fragment lodged between gill filaments of mud shrimp, *Axius serratus*.

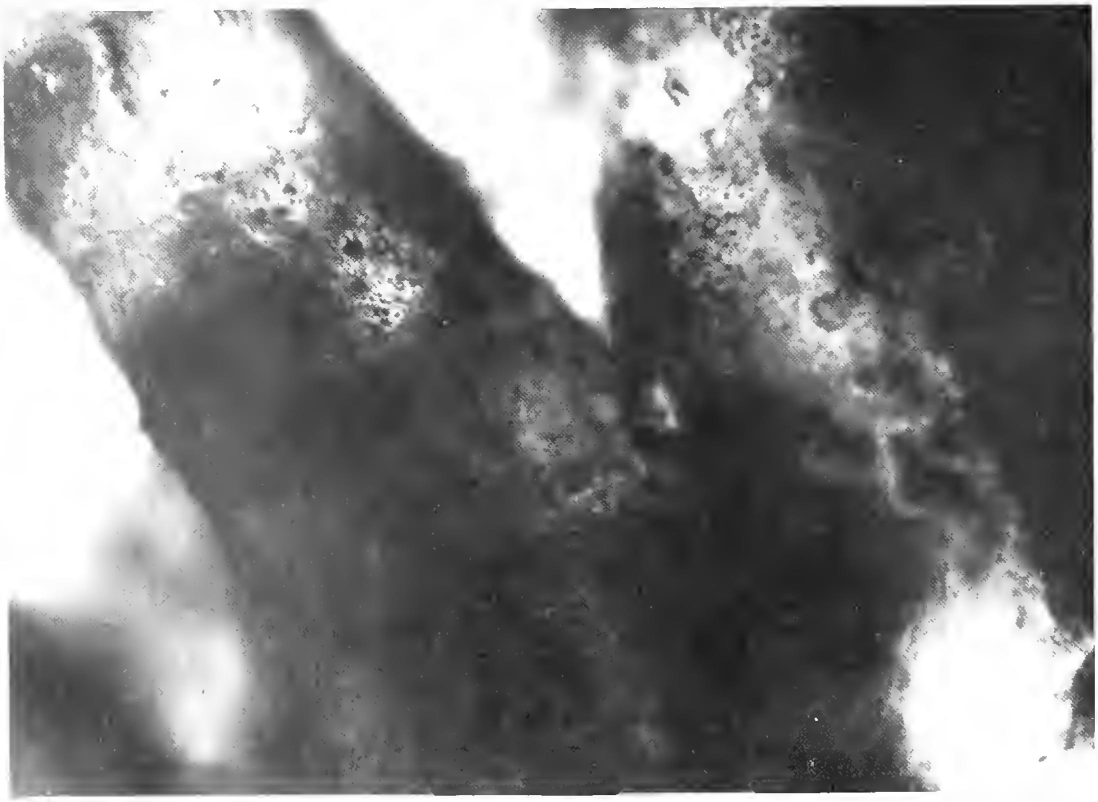

FIGURE 9.2-10 —Mud shrimp gill choked with floc material

coast the bottom received large quantities of phytoplankton from the bloom in Lower New York Bay. The *Olisthodiscus* bloom may not have added measurably to the 1976 oxygen depletion, because it was small compared to the *C. tripos* bloom. Perhaps a more important implication is that material from chronic seasonal blooms of phytoflagellates would contribute to annual bottom water oxygen sag in at least the coastal area near the bay. Segar and Berberian (1976) determined that oxidation of phytoplankton material below the thermocline was a major cause of the low oxygen values they observed in the bottom waters of the Bight Apex.

## ACKNOWLEDGMENTS

Frank Steimle coordinated the surveys that provided most of the water samples which were examined. The samples were collected primarily by Robert Reid, David Radosh, John Ziskowski, and Charles Byrne.

## REFERENCES

Lackey, J. B., 1936. Occurrence and distribution of the marine protozoan species in the Woods Hole area, *Biol. Bull.* 70(2):264–278.

Segar, D. A., and Berberian, G. A., 1976. Oxygen depletion in the New York Bight Apex: causes and consequences, *Amer. Soc. Limnol. Oceanogr. Spec. Symp.* 2:220–239.

Vaughan, J., 1977. Abundance determinations of the marine dinoflagellate *Ceratium tripos* off the New Jersey coast during the summer and fall, 1976, Tech. Rep. No. 22, New Jersey Department of Environmental Protection, Nacote Creek Research Station, Absecon, N.J., 15 pp.

Waksman, S. A., Carey, C. L., and Reuszer, H. W., 1933. Marine bacteria and their role in the cycle of life in the sea. I. Decomposition of marine plant and animal residues by bacteria, *Biol. Bull.* 65(1):57–79.

Zobell, C. E., 1946. *Marine microbiology*, Chronica Botanica Co., Waltham, Mass., 240 pp.

## Oxygen Depletion and Associated Benthic Mortalities in New York Bight, 1976

# Chapter 10. Biological Processes: Productivity and Respiration

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## INTRODUCTION

This chapter describes the distribution and magnitude of biological processes in the water column and on the seabed in the New York Bight in August-September 1976. Whereas most previous chapters dealt with the establishment of oxygen depletion, this chapter discusses processes occurring about 2 months after the onset of the peak anoxic condition. Major emphasis is placed on primary productivity and dissolved oxygen (D.O.) utilization in the water column and on the seabed.

## METHODS

From August 24 to September 9, 1976, measurements were made of primary production, rates of oxygen consumption in the water-column and on the seabed, and of concentrations of nutrients, organic carbon, phytoplankton, chlorophyll *a*, and bacteria (fig. 10–1). Most of the data are presented in Thomas et al. (in press).

Large-volume (20–30 l) Niskin bottles were used to collect all water samples. Five to nine depths in the water column were sampled, based on profiles of temperature, chlorophyll-*a* fluorescence, and photosynthetically active radiation (PAR; 400–700 nm). A bottom-tripping Niskin bottle collected water 20 to 50 cm above the bottom. Expendable bathythermographs (XBTs) and reversing thermometers were used simultaneously to measure temperature at all stations. A submersible pump was used to obtain vertical profiles of *in vivo* chlorophyll-*a* fluorescence. A Lambda submersible quantum photometer was used to determine extinction of PAR.

Salinity was measured with a Beckman RS 7-C induction salinometer. Alkalinity, sulfide, pH, ammonium, and particulate organic carbon were determined using methods described by Strickland and Parsons (1972). Seawater

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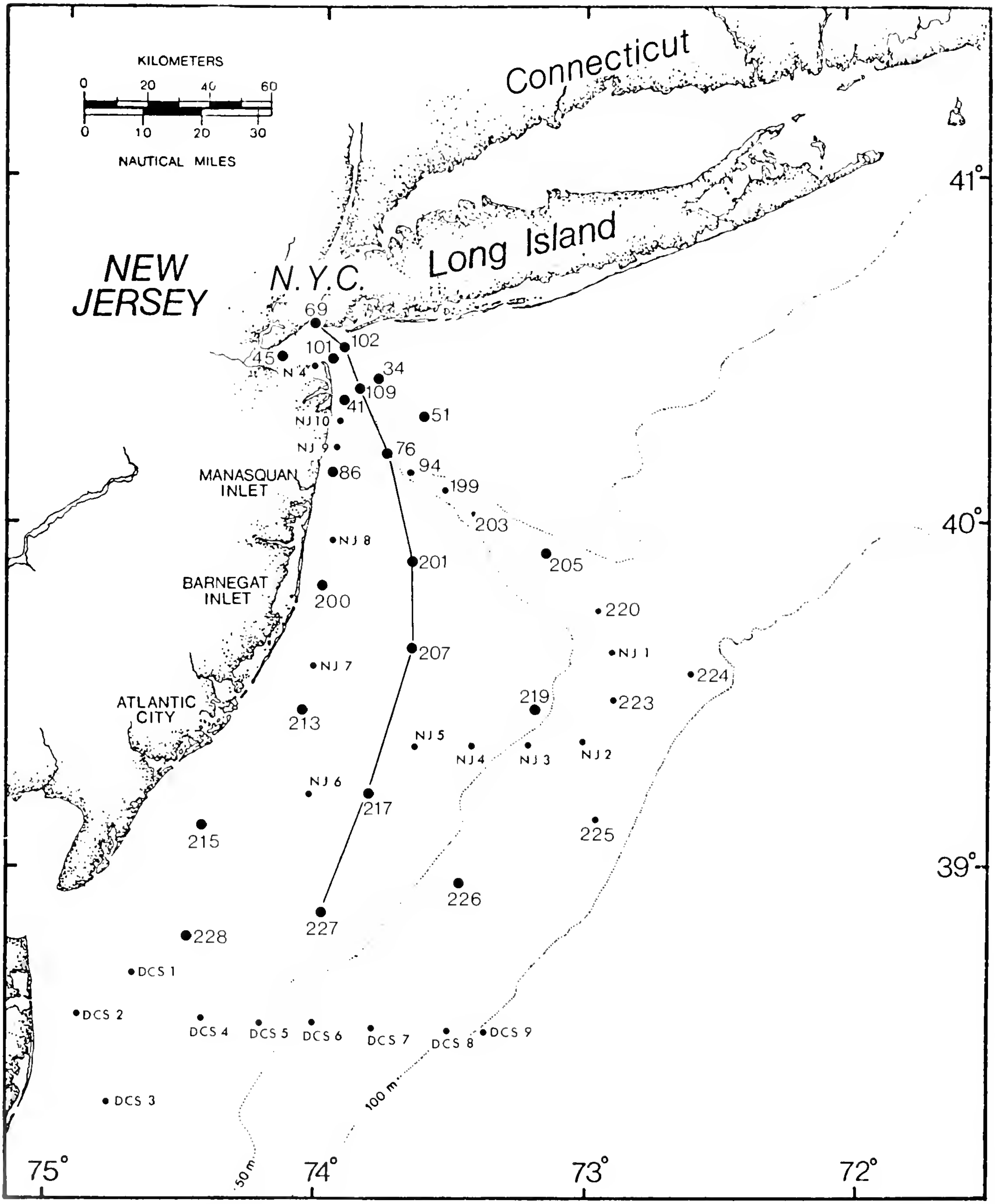


FIGURE 10-1.—Stations sampled during NOAA ship *Albatross IV* cruise (AL-76-10), August 24-September 9, 1976. Transect 102-227 indicated by solid line.

samples filtered with Whatman GF/F filters were analyzed for nitrate, nitrite, phosphate, and silicate by NOAA Atlantic Oceanographic and Meteorological Laboratories (AOML), Ocean Chemistry Laboratory, on a four-channel Technicon Auto Analyzer using procedures outlined in Hazelworth et al. (1974). Samples for dissolved organic carbon (DOC) were filtered using precombusted, rinsed glass fiber filters (Whatman GF/F) and analyzed by the University of Delaware Marine Chemistry Laboratory using the method of Menzel and Vacarro (1964) as adapted by Sharp (1973).

Chlorophyll *a* was determined spectrophotometrically and corrected for phaeopigments (Strickland and Parsons 1972). Chlorophyll-*a* netplankton (>20μm) and nannoplankton (<20μm) size fractions were determined by serial filtration of seawater samples through 20 μm Nitex and 0.45 μm Millipore filters and reading acetone extracts on a fluorometer (Strickland and Parsons 1972). Phytoplankton in whole water samples, preserved with $KI$-$I_2$, were speciated and enumerated using an inverted microscope.

Phytoplankton primary productivity was measured using the $^{14}C$ method as described by O'Reilly et al. (1976) and O'Reilly and Thomas (in press). Zooplankton larger than 300 μm were removed with a Nitex screen before incubation, during subsampling of Niskin bottles. Duplicate light and dark bottles were incubated under sunlight (simulated in situ 100%, 68%, 47%, 30%, 11%, 4%, and 1%) and artificial light (photosynthetic capacity at saturating—0.089 ly/min—light intensities). Following incubation, the organic $^{14}C$ activity in netplankton (>20 μm), nannoplankton (<20 μm but >0.45 μm), and dissolved organic matter (<0.45 μm) size fractions was determined by serial filtration through 20-μm and 0.45-μm filters and subsequent acidification and counting in a liquid scintillation counter.

The rate of oxygen consumption (total plankton respiration) for each depth in the water column was estimated from changes in D.O. occurring between five initial and five final whole water samples incubated in acid-cleaned, baked (232° C for 1h) 300-ml BOD bottles. Of these 10 samples, 5 initial samples from each depth were fixed immediately according to the azide modification of the Winkler method (American Public Health Association 1975) and 5 final samples were incubated in the dark at ±1° C of in-situ temperature for 12 to 24 hours, fixed as before, and titrated using phenylarsine oxide in place of sodium thiosulphate and thyodene in place of starch (Kroner et al. 1964; U.S. EPA 1974). The average coefficient of variability for the five initial determinations was 2.20 percent (N = 134).

Seabed (sediment plus bottom 12 cm of water) oxygen consumption rates were measured as described by Thomas et al. (1976b) after Pamatmat 1971. Rates of oxygen consumption by the seabed and water column are expressed both as oxygen consumed and as equivalent carbon oxidized, assuming a respiratory quotient (RQ) of 1 so that comparisons between production and decomposition of organic matter can be made.

Total direct bacterial counts were made on surface and bottom water samples using a fluorescence technique (Hobbie et al. 1977). Bacterial biomass was calculated from cell measurements obtained from photographs and transparencies made of the bacteria during the counting procedure.

## HYDROGRAPHIC AND NUTRIENT CONDITIONS

Figures 10–2 and 10–3A and 3B show the location, size, and shape of the low D.O. area and hydrographic conditions at the time of the cruise (about 2 months after the onset of severe oxygen depletion). Bottom water temperature was highest and salinity lowest along the New Jersey coast and toward the Hudson-Raritan estuary (fig. 10–2). The exception was station 41 (off Monmouth Beach, N.J.), which appeared affected by cooler and more saline water from the Hudson Shelf Valley. A strong thermocline and halocline combined to produce a sharp pycnocline (fig. 10–3A). At station 217 in the middle of the low D.O. area (fig. 10–3B), the water was saturated with oxygen immediately above the pycnocline, while immediately below it was anoxic. Below the pycnocline in the anoxic area sulfide concentrations were especially high (fig. 10–3B)—18.0 μM/1 at stations 213 (fig. 10–5) and pH was particularly low (7.3 to 7.4) compared to surrounding areas (7.5 to 7.9).

The highest concentrations of nitrate and nitrite (fig. 10–4A) were found in the estuarine surface outflow, in the near-bottom water of the Hudson Shelf Valley (station 76) and in the colder, more saline bottom water away from the anoxic area (station 227). Beyond the Apex both nitrate and nitrite were depleted or nearly depleted in the waters above the pycnocline. In bottom water on the perimeter of the anoxic area, small quantities of nitrite were present, whereas nitrate was absent. In the anoxic area concentrations of both nitrate and nitrite were highest just below the pycnocline where D.O. concentrations were zero. Otherwise, their concentrations were zero except for a trace of nitrite at the bottom depth at station 217.

Ammonium concentration decreased from the estuary seaward, approaching zero to 0.5 μM/1 in surface water at the outer Apex (station 76) and beyond (fig. 10–4A). The highest concentrations of ammonium (30 μM/1) were found in the estuary. Away from the estuary, ammonium concentrations were highest in the bottom water of the oxygen-depleted area (station 213, 19 μM/1, fig. 10–5).

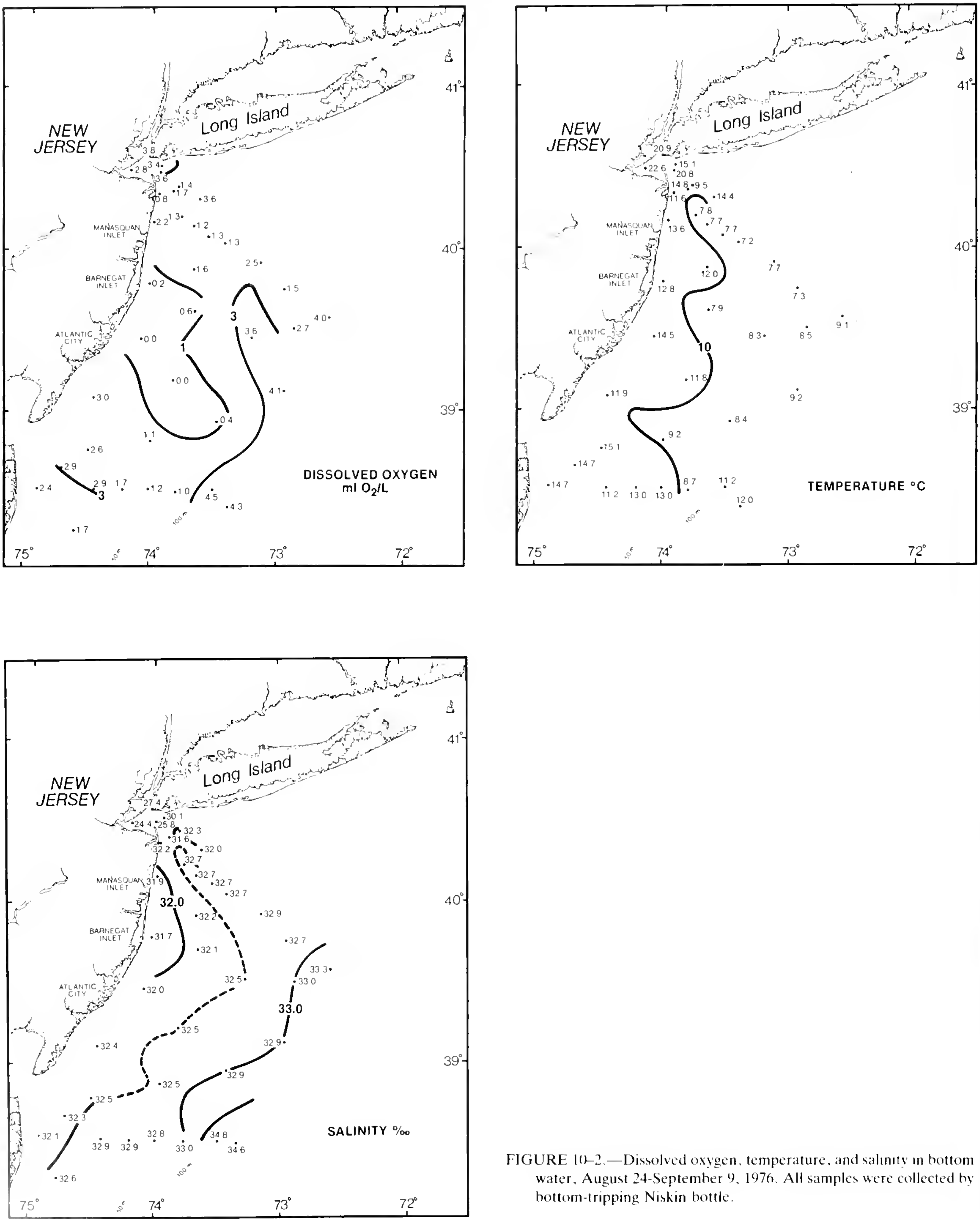


FIGURE 10-2.—Dissolved oxygen, temperature, and salinity in bottom water, August 24-September 9, 1976. All samples were collected by bottom-tripping Niskin bottle.

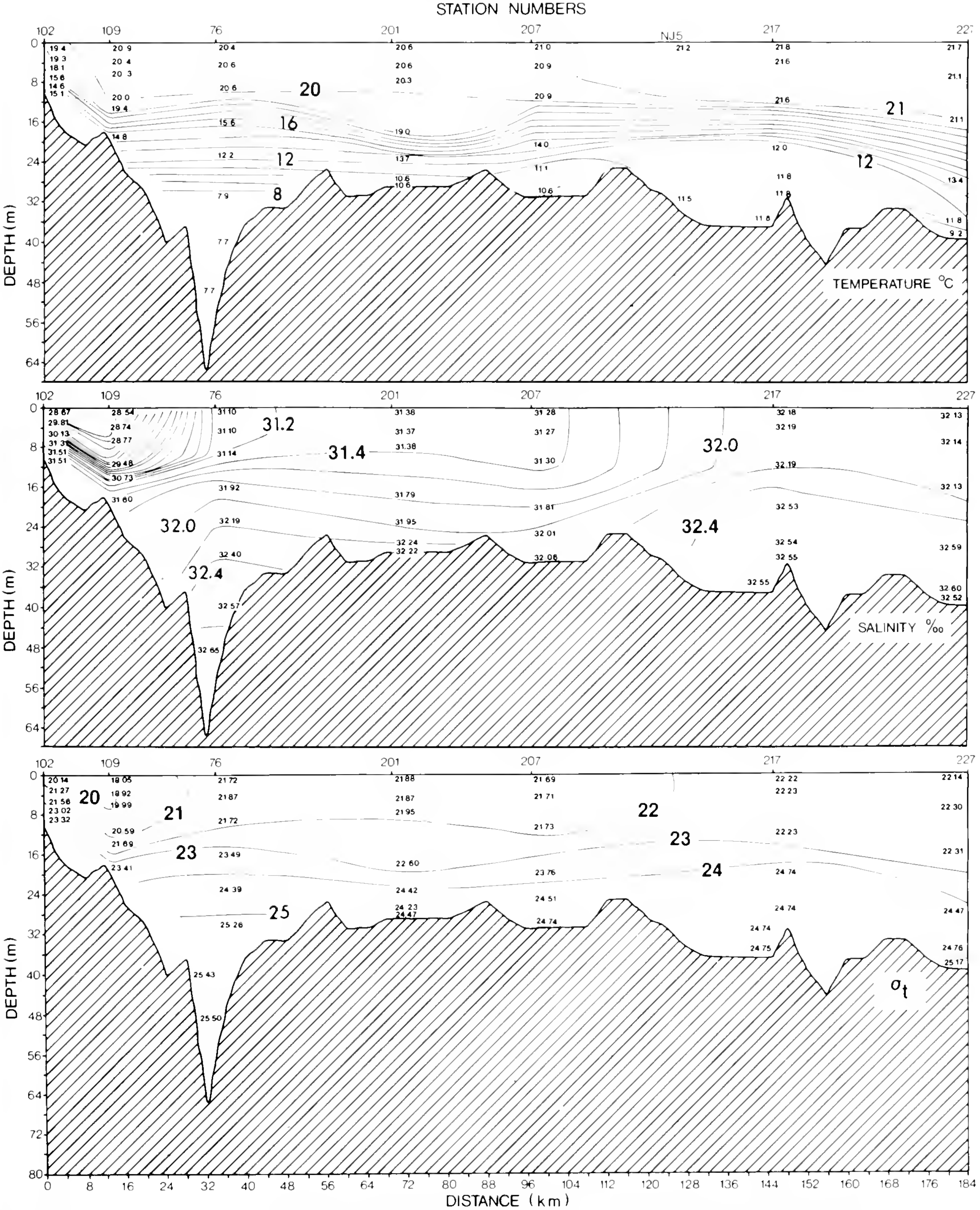


FIGURE 10-3A.—Temperature, salinity, and sigma-*t* along transect 102–227 of figure 10–1, August 24-September 9, 1976. Values offset to right of station sample depths.

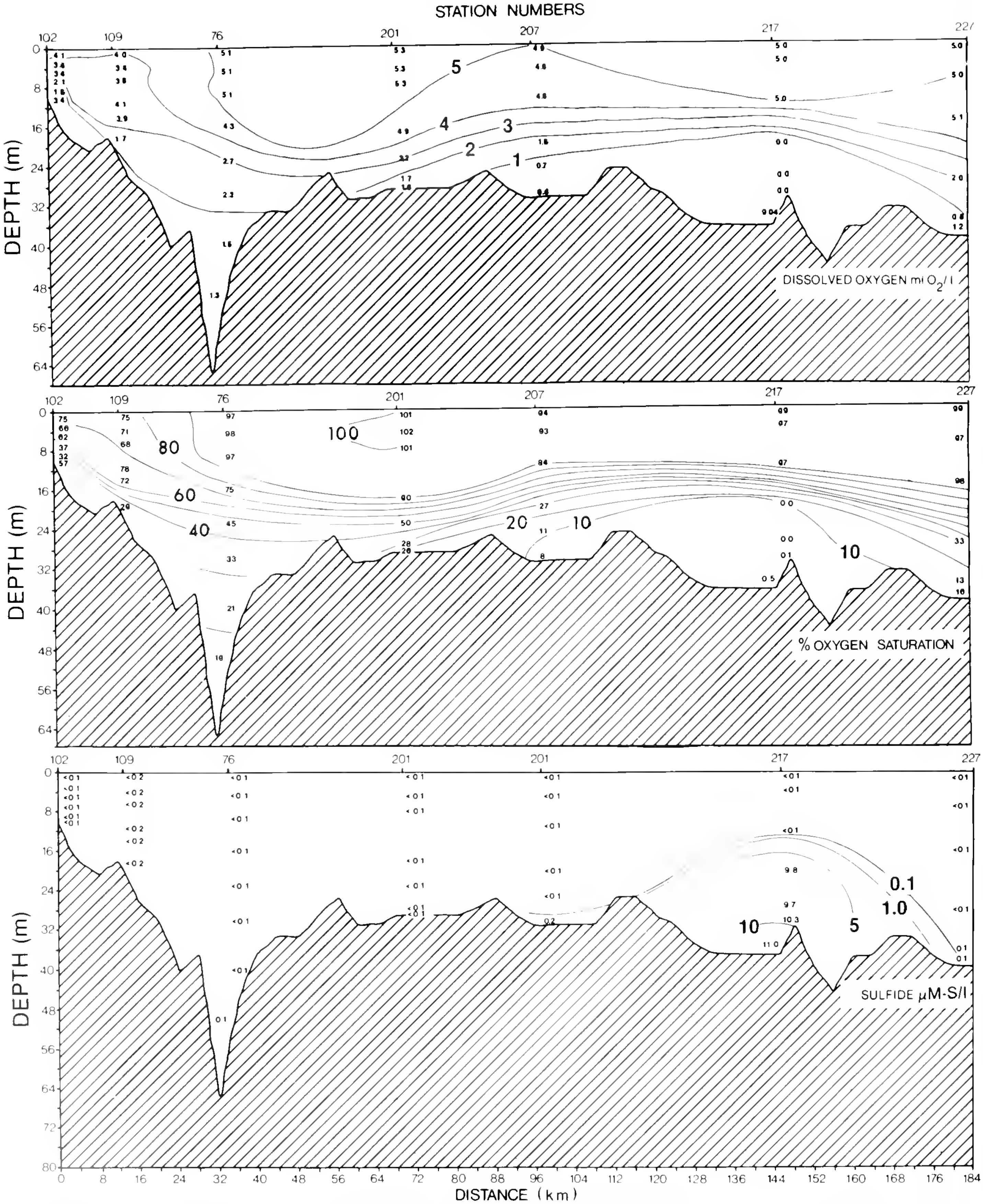


FIGURE 10–3B.—Dissolved oxygen, percent oxygen saturation, and sulfide along transect 102–227 of figure 10–1, August 24-September 9, 1976. Values offset to right of station sample depths.

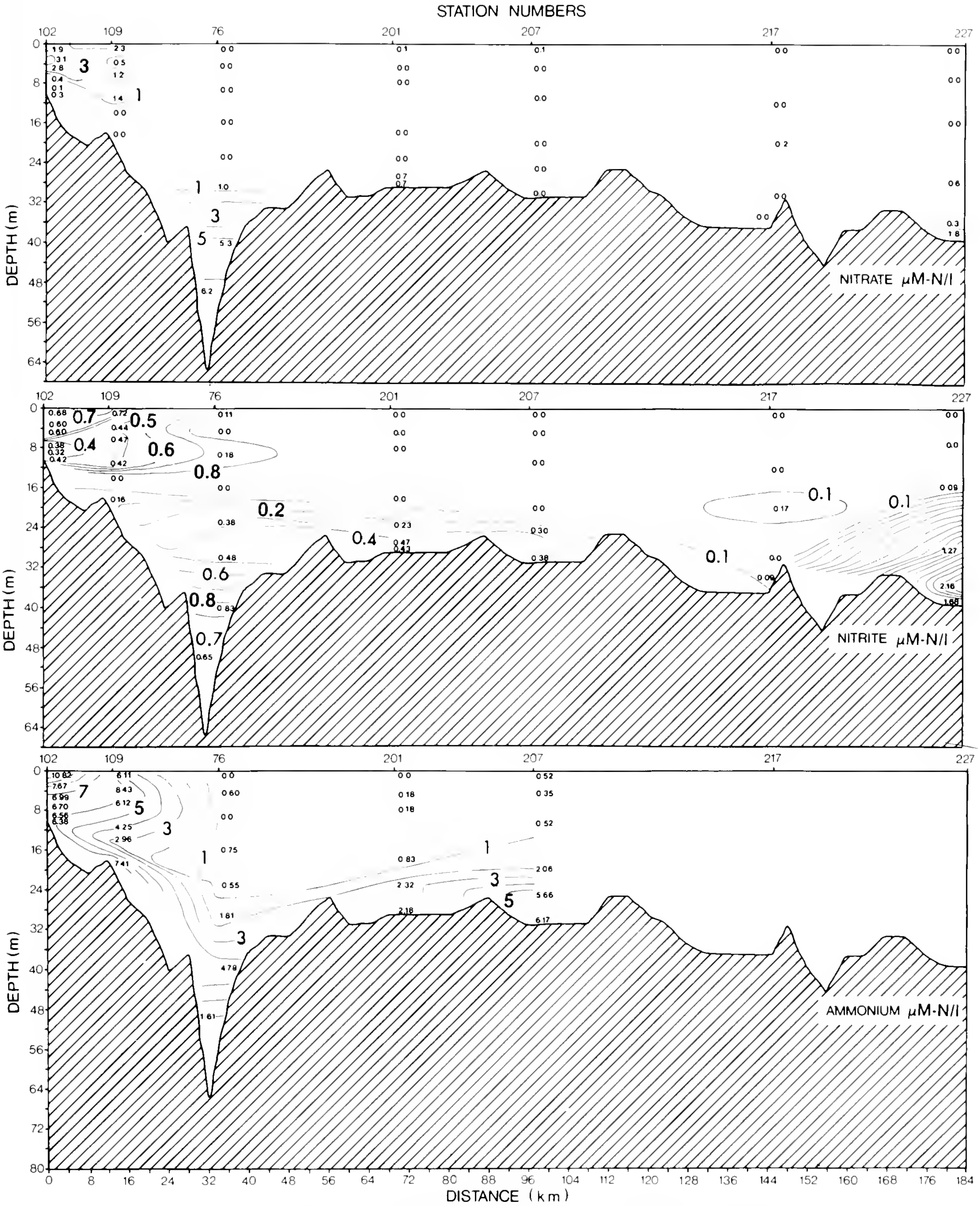


FIGURE 10–4A.—Nitrate, nitrite, and ammonium along transect 102–227 of figure 10–1, August 24-September 9, 1976. Values offset to right of station sample depths

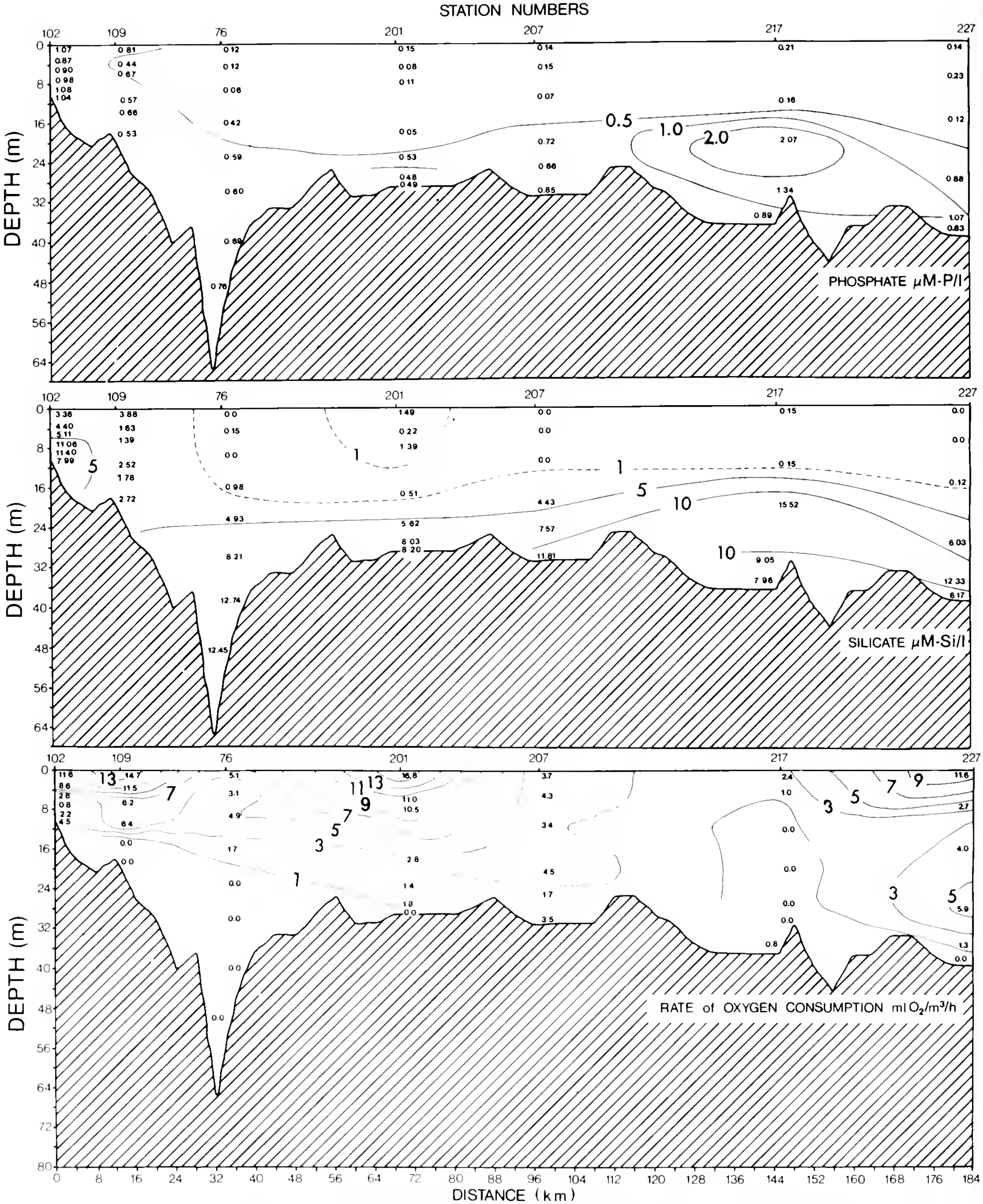


FIGURE 10–4B.—Phosphate, silicate, and rate of oxygen consumption along transect 102–227 of figure 10–1, August 24-September 9, 1976. Values offset to right of station sample depths

Above the pycnocline, inorganic phosphorus concentrations (fig. 10–4B) were less than 0.4 μM/1, except near the estuary where they reached 1.1 μM/1. Away from the estuary, phosphate concentrations generally were higher below the pycnocline than above. The highest concentration (3.6 μM/1) was observed just below the pycnocline at station 213 in the anoxic area (fig. 10–5).

Silicate concentrations were generally highest (5–20 μM/1) in the subpycnocline waters throughout the area sampled, particularly where oxygen was low (fig. 10–4B). No silicate was detected in surface waters except at estuarine stations and at stations 200, 201, and 207 just north of the anoxic area. The highest concentrations of silicate (up to 20 μM/1) were found in or just below the pycnocline at stations 226, 213, and 217 in and adjacent to the low D.O. area (fig. 10–5 and Thomas et al., in press).

According to Richards (1965), during anaerobic decomposition sulfide should accumulate over phosphorus in an atomic ratio of 53:1. Our observed ratios of S:P (1.8:1 to 12.2:1) were considerably less. However, the anoxic systems examined by Richards et al. (1965), such as Lake Nitinat, have a deep subpycnocline layer (100–200 m) where anoxia occurs at some distance below the oxygen interface. The thickness of the subpycnocline layer in the anoxic area for this study was 6 to 15 m. There was a direct relationship between S:P ratios and distance below the pycnocline ($r = +0.82$, $n = 5$). Oxygen appears to have diffused downward through the pycnocline to oxidize the sulfide, and thereby decreased (oxidized) the sulfide concentrations to the levels observed (A. Draxler and C. Byrne, NMFS, in press).

## ORGANIC CARBON AND PHYTOPLANKTON

The DOC concentrations ranged from 1 to 13 mg C/1 (figs. 10–6 and 10–7A) and are considered unusually high compared to other areas (ch. 4). Concentrations generally decreased from the estuary to the shelf (fig. 10–6). However, the highest concentrations of DOC were found in the middle and outer portions of the Apex (stations 41, 109, 34, 86, 76, 51; figs. 10–6 and 10–7A).

Particulate organic carbon (POC) concentrations decreased seaward from the estuary (fig. 10–6).At station 102 near the estuary, POC was generally distributed uniformly with depth. Farther south along transect 102–227, progressively larger concentrations of POC were measured in and below the pycnocline (fig. 10–7A).

The ratio of integral DOC to integral POC, integrated from surface to bottom, ranged from 3:1 to 25:1 and was generally highest in the outer portion of the APEX where standing stocks of DOC were highest. Thus, most of the organic carbon in the New York Bight is in dissolved forms, which is generally true of most marine environments (Riley 1973).

Chlorophyll-*a* (Chl*a*) concentrations generally decreased from 3 to 6 mg/m$^3$ near the estuary to 0.4 to 0.8 mg/m$^3$ offshore (fig. 10–6). Especially high concentrations of phytoplankton (16 mg Chl*a*/m$^3$) occurred at station 34 near the sewage sludge disposal site (fig. 10–6). At stations outside the Apex, adjacent to the New Jersey coast, and in the oxygen-depleted area, large increases in chlorophyll-*a* concentrations were observed in the pycnocline and directly above the seabed (fig. 10–7B). Most of the chlorophyll *a* was attributable to nannoplankton (<20 μm) (fig. 10–7B). Proceeding away from the estuary, netplankton (>20 μm) increased in relative abundance over nannoplankton. However, the maximum netplankton contribution to the phytoplankton community biomass was only 66 percent at station 227. (See chapter 9, part 1.)

Identification and enumeration of phytoplankton in whole water samples collected from the surface, pycnocline, and bottom water at stations 102, 109, 76, 201, 217, and 227 further confirmed that nannophytoplankton predominated over netphytoplankton. A spherical phytoplankton species 1.5 to 3 μm in diameter and fitting the description of *Nannochloris atomus* given by Ryther (1954) and Patten (1959) was numerically dominant in the 21 samples examined. Its cell densities in surface water generally decreased from 270,000 cells/ml near Sandy Hook (station 102) to 90,000 cells/ml offshore at stations 217 and 227. Cell densities for the remainder of the phytoplankton community were 100 to 900 cells/ml. Other than the small chlorophyte (probably *Nannochloris atomus*), chain-forming diatom species such as *Skeletonema costatum, Nitzchia seriata, Melosira* sp., *Rhizosolenia delicatula,* and *Chaetoceros curvisetum* dominated in samples collected near bottom and in the pycnocline, whereas flagellated species such as *Heterocapsa triquetra, Massartia rotundata,* (=*Katodinium rotunatum*), *Peridinium trochoideum,* and *Olisthodiscus luteus* dominated counts in surface samples. *Ceratium tripos* was not seen in any of the 21 samples examined. Mahoney (ch. 9, pt. 2) also noted the absence of *C. tripos* in his samples from late August. These findings verify that the *C. tripos* bloom, which occurred earlier in the year (Malone 1978), had dissipated by the end of August.

Mandelli et al. (1970) observed that *C. tripos* was the dominant species in their sampling area during June-August 1966. They also noted a decline in diatom (netplankton) abundance during the summer. This finding has been confirmed by Malone (1976) and O'Reilly et al. (1976) for the Bight Apex and the Hudson-Raritan estuary.

The general depletion of silicate in surface waters throughout the offshore and oxygen-depleted areas may have contributed to the relative abundance of nannophytoplankton (phytoplankton requiring little or no silicate)

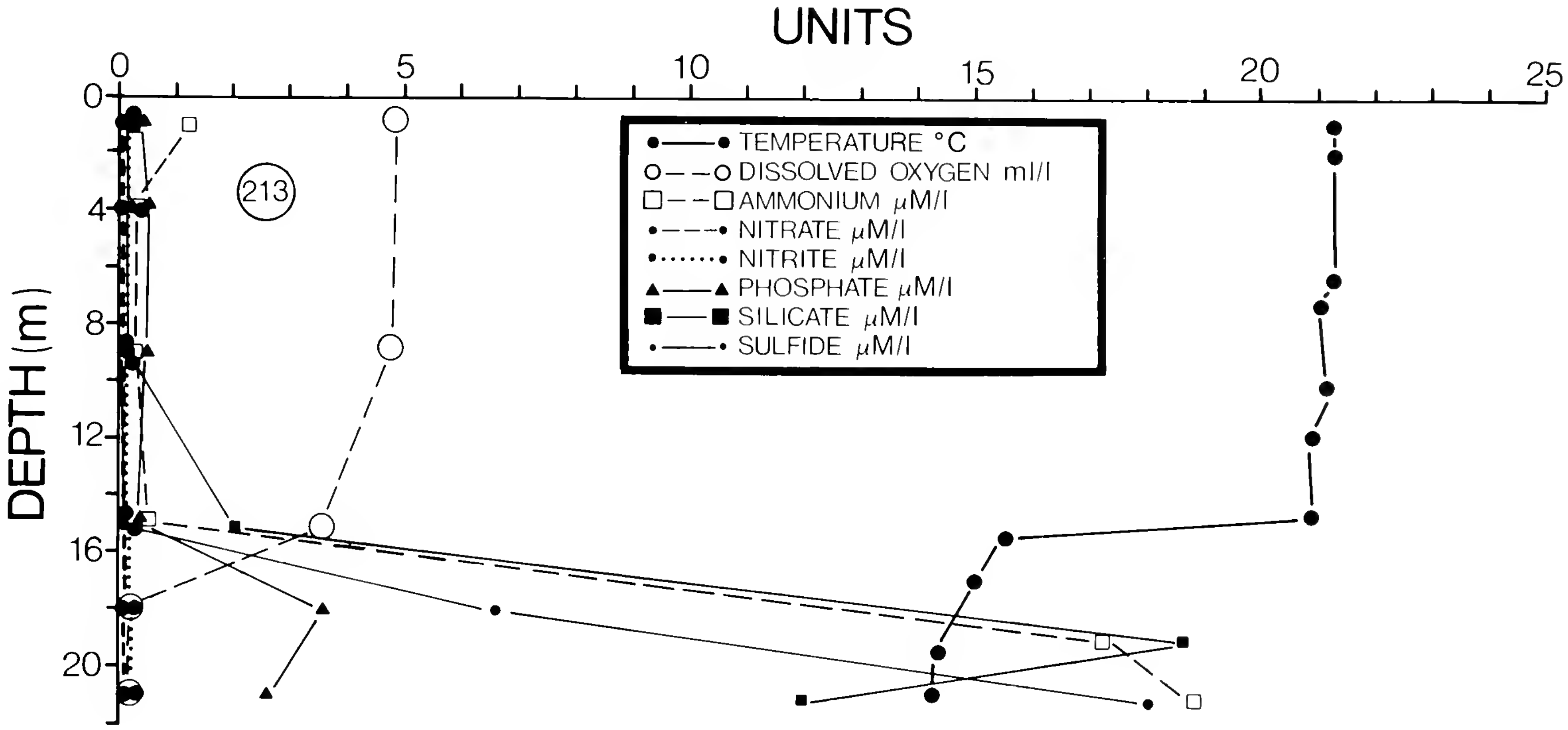


FIGURE 10-5.—Vertical profile of temperature, dissolved oxygen, ammonium, nitrate, nitrite, phosphate, silicate, and sulfide at station 213, September 4, 1976.

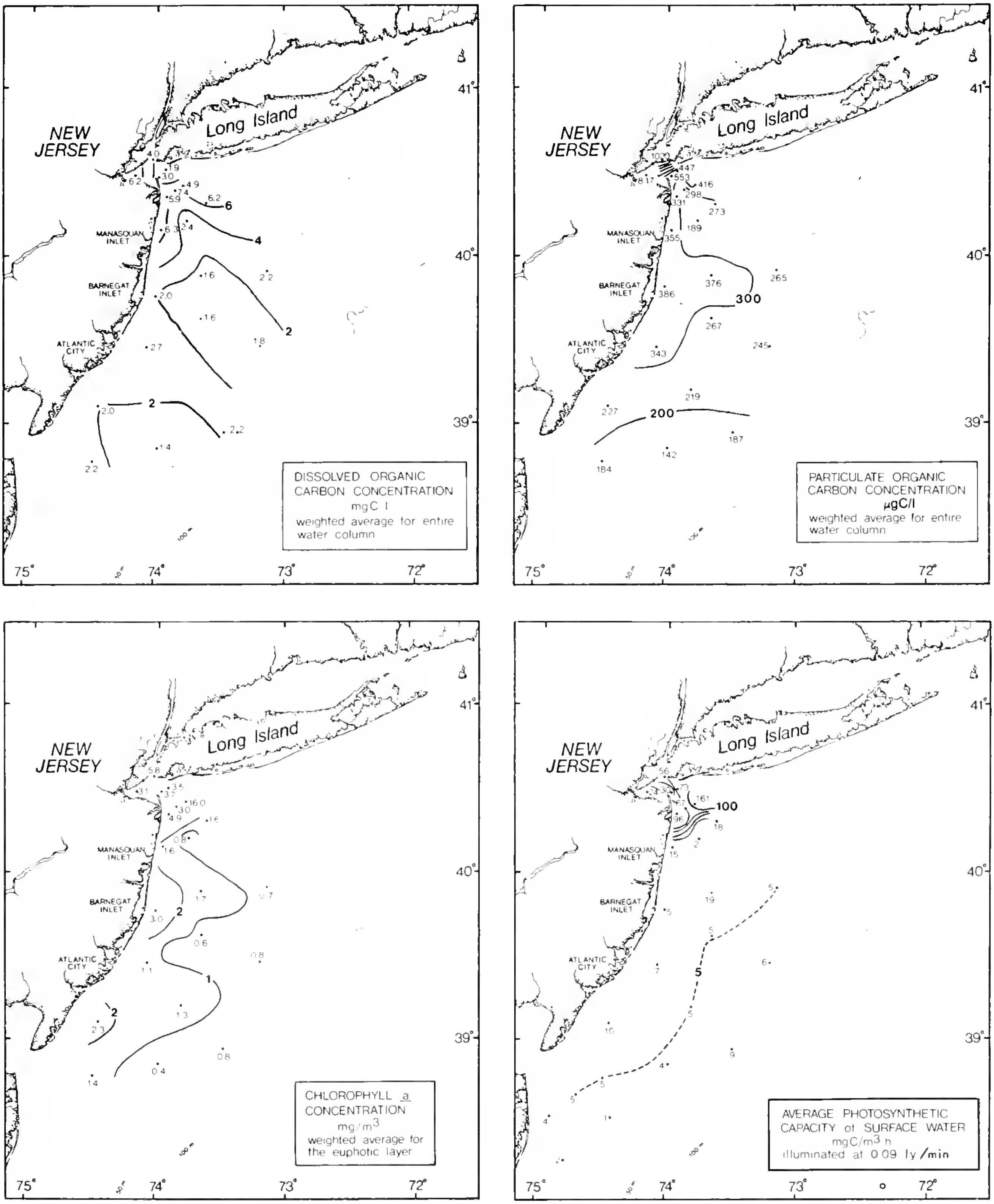


FIGURE 10-6.—Dissolved organic carbon, particulate organic carbon, chlorophyll *a*, and average photosynthetic capacity of surface water, August 24-September 9, 1976

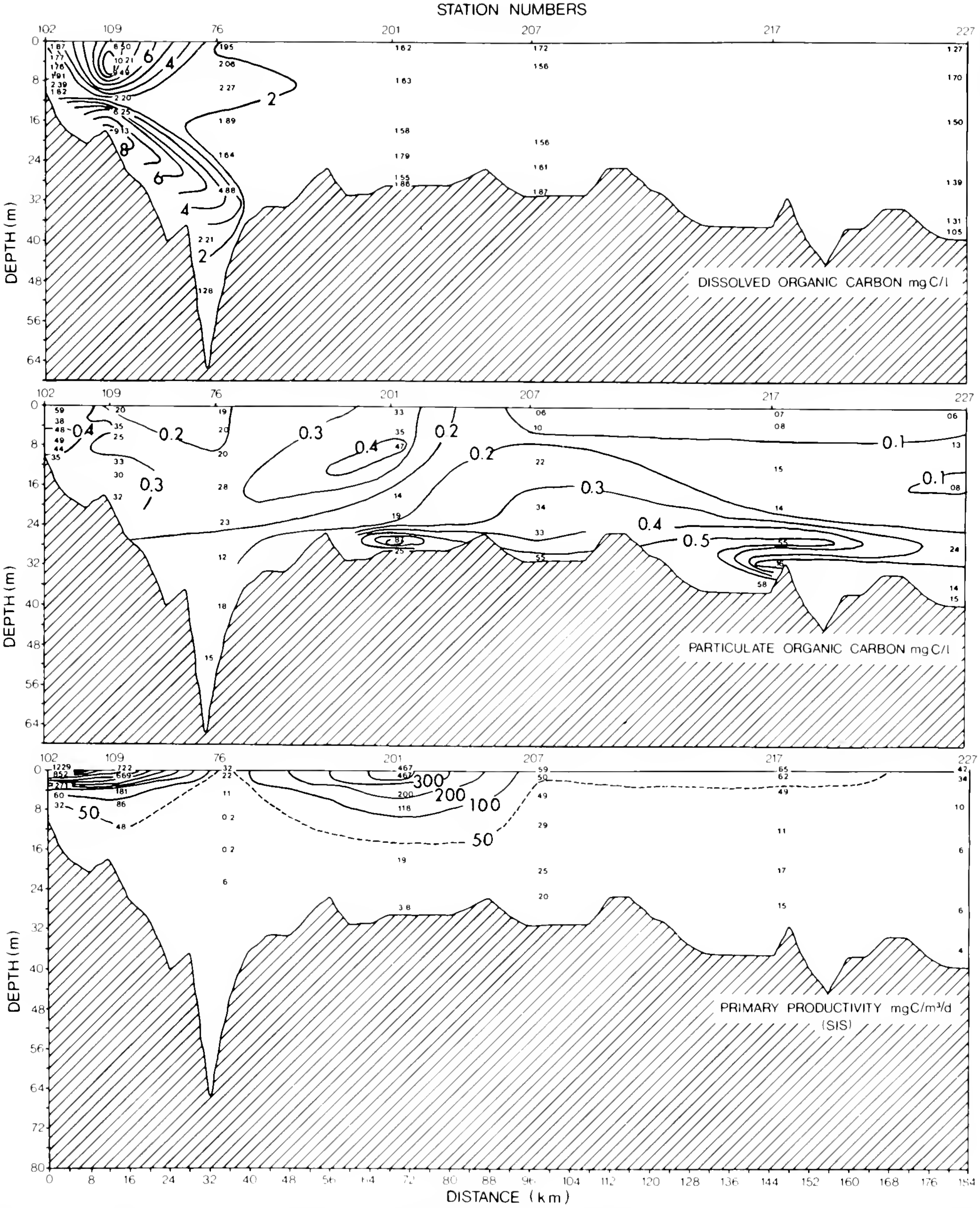


FIGURE 10–7A.—Dissolved organic carbon, particulate organic carbon, and simulated in situ (SIS) primary productivity along transect 102–227 of figure 10–1, August 24-September 9, 1976. Values offset to right of station sample depths.

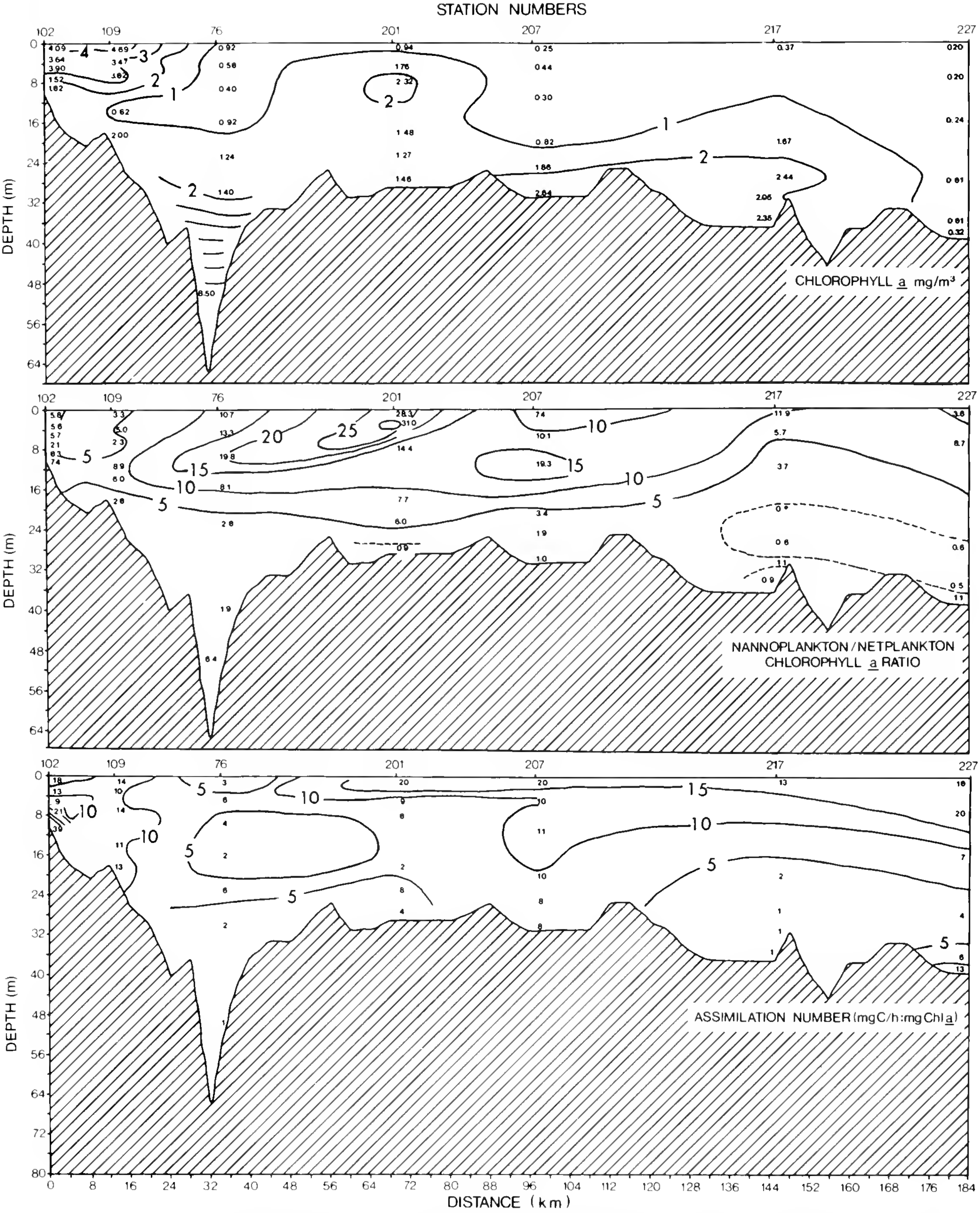


FIGURE 10–7B.—Chlorophyll *a*, nannoplankton/netplankton chlorophyll-*a* ratio, and assimilation number along transect 102–227 of figure 10–1, August 24-September 9, 1976. Values offset to right of station sample depths.

over netphytoplankton above the pycnocline. The rapid growth of these small, nonsiliceous nannoplankton (e.g., *Nannochloris atomus*) was primarily responsible for the high productivity and low nutrient concentrations observed above the pycnocline during August-September 1976.

## PHYTOPLANKTON PRODUCTIVITY

Integral daily rates of phytoplankton productivity were generally high throughout the Bight, ranging from 0.1 g C/m$^2$/d at station 76 in the upper Hudson Shelf Valley to 12.7 g C/m$^2$/d at station 34 in the central Christiaensen Basin (figs. 10–8 and 10–9A). Of the 21 stations, daily productivity exceeded 1 g C/m$^2$/d at 11 stations and 3 g C/m$^2$/d at 5 stations. Photosynthetic efficiencies per unit light energy and estimated growth rates (based on productivity to chlorophyll-*a* ratios) were very high (table 10–1). At many stations, growth rates of phytoplankton exceeded two divisions per day. At highly productive stations (i.e., station 34) adjacent to the estuary the euphotic layer was less than 10 m, whereas the euphotic layer at offshore stations was 20 to 40 m deep (figs. 10–8 and 10–9A). Outside the Apex, adjacent to the New Jersey coast (i.e., stations 200 and 213), the euphotic layer occupied the entire water column (figs. 10–8 and 10–9). At these stations the typical vertical profile (i.e., station 34, fig. 10–9) with the highest productivity at or near the surface is not seen. Instead, the simulated in situ (SIS) and photosynthetic capacity (PC) primary productivity of these stations (i.e., station 200) is maximal below the pycnocline (thermocline, fig. 10–9A and B) and near the bottom (table 10–2 and fig. 10–9A). In the oxygen-depleted area (i.e., stations 213, fig. 10–9A) phytoplankton biomass was high below the pycnocline as evidenced by PC measurements. Vertical profiles of SIS and PC data for all stations can be found in Thomas et al. (in preparation).

The levels of primary productivity observed in the Apex and the estuary are comparable to summer values reported by Malone (1976) and O'Reilly et al. (1976). The value of 12.7 g C/m$^2$/d observed at station 34 near the sewage sludge disposal site seems anomalously high (fig. 10–8). However, the average concentrations of euphotic chlorophyll *a* were high (16 mg/m$^3$, fig. 10–6) and the ratio of integral daily productivity to integral chlorophyll *a* (79.8 g C/m$^2$/d:g Chl*a*/m$^2$) was within the range observed for the estuary and Apex (table 10–1). The productivity observed outside the Apex and in and around the low D.O. area seems high when compared with the values (0.2–0.3 g C/m$^2$/d) estimated from chlorophyll and light data by Ryther and Yentsch (1958) for stations off Barnegat Inlet in late summer. However, comparison of our August-September 1976 and June 1977 data for the same area shows that total primary productivity was about the same in both years for the entire area studied, but was slightly higher in June 1977 than in August-September 1976 for the low D.O. area. The euphotic layer did not occupy the entire water column in June 1977 in contrast to August-September 1976.

Photosynthetic capacity (at saturating artificial light intensities) in surface waters ranged from 50 to 100 mg C/m$^3$/h in the Apex and near Sandy Hook to between 1 and 5 mg C/m$^3$/h along the 50-m isobath at the eastern edge of the sampling area off Delaware Bay (fig. 10–6). The largest change in this estuarine-offshore gradient was near stations 86, 76, and 51 at the outer perimeter of the Apex.

Photosynthetic capacity and simulated in-situ productivity of nannoplankton was much greater than that observed for netplankton (figs. 10–8 and 10–9A). Note that at station 200 (fig. 10-9A) netplankton productivity is greater than nannoplankton productivity below the pycnocline. The predominance of netphytoplankton in bottom water was previously noted in the discussion on the distribution of phytoplankton species. The lowest nannoplankton/netplankton productivity ratios observed, 1.0 to 1.5, were found at stations 41, 34, and 200 (fig. 10–8). During the June 1977 survey, nannophytoplankton also dominated primary productivity.

Throughout our study area, phytoplankton above the pycnocline were metabolically active and community growth rates were high (table 10–1). Assimilation numbers of 10 and above (fig. 10–7) indicated that phytoplankton were not nutrient limited (Curl and Small 1965) even though low and near zero concentrations of nutrients (ammonium, nitrate, nitrite, and silicate) were observed in surface water. The high values for community primary productivity and high photosynthetic efficiencies above the pycnocline were due in part to the small size of the nannoplankters, high surface area to cell volume ratios, and high nutrient uptake rates, which are often (but not necessarily always) associated with smallness (Taguchi 1976). These actively growing populations may have contributed to maintenance of the depressed D.O. episode by continually loading bottom water with a portion of the surface layer production or organic matter derived from phytoplankton (i.e., fecal pellets, Malone 1978).

Phytoplankton below the pycnocline, where light intensity was low (1% to 3% of surface intensity), had low assimilation numbers (fig. 10–7) and low photosynthetic efficiencies. High rates of photosynthetic capacity under optimal light conditions (fig. 10–9A), low assimilation numbers, and low chlorophyll/phaeopigment ratios where chlorophyll *a* was elevated indicate that the subpycnocline phytoplankton, though very abundant, were probably physiologically debilitated. They were not nutrient limited, because nitrogen, phosphorus, and silica were abundant.

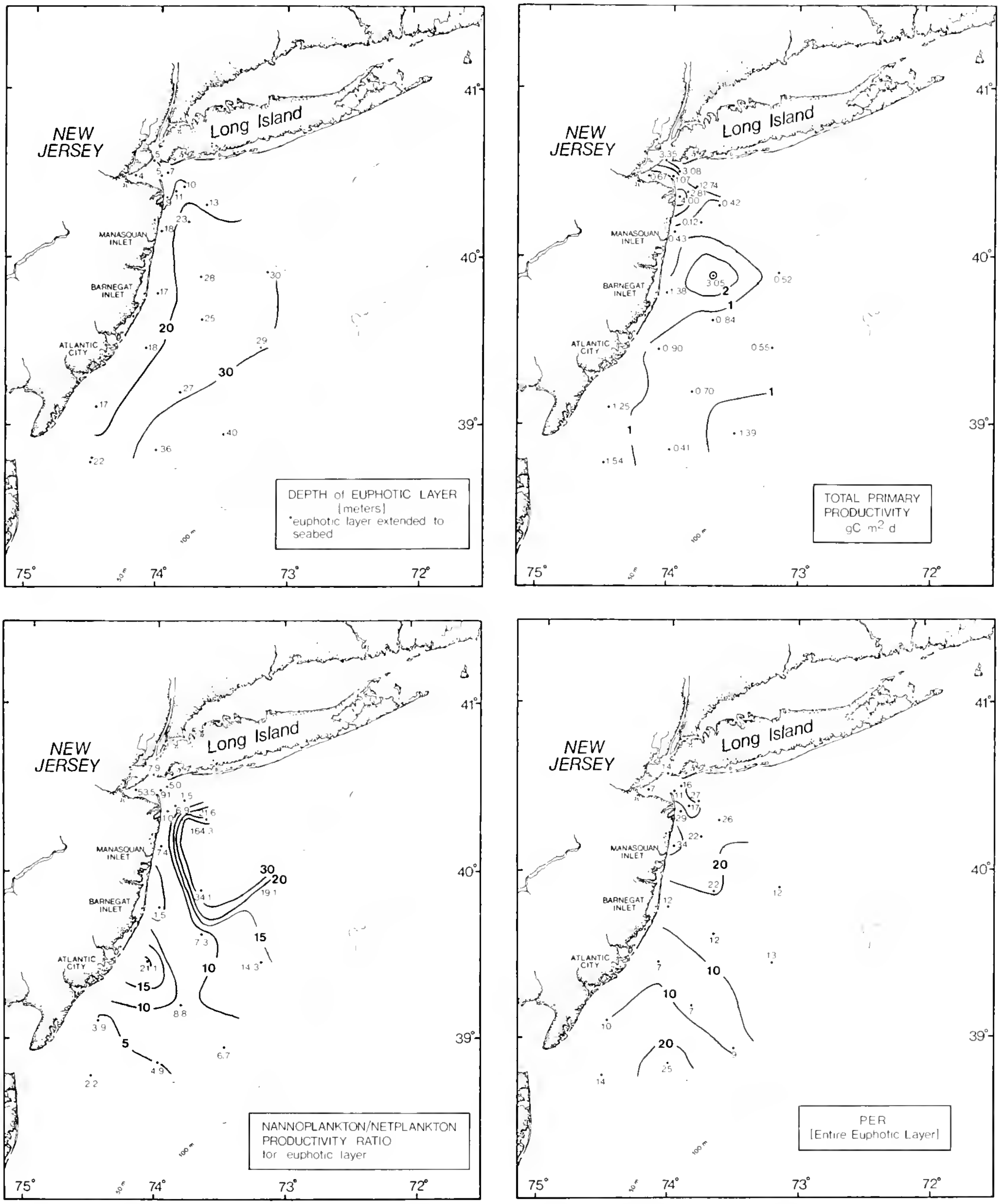


FIGURE 10–8.—Depth of euphotic layer, total (SIS) primary productivity, nannoplankton/netplankton productivity ratio, and percent extracellular release (PER), August 24-September 9, 1976.

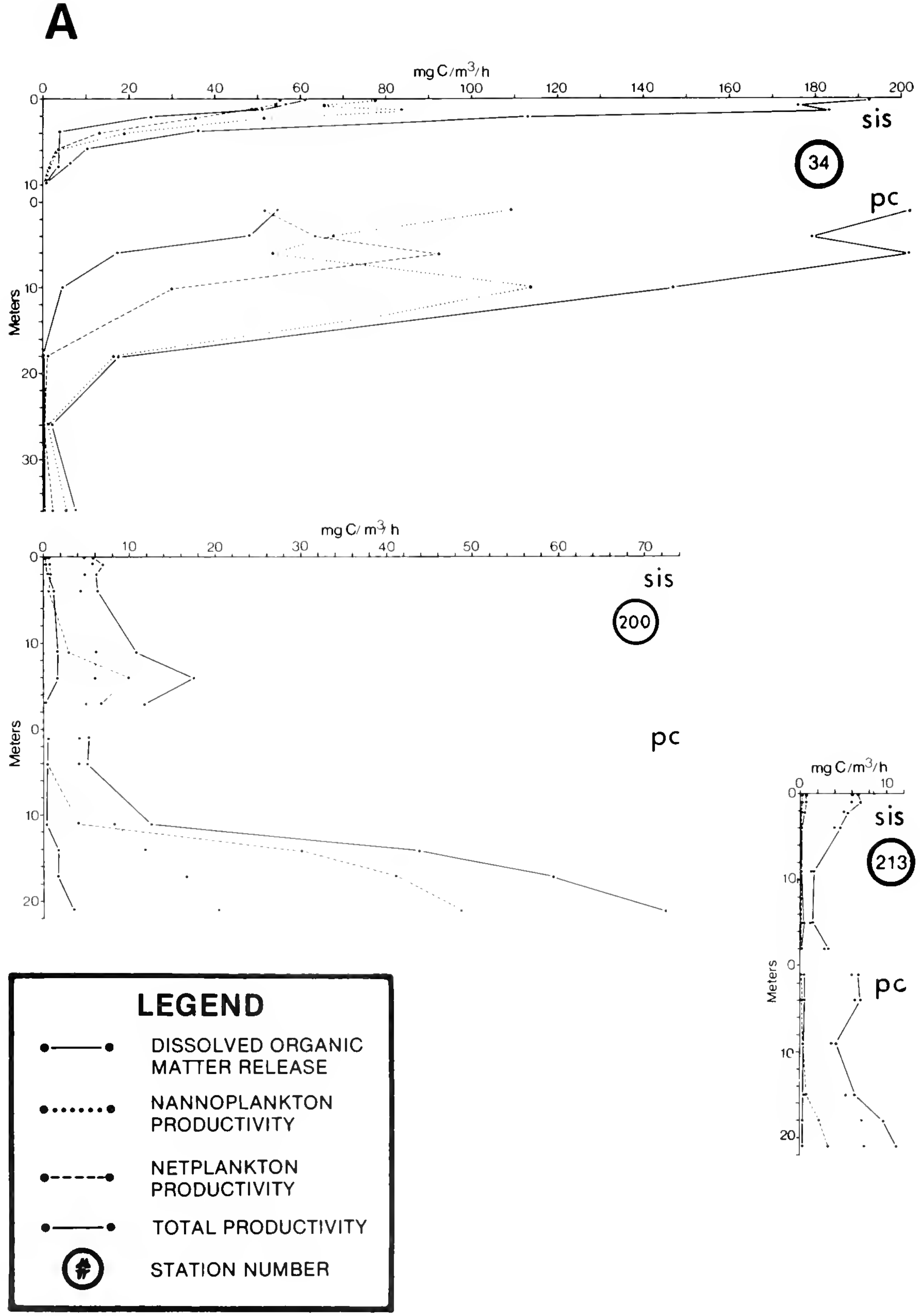


FIGURE 10–9A.—Vertical profiles of simulated in situ (SIS) and photosynthetic capacity (PC) total productivity, netplankton productivity, nannoplankton productivity, and dissolved organic matter release at stations 34, 200, and 213, September 1, 3, and 4, 1976.

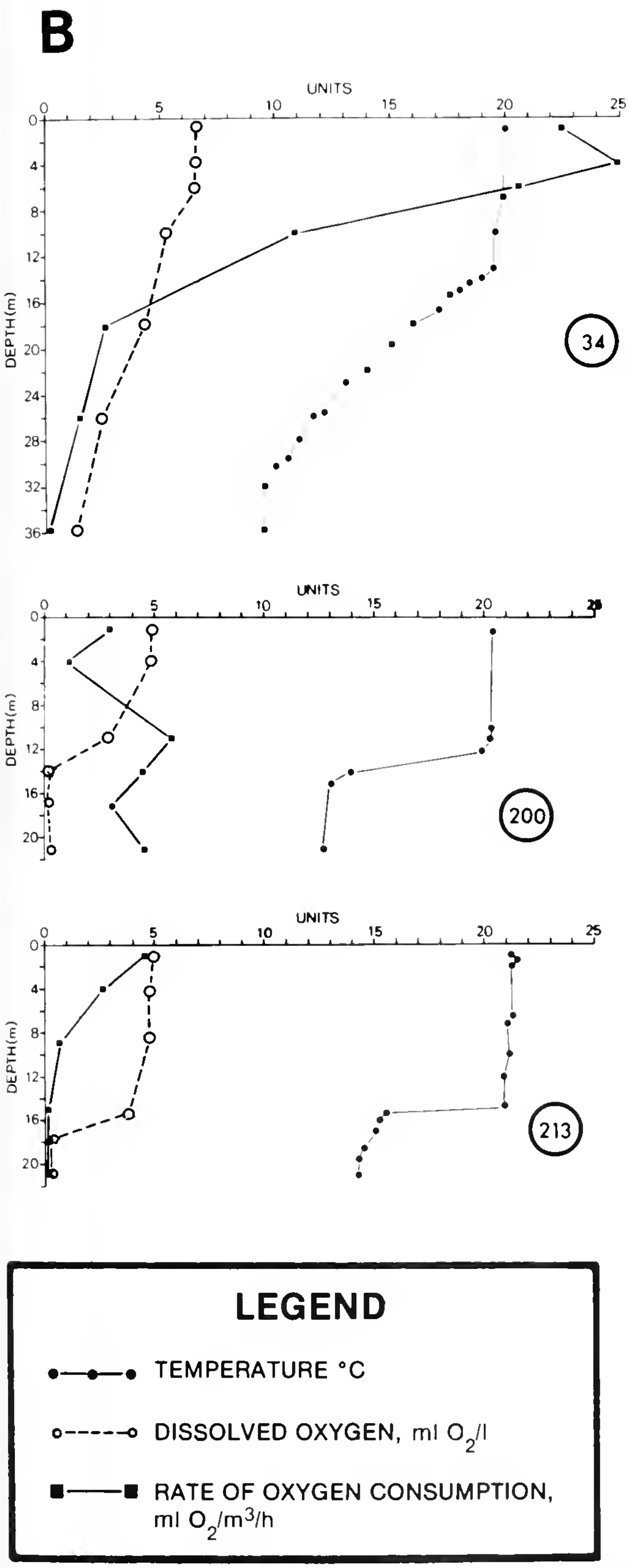


FIGURE 10–9B.—Vertical profiles of temperatures, dissolved oxygen, and rate of oxygen consumption in the water column at stations 34, 200, and 213, September 1, 3, and 4, 1976.

## CONTRIBUTIONS TO THE DOC POOL

The percentage of photoassimilated carbon released as dissolved organic matter (percentage of extracellular release, PER) ranged from 7 to 34 (fig. 10–8). The highest PER values were in the middle and outer Apex where total primary productivity (fig. 10–8) and DOC concentrations (fig. 10–6) were also highest. We suggest that phytoplankton production of dissolved extracellular carbon may be contributing significantly to the DOC pool and thereby counteracting seaward dilution of DOC concentrations. Considering the euphotic zone extracellular organic releases (fig. 10–8) and the euphotic standing stocks of DOC (fig. 10–6), the estimated turnover times for the DOC pool were 16 to 1,755 days. In general, it would take the phytoplankton community 120 to 200 days (most commonly observed frequencies) to release enough DOC to equal the euphotic stocks of DOC in the portion of New York Bight examined. These numbers take on added significance when one considers that the DOC pool is the largest (3 to 25 times POC) in the New York Bight.

Some recent measurements demonstrate that heterotrophic bacteria assimilate between 0 and 30 percent of the DOC released by phytoplankton communities during relatively short-term (6-h) incubations (Derenbach and Williams 1974; Williams and Yentsch 1976; Iturriaga and Hoppe 1977). Consequently, the measurements underestimate the rate of release of DOC from phytoplankton and overestimate turnover time. Because DOC may be partly related to PER, a portion of DOC may be very active biologically, making DOC important not only for its abundance, but also for its potential for decomposition and relevance to oxygen problems.

## OXYGEN CONSUMPTION

### In the Water Column

Total plankton respiration rates in the New York Bight during the August-September 1976 cruise were moderately high, ranging from zero to about 25 ml $O_2/m^3/h$. Integral rates of carbon mineralization ranged from 0.0 to 5.9 g $C/m^2/d$, assuming a respiratory quotient of 1 (figs. 10-4 and 10-10). In the low D.O. area, surface water rates were 2 to 5 ml $O_2/m^3/h$, consequently integral rates of aerobic carbon mineralization were low (0.2–0.3 g $C/m^2/d$). Proceeding from the low D.O. area, higher integral mineralization rates occurred (up to 6 g $C/m^2/d$) toward the deeper water to the southeast and in the shallower water of the estuary and Apex.

For comparison, in the New York Bight during July 1977 the highest rate measured was 82 ml $O_2/m^3/h$. Pomeroy and Johannes (1966) measured a rate of 0.17 ml $O_2/m^3/h$ for the surface layer of the Sargasso Sea in July;

TABLE 10–1.—*Synopsis of primary productivity and related measurements in New York Bight, August-September 1976*

| | | Euphotic integral hourly production | | | | Percentage of total production | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1976 date | Station | Net-plankton | Nanno-plankton | DOM[1] | Total | Net-plankton | Nanno-plankton | POM[2] | DOM | Nanno- to net-plankton productivity ratio | Incubation period | Duration of exp. | Daily PAR[3] |
| | | mg C/m² | | | | % | % | % | % | | E.S.T. | h | Ei/m²/d |
| Aug. 27 | 51 | 1.3 | 28.0 | 10.3 | 39.6 | 3.3 | 70.8 | 74.1 | 25.9 | 21.6 | 1010–1847 | 8.62 | 12.0 |
| 28 | 109 | 26.3 | 180.5 | 42.8 | 249.6 | 10.5 | 72.3 | 82.8 | 17.2 | 6.9 | 1400–1716 | 3.27 | 24.9 |
| 30 | 45 | 1.2 | 63.8 | 5.1 | 70.1 | 1.7 | 91.0 | 92.7 | 7.3 | 53.5 | 0700–1415 | 7.25 | 29.5 |
| 30 | 69 | 15.3 | 120.9 | 21.6 | 157.8 | 9.7 | 76.6 | 86.3 | 13.7 | 7.9 | 1245–1845 | 6.00 | 29.5 |
| 31 | 101 | 9.9 | 90.3 | 12.2 | 112.4 | 8.8 | 80.3 | 89.1 | 10.9 | 9.1 | 0700–1300 | 6.00 | 34.9 |
| Aug. 31 | 102 | 28.2 | 140.2 | 33.1 | 201.5 | 14.0 | 69.6 | 83.6 | 16.4 | 5.0 | 1300–1830 | 5.50 | 34.9 |
| Sept. 1 | 41 | 165.2 | 170.3 | 137.8 | 473.3 | 34.9 | 36.0 | 70.9 | 29.1 | 1.0 | 0725–1345 | 6.33 | 33.2 |
| 1 | 34 | 167.8 | 245.4 | 149.9 | 563.1 | 29.8 | 43.6 | 73.4 | 26.6 | 1.5 | 1345–1830 | 4.75 | 33.2 |
| 2 | 76 | .07 | 11.5 | 3.2 | 14.8 | 0.5 | 77.9 | 78.4 | 21.6 | 164.3 | 0810–1530 | 7.33 | 6.7 |
| 2 | 86 | 1.8 | 12.9 | 7.7 | 22.4 | 8.0 | 57.6 | 65.6 | 34.4 | 7.4 | 1330–1815 | 4.75 | 6.7 |
| 3 | 200 | 60.3 | 91.7 | 21.1 | 173.1 | 34.8 | 53.0 | 87.8 | 12.2 | 1.5 | 0733–1420 | 6.78 | 31.9 |
| 3 | 201 | 1.8 | 61.0 | 17.7 | 80.5 | 2.2 | 75.8 | 78.0 | 22.0 | 34.1 | 1420–1830 | 4.17 | 31.9 |
| 4 | 207 | 10.0 | 72.3 | 11.0 | 93.3 | 10.7 | 77.5 | 88.2 | 11.8 | 7.3 | 0740–1330 | 5.83 | 33.8 |
| 4 | 213 | 2.3 | 47.8 | 3.7 | 53.8 | 4.3 | 88.8 | 93.1 | 6.9 | 21.1 | 1330–1830 | 5.00 | 33.8 |
| 5 | 217 | 7.9 | 69.2 | 5.6 | 82.7 | 9.6 | 83.7 | 93.3 | 6.7 | 8.8 | 0815–1410 | 5.92 | 25.9 |
| 6 | 215 | 24.6 | 94.8 | 13.5 | 132.9 | 18.5 | 71.3 | 89.8 | 10.2 | 3.9 | 0730–1330 | 6.00 | 31.0 |
| 6 | 228 | 25.0 | 54.3 | 12.9 | 92.2 | 27.1 | 58.9 | 86.0 | 14.0 | 2.2 | 1330–1830 | 5.00 | 31.0 |
| 7 | 226 | 19.0 | 126.7 | 14.8 | 160.5 | 11.8 | 78.9 | 90.7 | 9.3 | 6.7 | 0740–1345 | 6.08 | 28.9 |
| 7 | 227 | 2.7 | 13.3 | 5.4 | 21.4 | 12.6 | 62.1 | 74.7 | 25.3 | 4.9 | 1345–1830 | 4.75 | 28.9 |
| 8 | 219 | 3.7 | 53.2 | 8.7 | 65.6 | 5.6 | 81.1 | 86.7 | 13.3 | 14.3 | 0755–1258 | 5.05 | 23.8 |
| Sept. 8 | 205 | 1.2 | 22.8 | 3.1 | 27.1 | 4.4 | 84.1 | 88.5 | 11.5 | 19.1 | 1430–1830 | 4.00 | 23.8 |

[1] DOM, photoassimilated carbon released as dissolved organic matter by phytoplankton

[2] POM, particulate organic matter (netplankton + nannoplankton) produced during photosynthesis.

[3] PAR, photosynthetically active radiation (400–700 nm).

[4] Daily integral productivity = total euphotic integral hourly production × duration of experiment × (100/% daily PAR).

[5] Efficiency = $[(\text{g C/m}^2\text{/d}\cdot\frac{15.8 \times 10.3 \text{ cal}}{\text{g C}}) / (\text{Einstein/m}^2\text{/d}\cdot\frac{57{,}391 \text{ cal}}{\text{Einstein}})]\cdot 100$. After Platt 1971

[6] MPZ, mean photic zone.

[7] Doublings per day = daily productivity: euphotic chlorophyll-*a* ratio / 30. Assuming 30:1 carbon/Chl*a* (Eppley 1968).

[8] After Bannister 1974.

Barlow et al. (1963) measured an average rate of 272 ml $O_2/m^3/h$ during the summer in the heavily fertilized eutrophic Forge River estuary. Sirois (1974) measured 72 and 53 ml/$O_2/m^3/h$ in July and September, respectively, in the surface water of the lower Hudson River above the major influence of New York metropolitan area, about 15 km north of station 69. Farther north in the Hudson River, Sirois reported lower rates (44 and 24 ml $O_2/m^3/h$ in July and September, respectively). During June 1977, a "normal" summer, total plankton respiration rates measured in the previously affected low D.O. area were about 2 g C/m²/d oxidized and were several times higher than the rates of integral aerobic respiration measured there during August-September 1976.

Above the pycnocline, during August-September 1976, oxygen consumption rates were generally highest and decreased with depth from the surface (figs. 10–4 and 10–9, station 34). Aerobic respiration in the water column above the pycnocline in the low D.O. area was much less, relative to adjacent stations, even though oxygen was near saturation and therefore not limiting (figs. 10–4 and 10–10; fig. 10–9B, station 213).

Below the pycnocline, total plankton aerobic respiration rates were frequently near zero except at stations adjacent to the oxygen-depleted area (figs. 10–4 and 10–9B, station 200) and in the estuary (Thomas et al., in press). Below the pycnocline in the anoxic area no measurable aerobic respiration occurred (figs. 10–4 and 10–9B, station 213). However, the highest concentrations of phosphate and silicate were measured in the anoxic area just below the pycnocline, suggesting that anaerobic metabolism may have played a major role in the regeneration of nutrients from particulate and dissolved organic matter or that a residual buildup from previous aerobic metabolism was solubilized under low D.O. conditions or that water of higher nutrient concentration was advected into that area.

| Station | Percentage of daily PAR during incubation | Est. daily integral productivity[4] | Photosynthetic efficiency[5] | Euphotic depth | Euphotic Chl*a* integral | MPZ[6] Chl*a* | Daily productivity to euphotic Chl*a* ratio | Growth rate doublings per day[7] | PAR extinction coefficient | Percent of total PAR extinction due to phytoplankton[8] |
|---|---|---|---|---|---|---|---|---|---|---|
| | % | mg C/m²/d | % | m | mg Chl*a*/m² | mg/m³ | g C/m²/d / g Chl*a*/m³ | | m$^{-1}$(base e) | % |
| 51 | 82 | 416 | 0.95 | 14n | 22.7 | 1.62 | 18.3 | 0.6 | −0.23 | 11.3 |
| 109 | 29 | 2,814 | 3.11 | 14n | 41.7 | 2.98 | 67.5 | 2.3 | −0.36 | 13.2 |
| 45 | 76 | 669 | 0.62 | 4.3 | 18.6 | 3.10 | 36.0 | 1.2 | −1.06 | 4.7 |
| 69 | 28 | 3,381 | 3.16 | 5.4 | 31.1 | 5.76 | 108.7 | 3.6 | −0.82 | 11.2 |
| 101 | 63 | 1,070 | 0.84 | 5n | 18.3 | 3.66 | 58.5 | 1.9 | −0.85 | 6.9 |
| 102 | 36 | 3,078 | 2.43 | 7.2 | 25.4 | 3.53 | 121.2 | 4.0 | −0.66 | 8.6 |
| 41 | 75 | 3,995 | 3.31 | 9n | 44.1 | 4.90 | 90.6 | 3.0 | −0.42 | 18.7 |
| 34 | 21 | 12,737 | 10.56 | 10n | 159.6 | 15.96 | 79.8 | 2.7 | −0.47 | 54.3 |
| 76 | 91 | 119 | 0.49 | 23n | 17.9 | 0.78 | 6.6 | 0.2 | −0.20 | 6.2 |
| 86 | 25 | 426 | 1.75 | 18n | 28.9 | 1.61 | 14.7 | 0.5 | −0.30 | 8.6 |
| 200 | 85 | 1,381 | 1.19 | 17n | 50.5 | 2.97 | 27.3 | 0.9 | −0.31 | 15.3 |
| 201 | 11 | 3,052 | 2.63 | 28n | 47.6 | 1.70 | 64.1 | 2.1 | −0.17 | 16.0 |
| 207 | 65 | 837 | 0.68 | 25n | 15.6 | 0.62 | 53.7 | 1.8 | −0.16 | 6.2 |
| 213 | 30 | 897 | 0.73 | 18n | 19.8 | 1.10 | 45.3 | 1.5 | −0.32 | 5.5 |
| 217 | 70 | 699 | 0.74 | 27 | 34.2 | 1.27 | 20.4 | 0.7 | −0.16 | 12.7 |
| 215 | 64 | 1,246 | 1.11 | 17 | 38.3 | 2.25 | 32.5 | 1.1 | −0.23 | 15.7 |
| 228 | 30 | 1,537 | 1.36 | 22n | 30.0 | 1.36 | 51.2 | 1.7 | −0.13 | 16.7 |
| 226 | 70 | 1,394 | 1.33 | 40n | 32.7 | 0.82 | 42.6 | 1.4 | −0.13 | 10.1 |
| 227 | 25 | 407 | 0.39 | 36n | 13.0 | 0.36 | 31.3 | 1.0 | −0.13 | 4.4 |
| 219 | 60 | 552 | 0.64 | 29n | 21.8 | 0.75 | 25.3 | 0.8 | −0.16 | 7.5 |
| 205 | 21 | 516 | 0.60 | 30n | 20.6 | 0.69 | 25.0 | 0.8 | −0.16 | 6.9 |

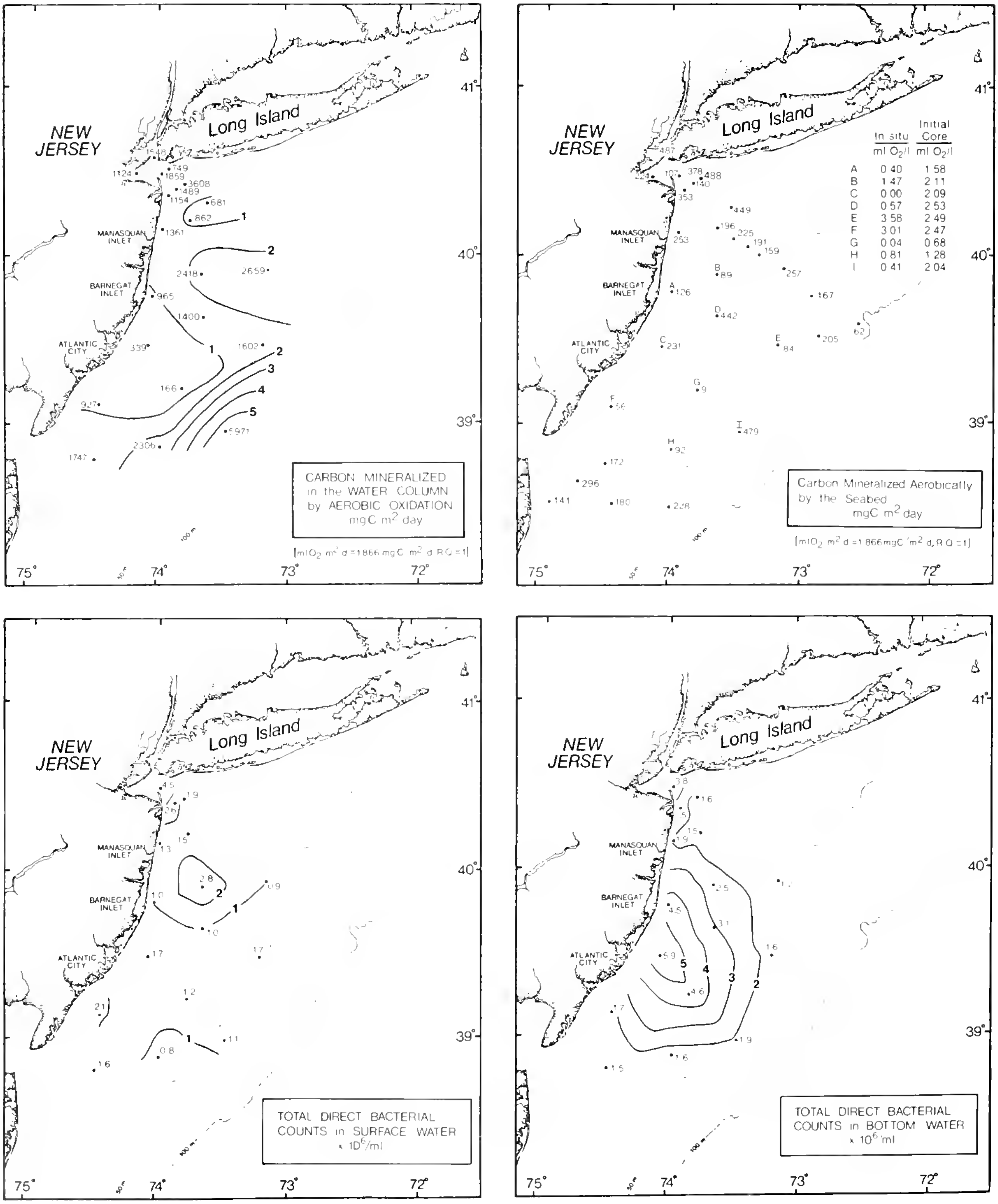
However, water of similar density (fig. 10–3) on either side of the anoxic region had lower nutrient concentrations (fig. 10–4), suggesting that advection was not a factor. The highest concentrations of nutrients were often observed immediately below the pycnocline, suggesting that the seabed played a subordinate role in regeneration or dissolution of nutrients.

### By the Seabed

In the present study, rates of oxygen consumption by the seabed ranged between 0.7 and 38 ml $O_2$/m²/h (average 16.9 ml $O_2$/m²/h, N = 31 stations). In a previous study over an annual cycle in the Bight Apex we measured a range between 1 and 68 ml $O_2$/m²/h (Thomas et al. 1976b). The average rates of seabed oxygen consumption in the Apex for summer 1974 and 1975 were similar (18.2 and 16.6 ml $O_2$/m²/h, N = 58 and 60 respectively). Smith and Teal (1973) measured low rates of seabed oxygen consumption (0.5 ml $O_2$/m²/h) on the continental slope south of New England. Pamatmat (1973) measured the metabolism of the benthic community on the relatively pristine continental shelf off the Washington-Oregon coasts during summer. For depths 100 m or less he found rates of 2 to 12 ml $O_2$/m²/h (average 6.4 ml $O_2$/m²/h, N = 8), which are generally lower than those in the New York Bight.

Aerobic measurements of seabed oxygen consumption could not be made under in-situ oxygen conditions in the anoxic area because of the technique used. However, within and immediately surrounding the anoxic area, high rates of oxygen uptake (up to 37 ml $O_2$/m²/h) were measured when the cores were aerated above seabed in-situ levels (fig. 10–10). These high rates may have been caused in part by the rapid consumption of oxygen by sulfide as well as by microorganisms capable of surviving low D.O. and responding to input of oxygen. They also suggest that large inputs of oxidizable organic carbon to the seabed stimulated seabed oxygen consumption rates to levels higher than might be expected for that area. At the seabed in July, Mahoney (ch. 9, pt. 2) found decaying floc of *C. tripos* that may have been responsible for the elevated rates of seabed oxygen consumption measured in August-September.

Rates of seabed oxygen uptake measured between the Apex and the northern perimeter of the low D.O. area during August-September 1976 do not appear different from those during August 1975. (See Thomas et al. 1976a, 1976b.) Measurements of seabed oxygen consumption were also taken in the area during June 1977 (Thomas, unpublished data). Comparing June 1977 with August-September 1976 is difficult, because of the temporal and



| | In situ ml $O_2$/l | Initial Core ml $O_2$/l |
|---|---|---|
| A | 0 40 | 1 58 |
| B | 1 47 | 2 11 |
| C | 0 00 | 2 09 |
| D | 0 57 | 2 53 |
| E | 3 58 | 2 49 |
| F | 3 01 | 2 47 |
| G | 0 04 | 0 68 |
| H | 0 81 | 1 28 |
| I | 0 41 | 2 04 |

FIGURE 10–10.—Carbon mineralized and total direct bacterial counts, August 24-September 9, 1976.

spatial heterogeneity and low sampling density. However, rates did appear to be higher around the oxygen-depleted area (12.5 ± s.d. 5.5 ml $O_2/m^2/h$, n = 21, in August-September 1976) than in the same area during the following summer (6.5 ± s.d. 3.6 ml $O_2/m^2/h$, n = 19, in June 1977). The 1977 rates of seabed oxygen consumption in the area of former low D.O. were comparable to rates measured in surrounding areas in 1977. Away from the oxygen-depleted area no differences between summers were readily apparent. These data further suggest that during the 1976 event the seabed received additional organic loading in and adjacent to the low D.O. area.

The contribution of the seabed to the total oxygen consumption (water column plus seabed) ranged from zero in the low D.O. area (because aerobic respiration could not be measured) to 40 percent at station 51 in the Apex and averaged 14 percent over the area sampled (table 10–2). Two stations on the periphery of the anoxic area (200, 207), as well as stations in the estuary and Apex, had seabed oxygen consumption rates that accounted for more than 10 percent of the carbon oxidized in the entire water column, including the seabed. At the remaining stations, the seabed contributed less than 10 percent to the aerobic mineralization of organic carbon. These data suggest higher than expected contributions for the seabed at stations 200 and 207 and indicate additional organic loading to the seabed in and around the low D.O. area.

An August 1975 study in the Apex demonstrated that the seabed contributed only 3 to 7 percent of the total oxygen consumption—water column plus seabed (Thomas et al. 1976b). During June 1977, oxygen consumption rates in the water column and on the seabed were measured concurrently over the same area sampled during the low D.O. episode of 1976. The seabed contribution to the total aerobic oxygen consumption (water plus seabed) ranged from 1 to 11 percent and averaged 6 percent. The highest contributions (8%-11%) were within 20 km of the New Jersey coast in a band from Sandy Hook to Atlantic City. The remaining stations contributed less than 6 percent including those in the area of depressed D.O. in the previous year. Again, these temporal and spatial comparisons indicate that the seabed at stations adjacent to the anoxic area in 1976 contributed disproportionately to total aerobic respiration. The relatively greater contribution of the

TABLE 10–2.—*Contribution of the seabed and subpycnocline water to total aerobic oxygen consumption and relationship of total primary production to total aerobic decomposition above and below pycnocline*

| Station | Depth | Pycnocline depth | Total oxygen consumption: water column and seabed | Oxygen consumed in water above pycnocline | Oxygen consumed in water below pycnocline | Oxygen consumed by the seabed | Total primary production | Production-respiration ratio above pycnocline[1] | P/R ratio below pycnocline including seabed[1] |
|---|---|---|---|---|---|---|---|---|---|
| | m | m | mg C/m²/d | Percent | Percent | Percent | mg C/m²/d | | |
| 45 | 6[a] | 6[a] | 1348 | 83.4 | 0[a] | 16.6 | 669 | 0.60 | < .01 |
| 69 | 11 | 11[a] | 2036 | 76.1 | 0[a] | 23.9 | 3381 | 2.18 | < .01 |
| 101 | 11 | 11[a] | 1967 | 94.6 | 0[a] | 5.4 | 1070 | .58 | < .01 |
| 102 | 13 | 8.5 | 1126 | 55.9 | 10.5 | 33.6 | 3078 | 4.89 | < .01 |
| 109 | 21 | 13 | 1630 | 88.9 | 2.5 | 8.6 | 2814 | 1.94 | < .01 |
| 41 | 20 | 12.5 | 1508 | 73.7 | 2.9 | 23.4 | 3995 | 3.59 | < .01 |
| 34 | 36 | 17.5 | 4097 | 79.5 | 8.6 | 11.9 | 12737 | 3.91 | < .01 |
| 86 | 18 | 11 | 1615 | 66.8 | 17.5 | 15.7 | 426 | .32 | 0.15 |
| 76 | 50 | 17.5 | 1058 | 75.7 | 5.8 | 18.5 | 119 | .14 | .03 |
| 51 | 23 | 7.5 | 1131 | 31.5 | 28.8 | 39.7 | 416 | .96 | .10 |
| 200 | 21 | 13 | 1092 | 50.8 | 37.7 | 11.5[b] | 1381 | 1.64 | .87 |
| 201 | 33 | 21 | 2508 | 87.6 | 8.9 | 3.5 | 3052 | 1.35 | .25 |
| 207 | 31 | 19.5 | 1849 | 52.9 | 23.1 | 23.9[b] | 837 | 72 | .14 |
| 205 | 80 | 23 | 2917 | 43.1 | 48.1 | 8.8 | 516 | .36 | .04 |
| 219 | 41 | 23.5 | 1687 | 76.3 | 18.7 | 5.0 | 552 | .36 | .23 |
| 213 | 21 | 15.5 | 340 | 100.0 | 0[c] | 0.0[c] | 897 | 2.35 | .41[d] |
| 217 | 35 | 22 | 165 | 90.0 | 10.0 | 0.0 | 699 | 4.16 | .43[d] |
| 215 | 20 | 15 | 983 | 91.3 | 3.0 | 5.7 | 1246 | 1.05 | 3.59 |
| 228 | 22 | 12.5 | 1920 | 63.5 | 27.5 | 9.0 | 1537 | .73 | .92 |
| 227 | 40 | 29 | 2400 | 81.3 | 14.9 | 3.8 | 407 | .19 | .07 |
| 226 | 54 | 26.5 | 6455 | 87.5 | 5.1 | 7.4[b] | 1394 | .22 | .18 |

[1] P is the daily production using $^{14}C$ method; R is the daily respiration using oxygen method (assumed RQ = 1).

[a], No pycnocline present.

[b], May reflect an elevated rate caused by aeration of sediment core prior to rate measurements.

[c], Dissolved oxygen concentration was 0. Anaerobic rate could not be measured at ambient D.O. concentration.

[d], Anaerobic metabolism estimated from phosphate accumulated below pycnocline. (See text.)

seabed on the periphery of the low D.O. area in 1976 was due to the combination of higher rates of seabed oxygen consumption and lower rates of total plankton respiration, presumably due to oxygen limitation and other unknown factors. It seems certain that the seabed received larger fluxes of oxidizable carbon in 1976 than in 1977.

## NET OXYGEN DEPLETION AND UTILIZATION RATES

Atwood et al. (ch. 4) calculated oxygen depletion rates for subpycnocline waters. Depletion rates are regressions of observed oxygen concentrations versus time. From the slope of these regressions these authors estimated an average oxygen depletion rate of 2.2 ml $O_2/m^3/h$ for subpycnocline water (segments A, J1, J2, M1, and H in ch. 1, fig. 1–9) comparable to our study area. Han et al. (ch. 8) calculated an average net oxygen utilization rate of 4.0 ml $O_2/m^3/h$ for May-June 1976 and included advective inputs and outputs of oxygen and water for the various boxes in their model. In this study (August-September 1976), the measured rates of total plankton respiration in subpycnocline waters (average thickness 9.4 m) were 0.1 to 5.0 ml $O_2/m^3/h$ and averaged 1.8 ml $O_2/m^3/h$. Our measured rates of seabed oxygen consumption averaged 16.9 ml $O_2/m^2/h$. Adding the oxygen consumed by the overlying subpycnocline waters results in an average of 3.7 ml $O_2/m^3/h$ consumed below the pycnocline. This compares favorably with the net utilization rates derived from the model of Han et al. (ch. 8). Despite this agreement it must be stated that our measurements of oxygen consumption in the water column were taken several months after the time frame used in the model. In June 1977 we again measured oxygen uptake both in the water column and on the seabed. From these we calculated that an average of 4.2 ml $O_2/m^3/h$ was used below the pycnocline (27 m). For comparison, Tsuji et al. (1974), also dealing with a shallow (20 m) two-layered aerobic/anaerobic system, estimated an oxygen utilization rate of 6.8 ml $O_2/m^3/h$, based on measured decreases in organic carbon over a 2-month period in conjunction with a red tide in the highly eutrophic waters of Tokyo Bay.

## ANAEROBIC METABOLISM

Our method for measuring aerobic respiration rates via oxygen changes could not be used in the anoxic subpycnocline water. However, we did observe high concentrations of sulfide in the subpycnocline waters of the anoxic area, indicating that anaerobic metabolism must have occurred.

Estimates of anaerobic metabolism may be made using Richards' model (1965) relating organic carbon, anaerobically decomposed, to the phosphate liberated. In figure 10–11, soluble reactive phosphate concentrations are plotted against oxygen concentrations for all samples collected during our cruise except those samples near the estuary (stations 45, 69, 101, 102, 109) and above the pycnocline at stations 41 and 34. The high concentrations of phosphate plotted along the ordinate (1.35–3.6 μM-P/l) were measured in near-bottom anoxic water having high sulfide concentrations (figs. 10–3B and 10–5; stations 213, 217). Excluding points representing less than 0.1 ml $O_2/l$, the correlation coefficient between oxygen and phosphate is $-0.85$ ($n=83$). The functional regression line (Ricker 1973), drawn in figure 10–11, intercepts the y-axis at a phosphate concentration of 1.03 μM/l. This value provides an estimate of the phosphate concentration immediately before anoxia.

Examining stations 213 and 217 (the low D.O. area), we estimate that 9,175 and 7,785 $\mu M\text{-}P/m^2$, respectively, were more than the expected concentration of phosphate (1 μM/l) in the 6-m and 15-m subpycnocline water, respectively, at the start of oxygen depletion. Multiplying the phosphate values by an atomic ratio of 106C:1P yields an estimated 12 and 10 g of organic carbon needed to account for the excess phosphate mineralized. The elapsed time between our visit to station 213 and the first reports of oxygen depletion in the vicinity of 213 was about 45 days. The estimated hourly rates of anaerobic metabolism of carbon for station 213 and 217 are 1.8 mg $C/m^3/h$ and 0.6 mg $C/m^3/h$. These estimates are slightly lower than the measured aerobic rates of water column carbon mineralization for subpycnocline water at stations adjacent to the low D.O. area (2–4 mg $C/m^3h$) and are conservative, because some proportion of the inorganic phosphate formed diffused upward through the pycnocline.

Bacterial densities and biomass were greater in oxygen-depleted areas than in adjacent regions (fig. 10–10, table 10–3). Different cell morphology and larger bacteria below the pycnocline in the anoxic area (fig. 10–12) suggest that different bacterial species or populations with different functional capabilities and responses developed there. The greater density of bacteria below the pycnocline in and surrounding the anoxic area (fig. 10–10) suggests an additional nutritive source, oxidizable organic carbon, present as DOC and POC. Bacterial biomass in the bottom water of the low D.O. area in 1976 (table 10–3) was about twice the value reported by Barvenik et al. (1976) for spring 1974 and 1975 (48 mg $C/m^3$). POC and DOC substrates were comparable in both areas. We might expect aerobic-anaerobic mineralization rates also to be comparable.

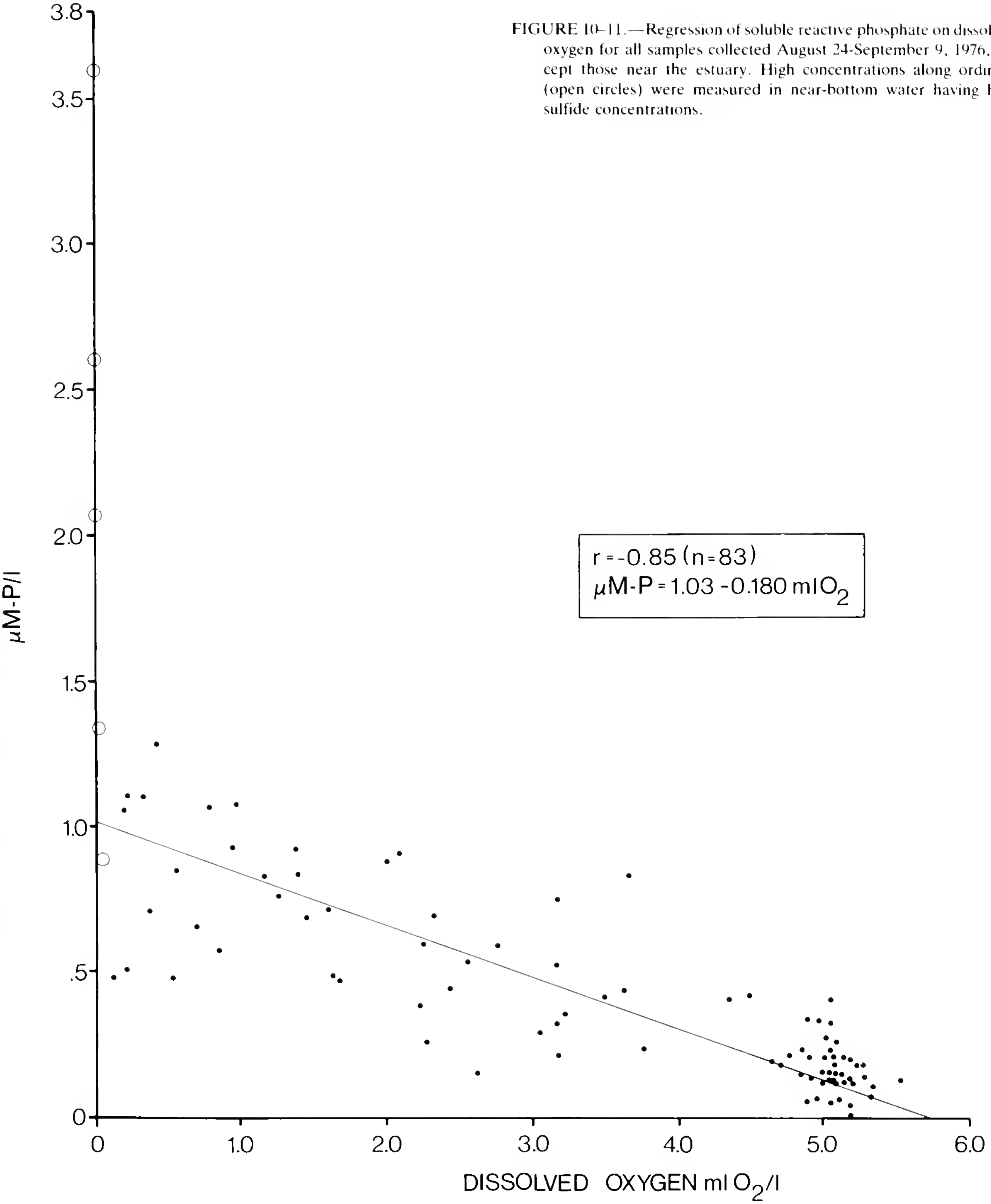


FIGURE 10-11.—Regression of soluble reactive phosphate on dissolved oxygen for all samples collected August 24-September 9, 1976, except those near the estuary. High concentrations along ordinate (open circles) were measured in near-bottom water having high sulfide concentrations.

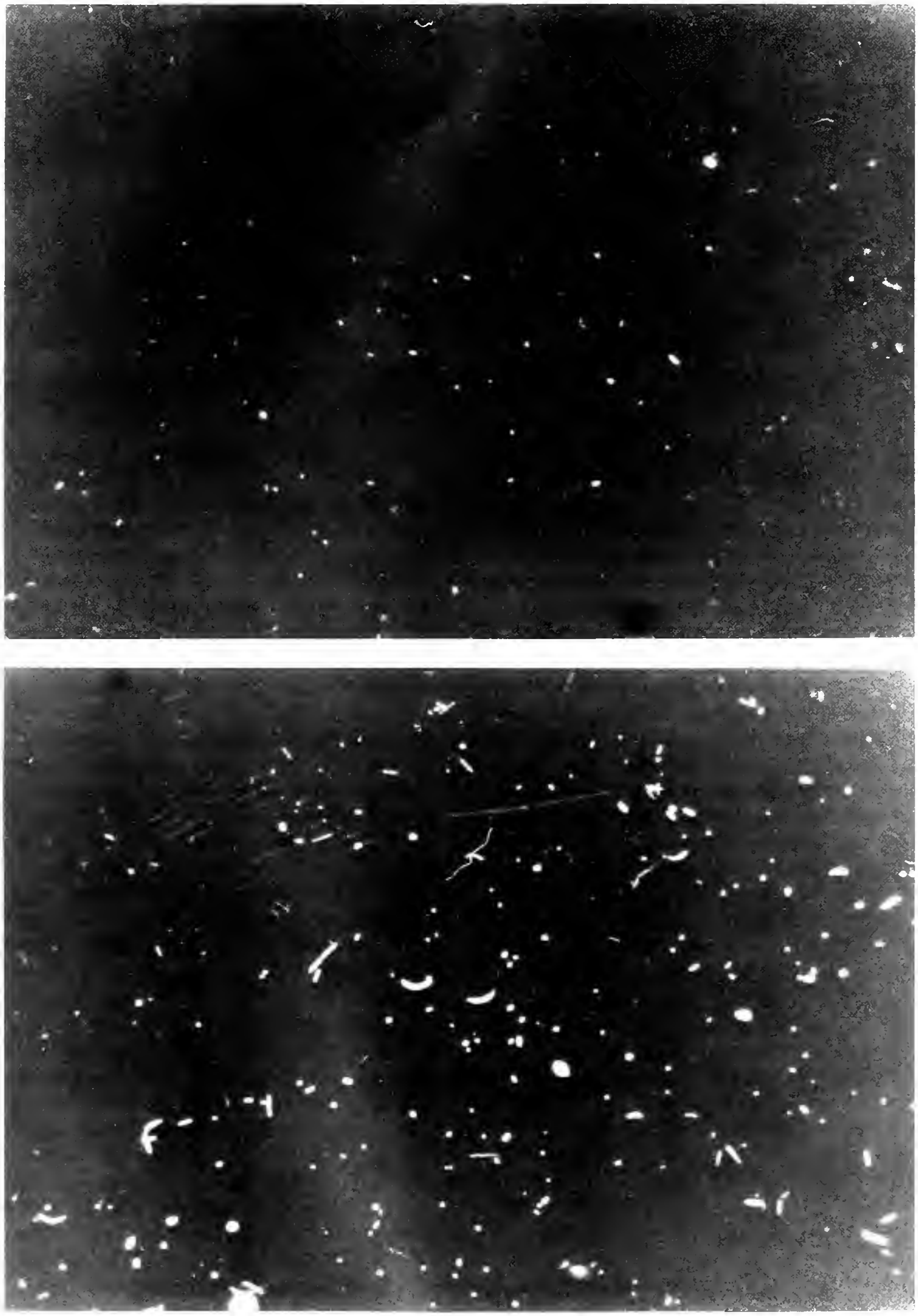


FIGURE 10-12.—Photograph of surface water bacteria (top) and bottom water bacteria (bottom) at station 213, September 4, 1976. Magnification and volume considered for each photograph are identical.

TABLE 10-3.—*Bacterial carbon measurements at station 213 (anoxic area) and station 219 (control area)*

| Station | Depth | Bacteria measured | Mean cell volume | Bacterial cell density | Bacterial carbon[1] |
|---|---|---|---|---|---|
| | | Number | $\mu m^3$ | × $10^6$/ml | mg C/$m^3$ |
| 213 | surface | 196 | 0.1183 | 1.68 | 17.3 |
| 213 | bottom | 307 | 0.1755 | 5.93 | 90.6 |
| 219 | bottom | 80 | 0.1221 | 1.60 | 17.0 |
| 219 | surface | a | a | 1.68 | a |

[1] Bacterial carbon was estimated by multiplying mean cell volume by the number of bacterial cells per sample, and assuming a density of 1.1 g C/$m^3$, a dry to wet weight ratio of 0.23 and a carbon to dry weight ratio of 0.344 (Ferguson and Rublee 1976).

a, Not done.

## PROBABLE ORGANIC CARBON SOURCES

Let us consider that the organic carbon contained in *Ceratium tripos* has already undergone aerobic decay at the time of anoxia (0 ml $O_2$/1). If the assumptions in the model by Malone et al. (ch 9, pt. 1) are correct, the *C. tripos* biomass consumed 71 percent of the oxygen lost below the pycnocline. In the temporally and spatially averaged scenario presented here, *C. tripos* carbon does not account for the excesses of phosphate that we believe originate anaerobically.

The logical sources of organic carbon that could provide the organic material necessary to generate observed phosphate concentrations are primary production, the DOC pool, and decaying benthic macrofauna. Decaying benthic macrofaunal biomass could have provided a significant proportion of the organic carbon anaerobically decomposed. An estimated benthic macrofaunal biomass off Atlantic City near our stations 213 and 217 ranges from 25 to 100 g wet weight/$m^2$ (Wigley and Theroux 1976). A second estimate for this area is 67 g wet weight/$m^2$ of mollusca, annelida, echinodermata, and crustacea (Boesch et al. 1977). A third estimate, based on the major molluscan biomass components (surf clam and ocean quahog), censused between 18.6 and 36.6 m off the New Jersey coast (April 1976) was 75 g shellfish meat/$m^2$ (Chang et al. 1976; Chang, personal communication).

Most of the demersal finfish apparently avoided the low D.O. area (ch. 13) and consequently did not materially add to the carbon pool, which decomposed anaerobically. For discussion, we will use the upper value of 100 g wet weight/$m^2$ to represent the potential contribution by the benthos. This does not include the benthic meiofaunal biomass. However, using the upper value of 100 g wet weight/$m^2$ may amend this oversimplification. An estimate of total macrofaunal biomass of 5.5 g C/$m^2$ results from a conversion factor of 500 cal/g wet weight (F. W. Steimle, NMFS Sandy Hook Laboratory, personal communication), which applies to the surf clam and other affected dominant benthic species and an oxi-caloric equivalent of 4.9 cal/ml $O_2$ (Odum 1971) and an RQ of 1. If all this biomass were actually killed and anaerobically decomposed, it would represent 47 and 56 percent of the organic carbon anaerobically mineralized at stations 213 and 217, respectively.

Atwood et al. (ch. 4) suggest that concentrations of DOC in excess of expected "normal" oceanic values (0.8 mg. C/1) may represent biologically labile carbon and a potential BOD load. If DOC in subpycnocline-low D.O. water was the sole resource of carbon mineralized anaerobically to account for the observed phosphate concentrations, then DOC at the beginning of our 45-day interval might have been double the concentrations observed below the pycnocline during our cruise (1.6 mg C/1). Subpycnocline DOC concentrations at station 213 are about half those above the pycnocline. This hypothesis is difficult to evaluate in the absence of DOC data before our cruise and poor quantitative understanding of the dynamic interactions between phytoplankton and bacteria and the DOC and POC pools in the New York Bight.

In situ primary production can potentially supply to subpycnocline waters the quantity of organic carbon needed over the 45-day period. The photosynthesized carbon actually available is the portion remaining after water column aerobic carbon mineralization is subtracted from the rates of carbon photosynthesis. Total primary productivity and total water column respiration appear to be related, but offset in time. A large portion of the daily nutrient requirement of phytoplankton can be satisfied directly through upper water column respiration and mineralization of organic matter. Measured rates of daily integral total primary productivity in the oxygen-depleted area and vicinity were about 1 g C/$m^2$/d (fig. 10-8). About 0.22 g C/$m^2$/d would have to be supplied to the subpycnocline waters, which is about 22 percent of the daily photoassimilated carbon. A production/respiration (P/R) ratio over the water column of 1.28 (assuming primary productivity = 1 g C/$m^2$/d) would be required over the 45-day period to account for the observed phosphate concentrations. We observed P/R ratios between 0.5 and 2.0 (including esti-

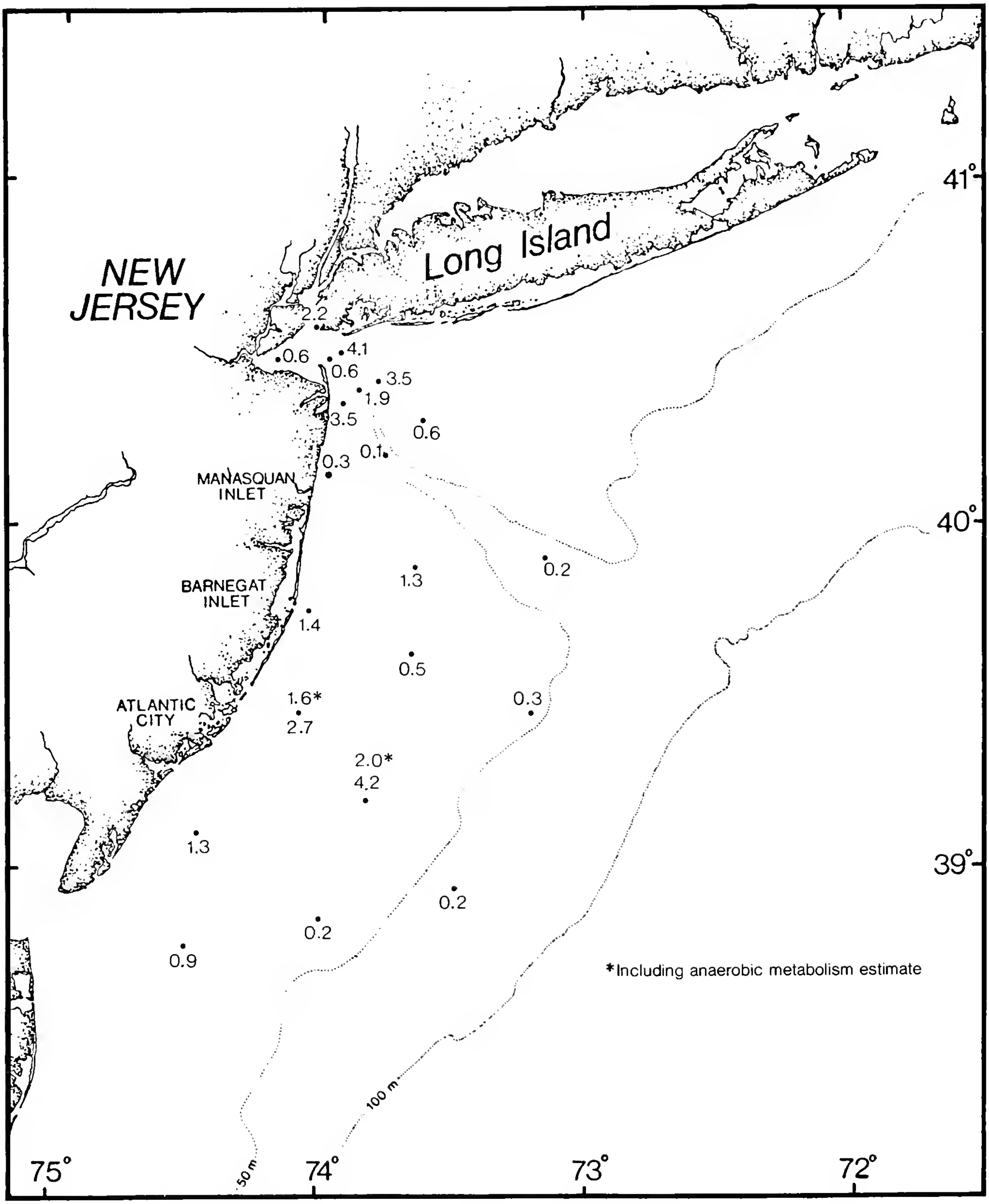


FIGURE 10-13.—Production/respiration ratio for water column exclusive of seabed, August 24-September 9, 1976. Production is the daily total (SIS) using $^{14}$C method. Respiration is the daily total plankton respiration using oxygen method (assumed RQ = 1).

mate of anaerobic metabolism) in the vicinity of the oxygen-depleted area (fig. 10–13). On the average, the seabed consumed an amount of carbon equivalent to about 20 percent of the carbon photoassimilated throughout the water column per day. The seabed and water below the pycnocline together consumed a quantity of carbon equivalent to 57 percent of the carbon photosynthesized each day. This suggests that large fluxes of oxidizable organic carbon must have been supplied to subpycnocline waters daily. In fact, at stations in and adjacent to the oxygen-depleted area (photosynthetic capacity profile fig. 10–9A, stations 200 and 213) large increases in both netplankton and nannoplankton and in POC were observed in the pycnocline and below where PAR intensity was low. The assimilation numbers (productivity per unit biomass-chlorophyll *a*) for the pycnocline and subpycnocline phytoplankton were low (fig. 10–7), and, in general, respiration greatly exceeded photosynthesis (table 10–2).

## EXPANDED APEX HYPOTHESIS

Production (P) and respiration (R) ultimately balance one another since stoichiometrically the oxygen produced during photosynthesis should balance the oxygen consumed during respiration and mineralization of the newly photosynthesized carbon. However, very often production and respiration are uncoupled over time and space (both vertically and horizontally). For instance we know that P/R ratios are much greater than 1 during the spring bloom, while following the bloom they are much less than 1. Our data (table 10-2) demonstrate the vertical uncoupling of photosynthesis and mineralization where P/R ratios above the pycnocline are considerably greater than 1 while those below are considerably less than 1. The large quantities of decaying organic carbon in *Ceratium tripos* transported to the subpycnocline waters of the New York Bight during 1976 further exacerbated the uncoupling of production and consumption activities above and below the pycnocline, respectively. Horizontally, additional organic carbon as sewage discharged to the Apex represents a BOD load, (i.e., not a source of photosynthetic oxygen) and will support more respiration. Because of temporal and spatial partitioning of organic carbon and oxygen sources as described above, we believe that the eutrophic effects of riverborne, sewage-derived nutrients (including organic components) may actually occur over a larger area than the estimated affected area, based on the stimulatory effects of inorganic nutrients alone (*sans* nutrient regeneration) on primary production (Garside et al. 1976).

Water column mineralization probably supplies the major portion of nitrogen-nutrients required by assimilating phytoplankton in the New York Bight. Garside et al. (1976) indicated that during the summer 120 t of dissolved inorganic nitrogen (ammonium, nitrate, nitrite) are discharged into the Bight Apex. These authors estimated that the sewage-derived nitrogen (inorganic) would be assimilated by phytoplankton in a 257 km$^2$ area of the Apex during summer. If we consider the large quantities of daily and annual primary productivity measured in the lower Hudson-Raritan estuary—6 to 8 g C/m$^2$/d at summer maximum, 750 to 1053 g C/m$^2$/yr (O'Reilly et al. 1976)—and the high concentration of phytoplankton biomass transported out of the estuary into the Apex (Duedall et al. 1976; Parker et al. 1976) then much more nitrogen as organic N will be transported from the estuary into the Bight during summer. Furthermore, the dissolved organic nitrogen (DON) contributed by sewage effluent could double the estimate of nitrogen loading based solely on ammonium, nitrate, and nitrite.

Mueller et al. (1976) estimated that (average) 209 t of inorganic nitrogen (ammonium + nitrate + nitrite) and 130 t of organic nitrogen are transported into the Apex each day. Subtracting the Mueller et al. (1976) estimates of barged nitrogen via dredge materials (because the barged material might be expected to be derived from wastewater and gauged and nongauged runoff already counted in riverborne output) results in 172 t N/d of dissolved inorganic nitrogen (DIN) and 104 t N/d of DON transported to the Apex. Ultimately, barged nitrogen is also added to the Apex but not as part of the river flow. This estimate of DIN is slightly greater than the Garside et al. (1976) estimate of total DIN (160 t N/d before estuarine phytoplankton uptake is subtracted).

Few measurements of the relative proportions of DIN to DON are available for marine waters receiving sewage effluent. The data presented by Epply et al. (1972), collected near coastal sewage outfalls off California indicate that the average water column concentrations of nitrate plus ammonium are 1.2 times (by atomic weight) the concentration of DON. Using the Mueller et al. data above, the ratio of DIN to DON in estuarine effluent is 1.7:1. At the time of our cruise, we measured an average of 33.2 μM/l of DIN for the entire water column under the Verrazano Bridge at station 69. The average water column concentration of DOC was 4 mg C/l. If we assume an atomic composition ratio of 106C:16N, then this represents 50.3 μM/l of DON, or a DIN/DON ratio of 0.7:1. The area actually stimulated by human nitrogen loading could be double the previous estimates (Garside et al. 1976) if the DON pool is biologically labile and not refractory to heterotrophic bacteria in the water column. Litchfield et al. (in press) show that substantial heterotrophic activity and mineralization of organic nitrogen compounds do occur with the sediment bacteria in New York Bight. This activity also extends upward into the water column as well (C. D. Litchfield, personal communication).

Both Ryther and Dunstan (1971) and Garside et al.

(1976) reported that inorganic nitrogen drops to very low levels between 20 and 50 km from New York Harbor. However, Garside et al. (1976) indicated that inorganic nitrogen probably does not limit chlorophyll-specific growth rates of phytoplankton within the Bight Apex. Therefore, the effect of additional large inputs of DON would be to enlarge the area of high phytoplankton productivity and biomass.

During our survey, eutrophic concentrations of DIN decreased from 33 μM/l in Lower Bay to just above detection at the outer perimeter of the Apex (50 km from station 69). This means that by the Apex and beyond most of the nitrogen in the water column is bound organically, as autotrophic and heterotrophic biomass and as DON. Despite the low euphotic DIN concentrations between 50 and 200 km from Lower Bay, we observed high rates of organic carbon production. Although average chlorophyll-*a* and POC concentrations decreased considerably (15:1, 8:1) from the estuary to the 50-m isobath, integral euphotic zone concentrations (per square meter) of chlorophyll *a* and DOC decreased only slightly (table 10–1). The total water column P/R ratios (fig. 10–13) decreased from 3.5 in the Apex to 1.3 off Barnegat Inlet to 0.2 to 0.9 east of there and south offshore to Cape May. Thus active regeneration of nutrients and recycling of carbon had to occur to sustain the system as described above.

Organic loading from the New York metropolitan area during 1976 was superimposed on and may have aggravated natural conditions leading to oxygen depletion (Segar and Berberian 1976). Future research should evaluate the stimulation of both production and decomposition processes in the water column and on the seabed by DIN and DON compounds in sewage wastes. One hypothesis to evaluate is that the initial effects of sewage-derived inorganic nitrogen is the stimulation of autotrophy in the Bight Apex. The "unused" Apex DON compounds plus the organic compounds photosynthesized in the Apex stimulate heterotrophy. However, the full effect of this heterotrophic stimulation (P/R<<1, and reduced oxygen concentrations) is delayed in time and occurs down the plume of the estuary, seaward of the Apex along the New Jersey coast.

## SUMMARY

Between August 24 and September 9, 1976, about 2 months after the onset of oxygen depletion, data concerning primary production, water-column and seabed oxygen consumption, nutrients, organic carbon, phytoplankton identification and abundance, chlorophyll *a*, and bacteria were collected to document conditions. Our findings follow.

1. A strong, deep (12–20 m) pycnocline was present.
2. A subpycnocline low D.O. area with sulfide existed.
3. Nutrients generally were low above the pycnocline and were plentiful below except for nitrate and nitrite.
4. Nutrient regeneration supplied most of the nutrients required by phytoplankton, but the estuary appeared to be the major nutrient source for the Apex while in-situ nutrient regeneration appeared to be the major source for primary production offshore.
5. In the oxygen-depleted area the subpycnocline water had high concentrations of sulfide, ammonium, silicate, and phosphate. The highest concentrations were associated with the pycnocline and not with the seabed.
6. Based on sulfide to phosphorus ratios measured in other anoxic systems, apparently more sulfide was produced than was measured. The presence of sulfide suggests very active anaerobic metabolism during the oxygen depletion episode.
7. DOC concentrations were unusually high throughout the region, relative to other coastal/shelf areas.
8. Highest DOC concentrations were in the middle and outer Apex.
9. DOC was the largest organic carbon pool in New York Bight—3 to 25 times more abundant than the POC present.
10. DOC concentrations appeared to counteract seaward dilution when compared to other forms of organic carbon. This suggested that significant additions to the DOC pool took place.
11. Beyond the Apex, adjacent to the New Jersey coast, and in the oxygen-depleted area, large increases in chlorophyll-*a* and POC concentrations were observed in the pycnocline and directly above the seabed, suggesting organic loading to the subpycnocline layer.
12. Most chlorophyll *a* was attributable to nannoplankton (<20 μm).
13. The most abundant phytoplankton species present was a small (1.5–3m), spherical, unicellular green form, probably *Nannochloris atomus*.
14. Chain-forming diatom species dominated pycnocline and near-bottom waters; flagellated (motile) species dominated surface waters.
15. No *Ceratium tripos*, a large dinoflagellate, were observed in samples during the August-September 1976 cruise.
16. Integral daily rates of total phytoplankton primary productivity were high. Daily productivity exceeded 1 g C/m$^2$/d at 11 of 21 stations surveyed and exceeded 3 g C/m$^2$/d at 5 of the stations. At many stations phytoplankton growth rates exceeded two divisions per day.
17. Comparison of our August-September 1976 and June 1977 data for the same area shows that total primary productivity was about the same both years for the entire area studied, but was slightly higher in June 1977 than in August-September 1976 for the oxygen-depleted area.

18. At stations outside the Apex, adjacent to the New Jersey coast and in the oxygen-depleted area, the euphotic layer occupied the entire water column. At these stations the typical vertical profile, with the highest productivity at or near the surface, was not seen. Instead, the simulated in-situ and photosynthetic capacity primary productivity of these stations was maximal below the pycnocline.

19. Phytoplankton above the pycnocline appeared healthy, based on high productivity, high assimilation numbers, and high photosynthetic efficiencies.

20. Phytoplankton below the pycnocline appeared less healthy, based on low chlorophyll/phaeopigment ratios, low assimilation numbers, and low photosynthetic efficiencies.

21. The percent of photoassimilated carbon released as dissolved organic matter from phytoplankton was 7 to 34 percent and was highest where total primary productivity and DOC were highest, suggesting that phytoplankton release of dissolved extracellular products may be contributing significantly to the total DOC pool.

22. Total plankton respiration rates generally were high, up to 25 ml $O_2/m^3/h$ or on an integral basis 5.9 g $C/m^2/d$ assuming an RQ of 1.

23. Total plankton respiration rates generally were highest at or near the surface and decreased with depth except on the periphery of the oxygen-depleted area where rates were highest at or below the pycnocline.

24. In the oxygen-depleted area, total plankton respiration rates above the pycnocline were low, 2 to 5 ml $O_2/m^3/h$, or on an integral basis 0.2-0.3 g $C/m^2/d$, assuming an RQ of 1. No measureable aerobic metabolism occurred below the pycnocline.

25. During June 1977, a "normal" summer, total plankton respiration rates measured were equivalent to about 2 g $C/m^2/d$ oxidized and were several times higher than the rates measured in the oxygen-depleted area during August-September 1976.

26. Aerobic measurements of seabed oxygen consumption could not be made under in situ oxygen conditions in the oxygen-depleted area. However, within and immediately surrounding the oxygen-depleted area, high rates of oxygen uptake (up to 37 ml $O_2/m^2/h$) were measured, suggesting that additional organic loading of the seabed occurred in the vicinity of the oxygen-depleted area during 1976.

27. Rates of seabed oxygen consumption appeared to be higher around the periphery of the oxygen-depleted area during August-September 1976 than during June 1977. Rates of seabed oxygen consumption during June 1977 in the area of former oxygen depletion were comparable to rates measured in surrounding areas. Away from the oxygen-depleted area no differences among the summers of 1975, 1976, and 1977 were readily apparent.

28. The contribution of the seabed to total oxygen consumption rates (water column plus seabed) was unusually high (>10%) around the periphery of the oxygen-deleted area, further supporting the idea that additional organic loading to the seabed took place during 1976.

29. The relatively greater contribution of the seabed to total (water plus seabed) oxygen uptake on the periphery of the oxygen-depleted area in 1976 was due to the combination of higher rates of seabed oxygen consumption and relatively lower rates of total plankton respiration compared with June 1977.

30. Our measurements of an average oxygen consumption rate below the pycnocline (includes bottom 9.4 m of water plus seabed) was 3.7 ml $O_2/m^3/h$. This measurement appears to support the net oxygen utilization rate estimate of 4.0 ml $O_2/m^3/h$ derived by Han et al. (ch. 8) for May-June 1976.

31. Estimated rates of anaerobic metabolism for the subpycnocline waters of the oxygen-depleted area were based on observed phosphate concentrations and found to be slightly lower than aerobic rates of water column carbon mineralization for the subpycnocline water at stations adjacent to the oxygen-depleted area.

32. The large increase in bacterial numbers and biomass and different morphology of bacteria in the subpycnocline waters of the oxygen-depleted area suggest the presence of additional labile organic material and its probable anaerobic decomposition.

33. The logical sources of organic carbon, which could provide the organic material necessary to account for the estimated anaerobic metabolism and for the maintenance of low D.O., include decaying benthic macrofaunal biomass, DOC, and primary productivity. Decaying benthic macrofauna can account for only about 50 percent of the estimated anaerobic metabolism. The DOC pool is difficult to evaluate because of scarcity of information and lack of understanding of the dynamic interactions among bacteria, DOC and POC pools, and phytoplankton. Primary production appears to be the most likely major supply of labile organic carbon, based on observed productivity to respiration ratios.

34. Primary productivity and respiration were uncoupled both vertically and horizontally as evidenced by P/R ratios above and below the pycnocline and over the New Jersey shelf.

35. Based on measurements of DIN and DOC for the entire water column in the Verrazano Narrows a DIN/DON ratio of 0.7:1 was estimated (assumed atomic composition ratio of 106C:16N). Thus the area actually stimulated by human nitrogen loading could be double previous estimates which considered only DIN.

36. Wastes (including inorganic and organic nitrogen) from the New York metropolitan area are normally superimposed upon the natural organic loading of the New York Bight. These compounds may affect the system well be-

yond the Apex by aggravating imbalances both in time and space between organic production and decomposition.

37. One hypothesis to evaluate is that the initial effects of sewage-derived inorganic nitrogen is the stimulation of autotrophy in the Bight Apex. The "unused" Apex DON compounds plus the organic compounds photosynthesized in the Apex stimulate heterotrophy. However, the full effect of this heterotrophic stimulation (P/R <<1, low D.O.) is delayed in time and occurs down the plume of the estuary, seaward of the Apex along the New Jersey coast.

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## REFERENCES

American Public Health Association, 1975. *Standard Methods for the Examination of Water and Wastewater*, 3d ed., 1193 pp.

Bannister, T. T., 1974. Production equations in terms of chlorophyll concentration, quantum yield and upper limit to production, *Limnol. Oceanogr.* 19(1):1–12.

Barlow, J. P., Lorenzen, C. J., and Myren, R. T., 1963. Eutrophication of a tidal estuary, *Limnol. Oceanogr.* 8(2):251–262.

Barvenik, F. W., Dagg, M. J., Judkins, D. C., Scott, J. T., Tingle, A. G., Walsh, J. J., Whitledge, T. E., and Wrick, C. D., 1976. An analysis of time dependent factors leading to anoxic conditions within the Middle Atlantic Bight during 1976, in J. H. Sharp (ed.), Anoxia on the Middle Atlantic Shelf during the summer of 1976, International Decade of Ocean Exploration/National Science Foundation workshop report.

Boesch, D. F., Kraeuter, J. N., and Serafy, D. K., 1977. Chemical and biological benchmark studies on the Middle Atlantic outer continental shelf, *Benthic Ecological Studies: Megabenthics and Macrobenthics*, vol. II., Draft final report, chapter 6. Virginia Institute of Marine Sciences, Gloucester Pt., Va., pp. 59–62.

Chang, S., Ropes, J. W., and Merrill, A. S., 1976. An evaluation of the surf clam population and fishery in the Middle Atlantic Bight, unpublished manuscript presented at Shellfish Stock Assessment Symposium, ICES, Copenhagen.

Curl, H., Jr., and Small, L. F., 1965. Variations in photosynthetic assimilation ratios in natural marine phytoplankton communities, *Limnol. Oceanogr.* 10 (suppl.):R67–73.

Derenbach, J. P., and Williams, P. J., 1974. Autotrophic and bacterial production: fractionation of plankton populations by differential filtration of samples from the English Channel, *Mar. Biol.* 25:263–269.

Draxler, A. F. J. and Byrne, C. J., in press. Sulfide in the New York Bight during an extended period of anoxia. *Estuar. and Coast. Mar. Sci.*

Duedall, I. W., O'Conners, H. B., Parker, J. H., Wilson, R. W., and Robins, A. S., 1976. The abundances, distribution, and flux of nutrients and chlorophyll *a* in the New York Bight Apex. Final Report to Part I, MESA NOAA, Stony Brook, N.Y.

Eppley, R. W., 1968. An incubation method for estimating the carbon content of phytoplankton in natural samples, *Limnol. Oceanogr.* 13(4):574–582.

Eppley, R. W., Carlucci, A. F., Holm-Hansen, O., Kiefer, D., McCarthy, J. J., and Williams, P. M., 1972. Evidence for eutrophication in the sea near southern California coastal sewage outfalls, July 1970, Calif. Mar. Res. Comm., *Cal COFI Rept.* 16:74–83.

Ferguson, R. L., and Rublee, P., 1976. Contribution of bacteria to standing crop of coastal plankton, *Limnol. Oceanogr.* 21:141–145.

Garside, C., Malone, T. C., Roels, O. A., and Sharfstein, B. A., 1976. An evaluation of sewage-derived nutrients and their influence on the Hudson Estuary and New York Bight, *Estuar. Coastal Mar. Sci.* 4:281–289.

Hazelworth, J. B., Kolitz, B. L., Starr, R. B., Charnell, R. L., and Berberian, G. A., 1974. New York Bight Project, water column sampling cruises #1–5 of NOAA ship *Ferrel* August-November 1973, *MESA Rep.* No. 74–2, 191 pp.

Hobbie, J. E., Daley, R. J., and Jasper, S., 1977. Use of nuclepore filters for counting bacteria by fluorescence microscopy, *Appl. Environ. Microbiol.* 33:1225–1228.

Iturriaga, R., and Hoppe, H. G., 1977. Observations of heterotrophic activity on photoassimilated organic matter, *Mar. Biol.* 40:101–108.

Kroner, R. C., Longbottom, J. E., and Gorman, R., 1964. A comparison of various reagents proposed for use in the Winkler procedure for dissolved oxygen, PHS Water Pollut. Surveillance System Appl. Develop. Rep. 12, Public Health Service, HEW, 18 p.

Litchfield, C. D., Devanas, M. W., and Zindulus, J., in press. Impact of a *Ceratium* bloom on microbial biomass and activities in sediments of the New York Bight, Submitted to *Limnol. Oceanogr.* Also NOAA/MESA New York Bight Annual Report 1977.

Malone, T. C., 1976. Phytoplankton productivity in the Apex of the New York Bight: Environmental regulation of productivity/chlorophyll *a*, *Amer. Soc. Limnol. Oceanogr. Spec. Symp.* 2:260–272.

Malone, T. C., 1978. The 1976 *Ceratium tripos* bloom in the New York Bight: Causes and consequences, *NOAA Tech. Rep.* NMFS Circ. 410, National Marine Fisheries Service, 14 pp.

Mandelli, E. F., Burkholder, P. R., Doheny, T. E., Brody, R., 1970. Studies of primary productivity in coastal waters of southern Long Island, New York, *Mar. Biol.* 7:153–160.

Menzel, D. W., and Vaccoro, F. R., 1964. The measurement of dissolved organic and particulate carbon in seawater, *Limnol. Oceanogr.* 9:138–142.

Mueller, J. A., Jeris, J. S., Anderson, A. R., and Hughes, C. F., 1976. Contaminant inputs to the New York Bight, *NOAA Tech. Mem.* ERL MESA-6, Marine Ecosystems Analysis Program, Environmental Research Laboratories, Boulder, Colo., 347 pp.

National Marine Fisheries Service, 1977. Oxygen depletion and associated environmental disturbances in the Middle Atlantic Bight in 1976, *Northeast Fisheries Center Tech. Ser. Rep.* No. 3, Sandy Hook Laboratory, Highlands, N.J., 471 pp.

Odum, E. P., 1971. *Fundamentals of Ecology*, 3d ed., W. B. Saunders Co., Philadelphia, Pa.

O'Reilly, J. E. and Thomas, J. P., in press. A manual for the measurement of total daily primary productivity using $^{14}$C simulated in-situ sunlight incubation. *NOAA Tech. Mem.*

O'Reilly, J. E., Thomas, J. P., and Evans, C. E., 1976. Annual primary production (nannoplankton, netplankton, dissolved organic matter) in the Lower New York Bay, in W. H. McKeon and G. J. Lauer (eds.), Fourth Symposium on Hudson River Ecology, Paper No. 19, Hudson River Environmental Society, Inc., N.Y., 39 pp.

Pamatmat, M. M., 1971. Oxygen consumption by the seabed, 4. Shipboard and laboratory experiments, *Limnol. Oceanogr.* 16:536–550.

Pamatmat, M. M., 1973. Benthic community metabolism on the continental terrace and in deep sea in the North Pacific, *Int. Rev. Gesamten Hydrobiol* 58:345–368.

Parker, J. H., Duedall, I. W., O'Connors, H. B., Jr., and Wilson, R. E., 1976. Raritan Bay as a source of ammonium and chlorophyll *a* for the New York Bight Apex, *Amer. Soc. Limnol. Oceanogr Spec. Symp.* 2:212–219.

Patten, B. 1959. Diversity of species in net phytoplankton of the Raritan estuary, Ph.D. thesis, Rutgers University, New Brunswick, N.Y. 111 pp.

Platt, T., 1971. The annual production by phytoplankton in St. Margaret's Bay, Nova Scotia, *J. Cons. Int. Explor. Mer.* 33(3):324–333.

Pomeroy, L. R., and Johannes, R. E., 1966. Total plankton respiration, *Deep-Sea Res.* 13:971–973.

Richards, F. A., 1965. Anoxic basins and fjords, in J. P. Riley and G. Skirrow (eds.), *Chemical Oceanography*, vol. 1, Academic Press, New York, pp. 611–645.

Richards, F. A., Cline, J. D., Breonkow, W. W., and Atkinson, L. P., 1965. Some consequences of the decomposition of organic matter in Lake Nitinat, an anoxic fjord. *Limnol. Oceanogr.* 10 (suppl.):R185–201.

Ricker, W. E., 1973. Linear regressions in fishery research, *J. Fish. Res. Board Can.* 30:409–434.

Riley, G. A., 1973. Particulate and dissolved organic carbon in the oceans, in G. M. Woodwell and E. V. Pecan (eds.), *Carbon and the Biosphere.* National Technical Information Service, Springfield, Va.

Ryther, J. H., 1954. The ecology of phytoplankton blooms in Moriches Bay and Great South Bay, New York, *Biol. Bull.* 106:198–209.

Ryther, J. H., and Dunstan, W. M., 1971. Nitrogen, phosphorus, and eutrophication in the coastal marine environment, *Science* 171:1008–1013.

Ryther, J. H., and Yentsch, C. S., 1958. Primary production of continental shelf waters off New York, *Limnol. Oceanogr.* 3:227–235.

Segar, D. A., and Berberian, G. A., 1976. Oxygen depletion in the New York Bight Apex: causes and consequences, *Amer. Soc. Limnol. Oceanogr. Spec. Symp.* 2:220–239.

Sharp, J. H., 1973. Total carbon in seawater, comparison of measurements using persulfate oxidation and high temperature combustion, *Mar. Chem.* 1:211–229.

Sirois, D. L., 1974. Community metabolism and water quality in the lower Hudson River Estuary, in G. P. Howells and G. J. Lauer (eds.), Third Symposium on Hudson River Ecology, Paper No. 15, Hudson River Environmental Society, Inc., New York, N.Y.

Smith, K. L., and Teal, J. M., 1973. Deep-sea benthic community respiration: an in situ study at 1850 meters, *Science* 179:282–283.

Strickland, J. D. H., and Parsons, T. R., 1972. A practical handbook of seawater analysis, *Bull. Fish. Res. Board Can.* 167, 311 pp.

Taguchi, S., 1976. Relationship between photosynthesis and cell size of Marine diatoms, *J. Phycology* 12(2):185–189.

Thomas, J. P., O'Reilly, J. E., Draxler, A., Babinchak, J. A., Robertson, C. N., Phoel, W. C., Waldhauer, R., Evans, C. A., Matte, A., Cohn, M., Nitkowksi, M., and Dudley, S., in press. Biological processes (primary productivity and water column and seabed respiration) during the anoxic episode in the New York Bight, *NOAA Tech. Mem.* ERL MESA.

Thomas, J. P., Phoel, W. C., O'Reilly, J. E., and Evans, C. A., 1976a. Seabed oxygen consumption in the lower Hudson Estuary, in H. McKeon and G. J. Lauer (eds.), Fourth Symposium on Hudson River Ecology, Paper No. 12. Hudson River Environmental Society, Inc., New York.

Thomas, J. P., Phoel, W. C., Steimle, F. W., O'Reilly, J. E., and Evans, C. A., 1976b. Seabed oxygen consumption in the New York Bight Apex, *Amer. Soc. Limnol. Oceanogr. Spec. Symp.* 2:354–369.

Tsuji, T., Seki, H., and Hattori, A., 1974. Results of red tide formation in Tokyo Bay, *J. Water Pollut. Control Fed.* 46(1):165–172.

U.S. Environmental Protection Agency, 1974. Methods for chemical analysis of water and wastes, Methods Development Quality Assurance Res. Lab. NERC EPA-625/6–74/003.

Wigley, R. L., and Theroux, R. B., 1976. Macrobenthic composition invertebrate fauna of the Middle Atlantic Bight. Part II. Faunal composition and quantitative distribution, Northeast Fisheries Center, National Oceanic and Atmospheric Administration, U.S. Department of Commerce.

Williams, P. J. L., and Yentsch, C. S., 1976. An examination of photosynthetic production, excretion of photosynthetic products, and heterotrophic utilization of dissolved organic compounds with reference to results from a coastal subtropical sea, *Mar. Biol.* 35:31–40.

## Oxygen Depletion and Associated Benthic Mortalities in New York Bight, 1976

# Chapter 11. Impact on Clams and Scallops

## Part 1. Field Survey Assessments

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## INTRODUCTION

The large mass of bottom water—deficient in oxygen, and containing above normal quantities of hydrogen sulfide—caused stress and mortalities in bivalve mollusks off the New Jersey coast beginning in June and July 1976. Reports of surf clams (*Spisula solidissima*) showing stress reactions and mortalities were received from divers, otter trawl fishermen, and clammers in early July. From July through September, commercial fishing vessels from Massachusetts and New Jersey ports reported catches of dead and dying sea scallops (*Placopecten magellanicus*) off New Jersey. In early August, dead and dying ocean quahogs (*Arctica islandica*) were found off New Jersey. The general distribution of surf clams and ocean quahogs in the Bight were reported by Merrill and Ropes (1976); sea scallops were reported by Merrill (1962).

During August through early October, NOAA's National Marine Fisheries Service (NMFS) used commercial hydraulic dredges to survey surf clams in and beyond the area of suspected oxygen deficiency. The surveys assessed the effects of the adverse environmental conditions on the surf clam resource, and observed mortalities of other invertebrates and bivalves, including the commercially important ocean quahog and sea scallop, although the full range of the latter two was not covered. Assessment surveys on sea scallops were made in October and November.

This chapter summarizes the observations and data gathered during the oxygen depletion event. Detailed data from specific survey cruises are included in a workshop publication (Northeast Fisheries Center 1977b). Clam asessment surveys in April-May 1976 and January-March 1977 provided data on clam stock sizes before and after the event and made it possible to estimate the stock loss (Northeast Fisheries Center 1976a, 1977a).

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## METHODS

Commercial hydraulic dredges, scallop dredges, and otter trawls were used to sample the bivalves. Table 11.1–1 lists the dates, vessels, affiliations, and types of gear used to collect the clams and scallops.

Stress in and deaths of bivalves could be recognized visually. Divers saw clams lying on the bottom, and scallops gaping. Gaped bivalves were also collected in dredges and trawls. The gaped bivalves were extremely lethargic.

The bivalves killed by the oxygen depletion event could be easily recognized. Some had meats attached to their valves. With most, however, only paired valves remained. The outer surfaces were at least partially blackened, and the inner surfaces were white and did not contain fouling organisms. A few of the collected bivalves had died before the event. Surf clams and sea scallops did not have blackened valves and most contained fouling organisms. Ocean quahogs had a brown scum on the inner surface of their valves.

The catch and percentage of live and dead clams or scallops (mortality ratios) were recorded by dredge tow and by specific depth ranges and plotted on charts. The bottom area sampled by the dredge during one tow was divided into the total area being sampled to obtain the total number of sampling units. The number of clams or scallops in the total area then was estimated by multiplying the mean catch per tow by the number of sampling units. For determining clam biomass, estimates of total clam numbers were converted to meat weights; only total numbers of scallops in each area were compared.

## EARLY REPORTS AND INTERVIEWS

The first signs of stress and mortality of surf clams were reported by scuba divers in New Jersey on July 4, 1976. One diver saw surf clams lying on the bottom off Manasquan Inlet. Twenty days later (July 24, 1976), another scuba diver saw 1 live clam and 24 dead ones lying on the bottom 6 km northeast of Absecon Inlet. The observations of surf clams lying on the bottom were unusual, because the clam is normally embedded (Ropes and Merrill 1973).

Otter trawl vessels working off New Jersey provided observations on stress and mortality of clams and scallops. On July 9, 1976, a vessel sampled two sites. Dead clams were found at a site 17 km east of Belmar, but no clams were collected at the second site.

On July 13 and 15, 1976, a vessel reported gaping surf clams in four tows 19 and 28 km east of Ship Bottom, Barnegat Inlet, and Bayhead.

On July 20 and 21, 1976, a vessel sampled two sites 18.5 km east of Bayhead and Barnegat Inlet. Dead surf clams, paired valves, clam meats, and live clams were in the catch. The paired valves of one sea scallop were taken in the sample off Bayhead.

On July 28 and 30, 1976, a vessel sampled three sites east of Manasquan Inlet and Barnegat Inlet. Dead sea scallops were found east of Manasquan Inlet; dead surf clams, paired valves, and gaping live clams were found east of Barnegat Inlet. Separated meats were in the trawl netting.

Samples from surf clam dredges were observed for survival, stress, and death of benthic epifauna and infauna. On July 9, 1976, three locations 4 to 11 km east of Barnegat Inlet were sampled. Gaping clams were collected at one location. On July 28, 1976, a commercial surf clam vessel dredged at four sites from Seaside Park to Barnegat Inlet 5 to 11 km offshore and where the captain had found extensive mortalities a week earlier. Clam mortalities were 10 to 56 percent.

Surf clam fisherman reported clam mortalities from Manasquan Inlet to Ocean City, N.J., during July 12 to August 26, 1976.

## ASSESSMENT SURVEYS

During August 6–17, 1976, observations of stress and mortality in surf clams and sea scallops were provided from otter trawl samples for finfish (Northeast Fisheries Center 1976b). Samples were taken at 97 stations from Sandy Hook, N.J., to off Assateague Island, Md., from nearshore to 117 km offshore at depths of 7 to 66 m. Stressed and dead surf clams were collected at 28 stations off Barnegat Inlet, Little Egg Inlet, and Townsend Inlet about 5 to 60 km from shore at 14 to 38 m. Most surf clams collected were dead (59.9%), although the remaining live clams (40.1%) were obviously lying on the bottom. The meat of one sea scallop was collected 46 km east of Barnegat Inlet at 37 m, and two dead scallops with meats and three paired shells were found 54 km east of Beach Haven Inlet at 35 m.

During September 28 to October 18, 1976, observations of stress and mortality of surf clams, ocean quahogs, and sea scallops were again obtained from otter trawl samples for finfish (Northeast Fisheries Center 1976c). Samples were taken at 179 stations from Martha'a Vineyard, Mass., to Cape Hatteras, N.C., at 16 to 365 m. Of 39 stations off the New Jersey coast, stress and mortality in surf clams and ocean quahogs were recorded at only 4 stations. Stressed sea scallops were found at a station east of Asbury Park at 40 m.

During December 5–21, 1976, stressed and dead surf clams, ocean quahogs, and sea scallops continued to be collected in otter trawl samples for finfish (Northeast Fisheries Center 1976d). Samples were taken at 45 stations off

TABLE 11.1-1—*Dates, vessels, affiliations, and types of gear used to collect clams and scallops before, during, and after the 1976 oxygen depletion event*

| Dates | Vessel | Affiliation | Type of gear |
|---|---|---|---|
| **1975** | | | |
| Aug. 7–16 | *Albatross IV* | NOAA | scallop dredge |
| **1976** | | | |
| Apr. 6-May 13 | *Delaware II* | NOAA | clam dredge |
| July 9 | *Xiphias* | NOAA | otter trawl |
| July 9 | *Richard J. Sullivan* | State of N.J | clam dredge |
| July 13 and 15 | *Grand Larson* | Commercial | otter trawl |
| July 20–21 | *Rorqual* | NOAA | otter trawl |
| July 28 and 30 | *Xiphias* | NOAA | otter trawl |
| July 28 | *Harold F. Snow* | Commercial | clam dredge |
| Aug. 6–8 | *Valerie E.* | Commercial | clam dredge |
| Aug. 6–17 | *Atlantic Twin* | Commercial | otter trawl |
| Sept. 9–11 | *Gail Snow* | Commercial | clam dredge |
| Sept. 13–25 | *Cora May Snow* | Commercial | clam dredge |
| Sept. 28-Oct. 18 | *Albatross IV* | NOAA | otter trawl |
| Oct. 6–15 | *Atlantic Twin* | Commercial | otter trawl |
| Oct. 7–8 | *Margaret & Nancy* | Commercial | clam dredge |
| Nov. 8–17 | *George B. Kelez* | NOAA | scallop dredge |
| Dec. 5–21 | *Delaware II* | NOAA | otter trawl |
| **1977** | | | |
| Jan. 26-Mar. 17 | *Delaware II* | NOAA | clam dredge |

New Jersey. Evidence of mortality in surf clams was recorded at 12 stations, ocean quahogs at 9 stations, and sea scallops at 1 station.

**Surf Clam Mortality**

Mortalities in surf clams had been determined before the anoxic event. During an April 6 to May 13, 1976, resource assessment survey, 217 clam stations were sampled in the Middle Atlantic Bight, and included 82 stations at 11.0 to 85.3 m off New Jersey (Northeast Fisheries Center 1967a). Only 5.0 percent of the clams off New Jersey had recently died.

Surveys in the affected area off New Jersey on August 6–8, September 9–14, and October 7–8, sampled a total of 25, 31, and 11 stations, respectively (Northeast Fisheries Center 1977a). The stations were about 18.5 km apart. The entire area was not surveyed during October, because the weather was inclement.

During the August 6–8, 1976, cruise, mortalities from 4.5 to 34.3 percent were observed at 11 stations. The average mortality value for 25 stations was 7.5 percent, compared with 5.0 percent for the April-May 1976 cruise. Data were separated into three depth ranges: 0–18 m (shallow), 19 to 37 m (middepth), and 38 to 54 m (deep). Middepth stations had the highest mortalities. During the September 9–14, 1976, cruise, the overall mortality for the area surveyed was 53.4 percent. Again mortality was highest at middepths. During the October 7–8, 1976, cruise, the clam mortality for the entire area surveyed was 92.1 percent. At several stations mortality was 100 percent. Mortalities averaged 97.4 and 98.2 percent at the shallow and middepth ranges, respectively. High mortality at the deep stations was observed for the first time, showing that the clam kill had progressed offshore.

**Ocean Quahog Mortality**

In the New Jersey study area, ocean quahogs were sampled only from the shoreward margin of the quahog population; most quahogs are in the outer half of the continental shelf. During the August 6–8 cruise, mortalities were low (0.8%). By the September 9–14 cruise, quahog mortality in the area surveyed had increased to 13.3 percent. During the October 7–8 cruise, the quahog mortality was 9.2 percent.

**Sea Scallop Mortality**

Sea scallops were assessed before the anoxia event. During August 7–16, 1975, 99 scallop stations sampled in the Middle Atlantic Bight (Northeast Fisheries Center 1975), and 27 stations were sampled off New Jersey. Insubstantial mortality was observed.

In October and November 1976, two surveys were made to assess the effects of the anoxic conditions on the sea scallop resource (Northeast Fisheries Center 1977a). During the October 6–15 survey, 17 stations were sampled on the inner half of the continental shelf off New Jersey. The stations were about 9.3 km apart. Stations at depths of 22 to 59 m and 2 to 56 km from shore were sampled. The survey did not cover the entire Middle Atlantic Bight scallop resource, because the weather was inclement, but substantial numbers of scallops had been killed by the anoxic conditions. During November 8–17, the entire New Jersey scallop resource was surveyed. A total of 45 stations about 9.3 km apart and 13 to 70 km from shore were sampled. The scallop mortality was somewhere between 8.8 to 12.9 percent.

Assessment cruises were made south of Long Island before, during, and after the oxygen-depletion event. No abnormal clam, quahog, and scallop mortalities were observed (Northeast Fisheries Center 1977a).

### Post-Anoxia Surveys

During the January 26 to March 17, 1977, resource assessment survey, 224 stations were sampled in the Middle Atlantic Bight and southern New England area (Northeast Fisheries Center 1977b). In the New Jersey area, 70 stations were sampled at depths of 9.1 to 82.3 m in and beyond the area affected by the 1976 anoxic conditions. Some evidence of mortality may have been lost in the period after the October 1976 sampling and the 1977 survey, because paired valves had separated. An analysis comparing the results of the April-May 1976 and 1977 assessment cruises, however, clearly showed that the highest mortality of surf clams and ocean quahogs was off New Jersey (table 11.1–2). Some 20.7 percent of the surf clams and 26.6 percent of the ocean quahogs were dead off New Jersey in 1977, compared with 5.0 percent and 3.9 percent in 1976. For the Long Island area in 1977, mortalities of the clam and quahog were both $\leq$3.5 percent, for the Delmarva area, both $\leq$8.3 percent. Surveys since 1970 did not include the southern New England area.

The surf clam impact or mortality area (fig. 11.1–1), as defined from assessment cruises and fishermen's reports, extended from immediately north of Manasquan Inlet (40° 10′N), southward to immediately south of Atlantic City (39° 10′N), and offshore to about 37 m depth (Northeast Fisheries Center 1977b). Mortalities were noted in inshore areas (3–5 km from the beach), but the effects of the mortality were sporadic and less severe than offshore (Milstein et al. 1977; Northeast Fisheries Center 1977b; Schneider et al. 1977). Ocean quahog mortalities were noted within the same latitudinal boundaries (fig. 11.1–1) from 18 to 55 m depth (Northeast Fisheries Center 1977b). Figure 11.1–2 shows two areas of the continental shelf off New Jersey with live (unaffected) and dead or stressed (affected) sea scallops. Affected scallops were at the shoreward edge of the scallop distribution and along about 60 percent of its north to south length. Apparently all scallops were dead within the affected area. The areas of maximum mortality were 6,750 km$^2$ for surf clams, 9,105 km$^2$ for ocean quahogs, and 4,300 km$^2$ for sea scallops.

### Analysis of Catch-Per-Tow

Catch-per-tow data from the April-May 1976 (Northeast Fisheries Center 1976a) and January-March 1977 (Northeast Fisheries Center 1977b) assessment cruises off the New Jersey coast were stratified by areas corresponding with the impact area and depth distribution of each species. Three strata were defined for surf clams: 1) within the impact area ($\leq$37 m), 2) north and south of the impact area ($\leq$37 m), and 3) east of the impact area ($>$37 – $\leq$55 m). Ocean quahog data were also grouped into three strata: 1) within the impact area ($>$18 – $\leq$55 m), 2) north and south of the impact area ($>$18 – $\leq$55 m), and 3) east of the impact area ($>$55 m).

For an initial comparison of the data from the surveys, the catches in each stratum were reduced to the mean number per tow, standard deviation, and standard error. Confidence intervals of 95 percent were calculated for the means.

The mean meat weight of individuals caught in a particular stratum and year was computed for each species by the following methods. The shell length composition from each station in the stratum was determined by prorating the total catch by the measured subsample. The cumulative stratum length frequency was then calculated by summing the catches from each station. Weights for each millimeter length interval were calculated from the appropriate length/weight relation for each species (Ropes 1971; unpublished Northeast Fisheries Center data). The overall stratum mean weight was derived by multiplying the weight at each millimeter interval by the corresponding frequency, summing over all intervals, and then dividing by the total number caught in the stratum.

Table 11.1–3 summarizes catch data and associated statistics for surf clams. Numbers per tow within the mortality area declined by 81.3 percent from 1976 to 1977; mean weight per tow decreased 86.5 percent. At stations outside the mortality area ($\leq$37 m), catch per tow decreased 37.1 percent, average weight decreased 57.9 percent because the mean weight of clams measured also declined. Few clams were collected in the $>$37 to $\leq$ 55 m zone, and number per tow decreased by only 71.1 percent. The results of statistical tests suggest a significant ($P < 0.01$) decline in the impact areas. All other comparisons were nonsignificant at the 0.05 level.

Within the impact area, mean catch of ocean quahogs per tow decreased 26.6 percent and mean weights 25.6 percent (table 11.1–4). East of the mortality area, at depths of $>$18 to $\leq$55 m, average numbers and weights increased 10.1 percent and 26.9 percent, respectively. At depths $>$55 m, average numbers and weights decreased 52.2 percent and 58.0 percent, respectively. Although mean numbers per tow decreased at depths $>$55 m, the difference was not significant, because one exceptionally large catch in 1976 (958 individuals) again increased the mean and variance for that year. Differences in catches

TABLE 11.1-2.—*Live and dead surf clams and ocean quahogs, NMFS 1976 and 1977 assessment cruises*

| Area | Surf clams | | | Ocean quahogs | | |
|---|---|---|---|---|---|---|
| | Live | Dead | Percent dead[1] | Live | Dead | Percent dead[1] |
| **1976** | | | | | | |
| Long Island | 281 | 5 | 1.7 | 15,942 | 513 | 3.1 |
| New Jersey | 416 | 22 | 5.0 | 5,448 | 219 | 3.9 |
| Delmarva Peninsula | 781 | 21 | 2.6 | 1,218 | 157 | 11.4 |
| Total | 1,478 | 48 | 3.1 | 22,608 | 889 | 3.8 |
| **1977** | | | | | | |
| Long Island | 33 | 1 | 2.9 | 6,703 | 243 | 3.5 |
| New Jersey | 107 | 28 | 20.7 | 4,244 | 1,537 | 26.6 |
| Delmarva Peninsula | 354 | 32 | 8.3 | 1,855 | 96 | 4.9 |
| Total | 494 | 61 | 11.0 | 12,802 | 1,876 | 12.8 |

[1] Paired valves.

per tow outside the kill area (>18 – ≤55 m) were also insignificant.

The sea scallop has substantially higher density on the offshore than the inshore part of its distribution off New Jersey. The average number of scallops per station, as determined by the 1975 survey and the November 8–17, 1976, survey, were 6.2 and 4.0 times larger, respectively, in the unaffected than in the affected areas. The mortality of the total New Jersey scallop resource was between 8.8 and 12.9 percent.

### Estimates of Population Loss

A measure of the New Jersey surf clam and ocean quahog populations was calculated from the 1976 and 1977 assessment data, using the catch-per-tow data. The minimum number of clams and quahogs in each stratum was computed by obtaining the possible number of sampling units in a stratum area, based on the average area swept by the dredge and multiplying the resultant weighting factor by the mean catch (in numbers) per tow. The standing stock in meat weight was determined by multiplying the number by the average meat weight of each clam.

Tables 11.1-5 and 11.1-6 show biomass data of surf clams and ocean quahogs computed from areal expansions of mean catch-per-tow data. The calculations are minimal estimates of population sizes, because the hydraulic dredge is not 100 percent efficient in sampling (Northeast Fisheries Center 1977b).

The biomass of all New Jersey surf clams decreased 78.5 percent from 1976 to 1977. Within the mortality area, the estimated decrease in meat weight of surf clams was 147,000 metric tons (t), or 62.6 percent of the total New Jersey biomass of surf clams. Removal of clams by fishing accounted for a very small proportion of the biomass decline in the mortality zone. From May to December 1976 (after the 1976 survey, before the 1977 cruise) landings at Pt. Pleasant and Atlantic City were 2,376 t. If the quantities are subtracted from the total, about 62 percent of the biomass of New Jersey surf clams and 85 percent of the biomass within the mortality area was lost.

Effects of oxygen depletion on ocean quahog populations were much smaller because the largest concentrations of quahogs off New Jersey were east of the mortality area. The biomass of New Jersey quahogs declined 7.1 percent from 1976 to 1977; however, we know that vessels from Pt. Pleasant and Atlantic City began removing some of the quahogs in 1976. If the quantities are subtracted from the losses, the anoxic conditions killed 25.4 percent of the biomass within the mortality area and 6.3 percent of the New Jersey total.

Data were not available to estimate the loss of sea scallop biomass.

## EFFECTS ON COMMERCIAL LANDINGS

### Surf Clam

The effects of clam mortality were reflected in areas where clammers fished and lower landings of surf clams at New Jersey ports. In the first 4 months of 1976, vessels from Atlantic City, Cape May-Wildwood, and Pt. Pleasant concentrated fishing on dense beds of small clams near shore; landings at Atlantic City were particularly high (fig. 11.1-3). After May 1, 1976, landings decreased as the vessels moved offshore to comply with State of New Jersey regulations that limited fishing on the inshore clams. Although landings in July increased over those in June for all ports, fishermen from Pt. Pleasant and Atlantic City found dead and dying clams in their catch by mid- to late July. Thereafter, landings declined substantially. At Pt. Pleasant in August, landings were 57.1 t, as compared with 120.4 t landed in July, a drop of 52.8 percent; at Atlantic City in August landings were 184.8 t, as compared with 613.8 percent in July, a drop of 69.9 percent. Land-

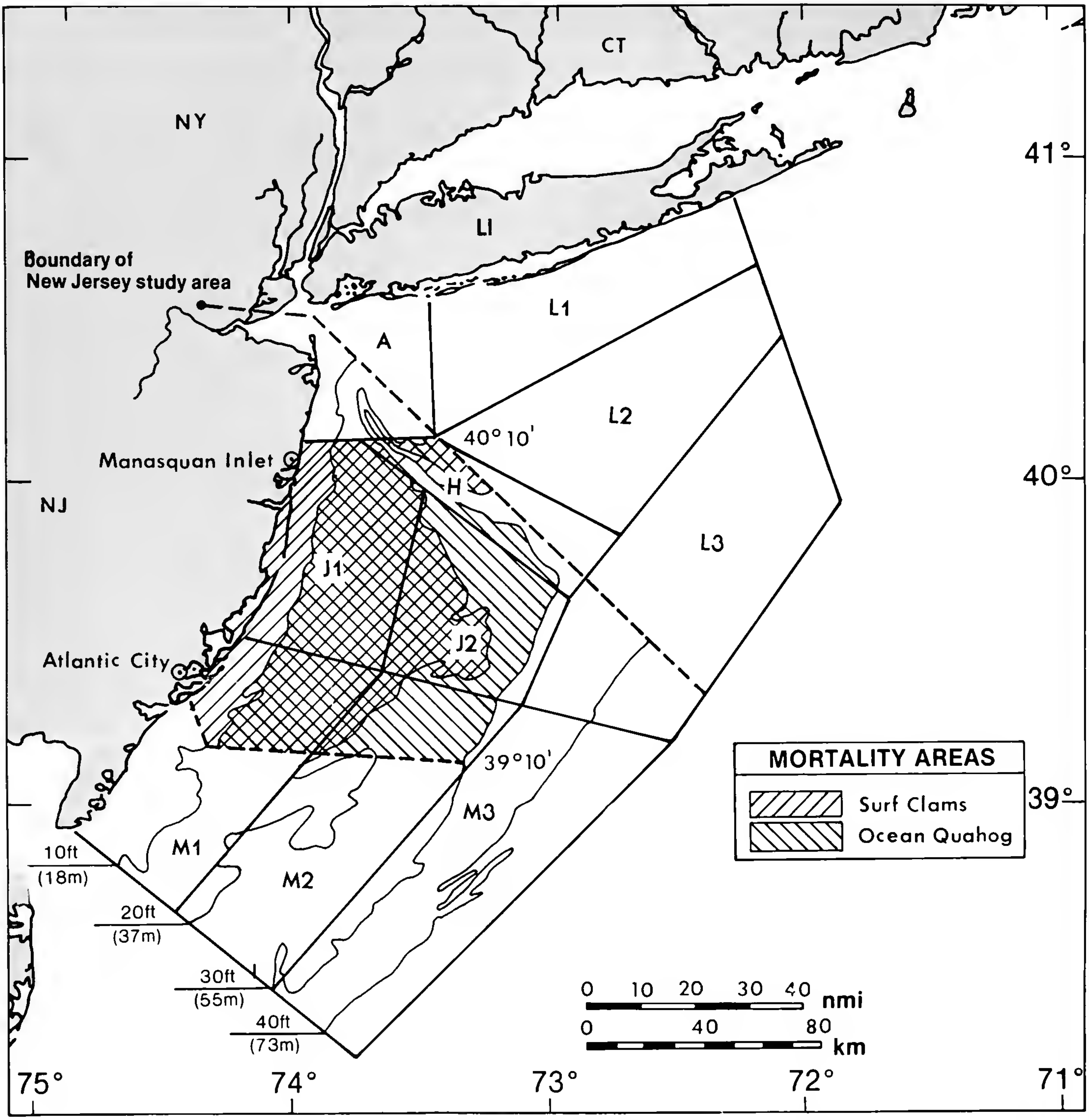

FIGURE 11.1-1.—Surf clam and ocean quahog mortality areas in New York Bight by depth zones. From data collected during January 26 to March 16, 1977, NMFS assessment cruise.

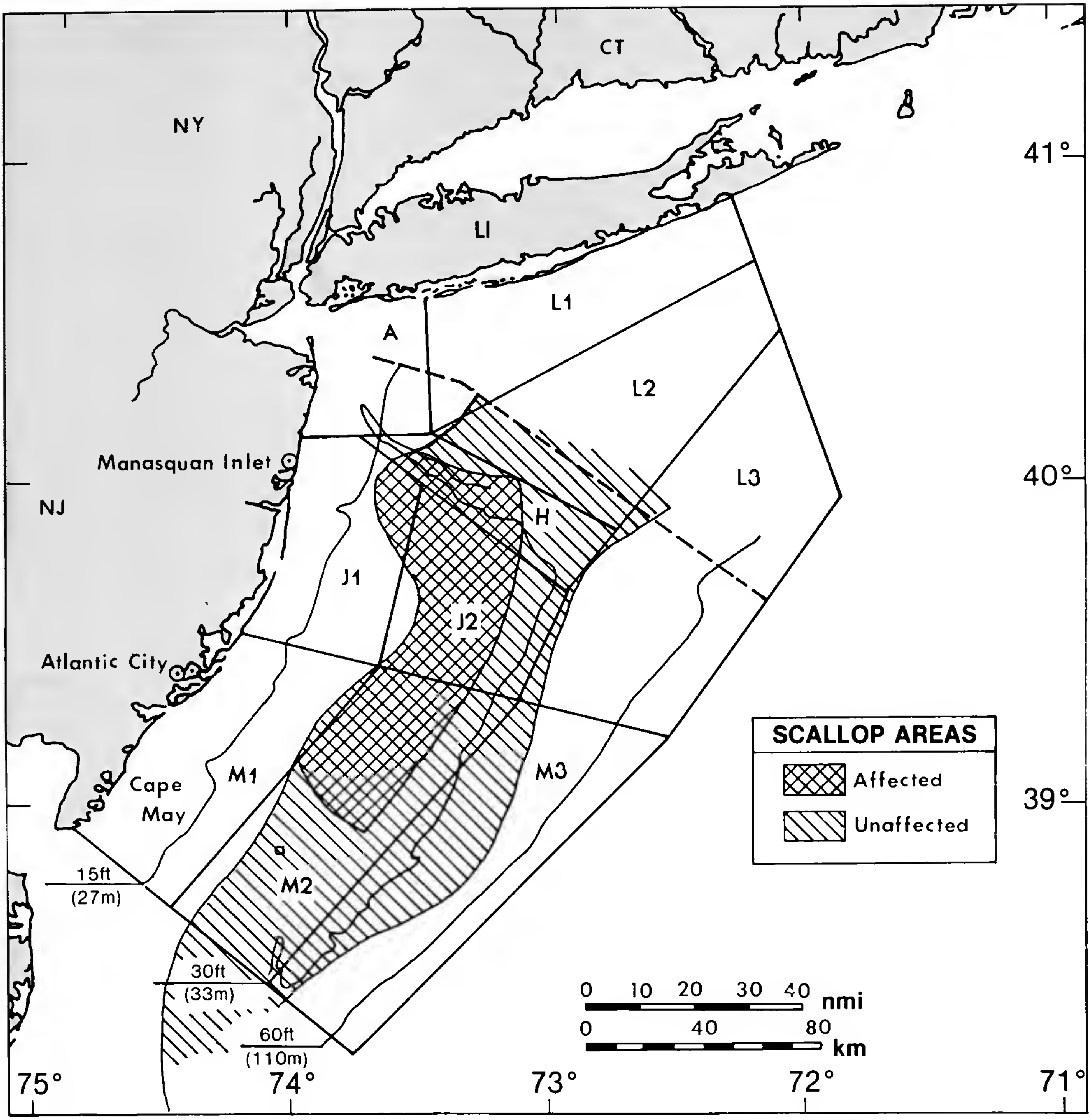

FIGURE 11.1-2.—Sea scallop affected and unaffected areas in New York Bight by depth zones. From combined reports and operations during July to November 1976 off New Jersey coast.

TABLE 11.1–3.—*Catches of surf clams during NMFS surveys off New Jersey coast, 1976–77*

| Area and station depth | Year | Number of stations | Mean number per tow | Standard deviation | Standard error | 95-percent confidence interval | Mean weight (g) |
|---|---|---|---|---|---|---|---|
| Within mortality area ≤37 m | 1976 | 24 | 12.04 | 13.15 | 2.68 | ±5.55 | 157.4 (257)a |
| | 1977 | 16 | 2.25 | 5.66 | 1.42 | ±3.02 | 114.1 (26) |
| East of mortality area ≤37 m | 1976 | 19 | 6.53 | 11.64 | 2.67 | ±5.59 | 163.4 (98) |
| | 1977 | 18 | 4.11 | 8.33 | 1.96 | ±4.13 | 109.3 (57) |
| Outside mortality area >37 m to ≤55.0 m | 1976 | 18 | 0.28 | 0.96 | 0.23 | ±0.48 | 35.1 (5) |
| | 1977 | 23 | 0.26 | 0.62 | 0.13 | ±0.27 | 22.4 (6) |

a, Number measured.

TABLE 11.1–4.—*Catches of ocean quahogs during NMFS surveys off New Jersey coast, 1976–77*

| Area and station depth | Year | Number of stations | Mean number per tow | Standard deviation | Standard error | 95-percent confidence interval | Mean weight (g) |
|---|---|---|---|---|---|---|---|
| Within mortality area >18 m to ≤55.0 m | 1976 | 29 | 45.24 | 151.98 | 28.21 | ±57.80 | 36.6 (676)a |
| | 1977 | 27 | 33.22 | 58.88 | 11.33 | ±23.30 | 37.1 (843) |
| East of mortality area >18 m to ≤55.0 m | 1976 | 20 | 111.10 | 237.14 | 53.03 | ±110.61 | 28.8 (1,140) |
| | 1977 | 22 | 122.32 | 210.23 | 44.82 | ±93.23 | 33.2 (1,274) |
| Outside mortality area >55.0 m | 1976 | 21 | 91.95 | 208.00 | 45.39 | ±94.41 | 33.3 (1,138) |
| | 1977 | 15 | 43.93 | 68.45 | 17.67 | ±37.91 | 29.3 (588) |

a, Number measured.

ings at the two ports continued to decline and remained low through November. Some vessels moved to other ports to be near unaffected beds or went farther offshore to fish for ocean quahogs. Surf clam landings for New Jersey were 11,056 t in 1976, 31 percent lower in 1975. NMFS data show that landings from the southern New Jersey offshore area (>3 miles) increased almost threefold in 1976 over 1975. Thus, the decline in average catch per tow in the nonmortality area, ≤37 m, although not statistically significant, may reflect the increase in fishing intensity directed away from the mortality area during 1976 (NMFS 1976, 1977).

## Ocean Quahog

Substantial quantities of ocean quahogs were landed for the first time at New Jersey ports in 1976, in part to compensate for the loss of surf clams (fig. 11.1–4). Vessels from Cape May-Wildwood began fishing for quahogs in March. Vessels from Atlantic City fished surf clams until August when they shifted to ocean quahogs. Landings at Cape May-Wildwood accounted for 77.9 percent, and those at Atlantic City 22.9 percent, of the New Jersey total. November landings at Pt. Pleasant were only 0.04 percent. If the mass mortality had not occurred, vessels from Atlantic City and Pt. Pleasant would have continued fishing for surf clams throughout 1976. New Jersey landings of ocean quahogs were 71.7 percent (1,859 t) of the U.S. total (2,593 t) and landings at Atlantic City and Pt. Pleasant were 15.9 percent of the total.

## Sea Scallop

In 1976, sea scallop landings at New Jersey ports quadrupled over 1975, to 1,304 from 322 t. In 1975 and 1976, about three-quarters of the landings were at Cape May-Wildwood, 24 percent were at Point Pleasant, and the rest at Atlantic City. Thus, it is clear that the oxygen-depletion event minimally affected the scallop fishery.

TABLE 11.1-5.—*Estimated biomass loss of surf clams off New Jersey, 1976–77*

| Area and station depth | Size of area | Estimated biomass 1976 | 1977 | Loss |
|---|---|---|---|---|
| | km² | —1,000 metric tons— | | |
| Within mortality area ≤37 m | 6,758 | 170.1 | 23.0 | 147.1 |
| East of mortality area ≤37 m | 4,497 | 63.7 | 26.8 | 36.9 |
| North and south of mortality area >37 to 55.0 m | 10,224 | 1.3 | 0.8 | 0.5 |
| Total | 21,479 | 235.1 | 50.6 | 184.5 |

TABLE 11.1-6.—*Estimated biomass loss of ocean quahogs off New Jersey, 1976–77*

| Area and station depth | Size of area | Estimated biomass 1976 | 1977 | Loss |
|---|---|---|---|---|
| | km² | —1,000 metric tons— | | |
| Within mortality area 18 to 55.0 m | 9,105 | 200.2 | 149.0 | −51.2 |
| East of mortality area 18 to 55.0 m | 9,606 | 408.1 | 518.0 | +109.9 |
| North and south of mortality area ≥55.0 m | 4,920 | 200.0 | 84.1 | −115.9 |
| Total | 23,631 | 808.3 | 751.1 | −167.1<br>+109.9 |

## DISCUSSION

The low dissolved oxygen (D.O.) water mass associated with early mortalities (June and July) of finfish and invertebrates included an extensive area off central New Jersey in early August and September. Finfish were virtually absent from the region, but the much less mobile benthic invertebrates could not escape the anoxic water. With each mortality in the affected area, the demand on the available oxygen increased, because of the natural decay processes. The condition persisted for all least 13 weeks, July 1 to September 30, and probably had developed to some degree before July.

Mortalities of marine organisms off the New Jersey coast have been reported in the past. Most recently (Young 1973), scuba divers saw lobster (*Homarus americanus*) and rock crab (*Cancer irroratus*) during October 1971, but did not mention clams. Although accurate diagnosis was not possible, low D.O., high temperature, and flocculated material in the water were suspected to have affected the lobsters and crabs. Ogren and Chess (1969) listed numerous observations around shipwrecks, reefs, and bottom communities during September and October 1968; Ogren (1969) summarized the event. Several species of finfish and invertebrates were seen living, dying, and dead. Surf clams (*Spisula solidissima*) were found lying on the bottom. Water temperatures taken at one site (the *Delaware* wreck) were considered normal for the season. Levels of D.O., however, were abnormally low (range: 0.34 ml/l to 0.72 ml/l) and were believed responsible for the unusual behavior and mortalities of the finfish and invertebrates. The D.O. levels recorded during 1976 were as low and lower than normal.

The effect of D.O. thresholds in producing some physiological, behavioral, or other response in marine invertebrates is poorly known, and determinations are complicated by the ability of many marine invertebrates to survive anaerobically (Davis 1975). Some invertebrates can tolerate very low levels of oxygen and even show an independence above a low critical tension. Davis included the soft clam (*Mya arenaria*) as an oxygen-independent species with critical oxygen tension values of 40 to 50 mm Hg. Although the experimental conditions under which the values for soft clams were obtained may not be strictly comparable, Savage (1976) found that the median burrowing time of the surf clam was substantially slower at a concentration of 1.0 ml $O_2$/l (ca. 123 mm/Hg) and at 11° C. Surf clams ceased burrowing after 3 days at 15.4° to 15.8° C and 0.6 ml $O_2$/l (ca. 68–77 mm Hg). In one experiment in which the ambient temperature was increased about 6° C and during experiments at seasonally high temperatures of 20.8° and 21.0° C in July and August, clams also died in water of the lowest oxygen content (0.62 ml $O_2$/l or ca. 92–93 mm Hg). Oxygen depletion, then, had the greatest effect on burrowing, and, coupled with high temperatures, on survival too. It is not known whether surf clams exhibit independence, as soft clams do; a comparison of oxygen tension values may not be justified. The generally higher values for surf clams may be the result of experimental or special specific differences.

Studies have related the reactions of ocean quahogs to low D.O. levels. Brand and Taylor (1974) reported on pumping behavior. In well-oxygenated water (160 mm Hg), active pumping of currents in and out of ocean quahogs' siphons to fulfill respiratory and digestive requirements alternated with periods of inactivity. The pumping activity was independent of shell movements. Complete closure of the shell often resulted in quiescence for several hours. For ocean quahogs, and some other subtidal species, periods of pumping varied, but amounted to 40 to 60 percent of the observation time. In water with low D.O. (30–50 mm Hg), pumping time increased to over 95 percent; at lower oxygen tensions, it stopped and the shells closed. Taylor and Brand (1975) investigated the effect of hypoxia on the rate of oxygen consumption in ocean

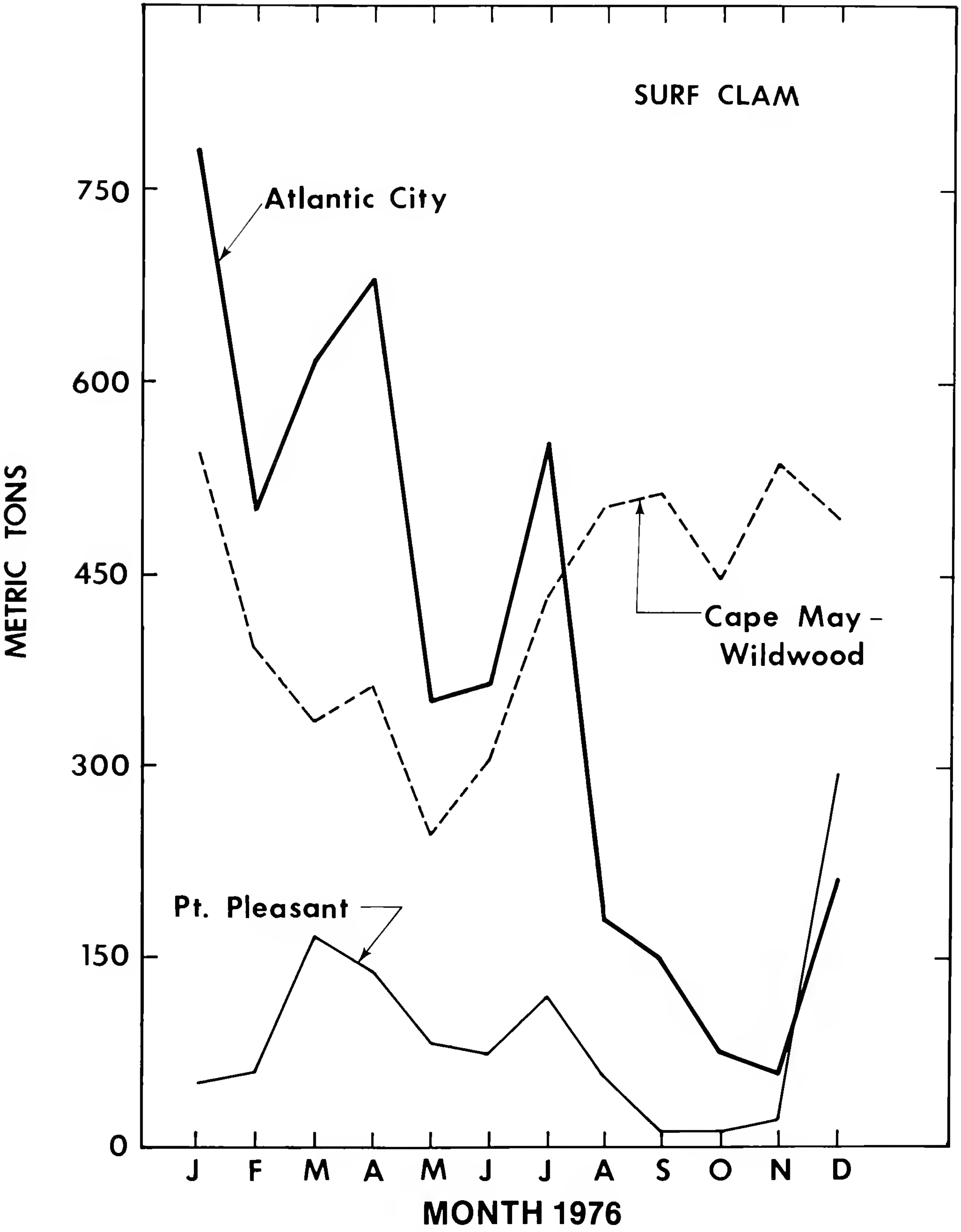

FIGURE 11.1-3.—New Jersey commercial surf clam landings during 1976, by port and month.

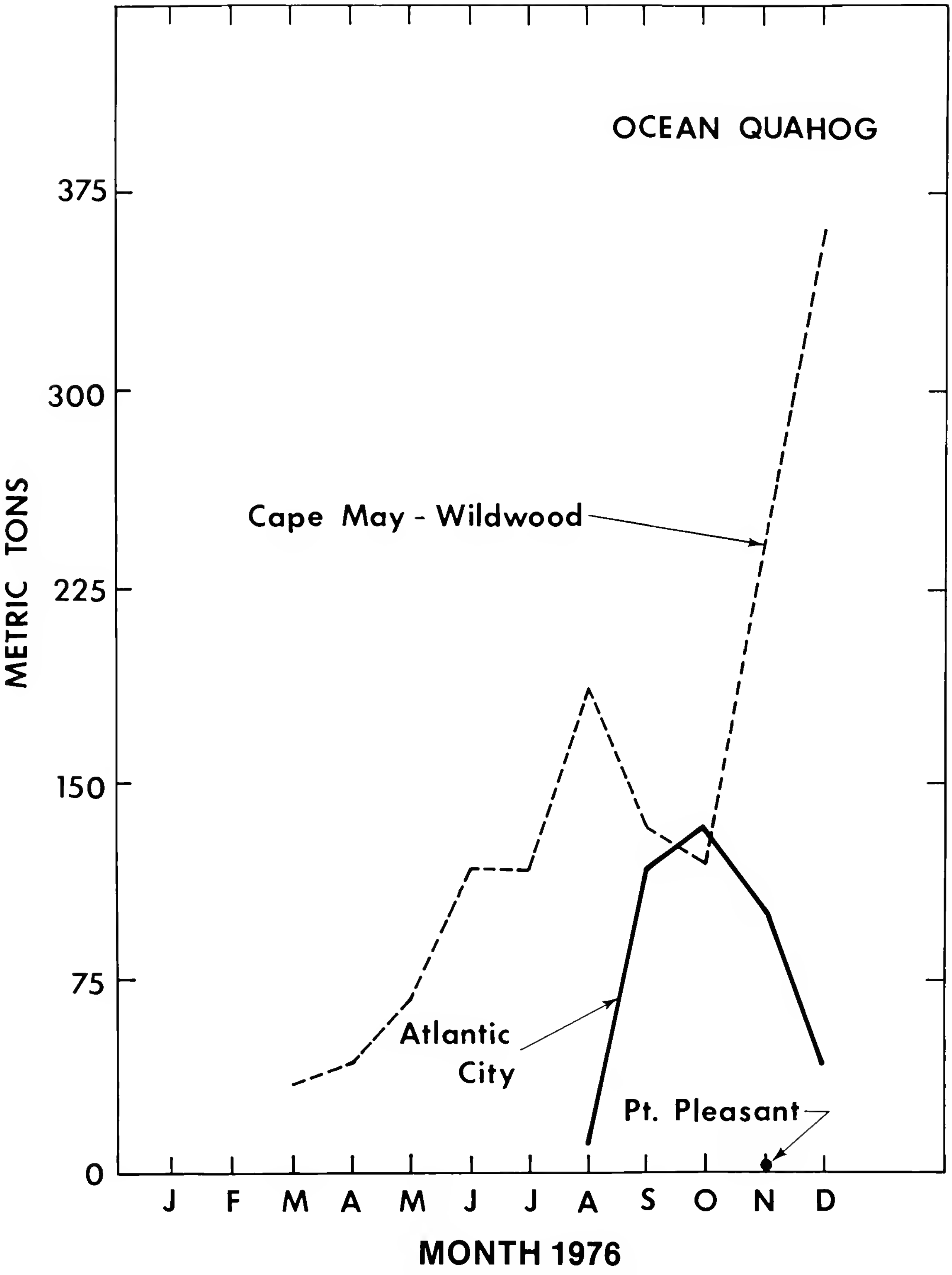

FIGURE 11.1-4.—New Jersey commercial ocean quahog landings during 1976, by port and month.

quahogs held in water at 10° C and 34‰ salinity. Oxygen consumption by large ocean quahogs (2.9–16 g dry weight) was more or less constant to levels of 40 to 50 mm Hg, which are values considered to be critical oxygen tensions for the species. Above critical levels, the clams exhibited respiratory independence, but small-sized clams (1 g dry weight) showed respiratory dependence under hypoxic conditions. The differences in response to oxygen were also believed to be modified by temperature and the physiological condition of the clam, other factors that complicate the identification of a species as an oxygen regulator or oxygen conformer. The critical oxygen tension (Pc) values for ocean quahogs compare with those for soft clams (Davis 1975) and are lower than those for surf clams (Savage 1976). As reported by Brand and Taylor (1974), ocean quahogs can compensate for oxygen levels lower than the Pc values by greatly increasing pumping activity or closing their shells. Both are reactions to stress.

The larger capacity of ocean quahogs to function under low oxygen conditions appears to be species specific. Theede et al. (1969) compared the resistance of a number of marine bottom invertebrates to oxygen deficiency and hydrogen sulfide. *Spisula solida* (a European relative of the surf clam) and the ocean quahog were among several bivalves used in the experiments. Resistance was measured in hours over which 50 percent survived experimental conditions (LD–50). All ocean quahogs survived for 55 days in water of 0.15 ml $O_2$/l (10° C, 15‰) and for 33 to 41 days in water of similar oxygen deficiency, but treated to create a hydrogen sulfide ($H_2S$) condition. The survival times were the longest for any of the invertebrates tested, but *S. solida* was not among the species listed.

In experiments with isolated gill pieces in water of a similar oxygen deficiency and $H_2S$ level but higher salinity (30‰), the survival of *S. solida* tissues was affected 3 to 7 days earlier than those of *Mytilus edulis, Modiolus modiolus*, and soft clams. For *S. solida*, ciliary activity ceased and cell damage was irreversible after 24 hours in oxygen-deficient water treated to create $H_2S$. The tissue pieces survived the experimental conditions for 3 to 4 days. Under similar oxygen and $H_2S$ conditions, but lower salinity (15‰), isolated gill tissue pieces of ocean quahogs survived for 8 days, although ciliary activity ceased and was irreversible after 8 to 24 hours. Lower experimental temperatures and higher salinity greatly increased survival and recovery of ciliary activity for ocean quahogs. Ocean quahogs were considered to be highly resistant to oxygen deficiency and hydrogen sulfide.

Off New Jersey, the bottom temperature increased sharply in early October, after the low D.O. levels had been affecting the benthic fauna for several weeks. Scallop mortalities, although less intense than surf clam mortalities, were found in the shoreward portion of the resource and in the area of low D.O. levels. Temperature increases may have been only an added stress on individuals near death from the effects of low D.O. Thermal stress may have delayed death. Waugh (1975) observed mortalities for intertidal bivalves [the ribbed mussel, *Modiolus demissus* (=*Geukensia demissa*), the blue mussel, *Mytilus edulis*, and the soft clam, *Mya arenaria*] after removal from experimental lethal stress conditions and return to normal conditions. Delayed mortalities were higher and occurred earlier in short-term experiments than in long-term experiments.

As Davis (1975) pointed out, many invertebrates can tolerate low levels of oxygen, but intolerant or less tolerant species may be lost from communities. As a result, a new species may invade the commmunity or some species already present may increase. Relative to the surf clam fishery, which is currently faced with a low supply and a low recommended annual yield (Brown et al. 1977), the loss of a substantial quantity of clams and uncertain recruitment in the affected area have a serious socioeconomic impact. Relocation of vessels to fish the remaining stock increases the effort on the already low supply. Some vessels may not be able to fish stocks at greater depths and farther from shore. The biological implication is that a sizable brood stock has been lost.

The surf clam, ocean quahog, and sea scallop were each affected in different degree by the oxygen depletion event off New Jersey. The surf clam is highly susceptible to low D.O. levels and $H_2S$, and most of the clams were killed within the mortality area; thus it was the most severely affected of the three bivalves. The ocean quahog was mostly offshore of the affected area and was little affected. The sea scallop also was outside the affected area and was little affected.

## SUMMARY

For surf clams, a 6,750-km$^2$ area of mortality was delimited off New Jersey. The area extended from immediately north of Manasquan Inlet to immediately south of Atlantic City, and seaward to about 37 m. An almost complete kill (92%) took place in the mortality area, but was least intense in the 3- to 15-km-wide beach zone. An estimated 61.5 percent of the total surf clam biomass was lost off New Jersey. Surf clam landings were substantially lower (31%) in New Jersey during 1976 than during 1975.

The principal ocean quahog resource occurs deeper than 37 m and thus only the shoreward margin of the population was affected. The mortality area was 9,105 km$^2$, and 25.4 percent of the quahog biomass within it was lost. Of the entire New Jersey ocean quahog resource, 6.3 percent of the biomass was lost. New Jersey vessels began fishing ocean quahogs in 1976 and landed 71.7 percent of the U.S. total.

The principal sea scallop resource also occurs deeper than 37 m, and only the shoreward margin of the population was affected. From 8.8 to 12.9 percent of the entire New Jersey scallop resource was killed. Scallop landings increased four-fold in 1976.

## ACKNOWLEDGMENTS

Harold F. Snow, Snow Food Products, Inc., Old Orchard Beach, Maine, provided several commercial surf clam vessels for surveys during summer 1976. The captains and crews of the following vessels provided expert assistance in obtaining samples: *Harold F. Snow*, Captain Dan Frew; *Valerie E.*, Captain Edward McVey; *Gail Snow*, Captain Russell Stump; *Cora May Snow*, Captain Edward Nichols; and *Margaret & Nancy*, Captain Robert Farmer.

## REFERENCES

Brand, A. R., and Taylor, A. C., 1974. Pumping activity of *Arctica islandica* (L.) and some other common bivalves, *Mar. Physiol.* 3:1–15.

Brown, B. E., Henderson, E.M., Murawski, S. A., and Serchuk, F. M., 1977. Review of status of surf clam populations in the Middle Atlantic, Woods Hole Lab., National Marine Fisheries Service, U.S. Department of Commerce. Ref. 77–08, 12 pp.

Davis, J. C., 1975. Minimal dissolved oxygen requirements of aquatic life with emphasis on Canadian species: a review, *J. Fish. Res. Board Can.* 32:2295–2332.

Dickie, L. M., 1958. Effects of high temperature on survival of the giant scallop, *J. Fish. Res. Board Can.* 15:1189–1211.

Merrill, A. S., 1962. Abundance and distribution of sea scallops off the Middle Atlantic coast, *Proc. Nat. Shellfish Assoc.* 51:74–80.

Merrill, A. S., and Ropes, J. W., 1969. The general distribution of the surf clam and ocean quahog, *Proc. Nat. Shellfish Assoc.* 59:40–45.

Milstein, C. B., Garlo, E. V., and Jahn, A. E., 1977. A major kill of marine organisms in the Middle Atlantic Bight during summer 1976, *Ichthyological Associates Bull.* No. 16, 56 pp.

National Marine Fisheries Service, 1976. Fisheries of the United States, 1975, its *Curr. Fish. Stat.* 6900, NOAA, U.S. Department of Commerce, 100 pp.

National Marine Fisheries Service, 1977. Fisheries of the United States, 1976, its *Curr. Fish. Stat.* 7200, NOAA, U.S. Department of Commerce, 96 pp.

National Marine Fisheries Service, Northeast Fisheries Center, 1975. Cruise report, R/V *Albatross IV*, August 7–16, 1975 and September 27-October 3, 1975. NOAA, U.S. Department of Commerce, 22 pp.

National Marine Fisheries Service, Northeast Fisheries Center, 1976a. Cruise report, R/V *Delaware II*, April 6 to May 13, 1976. NOAA, U.S. Department of Commerce, 32 pp.

National Marine Fisheries Service, Northeast Fisheries Center, 1976b. Cruise report, R/V *Atlantic Twin* 76–01 (Code Number 076), August 6–17, 1976. NOAA, U.S. Department of Commerce, 16 pp.

National Marine Fisheries Service, Northeast Fisheries Center, 1976c. Cruise report, R/V *Albatross IV* 76–09, September 28 to October 18, 1976. NOAA, U.S. Department of Commerce, 11 pp.

National Marine Fisheries Service, Northeast Fisheries Center, 1976d. Cruise report, R/V *Delaware II* 76–12, December 5–21, 1976. NOAA, U.S. Department of Commerce, 4 pp.

National Marine Fisheries Service, Northeast Fisheries Center, 1977a. Cruise results, R/V *Delaware II* 77–01, January 26 to March 17, 1977. NOAA, U.S. Department of Commerce, 26 pp.

National Marine Fisheries Service, Northeast Fisheries Center, 1977b. Oxygen depletion and associated environmental disturbances in the Middle Atlantic Bight in 1976, *Northeast Fisheries Center, Tech. Ser. Rep.* No. 3, Sandy Hook Laboratory, Highlands, N.J., 471 pp.

Ogren, L. 1969. New Jersey fish/crustacean mortality, Smithsonian Institution, Center for Short-Lived Phenomenon, Event No. 38–69, Card Nos. 509–510.

Ogren, L., and Chess, J., 1969. A marine kill in New Jersey wrecks, *Underwater Naturalist* 6:4–12.

Ropes, J. W., 1971. Percentage of solids and length-weight relationship of the ocean quahog. *Proc. Nat. Shellfish Assoc.* 61:88–90.

Ropes, J. W., and Merrill, A. S., 1973. To what extent do surf clams move? *Nautilus* 87:19–21.

Savage, N. B., 1976. Burrowing activity in *Mercenaria mercenaria* (L.) and *Spisula solidissima* (Dillwyn) as a function of temperature and dissolved oxygen, *Mar. Behav. Physiol.* 3:221–234.

Schneider, R., Tarnowski, M., and Haskin, H. H., 1977. Management studies of surf clam resources off New Jersey, State/Federal Surf Clam Report No. 7, Rutgers the State University/National Marine Fisheries Service, Gloucester, Mass., 37 pp.

Taylor, A. C., and Brand, A. R., 1975. Effects of hypoxia and body size on the oxygen consumption of the bivalve *Arctica islandica* (L.), *J. Exp. Mar. Biol. Ecol.* 19:187–196.

Theede, H., Ponat, A., Hiroki, K., and Schlieper, C., 1969. Studies on the resistance of marine bottom invertebrates to oxygen deficiency and hydrogen sulfide, *Mar. Biol.* 2:325–337.

van Dam, L., 1954. On the respiration of scallops (*Lamellibranchiata*), *Biol. Bull.* 107:192–202.

Waugh, D., 1975. Delayed mortality following thermal stress in three species of intertidal pelecypod molluscs (*Modiolus demissus*, *Mya arenaria*, and *Mytilus edulis*), *Can. J. Zool.* 55:1658–1662.

Young, J. S., 1973. A marine kill in New Jersey coastal waters, *Mar. Poll. Bull.* 3:70.

**Oxygen Depletion and Associated Benthic Mortalities in New York Bight, 1976**

# Chapter 11. Impact on Clams and Scallops

## Part 2. Low Dissolved Oxygen Concentrations and Surf Clams—A Laboratory Study

*Frederick P. Thurberg and Randolph O. Goodlett*[1]

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## INTRODUCTION

Most aquatic organisms can use several aerobic or anaerobic metabolic pathways to obtain energy (Davis 1975). Oysters become facultative anaerobes under low dissolved oxygen (D.O.) conditions and are thus able to withstand low D.O. for extended periods of time. (Hochachka and Mustafa 1972). *Modiolus demissus*, *Mytilus edulis*, and *Rangia cuneata* are other bivalves capable of sustaining energy production during low oxygen conditions by shifting away from oxygen-dependent pathways (Hammen 1969; Rossi and Reish 1976). The tolerance of bivalves to low D.O. conditions varies with other environmental factors, however, and temperature seems to be very critical to some species' survival (Theede et al. 1969; Vernberg 1972).

The surf clam *(Spisula solidissima)* is able to endure low levels of oxygen in the environment for extended periods, because these conditions persisted for months along the New Jersey coast without a complete loss of the surf clam population (an estimated 25% of the offshore stocks were lost). Our study was designed to test the range of this animal's tolerance to low oxygen conditions. We also determined the effect of such conditions on metabolic activity by measuring whole-animal oxygen-consumption rates after exposure to various low concentrations of D.O. This report, therefore, provides experimental confirmation of several aspects of surf clam physiology that previously could only be assumed or extrapolated from published information on other species.

## METHODS

The large surf clams (6–12 cm long) used in this study were collected by hand from shallow beds in coastal waters near Point Judith, R.I. The small clams used in this study

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were obtained from stock reared at NMFS Milford Laboratory (Rhodes et al. 1975). All animals were maintained in the laboratory in running seawater at laboratory ambient conditions for at least 2 weeks before experimentation. Damaged clams or any in obviously poor condition were discarded. No supplemental food was given to any clam beyond that available in the seawater.

Clams were held in a temperature-controlled bath in 3.8-1 (1-gal) glass jars for up to 8 weeks. A biomass no greater than 250 g (equal to one large 12-cm clam) was placed in each jar. The water in each container was changed every other day to eliminate metabolic waste products. Each clam was transferred to a holding jar containing the desired low D.O. water, the test container was rinsed and refilled with fresh seawater, nitrogen gas was bubbled through the water until the desired D.O. level was achieved, and the clam was replaced in its test container. On days without a water change, the D.O. level was readjusted to the predetermined level by bubbling with compressed air. Air pockets were carefully excluded when the jars were sealed. The D.O. levels were monitored with a Beckman fieldlab oxygen analyzer whose accuracy was periodically checked by Winkler titration. Although temperature, D.O., and animal condition were monitored daily, there were occasional weekend lapses. Animals in control jars were treated the same as the experimentals, except that D.O. was maintained at saturation with compressed air continuously bubbled through aquarium airstones. Test conditions included 0.7, 1.4, and 2.1 ml/l D.O. (1,2, and 3 ppm) at 10° C and 0.7 ml/l at 20° C. Unfiltered Milford Harbor seawater at 26 ± 2‰ salinity was used throughout this study.

An all-glass mixer was used to mix natural seawater with nitrogen gas. A D.O. level of 1.4 to 1.8 ml/l was maintained by adjusting the flow of nitrogen and seawater in this counter-current system. This water was continuously fed into holding trays of surf clams throughout the 8-week experimental period. Oxygen-saturated seawater was delivered to the control clams from the mixer line before contact with the nitrogen gas supply.

Because high levels of hydrogen sulfide were found in certain areas of the New Jersey low oxygen zone, some preliminary tests were made to examine the role of hydrogen sulfide interaction with low D.O. and test organisms. Sediments containing hydrogen sulfide were obtained from Milford Harbor. Glass jars (3.8-1) were filled to 4 cm with this sediment, then topped with seawater either saturated with oxygen or maintained at a D.O. level below 0.7 ml/l. Again, no more than 250 g of biomass were added per jar, and each container was monitored daily as in static water tests.

Metabolic studies were made on 3.5- to 3.7-cm clams held in 0.7, 1.4, or 2.1 ml/l D.O. water at 10° C. Two clams were placed in each jar, and oxygen levels were measured at the same each day to determine a daily oxygen-consumption value for the pair. D.O. levels were readjusted each day, with water changes every other day as described above. During the period of this study, Milford Harbor had a heavy phytoplankton bloom. To compensate for oxygen consumed by these planktonic organisms and for oxygen used during decomposition of dead plankton, a series of 10 jars was monitored as "blanks" to obtain a representative value for oxygen use by material other than the clams. This value was subtracted from the daily oxygen depletion values before calculating oxygen as microliters of oxygen consumed per hour per gram (wet weight), including shell. Oxygen consumption values obtained at each D.O. level were calculated by averaging 100 daily readings for 10 to 16 clams.

## RESULTS

Table 11.2-1 summarizes results of static water tests at 10° C. Clams in the smallest size range (group 4) survived for 8 weeks at 0.7 ml/l D.O. Three experiments dealt with slightly larger clams (groups 2, 3, and 8) at 0.7 ml/l. The clams in group 2 died in 7 to 9 days. Those in group 3 died in 4 to 8 days. Clams in group 8 were initially exposed to 2.1 ml/l D.O. for 8 weeks before being placed in 0.7 ml/l D.O. water, and survived an additional 8 weeks at 0.7 ml/l. One group of large clams (group 1) was held in 0.7 ml/l water; clams began dying on day 8, and all were dead by day 30; 50 percent were dead by day 15. Two experiments (groups 5 and 6) were run for 8 weeks each at 1.4 ml/l D.O. In both experiments 50 percent of the clams died within 3 weeks (five died in 10 to 21 days in the first experiment, and five died in 11 to 25 days in the second). One experiment (group 7) was run for 8 weeks at 2.1 ml/l D.O.; all 12 clams survived. These clams were subsequently held at 0.7 ml/l D.O. for 8 weeks, with 100 percent survival.

A series of 42 clams (2.4–4.8 cm, 4/jar) was tested at 0.7 ml/l D.O. and 20° C. These died within 8 days. Held under these same conditions, 20 clams (8–11 cm, 1/jar) died within 13 to 14 days.

Twelve small clams (3.1–5.0 cm) and 12 adult clams (6.0–12.1 cm) were held in flowing water at 1.4 to 1.8 ml/l D.O. for 8 weeks at 20° C. This group had no mortalities.

Two experiments were performed with hydrogen sulfide-laden sediment; one with oxygen-saturated seawater and one with seawater below 0.7 ml/l D.O. The first experiment included 19 clams (5 large clams of 10.8–12.3 cm and 14 small clams of 4.1–4.9 cm) held in open 3.8-1 aerated jars. Four clams died in 20 to 36 days (3 adults, 1 juvenile); the remaining 15 clams survived for 68 days. The second experiment included 10 clams (3.6–3.9 cm, 1/jar) that were subjected to D.O. levels below 0.7 ml/l in

TABLE 11.2-1—*Survival of surf clams at different dissolved oxygen concentrations at 10° C*

| Group No. | Dissolved oxygen | Size of clams | No./Jar | Total No. | Day/Deaths | No. days | Survival |
|---|---|---|---|---|---|---|---|
| | ml/l | cm | | | | | Percent |
| 1 | 0.7 | 102–11.8 | 2 | 12 | 8/1, 11/1, 13/2, 14/1, 15/2, 16/2, 17/1, 21/1, 30/1 | 30 | 0 |
| 2 | 0.7 | 3.7–5.0 | 2 | 12 | 7/8, 8/3, 9/1 | 9 | 0 |
| 3 | 0.7 | 4.2–4.6 | 2 | 10 | 4/2, 6/4, 7/3, 8/1 | 8 | 0 |
| 4 | 0.7 | 1.8–2.2 | 5 | 15 | —— | 58 | 100 |
| 5 | 1.4 | 4.0–4.2 | 2 | 10 | 10/3, 20/1, 21/1 | 75 | 50 |
| 6 | 1.4 | 3.8–4.6 | 2 | 10 | 11/1, 12/2, 21/1, 25/1 | 58 | 50 |
| 7 | 2.1 | 3.8–4.0 | 2 | 12 | —— | 52 | 100 |
| 8 | *2.1/0.7 | 3.8–4.0 | 1 | 10 | —— | 59 | 100 |

* 8 weeks at 2.1 ml/l followed by 8 weeks at 0.7 ml/l

sealed jars. The first clam died on day 8; all clams were dead by day 30.

The mean oxygen consumption value for clams held in 2.1 ml/l D.O. water was 9.91 $\mu lO_2$/h/g, with a standard error of ± 0.45. The mean value for clams held in 1.4 ml/l D.O. water was 14.58 $\mu lO_2$/h/g, with a standard error of ± 0.33. Student's "t"-test indicates that the difference between these two mean values of 100 readings each is highly significant ($P < 0.001$). Clams held in 0.7 ml/l water consumed all the detectable ogygen in 24 hours; thus they had the lowest calculated rate of oxygen consumption. The background level of oxygen consumption by other components in the seawater "blanks" was 0.29 ml/l per day. Hourly rate studies were not made, thus the point at which oxygen was depleted in the 24-hour cycle was not determined.

## DISCUSSION

Survival of surf clams in this study was clearly related to the amount of oxygen available in the water. Levels below 1.4 ml/l were nearly always fatal. Surf clams were able to live for various prolonged periods of time at 1.4 ml/l D.O. or above, similar to conditions in the low oxygen zone in New Jersey.

In our studies, no deaths were recorded at 2.1 ml/l D.O. and clams placed in water at 0.7 ml/l after previous exposure to 2.1 ml/l survived for 8 weeks, an indication that a gradual shift to anaerobic pathways is possibly advantageous.

Studies with flowing-water systems indicated that prolonged survival was possible at or near 1.4 ml/l. Flowing water helped eliminate a possible buildup of toxic materials and prevented temporary low D.O. pockets from forming around clams, as might occur in static water. Even with water movement, however, a prolonged or repeated low oxygen condition causes mortality of clams and may lead to the eventual elimination of a viable population.

Size apparently plays a role in surf clam survival under low D.O. conditions. A direct correlation was noted between size and survival; large clams withstood low D.O. better than small ones. The one exception in this study was a group of 1.8 to 2.2 cm clams that survived 0.7 ml/l D.O. for 58 days. We believe this to be an anomalous condition perhaps due to some experimental error. Another group of researchers at this laboratory, working on aquacultural aspects of surf clam biology, found a massive mortality of juvenile clams when the D.O. level accidentally dropped below 2.1 ml/l in an outdoor tank system. A careful examination showed that the survival rate increased with size (R. Goldberg, National Marine Fisheries Service, Milford Laboratory, personal communication.)

Hydrogen sulfide probably contributes an additive toxic element to the low D.O. problem (Theede et al. 1969). Our preliminary tests with hydrogen sulfide-laden sediments were inconclusive, however, as were some tests performed with sodium sulfide solutions at the NMFS Sandy Hook Laboratory (R. K. Tucker, personal communication). Several technical problems complicated the measurement of hydrogen sulfide levels.

Although temperature has been reported as a critical factor in survival of marine animals under low D.O. conditions (Theede et al. 1969; Vernberg 1972), we found no appreciable differences in survival among clams held at 10° and 20° C. Future studies might include a broader range of temperatures.

Oxygen consumption values for 24-hour periods were calculated for clams held at three D.O. levels, at 10° C. The lowest values were obtained from clams held in 0.7 ml/l D.O. water, not an unexpected observation, because the limited amount of detectable oxygen was completely consumed during this period. Clams held at 1.4 ml/l consumed oxygen over 24 hours at a rate 50 percent higher than clams at a level of 2.1 ml/l. The higher rate of oxygen consumption at a lower oxygen tension probably signals metabolic stress. Several researchers have reported higher metabolic activity in other bivalves under reduced oxygen conditions (Bayne 1971 in *Mytilus edulis;* Taylor 1976 in *Arctica islandica;* and Deaton and Mangum 1976 in *Noetia ponderosa*). Any further interpretation of oxygen consumption rates reported here must await future studies. These ideally should include hourly rate studies to determine diurnal patterns of oxygen consumption rates for both normal clams and clams held in low D.O. water.

Although *S. solidissima* is able to tolerate low oxygen conditions at or above 1.4 ml/l for extended periods of time, the survival of a population depends on a variety of other environmental factors during an oxygen depletion episode. Future studies should concentrate on synergistic effects of low D.O. and other toxicants. Such studies are particularly important in the New York-New Jersey area where portions of the coastal and offshore waters receive continual doses of municipal and industrial wastes that lead to these stresses.

## SUMMARY

Under laboratory conditions, the surf clam survived low levels of D.O. for extended periods of time. Levels below 1.4 ml/l were nearly always fatal. No deaths were recorded after 8 weeks at 2.1 ml/l D.O., and clams placed in water at 0.7 ml/l after previous exposure to 2.1 ml/l survived for 8 weeks, indicating that a gradual shift to anaerobic pathways is possibly advantageous. Flowing water exposures permitted better survival than did static water systems. Metabolic studies indicated that animals held under low oxygen conditions consumed oxygen at higher rates than normal.

## REFERENCES

Bayne, B. L., 1971. Ventilation, the heart beat and oxygen uptake by *Mytilus edulis* L. in declining oxygen tension. *Comp. Biochem. Physiol.* 40A:1065–1085.

Davis, J. C., 1975. Minimal dissolved oxygen requirements of aquatic life with emphasis on Canadian species: a review, *J. Fish. Res. Board Can.* 32:2295–2332.

Deaton, L. E., and Mangum, C. P., 1976. The function of hemoglobin in the arcid clam *Noetia ponderosa*—II. Oxygen uptake and storage. *Comp. Biochem. Physiol.* 53(A):181–186.

Hammen, C. S., 1969. Metabolism of the oyster, *Crassostrea virginica, Amer. Zool.* 9:309–318.

Hochachka, P. W., and Mustafa, T., 1972. Invertebrate facultative anaerobiosis, *Science* 178:1056–1060.

Rhodes, E. W., Calabrese, A., Cable, W. D., and Landers, W. S., 1975. The development of methods of rearing the coot clam, *Mulinia lateralis*, and three species of coastal bivalves in the laboratory, in W. L. Smith and M. H. Chanley (eds.) *Culture of Marine Invertebrate Animals*, Plenum Press, New York, N.Y., pp. 273–281.

Rossi, S. S., and Reish, D. J., 1976. Studies on the *Mytilus edulis* community in Alamitos Bay, California, VI. Regulation of anaerobiosis by dissolved oxygen concentration. *Veliger* 18:357–360.

Taylor, A. C., 1976. Burrowing behavior and anaerobiosis in the bivalve *Arctica islandica* (L), *J. Mar. Biol. Assoc. U.K.* 56:95–109.

Theede, H., Ponat, A., Hiroki, K., and Schlieper, C., 1969. Studies on the resistance of marine bottom invertebrates to oxygen deficiency and hydrogen sulfide, *Mar. Biol.* 2:325–337.

Vernberg, F. J., 1972. Dissolved gasses: Animals, in O. Kinne (ed.), *Marine Ecology*, vol. 1 (3), Wiley-Interscience, London, pp. 149–1526.

## Oxygen Depletion and Associated Benthic Mortalities in New York Bight, 1976

# Chapter 12. Effects on the Benthic Invertebrate Community

*Frank W. Steimle, Jr., and David J. Radosh*[1]

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## INTRODUCTION

Assessment of the impact of the 1976 oxygen depletion on benthic invertebrates is based on: 1) in-situ diver observations; 2) incidental collections of benthic invertebrates in finfish trawling and shellfish dredging surveys; and 3) benthic grab collections.

Diver observations were composed of reports from NMFS divers and reliable sport divers of the species and relative numbers affected around wrecks in New York Bight. These reports included observations on the behavior of organisms that appeared to be affected and on other conditions apparently relevant to the phenomenon—for example, a dark, organic flocculent layer on the bottom.

Trawl surveys assessing the effect on finfish and shellfish resources began a few days after the initial reports of mortalities; dredge surveys began a few weeks later. Although commercially valuable species were the primary targets of the surveys, many noncommercial benthic invertebrates also were collected and used to assess the impact on larger invertebrate species.

Five surveys examined the effects on benthic infauna. Whenever possible stations that were occupied before the oxygen depletion event were reoccupied, but many stations were sampled for the first time. Thirty stations were examined between July and November 1976. Three 0.1-$m^2$ Smith-McIntyre grab samples were collected at each station. Each sample was washed through a 0.1-mm mesh screen, fixed in 10-percent buffered Formalin, and later transferred to 70-percent ethanol for storage. At least one of the triplicate samples, or a total of 46 samples, has been processed (fig. 12–1), with species identified and counted. The surveys selected both control stations and stations that could be expected to be affected greatly, i.e., in the area of the most severe anoxic and hydrogen sulfide conditions. The processed data were analyzed for H′ diversity (Shannon and Weaver 1963) and J′equitability (Pielou 1969).

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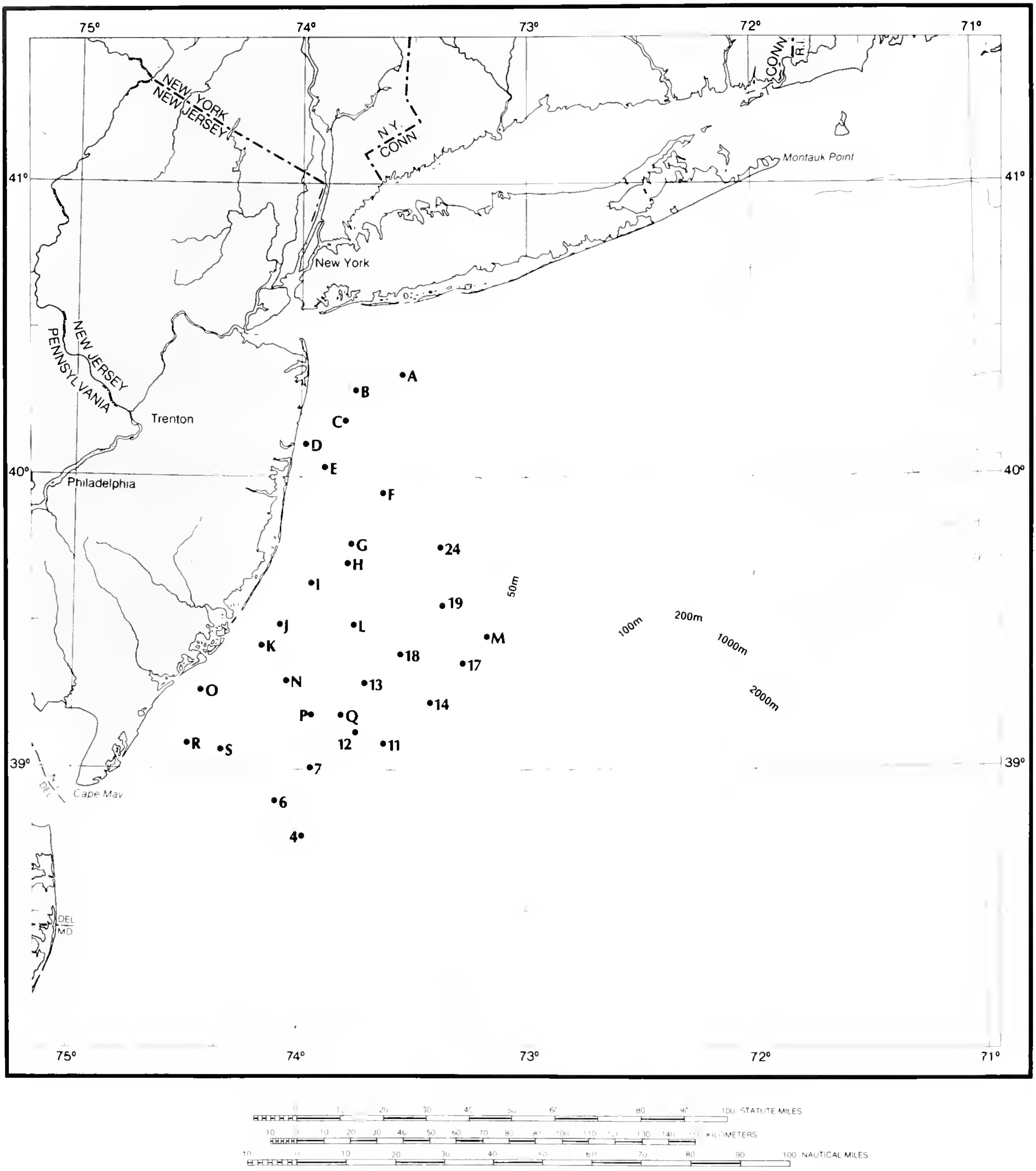

FIGURE 12-1.—Station locations for benthic grab collections. Numbered stations are part of Outer Continental Shelf series used for yearly comparisons.

Additional samples were collected during June and July 1977 and July 1978 to examine recolonization and long-term impacts. Only preliminary data are available for these samples.

## DIVER OBSERVATIONS

Benthic fauna was one of the first groups of organisms observed to be affected by the oxygen depletion. Initial clues to a developing problem came during the weekend of June 27, 1976. Sport divers visiting wrecks off central New Jersey observed lobsters (*Homarus americanus*) and rock crabs (*Cancer* sp.) congregated on the highest parts of wrecks, indicative of stressful but not yet lethal conditions at the bottom of the water column, below the 20-m-deep thermocline. They also observed surf clams (*Spisula solidissima*) lying on their sides on the sediment surface, also considered an indication of stress—for instance, hypoxia (Savage 1976). Initial reports of actual marine mortalities came during the July 4, 1976, weekend (Bullock 1976; E. Geer, American Littoral Society, personal communication). Sport divers reported many dead fish and invertebrates on or near wrecks and other diving spots off the north-central New Jersey coast in a zone extending from Long Branch to Barnegat Inlet and from about 5 to 40 km offshore. The invertebrate mortalities consisted mostly of rock crabs, lobsters, blue mussels (*Mytilus edulis*), and starfish (*Asterias forbesi*). Some lobsters were very sluggish, lying exposed, out of their shelters, with some sharing holes or dens. As the area of oxygen depletion increased, sport divers reported mortalities on wrecks as far south as Atlantic City by July 17. Divers reported mortalities off the central New Jersey coast throughout the summer.

In September, sport divers reported partial recovery and recolonization at some affected wrecks northeast of Manasquan Inlet. The recolonizers were mostly finfish, but a few rock crabs and lobsters were also found, where previously all were dead or had left the area.

During March 1977, NOAA divers reexamined an area near the center of the 1976 anoxia zone, southeast of Manasquan Inlet. They observed dense aggregations of the tube-dwelling polychaete, *Asabellides oculata* (fig. 12–2).

FIGURE 12–2.—Dense clumps of *Asabellides oculata* tubes located by NOAA divers off Manasquan Inlet during March 1977. Tubes are 5 to 10 cm long. (Photograph courtesy of E. Geer, American Littoral Society, Highlands, N.J.)

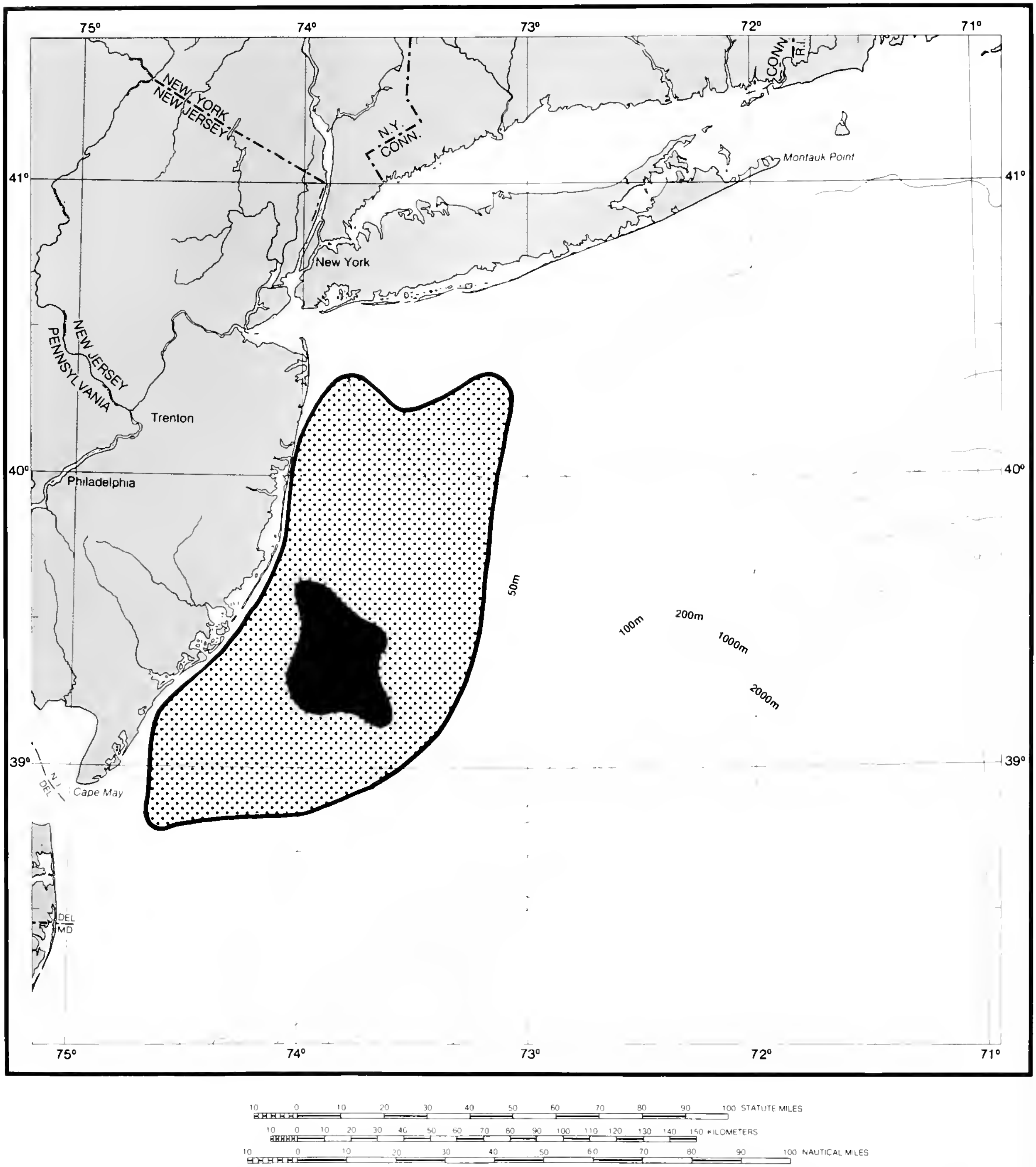

FIGURE 12-3.—Distribution of observed benthic mortalities July-November 1976. Dark area had greatest number of mortalities.

## TRAWL AND DREDGE SURVEYS

July survey results (Azarovitz, unpublished data; Ropes 1976a) indicated that benthic fauna at stations in a small area 5 to 10 km east-northeast of Barnegat Inlet (fig. 12–3) were severely impacted—greater than 50 percent total mortalities for all invertebrates collected. Surf clams were affected most; other mortalities included: burrowing anemones (*Ceriantheopsis americanus*); mollusks—sea scallops (*Placopecten magellanicus*), razor clams (*Ensis directus*), moon snails (*Lunatia heros*), and ocean quahogs (*Arctica islandica*); polychaete worms (mostly *Sigalion arenicola* but including *Aglaophamus circinata, Orbinia swani, Glycera dibranchiata, Lumbrineris fragilis*, and *Nephtys longosetosa*); unidentified sipunculans; crustaceans—rock crabs, mud shrimp (*Axius serratus*), lobsters, and mantis shrimp (*Platysquilla enodis*); and echinoderms—starfish, sand dollars (*Echinarachnius parma*), and sea cucumbers (*Caudina arenata*). Moderate impacts (10% to 50% total mortalities) involving the same species were found over a wider area, from Long Branch to Beach Haven, N.J., and between 5 and 35 km offshore. Other species, many that normally burrow in the sediments below the penetration of grabs, trawls, or dredges—for example, larger polychaetes, mud shrimp, mantis shrimp, sea cucumbers, sipunculans, and surf clams—were collected in finfish trawls, alive but in an obviously stressed state (fig. 12–4). Very little impact was observed within 3 km of shore except during two short periods when suspected upwellings of anoxic bottom water occurred in the surf zone; large numbers of dead calico crabs (*Ovalipes ocellatus*), rock crabs, and lobsters, as well as some finfish washed up on beaches near Manasquan and Beach Haven.

Surveys in August through November (Azarovitz 1976; Ropes 1976b, 1976c) showed the impacted area had expanded to that outlined in figure 12–3. Moderate impact was found as far south as Cape May and, as in July, the surf clam mortalities were the most extensive in relative numbers and biomass of dead animals collected. Putrifying surf clam meats were found in trawls at several stations during August collections.

Surveys in October and November showed continued scattered evidence of mortalities; mostly "clapper" (defined in ch. 11, pt. 1) razor clams and ocean quahogs were

FIGURE 12–4.—Normal deep-burrowing benthic species collected in trawl nets (clockwise from upper right): *Nereis longosetosa, Sigalion arenicola, Axius serratus, Spisula solidissima* (meats only), *Ensis directus, Caudina arenata, Cancer irroratus* (not a burrower), more *Caudina*, and near center *Platysquilla enodis*. Compare size with nickel.

TABLE 12–1.—*Affected benthic invertebrate species collected in trawl or dredge samples, with observations on extent of impact*

| Species | Common name | Comments |
|---|---|---|
| *Ceriantheopis americanus* | burrowing anemone | a few dead observed by divers and collected by trawl surveys |
| Various polychaetes (mostly *Sigalion arenicola*) | marine worms | hundreds collected hanging dead from trawl net mesh |
| *Axius serratus* | mud shrimp | a few collected in trawl collections |
| *Platysquilla enodis* | mantis shrimp | a few collected in trawl collections |
| *Libinia emarginata* | spider crab | a few collected in trawl collections |
| *Cancer irroratus* | rock crab | hundreds reported dead by divers and collected in surveys |
| *Cancer borealis* | Jonah crab | dozens reported dead by divers and collected in surveys |
| *Homarus americanus* | American lobster | dozens reported dead by divers and collected in surveys |
| *Mytilus edulis* | blue mussel | thousands reported dead on wrecks by divers |
| *Placopecten magellanicus* | sea scallop | dozens dead and recent empty clappers collected in surveys |
| *Astarte castanea* | chestnut astarte | a few collected in surveys |
| *Arctica islandica* | ocean quahog | hundreds collected dead or as recent empty clappers in surveys, especially in the autumn and offshore |
| *Spisula solidissima* | surf clam | thousands of dead clams and clappers and bushels of unattached meats collected during surveys |
| *Ensis directus* | razor clam | dozens of dead or recent clappers found in surveys |
| *Lunatia heros* | moon snail | several collected dead in surveys |
| *Asterias forbesi* | starfish | hundreds reported dead by divers and collected in surveys |
| *Echinarachnius parma* | sand dollar | hundreds collected dead in surveys |
| Unidentified holothurian | sea cucumber | a few collected dead in surveys |
| Sipunculans | no common name | a few collected in trawl surveys |

found. There was also some recolonization by cancroid crabs and starfish in this area.

Table 12–1 lists invertebrate macrofaunal species collected in New York Bight by trawls or dredges during July-November 1976. Detailed listings of impacts are available (Steimle 1977).

## GRAB COLLECTIONS

Data from 11 stations sampled in April 1975 (table 12–2) and resampled during October and November 1976 (Pearce et al. 1977) are compared. To simplify analysis and interpretation of impacts, the tables include only species taken at three or more stations. Table 12–3 shows the results from the remaining 19 processed stations.

## DISCUSSION

The benthic invertebrate fauna of New York Bight is dominated by organisms adapted to relatively clean porous sands (Pratt 1973; Pearce et al., in press). This fauna does not normally experience extended periods of anoxia or significant levels of hydrogen sulfide; thus most species have a low tolerance level to these conditions (Theede et al. 1969; Davis 1975; Shick 1976). When the bottom waters of the Bight became depleted of oxygen and significant hydrogen sulfide concentrations subsequently developed, it could be anticipated that mortalities within the benthic community would be extensive. Diver observations and results of biological surveys, using various sampling equipment, support this hypothesis.

The best evidence of impacts to the benthic community are from trawl and dredge collections. These impacts (table 12–1) indicate that a wide variety of benthic species in the area of oxygen depletion had extensive mortalities. Organisms involved included over 20 species of invertebrates, most incidental to survey target species, that is, commercially important shellfish and finfish. Both epifaunal (e.g., crabs and lobsters) and macroinfaunal species (e.g., polychaete worms and other deep-burrowing organisms, *Axius, Platysquilla, Caudina,* and sipunculans) were noted. Of interest were deep-burrowers, which have been rare in most previous New York Bight benthic collections, mainly because they are generally below the sampling range of most standard benthic equipment. For a few species, especially surf clams, the effects were massive in numbers and biomass of animals affected. For other species, like lobsters, the response was mainly avoidance and disruption of normal seasonal migrations. Chapters 11 and 13 discuss the effects on commercially valuable species.

Unfortunately, Smith-McIntyre grab collections resulted in mostly circumstantial evidence of effects on the macrofauna. Actual mortalities were observed in only two samples, station 24, including some sand dollars and one polychaete (*Sthenelais limicola*), and station B near the head of the Hudson Shelf Valley, where dead holothuroideans (*Thyone* sp.) were found in one of the three samples taken. Also available from our grab samples are data on numbers of clapper bivalves present, indicating recent mortalities (table 12–4).

What appear to be the best indications of effects on the infauna are the low numbers of species, individuals, and diversities (H′) found at stations E, F, I, J, L, N, P, Q, and 18 (tables 12–2 and 12–3). Again, this evidence has its limitations, because of variability and inadequate baselines for most of the area affected by the oxygen-depleted water mass. Triplicate samples were processed for several stations, however, and where numbers of species and individuals were consistently low, we believe this indicates an impact from anoxia. Stations I, L, and N appeared to be particularly affected. Stations P and Q may also have been affected, but the data are less convincing, because of variability (P) or lack of replication (Q).

A possible alternate approach to assessing impacts on the infauna is to concentrate on population changes in species known to be fairly ubiquitous in the sandy sediments off New Jersey. Such species have been identified in several studies (Boesch et al. 1977a, 1977b; Radosh et al. 1978). Based on these studies and on numbers of station occurrences in table 12–2, these species include *Ceriantheopsis americanus, Aglaophamus circinata, Leiochone dispar, Spiophanes bombyx, Byblis serrata, Cirolana polita,* and *Echinarachnius parma. Spiophanes* and *Ceriantheopsis,* known to be tolerant species occurring in stressed environments like sewage disposal areas, increased markedly in abundance. Boesch et al. (1977a, 1977b) also found these two species to resist the anoxia and found *Spiophanes* to be opportunistic as well. We know the low tolerances of *Echinarachnius* and crustaceans (Boesch et al. 1977a, 1977b) to anoxia. Based on increases in *Spiophanes* and *Ceriantheopsis* and decreases in the other species listed above, there were probably severe anoxia impacts at stations 11 and 13, moderate effects at stations 4, 18, and 24, and little or no impact at stations 6, 7, 8, 12, 14, 17, and 19. Figure 12–3 shows the area of greatest impact to the benthic macrofauna, based on tables 12–2 and 12–3.

The substantial postanoxia increases in populations of *Spiophanes* and *Ceriantheopsis* may be due to rapid recolonization as well as to tolerance of anoxia and sulfide. The polychaete, *Goniadella gracilis,* was abundant at the heavily impacted stations I, L, and N, implying high tolerance to oxygen depletion. This was unexpected, since *Goniadella* is characteristic of ridge environments (Boesch et al. 1977a, 1977b; Radosh et al. 1978) in which anoxic episodes must be relatively rare. There is evidence that the polychaetes, *Aricidea cerruti* and *Tharyx acutus,* and the bivalve *Astarte castanea* may also be tolerant to anoxia. The increased occurrence in our samples of the deep-burrowing mantis shrimp, *Platysquilla enodis,* is undoubtedly a sign of stress rather than of resistance.

The absence of any appreciable effects on the benthic fauna at stations G and H near the center of the anoxic water mass can be attributed to these two stations being on an elevated sand-gravel ridge. The height of this ridge is near the depth of the thermocline (25–30m), and more oxygen is expected to be available here, at least intermittently, than in the surrounding deeper waters.

Two other benthic studies in the area during the low oxygen condition also found affects to the benthic invertebrate community. Boesch et al. (1977a, 1977b) reported the megabenthos to be severely affected at a station about 30 km east of Atlantic City in August 1976, but little affected in November at a station farther east. They found drastic reductions in the populations of the sand shrimp, *Crangon septemspinosus;* the rock crab, *Cancer irroratus;* the small peracaridean crustaceans, *Tanaissus liljeborgi, Protohaustorius wigleyi,* and *Pseudunciola obliquua;* the starfish, *Asterias forbesi;* and the sand dollar, *Echinarachnius parma.* They noted large quantities of decayed

TABLE 12-2.—*Comparison of benthic data at 12 stations occupied in April 1975 before the oxygen depletion event and again in October-November 1976 after the oxygen depletion event*

| Benthic organisms observed | At number of stations each year | | Number observed at each station each year[1] | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 4 | | 6 | | 7 | | 8 | | 11 | | 12 | |
| | 75 | 76 | 75 | 76 | 75 | 76 | 75 | 76 | 75 | 76 | 75 | 76 | 75 | 76 |
| Archiannelida | 8 | 8 | — | 1 | 266 | — | — | 4 | 21 | — | 4 | 22 | 2 | 1 |
| Ceriantharia: | 1 | 10 | — | — | — | — | — | — | — | — | — | — | — | — |
| *Ceriantheopsis americanus* | — | — | — | 6 | — | — | — | — | — | 1 | 1 | 13 | — | 1 |
| Rhynchocoela | 7 | 11 | 4 | 4 | 2 | 4 | 2 | 4 | — | 1 | — | 30 | 1 | 2 |
| Polychaeta: | | | | | | | | | | | | | | |
| *Phyllodoce arenae* | 3 | 3 | 1 | — | — | — | — | — | — | 12 | — | — | — | — |
| *Sthenelais limicola* | 3 | 3 | 1 | — | — | — | — | — | 1 | — | — | 3 | — | — |
| *Glycera dibranchiata* | 8 | 6 | 4 | 2 | 2 | — | — | — | — | — | 2 | — | — | 1 |
| *Goniadella gracilis* | 4 | 5 | — | — | 45 | — | — | — | 28 | — | — | — | — | — |
| *Nephtys picta* | 2 | 3 | — | — | — | — | — | 3 | — | — | — | 2 | 1 | 3 |
| *Aglaophamus circinata* | 10 | 5 | 11 | 16 | — | 1 | 2 | — | 2 | 4 | 1 | — | 2 | — |
| *Exogone hebes* | 5 | 8 | — | — | 2 | — | — | 2 | 1 | 21 | — | 1 | — | — |
| *Nereis grayi* | 3 | 3 | 1 | — | 4 | — | — | — | — | 2 | — | — | — | — |
| *Scalibregma inflatum* | 2 | 3 | — | 2 | — | — | — | — | — | — | — | — | — | — |
| *Clymenella zonalis* | 6 | 5 | 10 | — | 8 | 8 | 1 | — | 33 | 17 | — | — | — | 1 |
| *Leiochone dispar* | 10 | 0 | 3 | — | 1 | — | 1 | — | 2 | — | — | — | 2 | — |
| *Spiophanes bombyx* | 9 | 11 | 272 | 199 | — | 3 | 1 | 3 | 1 | 193 | 34 | 321 | 10 | — |
| *Aricidea cerruti* | 4 | 10 | — | 7 | 1 | 10 | 1 | — | 7 | 9 | — | 6 | — | — |
| *Aricidea wassi* | 4 | 6 | — | — | — | 3 | — | 4 | — | 1 | — | 1 | 2 | 3 |
| *Lumbrinerides acuta* | 4 | 5 | — | — | 2 | — | — | — | 35 | 1 | — | — | — | 2 |
| *Lumbrineris fragilis* | 5 | 3 | 1 | 1 | 2 | 1 | — | — | — | 3 | — | — | — | — |
| *Lumbrineris tenuis* | 3 | 3 | 4 | — | 2 | — | — | — | 1 | — | — | — | — | — |
| *Drilonereis magna* | 4 | 3 | — | — | 1 | — | — | — | 5 | — | 1 | — | 2 | — |
| *Dorvillea caeca* | 0 | 6 | — | 7 | — | — | — | — | — | 5 | — | 1 | — | — |
| *Tharyx acutus* | 6 | 5 | — | 2 | 264 | — | 1 | — | 4 | 14 | — | — | — | — |
| *Tharyx annulosus* | 3 | 5 | — | — | 3 | — | — | — | — | 1 | — | — | 2 | — |
| *Caulleriella killariensis* | 4 | 4 | — | — | — | — | — | 1 | 5 | 9 | — | — | — | — |
| *Ampharete arctica* | 5 | 7 | 5 | 6 | — | — | — | 1 | — | 6 | — | 17 | — | — |
| *Euchone rubrocincta* | 6 | 0 | 3 | — | — | — | — | — | 1 | — | 1 | — | — | — |
| Mollusca: | | | | | | | | | | | | | | |
| *Cyclocardia borealis* | 1 | 4 | 2 | — | — | — | — | — | — | — | — | — | — | — |
| *Ensis directus* | | | | | | | | | | | | | | |
| Crustacea: | | | | | | | | | | | | | | |
| *Leptognatha caeca* | 4 | 1 | — | — | — | — | — | — | 1 | — | — | — | 2 | — |
| *Ptilanthura tricarina* | 1 | 5 | — | 1 | — | — | — | — | — | — | — | — | — | — |
| *Cirolana polita* | 6 | 2 | 2 | — | — | — | 1 | 4 | 3 | — | 14 | — | — | — |
| *Edotea tribola* | 4 | 1 | — | — | — | — | — | — | — | 1 | 2 | — | — | — |
| *Ampelisca vadorum* | 2 | 3 | 3 | 1 | — | — | — | — | — | 5 | — | — | — | — |
| *Ampelisca agassizi* | 3 | 3 | — | — | 1 | — | — | — | — | — | — | — | — | — |
| *Byblis serrata* | 10 | 5 | 4 | — | 2 | — | 17 | 1 | 5 | 6 | 25 | — | — | — |
| *Unciola irrorata* | 6 | — | 4 | 10 | — | — | 3 | 1 | — | 17 | 1 | 29 | — | — |
| *Unciola inermis* | 3 | 4 | — | — | 1 | — | — | — | — | — | — | — | — | — |
| *Pseudunciola obliquua* | 4 | 4 | 1 | 5 | — | — | 467 | — | — | — | — | 1 | 3 | 7 |
| *Protohaustorius wigleyi* | 4 | 4 | — | — | — | 14 | 8 | 1 | — | — | 1 | — | 2 | 3 |
| *Acanthohaustorius spinosus* | 2 | 3 | — | — | — | — | — | 1 | — | — | — | — | 1 | — |
| *Leptocheirus pinguis* | 2 | 3 | — | — | — | — | — | — | — | — | — | — | — | — |
| *Phoxocephalus holbolli* | 4 | 1 | — | — | 1 | — | — | — | 1 | — | — | — | — | — |
| *Paraphoxus epistomus* | 8 | 8 | 16 | 21 | — | 24 | 17 | 5 | 3 | 2 | 8 | 1 | — | 13 |
| *Cancer irroratus* | 2 | 4 | — | — | 1 | 1 | — | 1 | — | — | — | — | — | — |
| Phoronida: | | | | | | | | | | | | | | |
| *Phoronis psammophila* | 0 | 9 | — | 149 | — | — | — | — | — | 1 | — | 90 | — | 2 |
| Echinodermata: | | | | | | | | | | | | | | |
| *Echinarachnius parma* | 10 | 5 | 3 | — | — | 8 | 9 | — | 6 | 4 | 14 | — | 15 | 22 |
| Total # species | | | 27 | 31 | 25 | 19 | 16 | 19 | 23 | 35 | 19 | 17 | 19 | 13 |
| Total # individuals | | | 370 | 472 | 624 | 93 | 113 | 40 | 168 | 387 | 118 | 543 | 52 | 61 |
| H′ diversity | | | 1.34 | 1.81 | 1.34 | 2.43 | 1.93 | 2.73 | 2.38 | 2.21 | 2.18 | 1.46 | 2.40 | 2.00 |
| Equitability | | | 0.41 | 0.53 | 0.42 | 0.82 | 0.89 | 0.93 | 0.76 | 0.62 | 0.74 | 0.51 | 0.83 | 0.78 |

[1] See figure 12-1 for station locations.

TABLE 12-2.—*Comparison of benthic data at 12 stations occupied in April 1975 before the oxygen depletion event and again in October-November 1976 after the oxygen depletion event—(continued)*

| Benthic organisms observed | Number observed at each station each year[1] | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 13 | | 14 | | 17 | | 18 | | 19 | | 24 | |
| | 75 | 76 | 75 | 76 | 75 | 76 | 75 | 76 | 75 | 76 | 75 | 76 |
| Archiannelida | — | 4 | 15 | 293 | 13 | 105.5 | 1 | — | — | 5 | 102 | — |
| Ceriantharia: | | | | | | | | | | | | |
| *Ceriantheopsis americanus* | — | 30.5 | — | 3 | — | 7.5 | — | 2 | — | 7 | — | 21 |
| Rhynchocoela | 3 | 55 | 1 | 2.5 | — | 16 | 1 | — | — | 3 | — | 2 |
| Polychaeta: | | | | | | | | | | | | |
| *Phylodoce arenae* | — | — | 1 | 2.5 | 2 | 9 | — | — | — | — | — | — |
| *Sthenelais Limicola* | — | 3 | — | 2 | 1 | — | — | — | — | — | — | — |
| *Glycera dibranchiata* | 1 | — | 1 | .5 | 5 | 5 | 1 | 1 | — | — | 3 | 2 |
| *Goniadella gracilis* | — | 13.5 | — | — | — | 4 | — | .5 | 10 | 10 | 5 | 3 |
| *Nephtys picta* | 1 | — | — | — | — | — | — | — | — | — | — | — |
| *Aglaophamus circinata* | 2 | — | 3 | 5.5 | 2 | 3.5 | 1 | — | — | — | 1 | — |
| *Exogone hebes* | — | 1 | — | 5.5 | 1 | 21 | — | 1 | 1 | 1 | 5 | — |
| *Nereis grayi* | — | .5 | — | — | — | 2.5 | — | — | — | — | — | — |
| *Scalibregma inflatum* | — | — | — | .5 | 2 | 19 | 1 | — | — | — | — | — |
| *Clymenella zonalis* | — | .5 | 1 | — | — | 90 | — | — | 1 | — | — | — |
| *Leiochone dispar* | 1 | — | 3 | — | 3 | — | 4 | — | — | — | 1 | — |
| *Spiophanes bombyx* | 2 | 62 | 40 | 356 | 24 | 46 | 1 | 4 | — | 138 | — | 64 |
| *Aricidea cerruti* | — | 11 | — | 1.5 | — | .5 | — | — | — | — | 1 | — |
| *Aricidea wassi* | — | — | 1 | — | — | 16.5 | — | 2.5 | — | 2 | 6 | 1 |
| *Lumbrinerides acuta* | — | — | — | 3 | 1 | — | 1 | — | — | 1 | — | — |
| *Lumbrineris fragilis* | — | — | 1 | — | — | 2.5 | — | — | 4 | — | 18 | 15 |
| *Lumbrineris tenuis* | — | 6 | — | — | — | — | — | — | 4 | — | 1 | — |
| *Drilonereis magna* | — | — | — | 1.5 | — | 10 | — | — | — | 13 | — | — |
| *Dorvillea caeca* | — | — | — | 12 | — | — | — | — | — | — | 1 | 2 |
| *Tharyx acutus* | 1 | 1 | — | — | — | 21.5 | — | — | — | — | — | 4 |
| *Tharyx annulosus* | — | 2 | — | — | 1 | 92.5 | — | — | — | — | 16 | 2 |
| *Caulleriella killariensis* | — | — | 1 | 7 | — | 12.5 | — | .5 | — | — | 1 | 1 |
| *Ampharete arctica* | — | 12 | 6 | 12.5 | 2 | 10 | — | — | — | — | 1 | — |
| *Euchone rubrocincta* | — | — | 39 | — | 2 | 4 | 1 | — | — | — | 1 | — |
| Mollusca: | — | — | — | — | 27 | — | 1 | — | — | — | — | — |
| *Cyclocardia borealis* | — | .5 | — | — | — | — | — | — | — | — | — | — |
| *Ensis directus* | — | 6.5 | 1 | — | — | 1 | — | — | — | — | — | — |
| Crustacea: | — | — | — | — | 1 | — | — | — | — | — | — | — |
| *Leptognatha caeca* | — | — | 1 | — | — | — | — | — | — | — | — | — |
| *Ptilanthura tricarina* | — | .5 | — | .5 | — | 1.5 | — | — | — | — | — | — |
| *Cirolana polita* | 1 | — | 1 | — | — | 2 | — | — | — | — | — | — |
| *Edotea triloba* | — | — | — | — | — | — | 1 | — | 1 | — | — | — |
| *Ampelisca vandorum* | — | — | — | — | — | — | — | 1 | — | — | — | 1 |
| *Ampelisca agassizi* | — | — | — | — | — | .5 | — | — | — | — | — | — |
| *Byblis serrata* | 6 | — | 9 | 1.5 | — | 5.5 | — | — | — | — | — | — |
| *Unicola irrorata* | — | 1.5 | 13.5 | — | 8 | 6 | — | — | — | — | — | — |
| *Unicola inermis* | — | — | 6 | — | — | 52.5 | 2 | — | — | — | 1 | — |
| *Pseudunciola obliquua* | — | — | — | — | — | 75 | — | — | — | — | — | — |
| *Protohaustorius wigleyi* | — | — | — | 3 | — | — | — | — | — | — | — | — |
| *Acanthohaustorius spinosus* | 1 | — | — | .5 | — | — | — | — | — | — | — | — |
| *Leptocheirus pinguis* | — | — | — | 1 | — | — | — | 1 | — | — | 1 | — |
| *Phoxocephalus holbolli* | — | — | — | — | — | .5 | — | — | — | — | — | — |
| *Paraphoxus epistomus* | — | — | — | — | — | — | — | — | — | — | — | 4 |
| *Cancer irroratus* | 5 | — | 7 | 7.5 | 3 | 7.5 | 1 | — | — | — | — | — |
| Phoronida: | | | | | | | | | | | | |
| *Phoronis psammophila* | — | 13 | — | 8 | — | 14.5 | — | 10 | — | 26 | — | — |
| Echinodermata: | | | | | | | | | | | | |
| *Echinarachnius parma* | 10 | — | 14 | 8 | 10 | 3 | 9 | — | — | — | — | — |
| Total # species | 14 | 27 | 24 | 26 | 25 | 50 | 23 | 6 | 10 | 14 | 21 | 15 |
| Total # individuals | 37 | 636 | 157 | 783 | 116 | 1,045 | 40 | 26 | 23 | 210 | 174 | 125 |
| H' diversity | 2.28 | 1.41 | 2.31 | 1.51 | 2.50 | 2.61 | 2.75 | 0.95 | 1.83 | 1.31 | 1.67 | 1.68 |
| J' equitability | 0.86 | 0.43 | 0.73 | 0.56 | 0.77 | 0.69 | 0.88 | 0.90 | 0.79 | 0.49 | 0.55 | 0.62 |

TABLE 12–3.—*Abundance and distribution of macrofaunal species occurring at 3 or more of 19 other stations, including replicate grab data for stations B, D, I, L, N, and P*

| | Stations[1] | | | | | | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | A | B | | | C | D | | | E | F | G | H | I | | | J | K |
| Macrofaunal species | | 1 | 2 | 3 | | 1 | 2 | 3 | | | | | 1 | 2 | 3 | | |
| *Ceriantheopsis americanus* | 1 | — | — | 12 | 2 | 5 | 9 | 2 | — | — | 2 | 6 | — | — | — | — | — |
| *Sthenelais limicola* | 1 | — | — | 1 | — | — | — | 1 | — | — | 1 | — | — | — | — | 2 | — |
| *Sigalion arenicola* | 1 | — | — | — | 1 | — | — | — | — | 1 | — | — | — | — | — | — | — |
| *Phyllodoce arenae* | — | — | — | 1 | — | — | — | — | — | — | — | — | — | — | — | — | 2 |
| *Exogone hebes* | — | — | — | — | — | — | 1 | — | 2 | 2 | — | — | — | — | — | — | — |
| *Nephtys picta* | 5 | — | — | — | — | — | 16 | 12 | 7 | — | 1 | — | — | — | — | 2 | — |
| *Goniadella gracilis* | — | — | — | — | — | 3 | 6 | — | — | 5 | 8 | 16 | 3 | 9 | 6 | — | 14 |
| *Capitella capitata* | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | 4 |
| *Macroclymene zonalis* | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — | — |
| *Aricidea cerrutii* | — | — | — | 4 | — | — | — | — | 1 | — | 10 | 8 | — | — | — | — | — |
| *Aricidea wassi* | 2 | — | — | — | — | 1 | 4 | 5 | — | 3 | — | — | — | — | — | — | — |
| *Scolelepis squamata* | — | — | — | — | — | — | — | — | — | — | — | 3 | — | — | — | 1 | 3 |
| *Spiophanes bombyx* | 1 | — | — | 3 | — | 41 | 17 | 2 | — | 17 | 1 | 9 | 2 | — | 1 | 63 | 92 |
| *Lumbrineris tenuis* | — | 128 | 14 | 27 | — | — | 1 | — | — | — | — | — | — | — | — | — | — |
| *Lumbrineris fragilis* | — | — | — | — | 1 | 3 | 1 | 1 | 3 | — | — | 1 | — | — | — | — | — |
| *Lumbrinerides acuta* | — | — | — | — | — | 1 | — | — | — | 1 | 4 | 5 | — | — | — | — | — |
| *Magelona rosea* | 1 | — | — | — | — | 1 | 1 | 1 | — | — | — | — | — | — | — | 65 | — |
| *Tharyx annulosus* | — | 62 | 2 | 5 | — | — | — | — | 6 | 2 | 7 | — | — | — | — | — | 7 |
| *Tharyx acutus* | 1 | 1 | 2 | 40 | — | — | 2 | — | — | 2 | 3 | 1 | — | — | — | — | — |
| *Caulleriella killariensis* | — | — | — | — | — | — | — | 3 | — | — | — | 1 | — | — | — | — | — |
| *Asabellides oculata* | — | — | — | — | — | 1 | 4 | — | — | 2 | — | 1 | — | — | — | 6 | 120 |
| *Ampharete arctica* | 1 | — | — | — | — | 9 | 18 | 2 | — | — | — | 1 | — | — | — | — | — |
| *Nassarius trivittatus* | — | — | — | — | — | 1 | — | — | — | — | — | — | — | — | — | 2 | — |
| *Ensis directus* | — | — | — | — | — | — | — | — | — | — | — | 1 | — | — | — | — | 17 |
| *Nucula proxima* | — | 32 | 3 | 88 | 1 | 2 | 3 | 3 | 1 | — | — | — | — | — | — | — | — |
| *Astarte castanea* | — | — | — | — | 3 | — | 2 | — | — | — | 3 | 3 | — | — | — | — | 4 |
| *Tellina agilis* | 9 | — | — | 2 | 1 | 31 | 11 | 13 | 21 | 2 | — | 4 | — | — | — | — | 6 |
| *Spisula solidissima* | — | — | — | — | 3 | 4 | — | — | — | — | 2 | — | — | — | — | — | 1 |
| Unidentified copepod | — | — | — | 6 | — | — | — | — | 58 | — | 19 | — | 1 | — | 1 | 1 | 8 |
| *Oxyurostylis smithi* | — | — | — | — | — | — | — | — | — | — | — | 1 | — | — | — | — | 4 |
| *Cirolana polita* | — | — | — | — | — | — | — | — | — | — | — | 1 | — | — | — | — | — |
| *Pseudunciola obliquua* | 1 | — | — | — | — | 5 | 1 | — | — | — | — | — | — | — | — | — | 1 |
| *Unciola irrorata* | 1 | — | — | 43 | 2 | 4 | — | — | — | — | — | — | — | — | — | — | — |
| *Trichophoxus epistomus* | 7 | — | — | — | 8 | 1 | 2 | 2 | — | — | — | — | — | — | — | — | — |
| *Platysquilla enodis* | — | — | — | — | — | — | — | — | — | — | — | — | — | — | 1 | 1 | — |
| *Cancer irroratus* | 1 | — | — | 2 | 2 | — | — | 1 | — | — | — | — | — | — | — | — | — |
| *Phoronis psammophila* | — | — | — | 1 | — | 13 | 25 | 10 | 9 | — | 9 | — | — | — | — | — | 1 |
| *Asterias forbesi* | — | — | — | — | — | — | 1 | — | — | — | — | — | — | — | — | — | — |
| *Echinarachnius parma* | 2 | — | — | — | — | 3 | — | — | — | — | — | 4 | — | — | — | — | 8 |
| Total # species | 19 | 27 | 24 | 56 | 16 | 24 | 30 | 20 | 12 | 13 | 18 | 30 | 3 | 4 | 5 | 11 | 23 |
| Total # individuals | 43 | 530 | 152 | 705 | 39 | 136 | 173 | 70 | 72 | 61 | 95 | 1139 | 10 | 22 | 12 | 164 | 305 |
| H′ diversity | 2.57 | 2.40 | 2.77 | 3.06 | 2.47 | 2.33 | 2.87 | 2.56 | 1.97 | 1.95 | 2.43 | 0.72 | 1.03 | 0.99 | 1.31 | 1.43 | 1.89 |
| J′ equitability | .873 | .728 | .872 | .760 | .891 | .732 | .844 | .856 | .792 | .761 | .841 | .211 | .937 | .717 | .817 | .595 | .602 |

[1] See figure 12–1 for station locations.

TABLE 12–3 (continued)

| | L | | | M | N | | | O | P | | | Q | R | S |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | | 1 | 2 | 3 | | 1 | 2 | 3 | | | |
| *Ceriantheopsis americanus* | — | — | — | 3 | — | — | 1 | 1 | — | 1 | 3 | — | 2 | 4 |
| *Sthenelais limicola* | — | — | — | — | — | — | — | — | — | — | — | — | 1 | 1 |
| *Sigalion arenicola* | — | — | — | — | — | — | — | 3 | — | 1 | — | 1 | — | — |
| *Phyllodoce arenae* | — | — | — | 5 | — | — | — | — | — | — | — | — | — | — |
| *Exogone hebes* | — | — | — | 5 | — | — | — | — | — | 1 | — | — | 1 | — |
| *Nephtys picta* | — | — | — | — | — | — | — | 13 | — | — | — | — | 2 | 4 |
| *Goniadella gracilis* | 9 | 6 | 18 | 4 | 1 | 14 | 5 | — | 31 | 2 | — | 9 | 1 | — |
| *Capitella capitata* | — | — | — | 10 | — | — | — | — | — | 2 | — | — | 7 | 1 |
| *Macroclymene zonalis* | — | — | — | 17 | — | — | — | — | 1 | — | — | — | — | — |
| *Aricidea cerruti* | — | — | — | 1 | — | — | — | — | 5 | 4 | — | 1 | 23 | — |
| *Aricidea wassi* | — | — | — | — | — | — | — | — | — | 2 | — | — | — | — |
| *Scolelepis squamata* | — | — | — | — | 1 | — | — | — | — | — | — | — | — | — |
| *Spiophanes bombyx* | — | — | — | 288 | 1 | — | — | 20 | — | 1 | — | — | 2 | 1 |
| *Lumbrineris tenuis* | — | — | — | — | — | — | — | — | — | — | 1 | — | — | — |
| *Lumbrineris fragilis* | — | — | — | 1 | — | — | — | — | — | — | — | — | 5 | — |
| *Lumbrinerides acuta* | — | — | — | 12 | — | — | — | — | — | — | — | 1 | — | — |
| *Magelona rosea* | — | — | — | — | — | — | — | 496 | — | — | — | — | — | 2 |
| *Tharyx annulosus* | 10 | 1 | 2 | — | — | — | — | — | 2 | — | — | — | 1 | 2 |
| *Tharyx acutus* | — | — | — | — | — | — | — | 3 | — | 1 | 1 | 1 | 1 | — |
| *Caulleriella killariensis* | — | — | — | 1 | — | — | — | 1 | — | — | 1 | — | — | — |
| *Asabellides oculata* | — | — | — | — | — | — | — | 1 | — | — | — | — | — | — |
| *Ampharete arctica* | — | — | — | 1 | — | — | — | — | — | — | — | — | — | 2 |
| *Nassarius trivittatus* | — | — | — | — | — | — | — | 1 | — | — | — | — | — | 2 |
| *Ensis directus* | — | — | — | — | — | — | — | — | — | — | — | — | — | 6 |
| *Nucula proxima* | — | — | — | — | — | — | — | — | — | — | — | — | 2 | — |
| *Astarte castanea* | — | — | — | — | — | 3 | 6 | — | — | — | — | — | — | — |
| *Tellina agilis* | — | — | — | — | — | — | — | 10 | 1 | 2 | — | — | — | 26 |
| *Spisula solidissima* | — | — | — | — | — | — | — | — | — | — | — | — | 4 | — |
| Unidentified copepod | — | — | — | — | — | — | — | — | — | — | — | — | X | — |
| *Oxyurostylis smithi* | — | — | — | — | — | 1 | — | — | — | — | — | — | — | — |
| *Cirolana polita* | — | 1 | — | 3 | — | — | — | — | — | — | — | 1 | — | — |
| *Pseudunciola obliquua* | — | — | — | — | — | — | — | 1 | — | 1 | 1 | — | — | — |
| *Unciola irrorata* | — | — | 11 | — | — | — | — | — | — | — | — | 1 | 1 | — |
| *Trichophoxus epistomus* | — | — | 13 | — | — | — | — | — | — | — | — | — | — | 24 |
| *Platysquilla enodis* | — | 1 | — | — | — | — | — | — | — | — | — | — | — | — |
| *Cancer irroratus* | — | — | — | — | — | — | — | — | — | — | 1 | — | — | — |
| *Phoronis psammophila* | — | — | 2 | — | — | — | — | 9 | 3 | 20 | 40 | — | 3 | 6 |
| *Asterias forbesi* | — | — | 2 | — | — | — | — | — | — | — | — | — | 5 | — |
| *Echinarachnius parma* | — | — | 3 | — | — | — | — | 1 | — | — | — | — | — | 6 |
| Total # species | 4 | 4 | 5 | 31 | 4 | 4 | 4 | 20 | 7 | 20 | 8 | 9 | 32 | 20 |
| Total # individuals | 33 | 25 | 33 | 421 | 30 | 30 | 22 | 608 | 57 | 54 | 63 | 17 | 529 | 93 |
| H′ Diversity | 1.19 | 0.86 | 1.00 | 1.56 | 0.43 | 1.07 | 1.19 | 0.91 | 1.30 | 2.31 | 0.92 | 1.67 | 1.44 | 2.28 |
| J′ equitability | .858 | .622 | .670 | .454 | .314 | .768 | .858 | .304 | .670 | .770 | .445 | .760 | .416 | .760 |

TABLE 12–4.—*Benthic mortalities indicated by clappers in grab samples, August-November 1976*

| Month | Station[1] | Grab No. | Number of clappers |
|---|---|---|---|
| August | E | 1 | 7 *Tellina*, 1 *Astarte*, 1 *Cyclocardia* |
| October | A | 1 | 4 *Tellina* |
| October | I | 1 | 5 *Tellina*, 1 *Spisula*, 1 *Pitar* |
| | | 2 | 7 *Tellina* |
| | | 3 | 2 *Tellina*, 5 *Astarte*, 1 *Nucula* |
| November | J | 1 | 5 *Tellina* |
| October | L | 1 | 2 *Spisula*, 1 *Cyclocardia* |
| October | M | 2 | 1 *Spisula* |
| | | 3 | 2 *Spisula*, 2 *Tellina* |
| November | N | 1 | 6 *Tellina* |
| October | O | 2 | 2 *Ensis*, 7 *Tellina*, 1 *Spisula*, 1 *Cerastoderma* |
| | | 3 | 1 *Tellina*, 1 *Nucula* |
| October | R | 1 | 1 *Tellina*, 2 *Pitar*, 1 *Ensis* |
| October | 4 | 1 | 2 *Cyclocardia*, 1 *Astarte* |
| October | 6 | 1 | 2 *Tellina* |
| October | 14 | 2 | 1 *Ensis* |
| October | 18 | 1 | 5 *Tellina*, 3 *Ensis*, 1 *Spisula* |
| October | 19 | 1 | ?# *Spisula* |
| October | 24 | 1 | 2 *Ensis;* Dead: many *Echinarachnius* and 1 *Sthenelais limicola* |

[1] See figure 12–1 for station locations.

surf clam meats in trawl nets and dead or dying specimens of other species, for example, the polychaetes, *Glycera dibranchiata* and *Sigalion arenicola;* the sipunculan, *Phascolopsis gouldii;* the mantis shrimp, *Platysquilla enodis;* and unidentified burrowing anemones. They also observed that the bivalve, *Astarte castanea*, and the gastropod, *Nassarius trivittatus*, appeared unaffected.

Another study, at an inshore area off Little Egg Harbor, N.J., also found benthic and epibenthic mortalities during the late summer; the species affected were similar to those reported here (Garlo, Milstein, and Jahn 1979).

Mortalities caused by the oxygen depletion are only the immediate manifestation of the total impact to the benthic invertebrate community. One latent aspect of the impact is the recovery time of the benthos. After the 1968 fishkill, Ogren and Chess (1969) reported that the megafauna (e.g., crabs and lobsters) appeared to have completely recovered the following summer. Recolonization studies have indicated incomplete recovery in 1977 and, to a lesser extent, in 1978. This is evident in the blooms of some opportunistic organisms and continued low numbers of other previously abundant species. The abundant species in 1977 were small, tube-dwelling polychaetes, *Asabellides oculata*, *Polydora socialis*, and *Spiophanes bombyx*, which were collected in the 1976 oxygen depleted area during March, June, and July. The last two species belong to the family Spionidae, which contains many species classified as opportunistic (Ziegelmeier 1970; Grassle and Grassle 1974). In an earlier unpublished study, *Asabellides*, although not previously regarded as an opportunistic species, was reported in large numbers at an ocean sewer outfall off Deal, N.J. (J. Pearce and J. Caracciolo, NMFS, Highlands, N.J., personal communication). Opportunists commonly dominate stressed, unstable areas, such as sewer outfalls. Boesch et al. (1977a) also reported a population increase of *Spiophanes* in their November 1976 and February 1977 collections off Atlantic City. Some recolonization by juvenile surf clams and sand dollars was reported.

Total recovery of the affected benthic community may take several years, because of the extensive dimensions of the affected area. Recolonization by some species can be expected to be rapid, especially those with planktonic eggs or larvae. The population expansion of *Asabellides*, *Spiophanes*, and *Polydora* and the appearance of juvenile sand dollars and surf clams are probably expressions of this mode of dispersal. Recovery will be slower for other species without a planktonic phase, for instance many species of amphipods that brood their young. In the end we may not even be able to determine definitely when recovery is complete, because of such factors as the heterogeneity of the environment and the dynamic aspects of the inshore benthic community.

## SUMMARY

The oxygen depletion event of 1976 killed many benthic invertebrates, especially surf clams off central New Jersey. Some organisms, mostly polychaetes, showed tolerance. Recolonization and stabilization of the benthic invertebrate population appeared to be incomplete 1 year after the disturbance. Several years may be required for some species—e.g., those with nonplanktonic larval dispersal—

to return to preanoxic levels and for the benthic invertebrate community to stabilize to a preanoxic state.

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## REFERENCES

Boesch, D. F., Kraeuter, J. N., and Serafy, D. K., 1977a. Benthic ecological studies, in Third Quarterly Summary Report to Bureau of Land Management, U.S. Department of Interior, Virginia Institute of Marine Sciences, Gloucester Pt., Va.

Boesch, D. F., Kraeuter, J. N., and Serafy, D. K., 1977b. Chemical and biological benchmark studies on the Middle Atlantic outer continental shelf, *Benthic Ecological Studies. Megabenthos and Macrobenthos*, vol. II, Draft final report, chapter 6, Virginia Institute of Marine Sciences, Gloucester Pt., Va., pp. 59–62.

Bullock, D. K., 1976. Ocean kill in the New York Bight. Summer 1976, *Underwater Naturalist* 10(1):4–12.

Davis, J. C., 1975. Minimal dissolved oxygen requirements of aquatic life with emphasis on Canadian species: a review, *J. Fish. Res. Board Can.* 32:2295–2332.

Garlo, E. V., Milstein, C. B., and Jahn, A. E., 1979. Impact of hypoxic conditions in the vicinity of Little Egg Inlet, New Jersey, in summer 1976, *Estuar. Coastal Mar. Sci.* 8:421–432.

Grassle, J. F., and Grassle, J. P., 1974. Opportunistic life histories and genetic systems in marine benthic polychaetes, *J. Mar. Res.* 32(2):253–284.

Pearce, J., Caracciolo, J., Halsey, M., and Rogers, L., 1977. Distribution and abundance of benthic organisms on the New York-New Jersey outer continental shelf, *NOAA Data Report* ERL MESA-30, Environmental Research Laboratories, Boulder, Colo.

Pearce, J., Radosh, D., Caracciola, J., and Steimle, F., in press: Benthic Fauna, *MESA New York Bight Atlas Monogr.* 14, New York Sea Grant Institute, Albany, N.Y.

Pielou, E. C., 1969. *An Introduction to Mathematical Ecology*, Wiley-Interscience, New York, N.Y., 289 pp.

Pratt, S. D.,1973. Benthic fauna, in Coastal and offshore environmental inventory, Cape Hatteras to Nantucket Shoals, Mar. Publ. Ser. No. 2, University of Rhode Island.

Radosh, D. J., Frame, A. B., Wilhelm, T. E., and Reid, R. N., 1978. Benthic survey of the Baltimore Canyon Trough, May 1974, Final Data Report, prepared under Interagency Agreement AA 550–IA7–35 between Bureau of Land Management and National Marine Fisheries Service, Sandy Hook Laboratory Report 78–14, unpublished.

Ropes, J., 1976a. Trip report—July 27, 1976 (chartered commercial vessel *Valerie E*), Northeast Fisheries Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, Oxford, Md.

Ropes, J., 1976c. Trip report—October 7–8, 1976 (chartered commercial vessels *Gail Snow* and *Cora May Snow*), Northeast Fisheries Center, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, Oxford, Md.

Savage, N. G., 1976. Burrowing activity in *Mercenaria mercenaria* (L.) and *Spisula solidissima* (Dillwyn) as a function of temperature and dissolved oxygen, *Mar. Behav. Physiol.* 3:221–234.

Shannon, C., and Weaver, W., 1963. *The Mathematical Theory of Communication*, University of Illinois.

Shick, J. M., 1976. Physiological and behavioral responses to hypoxia and hydrogen sulfide in the infaunal Asteroid *Ctenodiscus crispatus*, *Mar. Biol.* 37:279–289.

Steimle, F. W., 1977. A preliminary assessment of the impact of the 1976 N.Y. Bight oxygen depletion phenomenon on the benthic invertebrate megafauna, in Oxygen depletion and associated environmental disturbances in the Middle Atlantic Bight in 1976, *Northeast Fisheries Center Tech. Ser. Rep.* No. 3, Sandy Hook Laboratory, Highlands, N.J., pp. 127–165.

Theede, H., Ponat, A., Hiroki, K., and Schlieper, C., 1969. Studies on the resistance of marine bottom invertebrates to oxygen deficiency and hydrogen sulfide, *Mar. Biol.* 2:325–337.

Ziegelmeier, E., 1970. Uber Massenvorkommen verschiedener Makrobenthala Wirbelloser während der Wiederbesiedlungsphase nach Schädigungen durch "Katastrophale" Umwelteinflusse, *Helgoländer Wiss. Meersunters.* 21:9–20.

# Oxygen Depletion and Associated Benthic Mortalities in New York Bight, 1976

# Chapter 13. Effects on Finfish and Lobster

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## INTRODUCTION

In late June 1976, the Sandy Hook (N.J.) Laboratory of the National Marine Fisheries Service (NMFS) received reports—from fishermen and divers—of dead and dying fish off northern New Jersey. Immediate attempts were made to confirm these reports by taking hydrographic and biological samples from the reported areas. The two small research vessels used were limited to day trips because of their size, speed, and accommodations; thus sampling, especially for biological specimens was not adequate. In early July several exploratory surveys with a small trawl were made along the northern edge of the low-oxygen water mass. Reports continued to be received from scuba divers, indicating that the mortalities were occurring at previously unaffected wrecks off southern New Jersey. The first reports, in early July, were off Monmouth Beach, then in a southerly progression off Manasquan Inlet, Barnegat Inlet, and finally, by the third week in July, Atlantic City. In mid-July, a commercial trawler out of Barnegat Light was chartered, and, for the first time, trawl hauls were made in waters reported to be anoxic. The two small research vessels were sent to occupy stations in the oxygen-depleted area, but they were inadequate for the kind of surveys required and soon returned to Sandy Hook. Finally, in August the anoxic area was intensively sampled and not only was trawl data collected, but fairly complete hydrographic and associated biological data collections were also made.

In late 1976, the Northeast Fisheries Center (NEFC) Resource Assessment Investigation Unit made two routine finfish stock assessment cruises over the entire Middle Atlantic shelf (Cape Cod—Cape Hatteras)—one in late September through mid-October, the other in December.

NMFS has made assessment surveys of Middle Atlantic finfish stocks since 1967. During several summer and au-

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tumn cruises from this time series, stations were occupied off the New Jersey coast in the same area as the 1976 low-oxygen water mass. Data from this time series are used and discussed in relation to the anoxic event.

In addition to the otter trawl assessment information, we used data obtained from ongoing State and Federal studies, recreational and commercial statistics, and numerous reports received from fishermen, naturalists, and concerned citizens.

Detailed tabulations of much of the data used in this report are included in a workshop publication (National Marine Fisheries Service 1977).

## METHODS

Cruises to study the low-oxygen water mass were designed to investigate the extent of a phenomenon in a relatively small area; stations were laid out in simple transects or grids. Resource assessment cruises were designed to show seasonal distribution and relative abundance of finfish over a large portion of the continental shelf, and stations were randomly selected. A description of station procedures, sampling methods, and gear used can be found in the NMFS 1977 publication.

Listings of finfish catches in this paper have been grouped into demersal or nondemersal categories, based on our knowledge of certain fishes' close association with or degree of dependence on the seafloor. This is not to say that demersal types are not occasionally found in the upper waters or the nondemersals (pelagics) close to or on the bottom. But if only nondemersal fish are taken where the waters below the thermocline are unsuitable for their existence, we assumed they were caught in the upper waters while the trawl was being lowered or raised. Several demersal species were usually present in the vast majority of trawl catches made during our surveys in the Middle Atlantic shelf waters. The number of fish species and individuals taken varied considerably, but only rarely was none present. If several standard assessment tows are made in any area in New York Bight and none of the demersal types listed here is caught, the existence of a stressed or unsuitable environment is suggested.

Another indication of a stressed environment is the catch of certain benthic invertebrates in trawls. These animals, such as surf clams, mud shrimp, and marine worms, usually avoid capture, because they live in deeper sediments or they burrow as the trawl approaches. Chapter 12 discusses such invertebrates caught during our 1976 surveys.

Also included are data that show the effects of the low-oxygen water on the American lobster (*Homarus americanus*), bluefish (*Pomatomus saltatrix*), and the summer flounder (*Paralichthys dentatus*). The lobster data are from commercial catch statistics and a special study made of lobster pot catches by the State of New Jersey (NMFS 1977). The summer flounder discussion was based on a NMFS study (Freeman et al. 1976; NMFS 1977) and a 10-year State of New Jersey creel census (ending in 1976) of a small-boat fishery (NMFS 1977). The bluefish data are from a NMFS tagging program during the summer of 1976 and unpublished NMFS tagging data from the 1960s (NMFS 1977).

NMFS's Sandy Hook Laboratory has made ichthyoplankton surveys off the New Jersey coast since 1966. Summer surveys by the RV *Dolphin*, on June 17–24 and August 5–10, 1966, and by the RV *Delaware II*, on June 3–9, 1975, and June 9–13, 1976, are considered here. The methods used in 1966 are described by Clark et al. (1969); those used in 1975 and 1976 are described by Jossi et al. (1975).

## SURVEY RESULTS

### Trawl and Ichthyoplankton Surveys

The catch results of trawl hauls from eight investigatory and assessment cruises (table 13–1) made during summer and autumn 1976 may be found in the NMFS workshop report. Included also are data from eight assessment cruises made during summer and autumn between 1971 and 1975. Some of the sampling area considered (fig. 13–1) was never reported to be anoxic, but data from these areas are included for comparison. The report (1977) contains a brief summary of each anoxic investigatory cruise along with a detailed description of the catch. Table 13–2 lists all finfish species taken during the investigation cruises of 1976 and historical trawl surveys.

An analysis of the 1976 catch data and confirmed reports from divers, fishermen, lifeguards, and others show that fishes normally found within the 11,300 km$^2$ outlined in figure 13–1 were at one time or another disrupted by the low-oxygen water mass. What effects these "disruptions" had on finfish resources is difficult to estimate; this paper later discusses a qualitative appraisal of some possible effects.

During the 1976 RV *Atlantic Twin* cruise, a 2,900-km$^2$ area (fig. 13–1) was found to be without any demersal finfish species. This is most unusual and can be attributed without doubt to the anoxic waters.

Table 13–3 lists the fish larvae caught during the four historic ichthyoplankton surveys. The 33 families, genera, and species listed represent many of our most important recreational and commercial species.

### Recreational Fish Surveys

#### *Summer Flounder*

The results from the State of New Jersey creel census and the NMFS recreational fish survey indicate that the

TABLE 13–1.—*Northeast Fisheries Center investigation of oxygen depletion and resource assessment cruises from Sandy Hook, N.J., to Cape Henlopen, Del., and seaward to about 73° W longitude*

| Date | Vessel | Trawl specifications | Tow duration | Trawl stations |
|---|---|---|---|---|
| **1976** | | | Minutes | Number |
| July 8 | *Rorqual* | bay trawl, 9.1 m chain sweep, no liner | 15 | 4 |
| July 9 | *Xiphias* | bay trawl, 9.1 m chain sweep, no liner | 15 | 2 |
| July 13 and 15 | *Grand Larson* | 50/70 trawl, 21.3 m chain sweep, no liner | 15 | 7 |
| July 20–22 | *Rorqual* | bay trawl, 9.1 m chain sweep, 1.27 cm liner | 15 | 2 |
| July 28–30 | *Xiphias* | bay trawl, 9.1 m chain sweep, 1.27 cm liner | 15 | 4 |
| August 6–17 | *Atlantic Twin* | 3/4 #36 Yankee, 16.5 m chain sweep, 1.27 cm liner | 15 | 55 |
| September 28–October 17 | *Albatross IV* | #36 Yankee, 24.4 m roller sweep, 1.27 cm liner | 30 | 50 |
| December 5–21 | *Delaware II* | #36 Yankee, 24.4 m chain sweep, 1.27 cm liner | 30 | 45 |
| **1971** | | | | |
| August 23–27 | *Dolphin* | 3/4 #36 Yankee, 16.5 m chain sweep, no liner | 15 | 22 |
| **1973** | | | | |
| July 29–August 2 | *Albatross IV* | 3/4 #36 Yankee, 16.5 m chain sweep, 1.27 cm liner | 30 | 36 |
| **1974** | | | | |
| July 24–29 | *Delaware II* | #36 Yankee, 24.4 m chain sweep, 1.27 cm liner | 30 | 24 |
| August 16–21 | *Delaware II* | #36 Yankee, 24.4 m chain sweep, 1.27 cm liner | 30 | 25 |
| September 23–29 | *Delaware II* | #36 Yankee, 24.4 m chain sweep, 1.27 cm liner | 30 | 24 |
| **1975** | | | | |
| September 8–18 | *Delaware II* | #36 Yankee, 24.4 m chain sweep, 1.27 cm liner | 30 | 34 |
| October 15–November 7 | *Delaware II* | #36 Yankee, 24.4 m chain sweep 1.27 cm liner | 30 | 48 |
| December 1–18 | *Delaware II* | #36 Yankee, 24.4 m chain sweep, 1 27 cm liner | 30 | 44 |

distribution of summer flounder was dramatically affected by the low-oxygen water mass.

The 1976 State survey showed that anglers in Great Bay averaged 3.3 summer flounder per completed trip, representing the second highest seasonal mean in the history of the 10-year census. The July 1976 mean of 5.6 summer flounder per trip is the highest monthly average to be recorded in the survey. This is attributed to the extreme daily figures of 10.6 and 7.2 recorded on July 15 and July 26, respectively (table 13–4, fig. 13–2). These extremely high values are separated by a low value of 1.1 summer flounder per trip recorded on July 22. The large variability in catch rates during July appears to be directly related to movement of the oxygen-depleted water mass that extended inshore to coastal waters in July and actually entered inlet and bay waters on July 21, 1976.

TABLE 13-2.—*Phylogenetic listing of finfish species captured during recent (post-July 1, 1976) and selected historic (pre-July 1, 1976) NEFC resource*

(Asterisks indicate nondemersal fish.)

| Species | | *Rorqual* | *Xiphias* | *Grand Larson* | *Rorqual* | *Xiphias* | *Atlantic Twin* | *Albatross IV* |
|---|---|---|---|---|---|---|---|---|
| Common Name | Scientific Name | July 8, 1976 | July 9, 1976 | July 13 & 15, 1976 | July 20–22, 1976 | July 28–30, 1976 | Aug. 6–17, 1976 | Sept. 28–Oct. 17, 1976 |
| *White shark | *Carcharodon carcharias* | — | — | — | — | — | — | — |
| Sandbar shark | *Carcharhinus milberti* | — | — | — | — | — | — | — |
| Smooth dogfish | *Mustelus canis* | — | — | X | — | — | X | X |
| Spiny dogfish | *Squalus acanthias* | — | — | — | — | — | — | — |
| Atlantic angel shark | *Squatina dumerili* | — | — | — | — | — | — | X |
| Shark | | — | — | — | — | — | — | — |
| Clearnose skate | *Raja eglanteria* | — | — | — | — | X | X | X |
| Little skate | *Raja erinacea* | — | X | — | X | — | X | X |
| Rosette skate | *Raja garmani* | — | — | — | — | — | — | — |
| Winter skate | *Raja ocellata* | — | — | — | — | — | — | — |
| Roughtail stingray | *Dasyatis centroura* | — | — | — | — | — | X | — |
| Bluntnose stingray | *Dasyatis sayi* | — | — | — | — | — | X | — |
| Spiny butterfly ray | *Gymnura altavela* | — | — | — | — | — | — | X |
| Bullnose ray | *Myliobatis freminvillei* | — | — | — | — | — | — | — |
| Stingray | Dasyatidae | — | — | — | — | — | — | — |
| American eel | *Anguilla rostrata* | — | — | — | — | — | — | — |
| Conger eel | Congridae | — | — | — | — | — | — | X |
| Snake eel | *Callechelys* sp. | — | — | — | — | — | — | — |
| Eel | | — | — | — | — | — | — | — |
| *Blueback herring | *Alosa aestivalis* | — | — | — | — | — | — | X |
| *Alewife | *Alosa pseudoharengus* | — | — | — | — | — | — | — |
| *Hickory shad | *Alosa mediocris* | — | — | — | — | — | — | — |
| *American shad | *Alosa sapidissima* | — | — | — | — | — | — | — |
| *Atlantic menhaden | *Brevoortia tyrannus* | — | — | — | — | — | — | X |
| *Atlantic herring | *Clupea harengus harengus* | — | — | — | — | — | — | — |
| *Round herring | *Etrumeus teres* | — | — | — | — | — | — | X |
| *Striped anchovy | *Anchoa hepsetus* | — | — | — | — | — | X | X |
| *Bay anchovy | *Anchoa mitchilli* | — | — | — | — | — | — | X |
| *Silver anchovy | *Engraulis eurystole* | — | — | — | — | — | — | X |
| *Anchovy | Engraulidae | — | — | — | — | — | — | — |
| Inshore lizardfish | *Synodus foetens* | — | — | — | — | — | — | X |
| Snakefish | *Trachinocephalus myops* | — | — | — | — | — | — | — |
| Oyster toadfish | *Opsanus tau* | — | — | — | — | — | — | — |
| Clingfish uncl. | Gobiesocidae | — | — | — | — | — | — | — |
| Goosefish | *Lophius americanus* | — | — | — | — | — | — | X |
| Atlantic batfish | *Dibranchus atlanticus* | — | — | — | — | — | — | — |
| Fourbeard rockling | *Enchelyopus cimbrius* | — | — | — | — | — | — | — |
| Atlantic cod | *Gadus morhua* | — | — | — | — | — | — | — |
| Haddock | *Melanogrammus aeglefinus* | — | — | — | — | — | — | — |
| Offshore hake | *Merluccius albidus* | — | — | — | — | — | — | — |
| Silver hake | *Merluccius bilinearis* | X | X | X | X | X | X | X |
| Red hake | *Urophycis chuss* | X | X | X | — | X | X | X |
| Spotted hake | *Urophycis regius* | X | X | — | — | X | X | X |
| White hake | *Urophycis tenuis* | — | — | — | — | — | — | — |
| Fawn cusk-eel | *Lepophidium cervinum* | — | — | — | — | — | — | — |
| Blotched cusk-eel | *Ophidion grayi* | — | — | — | — | — | — | — |
| Striped cusk-eel | *Rissola marginata* | — | — | — | — | — | X | X |
| Cusk-eel | Ophidiidae | — | — | — | — | — | — | — |
| Ocean pout | *Macrozoarces americanus* | X | — | — | — | — | — | — |
| *Atlantic silverside | *Menidia menidia* | — | — | — | — | — | — | — |
| *Bluespotted cornetfish | *Fistularia tabacaria* | — | — | — | — | — | — | — |
| Lined seahorse | *Hippocampus erectus* | — | — | — | — | — | X | — |
| Northern pipefish | *Syngnathus fuscus* | — | — | — | — | — | — | — |
| Pipefish | Syngnathidae | — | — | — | — | — | — | — |
| Striped bass | *Morone saxatilis* | — | — | — | — | — | — | — |
| Black sea bass | *Centropristis striata* | X | X | X | X | X | X | X |
| Bigeye | *Priacanthus arenatus* | — | — | — | — | — | — | — |
| Short bigeye | *Pristigenys alta* | — | — | — | — | — | — | — |

*assessment cruises, Sandy Hook, N.J., to Cape Henlopen, Del., from the coastline to approximately 73° W longitude*

| *Delaware II* Dec. 5–21, 1976 | *Dolphin* Aug. 23–27, 1971 | *Albatross IV* July 29–Aug. 2, 1973 | *Delaware II* July 24–29, 1974 | *Delaware II* Aug. 16–21, 1974 | *Delaware II* Sept 23–29, 1974 | *Delaware II* Nov 7, 1975 | *Delaware II* Oct. 15–Nov. 7, 1975 | *Delaware II* Dec. 1–18, 1975 | Common name |
|---|---|---|---|---|---|---|---|---|---|
| — | — | — | — | X | — | — | — | — | *White shark |
| — | — | X | — | — | — | X | — | — | Sandbar shark |
| — | X | X | X | X | X | X | X | — | Smooth dogfish |
| X | X | — | — | — | — | — | X | X | Spiny dogfish |
| — | — | — | — | — | — | — | — | — | Atlantic angel shark |
| — | — | X | — | — | — | — | — | — | Shark |
| — | X | — | X | X | X | X | X | — | Clearnose skate |
| X | X | X | X | X | X | X | X | X | Little skate |
| — | — | — | — | — | — | X | — | — | Rosette skate |
| X | — | — | — | — | X | — | X | X | Winter skate |
| — | X | X | — | X | — | — | — | — | Roughtail stingray |
| — | X | — | — | — | — | X | — | — | Bluntnose stingray |
| — | — | — | — | — | — | X | — | — | Spiny butterfly ray |
| — | X | — | — | — | — | X | — | — | Bullnose ray |
| — | — | X | — | — | — | — | — | — | Stingray |
| — | — | — | — | — | — | — | — | X | American eel |
| X | — | X | — | — | X | X | — | X | Conger eel |
| — | — | — | — | X | X | X | — | — | Snake eel |
| — | — | — | X | — | — | — | — | — | Eel |
| X | — | X | — | — | — | — | X | X | *Blueback herring |
| X | — | — | — | — | — | — | — | X | *Alewife |
| — | — | X | — | — | — | — | — | — | *Hickory shad |
| X | — | — | — | — | — | — | — | X | *American shad |
| X | — | — | — | — | — | — | X | X | *Atlantic menhaden |
| X | — | — | — | — | — | — | — | — | *Atlantic herring |
| — | X | X | X | X | X | X | X | — | *Round herring |
| — | — | X | — | — | — | — | X | X | *Striped anchovy |
| X | — | — | — | — | X | X | X | X | *Bay anchovy |
| — | — | — | — | — | — | — | — | X | *Silver anchovy |
| — | — | — | — | X | X | — | — | — | *Anchovy |
| — | — | — | — | — | X | — | X | — | Inshore lizardfish |
| — | — | — | — | — | X | — | — | X | Snakefish |
| — | — | — | — | — | — | — | — | X | Oyster toadfish |
| — | X | — | — | — | — | — | — | — | Clingfish uncl. |
| X | X | X | X | X | X | X | X | X | Goosefish |
| — | — | — | — | — | — | — | — | X | Atlantic batfish |
| — | — | X | — | X | X | X | — | — | Fourbeard rockling |
| X | — | — | — | — | — | — | X | X | Atlantic cod |
| — | — | X | — | — | — | X | — | — | Haddock |
| — | — | — | — | X | — | — | — | — | Offshore hake |
| X | X | X | X | X | X | X | X | X | Silver hake |
| X | X | X | X | X | X | X | X | X | Red hake |
| X | X | X | X | X | X | X | X | X | Spotted hake |
| — | — | — | — | X | — | X | — | X | White hake |
| X | — | — | — | X | — | — | X | — | Fawn cusk-eel |
| — | — | — | — | — | — | X | X | X | Blotched cusk-eel |
| X | — | — | — | X | X | X | — | X | Striped cusk-eel |
| — | — | X | X | — | — | — | — | X | Cusk-eel |
| — | — | X | — | X | X | X | — | — | Ocean pout |
| X | — | — | — | — | — | — | — | X | *Atlantic silverside |
| — | — | — | — | X | — | — | X | — | *Bluespotted cornetfish |
| — | — | — | — | — | X | — | — | X | Lined seahorse |
| — | — | — | — | X | — | X | — | X | Northern pipefish |
| — | — | — | — | — | X | — | — | — | Pipefish |
| — | — | — | — | — | — | — | X | X | Striped bass |
| X | — | X | X | X | X | X | X | X | Black sea bass |
| — | — | — | — | — | — | X | X | — | *Bigeye |
| — | — | — | — | — | — | X | — | — | *Short bigeye |

TABLE 13–2.—*Phylogenetic listing of finfish species captured during recent (post-July 1, 1976) and selected historic (pre-July 1, 1976) NEFC resource*

(Asterisks indicate nondemersal fish.)

| Species | | *Rorqual* | *Xiphias* | *Grand Larson* | *Rorqual* | *Xiphias* | *Atlantic Twin* | *Albatross IV* |
|---|---|---|---|---|---|---|---|---|
| Common Name | Scientific Name | July 8, 1976 | July 9, 1976 | July 13 & 15, 1976 | July 20–22, 1976 | July 28–30, 1976 | Aug. 6–17, 1976 | Sept. 28–Oct. 17, 1976 |
| *Bluefish | *Pomatomus saltatrix* | — | — | — | — | — | X | X |
| *Mackerel scad | *Decapterus macarellus* | — | — | — | — | — | — | — |
| *Round scad | *Decapterus punctatus* | — | — | — | — | — | X | — |
| *Blue runner | *Caranx crysos* | — | — | — | — | — | — | X |
| *Bigeye scad | *Selar crumenophthalmus* | — | — | — | — | — | — | — |
| *Banded rudderfish | *Seriola zonata* | — | — | — | — | — | — | — |
| *Rough scad | *Trachurus lathami* | — | — | — | — | — | — | X |
| *Lookdown | *Selene vomer* | — | — | — | — | — | — | — |
| *Atlantic moonfish | *Vomer setapinnis* | — | — | — | — | — | — | X |
| *Pompano | *Carangidae* | — | — | — | — | — | — | — |
| Snapper | Lutjanidae | — | — | — | — | — | — | — |
| Porgy | Sparidae | — | — | — | — | — | — | — |
| Scup | *Stenotomus chrysops* | — | — | X | — | — | X | — |
| Silver perch | *Bairdiella chrysura* | — | — | — | — | — | — | — |
| Weakfish | *Cynoscion regalis* | — | — | — | — | — | X | X |
| Spot | *Leiostomus xanthurus* | — | — | — | — | — | X | X |
| Northern kingfish | *Menticirrhus saxatilis* | — | — | — | — | — | — | X |
| Atlantic croaker | *Micropogon undulatus* | — | — | — | — | — | — | X |
| Red goatfish | *Mullus auratus* | — | — | — | — | — | — | — |
| Butterflyfish | Chaetodontidae | — | — | — | — | — | — | — |
| Tautog | *Tautoga onitis* | — | — | X | — | — | — | X |
| Cunner | *Tautogolabrus adspersus* | X | X | — | — | X | — | — |
| *Guaguanche | *Sphyraena guachancho* | — | — | — | — | — | X | — |
| *Barracuda | Sphyraenidae | — | — | — | — | — | — | — |
| Southern stargazer | *Astroscopus y-graecum* | — | — | — | — | — | — | — |
| Rock gunnel | *Pholis gunnellus* | — | — | — | — | — | — | — |
| Wrymouth | *Cryptacanthodes maculatus* | — | — | — | — | — | — | — |
| American sand lance | *Ammodytes americanus* | — | — | — | — | — | X | X |
| *Atlantic cutlassfish | *Trichiurus lepturus* | — | — | — | — | — | — | — |
| *Atlantic mackerel | *Scomber scombrus* | — | — | — | — | — | — | — |
| *Butterfish | *Peprilus triacanthus* | — | — | X | — | — | X | X |
| Black bellied rosefish | *Helicolenus dactylopterus* | — | — | — | — | — | — | — |
| Northern searobin | *Prionotus carolinus* | X | X | X | X | X | X | X |
| Striped searobin | *Prionotus evolans* | X | — | — | — | — | X | X |
| Sea raven | *Hemitripterus americanus* | — | — | — | — | — | — | — |
| Longhorn sculpin | *Myoxocephalus octodecemspinosus* | — | — | — | — | — | — | — |
| Striped seasnail | *Liparis liparis* | — | — | — | — | — | — | — |
| Gulf Stream flounder | *Citharichthys arctifrons* | — | — | — | — | — | X | X |
| Smallmouth flounder | *Etropus microstomus* | X | X | — | — | — | — | — |
| Summer flounder | *Paralichthys dentatus* | — | — | — | — | — | X | X |
| Fourspot flounder | *Paralichthys oblongus* | X | — | — | — | — | X | X |
| Windowpane | *Scophthalmus aquosus* | X | X | X | — | X | X | X |
| Witch flounder | *Glyptocephalus cynoglossus* | — | — | — | — | — | — | — |
| Yellowtail flounder | *Limanda ferruginea* | — | — | — | — | — | — | X |
| Winter flounder | *Pseudopleuronectes americanus* | X | X | — | — | — | X | X |
| Hogchoker | *Trinectes maculatus* | — | — | — | — | — | — | X |
| Tonguefish uncl. | Cynoglossidae | — | — | — | — | — | — | — |
| *Scrawled filefish | *Aluterus scriptus* | — | — | — | — | — | — | — |
| *Orange filefish | *Aluterus schoepfi* | — | — | — | — | — | — | — |
| *Planehead filefish | *Monacanthus hispidus* | — | — | — | — | — | — | — |
| Northern puffer | *Sphoeroides maculatus* | — | — | — | — | — | — | X |
| Puffer uncl. | Tetraodontidae | — | — | — | — | — | — | X |
| Striped burrfish | *Chilomycterus schoepfi* | — | — | — | — | — | — | X |

*assessment cruises, Sandy Hook, N.J., to Cape Henlopen, Del., from the coastline to approximately 73° W longitude—continued*

| *Delaware II* | *Dolphin* | *Albatross IV* | *Delaware II* | *Delaware II* | *Delaware II* | *Delaware II* | *Delaware II* | *Delaware II* | |
|---|---|---|---|---|---|---|---|---|---|
| Dec. 5–21, 1976 | Aug. 23–27, 1971 | July 29–Aug. 2, 1973 | July 24–29, 1974 | Aug. 16–21, 1974 | Sept. 23–29, 1974 | Nov. 7, 1975 | Oct. 15–Nov. 7, 1975 | Dec. 1–18, 1975 | Common name |
| — | — | X | — | X | X | X | X | X | *Bluefish |
| — | — | — | — | — | X | — | — | — | *Mackerel scad |
| — | — | — | — | X | X | X | X | — | *Round scad |
| — | — | — | X | — | — | — | — | — | *Blue runner |
| — | — | — | X | — | — | — | — | — | *Bigeye scad |
| — | — | — | — | X | — | — | — | — | *Banded rudderfish |
| — | — | — | X | — | X | — | — | — | *Rough scad |
| — | — | — | — | X | X | — | — | — | *Lookdown |
| — | — | — | — | — | X | — | X | — | *Atlantic moonfish |
| — | — | — | — | X | — | — | — | — | *Pompano |
| — | — | — | — | — | X | — | — | — | Snapper |
| — | — | — | — | X | — | — | — | — | Porgy |
| X | — | X | X | X | X | X | X | X | Scup |
| — | — | — | — | — | — | — | — | X | Silver perch |
| X | — | — | X | — | X | X | X | X | Weakfish |
| X | — | — | — | — | X | X | — | — | Spot |
| — | — | — | — | — | X | X | X | X | Northern kingfish |
| X | — | — | — | — | X | X | X | X | Atlantic croaker |
| — | — | — | X | X | — | — | — | — | Red goatfish |
| — | — | — | — | — | — | X | — | — | Butterflyfish |
| X | — | X | — | — | — | X | X | X | Tautog |
| — | — | X | X | X | — | X | — | X | Cunner |
| — | — | — | — | — | — | — | — | — | *Guaguanche |
| — | — | — | — | — | X | X | — | — | *Barracuda |
| — | — | — | — | — | — | — | X | — | Southern stargazer |
| — | — | — | X | X | — | — | — | — | Rock gunnel |
| — | — | — | — | — | — | X | — | — | Wrymouth |
| X | — | X | X | X | X | X | X | X | American sand lance |
| — | — | — | — | — | — | — | X | — | *Atlantic cutlassfish |
| X | — | X | — | — | — | X | — | — | *Atlantic mackerel |
| X | X | X | X | X | X | X | X | X | *Butterfish |
| — | — | — | — | — | — | — | — | X | Black bellied rosefish |
| X | X | X | X | X | X | X | X | X | Northern searobin |
| X | X | X | X | X | X | X | X | X | Striped searobin |
| X | X | X | — | X | — | — | — | — | Sea raven |
| X | X | X | — | X | — | — | — | X | Longhorn sculpin |
| — | — | — | — | — | — | — | X | X | Striped seasnail |
| X | X | — | — | X | — | X | X | X | Gulf Stream flounder |
| X | — | X | X | X | X | X | X | X | Smallmouth flounder |
| X | X | X | X | X | X | X | X | X | Summer flounder |
| X | X | X | X | X | X | X | X | X | Fourspot flounder |
| X | X | X | X | X | X | X | X | X | Windowpane |
| X | — | X | — | — | X | — | — | X | Witch flounder |
| X | X | X | — | X | — | X | — | X | Yellowtail flounder |
| X | X | X | — | X | X | X | X | X | Winter flounder |
| — | X | — | — | — | — | — | X | X | Hogchoker |
| X | — | — | — | — | — | — | — | — | Tonguefish uncl. |
| — | — | — | — | — | — | X | — | — | *Scrawled filefish |
| — | — | — | — | — | — | — | X | — | *Orange filefish |
| — | — | — | X | X | X | X | X | X | *Planehead filefish |
| — | — | — | X | X | X | X | X | X | Northern puffer |
| — | — | — | — | — | — | — | — | — | Puffer uncl. |
| — | — | — | — | — | — | — | — | — | Striped burrfish |

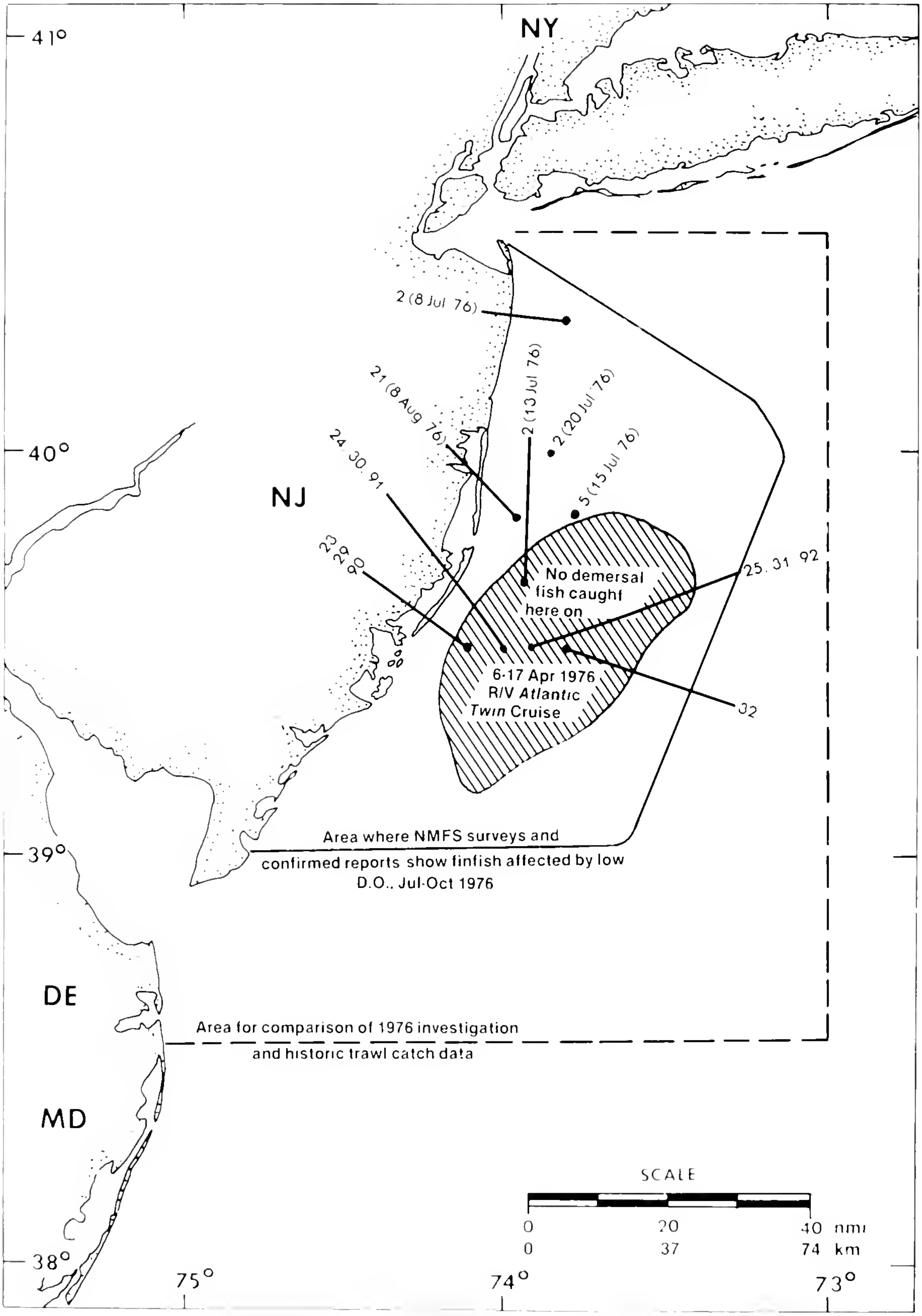

FIGURE 13–1.—Finfish survey areas and location of stations.

TABLE 13-3.—*Phylogenetic listing of fish larvae caught at 24 sampling sites within 81 km of the New Jersey coast during June and August 1966 and at 7 sampling sites off northern New Jersey in June 1975 and 1976*

| | | June 1966 | | August 1966 | | June 1975 | | June 1976 | |
|---|---|---|---|---|---|---|---|---|---|
| Common name | Scientific name | Larvae number | Occurrence[1] | Larvae number | Occurrence[1] | Larvae number | Occurrence[1] | Larvae number | Occurrence[1] |
| Atlantic menhaden | *Brevoortia tyrannus* | 13 | 13 | 7 | 16 | | | | |
| Bay anchovy | *Anchoa mitchelli* | 1378 | 13 | 42 | 13 | | | | |
| Striped anchovy | *Anchoa hepsetus* | 28 | 8 | 12 | 4 | | | | |
| Silver anchovy | *Engraulis eurystole* | | | 856 | 62 | | | | |
| Lanternfish | Myctophidae | 5 | 4 | 6 | 20 | 1 | 14 | | |
| Goosefish | *Lophius americanus* | 74 | 67 | 6 | 20 | 1 | 14 | | |
| Atlantic cod | *Gadus morhua* | 15 | 21 | | | | | | |
| Fourbeard rockling | *Enchelyopus cimbrius* | 330 | 83 | 71 | 25 | 32 | 100 | 4 | 50 |
| Haddock | *Melanogrammus aeglefinus* | 1 | 4 | | | | | | |
| Red hake | *Urophysis chuss* | 7 | 8 | 175 | 42 | | | | |
| Silver hake | *Merluccius bilinearis* | 17 | 16 | 72 | 42 | 1 | 14 | 6 | 14 |
| Hake | *Urophysis* sp. | 1 | 4 | | | | | | |
| Northern pipefish | *Syngathus fuscus* | | | | | | | 1 | 14 |
| Black sea bass | *Centropristis striata* | | | 4 | 4 | | | | |
| Bluefish | *Pomatomus saltatrix* | | | 1057 | 54 | | | | |
| Kingfish | *Menticirrhus* sp. | 3 | 8 | 1 | 4 | | | | |
| Sea trout | *Cynoscion* sp. | 71 | 12 | | | | | | |
| Cunner | *Tautogolabrus adspersus* | 28 | 33 | 241 | 46 | | | | |
| Tautog | *Tautoga onitis* | 5 | 25 | | | | | | |
| Blenny | Blenniidae | | | | | | | 1 | 14 |
| Atlantic bonito | *Sarda sarda* | | | 66 | 29 | | | | |
| Atlantic mackerel | *Scomber scombrus* | 359 | 54 | | | 489 | 100 | 39 | 100 |
| Mackerel | *Auxis* sp. | | | 242 | 25 | | | | |
| Butterfish | *Peprilus triacanthus* | | | 531 | 79 | | | | |
| Northern sea robin | *Prionotus carolinus* | 10 | 21 | 10 | 25 | | | | |
| Striped sea robin | *Prionotus evolans* | | | 9 | 12 | | | | |
| Inquiline snailfish | *Liparis inquilinis* | 7 | 21 | | | | | | |
| Snailfish | *Liparis* sp. | | | | | | | 1 | 14 |
| Fourspot flounder | *Paralichthys oblongus* | 2 | 8 | 581 | 63 | | | | |
| Gulf Stream flounder | *Citharichthys arctifrons* | | | 143 | 33 | | | | |
| Small mouth flounder | *Etropus microstomus* | | | 38 | 29 | | | | |
| Windowpane | *Scophthalmus aquosus* | 34 | 38 | 17 | 16 | | | 2 | 14 |
| Yellowtail flounder | *Limanda ferruginea* | 2344 | 67 | 43 | 29 | 337 | 100 | 23 | 86 |
| Witch flounder | *Glyptocephalus cynoglossus* | 5 | 50 | 96 | 17 | 31 | 100 | 1 | 14 |

[1] Percentage of sites.

The NMFS recreational fish survey showed much the same results as the State survey. Data calculated from party boat anglers fishing along the New Jersey coast (Freeman et al. 1976) and from communications with recreational fishermen during 1976 indicated that the summer flounder arrived inshore in mid-May. Then and throughout the rest of the month, anglers' catch rates were relatively low. During the first half of June, however, catch rates increased considerably, especially along the southernmost and northernmost parts of the State. Later in June, the best catch rates occurred along the northernmost New Jersey beaches. During the last of June and the beginning of July when dead fish (presumably due to the anoxia) were first observed along the ocean floor off northern New Jersey, the catch rates of summer flounder were highest close along the beaches nearby. Throughout the rest of July and August, summer flounder were caught only in areas free of the influence of low dissolved oxygen (D.O.) water. During this time, catch rates were highest at places along the coast where anoxic water pressed closest to the coast. Indeed, during these times, party boat anglers were fishing for fluke almost in the surf and in inlets and bays.

### *Bluefish*

On June 8, 1976, NMFS biologists tagged 139 bluefish weighing from 1.8 to 5.4 kg and measuring 49.5 to 73.7 cm. The bluefish recorded on the tagging vessel's sonar were mostly within 6.1 m of the seafloor. The water depth was 25.6 m; the temperature at the surface was 18° C and at the bottom 12° C. A week or so before this tagging, a large mass of bluefish weighing about 2.3 to 6.8 kg had been observed 11 to 22 km offshore—first off Five Fathom

TABLE 13–4.—*Summer flounder catch per angler trip in Great Bay, N.J., June through August 1976*

| Date of survey | Number of angler's trips interviewed | Reported catch | Catch per angler's trip |
|---|---|---|---|
| **June 1976** | | | |
| 3 | 19 | 19 | 1.00 |
| 4 | 11 | 4 | 0.36 |
| 8 | 30 | 26 | 0.87 |
| 17 | 10 | 2 | 0.20 |
| 22 | 24 | 76 | 3.17 |
| 29 | 50 | 121 | 2.42 |
| Subtotal | 144 | 248 | 1.72 |
| **July 1976** | | | |
| 6 | 55 | 182 | 3.31 |
| 15 | 39 | 415 | 10.64 |
| 22 | 31 | 35 | 1.13 |
| 26 | 62 | 440 | 7.10 |
| Subtotal | 187 | 1,072 | 5.73 |
| **August 1976** | | | |
| 2 | 57 | 225 | 3.95 |
| 12 | 23 | 18 | 0.78 |
| 17 | 29 | 52 | 1.79 |
| 24 | 37 | 68 | 1.84 |
| 25 | 31 | 37 | 1.19 |
| 27 | 16 | 11 | 0.69 |
| Subtotal | 193 | 411 | 2.13 |
| Seasonal total | 524 | 1,731 | 3.30 |

Bank, then off Atlantic City Ridge, and later off Barnegat Ridge. The sequence of anglers' catches indicates that the normal northward migration of bluefish was proceeding as expected.

On June 25, about 2 weeks after tagging, the first of these tagged fish was recaptured off Cape Henlopen, Del., more than 157 km south of where it had been released. On June 29, a second bluefish was recaptured off Avalon, N.J., 111 km south of where it had been released. On August 20 and 22, the third and fourth bluefish were recaptured 4 km and 83 km south, respectively, of where they had been released (about 28 km east-northeast of Barnegat Inlet). Where and when these specimens were captured is contrary to what might be expected of northward-migrating fish.

As a continuing program, members of the American Littoral Society tagged a number of bluefish along the New Jersey coast during the summer of 1975 and 1976. Two specimens, weighing about 1.4 kg each, were recaptured off New York City during 1976. Both had been tagged off Manasquan Inlet: one on June 16, 1975, the other on August 1, 1976. These small bluefish were recaptured north of the tagging site, as might be expected for northward-migrating fish.

Catch data regarding various species of fishes along the New Jersey coast during 1975 and 1976 are known from charter boat and party boat anglers (Freeman et al. 1976). In certain areas where bluefish had been abundant off New Jersey in previous years, they were notably absent in 1976. Those areas coincided for the most part with the low D.O. water.

### Commercial Lobster Fishery Survey

From 1971 through 1974, the lobster industry in New Jersey remained fairly stable, with commercial landings of 581, 590, 621, and 539 metric tons (t), respectively. In 1975 the landings dropped to 386 t. The first 4 months of 1976 suggested a comeback, as the landings were 22 percent greater than the same months in 1975. The May 1976 landings were down about 3 percent from May 1975 landings. June, July, August, and September, normally the most productive months of the year, showed decreases in the commercial landings of 28, 41, 30, and 16 percent, respectively, compared to the 1975 landings for the same period. At the end of September the 1976 cumulative commercial catch was down about 18 percent from the first 9 months of 1975 (table 13–5).

The inshore pot fishery, from 0 to 22 km offshore, was hit the hardest. The inshore landings for Ocean County decreased from over 52 t in the first 9 months of 1975 to less than 12 t for the same period in 1976. That represents a decrease of better than 75 percent for 9 months, when the 1976 catch was actually up 23 percent for the first 6 months. Most of the Ocean County landings are from the ports of Belmar, Point Pleasant, and Barnegat Light. Data on the catch per unit of effort in table 13–6 were collected aboard several commercial vessels of inshore lobster pot fishermen from the Belmar-Point Pleasant area over the past 2 years. These data show that the catch per unit of effort had decreased at about the same rate as the landings during July, August, and September 1976.

Much of the inshore pot fishing grounds for the Monmouth County ports of Belford and Atlantic Highlands are west and north of the area hardest hit by the low-oxygen conditions, and the 9-month catch showed an increase of about 42 percent over the same time period in 1975. Personal communication with lobster fishermen from this area, however, indicated that the consensus was that the "bad water" condition had adversely affected lobster fishing in that area. Local lobstermen contended that there were fewer offshore immigrants after the anoxic water conditions had been established. Offshore lobsters make up a fair proportion of the inshore catch, and lobstermen can often distinguish them by the lighter, redder color and generally larger size. A closer look at the catch data on tables 13–7 and 13–8 supports this contention to a great extent. The 1976 landings through June showed an increase of about 124 percent over the 1975 landings for the same period. The 1976 landings from July through September, however, showed a decrease of 15 percent compared to the 1975 landings for the same period. A

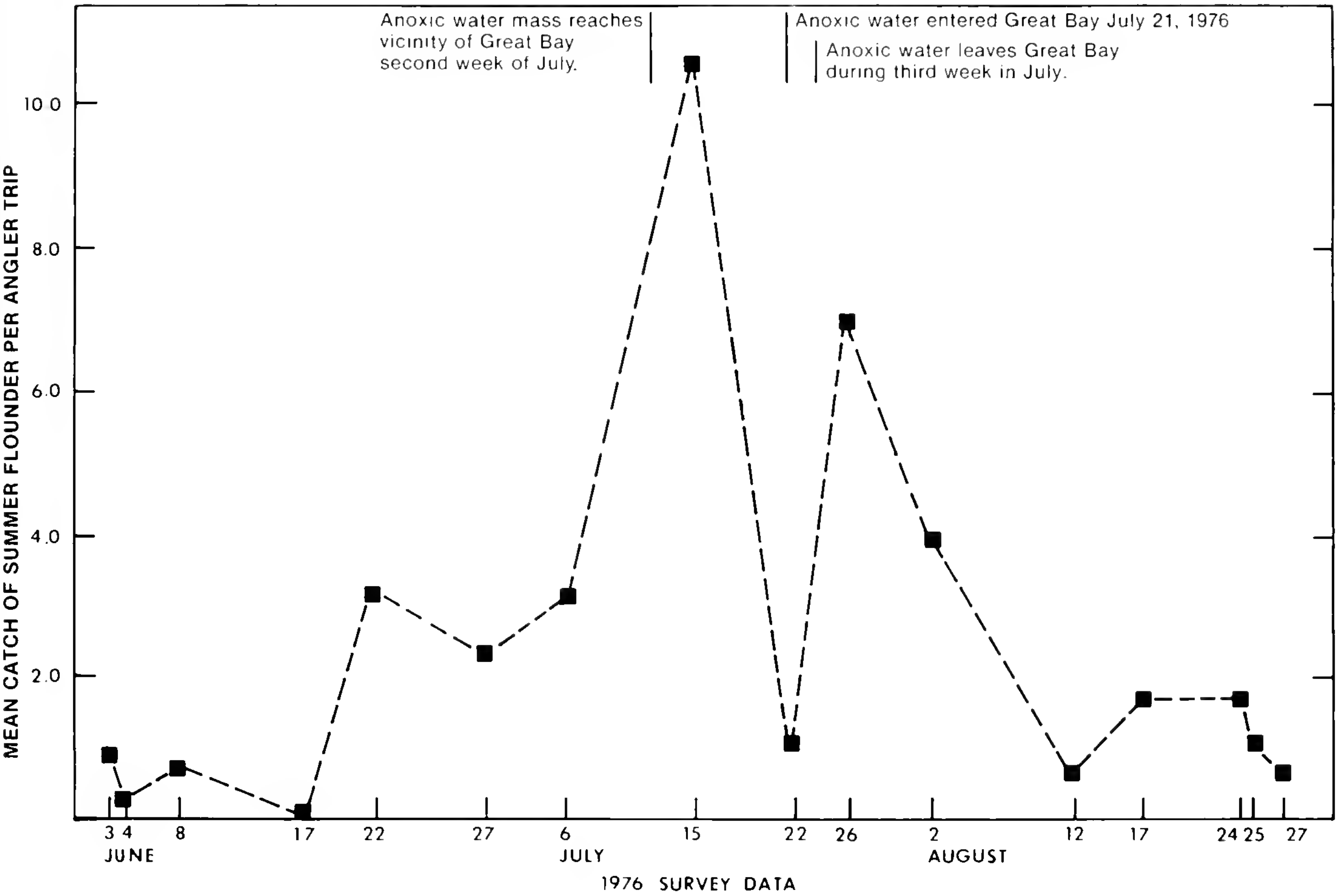

FIGURE 13–2.—Summer flounder catch per angler per trip in Great Bay, N.J., June-August 1976.

TABLE 13–5.—*New Jersey lobster catch by month, 1974–76 (in kilograms)*

| | 1974 | | 1975 | | 1976 | |
|---|---|---|---|---|---|---|
| | Month | Cumulative | Month | Cumulative | Month | Cumulative |
| January | 20,388 | 20,388 | 12,345 | 12,345 | 6,392 | 6,392 |
| February | 11,973 | 32,361 | 2,874 | 15,219 | 2,546 | 8,938 |
| March | 10,027 | 42,338 | 2,160 | 17,379 | 3,781 | 12,719 |
| April | 12,554 | 54,942 | 17,643 | 35,022 | 28,891 | 42,610 |
| May | 48,183 | 103,125 | 47,658 | 82,680 | 46,020 | 88,630 |
| June | 73,823 | 176,948 | 48,985 | 131,665 | 35,516 | 124,146 |
| July | 107,152 | 284,100 | 50,940 | 182,605 | 29,059 | 153,205 |
| August | 87,450 | 371,550 | 44,979 | 227,584 | 31,603 | 184,808 |
| September | 56,348 | 427,898 | 55,212 | 282,796 | 46,206 | 231,014 |
| October | 60,734 | 488,632 | 50,957 | 333,753 | 43,562 | 274,576 |
| November | 25,384 | 514,016 | 33,783 | 367,536 | 10,235 | 284,812 |
| December | 26,346 | 540,362 | 18,282 | 385,818 | 7,985 | 292,797 |

TABLE 13–6.—*Lobster catch per unit effort for New Jersey inshore pot fishery from Shark River and Point Pleasant area, 1975 and 1976*

| Year and month | Number of pots | Number of lobsters | Length of sets in days | Legal size (%) | Pot days | Lobsters per pot | Lobsters per pot set over day | Legal lobsters per pot | Legal lobsters per pot set over day |
|---|---|---|---|---|---|---|---|---|---|
| **1975** | | | | | | | | | |
| April | 150 | 264 | 2.00 | 46.0 | 300 | 1.76 | 0.88 | 0.81 | 0.40 |
| May | 411 | 897 | 3.00 | 30.5 | 1,233 | 2.18 | 0.73 | 0.66 | 0.22 |
| June | 855 | 1,118 | 3.07 | 46.0 | 2,627 | 1.31 | 0.43 | 0.60 | 0.20 |
| July | 638 | 809 | 3.43 | 41.0 | 2,186 | 1.27 | 0.37 | 0.52 | 0.15 |
| August | 596 | 1,493 | 3.52 | 39.9 | 2,095 | 2.50 | 0.71 | 1.00 | 0.28 |
| September | 255 | 657 | 5.31 | 42.2 | 1,353 | 2.58 | 0.49 | 1.09 | 0.21 |
| October | 735 | 1,209 | 4.00 | 36.6 | 2,942 | 1.64 | 0.41 | 0.60 | 0.15 |
| November | 313 | 128 | 4.00 | 60.2 | 1,252 | 0.41 | 0.10 | 0.25 | 0.06 |
| **1976** | | | | | | | | | |
| April | 148 | 189 | 7.00 | 44.0 | 1,029 | 1.28 | 0.18 | 0.56 | 0.08 |
| May | 186 | 316 | 3.00 | 30.7 | 558 | 1.70 | 0.57 | 0.52 | 0.18 |
| June | 567 | 1,009 | 4.00 | 34.8 | 2,268 | 1.78 | 0.44 | 0.62 | 0.15 |
| July | 89 | 24 | 10.00 | 50.0 | 890 | 0.27 | 0.03 | 0.12 | 0.015 |
| August | 126 | 90 | 9.00 | 43.3 | 1,134 | 0.71 | 0.08 | 0.31 | 0.03 |
| September | 229 | 192 | 8.02 | 47.4 | 1,837 | 0.84 | 0.10 | 0.40 | 0.05 |

drop in landings from over double the year before for the first 6 months of the year to only 85 percent for the next 3 months is very significant, especially since it coincides so well with the appearance of the anoxic conditions off the coast.

## EFFECTS ON FINFISH

The "fishkill" phrase often used to describe the anoxic water mass off the New Jersey coast in 1976 is misleading, because finfish populations did not have massive mortalities. The first indications of a fishkill were based on reports of dead fish caught in trawls of commercial fishermen (Steimle 1976). Diver observations on offshore wrecks (fig. 13–3)further substantiated these finfish death reports. Our first surveys in early July did find a few dead fish in areas reported to have extensive mortalities. But further intensive trawling throughout summer and autumn did not produce significant numbers of dead fish. In fact, of the 196 trawl hauls made (52 in waters of $\leq 1.40$ $mlO_2/l$) only 16 dead fish were found (table 13–9). Of these 16 fish, 12 ocean pout (*Macrozoarces americanus*) were caught at one station. Therefore, based on observations, we must conclude that a significant and sustained kill of adult fish did not take place, although scattered finfish mortalities continued throughout the summer (Steimle 1976). Table 13–10 is a compilation (after Steimle 1976) of all fish species reported to have been killed by anoxia.

### Tolerance to Reduced Oxygen Levels

Reduction in the D.O. level significantly affects physiological, biochemical, developmental, and behavioral processes in fish. These effects may range from increasing the respiration rate to switching to anaerobic metabolism or to death.

Each fish species has a critical oxygen level below which the fish depends on increased respiration rates (thus pumping greater volumes of water across the gills) to maintain its oxygen supply. Fry (1947) called this condition "respiration dependence." Baldwin (1923) found that Atlantic mackerel (*Scomber scombrus*), butterfish (*Peprilus triacanthus*) and scup (*Stenotomus chrysops*) were not as resistant to low D.O. as dogfish, skate, tautog (*Tautoga onitis*), black sea bass (*Centropristis striata*), or winter flounder (*Pseudopleuronectes americanus*). Hall (1929) found that the oyster toadfish (*Opsanus tau*) was more resistant to low D.O. levels than northern puffer (*Sphoeroides maculatus*) and northern puffer was more resistant than scup. Shelford and Allee (1913) suggested there is a relation between habitat preference and the oxygen levels necessary to sustain life. Hall felt that oxygen consumption is related to the level of activity and that a low activity level may have an adaptive value in areas prone to low D.O. levels.

Saunders (1963) found that when the ambient D.O. level was reduced from 7.0 to 2.1 ml/l, the rate of oxygen consumption for Atlantic cod (*Gadus morhua*) decreased only slightly, whereas the respiration rate increased (markedly at oxygen levels below about 3.5 ml/l). Voyer and Morrison (1971) found that winter flounder become respiration dependent between 2.1 and 3.1 $mlO_2/l$. Davis (1975) believed that the "average member of a species in a fish community (marine) starts to exhibit symptoms of oxygen distress" when the oxygen level is about 4.7 $mlO_2/l$. When fish become respiration dependent, they are in

TABLE 13-7.—*New Jersey 1975 lobster catch by county, month, and type of gear (in kilograms)*

| | Monmouth | | | Ocean | | | Atlantic | | | Cape May | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Month | Otter trawl | Inshore pots | Offshore pots | Otter trawl | Inshore pots | Offshore pots | Otter trawl | Inshore pots | Offshore pots | Otter trawl | Inshore pots | Offshore pots | Total |
| January | | 202 | | 8,122 | 354 | 3,666 | | | | | | | 12,344 |
| February | | 1,229 | | 582 | 41 | 1,023 | | | | | | | 2,875 |
| March | | 793 | | 1,080 | 60 | 227 | | | | | | | 2,160 |
| April | | 289 | | 11,509 | 479 | 2,337 | | | | 95 | | 2,933 | 17,642 |
| May | | 4,636 | | 34,400 | 1,469 | | 857 | | 63 | 269 | | 5,963 | 47,657 |
| June | | 10,029 | | 22,900 | 3,111 | | 410 | 33 | 191 | 44 | 130 | 12,137 | 48,985 |
| July | | 9,315 | | 13,077 | 7,935 | 1,971 | | 59 | 645 | 427 | 318 | 15,362 | 49,109 |
| August | | 7,747 | | 5,068 | 16,872 | 751 | 1,129 | 35 | 1,074 | 370 | 176 | 11,757 | 44,979 |
| September | | 7,276 | | 11,009 | 21,996 | 1,813 | | 86 | 544 | 899 | 483 | 11,106 | 55,212 |
| October | | 3,166 | | 17,265 | 15,123 | 5,714 | 63 | | 1,062 | 737 | 260 | 7,567 | 50,957 |
| November | | 2,479 | | 10,158 | 5,889 | 8,401 | | | 308 | 146 | 77 | 6,325 | 33,783 |
| December | | | | 4,396 | | 12,367 | | | | 304 | | 1,215 | 18,282 |
| Total | 0 | 47,161 | 0 | 139,566 | 73,329 | 38,270 | 2,459 | 213 | 3,887 | 3,291 | 1,444 | 74,365 | 383,985 |

TABLE 13-8.—*New Jersey 1976 lobster catch by county, month, and type of gear (in kilograms)*

| | Monmouth | | | Ocean | | | Atlantic | | | Cape May | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Month | Otter trawl | Inshore pots | Offshore pots | Otter trawl | Inshore pots | Offshore pots | Otter trawl | Inshore pots | Offshore pots | Otter trawl | Inshore pots | Offshore pots | Total |
| January | | | | 637 | 391 | 5,283 | | | | | | 81 | 6,392 |
| February | | 240 | | 691 | | 940 | | | | 152 | | | 2,023 |
| March | | 1,815 | | 1,814 | 15 | | | | | 312 | | 158 | 3,781 |
| April | | 11,626 | | 14,318 | 956 | | 61 | | | 266 | | 2,664 | 29,891 |
| May | | 12,475 | | 25,722 | 1,803 | | | | 145 | | 5,874 | 46,019 | |
| June | | 12,356 | | 11,010 | 3,603 | | 1,633 | | 1,179 | | | 5,736 | 35,517 |
| July | | 9,182 | | 4,155 | 2,788 | | 318 | | | 162 | | 12,909 | 29,514 |
| August | | 7,124 | | 990 | 1,530 | 2,407 | | | 1,021 | 253 | | 18,310 | 31,635 |
| September | | 4,275 | | 4,084 | 630 | 19,986 | | | 544 | 421 | | 16,264 | 46,204 |
| October | | 4,740 | | 4,762 | 826 | 18,247 | | 544 | | | 13,634 | 42,753 | |
| November | | 1,887 | | | 1,217 | 2,037 | | | | | | 4,552 | 9,693 |
| December | | 430 | | 2,236 | 729 | 3,370 | | | | | | 1,105 | 7,870 |
| Total | 0 | 66,150 | 0 | 70,086 | 14,488 | 52,270 | 2,012 | 544 | 2,744 | 1,711 | 0 | 81,287 | 291,292 |

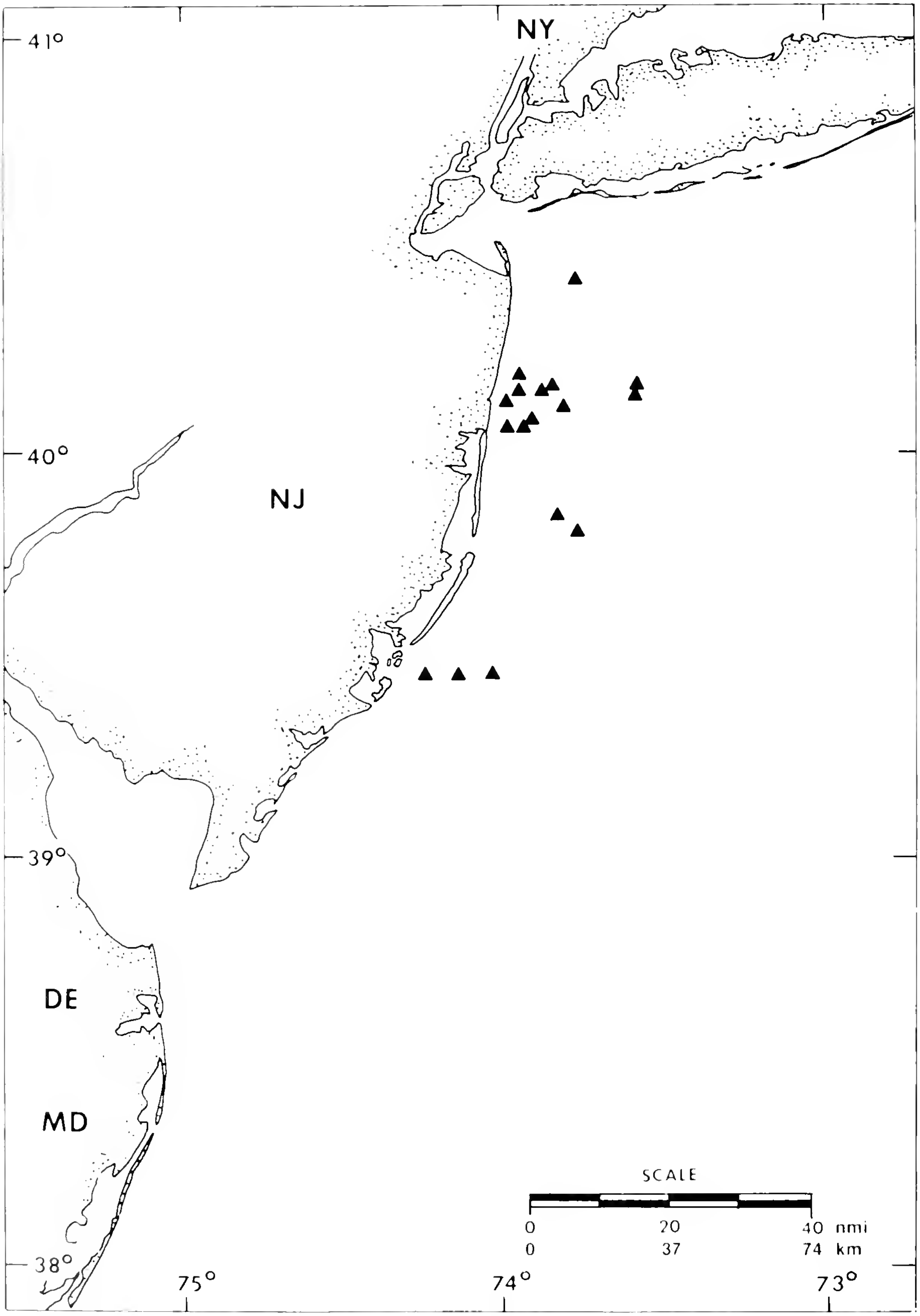

FIGURE 13–3.—Wrecks where divers reported finfish and lobster mortalities, July 3–18, 1976.

TABLE 13–9.—*Summary of dead finfish observed on oxygen-depletion investigation cruises in 1976*

| Vessel | 1976 date | Station | Species* | Number | Weight, kg |
|---|---|---|---|---|---|
| *Rorqual* | July 8 | 2 | Ocean pout *(Macrozoarces americanus)* | 12 | 4.6 |
| *Grand Larson* | July 2 | | Fawn cusk-eel *(Lepophidium cervinum)* | 1 | <0.1 |
| | July 15 | 5 | Little skate *(Raja erinacea)* | 1 | 0.2 |
| *Rorqual* | July 20 | 2 | Lined seahorse *(Hippocampus erectus)* | 1 | <0.1 |
| *Atlantic Twin* | August 8 | 21 | Silver hake *(Merluccius bilinearis)* | 1 | 0.1 |

* Stations locations are shown in figure 13–1.

TABLE 13–10.—*Species of finfish reported in 1976 mortality observations*[1]

| Species | | Reports of finfish mortality | | | |
|---|---|---|---|---|---|
| Common name | Scientific name | NEFC[2] survey | Sport dives | Commercial fishermen | Beach |
| Smooth dogfish | *Mustelus canis* | | | | X |
| Little skate | *Raja erinacea* | X | | | |
| Silver hake | *Merluccius bilinearis* | X | X | X | |
| Red hake | *Urophycis chuss* | X | X | X | |
| Fawn cusk-eel | *Lepophidium cervinum* | X | | | |
| Striped cusk-eel | *Rissola marginata* | | | | X |
| Ocean pout | *Macrozoarces americanus* | X | X | X | |
| Lined seahorse | *Hippocampus erectus* | X | | | |
| Black sea bass | *Centropristis striata* | | | X | |
| Bluefish | *Pomatomus saltatrix* | | | X | |
| Spot | *Leiostomus xanthurus* | | | | X |
| Tautog | *Tautoga onitis* | | | X | X |
| Cunner | *Tautogolabrus adspersus* | | X | X | |
| Northern stargazer | *Astroscopus guttatus* | | | | X |
| Searobin | *Prionotus sp.* | | | | X |
| Summer flounder | *Paralichthys dentatus* | | | X | X |
| Windowpane | *Scophthalmus aquosus* | | | | X |
| Winter flounder | *Pseudopleuronectes americanus* | X | | X | |
| Weakfish | *Cynoscion regalis* | | | | X |
| Striped bass | *Morone saxatilis* | | | | X |

[1] After Steimle 1976.

[2] Northeast Fisheries Center.

a stressed condition, because the rate of oxygen consumption does not keep pace with the increased metabolic cost of pumping water across the gills.

Davis et al. (1963) found that the sustained swimming performance capability of coho salmon (*Oncorhynchus kisutch*) and chinook salmon (*O. tsawytshcha*) is increasingly impaired as D.O. levels decrease. Possibly fish so impaired may have difficulty avoiding predators or catching prey, or both.

As D.O. level decreases, the metabolic cost of respiration exceeds the fish's ability to maintain respiratory processes and death ensues. The oxygen level at which this occurs varies with temperature. Voyer and Hennekey (1972) found that adult mummichogs (*Fundulus heteroclitus*), a species "more resistant to acute low dissolved oxygen levels than other marine fishes," are able to withstand 1.5 ml $O_2$/l (20° C, approx. 31°/oo). The (6-hour) mortality rate at 0.8 ml/$O_2$/l was 10 percent, and 100 percent at 0.3 ml $O_2$/l.About 50 percent of the test animals died in 6 hours when tested at 0.6 ml $O_2$/l (20° C).

Shepard (1955) found that brook trout (*Salvelinus fontinalis*) could withstand lower oxygen levels if gradually acclimated to them. When brook trout were acclimated to air saturation, the 50 percent lethal level (5,000 minutes) was 1.3 ml $O_2$/l, whereas the lowest concentration to which young brook trout could be acclimated without significant mortality was estimated to be 0.7 ml $O_2$/l. It would seem to follow that if the oxygen level of their environment began to drop slowly, fish could acclimate to reduced oxygen levels for a period of time.

In addition to acclimation, a few species are capable of varying degrees of anaerobic metabolism (Hochachka and

TABLE 13–11.—*Finfish avoidance of anoxic water mass and subsequent repopulation of an area as demonstrated by trawl catches, August 6–17, 1976*

| Location | | 39°30′N 74°08′W | | | 38°30′N 74°01′W | | | 39°30′N 73°55′W | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Station number | | 23 | 29 | 90 | 24 | 30 | 91 | 25 | 31 | 92 |
| Depth (m) | | 17 | 18 | 20 | 26 | 23 | 25 | 25 | 26 | 26 |
| Bottom temperature (° C) | | 11.1 | 17.4 | 16.3 | 10.8 | 15.0 | 13.4 | 11.1 | 17.4 | 11.6 |
| Bottom dissolved oxygen (ml/l) | | 0.00[a] | 3.36 | 0.28 | 0.00 | 2.91 | 0.01 | 0.00 | 3.36 | 0.61 |
| Date: Month | | August[b] | | | August | | | August | | |
| Day | | 9 | 10 | 16 | 9 | 11 | 16 | 9 | 11 | 16 |
| **Common name:** | **Scientific name:** | | | | | | | | | |
| Smooth dogfish | *Mustelus canis* | | X | | | | | | | |
| Striped anchovy | *Anchoa hepsetus* | X | | | | | | | | |
| Silver hake | *Merluccius bilinearis* | | | | | | | | | X |
| Spotted hake | *Urophycis chuss* | | | | | | | | X | X |
| Lined seahorse | *Hippocampus erectus* | | | | X | | | | | |
| Black sea bass | *Centropristis striata* | | | | | | | | | X |
| Scup | *Stenotomus chrysops* | | | | | | | | | X |
| Weakfish | *Cynoscion regalis* | | X | | | | | | | |
| American sand lance | *Ammodytes americanus* | | | | X | | | | | |
| Butterfish | *Peprilus triacanthus* | X | | | | X | | | X | X |
| Northern searobin | *Prionotus carolinus* | | X | | | X | | | | X |
| Summer flounder | *Paralichthys dentatus* | | X | | | | | | | |
| Windowpane | *Scophthalmus aquosus* | | | | | X | | | | X |
| Gulf Stream flounder | *Citharichthys arctifrons* | | | | | | | | | X |
| Longfin squid | *Loligo pealei* | X | | | | | | | X | |

[a] Indicates oxygen level below detection limit of method used.

[b] August 9, day before hurricane Belle; August 11, day after hurricane Belle; August 16, approximately 1 week after hurricane Belle.

Somero 1971). For example, during winter conditions European carp (*Cyprinus carpio*) often become "ice-locked" in small ponds that gradually become anaerobic and remain oxygen free for 2 to 3 months until the spring thaw. Coulter (1967) identified 10 species of benthic fishes that appear to live in, or tolerate, extremely low D.O. concentrations for extended periods in Lake Tanganyika. The number of fish species with anaerobic mechanisms is unknown. We would expect to find them in bodies of water with large fluctuations in D.O., such as some ponds or lakes, or in essentially stagnant waters, such as some fiords, or the abyssal areas of the Black Sea, rather than in the relatively shallow waters of the continental shelf off New Jersey (Davis 1975). Hall (1929) found that the oyster toadfish (which prefers estuaries) "often lives in stagnant water and readily survives 24 hours in oxygen-free water." Anaerobic metabolism, if possessed, seems to be used only when respiration is not feasible.

### Avoidance Behavior

What our data do show is that instead of dying, finfish in most cases were able to avoid the low D.O. area. This avoidance and subsequent repopulation is well demonstrated by the results of three stations that were sampled three times (table 13–11) during the August RV *Atlantic Twin* cruise. These three stations were first occupied the day before hurricane Belle passed (August 10, 1976). The second sampling was on the day after the hurricane passed. The last sampling was about 1 week later.

The first time these stations were sampled, the bottom D.O. levels were so low that they were below the detection limits of the method used. Of the species captured, only the American sand lance (*Ammodytes americanus*) is usually found closely associated with the bottom; the other species are able to thrive in, and probably were captured well up in, the water column above the anoxic water. The sand lance was probably taken in the upper layers, because the combination of anoxia and hydrogen sulfide poisoning would preclude life lower down.

Immediately after the passage of hurricane Belle, several demersal finfish species had repopulated the previously vacated area. This was a direct result of the extensive mixing that had brought the oxygen levels to over 2.8 ml/l at all three stations. However, offshore waters of depths greater than 33 m were unaffected by the storm and bottom D.O. remained low. Station 32 (NMFS 1977), which was 9.3 km farther offshore than station 31 (NMFS 1977), had a D.O. of 0.26 ml/l. No finfish were taken at this station. Bottom D.O. east of this station was not detectable.

About 1 week later, these stations were revisited and the anoxic water mass was again shifting toward the coastline. Two stations had less than 0.4 ml $O_2$/l, and no finfish were taken. At station 92 the D.O. was about 0.6 ml/l $O_2$, and seven species of demersal finfish were taken, probably from either a lens or a tongue of water with a higher oxygen level. In either case, obviously these fish actively sought out or stayed in waters with higher oxygen concentrations. This is further supported by the fact that no dead finfish were collected in any of the trawls in this general area.

Several studies support this avoidance behavior. Shelford and Alee (1913) noted results ranging from no reaction to a decided response when testing several freshwater species in an oxygen gradient. Jones (1952) found that the three-spine stickleback (*Gasterosteus aculeatus*), minnow (*Phoxinus phoxinus*), and brown trout fry (*Salmo trutta*) reacted to low oxygen only after respiratory distress developed. Whitmore et al. (1960), contrary to Jones' finding, found strong and pronounced avoidance reactions by chinook salmon (*Oncorhynchus tshawytscha*), coho salmon (*Oncorhynchus kisutch*), largemouth bass (*Micropterus salmoides*), and the bluegill (*Lepomis macrochirus*). All avoided some depressed level of oxygen. The two Pacific salmon species and the largemouth bass avoided 3.2 ml $O_2$/l. The coho salmon showed some avoidance to 4.2 ml $O_2$/l. All species avoided 2.1 and 1.1 ml$O_2$/l. Further, the observations of Whitmore et al. (1960) strongly suggest that the fish are capable of very rapid detection of changes in D.O., even before respiratory distress is apparent.

Therefore, when we consider that fish, which are highly mobile, are able to detect and survive (at least for short periods of time) decreasing oxygen levels, it is probable that they could successfully avoid hazardous conditions, barring entrapment.

Avoidance behavior is further supported by the movement of summer flounder and bluefish and the unusual catches made by anglers throughout most of summer 1976. Early in that season, summer flounder seemed to show up where they usually did in past years and in about their expected numbers. Off northern New Jersey, this normal pattern ended suddenly beginning late in June, coinciding with the formation of anoxic water along the seafloor. Our information indicates that summer flounder were concentrated along the leading edge of the anoxic water. At various times and points along the coast, the location of the anoxic water pushed great numbers of summer flounder, including many large specimens that usually inhabit deeper waters, into the surf zone and into inlets and bays where D.O. levels could sustain aquatic life. This resulted in masses of a very desirable species of fish within easy reach of anglers. Consequently, anglers fishing from shore as well as from boats made large catches. Such was the case in Sandy Hook Bay during mid-July and off Long Beach Island and Atlantic City in mid- and late July.

Surveys have shown that anglers can account for as much as half the total number of summer flounder removed from the sea during normal years (Hamer and Lux 1962; Murawski 1970). Because the annual combined harvest (commercial and recreational) has approached the maximum sustainable yield in recent years (Chang and Pacheco 1976), an increase in the recreational catch while maintaining the commercial catch, during July and August 1976 along New Jersey, may significantly affect future stocks.

Tagging returns, fishing reports, and catch rates of recreational fishermen indicate that most bluefish between 1.4 and 5.4 kg may have been blocked from migrating northward past New Jersey during summer 1976. Thus, bluefish were diverted from their normal patterns of spending the summer feeding and spawning along the coast from northern New Jersey to southern New England and feeding along northern New England. Upon encountering the low D.O. water these migrants apparently reversed their direction and headed south. During most of July, August, and September they milled about off the coast of southern New Jersey and the northern Delmarva Peninsula (Delaware, Maryland, and Virginia). Fishermen in the coastal States from New York to Maine reported catching few fish of this size.

A study of the 1976 catch records of New Jersey charter boat anglers shows that from early May to about mid-June bluefish were more or less evenly distributed along the New Jersey coast. But starting in the last week of June, catches fell off along the northern part of the State where the anoxic water first appeared and they tended to be greater along the central and southern parts of the coast where normal conditions still prevailed. This, and the fact that the first return from the June 8 tagging was off Cape Henlopen on June 25, indicates that the bluefish may have detected and avoided the anoxic water at least a week before the earliest reported fish mortality. During early and mid-July, the bluefish were caught almost entirely outside the oxygen-depleted water. Catches made over the anoxic water, especially in the Barnegat Ridge area, were from schools concentrated above the thermocline or in small isolated pockets where the bluefish apparently found tolerable D.O. This could explain the occurrence of large quantities of surf clams (*Spisula solidissima*) in the stomachs of bluefish caught off Barnegat Light during the first week or so in August, as observed during the RV *Atlantic Twin* cruise and reported by various captains. Throughout the rest of the summer, most of the bluefish were caught outside, above, or along the edge of the anoxic water mass. As stated above, specimens caught inside the anoxic region were likely living high in the water column and apparenly had not fed for some time. As expected under anoxic conditions, catch rates were often very light. No bluefish were caught in the area having either hazardous hydrogen sulfide concentrations or very low D.O.

The inshore contingent of bluefish, that is, those between 0.5 and 1.4 kg and migrating close along the ocean shore, seemed not to have been affected. Throughout most of the summer the anoxic water remained at least

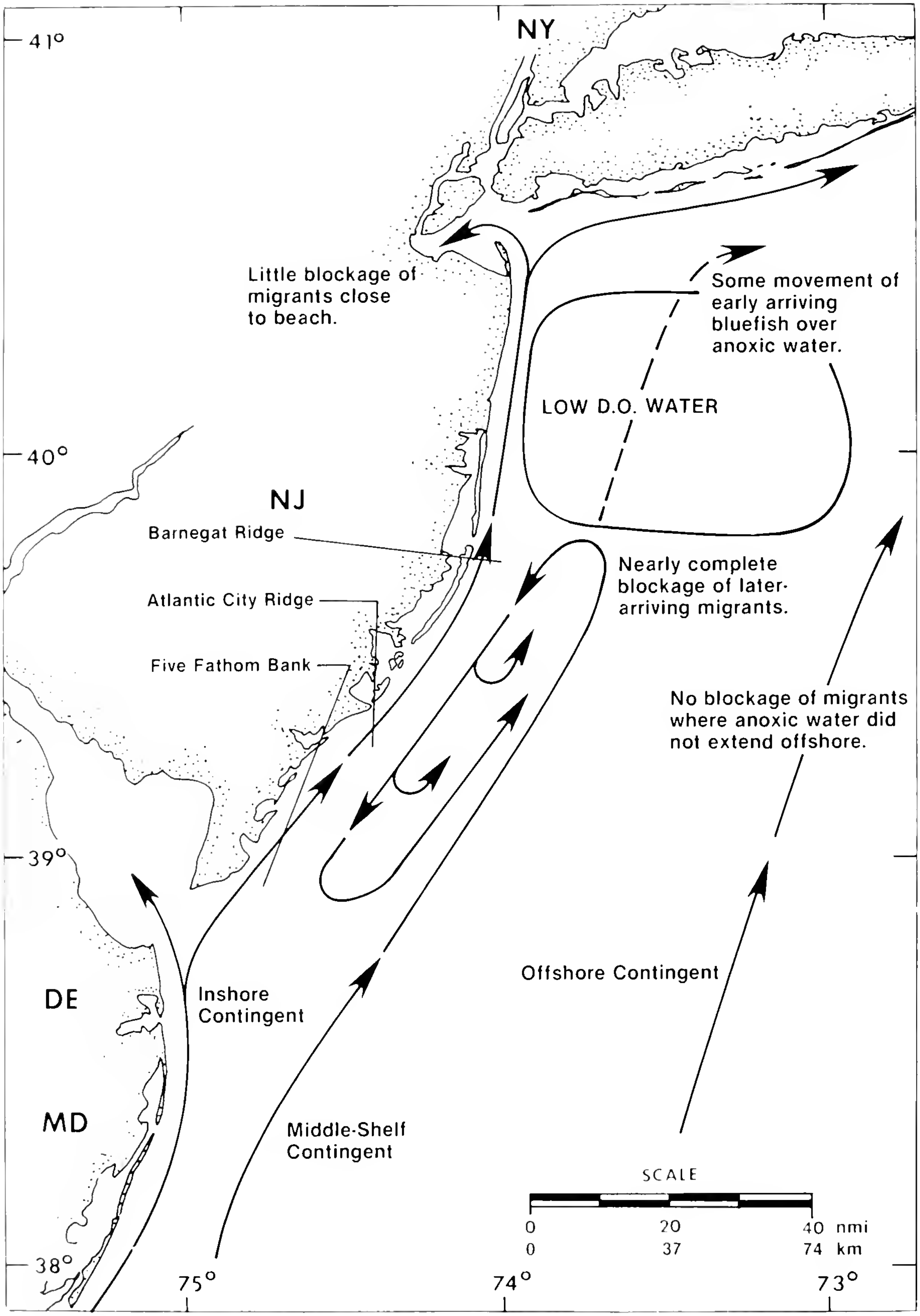

FIGURE 13–4.—Schematic migratory pathway for the various contingents of bluefish during summer 1976.

several kilometers away from shore; thus, the usual pathway for these fish remained open almost all of the time. This is supported by small-sized fish that had been tagged off New Jersey and captured off New York City. It is also supported by fishing reports of normal catches of this size fish from along the south shore and eastern end of Long Island and along the shores of Rhode Island and southern New England.

The offshore contingent of bluefish seemingly were not affected by the anoxic water and proceeded on their northward migration uninhibited. The usual pathway for these 2.7 to 6.8 kg fish was apparently seaward of the farthest extent of the anoxic water. Figure 4 illustrates the bluefish migratory pattern that emerged as a result of the existence of the anoxic water mass.

Although the fish were avoiding the anoxic water mass, on several occasions an undetermined number of fish were trapped in the low D.O. mass near beaches. This occurred in late July between Manasquan and Beach Haven, N.J., when persistent westerly winds apparently blew the oxygenated surface waters offshore, causing an inshore movement or upwelling of the anoxic bottom water. The trapped fish were observed to be gasping at the surface and behaving lethargically. Belding (1929) and Shepard (1955) both found this type of behavior to be symptomatic of depressed D.O. conditions. Species reportedly involved were striped bass (*Morone saxatilis*), bluefish, weakfish (*Cynoscion regalis*), windowpane (*Scophthalmus aquosus*), summer flounder, and northern searobin (*Prionotus carolinus*). It was impossible to obtain an accurate estimate of mortalities, because the gulls were very active; some dead fish were observed on the beach.

### Reproductive Success

In addition to supporting a diverse community of adult fishes, shelf waters between Sandy Hook and Cape May serve as spawning grounds for many of our most important commercial and recreational fishes, and nursery grounds for their young stages. Both eggs and larvae can be found year-round, but most spawning takes place in spring, summer, and autumn. Although a few species spawn throughout the year, most do so over a period of a few months and, for most, spawning peaks during a period of weeks. Successful spawning depends partly on an unknown combination of environmental requirements that differ with species and include such things as temperature, water quality, and available food. The eggs and small larvae are the most vulnerable life stage and therefore the most sensitive to environmental changes (Voyer and Hennekey 1972).

Alderdice et al. (1958) and Voyer and Hennekey (1972) have studied the direct effects of low D.O. levels on embryonic stages. Both studies concluded that depressed D.O. retards the development of the embryo and delays hatching. The effects of limited exposure can be reversed, but prolonged exposure results in irreversible damage (and the production of monstrosities) or death. When eggs in advanced developmental stages are exposed to depressed D.O., hatching may be premature.

Based on the information at hand, there seems no reason to doubt that spawning was disrupted off New Jersey during summer 1976. Adult fishes either avoided the large area of anoxic water or perished. Because ichthyoplankton samples were not collected during summer 1976, we do not know what effect the anoxic water mass had on the reproductive cycle of fishes that would have spawned off New Jersey. We do have data from both historical and recent cruises, indicating that a host of fishes spawn within the area where the low D.O. prevailed in 1976 (table 13–3). We should point out that collecting gear and methods used in 1966 were different from those used in 1975 and 1976, and, given only the information in the table, any attempt to equate catches from the two series of cruises would produce invalid results.

## EFFECTS ON AMERICAN LOBSTER

American lobster probably react to depressed oxygen levels like finfish do. McLeese (1956) found that oxygen uptake of small lobster is greater per unit weight than large lobster; lobsters are able to acclimate to low-oxygen concentrations; moulting lobsters are less resistant to low-oxygen than hard-shell lobster; and the minimum D.O. they can tolerate varies with temperature and salinity. As an example of the way the minimum D.O. varies, at 15° C with a salinity of 30°/oo the minimum D.O. is 0.54 ml/l, at 15° C with a salinity of 25°/oo the minimum is 0.63 ml/l, and at 5° C with a salinity of 30°/oo the minimum is 0.19 ml/l.

During the 1976 RV *Atlantic Twin* cruise the bottom temperature in the anoxic area was 7° C to 12° C, while the corresponding salinities were about 30 to 33°/oo (Azarovitz, unpublished data). Applying McLeese's observations to these would seem to indicate that the minimum D.O. level that lobster could survive would be between 0.26 ml/l and 0.43 ml/l. Much of the depressed D.O. water mass had oxygen levels below these. If lobsters resident to the areas affected did not leave, mortality would result.

Evidence is mixed on whether lobsters avoided or succumbed to anoxia. On June 27, 1976, divers observed that lobsters that were apparently residents of certain wrecks had climbed to the highest part of these wrecks. By July 4, 1976, these same lobsters were observed to be dead. In mid-July other lobsters were observed to be lethargic and lying outside their shelters, often with two or more close to each other. This observation is significant when we consider the aggressive behavior of lobsters. Late in September, lobsters again inhabited these same wrecks. The climbing behavior on the wrecks may indicate that lobsters can detect decreasing D.O. levels and areas of greater D.O. concentration.

Off southern New England and the middle Atlantic States the offshore lobster population has an inshore-offshore migration pattern (Uzmann et al. 1977). The onshore migration is from March to August; the offshore migration is from October to December. Uzmann et al. (1977) estimated that at least 20 percent of the offshore population annually migrates. This migration significantly affects the inshore lobster fishery. It is reasonable to hypothesize that the anoxic water mass blocked the 1976 shoreward migration, because lobsters could probably detect the decreased oxygen level and are capable of traveling up to 9.3 km/d on a sustained basis (Uzmann et al. 1977).

Lobster landings by otter trawl were also down in the Ocean County area, but cannot be attributed solely to the oxygen-depleted waters. For one, the otter trawl catch was down before the reported fishkills, and second, most lobster trawlers are able to fish far enough offshore to avoid the oxygen-depleted regions.

The offshore pot catch landed in Ocean County was up in August and September, owing primarily to inshore fishermen moving offshore if they had vessels and equipment to do so.

The lobster landings at the southern end of New Jersey (Cape May County) did not seem to be affected and were up slightly in 1976. Since the southernmost end of New Jersey was not affected by the anoxic water conditions, this area may be loosely compared with the rest of the State. With this in mind, it seems evident that the decreased landings to the north can be attributed to the change in water conditions rather than to natural fluctuation in the lobster population.

## REFERENCES

Alderdice, D. F., Wickett, W. P., and Brett, J. R., 1958. Some effects of temporary exposure to low dissolved oxygen levels on Pacific salmon eggs, *J. Fish. Res. Board Can.* 15:229–249.

Baldwin, F. M., 1923. Comparative rates of oxygen consumption in marine forms, *Proc. Iowa Acad. Sci.* 30:173–180.

Belding, D. L., 1929. The respiratory movements of a fish as an indicator of a toxic environment, *Trans. Amer. Fish. Soc.* 59:238–245.

Chang, S., and Pacheco, A. L., 1976. Evaluation of the summer flounder population in subarea 5 and statistical area 6, *Int. Comm. Northw. Atlantic Fish. Selected Papers* No. 1, p. 19

Clark, J., Smith, W. G., Kendall, Jr., A. W., and Fahay, M. P., 1969. Studies of estuarine dependence of Atlantic coastal fishes, Tech Paper 28, Bureau of Sport Fisheries and Wildlife, U.S. Department of Interior, Washington, D.C., 132 pp.

Coulter, G. W., 1967. Low apparent oxygen requirements of deep water fishes in Lake Tanganyika, *Nature* 215:317–318.

Davis, G. E., Foster, J., Warren, C. E., and Doudoroff, P., 1963. The influence of oxygen consumption on the swimming performance of juvenile Pacific salmon at various temperatures, *Trans. Amer. Fish. Soc.* 92:111–124.

Davis, J. C., 1975. Minimal dissolved oxygen requirements of aquatic life with emphasis on Canadian species: a review, *J. Fish. Res. Board Can.* 32:2295–2332.

Freeman, B. L., Turner, S. C., and Christensen, D. J., 1976. A preliminary report on the fishery for bluefin tuna (*Thunnus thynnus*)off New Jersey in relation to the catches made by charter and party boat anglers during 1975, Informal Report 108, Sandy Hook Laboratory, National Marine Fisheries Service, U.S. Department of Commerce, Highlands, N.J., 9 pp.

Fry, F. E. J., 1947. Effects of the environment on animal activity, Univ. Toronto Stud., Biol, Ser. No. 55, *Publ. Ontario Fish. Res. Lab.* No. 68, 62 pp.

Hall, F. G., 1929. The influence of varying oxygen tensions upon the rate of oxygen consumption in marine fishes, *Amer. J. Physiol.* 88:212–218.

Hamer, P. E., and Lux, F. E., 1962. Marking experiments on fluke (*Paralichthys dentatus*) in 1961, Atlantic States Mar. Fish. Comm., presented at the 28th meeting of the North Atlantic section, app. MA6, 6 pp.

Hochachka, P. W., and Somero, G. N., 1971. Biochemical adaptation to the environment, in W. S. Hoar and D. J. Randall (eds.), *Fish Physiology*, vol. 4, Academic Press, Inc., N.Y., pp. 99–156.

Jones, J. R. E., 1952. The reactions of fish to water of low oxygen concentration, *J. Exp. Biol.* 29:403–415.

Jossi, J. W., Marak, R., and Petersen, H., Jr., 1975. MARMAP Survey I Manual: At-sea data collection and laboratory procedures, MARMAP Program Office, National Marine Fisheries Service, National Oceanic and Atmospheric Administration, Washington, D.C., 70 pp.

McLeese, D. W., 1956. Effects of temperature, salinity and oxygen on the survival of the American lobster, *J. Fish. Res. Board Can.* 13(2):247–272.

Murawski, W. S., 1970. Results of tagging experiments of summer flounder, (*Paralichthys dentatus*), conducted in New Jersey waters from 1960 to 1967, Miscellaneous Report No. 5M, Division Fish, Game and Shellfisheries, New Jersey Department Environmental Protection, Trenton, N.J., 25 pp.

National Marine Fisheries Service, 1977. Oxygen depletion and associated environmental disturbances in the Middle Atlantic Bight in 1976, *Northeast Fisheries Center Tech. Ser. Rep.* No. 3, Sandy Hook Laboratory, Highlands, N.J., 471 pp

Saunders, R. L., 1963. Respiration in the Atlantic cod, *J. Fish. Res. Board Can.* 20:373–386.

Shelford, V. E., and Allee, W. C., 1913. The reactions of fishes to gradients of dissolved atmospheric gases, *J. Exp. Zool. 14:207–266.*

Shepard, M. P., 1955. Resistance and tolerance of young speckled trout (*Salvelinus fontinalis*) to oxygen lack, with special reference to low oxygen acclimation, *J. Fish. Res. Board Can.* 12:387–446.

Steimle, F. W., 1976. Mortalities of fish and shellfish associated with anoxic bottom water in the Middle Atlantic Bight, NOAA Red Flag Report, Sandy Hook Laboratory, Highlands, N.J., 26 pp.

Uzmann, J. R., Cooper, R. A., and Pecci, K. J., 1977. Migration and dispersion of tagged American lobsters (*Homarus americanus*) on the southern New England continental shelf, *NOAA Tech. Rep.* NMFS SSRF-705. U.S. Department of Commerce, Washington, D.C., 92 pp.

Voyer, R. A., and Hennekey, R. J., 1972. Effects of dissolved oxygen on two life stages of the mummichog, *Prog. Fish. Cult.* 34:222–225.

Voyer, R. A., and Morrison, G. E., 1971. Factors affecting respiration rates of winter flounder (*Pseudopleuronectes americanus*) (Walbaum), *J. Fish. Res. Board Can.* 28(12):1907–1911.

Whitmore, C. M., Warren, C. E., and Doudoroff, P., 1960. Avoidance reactions of salmonids and centrarchid fishes to low oxygen concentrations, *Trans. Amer. Fish. Soc.* 89:17–26.

# Oxygen Depletion and Associated Benthic Mortalities in New York Bight, 1976

# Chapter 14. Socioeconomic Impacts

*William Figley, Bruce Pyle, and Bruce Halgren*[1]

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## INTRODUCTION

New Jersey's marine fishery resources provide substantial food and recreation and are a valuable asset to the State's economy. In 1975, New Jersey had 3,056 resident commercial fishermen; 4,677 workers marketed and processed the harvest (National Marine Fisheries Service 1976). The dockside value of the 1975 commercial catch was $18 million (NMFS 1977), and the economy generated in processing and marketing was estimated at $46 million for a total commercial value of nearly $64 million.

During 1974, an estimated 1.46 million residents and 1.25 million nonresidents fished and crabbed for recreation in New Jersey's saltwaters (NMFS 1975). Over 32 million man-days of activity were spent in pursuit of sport fishing. The 1975 National Survey of Hunting, Fishing, and Wildlife-Associated Recreation estimated that New Jersey marine recreational fishermen spend $19.02 per trip on bait, tackle, equipment, food and lodging, transportation, and related items. Their approximate annual expenditure is over $600 million, if the estimated per-trip expenditure of each person engaged in marine recreational fishing and crabbing within the State is multiplied by the number of days. The absence of expenditures for other marine biota-related recreational activities (e.g., clamming) makes this estimate conservative. Undoubtedly, a portion of the expenditures by nonresidents accrue to neighboring States, so that estimated expenditures within New Jersey are considered to be about $500 million annually.

Thus, a conservative estimate of the total economy generated within the State by commercial and recreational marine fisheries in 1975 is $564 million. Most of these revenues were received by commercial fishermen, fish dealers and processors, bait shops, marinas, charter and party boats, restaurants, motels, and gas stations within five southern coastal counties, Monmouth, Ocean, Atlantic, Cape May, and Cumberland. The 1976 estimate of personal income for these five counties was $7.7 billion, and that for the State was $54 billion (Shirley Goetz, New

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[1] Division of Fish, Game, and Shellfisheries, State of New Jersey, P.O. Box 1809, Trenton, NJ 08625

Jersey Department of Labor and Industry, personal communication). Monies generated from use of marine fishery resources were 7.3 percent of the five coastal counties' annual personal income and 1.0 percent of the State's personal incomes. Locally, the economy generated by these fisheries is extremely important.

In addition to their monetary value, commercial and recreational harvests represent substantial sources of food and protein. The 1975 commercial catch was 65,306 t, most of which was processed for humans and livestock. There is no estimate of the tonnage landed by recreationalists, but the sport catch of many species far outweighs commercial landings.

Not surprisingly, commercial and sport fishermen, as well as the general public, were alarmed when extensive areas of oxygen-depleted water and marine mortalities were discovered along the Jersey coast during summer 1976. The disruption of ocean waters and destruction of marine life threatened both the State's valuable marine fishery resources and its second largest industry, the primarily ocean-based resort trade.

## PROCEDURES

Information regarding financial losses to commercial trawlers and party and charter boats resulting from the offshore oxygen-depleted water was obtained by a random telephone survey. Names of trawler captains were selected from a list of food fishermen who are licensed to fish between 3 and 5 km of the coast. Obviously, vessel captains could only estimate their landings. Total fleet losses were estimated by expanding average per-boat losses to include all boats operating in the affected area.

An important consideration is the difference between actual economic losses and losses based on resource mortality. Actual losses refer to dollar losses reported by fishermen as a result of smaller catches harvested, increased operating costs, fewer trips, or decreased revenues from fares. Losses from mortality are estimates of the potential dollar value of the standing crop lost. Resource losses can cause actual dollar losses to fishermen, processors, and marketers.

Estimates of dollar losses in processing and marketing the commercial catch were calculated by multiplying dockside losses by a factor of 2.5 (Rorholm 1974).

## LOSSES RELATED TO COMMERCIAL FISHERIES

Commercial landings fluctuate widely from year to year because of changes in market prices, availability and abundance of stocks, and weather. The interaction of these factors makes it extremely difficult to assess the impact of a single factor, such as oxygen depletion, upon the harvest of a given stock in any year. Table 14–1 compares the 1976 harvest with that of 1975, and with the average of 1971 through 1975 for those species that might have been affected by the anoxic event. Compared to the 5-year average for 1971–75, landings of cod, white hake, king whiting, striped bass, rock crabs, lobsters, and surf clams declined in 1976. Landings of cod, king whiting, striped bass, and lobster were declining before 1976. Increased landings were reported for bluefish, croakers, blackback flounder, fluke, red hake, scup, sea bass, tautog, weakfish, whiting, and sea scallops.

Although many commercially important species of finfish suffered mortalities during summer 1976 (ch. 13), Azarovitz et al. (1977) found few dead fish in their trawl samples and stated that finfish mortalities were minimal. The principal effect of oxygen depletion on finfish stocks was to reduce their abundance in affected areas and cause them to concentrate in unaffected areas. This disturbance of normal migratory patterns and summering areas caused reduced catches by some commercial fishermen and forced them into longer, more expensive runs to find fish. On the other hand, summer flounder were concentrated close to the beach and provided excellent inshore fishing.

In November 1976 we interviewed 13 captains of New Jersey-licensed commercial trawlers (table 14–2). Three who fished from Sea Isle City to Cape May reported no financial losses caused by the summer marine mortalities. We interviewed 8 of the 10 captains operating out of ports north of Sea Isle City; the 8 stated they had financial losses. Five reported losses between $6,000 and $40,000, with an average per-boat loss of $28,000; three did not estimate their losses.

According to the National Marine Fisheries Service's (NMFS) statistical agent for New Jersey, 181 commercial finfish trawlers operated from New Jersey ports. Of these, 82 operated from ports in Monmouth, Ocean, and Atlantic Counties. If reported per-boat losses are expanded to include the entire trawler fleet (80% suffered losses) in the three affected counties, the total estimated dockside loss was $1.9 million to the fishermen: Resulting losses to processing and marketing amounted to an additional $4.6 million. Thus, estimated losses to commercial trawl fisheries totaled $6.5 million.

Because the oxygen-depleted waters were limited to areas within 100 km of the shore, small inshore trawlers were undoubtedly affected more than larger offshore boats that could search farther for fish. Also, because the sample was limited to inshore trawlers, expansion to cover the entire fleet probably resulted in an overestimate of losses to New Jersey-based boats. No determination was made of possible losses to boats from other States fishing in New Jersey waters.

TABLE 14-1.—*Comparison of New Jersey's 1976 commercial landings with past harvests*

| Species | 1971-75 avg. y | 1975 | 1976 | Change in 1976 over 5-y avg. | Change in 1976 over 1975 |
|---|---|---|---|---|---|
| | t | t | t | Percent | Percent |
| Bluefish | 450 | 581 | 580 | 29 | ~0 |
| Cod | 137 | 140 | 41 | −70 | −71 |
| Croakers | 88 | 401 | 318 | 261 | −21 |
| Flounder, blackback | 53 | 48 | 64 | 21 | 33 |
| Fluke | 1,321 | 1,956 | 2,566 | 94 | 31 |
| Hake, red | 396 | 403 | 857 | 117 | 113 |
| Hake, white | 23 | 22 | 13 | −43 | −41 |
| King whiting | 76 | 1 | <1 | −100 | −93 |
| Scup | 1,904 | 2,842 | 3,044 | 60 | 7 |
| Sea bass | 307 | 534 | 663 | 116 | 24 |
| Striped bass | 225 | 155 | 62 | −72 | −60 |
| Tautog | 11 | 15 | 20 | 82 | 33 |
| Weakfish | 1,442 | 1,982 | 2,589 | 80 | 31 |
| Whiting | 2,660 | 2,933 | 3,590 | 35 | |
| Crabs, rock | 78 | 84 | 68 | −13 | −19 |
| Lobsters | 649 | 386 | 293 | −55 | −24 |
| Clams, surf | 11,778 | 16,032 | 11,056 | −6 | 31 |
| Scallops, sea | 165 | 322 | 1,304 | 690 | 305 |

TABLE 14-2.—*Losses in the commercial finfish industry*

| Port | Did kill affect business? | Value of decline | Was crew income affected? | How was income affected? |
|---|---|---|---|---|
| Belford | yes | minor | no | — — |
| Monmouth | no | 0 | no | — — |
| Pt. Pleasant | no | 0 | no | — — |
| Pt. Pleasant | yes | $15,000 | yes | reduced income |
| Pt. Pleasant | yes | no est. given | yes | reduced salary |
| Barnegat Light | yes | $ 6,000 | yes | 1 unemployed |
| Brigantine | yes | $40,000 | yes | reduced salary |
| Atlantic City | yes | $40,000 | yes | reduced income |
| Atlantic City | yes | no est. given | yes | reduced income |
| Ocean City | yes | $40,000 | yes | decreased salary |
| Sea Isle City | no | 0 | no | — — |
| Cape May | no | 0 | no | — — |
| Cape May | no | 0 | no | — — |

## Surf Clam

Ropes and Chang (1977) estimated that New Jersey's offshore (beyond 5 km of the coast) surf clam resource was 210,000 t of meats in spring 1976. Dredge surveys in September 1976 indicated that anoxic water conditions destroyed 140,000 t or 69 percent of the offshore stock.

Calculation of the potential economic value of the lost resource depends largely on the price per kilogram. The dockside value before the fishkill, January to June of 1976, was $0.53 to $1.19 per kilogram. Using this range, the estimated dockside value of the offshore standing crop lost through mortality was $76 million to $170 million, with an average of $123 million.

Haskin (personal communication) reported that the mortality of the inshore surf clam stocks was not as severe; about 1,500 t of clam meat resources were lost. The estimated dockside value of the lost inshore resource was $800,000 to $1.8 million; the average was $1.4 million.

Thus, the total potential dockside losses to inshore and offshore stocks combined were $77 million to $170 million, with an average of $120 million. Estimated potential losses to processors and marketers of surf clams were $190 million to $430 million, with an average of $310 million. The total potential loss, based on the averages, was estimated at $430 million.

Because surf clams generally reach market size in about

7 years, at least this long will be required for commercial stocks of surf clam to recover. The mass mortalities will cause economic losses to surf clammers and processors for at least the next 7 years. Until the stocks have recovered, both the weight and value of the harvest will steadily decline in succeeding years as the standing crop is reduced by fishing. To offset future declines in clam supplies, clammers and processors plan to increase the harvesting effort and use stocks of ocean quahogs.

### Ocean Quahog

Ropes et al. (ch. 11, pt. 1) estimate that 51,000 t of ocean quahog meats were lost off the New Jersey coast owing to the oxygen-depleted water. This represents about 6.3 percent of the standing crop of 810,000 t. The dockside prices of ocean quahogs were $0.51 to $0.84 per kilogram during March to June 1976. Thus, the estimated potential dockside value of the loss of the ocean quahog resource was $26 million to $43 million, with an average of $34 million. Potential losses to processors and marketers were an estimated $65 million to $110 million, with an average of $86 million. The total potential losses are estimated at about $120 million.

### Sea Scallop

MacKenzie (1977) estimated that between 8.8 and 12.9 percent of the sea scallops off New Jersey were killed in 1976. The dockside values of the annual landings of sea scallops in New Jersey during 1971 to 1975 were $160,000 to $1.4 million and averaged $670,000. Assuming that sea scallops reach harvestable size in 5 years, that the landings during 1976 through 1980 would have equalled those during the preceding 5 years, and that 8.8 to 12.9 percent annual reductions would be sustained as a result of the 1976 mortality, the average potential annual losses would be $58,000 to $86,000 (average $72,000). Total 5-year losses would be $290,000 to $430,000 (average $360,000). Potential economic losses to processors and marketers would be $150,000 to $220,000 (average $180,000) annually, and $725,000 to $1.1 million (average $900,000) for the 5-year period 1976–80. Thus, total potential losses are estimated at about $250,000 for 1977 and $1.3 million for the 5-year period.

It is noted that 1976 was a banner year for the sea scallop fishery, with dockside landings valued at $4.8 million. These landings overshadow the estimated potential losses; however, even greater landings might have been possible without the mortalities associated with the oxygen depletion. For this reason, although no economic losses were evident, the potential loss to the economy through the decreased resource should still be considered.

The estimated economic losses cited above are undoubtedly minimal, because many boats from North Carolina, Virginia, and New England also fish the scallop grounds off New Jersey and these boats would be expected to have similarly reduced catches.

### Lobster

Lobster fishery losses were suffered primarily by the northern inshore pot fishery. The offshore and southern pot and trawl fisheries were virtually unaffected.

The lobster harvest for the first 5 months of 1976 was 6.6 percent greater than it had been the previous year during the same period. From June 1976 on, the catch dropped significantly. Over the last 7 months of the year, the catch was 96.6 t less than it had been for the same period in 1975. That represents a 32-percent decrease in harvest, with a corresponding loss of $410,000 (at the 1976 dockside average value of $4.23 per kilogram). Assuming this reduction of catch was the result of the death of 32 percent of the lobsters normally available on the fishing grounds off New Jersey, we can foresee no increase to former numbers for 4 years; this is the minimum time it takes for a lobster to reach market size. Thus, potential dockside losses for the 4-year period prior to recruitment would total an estimated $1.6 million. Potential economic losses to processors and marketers are estimated at $1.0 million annually and $4.1 million for the 4-year recovery period. Overall potential losses are estimated at $1.4 million for the 4-year recovery preriod. Overall potential losses are estimated at $1.4 million for the first year and $5.7 million over the next 4 years.

### Fish Processing and Wholesaling Industries

The Division of Planning and Research of the New Jersey Department of Labor and Industry made a telephone survey of the State's fish and shellfish processors and wholesalers to assess the effects of the marine mortalities on their operations. Sixteen of the 17 companies classified as fish processors within the State and 15 of 37 seafood wholesalers in five southern counties (Monmouth, Ocean, Atlantic, Cape May, and Cumberland) were questioned. In the five counties surveyed, there were 932 jobs in processing and 174 jobs in wholesaling with firms covered by unemployment insurance (as of March 1976).

Of the 16 processing firms surveyed, 7 processed surf clams exclusively or with other fish products and 9 processed fish products only. The nine fish processors reported that the anoxia did not significantly affect their businesses. Clam processors, on the other hand, reported both lost work time and layoffs (table 14–3). The seven clam processors employed 550 workers from June to September. Although no layoffs were reported during summer, four firms cut their work week by at least 25 percent. For the 265 employees in these four firms, this represented a total loss of roughly 22 man-years of work and pay. During autumn, Snow Food Products closed one plant, but of the

TABLE 14–3.—*Effects of the 1976 surf clam mortalities as interpreted by representatives of the clam processing industry*

| Company | Estimated employees | Impact on employment | Processing level | Future prospects |
|---|---|---|---|---|
| | Number | | Percent | |
| No. 1 | 170 | lay-off 15 | 50 | may harvest ocean quahog |
| No. 2 | 104 | no effects | — — | now harvesting ocean quahog |
| No. 3 | 10–12 | no effects | — — | no adverse impact expected |
| No. 4 | 55 | shorter work week | 25 | — — |
| No. 5 | 40–50 | shorter work week | 15 | no adverse impact expected |
| No. 6 | 100 | shorter work week | 20 | anticipates lay-off |
| No. 7 | 65 | shorter work week | 46 | now processing fish as well as clams |

30 persons laid off one-half were reemployed at other plants in the State.

Other problems faced by the clam processors included difficulties in ordering adequate supplies of clams, rising costs, increased selling prices, and decreased sales volume.

The 15 seafood wholesalers generally reported no significant effects to their operations or employment levels during the summer. Employment was reduced in three firms; 1 individual was laid off and 10 persons lost 1 working day a week. Wholesalers indicated a reduction in seafood supplies, resulting in higher costs. Seven firms had to purchase more fish from out-of-State sources. Also, they felt the adverse publicity from the anoxic event may have discouraged prospective customers.

## LOSSES RELATED TO RECREATIONAL FISHERIES

A total of 99 party and 213 charter boats operate out of New Jersey's seacoast ports (table 14–4). A telephone survey contacted captains of 17 party (17% of the total fleet) and 23 charter (11%) boats (tables 14–5 and 14–6). The interviews indicated that party and charter boats in Cape May and Wildwood experienced no, or very minimal, losses because of the oxygen depletion whereas those to the north had significant losses. Thus, only those boats operating from ports north of Wildwood were included in determinations of economic losses. The survey sample north of Wildwood included 14 party (18% of fleet) and 17 charter (10%) boats. North of Wildwood, 93 percent of the party captains and 82 percent of the charter captains indicated they had lost business during July, August, and September, because of the anoxia. A small number of captains also indicated that some fishermen were reluctant to charter trips on account of the adverse publicity about fish contaminated with Kepone and PCB's. This factor was probably responsible for some portion of the economic losses herein attributed to the offshore anoxia. Party boat losses came primarily from a decrease in the number of fares. The low oxygen severely limited offshore botton and wreck fishing, which is the staple fishery for about half the party boat fleet. In addition, bluefish were distributed farther south than during previous years (Freeman and Turner 1977), and party and charter boats had to make much longer runs, thus adding considerably to their fuel costs. Estimated losses were $1,000 to $47,500 for party boats and $400 to $15,000 for charter boats, with per boat averages of $14,000 and $4,000, respectively. Expanding these figures to cover the entire fleet docked north of Wildwood yields estimated economic losses of $1 million to the 76 party boats and $690,000 to the 174 charter boats. In total, the charter and party boat fleet lost an estimated $1.7 million during July, August, and September 1976.

According to the 1975 National Survey of Hunting and Fishing, State residents spent $26 million on charter and party boat fees. Adding nonresidents, these expenditures increase to roughly $49 million. Thus, losses attributed to the anoxia resulted in an estimated 3.5 percent decline in the total annual revenues of the charter and party boat fleets.

Crew members on party and charter boats also lost money because of less business. Mates on charter boats lost a day's pay for each day of business lost. With fewer fares, many party boats reduced the number of crew members on board. In the entire fleet, an estimated 93 crew members lost summer jobs and 110 received reduced wages.

TABLE 14–4.—*Number of party and charter boats sailing five or more times from New Jersey ports during 1975*[1]

| Area | Party boats | Charter boats |
|---|---|---|
| Perth Amboy—Sea Bright | 14 | 29 |
| Belmar | 14 | 21 |
| Manasquan | 22 | 44 |
| Barnegat—Beach Haven | 11 | 66 |
| Atlantic City—Stone Harbor | 15 | 14 |
| Wildwood—Cape May | 23 | 39 |
| North of Wildwood (total) | 76 | 174 |
| State total | 99 | 213 |

[1] Freeman et al. 1976.

TABLE 14–5.—*Losses in the party boat industry caused by anoxic water condition*

| Port | Did kill affect business? | Decline of business | Value of decline | Did kill affect crew income? | How? |
|---|---|---|---|---|---|
| | | Percent | Dollars | yes/no | |
| Highlands* | yes | a | — — | — — | — — |
| Sea Bright | yes | — — | 5,000 | yes | salary loss of $3,000 |
| Belmar* | yes | 25 | — — | yes | fewer tips |
| Belmar | yes | 20–25 | 3,000 | no | |
| Belmar | yes | 62 | 47,500 | yes | 2 unemployed |
| Manasquan | yes | 20–25 | 14,000 | yes | 1 unemployed |
| Brielle | yes | 25 | 20,000 | yes | 2 unemployed |
| Brielle | yes | 25 | 20,000 | yes | 2 unemployed |
| Brielle | yes | 25 | 20,000 | yes | 2 unemployed |
| Brielle | no | 0 | 0 | no | |
| Pt. Pleasant | yes | — — | 13,000 | yes | fewer tips |
| Barnegat Lt. | yes | 30 | 12,000 | no | |
| Barnegat Lt. | yes | 30–35 | 15,000 | yes | fewer tips |
| Manasquan | yes | 20 | 11,000 | yes | 2 unemployed |
| Forked River* | yes | 20 | — — | yes | 1 unemployed |
| Margate | yes | 50 | 9,000 | yes | loss of 50% salary |
| Avalon | yes | 20 | 1,000 | no | |

*Not included in determinations of losses.

a, Substantial.

TABLE 14–6.—*Losses in the charter boat industry caused by anoxic water condition*

| Port | Did kill affect business? | Decline of business | Value of decline | Did kill affect crew income? | How? |
|---|---|---|---|---|---|
| | | Percent | Dollars | yes/no | |
| Highlands | no | 0 | 0 | no | — — |
| Highlands* | yes | — — | — — | — — | |
| Highlands | yes | — — | 3,900 | yes | $800 loss of salary |
| Highlands | no | 0 | 0 | no | — — |
| Sea Bright | yes | — — | 600 | yes | $120 loss of salary |
| Belmar | yes | — — | 6,500 | yes | lost tips |
| Belmar | yes | 45 | 9,000 | yes | 45% loss of salary |
| Belmar | yes | 60 | 15,000 | yes | 60% loss of salary |
| Belmar | yes | — — | 11,000 | yes | 4 unemployed |
| Manasquan | yes | 17 | 4,500 | yes | — — |
| Manasquan | yes | — — | 3,600 | yes | — — |
| Manasquan | yes | 20 | 5,500 | yes | 20% loss of salary |
| Forked River | yes | 30–35 | 1,200 | yes | 30% loss of salary |
| Forked River | yes | — — | 1,000 | — — | — — |
| Barnegat Light | yes | 15 | 900 | yes | 15% loss of salary |
| Barnegat Light | yes | 40 | 4,500 | yes | 40% loss of salary |
| Atlantic City | no | 0 | 0 | no | — — |
| Atlantic City | yes | — — | 400 | no | — — |
| Cape May* | no | 0 | 0 | no | — — |
| Cape May* | yes | — — | 400 | no | — — |
| Cape May* | no | 0 | 0 | no | — — |
| Cape May* | no | 0 | 0 | no | — — |
| Cape May* | no | 0 | 0 | no | — — |

*Not included in determination of losses.

The Eastern Dive Boat Association interviewed six of the nine dive boat captains operating north of Atlantic City and found that the six boats had lost $17,000 in charters, for an average boat loss of $2,800 (Pat Yanatan, personal communication). Thus, total loss to the dive boat industry was about $25,000.

With a reduced volume of party, charter, and dive boat trips and fares, other coastal businesses catering to fishermen (e.g., tackle shops, motels, restaurants, gas stations) undoubtedly sustained losses. The extent of these losses was not determined.

Because the anoxia was restricted primarily to offshore ocean waters, sportfishing decreased little if any from the surf and in bays and inlets. Although no statistical data were collected, general conversations with fishermen indicated that private boats made fewer offshore fishing trips during summer 1976.

Assuming the economic losses brought about by cancelled offshore fishing trips for private boat fishermen were similar to the losses of party and charter boats, the following are estimated:

1. Full-year losses to party and charter fleet = 3.5 percent;
2. Summer losses reported by charter and party boat captains—charter = 23 percent, party = 27 percent, average 25 percent;
3. Recreational private offshore fishing boat trips between July 13 and September 20, 1975 (Freeman et al. 1976) = 104,223;
4. Average number of anglers per boat trip = 4;
5. Average expenditure per angler trip (1975 National Survey of Hunting, Fishing and Wildlife-Associated Recreation) = $19.02; and
6. Calculation of losses based on 25-percent loss, 104,223 boat trips, four anglers/boat, and $19.02/angler = $2 million.

## SUMMARY

Table 14–7 summarizes the estimated, actual, and potential economic losses to New Jersey's commercial and

TABLE 14–7.—*Estimated losses to New Jersey's commercial and recreational marine fisheries-related industries as a result of 1976 anoxia*[1]

| Fishery | Type of loss | 1976 loss | Future loss | Total losses | Years to recover |
|---|---|---|---|---|---|
| | | — — — Millions of dollars — — — | | | |
| **Commercial:** | | | | | |
| Finfish: dockside | actual | 1.9 | ? | 1.9 | — — |
| processing/marketing | actual | 4.6 | ? | 4.6 | — — |
| Surf clam: dockside | resource | 17.8 | 106.5 | 124.3 | 7 |
| processing/marketing | resource | 44.4 | 266.4 | 310.8 | 7 |
| Ocean quahog: dockside | resource | — — | 34.4 | 34.4 | ? |
| processing/marketing | resource | — — | 86.0 | 86.0 | ? |
| Sea scallop: dockside | resource | .1 | .3 | .4 | 5 |
| processing/marketing | resource | .2 | .7 | .9 | 5 |
| Lobster: dockside | actual | .4 | 1.2 | 1.6 | 4 |
| processing/marketing | actual | 1.0 | 3.1 | 4.1 | 4 |
| Subtotals for dockside | | 20.1 | 142.4 | 162.5 | |
| processing and marketing | | 50.2 | 356.2 | 406.4 | |
| Total: | | 70.3 | 498.6 | 568.9 | |
| **Recreational:** | | | | | |
| Party boats | actual | 1.0 | ? | 1.0 | — — |
| Charter boats | actual | .7 | ? | .7 | — — |
| Dive boats | actual | .03 | ? | .03 | — — |
| Private boats | actual | 2.0 | ? | 2.0 | — — |
| Total | | 3.7 | ? | 3.7 | |
| **Commercial and** | actual | 11.6 | 4.3 | 15.9 | |
| **recreational:** | resource | 62.5 | 494.3 | 556.8 | |
| Total | | 74.0 | 498.6 | 572.7 | |

[1] Note: Using averages of estimated losses.

recreational marine fisheries as a result of oxygen depletion during summer 1976. The surf clam was by far the hardest hit commercial resource, followed by the ocean quahog, finfish, lobster, and sea scallop. During 1976 actual commercial losses sustained to finfish and lobster fisheries were an estimated $7.9 million, and potential losses to the entire commercial fishing industry, based upon estimates of resource losses, were estimated at $62.5 million. For commercial fisheries, total actual and resource losses until recruitment begins to replenish affected stocks are estimated at $569 million.

Resource losses cannot be directly converted into losses for the fishing industry. Fish prices usually fluctuate inversely with fish availability, and the fisherman is compensated for reduced catches by increased unit prices. Also, most fishermen do not depend upon a single species and are able to take advantage of other species that may be abundant. Despite not being able to determine industry losses directly, the tremendous losses experienced by several of New Jersey's fishery resources have caused significant financial losses to many fishermen and businesses. In fisheries that had significant mortalities, especially surf clam, the decline in harvest and economic losses is expected to continue in future years until recruitment begins to replenish stocks. In addition, the impact of the disruption of the food chain by the elimination of much of the benthic community may have far-reaching consequences that will hamper commercial fishermen in future years.

Losses to the recreational fisheries during 1976 were $3.7 million. The party, charter, and dive boat fleets absorbed most of the financial losses. Losses by the reduced number of private-boat ocean fishing trips were minimal and were distributed over a large number of recipients—tackle shops, marinas, restaurants, motels, gas stations.

## REFERENCES

Azarovitz, R. R., Byrne, C. J., and Silverman, M. J., 1977. Appendix III under Fish and Shellfish, *in* Oxygen depletion and associated environmental disturbances in the Middle Atlantic Bight in 1976, *Northeast Fisheries Center Tech. Ser. Rep.* No. 3, National Marine Fisheries Service, Sandy Hook Laboratory, Highlands, N.J., 365–415.

Freeman, B. L., and Turner, S. C., 1977. Appendix V under Fish and Shellfish, *in* Oxygen depletion and associated environmental disturbances in the Middle Atlantic Bight in 1976, *Northeast Fisheries Center Tech. Ser. Rep.* No. 3 National Marine Fisheries Service, Sandy Hook Laboratory, Highlands, N.J., pp. 431–450.

Freeman, B. L., Turner, S. C., and Christensen, D. L., 1976. A preliminary report of the fishery for bluefin tuna (Thunnus thynnus) off New Jersey in relation to catches made by charter and party boat anglers during 1975, *NMFS Informal Report* No. 108, 41 pp.

Mackenzie, C. L., 1977. Appendix II under Fish and Shellfish, *in* Oxygen depletion and associated environmental disturbances in the Middle Atlantic Bight in 1976, *Northeast Fisheries Center Tech. Ser. Rep.* No. 3, National Marine Fisheries Service, Sandy Hook Laboratory, Highlands, N.J., pp.341–364.

National Marine Fisheries Service, 1975. Participation in marine recreational fishing northeastern United States, 1973–74, its *Curr. Fish. Stat.* 6236, NOAA, U.S. Department of Commerce, 7 pp.

National Marine Fisheries Service, 1976. Fisheries of the United States, 1975, its *Curr. Fish. Stat.* 6900, NOAA, U.S. Department of Commerce, 100 pp.

National Marine Fisheries Service, 1977. New Jersey Landings, annual summary 1976, its *Curr. Fish. Stat.* 713, NOAA, U.S. Department of Commerce, 7 pp.

Ropes, J. W., and Chang, S., 1977. Appendix I under Fish and Shellfish, *in* Oxygen depletion and associated environmental disturbances in the Middle Atlantic Bight in 1976, *Northeast Fisheries Center Tech. Ser. Rep.* No. 3, National Marine Fisheries Service, Sandy Hook Laboratory, Highlands, N.J., pp. 263–340.

Rorholm, D., 1974. Statement before the Senate Committee on Commerce, Providence, R.I.

## Oxygen Depletion and Associated Benthic Mortalities in New York Bight, 1976

# Chapter 15. A Perspective on Natural and Human Factors

*Joel S. O'Connor*[1]

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## GLOBAL AND REGIONAL PATTERNS

Human activities had not been suggested as significant factors in any large-scale anoxic events of open coastal ocean waters until the 1976 event in the New York Bight. Large-scale mortalities in shallow productive seas and estuaries had been attributed to anoxia and hydrogen sulfide (Brongersma-Sanders 1957), and waste nutrient and carbonaceous contributions from human activities clearly contributed to the severity of many such anoxic events (National Academy of Sciences 1969, 1971). However, anoxia along open coasts of the world oceans has been attributed consistently and exclusively to upwelling (Deuser 1975). Related phenomena are the "oxygen minimum layers," which are most pronounced at tropical latitudes. These also are attributed to natural factors in open oceans (Richards 1957; Kester et al. 1973; Lambert et al. 1973; Deuser 1975) and are less relevant here.

Extensive coastal enrichment by riverborne material has been discussed: off the Mississippi by Riley (1937); off the Amazon by Ryther et al. (1967) and Gibbs (1976); and off the Hudson-Raritan estuary by Ketchum (1967), Ryther and Dunstan (1971), and Malone (1976a). Yentsch (1975) developed a model implying significant estuarine phosphate enrichment to the edge of the entire northeastern U.S. continental shelf. Recommendations, based upon simplified models of eutrophication in estuaries and marine waters with restricted circulation, have been made for much more serious consideration of ocean outfalls to carry domestic wastes to open coastal waters (Officer and Ryther 1977). Some investigators feel that "the concentration of nutrient elements in much of the coastal waters near urban regions of the world is now excessive" (Ketchum 1972). This assertion remains debatable because effects of nutrient contributions by humans are so difficult

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to assess and because interpretations of "excessive" vary (Bascom 1974a, 1974b; Woodwell 1974). In any case, riverine nutrient enrichment of certain coastal regions hundreds of square miles in area has been recognized for several years.

## OXYGEN DEPLETION AND THE NEW YORK BIGHT

The oxygen depletion event of 1976 stimulated a search for answers to two questions.

1. How much do human activities influence the processes leading to oxygen depletion in the New York Bight?
2. How large a region off New York is significantly enriched (in carbon and plant nutrients) by human activities?

Oxygen depletion in the Bight in 1976 and factors relating to it are summarized. Despite the widespread nature and severity of bottom oxygen decline in 1976, this was not a unique event. Less widespread oxygen declines were noted in the summer and autumn of 1968, 1971, 1974, and 1977 (fig. 15–1). Thus, the 1976 phenomenon was not necessarily caused by some special, or even rare, set of circumstances. The most important factors probably have contributed to other oxygen declines, including those in years when there were no observations of benthic mortalities or dissolved oxygen concentrations below 2 ml/l.

The most influential external controls (anomalies) acting upon the Bight are understood very well relative to within-Bight processes. An exception was the onwelling of nutrient-rich oceanic water in the spring and summer of 1976. Also anomalous atmospheric conditions in 1976 (ch. 3) led to unusually warm surface waters and prolonged density stratification (ch. 2 and 5; Bowman and Wunderlich 1977). Surface winds exhibited unusually persistent northward to northwestward flow from February through June and storm frequency fell to a 25-year minimum (ch. 3.).

Other significant external factors are the exceptionally large inputs of plant nutrients and carbon released to the Bight primarily by human activities. Of the plant nutrients, only nitrogen is discussed, because it is important in limiting phytoplankton productivity (Ryther and Dunstan 1971; Malone 1976a). Available estimates of total nitrogen and carbon reaching the Bight proved useful, but were less precise than desirable for assessing the relative importance of eutrophication and other factors controlling the concentrations of dissolved oxygen (D.O.).

The discussion of nutrient and carbon loads and other influences upon oxygen depletion emphasizes conditions over the New Jersey continental shelf to about 90 km offshore during the spring and summer. This is the region where substantial oxygen depletion was observed and the season during which short-term controlling factors are most influential. Nutrient and carbon loadings of the Bight during late autumn and winter contribute to oxygen depletion largely during the following year via accumulations of chemically reduced substances in sediments (Garside and Malone 1978). Hence, it is important to distinguish between annual and spring/summer (or stratified period) nutrient and carbon loadings.

### Nitrogen Loadings

Stimulation of phytoplankton productivity by nutrient enrichment from the Hudson-Raritan estuary is consistently one of the most striking features of the inner Bight under stratified conditions (Malone 1976a; Yentsch 1977). Nutrient enrichment from the estuarine source is less significant for the entire Bight, and probably is a relatively minor contribution (ch. 4).

It is difficult to estimate with much precision or accuracy the net seaward flux of carbon, nutrients, and other materials to the Bight from the Hudson-Raritan estuary. The tendency of estuaries, like New York Harbor, to accumulate dissolved as well as particulate contaminants from watersheds and from subsurface seawater contributions has been known for some time (Ketchum 1967; Riley 1967). Studies of the net estuary-to-Bight nutrient flux indicate that significant amounts of nitrogen from river runoff and from direct pollutant inputs are found accumulated in estuarine sediment (Parker et al. 1976).

Several investigators have stressed the importance of estuarine-derived nitrogen (and carbon) in stimulating the growth of nuisance algae and the depletion of oxygen in this region (e.g., Torpey 1967; Ryther and Dunstan 1971; Hardy 1972; Carpenter 1973). Unfortunately, these earlier estimates were made without the benefit of later research work on nutrient and carbon loading. Given the more extensive and reliable bases for recent flux estimates, the following newer estimates are almost certainly more accurate.

Nitrogen input to the Bight from the estuary was estimated by Garside et al. (1976) from statistics on the population of the New York/New Jersey metropolitan area and the per capita nitrogen discharges via sewage treatment plants. The amount of inorganic nitrogen discharged in wastewater to the Hudson-Raritan estuary was estimated to be about 160 t/d (comparable to that estimated by Howells et al. 1970). A more detailed estimate of all inorganic nitrogen loadings to the Hudson-Raritan estuary (including gaged and nongaged runoff) is 210 t/d, 120 t of which is from municipal and industrial wastewater (Mueller et al. 1976b). Garside et al. (1976) concluded that inorganic nitrogen in wastewater alone greatly exceeded (by four times) the amount assimilated by phytoplankton

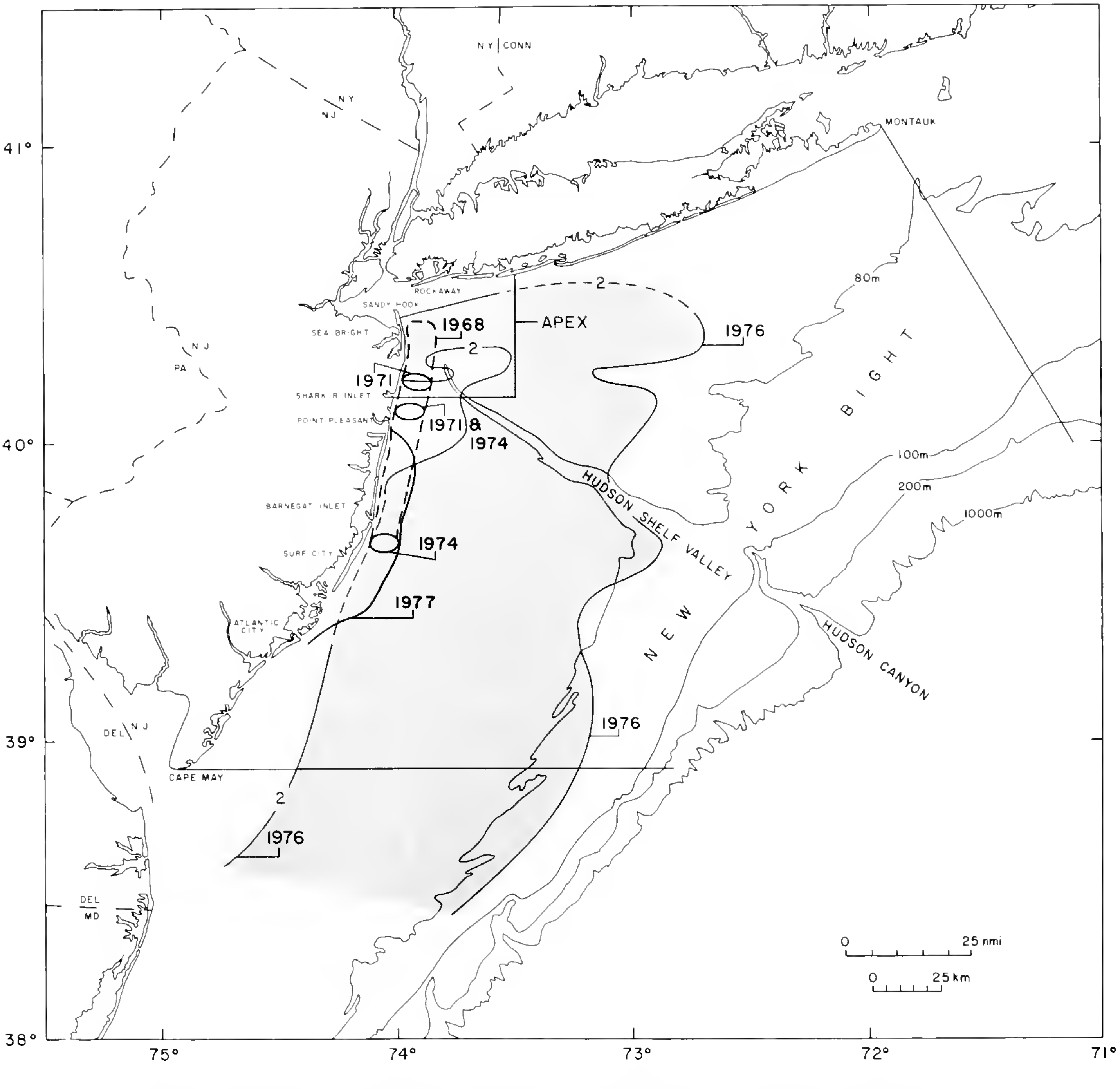

FIGURE 15–1.—Approximate regions of oxygen-depleted (< 2 ml/l) bottom waters in 1968, 1971, 1974, 1976, and 1977. Sources: 1977 based on data from RV *Cape Henlopen* cruise, Aug. 28–30, 1977; other years summarized from accounts in chapter 1.

in the estuary during summer. This assessment is shared by O'Connors and Duedall (1975), who estimated that phytoplankton took up only about 34 percent of the total dissolved nitrogen released to the New York area waters in June 1974 before it reached the Bight. Garside et al. (1976) estimated that 120 t of dissolved nitrogen per day enter the Bight via the estuary "during low-flow summer months" (generally June through September).

Another estimate of inorganic nitrogen flux to the Bight is based upon short-term measurements of nutrient concentrations and velocity profiles across the transect from Sandy Hook, N.J., to Rockaway Point, N.Y. (O'Connors and Duedall 1975; Parker 1976; Duedall et al. 1977). This estimate rests on assumptions about the representativeness of three measured velocity fields and one nutrient concentration field at the transect over different, short-time intervals. Though the assumptions are only partly evaluated, three lines of evidence tend to validate the calculations: 1) the calculated net salt flux yields an estimate of the longitudinal coefficient of eddy diffusion, which is comparable to values estimated for other estuaries; 2) a comparison of current meter records along the transect shows the velocity structure similar in June 1952, May 1958, and August 1959 (Kao 1975; Doyle and Wilson 1978); and 3) the estimate of June 1974 estuarine inorganic nitrogen flux to the Bight (58 t/d) is of the same order as the 120 t/d estimated by Garside et al. (1976).

These estimates of inorganic nitrogen flux do not include estuarine inputs of dissolved and particulate organic nitrogen, probably very important forms of nutrient input to the Bight. Mueller et al. (1976b) estimated that the Hudson-Raritan estuary received from all sources 130 t/d of organic nitrogen, or 38 percent of all nitrogen inputs. The large quantities of nitrogen flushed to the Bight as phytoplankton (O'Reilly et al. 1976; Parker 1976; Malone 1977) and as dissolved organic matter (O'Reilly et al. 1976) deserve consideration. This is particularly true, because nitrogen is recycled rapidly in summer. The nitrogen recycling rate above the pycnocline is estimated to be 0.5 to 2 days (Malone et al., ch. 9, pt. 1). Hence a significant quantity of organic nitrogen is probably exported to the Bight and mineralized rather quickly before settling below the pycnocline, to be further oxidized or assimilated by phytoplankton. Grazing copepods play an important role in nutrient regeneration (Chervin 1978). Indeed, Garside and Malone (1978) suggest that photosynthesized carbon does not sink below the pycnocline "to any great extent"—within an arc 40 km seaward of the Sandy Hook/Rockaway Point transect during stratified summer seasons.

A first-order estimate of 1.6 t/d of chlorophyll *a* is flushed to the Bight via the estuary during summer (Parker 1976). This estimate is a refinement of one using the same methodology by Duedall et al. 1977. The proportion of particulate nitrogen to chlorophyll *a*, by weight, in June 1975 was rather stable in the estuary and inner Bight and was estimated at 6.8 (N):(Chl *a*) by Duedall et al. (1978). Thus, the chlorophyll *a* flux estimate of Parker (1976) implies a flux of about 11 t/d of nitrogen bound as particulate nitrogen, primarily as phytoplankton biomass. Given the rapid cycling of this nitrogen in surface water during summer, and its tendency to remain above the pycnocline (ch. 9, pt. 1), it is likely that most of this nitrogen becomes available rather rapidly and promotes further primary productivity.

The June-August daily inputs of nitrogen from the New Jersey coast were calculated from sewage treatment plant flows in summer (New Jersey Department of Environmental Protection 1976) assuming 22 mg/l of total nitrogen in the average of primary and secondary effluents (Mueller et al. 1976b). This estimate (8.7 t/d) is only slightly higher than that of Mueller et al. (1976b), but the total summer nitrogenous inputs from the New Jersey coast are more than 20 percent of those from the transect (table 15–1).

Estimates are not available for nitrogenous releases to the water column by ocean dumping; however, an estimated 80 t total N/d is dumped as sewage sludge and dredge material (Mueller et al. 1976b). These authors estimate that about 60 percent of the nitrogen is in the form of ammonium and the remainder is bound with carbon. It seems likely that most of the ammonium in sewage sludge is released to the water column (O'Connors and Duedall 1975). Some ammonium is apparently released

TABLE 15–1.—*Estimates of nitrogen loadings to waters inshore of 30 fathoms (55 m) during June-August, in metric tons per day*

| Source | Annual ave. to N.Y. harbors and Bight[a] | June-August inorganic N only | June-August total N[e] |
|---|---|---|---|
| N.Y./N.J. harbors: | | | |
| Municipal and industrial wastewaters | 204 | 120[c] 58[d] | 131 |
| Gaged runoff | 102 | | |
| Nongaged runoff | 34 | | |
| New Jersey coast | 25 | | 27 |
| Long Island coast | 11 | | 11 |
| Ocean dumping: | | | |
| Dredge/material | 63[b] | | 44[b] |
| Sewage sludge | 17 | | 12 |
| Acid waste | neg. | | neg. |
| Atmospheric fallout | 46 | | 71 |
| Shelf onwelling | no est. | | ? |
| Regeneration from sediments | no est. | | ? |
| Totals | 502 | | 296 |

[a] Modified from Mueller et al. (1976b).

[b] Estimated from total Kjeldahl nitrogen analyses.

[c] From Garside et al. (1976).

[d] From Parker (1976); a refinement of an earlier estimate by Duedall et al. (1977).

[e] Derivations discussed in text.

below the pycnocline, as is indicated by the vertical distributions of ammonium found by O'Connors and Duedall (1975) and the rapid convective descent (≤10 cm/s) of sewage sludge material through the pycnocline (Proni et al. 1977). That unknown fraction of the ammonium released below the pycnocline is probably almost completely unavailable to phytoplankton until it is advected out of the Bight or is mixed within the photic zone after the autumnal breakdown of the pycnocline.

As with sewage sludge, most of the ammonium from dredged materials is probably released to the water column soon after dumping, with an unknown percentage released beneath the pycnocline. Some of the organic nitrogen in dredged material will no doubt be released to the water column through mineralization before reaching the bottom (Bremner 1965; Austin and Lee 1973; Blom et al. 1976). The same is true of sewage sludge, because many of the particles remain in the water column for long periods (Proni et al. 1977).

It seems probable that most of the nitrogen dumped in the Bight as dredged material and sewage sludge gets into the water column in dissolved inorganic forms. Given the findings outlined above, I assume here, conservatively, that roughly 70 percent of the dumped nitrogen in all forms becomes dissolved inorganic nitrogen within days after dumping. An unknown fraction of this amount is released below the pycnocline where it would not contribute to phytoplankton production until the autumnal breakdown of density stratification.

The atmosphere is also an important source of nitrogen for Bight waters. Mueller et al. (1976b) estimated a mass load of 66 t total N/d from the atmosphere; that is 13 percent of all nitrogenous inputs to New York harbors and the Bight. However, the atmospheric nitrogen input to the outer Bight almost certainly does not contribute to oxygen depletion farther inshore. The nitrogen falling on surface waters of the outer Bight (i.e., more than 90 km from shore) would tend to be carried to the southwest by surface currents during all seasons, although current speed and direction are extremely variable (Hansen 1977; Williams et al. 1977). Hence, my estimate of atmospheric nitrogen input considers the Bight sea surface within 90 km of shore.

Uttormark et al. (1974) summarized the atmospheric contribution of nitrogen to 60 locations in North America, on both land and water. These measurements give some indication of nitrogen fallout contours in the Bight region. Frizzola and Baier (1975a, 1975b) measured total nitrogen fallout at three points on Long Island from 1969 through 1974. Available nitrogen fallout values in the New York Bight region known to me are shown in figure 15–2; the contours are consistent with Uttormark et al. (1974). Integrating over the inner 34,300 km$^2$ of the Bight sea surface, the estimated fallout of total nitrogen is 71 t/d. There is some evidence that nitrogenous fallout during June and July is somewhat higher than the daily average over a year, and somewhat lower than average during late summer (Likens 1972; Likens and Bormann 1972). This tendency, together with the increasing concentrations of atmospheric nitrogen over recent years, makes this estimate of 71 t/d during summer a conservative one. Further, the above authors treat organic nitrogen in atmospheric fallout as a contaminant and eliminate it from consideration. Hence, any additional contribution of organic nitrogen fallout is assumed to be negligible, although supporting evidence is lacking.

Unfortunately, estimates are not yet available for nitrogenous inputs from sediments and from onwelling over the continental shelf. Both contributions could be substantial, relative to other sources.

### Carbon Loadings

In addition to nitrogen loading, unusually large carbonaceous inputs to the Bight contribute to oxygen depletion problems. Recently, Walsh et al. (1976), Ketchum (1976), and others discussed the significance of carbon loads relative to oxygen sags in the Bight. Work on the implications of BOD (biological oxygen demand) loads to the Hudson-Raritan estuary (with consequences for the Bight) dates from O'Connor (1960, 1962).

The total carbon loading to the Bight from the atmosphere is adjusted from Mueller et al. (1976a) in table 15–2. The conservative assumption is made that atmospheric fallout of carbon is evenly distributed over the entire Bight. Thus, about 67 percent of the atmospheric carbon is assumed to fall within the 34,300 km$^2$ area east of New Jersey.

Reliable estimates of spring/summer loadings to the Bight proper (seaward of the Sandy Hook/Rockaway Point transect) cannot be made simply from estimated contributions from rivers and harbors. The several processes that are important in determining how much of the estuarine inputs reach the Bight are not well understood. Perhaps the principal difficulty is the differential deposition of particulates from the estuarine water column and their short-term, large-scale resuspension and advection. These and other difficulties have led to alternative estimates of carbon inputs by different workers (Segar and Berberian 1976; Garside and Malone 1978).

The substantial quantities of oxidizable carbon (including plankton) from the estuary and from dumping (see table 15–2) have been estimated to be from 30 percent of phytoplankton production in the Apex (Garside and Malone 1978) to about 80 percent of Apex production (Segar and Berberian 1976). Both carbon sources originate above the pycnocline for the most part. Their influence and that of in-situ phytoplankton production upon the 1976 anoxic event, and upon bottom waters every year, depends on

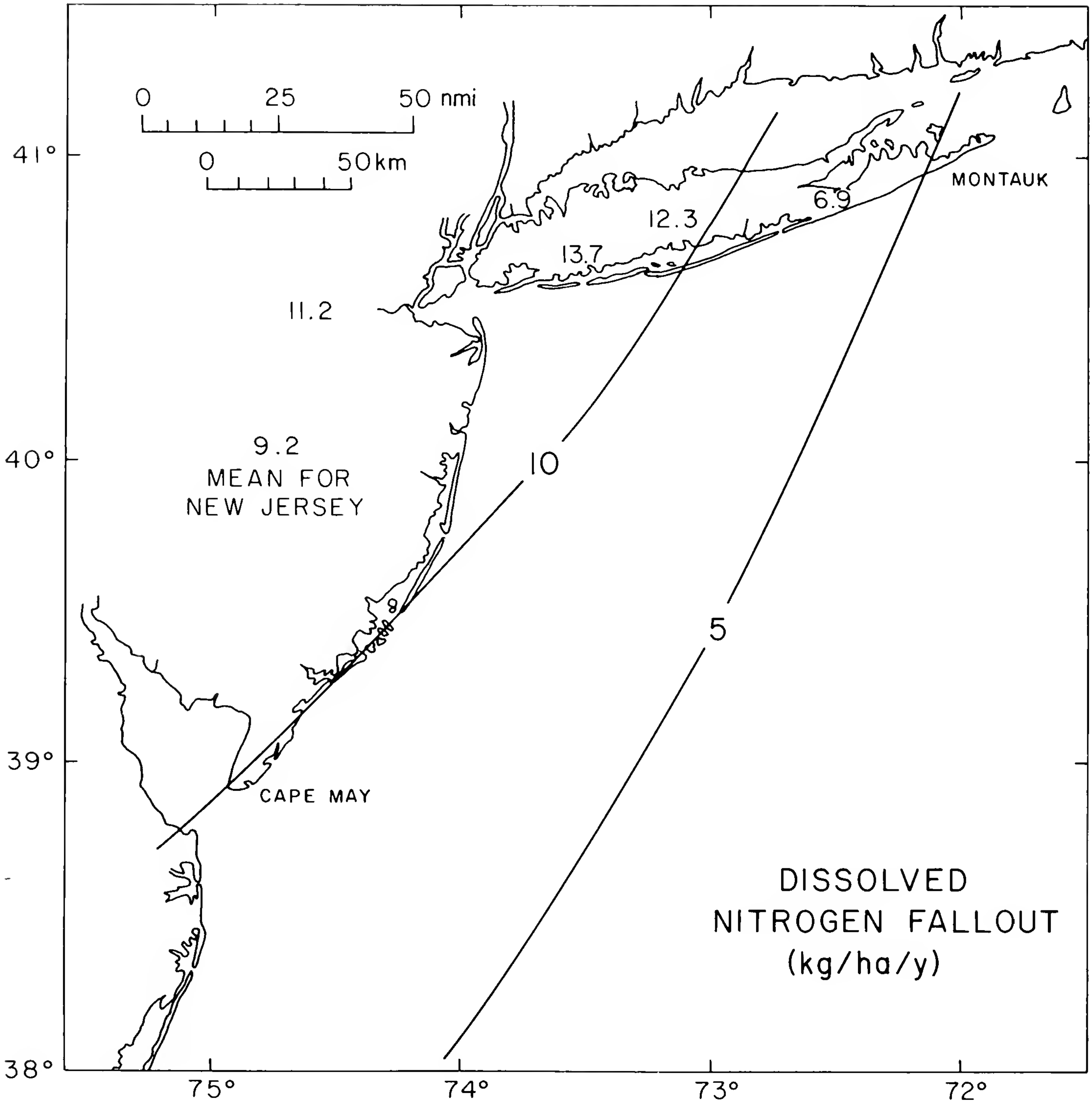

FIGURE 15-2.—Dissolved nitrogen fallout over the Bight.

TABLE 15-2.—*Estimates of organic carbon loadings to Apex waters and inshore of 30 fathoms (55 m) during June-August, in metric tons per day*

| Source | Annual ave. to N.Y. harbors and Bight[a] | | To Apex June-August[b] |
|---|---|---|---|
| N.Y./N.J. harbors | | | |
| Municipal and industrial wastwaters | 719 | 254[c] | 1,100[e] |
| Gaged runoff | 320 | | |
| Nongaged runoff | 450 | | |
| New Jersey coast | 105 | no est. | no est. |
| Long Island coast | 16 | no est. | no est. |
| Ocean dumping: | | | |
| Dredged material | 540 | (included in estuarine input, above) | 540 |
| Sewage sludge | 110 | 110 | 110 |
| Acid wastes | neg. | neg. | neg. |
| Atmospheric fallout | 206 | no est. | no est. |
| Totals | 2,466 | 364 | 1,750 |

[a] Modified from Mueller et al. (1976b).

[b] From Garside and Malone (1978), omitting their estimate of in situ primary production not considered an input loading here.

[c] This estimate (Garside and Malone 1978) includes particulate organic carbon only.

[d] From Segar and Berberian (1976), omitting in-situ primary production.

[e] Considerable uncertainty exists as to the dissolved fraction of this estimate. (See Segar and Berberian 1976.)

how quickly these materials fall below the pycnocline and how rapidly they are oxidized.

An interesting analysis of oxygen dynamics in the Apex concludes that the total carbon respired annually requires an input of 1,690 t C/d, of which 77 percent is produced by in-situ primary production (Garside and Malone 1978). These authors also estimate that 36 percent of the annual Apex carbon load is flushed from the Hudson-Raritan estuary during January and April alone, months when river runoff is exceptionally high, winter diatom blooms occur in part from low grazing pressure (ch. 9, pt. 1), and levels of resuspended organic material from estuarine sediments are probably exceptional. The large, short-term loadings in January and April probably fall to the inner Bight sediments to be oxidized over the following year.

The small cells normally dominating the spring/summer phytoplankton assemblages sink very slowly, and most are probably grazed or dispersed widely before falling below the pycnocline to consume bottom oxygen (ch. 9, pt. 1). However, the intensive summer/autumn zooplankton grazing upon phytoplankton and organic detritus results in zooplankton fecal material falling below the pycnocline and consuming oxygen. Copepods alone assimilate 23 to 41 percent of the phytoplankton productivity daily in the inner Bight (Malone and Chervin 1979). The extent of grazing by other zooplankton is not known, but copepods probably dominate grazing activity most of the year (Chervin, personal communication). Copepod assimilation efficiencies vary greatly, but an average of 70 percent seems reasonable (Conover 1956, 1966; Gaudy 1974; Chervin 1978). Given this major copepod grazing plus the additional grazing by other zooplankton (Malone 1976; Chervin 1978) and the relatively rapid sinking rates of zooplankton fecal material (Wiebe et al. 1976; Elder and Fowler 1977), more than 15 percent of the phytoplankton produced in and carried to the inner Bight probably sinks rapidly below the pycnocline as zooplankton fecal pellets.

There are as yet no estimates of average carbon loadings to the region of oxygen depletion from offshore waters. However, during April through June 1976 it seems likely that large inshore loadings of carbon as *Ceratium tripos* were translocated from offshore by onshore bottom water movements (ch. 7, 8, and 9, pt. 1). This was an exceptional year because of unusually dense *Ceratium* concentrations at the least, and the average onshelf flow of nearly 1.5 cm/s during May and June 1976 was probably atypical (ch. 7).

Annual fluctuations in the combined ocean dumping fractions of these carbon and nitrogen loadings are seldom greater than 25 percent, and are generally less. The quantities of dumped dredged materials and sewage sludge have increased almost 50 percent since 1960 (Gross 1976). Long-term historical data apparently are not compiled for annual total loadings from treated and untreated domestic wastes, but there is no reason to believe that their annual fluctuations are greater than those of dumped materials. A substantial increasing trend in total domestic waste effluents (treated plus untreated) has occurred since 1936. Total sewage discharges to waters under jurisdiction of the Interstate Sanitation Commission have increased by over 80 percent since 1936. This increase had essentially stabilized by 1970 (A. Mytelka, personal communication).

### Physical and Biochemical Processes

The proximate cause of oxygen depletion is oxidation of organic matter and chemically reduced species of nitrogen, primarily by bacteria. In the Bight, marked reductions in dissolved oxygen occur only when the water column is stratified, preventing oxygen replenishment from surface waters (ch. 6). Given effective stratification, annual differences in the extent of oxygen depletion in recent years must be due to the combined influences of year-to-year oxygen-demanding loadings beneath the pycnocline, physical transport and diffusion of these loadings, and the mass specific rates of oxidation. The physical features of the Bight are described in other chapters and are summarized in chapter 16.

The large dinoflagellate, *Ceratium tripos*, dominated the total particulate organic carbon loading in 1976. The 1976 population growth was a biochemical phenomenon of great significance, which, at least in 1976, exhibited a much larger annual fluctuation than nutrient and carbon loadings. Significantly, initial development of the *C. tripos* bloom "involved processes operative on spatial scales on the order of the continental shelf and time scales on the order of months to years" (ch. 9, pt. 1). The initial causes of this bloom are unknown, but the bloom apparently originated around January 1976 throughout the entire Bight and beyond (ch. 9, pt. 1). Thus, at least initially, the buildup of the *C. tripos* population may have been responding to the same atmospheric and oceanic factors leading to prolonged, intense stratification and reduced flushing in summer 1976. These physical factors need not have been strikingly exceptional to trigger the substantial bloom of *C. tripos*.

The later aggregation (during April through June) of very dense *C. tripos* accumulations near the base of the pycnocline off New Jersey may be explained in physical terms and as biochemical processes, both of which may have contributed. The evidence for and against physical aggregation by two-layered thermohaline circulation is summarized by Malone (ch. 9, pt. 1) and Mayer et al. (ch. 7). Five stations located from 50 to 110 km off New Jersey indicate an average westward current component of 34 km/mo. (1.3 cm/s) from April through June 1976. This amount of westward displacement beneath the pycnocline contributed to the observed *C. tripos* aggregation.

Possibly the inshore increase of *Ceratium* numbers also resulted in part from faster reproductive rates beneath the higher concentrations of particulate organic carbon in inshore waters. Some species of *Ceratium* are known to assimilate particulate material, and there is evidence that *C. tripos* also has this mode of nutrition (ch. 10). Most of the *C. tripos* population within 20 km of New Jersey was at depths where light was inadequate to maintain the population photosynthetically. The population increase in April through June in this region may have been partially due to faster growth rates than were possible offshore, because of the more concentrated organic particulates inshore. Although both the physical and biochemical hypotheses for the exceptional *C. tripos* buildup are plausible, there is no evidence as to their relative significance.

Assuming no photosynthesis below the pycnocline, the respiration of *Ceratium* would have utilized very significant quantities of water column oxygen (ch. 9, pt. 1). The quantity respired by *C. tripos* was estimated at 0.37 ml $O_2$/l/d in the Apex and coastal waters of New Jersey. This is about 12 times the rate of oxygen uptake by benthic respiration estimated by Thomas et al. (1976), and more than twice the rate of estimated oxygen usage in the Apex and New Jersey coastal waters from May 18 to June 29, 1976 (ch. 8). In addition to the respiration of *C. tripos*, the decay of this population must have placed a substantial demand on oxygen beneath the pycnocline. Oxidation of the *C. tripos* biomass over 60 days was estimated to require 0.16 ml $O_2$/l/d (ch. 16), the same as the rate of oxygen usage beneath the pycnocline estimated by Han et al. (ch. 8). Dead *C. tripos* cells are large enough to sink very rapidly and were not completely oxidized within the water column, but the remaining detritus apparently decayed rapidly on the sediment surface (ch. 10).

The remainder of the particulate organic carbon (POC)—apart from *C. tripos*—also contributed to oxygen depletion in 1976 and in each summer/autumn season. Malone (ch. 9, pt. 1) indicates that *C. tripos* accounted for 64 percent of the POC by April 1976 and that the rest of the phytoplankton bloom was apparently typical of that observed in previous years.

The average input rate of POC to the bottom layer has not been estimated; however, the average sinking rate of nannoplankton in the Bight is within the range of 0 to 2 m/d (Malone and Chervin 1979). The typical summer loading of POC to bottom waters is very sensitive to the actual average sinking rate of POC exclusive of *C. tripos*. If these particles, at an average summer concentration of 1.1 g C/m$^3$ (ch. 9, pt. 1) sink 1 m/d, then 66 g C/m$^2$ would be introduced through the pycnocline during the 60-day period used in the above calculations. Oxidation of this POC alone would require 5.4 ml $O_2$/l/d or more than 30 times the oxygen utilization rate estimated by Han et al. (ch. 8). There are, almost certainly, several spatial and temporal discontinuities in any particular summer/autumn season that cause departures from this calculation. For instance, POC tends to accumulate at the pycnocline and is perhaps thereupon grazed intensively; not all the potential BOD represented in POC beneath the pycnocline is oxidized before being eaten or flushed from the region of oxygen depletion. Additional complicating factors could be postulated, most of which would tend to minimize the actual oxygen demand of the POC. If these factors are not too influential, POC exclusive of *C. tripos* cannot be dismissed as an insignificant BOD loading. This is true even if much slower sinking rates are presumed.

If the average POC sinking rate (excluding *Ceratium*) is 0.1 m/d, the resulting BOD would still require more than three times the estimate of oxygen used—an amount equal to that attributed to *C. tripos* respiration and decay by Malone (ch. 9, pt. 1). Even assuming no replenishment of this residual POC in bottom waters, the quantities normally present would require more than half the estimated oxygen consumed, and 17 percent of that attributed to *C. tripos*. Despite the very imprecise knowledge of POC replenishment rates and its actual fates beneath the pycnocline, the subpycnocline oxygen demand of nannoplankton and detritus would seem to be of the order contributed by *C. tripos* in 1976, and perhaps more.

Oxidation of dissolved organic matter may also be very important. During August-September 1976 the concentrations of dissolved organic carbon were exceptionally high—"extraordinarily high" concentrations in the Apex relative to other coastal areas (ch. 4) and about 12 times the POC concentrations averaged over the oxygen depletion zone. Atwood et al. (ch. 4) present some evidence that dissolved organic carbon may have contributed significantly to oxygen depletion in 1976.

## CONCLUSIONS

While human activities are very important sources of nitrogen and carbon loadings to the Bight, the quantities of some natural loadings have not yet been estimated. The natural contributions of carbon and nitrogen from alongshelf transport, shelf onwelling, and sediment regeneration could be major, but estimates are not available.

While the bulk of these anthropogenic loadings enter the Bight through the Sandy Hook/Rockaway Point transect, nitrogenous loadings from the New Jersey coast are more than 20 percent of those from the transect. These sources largely from sewage treatment plant outfalls all along the New Jersey coast, may well have contributed to the nearshore oxygen depletion events in the past—particularly in 1968, 1971, 1974, and 1977 (fig. 15–1). It is not yet possible to link quantitatively the particular sources of nutrients and carbon to their roles in depleting oxygen from Bight waters.

Other contributors to this report have developed an entirely plausible hypothesis for the severe oxygen depletion in 1976. This hypothesis implies that the anthropogenic loadings of carbon and plant nutrients contribute to oxygen depletion of the inner Bight, but have not been the major cause of anoxia, even in 1976 when physical conditions favored oxygen depletion. However preponderant the anthropogenic loadings, the resulting summer phytoplankton blooms and detritus are actively grazed upon and dispersed widely while still in surface water. The particulate carbon falling into the bottom layer does not become concentrated enough to cause anoxia. The hypothesis invokes *C. tripos,* which bloomed in 1976 independently of known anthropogenic stimuli, as a mechanism for accumulating beneath the pycnocline unusually large quantities of carbon. Because *C. tripos* is seldom eaten, essentially all this biomass respires actively until death when the labile fractions of the cells are oxidized making *Ceratium* a very effective agent for oxygen depletion. This hypothesis is consistent with the extended duration of stratification, probable physical concentration of *C. tripos*, and increased residence time of New Jersey coastal bottom water, all of which contributed to oxygen depletion in 1976.

This hypothesis seems entirely consistent with realistic ranges of the loadings and processes involved. However, the realistic ranges are great for oxidation rates of POC and DOC in bottom waters. If sinking rates of nannoplankton and detritus are toward the high end of presently realistic values and if substantial quantities of this material are not incorporated in planktonic food webs before being oxidized, this fraction of POC would be more significant than the hypothesis allows. Also, despite the overwhelming concentrations of DOC, there seems to be very little quantitative evidence about its sources or oxidation rates. Turnover rates would not need to be very large to make DOC more significant than has been presumed. Substantially more precise and systematic evaluations are needed to determine the relative significance of nutrient and carbon loadings to oxygen depletion. Mathematical models of carbon/oxygen/nutrient dynamics in the Bight are being developed to refine the assessments in this volume.

The extent of human contributions to this coastal eutrophication and seasonal oxygen depletion remains arguable. Annual variation in the degree of oxygen depletion is pronounced. Reductions in any significant, relatively constant BOD loading would, on the average, reduce the likelihood of anoxic events. Consequently, curbs on human waste loadings would reduce BOD in bottom waters of the inner Bight and, hence, the probability and severity of benthic mortalities. Other alternatives to the same ends are not obvious to me.

## ACKNOWLEDGMENTS

The MESA New York Bight Project staff contributed ideas and useful criticism, particularly Paul Eisen, who developed another estimate of atmospheric nitrogen loading.

## REFERENCES

Austin, E. R., and Lee, G. F., 1973. Nitrogen release from lake sediments, *J. Water Pollut. Control Fed.* 45:810–879.

Bascom, W., 1974a. The disposal of waste in the ocean. *Sci. Am.* 231 (2):16–25.

Bascom, W., 1974b. Letter re Woodwell (1974), *Sci. Am.* 231 (5):8–9.

Blom, B. E., Jenkins, T. F., Leggett, D. C., and Rurrmann, R. P., 1976. Effect of sediment organic matter on migration of various chemical constituents during disposal of dredged material, Contract Report D–76–7. U.S. Army Engineer Waterways Experiment Station, 147 pp.

Bowman, M. J., and Wunderlich, L. D., 1977. Hydrographic Properties, *MESA New York Bight Atlas Monogr* 1, New York Sea Grant Institute, Albany, N.Y., 78 pp.

Bremner, J. M., 1965. Organic form of nitrogen, in G. A. Block (ed.), *Methods of Soil Analysis,* American Society of Agronomy, Madison, Wisc., pp. 1238–1255.

Brongersma-Sanders, M., 1957. Mass mortalities in the sea, in J. W. Hedgepeth (ed.), *Treatise on Marine Ecology and Paleoecology,* vol. I, Geolog. Soc. Amer. Memoir 67, pp. 941–1010.

Carpenter, J. J., 1973. Determining ultimate capacity of the coastal zone for wastewater residuals, in F. E. McJunkin and P. A. Vesilind (eds.), Ultimate Disposal of Wastewaters and Their Residuals, National Symposium, April 26–27, 1973, Water Resources Institute, University of North Carolina, Raleigh, pp. 216–225.

Chervin, M. B., 1978. Assimilation of particulate organic carbon by estuarine and coastal copepods, *Mar. Biol.* 49:265–275.

Conover, R. J., 1956. Oceanography of Long Island Sound, 1952–54 VI. Biology of *Acartia clausi* and *A. tonsa*, *Bull. Bingham Oceanogr. Coll.* 15:156–233.

Conover, R. J., 1966. Factors affecting the assimilation of organic matter by zooplankton and the question of superfluous feeding, *Limol. Oceanogr.* 11:347–354.

Deuser, W. G., 1975. Reducing environments, in J. P. Riley and G. Skirrow (eds.), *Chemical Oceanography*, 2d ed., vol. 3, Academic Press, N.Y., pp. 1–37.

Doyle B., and Wilson, R., 1978. Lateral dynamic balance in the Sandy Hook to Rockaway Point transect, *Estuar. Coastal Mar. Sci.* 6:165–174.

Duedall, I. W., Dayal, R., Jones, K. W., et al., 1978. Composition, distribution, and transport of particulate material in the New York Bight Apex, in M. Wiley (ed.), *Estuarine Interactions*, Academic Press, New York, pp. 533–564.

Duedall, I. W., O'Connors, H. B.,Parker, J. H., Wilson, R. E., and Robbins, A. S., 1977. The abundances, distribution and flux of nutrients and chlorophyll *a* in the New York Bight Apex, *Estuar. Coastal Mar. Sci.* 5:81–105.

Elder, D. L., and Fowler, S. W., 1977. Polychlorinated biphenyls: penetration into the deep ocean by zooplankton fecal pellet transport, *Science* 197:459–461.

Frizzola, J. A., and Baier, J. H., 1975a. Contaminants in rainwater and their relations to water quality, Part I, *Water and Sewage Works* 122:72–75.

Frizzola, J. A., and Baier, J. H., 1975b. Contaminants in rainwater and their relations to water quality, Part II, *Water and Sewage Works* 122:94–95.

Garside, C., and Malone, T. C., 1978. Monthly oxygen and carbon budgets of the New York Bight Apex, *Estuar. Coastal Mar. Sci.* 6:93–104.

Garside, C., Roels, O. A., and Scharfstein, B. A., 1976. An evaluation of sewage-derived nutrients and their influence on the Hudson Estuary and New York Bight, *Estuar. Coastal Mar. Sci.* 4:281–289

Gaudy, R., 1974. Feeding four species of pelagic copepods under experimental conditions, *Mar. Biol.* 25:125–141.

Gibbs, R. J., 1976. Distribution and transport of suspended particulate material of the Amazon River in the ocean, in M. Wiley (ed)., *Estuarine Processes*. Vol. II, Academic Press, Inc., New York, pp 35–47.

Gross, M. G., 1976. Waste Disposal, *MESA New York Bight Atlas Monogr.* 26, New York Sea Grant Institute, Albany, N.Y., 32 pp

Hansen, D. V., 1977. Circulation, *MESA New York Bight Atlas Monogr* 3, New York Sea Grant Institute, Albany, N.Y., 23 pp.

Hardy, C. D., 1972. *Movement and quality of Long Island Sound Waters, 1971*. Tech. Rep. No. 17, Marine Sciences Research Center, State University of New York, Stony Brook, 66 pp.

Howells, G. P., Kneip, T. J., and Eisenbud, M., 1970. Water quality in industrial areas: a profile of a river, *Environ. Sci. and Technol.* 4(1):26–35.

Kester, D. R., Crocker, K. T., and Miller, G. R., 1973. Small scale oxygen variations in the thermocline, *Deep-Sea Res.* 20:409–412.

Ketchum, B. H., 1967. Phytoplankton nutrients in estuaries, in G. H Lauff (ed.), Estuaries, Am. Assoc. for Adv. Sci., Pub. No. 83, Washington, D. C., pp. 329–335.

Ketchum, B. H. (ed.), 1972. *The Water's Edge—Critical Problems of the Coastal Zone*, MIT Press, Cambridge, Mass., 393 pp.

Koa, A., 1975. A study of the current structure in the Sandy Hook-Rockaway Point transect, unpublished MS res. paper. Marine Sciences Research Center, State University of New York, Stony Brook.

Lambert, R. B., Jr., Kester, D. R., Pilson, M. E. Q., and Kenyon, K. E., 1973. In situ dissolved oxygen measurements in the north and west Atlantic Ocean, *J Geophys. Res.* 78:1479–1483.

Likens, G. E., 1972. The chemistry of precipitation in the central Finger Lakes Region, Tech. Rep. 50, Cornell University Water Resources and Marine Sciences Center, Ithaca, N.Y., 30 pp.

Likens, G. E., and Bormann, F. H., 1972. Nutrient cycling, in J. Wiens (ed.), Ecosystems, Structure, and Function, University Press, Corvallis, Oreg., pp. 25–67.

Malone, T. C., 1976a. Phytoplankton productivity in the Apex of the New York Bight: Environmental regulation of productivity/chlorophyll *a*, *Amer. Soc. Limnol. Oceanogr. Spec. Symp.* 2:260–272.

Malone, T. C., 1976b. Phytoplankton productivity in the Apex of the New York Bight: September 1973-August 1974, *NOAA Tech. Memo. ERL MESA*-5, Environmental Research Laboratories, Boulder, Colo., 100 pp.

Malone, T. C., 1977. Environmental regulation of phytoplankton productivity in the lower Hudson Estuary, *Estuar. Coastal Mar. Sci.* 5:157–171.

Malone, T. C., and Chervin, M. B., 1979. The production and fate of phytoplankton size fractions in the plume of the Hudson River, New York Bight, *Limnol. Oceanogr.* 24:683–696.

Mueller, J. A., Anderson, A. R., and Jeris, J. S., 1976a. Contaminants entering the New York Bight: sources, mass loads, significance, *Amer. Soc. Limnol. Oceanogr. Spec. Symp.* 2:162–170.

Mueller, J. A., Jeris, J. S., Anderson, A. R., and Hughes, C. F., 1976b. Contaminant inputs to the New York Bight, *NOAA Tech. Memo. ERL MESA–6, Environmental Research Laboratories, Boulder, Colo., 347 pp.*

National Academy of Sciences, 1969. *Eutrophication: Causes, Consequences, Correctives*, Washington, D.C., 661 pp.

National Academy of Sciences, 1971. *Marine Environmental Quality*, National Academy of Sciences/National Research Council, Ocean Science Committee, Washington, D.C., 107 pp.

New Jersey Department of Environmental Protection, 1976. *Report to Commissioner Bardin for Submission to the New Jersey Senate Committee on Energy, Agriculture and the Environment on Ocean Pollution Causes and Remedies in the Atlantic Coastal Area,* Division of Water Resources, October 7, 1976, (processed) 14 pp.

O'Connor, D. J., 1960. Oxygen balance of an estuary, *J. Sanit. Engineer. Div. ASCE* 126:556–611.

O'Connor, D. J., 1962. Organic pollution of New York Harbor, theoretical considerations, *J. Water Pollut. Control Fed.* 34:905–919.

O'Connors, H. B., and Duedall, I. W., 1975. The seasonal variation in sources, concentrations, and impacts of ammonium in the New York Bight Apex, *Amer. Chem. Soc. Symp. Ser.* 18:636–663.

Officer, C. B., and Ryther, J. H., 1977. Secondary sewage treatment versus ocean outfalls: an assessment, *Science* 197:1056–1060.

O'Reilly, J. E., Thomas, J. P., and Evans, C., 1976. Annual primary production (nannoplankton, netplankton, dissolved organic matter) in the Lower New York Bay, in W. H. McKeon and G. J. Lauer (eds.), *Fourth Symposium on Hudson River Ecology*, Paper No. 19, Hudson River Environmental Society, Inc., N. Y., 39 pp.

Parker, J. H., 1976. Nutrient budget in the Lower Bay complex, M.S. thesis, Marine Sciences Research Center, State University of New York, Stony Brook, 30 pp.

Parker, J. H., Duedall, I. W., O'Connors, H. B., and Wilson, R. E., 1976. The role of Raritan Bay as a source of ammonium and chlorophyll *a* for the New York Bight Apex, *Amer. Soc. Limnol. Oceanogr. Spec. Symp.* 2:212–219.

Proni, J. R., Newman, F. C., Young, R. A., Walter, D., Sellers, R., McGillivary, P., Duedall, I., Stanford, H., and Parker, C., 1977.

Observations of the intrusion into a stratified ocean of an artificial tracer and concomitant generation of internal oscillations (unpublished manuscript).

Richards, F. A., 1957. Oxygen in the ocean, in J. W. Hedgpeth (ed.), *Treatise on Marine Ecology and Paleoecology*, vol. 1, Geolog. Soc. Amer. Memoir 67, pp. 185–238.

Riley, G. A., 1937. The significance of Mississippi River drainage for biological conditions in the northern Gulf of Mexico, *J. Mar. Res.* 1:60–74.

Riley, G. A., 1967. Mathematical model of nutrient conditions in coastal waters, *Bull. Bingham Oceanogr. Coll.* 19:72–80.

Rodin, L. E., Bazilevich, N. I., and Rozov, N. N., 1975. Productivity of the world's main ecosystems, in Productivity of World Ecosystems, National Academy of Sciences, Washington, D. C., pp.13–26.

Ryther, J. H., and Dunstan, W. M., 1971. Nitrogen, phosphorus, and eutrophic action in the coastal marine environment, *Science* 171:1008–1013.

Ryther, J. H., Menzel, D. W., and Corwin, N., 1967. Influence of Amazon River outflow on the ecology of the western tropical Atlantic, *J. Mar. Res.* 25:69–83.

Segar, D. A., and Berberian, G. A., 1976. Oxygen depletion in the New York Bight Apex: causes and consequences, *Amer. Soc. Limnol. Oceanogr. Spec. Symp.* 2:220–239.

Thomas, J. P., Phoel, W. C., Steimle, F. W., O'Reilly, J. E., and Evans, C. A., 1976. Seabed oxygen consumption in the New York Bight Apex. *Amer. Soc. Limnol. Oceanogr. Spec. Symp.* 2:354–369.

Torpey, W. N., 1967. Response to pollution of New York Harbor and Thames Estuary, *J. Water Pollut. Control Fed.* 39:1797–1809.

Uttormark, P. D., Chapin, J. D., and Green, K. M., 1974. Estimating nutrient loadings of lakes from nonpoint sources, U.S. Environmental Protection Agency, Washington, D. C. (EPA–660/3–74–020), 112 pp.

Walsh, J. J., Barvenik, F. W., Dagg, M. J., Judkins, D. C., Scott, J. T., Tingle, A. G., Whitledge, T. E., and Warick, D. C., 1976. An analysis of time dependent factors leading to anoxic conditions within the Middle Atlantic Bight during 1976, in J. H. Sharp (ed.), *Anoxia on the Middle Atlantic Shelf During the Summer of 1976*, International Decade Oceanography/National Science Foundation, pp. 71–76.

Wiebe, P. H., Boyd, S. H., and Winget, C., 1976. Particulate matter sinking to the deep sea floor at 2000 m in the Tongue of the Ocean, Bahamas, with a description of a new sedimentation trap, *J. Mar. Res.* 34:341–354.

Williams, R. G., Godshall, F. A., and Rasmusson, E. M., 1977. The summarization and interpretation of historical physical oceanographic and meteorological information for the mid-Atlantic region, Final report to the Bureau of Land Management, U. S. Department of Interior, April 1, 1977, 295 pp.

Woodwell, G. M., 1974. Letter re Bascom (1974a), *Sci. Am.* 231(5):8.

Yentsch, C. S., 1975. New England coastal waters—an infinite estuary, in T. M. Church (ed.), *Marine Chemistry in the Coastal Environment*, Amer. Chem. Soc. Symp. Series 18, Washington, D. C., pp. 608–617.

Yentsch, C. S., 1977. Plankton Production, *MESA New York Bight Atlas Monogr.* 12, New York Sea Grant Institute, Albany, N. Y., 25 pp.

**Oxygen Depletion and Associated Benthic Mortalities in New York Bight, 1976**

# Chapter 16. Oxygen Depletion and the Future: An Evaluation

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## INTRODUCTION

Marine research in the New York Bight region has increased greatly since the late 1960s. Much of it has related to problems of ocean dumping. To understand these problems better, intensified field investigations of oceanic processes in the Bight were begun in 1973. These investigations were underway in 1976 when the mass mortalities of benthic organisms (later determined to be associated with oxygen depletion in bottom waters) were first reported. The field investigation in 1976, although not designed to study oxygen depletion specifically, was fortuitous, because it provided (1) observing and sampling facilities required to study oxygen depletion and (2) much usable data on water characteristics and oceanic processes in the Bight. Field investigations were augmented immediately and modified as needed to study oxygen depletion and associated benthic mortalities.

Chapters 1 through 15 describe and evaluate the results of field investigations and special studies. The authors of this chapter have attempted to bring together the findings, and to identify the need to acquire and interpret specific kinds of information. They also make recommendations to aid decisionmaking processes in marine management.

## AREAL EXTENT

Mass mortalities of benthic organisms were reported from July through October 1976 in continental shelf waters off New Jersey—within an area of about 8,600 km$^2$ (fig. 16–1). Chapters 12 and 13 discuss in detail the affected commercial and recreational fisheries and geographic areas. The general pattern of observations suggests a north to south progression of stressed or dead organisms from

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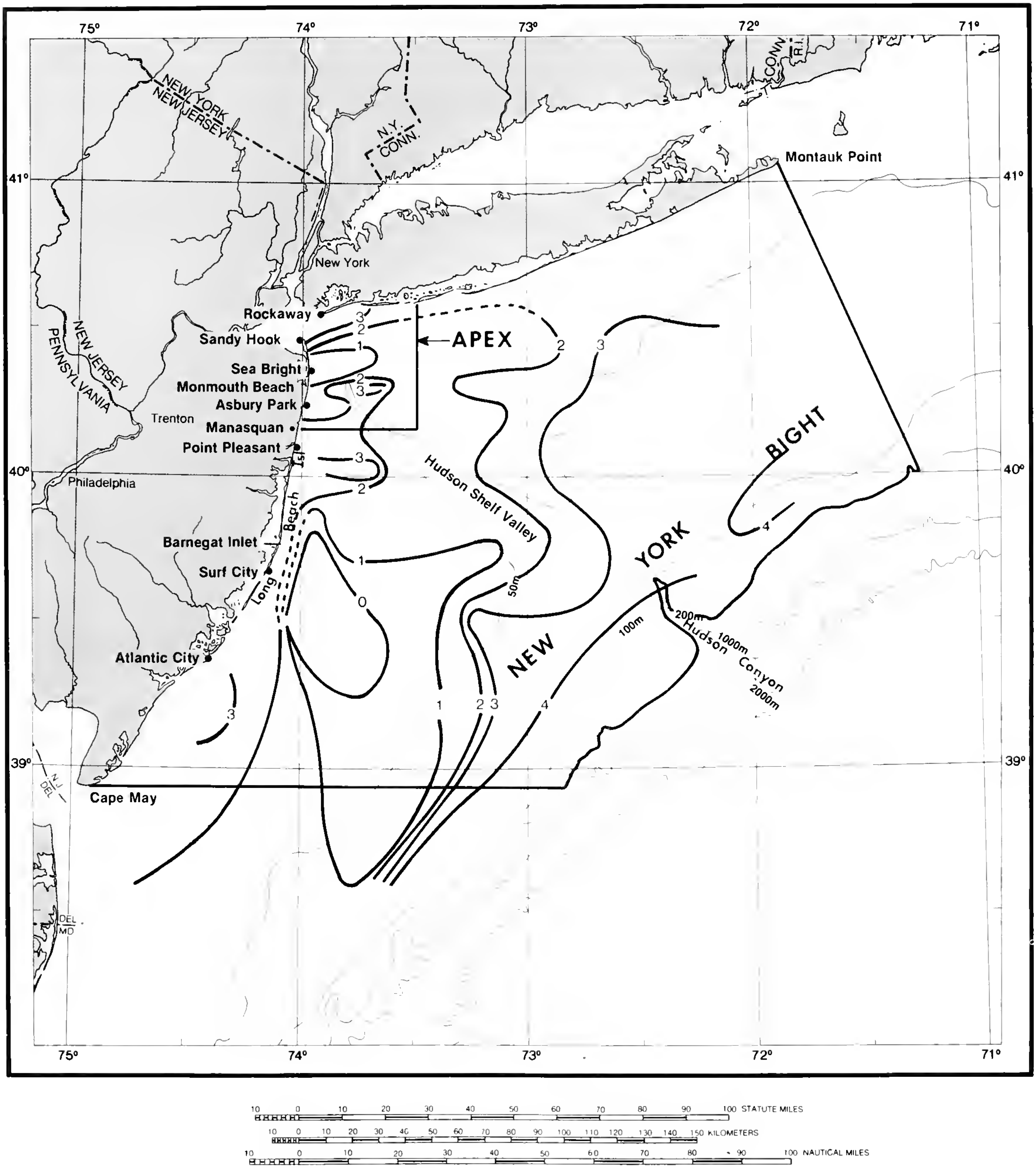


FIGURE 16–1.—Oxygen-depleted bottom water in New York Bight and off New Jersey coast, August-September 1976. Dissolved oxygen content in ml/l. (Source: fig. 1–1, ch. 1)

near Monmouth Beach in early July to Atlantic City by late July.

In late June 1976, dissolved oxygen (D.O.) concentrations in bottom waters were almost depleted ($\leq 1.0$ ml/l) from the Bight Apex region off Asbury Park south to Barnegat Inlet (fig. 16–1). By September, D.O. concentrations in the northern portion of this area were again generally from 1 to 2 ml/l. During July and August the region of low D.O. concentration ($\leq 2.0$ ml/l) appeared to shift south, within a 6,200-$km^2$ area extending 10 to 120 km offshore between Barnegat Inlet and the Delaware-Maryland boundary. Bottom waters in much of this area (1,500 $km^2$) had no D.O. in September, and hydrogen sulfide was observed at some locations.

## EFFECTS ON BIOTA

Surf clams, ocean quahogs, finfishes, lobsters, and sea scallops (in decreasing order of resource loss) were the commercial species most affected. There were minor mortalities of demersal fishes, but the greatest economic effects on finfish commercial catch resulted from movement of these organisms away from their normal geographic locations. Thus, they were not readily available to the commercial fishery.

Estimated economic impacts of the mass mortalities were considerable. Actual losses to fishing, processing, and marketing industries were about $7.9 million during 1976, and estimated losses of the resource were about $62.5 million (ch. 14). Until stocks are replenished through recruitment, which may take 7 years or more for surf clams, potential losses to the surf clam industry could exceed $550 million. Immediate losses to the sport fishery were estimated to be $3.7 million. However, recreational fishing for summer flounder was excellent in New Jersey, where this species was confined to the estuaries and immediate coastal area by oxygen-depleted water offshore (ch. 11, pt. 1).

Surf clams off New Jersey were affected more than other molluscan species. Their distribution coincided with the oxygen-depleted bottom waters where they were subjected to low D.O. levels and hydrogen sulfide poisoning (ch. 11, pt. 1). More than 60 percent of the New Jersey surf clam biomass was lost. Mortalities of up to 85 percent were estimated for the most severely impacted area. Total surf clam biomass loss from 1976 levels was estimated at $1.8 \times 10^5$ t.

Ocean quahogs and sea scallops off New Jersey had considerably less losses than surf clams. About 6 percent of the ocean quahog resource and 10 percent of the sea scallop resource were lost. Both occur seaward of the area most severely affected by low D.O. The reported (ch. 11, pt. 1) increase in 1976 sea scallop landings over 1975 is attributed to greater interest in sea scallops, brought about in part by their use as an alternative to the severely affected surf clam resource.

The 1976 mass mortalities in the New York Bight commonly were misnamed a fishkill, but few adult finfishes were killed. The greatest effect on adult finfishes was to disrupt normal migration routes and change locations of occurrence (ch. 13). Few live or dead finfishes were taken during trawling surveys in waters having extremely low D.O. ($<0.4$ ml/l), and these waters were repopulated soon after replenishment of oxygen.

That finfishes avoided areas of low dissolved oxygen is best documented by tagging surveys of bluefish (ch. 13). Their northward migration inshore (schools of 0.5- to 1.4-kg bluefish) and offshore (schools of 2.7- to 6.8-kg bluefish) occurred normally in 1976, but the midshelf migration (schools of 1.4- to 5.4-kg bluefish), which should have traversed the anoxic region, apparently did not occur. Bluefish in this size class remained near the Delmarva Peninsula, south of the area of low D.O. Also, the unusually good fishing for summer flounder along the New Jersey coast (noted previously) apparently resulted when these fish avoided waters of low D.O. offshore. Perhaps the most significant impact of oxygen depletion on finfish populations (and the most difficult to document) was reduced spawning and mortalities of eggs and larvae in affected areas.

American lobster catches for northern New Jersey declined in 1976 and are believed to be the result of oxygen-depleted bottom waters. It is difficult to assess the relative importance of lobster mortalities and disruption of their annual offshore to inshore summer migration. Lethargic and dead lobsters were found near wreck sites. To survive, lobsters require D.O. concentrations of at least 0.3 to 0.4 ml/l (Azarovitz et al. ch. 13).

Finfishes, lobsters, and crabs are now found in the Bight regions that had low D.O. concentrations in 1976, but the affected benthic ecosystem had not totally recovered by summer 1977 (ch. 12). Certain opportunistic organisms, such as the tube-dwelling polychaetes *Polydora socialis* and *Spiophanes bombyx*, have been observed, as have abundant *Asabellides oculata*. The latter is not usually identified as an opportunistic organism, but such a role has been suggested. Encouraging signs are the recolonization by juvenile surf clams and sand dollars observed off Atlantic City in 1977 (Steimle and Radosh, ch. 12) and the cumaceans, amphipods, and isopods observed in 1978 (Reid and Radosh 1979). In 1978, a year when D.O. concentrations were relatively high, juvenile surf clams were dense (10 per $m^2$) in the spring but much less dense in July.

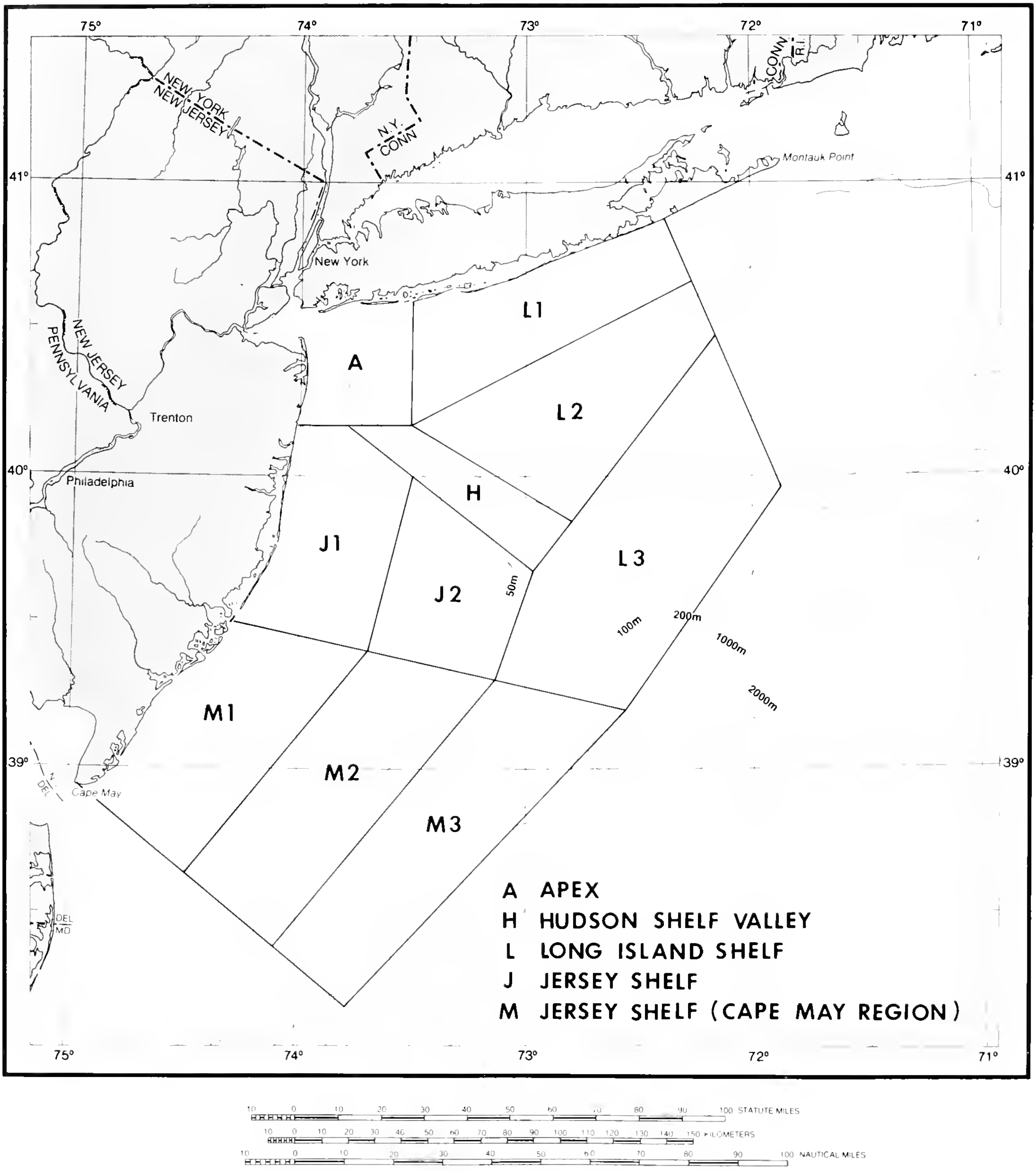


FIGURE 16–2.—Geographic subdivisions of New York Bight for analysis purposes. (Source: fig. 1–9, ch. 1)

## FACTORS LEADING TO OXYGEN DEPLETION

The cause of mass mortalities in portions of the New York Bight in 1976 has been clearly established as abnormally low D.O. concentrations in bottom waters and poisoning by sulfide generation at the low D.O. levels. Possible causes of previous oxygen depletion in the Bight Apex have been discussed by Segar and Berberian (1976) and Garside and Malone (1978). It is less clear why there was severe oxygen depletion in bottom waters throughout a larger area of the Bight in 1976.

Historical data on D.O. levels off the New Jersey coast are sparse, but Armstrong (ch. 6) gathered scattered observations for 30 years and constructed an annual cycle from the data. The cycle shows the D.O. in bottom waters normally declines during spring and summer to a minimum concentration in August. The usual minimum is about 3 ml/l. The minimum in 1976 was 1 ml/l or lower. Because D.O. concentrations probably approach critical levels (<2 ml/l) in localized areas during many years, a relatively small imbalance between rates of oxygen supply and utilization has the potential to change the normal coastal productivity of the region to one of mortality and decay.

Normally, D.O. concentrations in the bottom waters off both New Jersey and Long Island decline through spring and summer, paralleling the development of stratification. An unusual feature of the 1976 oxygen-depletion event was that bottom D.O. concentration values began (in April) to decline earlier than usual, and remained below normal until fall. During June 1976 bottom D.O. concentration values declined abruptly off both New Jersey and off Long Island (ch. 6), achieving values comparable to the normal minimum more than a month early. Values continued to decline throughout the summer.

Environmental factors that can contribute to oxygen depletion in bottom waters of the Bight are considered in the preceding chapters. In addition to these factors, high river discharge may influence biological and chemical processes in the Bight and therefore may be important. For some factors there is a substantial historical record of observations. Records for wind velocity, air temperature, sea-surface temperature, river discharge, and fish catches permit quantitative comparisons between conditions in previous years and conditions in 1976. Table 16–1 summarizes the occurrence of potentially important environmental conditions during the years 1966–76. Before 1976, at least two contributing environmental conditions occurred in each year when mortalities caused by oxygen depletion were observed. In 1976 six such conditions were observed: high Hudson River discharge, early water-column stratification, persistent southerly winds, larger than usual dumping of wastes, reversals of summer bottom currents off New Jersey, and an excessive phytoplankton bloom. Some information needed to make the table complete for the 1960s is not available, which lessens the value of this analysis. However, it is apparent that annual monitoring of these environmental factors and their seasonal development can be useful in anticipating the possible occurrence of mass benthic mortalities. Such a projection would be limited to about 1 month, although some indicators may be apparent earlier.

## SEQUENCE OF 1976 CAUSAL EVENTS

No single factor has been identified as causing the oxygen depletion and resulting mass mortalities of benthic organisms during the summer of 1976. The observed conditions seemed to develop in response to atmospheric and oceanic processes that departed from normal (average) in both intensity and time of occurrence—possibly aggravated by unusually large inputs of nutrients and organic carbon from human activities and wastes in the area surrounding the Bight.

The conditions causing depressed D.O. began early in the year. As early as January 1976 the dinoflagellate *Ceratium tripos* had a large bloom throughout New York Bight and over much of the northeastern continental shelf, peaking between April and June (ch. 9, pt. 1). Though the cause is not clear, the bloom was so large in geographic extent that nutrient inputs to the Bight from human sources cannot reasonably be regarded as the cause.

An early and warm spring also coincided with the bloom. This occurred when atmospheric circulation patterns inhibited transport of arctic air into the Northeast region (ch. 3). The unusual weather conditions contributed to greater river discharge and runoff throughout the region, and to earlier-than-normal warming of sea-surface waters. These conditions produced a lens of relatively warm, fresh surface water, contributed to early density stratification of coastal waters, and isolated bottom waters from replenishment of D.O. at the sea surface (chs. 2 and 6). Although stratification developed nearly 6 weeks earlier than usual, analysis has shown that this condition is not sufficient to have caused the extensive depletion.

Perhaps the most significant indirect factor influencing the development and duration of the 1976 oxygen-depletion event was the wind field generated by the anomalous atmospheric pressure patterns from late winter to midsummer 1976. Winds consistently had a southerly component during this period (ch. 3). Generally, the wind does not shift to the south until April. Also during May and June the wind was more persistently from the south. The resulting wind field established a potential for upwelling of bottom waters along the New Jersey coast. The bottom current-meter data (ch. 7) give evidence of upwelling off the New Jersey coast.

TABLE 16-1.—*Major benthic mortalities and potentially important associated environmental factors, 1966–76*

| Environmental factor | 1966 | 1967 | 1968 | 1969 | 1970 | 1971 | 1972 | 1973 | 1974 | 1975 | 1976 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| High Hudson River discharge[1] | ...... | ...... | ...... | x | ...... | ...... | x | x | ...... | ...... | x |
| Early formation of density stratification[2] | ...... | ...... | ...... | ...... | ...... | ...... | ...... | ...... | x | ...... | x |
| Late breakdown of density stratification[2] | x | ...... | x | ...... | ...... | x | | | | | |
| Persistent southerly winds[3] | ...... | ...... | x | x | x | ...... | ...... | ...... | ...... | x | x |
| Large ocean dumping inputs[4] | ...... | ...... | ...... | x | ...... | x | x | x | x | ...... | x |
| Reversals of summer bottom currents[5] | ? | ? | ? | no | ? | ? | ? | no | no | no | x |
| Extensive *C. tripos* bloom[6] | ? | ? | ? | ? | ? | no | no | no | no | no | x |
| Total number per year: | 1 | 0 | 2 | 3 | 1 | 2 | 2 | 2 | 2 | 1 | 6 |
| Major benthic mortalities observed | ...... | ...... | x | ...... | ...... | x | ...... | ...... | x | ...... | x |

[1] Years when the mean flow for February, March, and April exceeds the mean of record for these months by 1 standard error. Data from U.S Geological Survey.

[2] From Armstrong (ch. 6 ).

[3] Years when the southerly component of winds from April through September exceeded the resultant mean for April through September 1966–75. Data from National Oceanic and Atmospheric Administration, Environmental Data and Information Service, National Climatic Center.

[4] Years when ocean dumping (sewage sludge, dredge material, and acid waste) input in terms of $BOD_5$ exceeded the mean for the 1965–76 period. Data from U.S. Environmental Protection Agency, Region II.

[5] Years when major current reversals below the pycnocline were observed on the continental shelf during summer. Negative inferences from sources as follow: Bumpus 1969, Patchen et al. 1976, NOAA 1976.

[6] Information from Walsh et al. (in preparation).

A relation between the persistent southerly and southwesterly winds and the interruption of the expected southwestward flow of bottom water over the New Jersey shelf is noted (Mayer et al. ch. 7). In 1976 the spring southward flow at 100 km offshore was considerably less than in 1975, whereas the alongshore component on the inner shelf (50 km offshore) was reversed, flowing northward from mid-May through July.

During most of June the net flow near the bottom was to the northwest along the New Jersey coast into the Bight Apex, with strong onshore components, associated upwelling (ch. 8), and intensified flow up the Hudson Shelf Valley. This flow, particularly in the latter half of June, transported oxygen into the oxygen-depleted area. The same flow would, in all likelihood, also have transported *C. tripos* into the area and perhaps led to accumulation of this organism in coastal waters, despite its low doubling rate (ch. 9, pt. 1). The overall effect of the inferred accumulation of *C. tripos* would be to provide the high net utilization of oxygen calculated by the model—calculated to be 3 to 10 times larger in the Apex and New Jersey coastal segment than in other segments of the Bight.

*C. tripos* were observed to accumulate at the base of the pycnocline, which was below the photic zone (1% to 3% light level). Because photosynthetic processes were reduced at these depths, the *C. tripos* organisms possibly were living heterotrophically (depending upon external sources of organic substances for food and energy), thereby using oxygen through respiration (ch. 9, pt. 1). This bloom in May and early June could have been maintained by the large concentration of particulate organic material in the nearshore waters from the large Hudson-Raritan estuary discharge during spring, which may explain the absence of elevated nutrients and carbon concentrations in the water column (ch. 4). The stratification of nearshore waters and possible reduction of particulate organic material with the concomitant reduction in Hudson River discharge may have limited the availability of nourishment for continued growth of *C. tripos* below the pycnocline during late June. As a result, the bloom declined rapidly during July and created an area of organic floc at the bottom, corresponding to the area of depressed D.O. in bottom waters.

Respiration of *C. tripos* (ch. 9, pt. 1) plus benthic respiration (Thomas et al. 1976) can be determined and compared with the net utilization of oxygen as calculated by Han et al. (ch. 8) for segments of the Bight. The respiration rate of a single cell of *C. tripos* is given as 1.4 ×

$10^{-4}$ µl/cell/h. The average *C. tripos* cell counts below the pycnocline were $1.1 \times 10^8$ cells/m$^3$ off New Jersey (segment J1) and $0.64 \times 10^8$ cells/m$^3$ off Long Island (segment L1). Respiration rates for these cell concentrations are 0.37 ml/l/d and 0.22 ml/l/d, respectively. If the mean benthic respiration rate of 17 ml/m$^2$/h (Thomas et al. 1976) is distributed over the measured thickness of the lower layer—10 m for segment J1 and 16 m for segment L1—then the benthic respiration rates are 0.04 ml/l/d for segment J1 and 0.03 ml/l/d for segment L1. Thomas (personal communication) believes that 17 ml/m$^2$/h is a better estimate than the 11 ml/m$^2$/h used by Malone (ch. 9, pt. 1); however, the net effect of this assumption on the final result is small.

The total respiration of the *C. tripos* and benthic communities is then 0.41 ml/l/d for segment J1 and 0.25 ml/l/d for segment L1. The net utilization rates calculated from the observed oxygen concentrations using the diagnostic model (ch. 8) were 0.17 ml/l/d for segment J1, 0.05 ml/l/d for segment L1, and 0.15 ml/l/d for the Apex (segment A). Table 16–2 gives values computed for these segments.

In mid-May D.O. concentrations near the bottom were nearly the same in all segments. The time rates of change in concentration in the Apex and along the New Jersey coast were comparable, as were the rates of net utilization. The local rate of change and the net utilization were much less in bottom waters off the south shore of Long Island. The major difference was between the estimated rates of *C. tripos* respiration off the coast of New Jersey and the shelf waters off Long Island during this period of time. If there were no inputs of D.O. into the system, respiration alone could have caused anoxic conditions along the New Jersey coast in about 10 days. Thus, simply the respiration of the large population of *C. tripos* was sufficient to account for the observed oxygen decline through June. It is still unclear from these calculations why the anoxic conditions initially occurred in the southern Apex and extended to waters off Atlantic City about 3 weeks later. Diagnostic model computations and direct current observations indicated that southward advective processes did not transport low D.O. water from the Apex.

The average carbon loading to the Apex, including inputs from human activities, is insufficient to cause generalized anoxic conditions (Garside and Malone 1978). However, the normally large carbon load, in addition to the respiration of *C. tripos* (which to some degree may have been concentrated more in the southern Apex by flow up the Hudson Shelf Valley), likely created a greater total load in the southern Apex. Thus, the available D.O. in the Apex may have been utilized more rapidly than elsewhere in the Bight from mid-May until the end of June. The oxidation rates of the dissolved and particulate carbon are not known. The real impact of human inputs may have been to accelerate oxygen depletion locally in the Apex, but not to have caused the widespread oxygen depletion in 1976. Thus, while human inputs into the Apex are not considered important in causing the widespread anoxia observed in 1976, these inputs coupled with the convergent flow field there may explain the apparent anomaly in the spread of the anoxic area from north to south.

Thomas et al. (ch. 10) found that *C. tripos* were not present in the water column in August and September, though Mahoney (ch. 9, pt. 2) found a decaying floc of *C. tripos* near the bottom in July. Malone et al. (ch. 9, pt. 1) estimated the biological oxygen demand (BOD) from the decay of the *C. tripos*. Assuming that the average depth below the pycnocline was 10 m off New Jersey and that the decay took place over 60 days (July and August), we find that the oxidation rate is 0.16 ml/l/d compared to a *C. tripos* respiration rate of 0.37 ml/l/d. Thus, the BOD from the decay of *C. tripos* alone was much smaller than the respiration of *C. tripos* cells but it was probably sufficient to maintain anoxic conditions throughout the rest of the summer.

Thomas et al. (ch. 10) observed anaerobic conditions and sulfide generation in the anoxic area along with high rates of seabed D.O. consumption at the periphery of the area. The oxygen deficiency and hydrogen sulfide result-

TABLE 16–2.—*Comparison of mean bottom dissolved oxygen (D.O.) concentrations, local rates of change, and net utilization with* C. tripos *plus benthic respiration, May 18 to June 29, 1976, segments A, J1, and L1, New York Bight*

| Segment[1] | Mean bottom D.O. concentration[2] | | Local rate of change in bottom D.O. concentration[2] | Calculated bottom D.O. net utilization[2] | *C. tripos* respiration plus benthic respiration[2] |
|---|---|---|---|---|---|
| | May 18 | June 29 | | | |
| | ml/l | ml/l | ml/l/d | ml/l/d | ml/l/d |
| A | 5.5 | 1.9 | −0.086 | −0.15 | |
| J1 | 5.2 | 1.3 | −0.093 | −0.17 | −0.41 |
| L1 | 5.4 | 4.5 | −0.020 | −0.05 | −0.25 |

[1] Segments of New York Bight are shown in figure 16–2.

[2] Data from Han et al., chapter 8.

ing from the decaying floc increased stress on benthic organisms (ch. 11, pt. 2), and the continuous yet typical anthropogenic loadings and oxidation of dissolved and particulate matter and carbon could only intensify and maintain the already depressed conditions.

Anoxic conditions were not relieved until breakdown of the pycnocline in autumn when surface cooling caused mixing of the water column. Even the effects of hurricane Belle on mixing across the pycnocline were only transitory. During autumn bottom oxygen values continued to increase and reached saturation during winter.

New Jersey had three other open coastal mortality episodes since 1965, although none were as severe as that which occurred in 1976. We cannot define quantitatively the probability of a recurrence of a major mortality. However, based upon limited data over the last decade, a similar major occurrence can be expected in the future.

If both the interpretation of events causing the 1976 mass mortality and the assumption is correct that low bottom D.O. caused the earlier localized mortalities in the late 1960s and early 1970s, then the long-term trend of bottom D.O. should be considered. In order to do this it is necessary to examine several available data sets. Figure 16–3 shows the August history of Apex bottom D.O. concentrations from the MESA data base (1974 to present). August data are used, because generally the annual D.O. minimum occurs then. Data are sparse before 1974, but O'Connor et al. (1977) report a mean D.O. concentration and standard deviation in waters of the bottom 5 m of the Apex of 4.3 ± 0.4 ml/l in 1948 and 3.4 ± 0.3 ml/l in 1969.

A least-squares regression of the mean values shown in figure 16–3 was calculated for the MESA data. These values represent observations of D.O. within 6 m of the bottom and below the pycnocline. The hypothesis that the slope of the regression over the 1974–79 period was different than zero was tested by using the *F* statistic. The test leads to rejection of the hypothesis that the slope is not zero, based on this sample, and that there is no detectable change in the average value for D.O. of bottom waters in the Apex during August over the 6-year period. This conclusion appears to be consistent with the 1948 and 1969 values already mentioned. Thus, 1976, with all its unusual circumstances (table 16–1), appears to be an exception.

Changes of bottom D.O. occur rapidly during the period of the average D.O. minimum. Such changes occur as a result of short-term fluctuations in meteorological forcing and advective processes. The mean of four Apex stations near the mouth of the estuary and west of the Christiaensen Basin changed from 4.0 ± 1.2 ml/l during the first week of August 1978 to 3.7 ± 0.2 ml/l a week later. Note that while the change in the means are small the large change in the standard deviation indicates a considerable fluctuation. A fifth station, not included in the mean because it did not meet the criteria stated above, changed from 5.5 ml/l to 3.0 ml/l during the same period. The change at the fifth station apparently resulted from the pycnocline being at the bottom during the first period of observations and considerably above the bottom during the second.

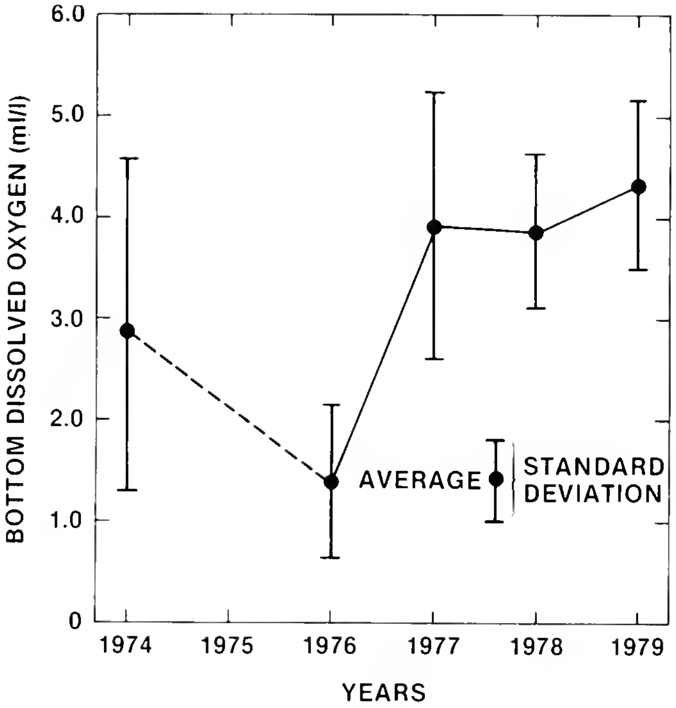


FIGURE 16–3.—Dissolved oxygen concentrations in bottom waters of New York Bight Apex during August, 1974–79. Source: National Oceanic and Atmospheric Administration, Environmental Data and Information Service, MESA data base.

In 1979, the means and standard deviations of three Apex stations in and west of the Christiaensen Basin varied in the sequence of 3.0 ± 1.0, 5.3 ± 0.3, and 3.6 ± 0.9 ml/l over the period August 13–23. Five other stations were excluded from the samples, because of large changes in D.O. related to the changes in depth of the pycnocline.

The documentation of these changes raises the question of why hurricane Belle did not have a more long-lasting effect on replenishment of bottom D.O. in 1976. Perhaps the reason is that this weak, fast-moving storm did not result in a breakdown of the pycnocline structure and replenishment of D.O. throughout the water column, but rather brought about advective oscillations due to the impulse nature of the storm.

The year-to-year fluctuations of bottom D.O. reflect a distribution with a large variance which, at this point, is still undersampled if we wish to predict confidently the long-term trend of the distribution. This is important to consider in terms of establishing monitoring programs assessing long-term effects. Actual payoffs in terms of detecting changes in the ecosystem will take many years. If future monitoring shows that there is a statistically significant decreasing trend, it might be presumed to be related to the continuous and probably increasing anthropogenic inputs of nutrients and carbon as pointed out by O'Connor (ch. 15).

Evidence to date suggests that human waste inputs to the New York Bight did not cause the 1976 oxygen-depletion event. Nevertheless, concern continues that human waste inputs could produce certain long-term effects and deplete the D.O. in waters off the New Jersey coast. Thus, in a sensitive system, even a slight imbalance in the normal cycle of environmental conditions (brought about by natural or human causes) might cause severe depletion of D.O. in any year. This leads to the question: Is it possible to predict the development of such conditions and the consequences?

## PREDICTING FUTURE EVENTS

After the publicity given the 1976 oxygen-depletion event and mass mortalities in the New York Bight, a frequent question was: Is it possible to predict oxygen depletion in waters of the New York Bight? Complexities of the marine ecosystem and many interacting environmental conditions limit development of a reliable predictive model. However, considerable attention is now given to carbon, oxygen, and nitrogen (C/O/N) modeling of Bight waters, in order to make it possible to detect trends in D.O. concentrations and identify the need to observe certain indicators more closely.

Before developing elaborate techniques for predicting D.O. depletion, consideration must be given to how the information could be used and who would use it beneficially. For example:

- If severe D.O. depletion in a region can be predicted several months in advance, who can use this information and how can it be used?
- Could alternative waste management strategies be put into effect quickly enough to alleviate any predicted oxygen depletion, if further studies indicate any bearing on such conditions?
- Could the fishing industry increase its efforts sufficiently to harvest the resource before mass mortalities occurred?
- Could onshore fish processing facilities handle the increased load if fishing efforts were accelerated, and how would the additional supply affect the market?

The answers to these questions are unclear at this time. It is apparent that techniques and strategies must be developed in industry and resource management areas to properly take advantage of the progress being made in predictive techniques.

Despite our present difficulties in reliably predicting or using information relative to D.O. depletion in the Bight, monitoring some of the contributing factors listed in table 16–1 is proposed to provide advanced warning of a severe problem. It seems likely that severe D.O. depletion might be predicted up to a month in advance.

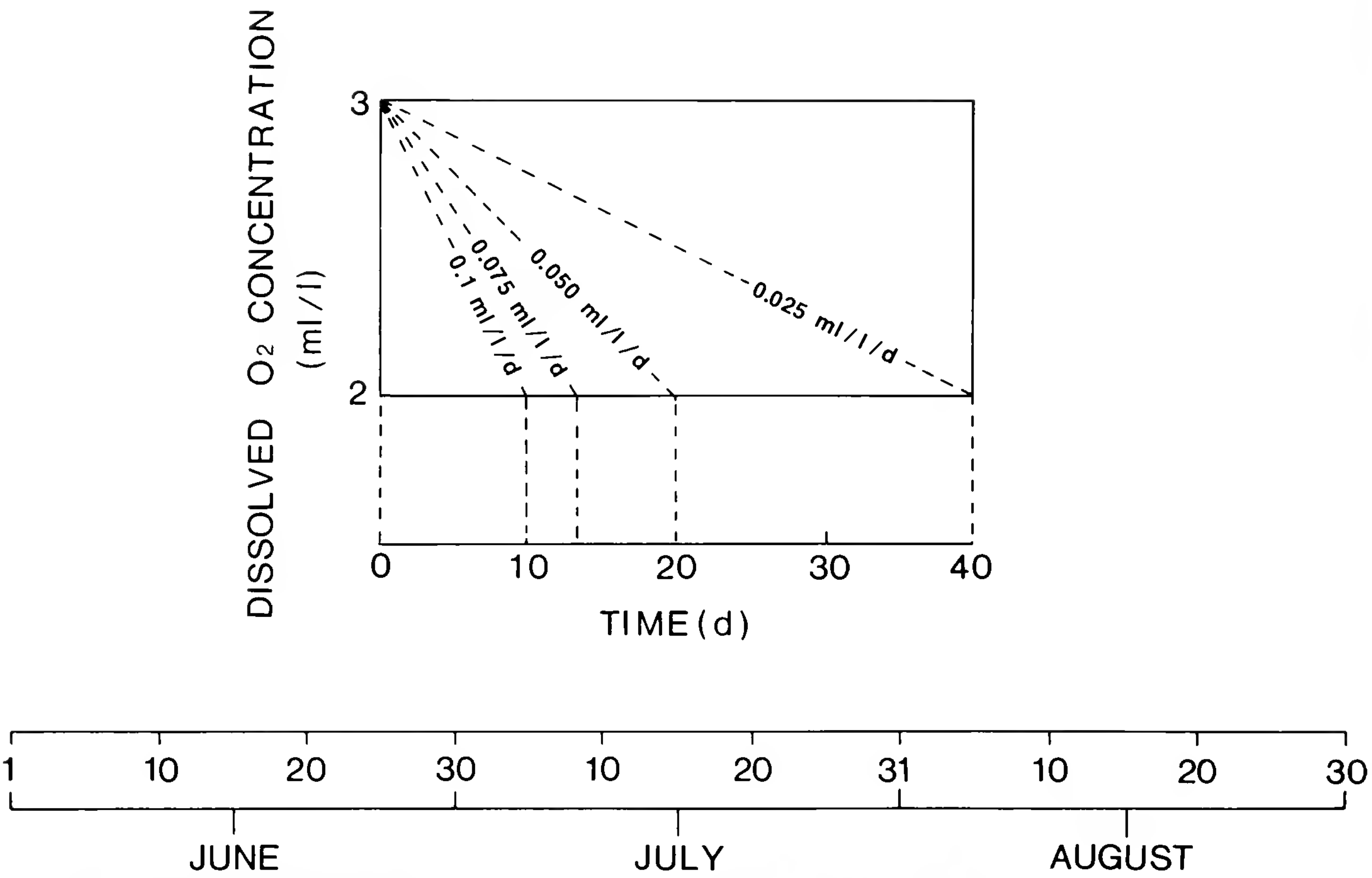
The positive occurrence of several contributing factors or indicators during spring and early summer is a warning of possible severe D.O. depletion along the New Jersey coast. Among these signs are early persistent southerly winds, early large river discharge, and massive plankton blooms, which tend to concentrate below the pycnocline in summer. An important sign would appear to be the early formation of a pycnocline below the photic zone. This would provide favorable conditions for accumulations of *C. tripos*, which function efficiently at low light levels. A bloom at that depth will consume the available D.O. near the bottom because of the organisms' net respiration.

The normal seasonal progression of D.O. levels in bottom waters of the Bight is reasonably well known. Monitoring during the period of critical annual decline can indicate a possible abnormal year. Off the New Jersey coast the critical period is between mid-May and mid-August (fig. 16–3). If there are usual D.O. concentrations of 6 ml/l in May, and a typical rate of decrease of about 0.025 ml/l/d, the depletion of D.O. should not be severe, because the minimum values reached would only be about 3 ml/l before reoxygenation at the autumn deterioration of the pycnocline. However, a later than normal autumn breakdown of the pycnocline by prolonging the period during which D.O. declines might also cause severe D.O. depletion. There also can be localized patches of water where oxygen is severely depleted, as observed in June 1977, August 1978, and July 1979. These can recover quickly and do not necessarily indicate the severe depletion of D.O. over an extensive area.

If the rate of decrease in D.O. is observed to be greater than 0.025 ml/l/d, close scrutiny is required. In 1976 off the New Jersey coast (segment J1) the rate of decrease was found to exceed 0.05 ml/l/d (ch. 4). For short periods a rate of decrease in D.O. approaching 0.1 ml/l/d has been observed.

Stress in surf clams has been observed when D.O. approaches 2 ml/l (Thurberg and Goodlet, ch. 11, pt. 2). Thus, the critical level of D.O. for this species is between the typical minimum of 3 ml/l and the critical level of 2 ml/l.

Figure 16–4 shows the days required for the D.O. concentration to drop from the typical annual minimum of 3 ml/l to the critical level of 2 ml/l for different rates of decrease. When the D.O. level decreases to the typical annual minimum of 3 ml/l, the number of days to further



**NOTE: Zero time of rate-of-depletion graph should be positioned over date of occurrence of 3 ml/l.**

FIGURE 16–4.—Oxygen depletion alert guide for New York Bight. Shows days required for dissolved oxygen concentration to decrease from typical annual minimum of 3 ml/l to critical level of 2 ml/l at four rates of depletion.

decline to the critical D.O. level of 2 ml/l can be predicted from the observed rate of decline. Depending on the rate of decline, there are 10 to 40 days in which to issue a warning that certain marine organisms will be subjected to stress and that mortalities are likely. Both the duration and severity of the potential oxygen-depletion event can be evaluated against the typical autumn date for the breakdown of the pycnocline (density stratification)—mid-September to end of October—or any observation of other environmental conditions contributing to D.O. concentrations in bottom waters.

This method of predicting any severe depletion in D.O. offers a reasonable likelihood of success. As models of carbon, oxygen, and nitrogen (C/O/N) cycles in the Bight are developed and refined, more reliable predictive approaches can be applied.

## RECOMMENDATIONS

Severe oxygen depletion in bottom waters of the New York Bight in 1976, especially off the New Jersey coast, was determined to have been caused from anomalous natural events, and probably will occur again. The phenomenon apparently cannot be controlled, but some reduction in its severity might be achieved by reducing the input of wastes and other substances from human activities. The intensive field investigations and study of the 1976 event revealed shortcomings in the data collected and research conducted before this event. It is clear that our understanding of dynamic processes in coastal waters must be improved, particularly the following:

1) development of the pycnocline—its timing, characteristics, and influence on ecosystem functions;
2) occurrence of large phytoplankton blooms—their relation to oceanic and climatic conditions; and
3) functions of the ecosystem—as they relate to C/O/N cycles and inputs to coastal waters from human activities.

In the light of these needs, as they relate to D.O. depletion and possible mass mortalities, and to improve our understanding about and management of coastal waters, certain recommendations are made and discussed.

**Recommendation 1**—*Continue to monitor D.O. in bottom waters, plankton populations, and related physical-chemical properties to detect D.O. concentrations, rates of decline during the critical spring-summer period, and the potential for severe oxygen depletion .*

Results of monitoring can be used to warn of possible mass mortalities. A monitoring plan is proposed for the New York Bight (Swanson et al., in press).

**Recommendation 2**—*Refine monitoring and predicting techniques (including models of C/O/N cycles), develop both short-term predictive capabilities and long-term determination of trends (including variability or probability of* n*-year events), and improve coordination of services which include the needs of socioeconomic and regional resource management systems.*

**Recommendation 3**—*Investigate the feasibility of harvesting and processing the fishery resource in the event of anticipated mass mortalities, in conjunction with shellfishing industries, and Middle Atlantic and New England Fisheries Councils.*

**Recommendation 4**—*Increase emphasis on further understanding of natural variability in marine ecosystems and its relation to human influences.*

Criteria must be developed that reflect variance as well as mean conditions. It is typical to consider coastal waters as being so vast that they can accommodate any use we might perceive, to design systems to manage the coastal marine environment based on mean conditions, and to assume that mean conditions prevail without adequately studying the departures from the mean. For example, residence times based on steady-state conditions and calculated from data that reflect long-term integration are often used. They reflect integrated measures of advective renewal of water (and associated properties) over a region, when all parts of the region probably do not share equally in the renewal. Whereas meteorologists and hydrologists use safety factors when designing for 100-year storms and low- and peak-flow conditions, oceanographers and ocean engineers often treat similar problems, including those relating to pollution, without considering such long-term variance in their design criteria.

## REFERENCES

Bumpus, D. F., 1969 Reversals in surface drift in the Middle Atlantic Bight Area, *Deep-Sea Res.* 16:17–23.

Garside, C., and Malone, T. C., 1978. Monthly oxygen and carbon budgets of the New York Bight Apex, *Estuar Coastal Mar. Sci.* 6:93–104.

National Oceanic and Atmospheric Administration, 1976. Evaluation of proposed sewage sludge dumpsite areas in the New York Bight, *NOAA Tech Memo.* ERL MESA–11. Environmental Research Laboratories, Boulder, Colo., 212 pp.

O'Connor, D. J., Thomann, R. V., and Salas, H. J., 1977. Water Quality, *MESA New York Bight Atlas Monogr.* 27, New York Sea Grant Institute, Albany, N.Y., 104 pp.

Patchen, R. C., Long, E. E., and Parker, B. B., 1976. Analysis of current meter observations in the New York Bight Apex, August 1973-June 1974, *NOAA Tech. Rep.* ERL 368–MESA 5. Environmental Research Laboratories, Boulder, Colo., 24 pp.

Reid, R. N., and Radosh, D. J., 1979. Benthic macrofaunal recovery after the 1976 hypoxia off New Jersey, *Coastal Oceanography and Climatology News* 1(3):35–36.

Segar, D. A., and Berberian, G. A., 1976. Oxygen depletion in the New York Bight Apex: causes and consequences, in M. G. Gross (ed.), Middle Atlantic Continental Shelf and New York Bight, *Amer. Soc. Limnol. Oceanogr. Spec. Symp.* 2:220–239.

Swanson, R. L., Stanford, H. M., Parker, C. A., Goodrich, D. M., O'Connor, J. S., and Chanesman, S., in press. A monitoring strategy for the New York Bight.

Thomas, J. P., Phoel, W. C., Steimle, F. W., O'Reilly, J. E., and Evans, C. A., 1976. Seabed oxygen consumption in the New York Bight Apex, in M. G. Gross (ed.), Middle Atlantic Continental Shelf and New York Bight, *Amer Soc. Limnol. Oceanogr. Spec. Symp.* 2:354–369.

Walsh, J. J., Falkowski, P. G., and Hopkins, J. S., in preparation Oxygen depletion within the New York Bight as a function of climatology and phytoplankton species succession.

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