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OXYGEN DEPLETION AND MASS MORTALITIES OF SHELLFISH IN THE MIDDLE ATLANTIC BIGHT OF THE UNITED STATES IN 1976

by

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SUMMARY

The continental shelf of the Middle Atlantic Bight, from Cape Cod to Cape Hatteras on the east coast of the United States, contains the largest known stocks of ocean shellfish of any comparable coastal area of North America. Principal species are surf clams, *Spisula solidissima*; ocean quahogs, *Arctica islandica*; and sea scallops, *Placopecten magellanicus*. In summer and autumn of 1976, mass mortalities of these species occurred in a 165 kilometer corridor of severe oxygen depletion paralleling the coast from 5 to 85 kilometers from shore. Mortalities of surf clams, the most severely affected species, were estimated in excess of 140,000 metric tons. A series of anomalous meteorological and hydrological events (particularly early warming of surface waters, early thermocline development, and a massive shelfwide phytoplankton bloom) superimposed on an already stressed coastal area, was considered to be responsible.

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INTRODUCTION

Mass mortalities in the sea are common events with a variety of causes -- physical, chemical, and biological. A "mass mortality" can be described as "an unusual and sharply defined increase in mortality rate, of sufficient proportions to significantly affect population size and to at least temporarily dislocate 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 miles of coastline. Causes of mass mortalities can be physical, chemical, or biological -- or combinations which produce stress beyond the limit of tolerance of individuals in the population. Physical causes include vulcanism, temperature changes and extremes, storms, seaquakes, and vertical upwelling currents. Chemical causes include salinity changes and extremes, oxygen depletion, contaminant chemicals, and H_2S. Biological causes include predation, disease, algal blooms and toxins.

Mass mortalities due to many of the above causes have been reported in the scientific literature, and summary papers have been published. Probably the most complete is that of Brongersma-Sanders (1957) -- an exhaustive review of all known mass mortalities in the sea to that time. Other reviews include those of Sindermann (1970, 1976).

An environmental event of heroic proportions, leading to mass mortalities of many marine species in a 12,000 square kilometer area of the continental shelf off the Middle Atlantic coast of the United States occurred during the period July-October, 1976, due apparently to extreme oxygen depletion and hydrogen sulfide formation in bottom waters. First reports of a developing environmental problem reached the scientific community during the July 4th weekend. Sport divers, lobstermen, and trawler fishermen had 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, just south of New York City. Within a few weeks the reported mortality areas had extended southward some 85 kilometers and well out on the continental shelf. A series of survey cruises was initiated to examine the extent of the problem and to assess the damage -- cruises which had to be expanded further and further southward, all the way to Maryland, and seaward for 100 kilometers. Oxygen deficient bottom water -- sometimes with zero dissolved oxygen levels -- was found for a north-south distance of 165 kilometers in a zone or corridor from 5 to 85 kilometers off the coast.

In the central part of this zone, oxygen values were zero, and hydrogen sulfide was formed below the thermocline. Oxygen depletion persisted until October, when lower surface temperatures and mixing, after disappearance of the thermocline, gradually reoxygenated the bottom water.

Mortalities of fish, lobsters, and molluscan shellfish were observed. The sedentary forms -- surf clams, ocean quahogs, and sea scallops -- suffered the greatest mortalities. From almost continuous surveys, it was estimated that 69% of the surf clam population off the New Jersey coast -- representing some 143,000 metric tons of meats -- had been destroyed by October, with significant but lesser mortalities of ocean quahogs and sea scallops. Lobster catches were reduced by 30% during the period. The New Jersey coast was declared a resource disaster area in November by the federal government because of this event.

As might be expected, the man in the street and the newspaper headline writers immediately jumped to the conclusion that ocean disposal of pollutants -- particularly sewage sludge dumping, which goes on at a grand scale (over 5 million tons were dumped in 1976) 20 kilometers from the coast, was responsible for this corridor of death. Concern was also expressed that this catastrophic event might be repeated, possibly even annually.

Scientific observations suggested that large-scale meteorological and oceanographic phenomena were involved in production of the zone of oxygen depletion which resulted in mortalities. A number of research groups -- federal, state, university and industry -- participated actively in data collection and analysis. The U. S. National Science Foundation convened a workshop on the problem in October (National Science Foundation, 1976), and the participating research groups organized a series of their own workshops in November, in an attempt to integrate what was known (National Marine Fisheries Service, 1977).

From all this activity a large amount of data has been assembled and a hypothesis developed, centering on a combination of unique atmospheric, hydrographic and biological events, which occurred in a coastal area already stressed by human organic loading.

The major environmental disturbance of 1976 in the Middle Atlantic Bight may prove to be one of the best-documented examples that we have of a mass mortality in the sea and its short- and long-term impacts on resource and foodchain species. Scientific studies are continuing, especially since the possibility of repetition of the event, at some level of intensity, exists for future years.

EXTENT OF OXYGEN DEPLETION

Sampling in mid-July, found the depressed dissolved oxygen (D.O.) values, some below the level of detection by standard Winkler procedure, in an area 3 to 35 kilometers off Barnegat Inlet, 115 kilometers south of New York City. Values of less than 2 ppm were found between Long Branch and Beach Haven, a coastal distance of 105 kilometers. Trawl surveys found dead epibenthic invertebrates and stressed surf clams in this zone and a notable absence of the normal fin-fish populations known to inhabit the area in the summer.

By early August, prior to Hurricane Belle, which passed the New Jersey coast on August 10, the anoxic area had moved or expanded southward, with the center of the oxygen-depleted area being found between Barnegat Inlet and Atlantic City, a distance of 70 kilometers on the central New Jersey coast. Extremely high levels of hydrogen sulfide (to 1.76 mg/l^{-1}) were also detected near the center of the depleted area. The hydrogen sulfide was present up to 15 meters from the bottom, but not above the thermocline (Draxler and Byrne, 1977).

Hydrogen sulfide was also evident in an apparent upwelling of anoxic bottom water along very restricted portions of the immediate shoreline in central New Jersey. Hundreds of fish of several species, including sharks, were trapped along the beach and killed. A period of strong westerly winds was thought responsible.

The hurricane, from which many had hoped for relief, did not significantly alter the situation. Immediately after its passage, resurveys of stations off Atlantic City which had been surveyed just prior to the storm found some possible coastal mixing or an offshore shift, resulting in the less than 2 ppm D.O. area moving from 3 kilometers off the coast to 25 kilometers offshore as the only apparent effect. This was only temporary, because a second resurvey, five days later, indicated the anoxic water mass had resumed most of its pre-hurricane distribution, with further movement or expansion south-southeast (Steimle, 1977a).

By mid-September, the anoxic area (defined here as the area where bottom water D.O.'s were less than 2 ppm), reached its greatest known distribution, covering approximately half the New York Bight, including a tongue off Long Island, and extending southward to the Maryland state border (Figure 1).

By the first week in October, surveys found that the thermocline was apparently decaying because bottom D. O. concentrations inshore, out from the coast to 40 kilometers, were increasing to non-hazardous levels. By early November no trace of oxygen depletion was evident and the 1976 oxygen depletion phenomenon had evidently ended.

RELATED METEOROLOGICAL AND HYDROLOGICAL EVENTS

Data from intensive field operations in the Middle Atlantic Bight during the critical period, combined with meteorological observations, were examined almost immediately in a series of workshops held in October and November, 1976, to which participating federal, state, university and industry research groups were invited. It was the general conclusion of the workshops that large-scale meteorological and oceanographic phenomena were involved in production of the anoxic zone which resulted in mortalities. The hypothesis which was developed focused on a somewhat unique combination of anomalous environmental events superimposed on a marginal coastal area, which has been made eutrophic by man's input of organic material.

Meteorological events included:

High February-March temperatures with peak river runoff in February instead of April;

Reduction of cyclonic storm activity during the summer to less than half the 25-year average;

A period of 4-6 weeks in June-July with persistent south or southwest winds.

Physical events included:

Early (February-March) warming of surface waters and development of the thermocline (thermal stratification usually begins in April and reaches a maximum in August);

Early onset of decline in subsurface dissolved oxygen values (January rather than March). Bottom water D.O. values in May 1976 off New Jersey were as low as they usually are in July (Armstrong, 1977).

Biological events included:

> A massive bloom of dinoflagellate *Ceratium tripos* over much of the Middle Atlantic Bight, but particularly concentrated in the New York Bight. The bloom began in February, persisted at least until July, and was concentrated at and just below the thermocline.

Since the Middle Atlantic Bight has been the focus of intensive research by elements of the National Oceanic and Atmospheric Administration for several years, and since a number of earlier investigations had been conducted, the historical data base enabled comparison with conditions which existed in previous years. Based on such comparisons, an explanation of the events of 1976 could be summarized in several steps:

(1) Oxygen demand from a declining phytoplankton bloom was superimposed on a shallow shelf area (New York Bight) already characterized by reduced dissolved oxygen in an average summer; (2) this organically rich oxygen demanding water was sealed off early in spring by the early onset of a thermocline; (3) water mass movement was reduced to a minimal southward flow of bottom water; and (4) cyclonic storm activity during the entire period was abnormally low. With these factors, the ingredients of disaster to marine animals were present.

FISH AND SHELLFISH STOCKS OF THE MIDDLE ATLANTIC BIGHT

Fish and shellfish populations of the Middle Atlantic Bight are abundant and 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% of 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 deeper waters of the Bight.

The National Marine Fisheries Service has conducted surveys of surf clam, ocean quahog, and scallop distribution and abundance in the Middle Atlantic Bight for a number of years. The most recent survey for clams, quahogs, and scallops was in April, 1976. Results of this survey are shown in figures 2, 3 and 4. Total estimated biomass of offshore surf clams in the Bight was 875,000 metric tons of meats, with the New Jersey sector containing 207,000 metric tons. Coastal stocks of surf clams (within 5 kilometers of shore) in New Jersey have been estimated at 34,000 metric tons. Total estimated biomass of ocean quahogs in the Bight was 2,450,000 metric tons of meats, with the New Jersey sector containing 818,000 metric tons. 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 square kilometers of the shelf off New Jersey.

Finfish species of significance 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 with the recreational catch predominating. Some of the species (such as striped bass) are estuarine-dependent, while others, such as summer flounder and bluefish, migrate vertically to and from the coast, or laterally north and south through the Bight. A few species (mackerel, silver hake) have until recently been exploited heavily by foreign distant-water fleets. Most of the Middle Atlantic finfish stocks of interest to U. S. fishermen (other than mackerel) have not declined drastically in recent decades, and increased landings characterize species such as bluefish, striped bass and weakfish since 1970).

The National Marine Fisheries Service (and predecessor agencies) has also conducted trawling surveys for demersal fish in the Middle Atlantic Bight for the past decade, to provide a basis for continuing stock assessments. Additionally, recreational fish surveys have been carried out during the past three years. Landing figures for important recreational and commercial species are summarized in Figure 5.

EFFECTS ON SHELLFISH POPULATIONS

Beginning in late July, assessments of the impact on the surf clam stocks were begun. Signs of stressed surf clams were noted by divers as early as the July 4th weekend. These were clams that were not burrowed in the sediment but were lying free on the surface. Several later trawl surveys also found live, but gaping clams in their nets. The first specific surf clam dredging survey was completed by the end of July. Mortalities were found in a restricted area off Barnegat Inlet ranging between 0 to 56%. A second survey, in early August, found an average mortality of 10% in clam stocks in the impacted area. The normal mortality is 2% (Ropes and Chang, 1977).

Subsequent expanded resurveys in September and October found that the average mortality had risen to 100% at some stations in a 12,000 square kilometer sector off New Jersey. It was estimated that this represented by October 1976, a loss of 143,000 metric tons of surf clam meats, representing about 69% of the offshore surf clam stocks of New Jersey, and 16% of the estimated total Middle Atlantic Bight population of the species (Figure 6). Of the coastal surf clam stocks (those within 5 kilometers of shore) an estimated 1,700 metric tons were killed in an area south of Beach Haven -- representing about 5% of the total inshore coastal population. Because July is the normal spawning season for surf clams, the impact on future stocks may also be severe.

Mortalities were observed also in New Jersey's ocean quahog population, a potentially valuable resource species, which is usually found in deeper water than the surf clam. In early August, mortalities for this species were less than 1%. Mortalities increased in September to almost 8%, with a high of 40% at some individual stations. The loss to New Jersey stocks of ocean quahogs was about 6,600 metric tons, or less than 1% of the stocks in that sector of the coast (Figure 7) (Ropes and Chang, 1977).

Sea scallops, which also occur in deeper water than surf clams, were affected by the anoxic event. Scallops occupy an area of 11,500 square kilometers off the New Jersey coast; of this, 4,300 square kilometers were within the anoxic zone, and an estimated 10% of the population was killed in a zone 35-55 m/deep (Figure 8).(MacKenzie, 1977).

The lobster industry off New Jersey also suffered. Some of the inshore stocks were killed, and the shoreward migration of offshore stocks was interrupted. During the months of June thru September, normally the most productive months of the year, landings declined an average 30% compared to the same period in 1975. The inshore pot fishery, which operates within 20 kilometers of shore, was most severely affected. Lobstermen stated that few offshore migrants entered the fishery in 1976 -- a highly unusual event.(Halgren, 1977).

Other benthic populations were affected by the anoxic water. Effects on the benthic infauna were most noticeable in the H_2S zone, with reductions in numbers of species and numbers of individuals. Species to species variability in survival was noted, with a number of polychaetes and sea anemones quite resistant to prevailing extreme environmental conditions. Among the benthic megafaunal species affected were rock crabs (Cancer irroratus, C. borealis), mud shrimp (Axius serratus), mantis shrimp (Squilla sp.), starfish (Asteria sp.), moon snail (Lunatia heros), sea cucumbers (Thyone sp.), and sand dollars (Echinarachnius parma). Many of the more mobile crustaceans were able to avoid the developing anoxia, but not all of them (Radosh et al., 1977; Steimle, 1977b).

Oxygen depletion in bottom waters may prove to be a common feature in localized areas where ocean shellfish occur. Drastic changes in abundance of species such as the surf clam, which have been observed previously, may in some instances be caused by anoxia. It may be too, that the presence of anoxic bottom waters may influence post-larval settling and survival of clams -- even eliminating set of a particular year class in certain areas. The existence and abundance of the 1976 year class of surf clams in the formerly anoxic zone will be surveyed in 1977.

The survival of molluscan shellfish in oxygen-depleted waters, and in the presence of hydrogen sulfide, has been examined, and additional experiments are being conducted by the National Marine Fisheries Service. Earlier studies (Theede et al., 1969) and preliminary results of current studies indicate survival of clams for periods of several weeks in water which approaches zero D.O., but shorter survival in hydrogen sulfide environments. These experimental findings agree with field observations in 1976. Surf clams began showing signs of stress early in July, but mortalities were not reported until the end of July. The extended period of anoxia, combined with hydrogen sulfide, resulted in 100% mortality by October at stations in the most severely affected zone along the central New Jersey coast, but lesser mortality in peripheral areas of less severe oxygen depletion.

EFFECTS ON FISH POPULATIONS

Even though some mortalities of finfish were reported early in the event, it seems that the principal effect of oxygen depleted waters below the thermocline was to modify the normal movements and migrations of a number of species. Summer flounder, Paralichthys dentatus, were crowded within a narrow coastal zone or in estuaries, where they were readily available in large numbers to fishermen. Bluefish, Pomatomus saltatrix, which normally migrate northward through the area in summer, were shown by results of tagging studies to have reversed their direction, and moved southward (Freeman and Turner, 1977a, 1977b; Festa, 1977).

Demersal species apparently abandoned the oxygen-minimum and hydrogen sulfide area completely. Several trawling surveys through the area in August, September, and October disclosed almost complete absence of any demersal fish species -- an unusual event when compared with similar trawling surveys conducted in the Middle Atlantic Bight since 1968. Very few dead fish were brought up in the nets during the 1976 surveys, although dead invertebrates were common (Azarovitz et al., 1977).

There is genuine concern, however, that survival of the 1976 year class of demersal spawning fish may have been severely affected in the anoxic zone.

DISCUSSION

Oxygen depletion in other coastal areas of the world.

There are of course other coastal areas in the world where extreme oxygen depletion in bottom waters is a frequent, sometimes even an annual, event.

Marine fish kills releated 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, e.g., 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 and 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 H_2S 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 14,000 square kilometers, but interestingly, there is a narrow coastal strip about 5 kilometers wide, extending to a depth of 40 meters, where sea life is normal and hydrogen sulfide does not occur (Copenhagen, 1934).

Similar mass mortalities of marine animals in a zone of upwelling have been reported by Falke (1950) from Concepcion 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 1958-1959. The total area affected was estimated at 33,000 square kilometers. The stagnation was broken in 1962 by a strong inflow of saline water from the Kattegat. It is significant that 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 had occurred in the early 1930's (Kalle, 1943; Meyer and Kalle, 1950). The most recent intrusion of North Sea water into the Baltic occurred in 1975 (Tiews, 1976) following several years of increasing oxygen depletion in bottom waters. This situation of periodic stagnation, broken by saline inflows, followed by uplift of nutrients, favors periodic increase in biological production -- unlike other areas of continuous anaerobiasis such as the deeper (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 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, Alabama -- one of the largest estuaries on the Gulf of Mexico. Stratification of the water column over 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. The shoreline phenomenon is called a "jubilee". Thirty-five such occurrences were reported by Loesch (1960) between 1946 and 1956, but newspaper accounts go back to the nineteenth century (the earliest being in 1867). May (1973) has reviewed the history of such events and finds no increase in their frequency in recent years. He carried out detailed oxygen determinations during a "jubilee" in 1971, and found large areas of the bay with less than 1 ppm dissolved oxygen in bottom water. Mortalities of fish, crabs, and oysters were observed.

Previous oxygen depletion events in the New York Bight.

There have been previous reports of fish kills off New Jersey -- in 1968, 1971, and 1974 (Ogren and Chess, 1969; Young, 1973; and Young, 1974), and there may have been earlier problems that were not observed or reported (P. Hamer, N. J. Dept. Environmental Protection, pers. comm.). Those which were documented resemble the events of 1976 in that: 1) the more sedentary organisms found around rocks and wrecks and near open bottom 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 previous years in that: (1) it began before the end of June, compared with the August-October period of earlier problems; (2) the low oxygen bottom water was cooler (ca. 10°C) than reported in earlier publications (14-18°C), with a strong thermocline present in 1976 -- a condition not clearly defined in all previous years, and (3) hydrogen sulfide, not previously reported, was detected in 1976 in lethal concentrations. It may have been present but not observed in earlier episodes.

The previous reports of mortalities also covered a much smaller area. 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 kilometers), from one to about ten kilometers offshore, with a total area of approximately 600-800 square kilometers (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 as follows: (1) mortalities were restricted to waters less than 30 meters deep; (2) bottom water temperatures were 14-16°C; (3) bottom dissolved oxygen values near the bottom were less than 1.0 ml/l; (4) a pronounced thermocline existed; and (5) beginning in July and extending to September a series of phytoplankton blooms occurred along the New Jersey coast.

Reexamination of the same area in May and July, 1969, disclosed that oxygen values near the bottom were in excess of 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 kilometers east of Point Pleasant, New Jersey, in depths of about 30 meters, and also at Shark River Inlet (Young, 1973). Bottom water temperatures 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, New Jersey (Young, personal communication). Bottom dissolved oxygen values were 1.0 ml/l, with heavy suspended flocculent material and bottom water temperatures of 14-15°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, New Jersey.

Thomas et al. (1976) reported that significant summer depletion of bottom D.O. in the restricted area of the sludge and dredge spoil dump sites, and also in an area close to the New Jersey shore off Asbury Park, occurred during the summer of 1974. Low D.O.'s have been reported previously in the New York Bight dump site areas (Pearce, 1972). D.O.'s in dump-site areas in summer of 1975 were higher than 1974, and above the level considered harmful to most marine life.

Phytoplankton blooms.

The appearance and persistence of a massive bloom of the dinoflagellate Ceratium tripos in the Middle Atlantic Bight in 1976 is considered to be a significant factor contributing to oxygen depletion. Beginning in February, an unusual bloom of the dinoflagellate was found to be in progress over most of the outer continental shelf area of the Middle Atlantic Bight. This bloom was also noticed at many stations during an ichthyoplankton survey during March; the dinoflagellates clogged coarse-mesh nets from Long Island to Virginia in abundances which had not been observed in the ten years previous experience of the ichthyoplankton group sampling in this area (Figure 9).

With onset of stratification, the bloom became concentrated in a band at or below the thermocline, within 100 kilometers of the New Jersey coast. The Ceratium population appeared to decline sharply by July, and its contribution to bottom oxygen depletion in June and July was strongly indicated by the accumulation on the bottom of a centimeter or more of a brown flocculent material, which consisted to a large extent of dead Ceratium. Additionally, the observation in late spring and early summer that much of the bloom was concentrated at or below the thermocline indicates another possible mechanism of oxygen depletion, since the organism may exist heterotrophically. Ceratium is not grazed upon by many planktonic herbivores, so the persistent bloom over a period of several months meant the accumulation of large amounts of oxygen-demanding organic material in the water column, and the gradual accretion of dead organic material on the bottom. All of this oxygen-consuming material, when combined with the unusual hydrographic events mentioned earlier, seems to provide a reasonable explanation for the observed extreme oxygen depletion in 1976 (Mahoney, 1977; Malone, 1977).

Annual phytoplankton blooms are now a reality in sections of the New York Bight, probably in part at least as a consequence of organic loading of coastal waters, particularly from the Hudson River. The mean residence time calculated for the New York Bight is 100 to 250 days, and estimated daily chemical inputs from the Hudson River estuary complex alone are 520 metric tons of nitrogen and 138 metric tons of phosphate. Sewage sludge dumping and other human sources of nutrients have been estimated to augment these figures by only minor amounts ($\leq$ 10%). In total though, when natural productivity of coastal waters is locally enriched by nutrients of human origin, a condition of increasing eutrophication can develop -- and oxygen depletion can be a consequence. It does seem, however, that the extent and duration of the 1976 Ceratium bloom in the Middle Atlantic Bight would indicate that it did not occur in response to local nutrient inputs, but was rather a shelf-wide long-term phenomenon.

Fig. 1. New York Bight -- with anoxic area outlined.

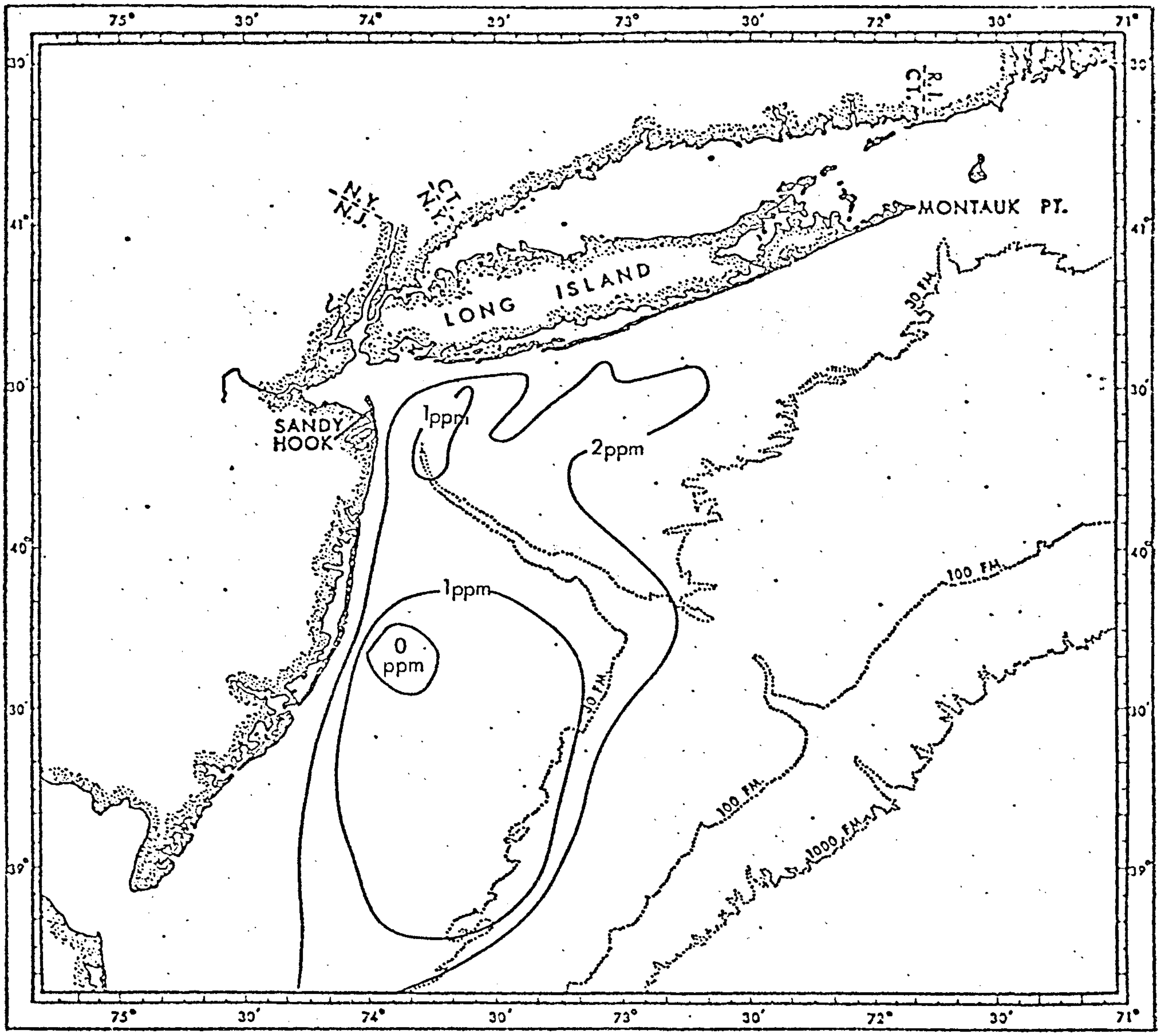
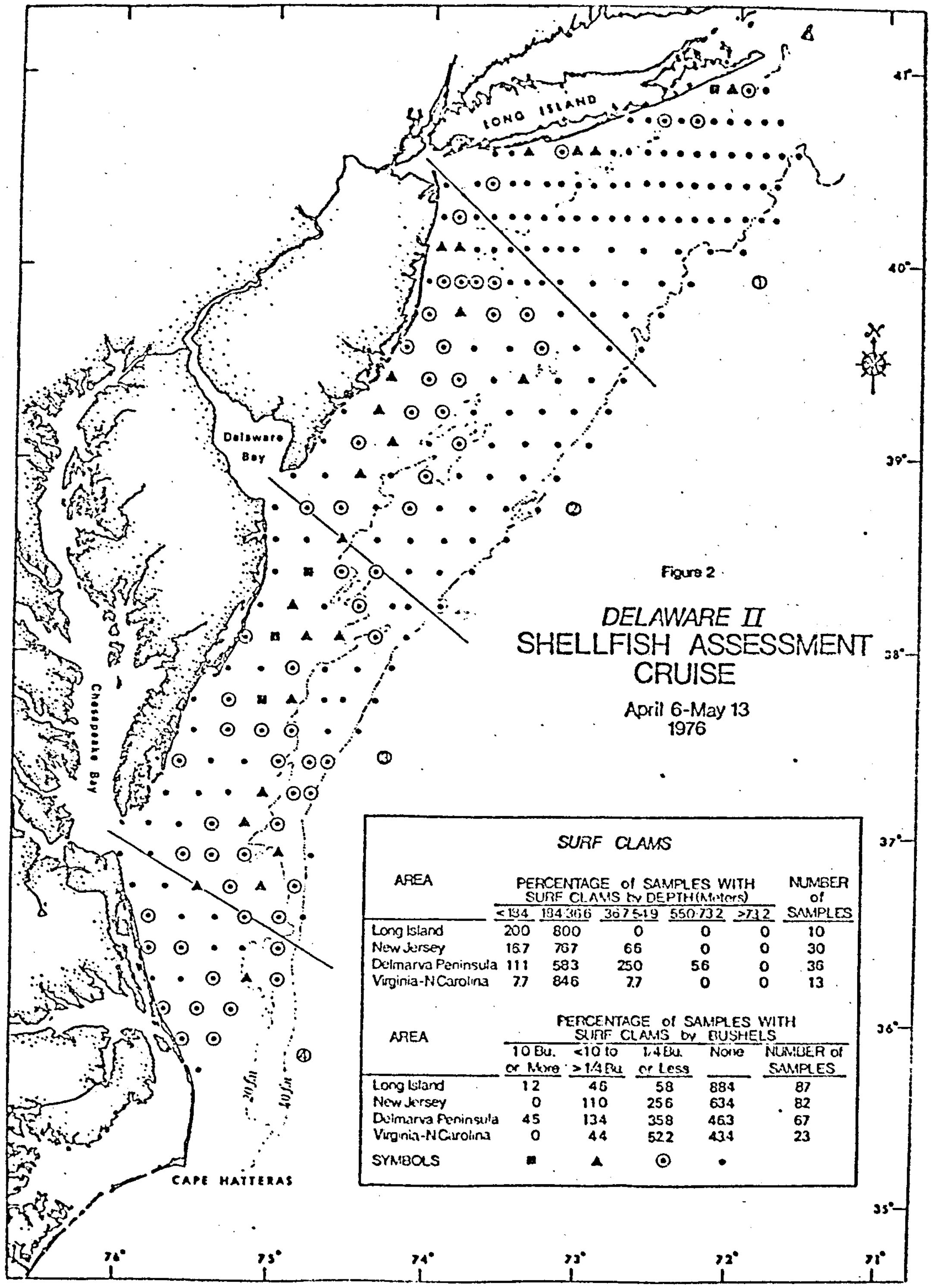


Fig. 2. Distribution and abundance of surf clams in the Middle Atlantic Bight.

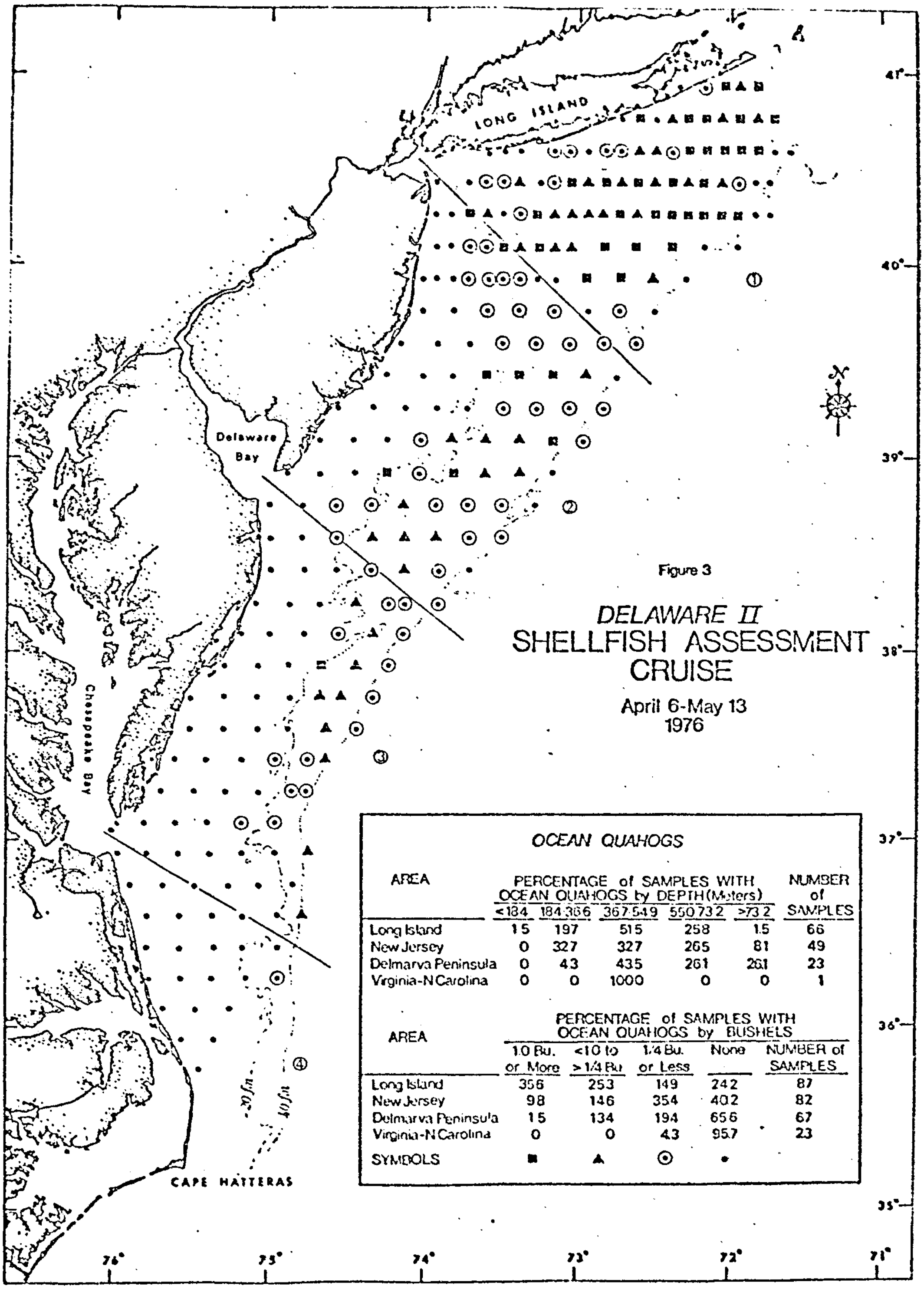


SURF CLAMS

AREA	PERCENTAGE of SAMPLES WITH SURF CLAMS by DEPTH (Meters)					NUMBER of SAMPLES
	<184	184-366	367-549	550-732	>732	
Long Island	200	800	0	0	0	10
New Jersey	167	767	66	0	0	30
Delmarva Peninsula	111	583	250	56	0	36
Virginia-N Carolina	7.7	846	7.7	0	0	13

AREA	PERCENTAGE of SAMPLES WITH SURF CLAMS by BUSHELS				NUMBER of SAMPLES
	10 Bu. or More	<10 to >1/4 Bu.	1/4 Bu. or Less	None	
Long Island	12	46	58	884	87
New Jersey	0	110	256	634	82
Delmarva Peninsula	45	134	358	463	67
Virginia-N Carolina	0	44	522	434	23
SYMBOLS	■	▲	⊙	•	

Fig. 3. Distribution and abundance of ocean quahogs in the Middle Atlantic Bight.

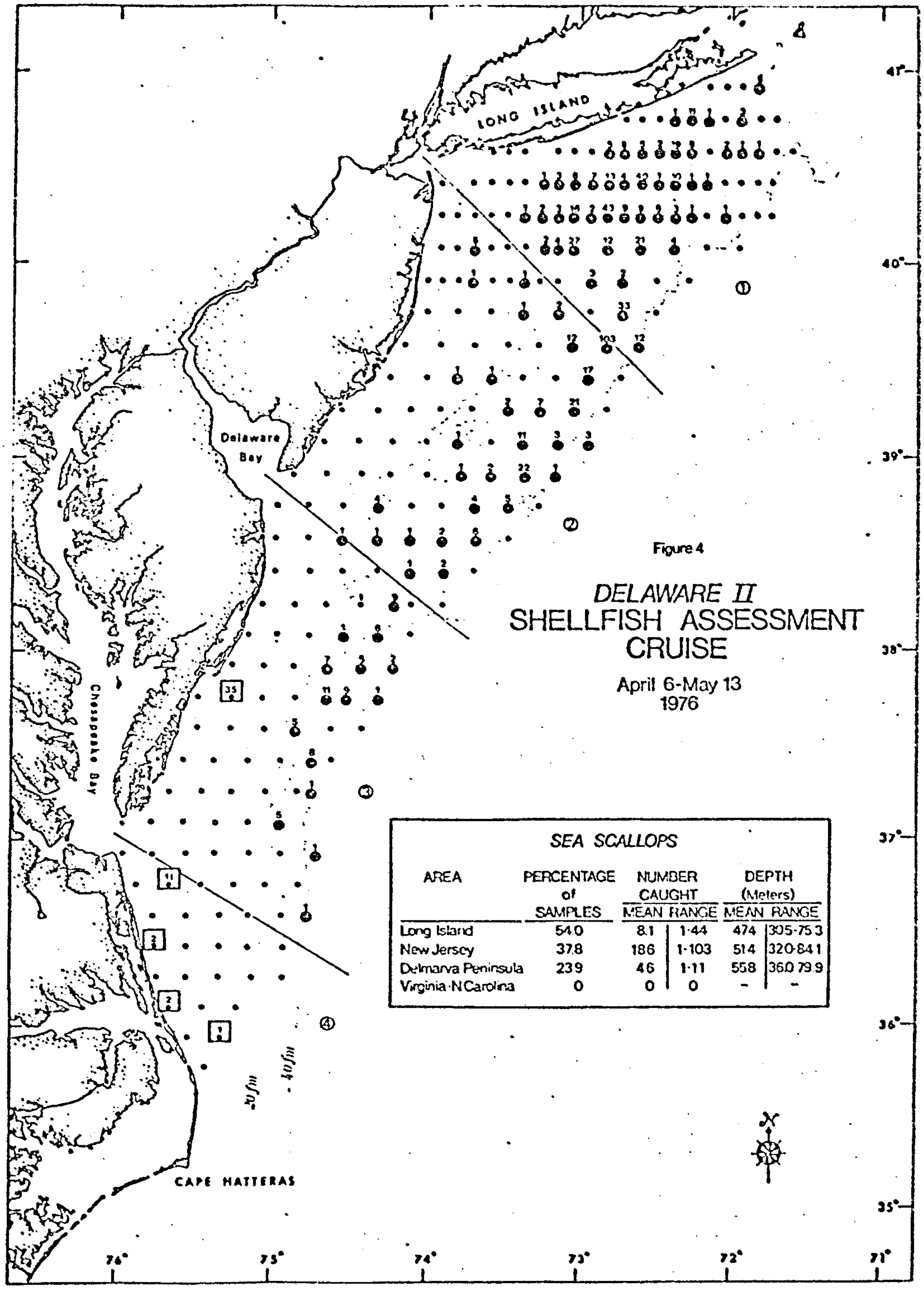


OCEAN QUAHOGS

AREA	PERCENTAGE of SAMPLES WITH OCEAN QUAHOGS by DEPTH (Meters) <184	184-366	367-549	550-732	>732	NUMBER of SAMPLES
Long Island	1 5	197	515	258	1.5	66
New Jersey	0	327	327	265	81	49
Delmarva Peninsula	0	43	435	261	261	23
Virginia-N Carolina	0	0	1000	0	0	1

AREA	PERCENTAGE of SAMPLES WITH OCEAN QUAHOGS by BUSHELS 1.0 Bu. or More	<1.0 to >1/4 Bu	1/4 Bu. or Less	None	NUMBER of SAMPLES
Long Island	356	253	149	242	87
New Jersey	98	146	354	402	82
Delmarva Peninsula	1 5	134	194	656	67
Virginia-N Carolina	0	0	43	957	23
SYMBOLS	■	▲	⊙	•	

Fig. 4. Distribution and abundance of sea scallops in the Middle Atlantic Bight.



SEA SCALLOPS

AREA	PERCENTAGE of SAMPLES	NUMBER CAUGHT		DEPTH (Meters)	
		MEAN	RANGE	MEAN	RANGE
Long Island	54.0	8.1	1-44	47.4	30.5-75.3
New Jersey	37.8	18.6	1-103	51.4	32.0-84.1
Delmarva Peninsula	23.9	4.6	1-11	55.8	36.0-79.9
Virginia-N Carolina	0	0	0	-	-

Fig. 5. Landings of recreational and commercial species in the Middle Atlantic Bight in 1970 (from NMFS, 1973).

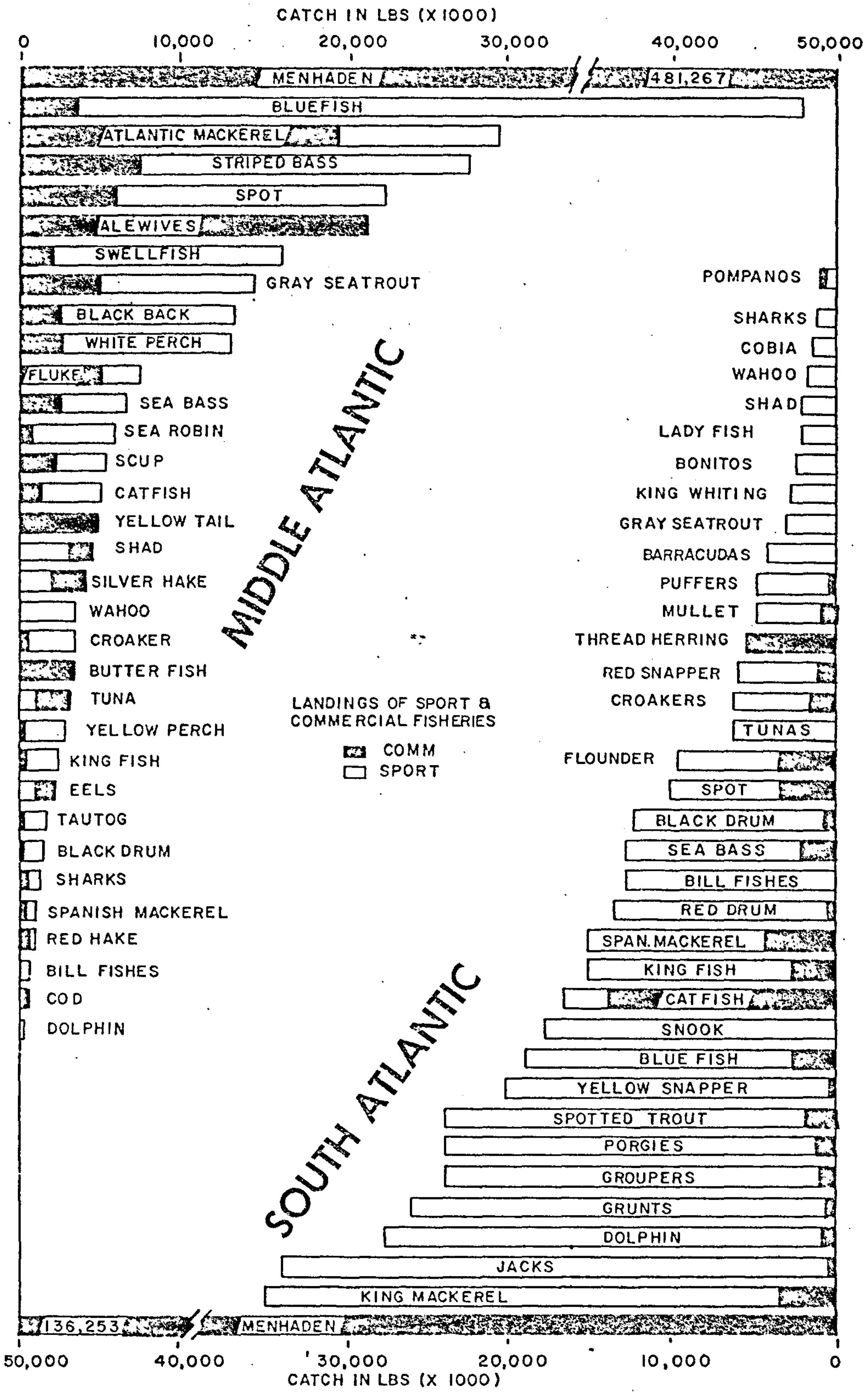


Fig. 6. Shelf area in the Middle Atlantic Bight where mortalities of surf clams occurred in 1976. (data from Ropes and Chang, 1977).

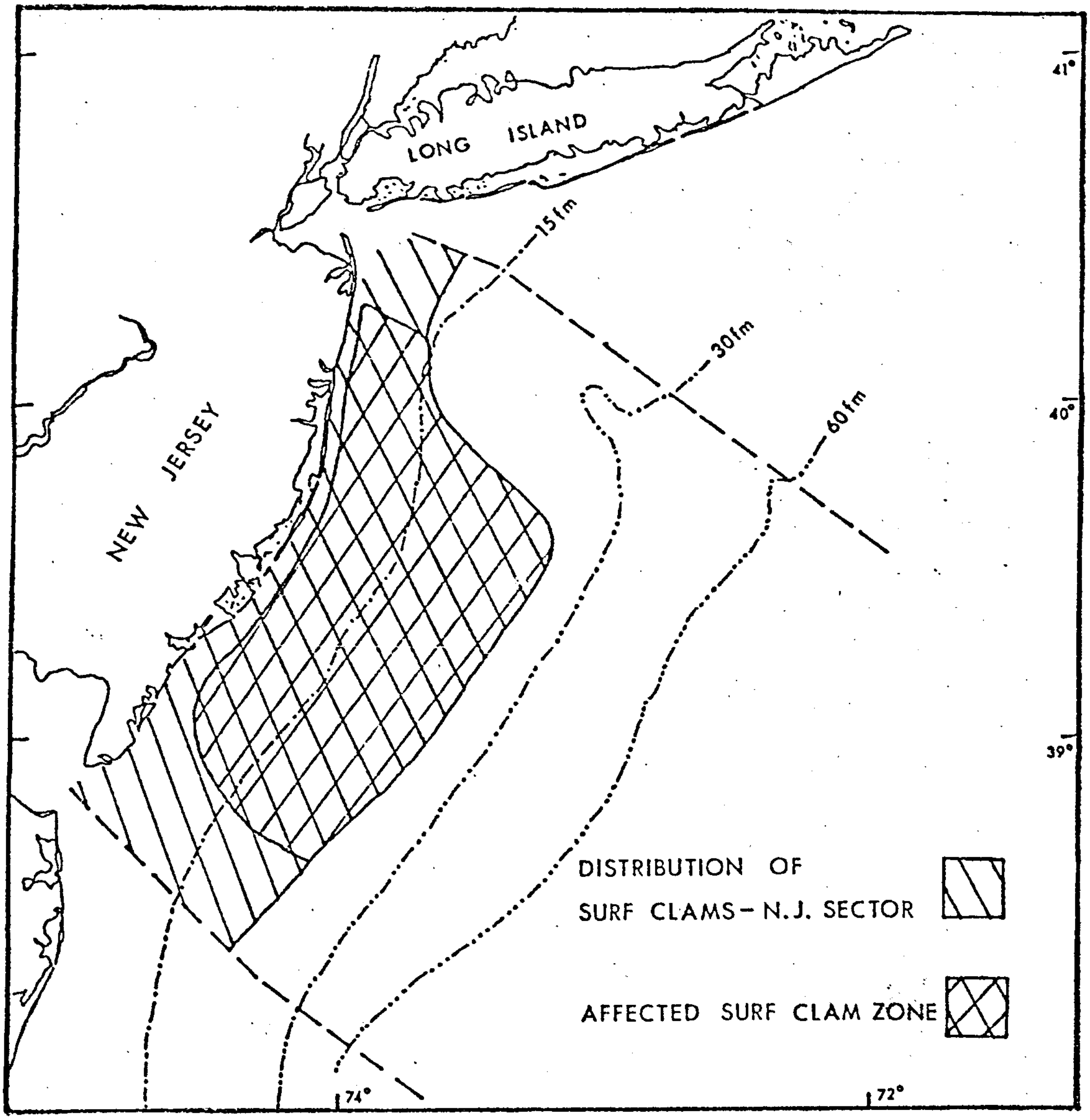


Fig. 7. Shelf area in the Middle Atlantic Bight where mortalities of ocean quahogs occurred in 1976. (data from Ropes and Chang, 1977).

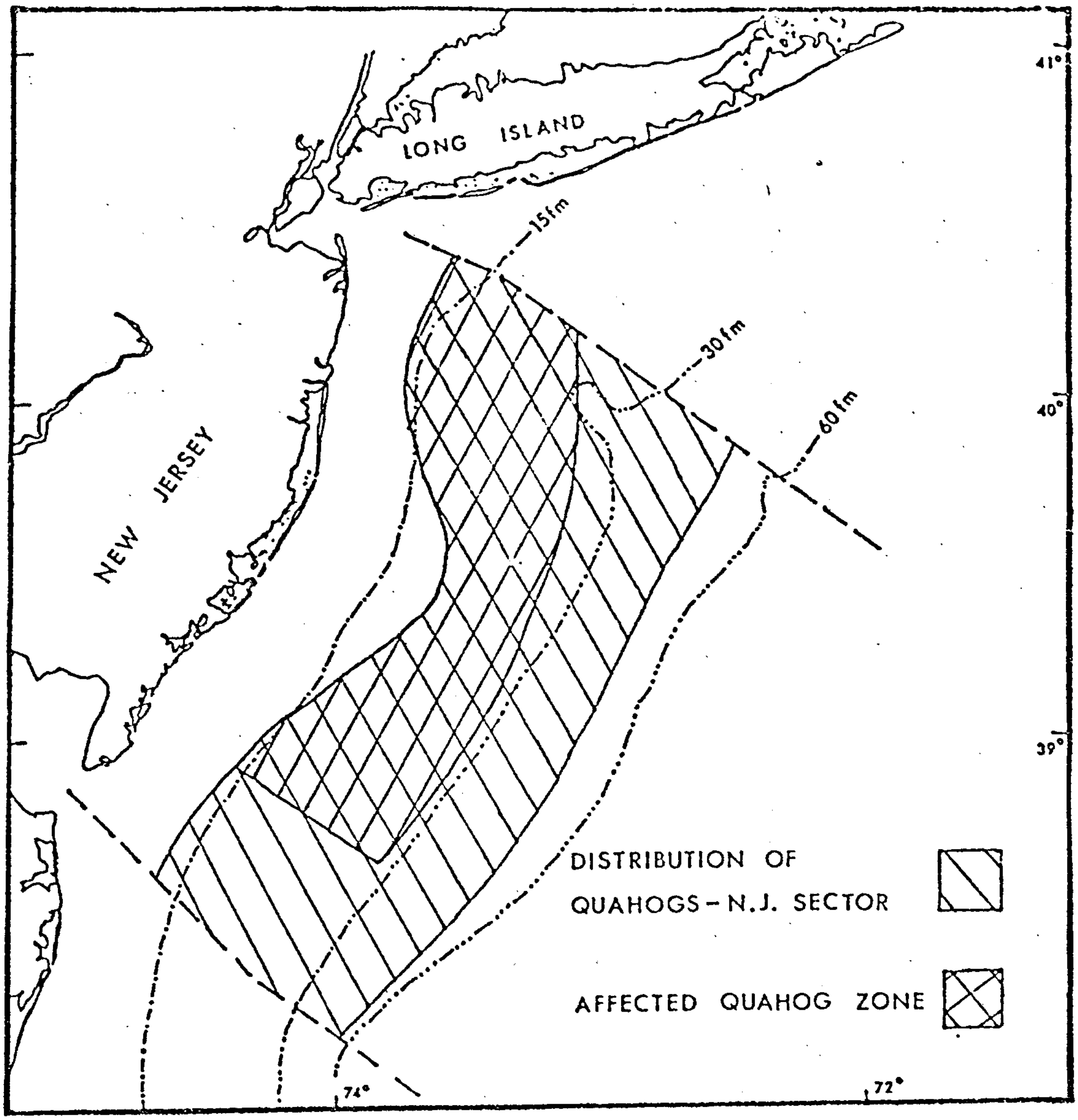


Fig. 8. Shelf area in the Middle Atlantic Bight where mortalities of sea scallops occurred in 1976. (from MacKenzie, 1977).

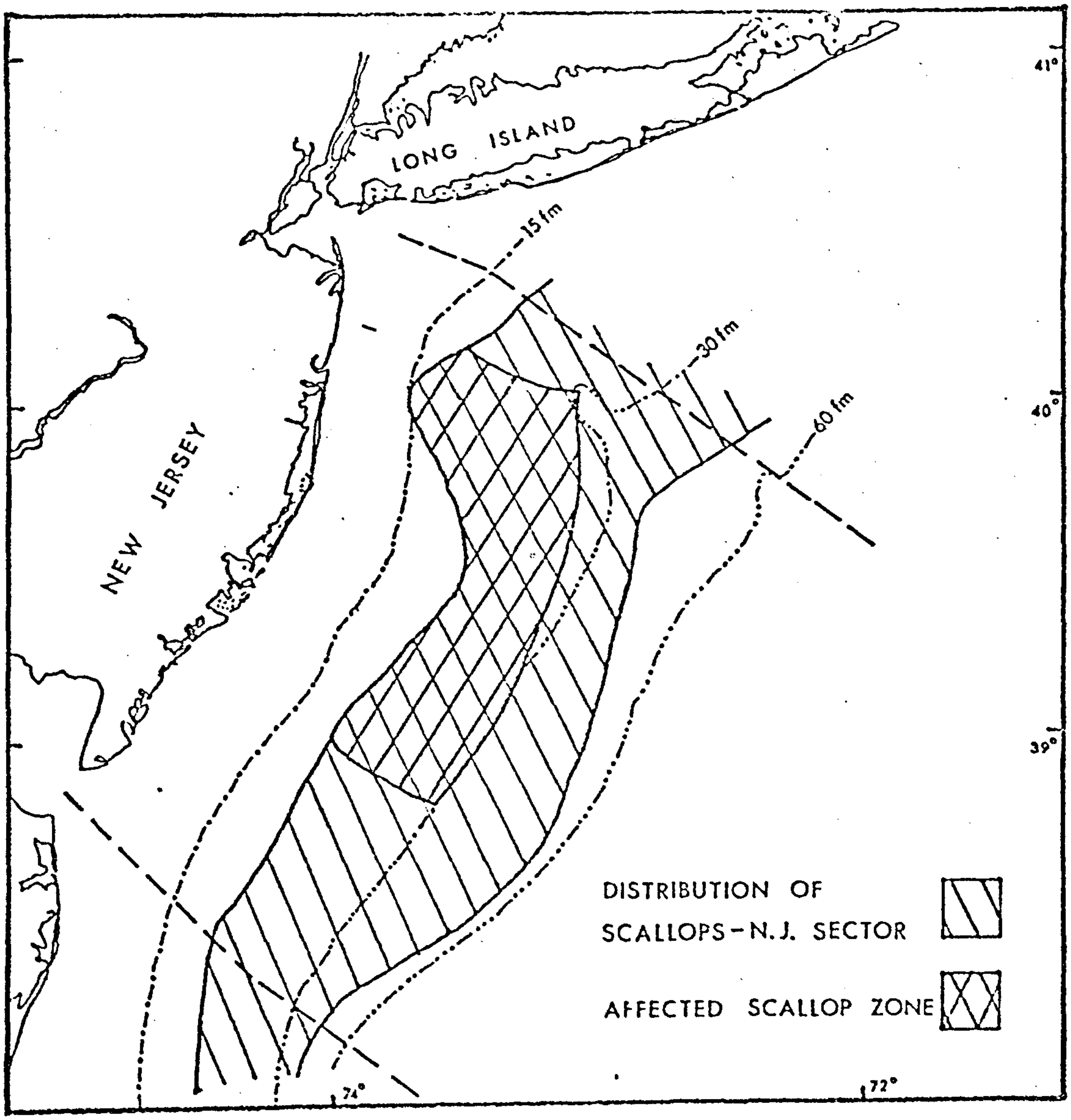
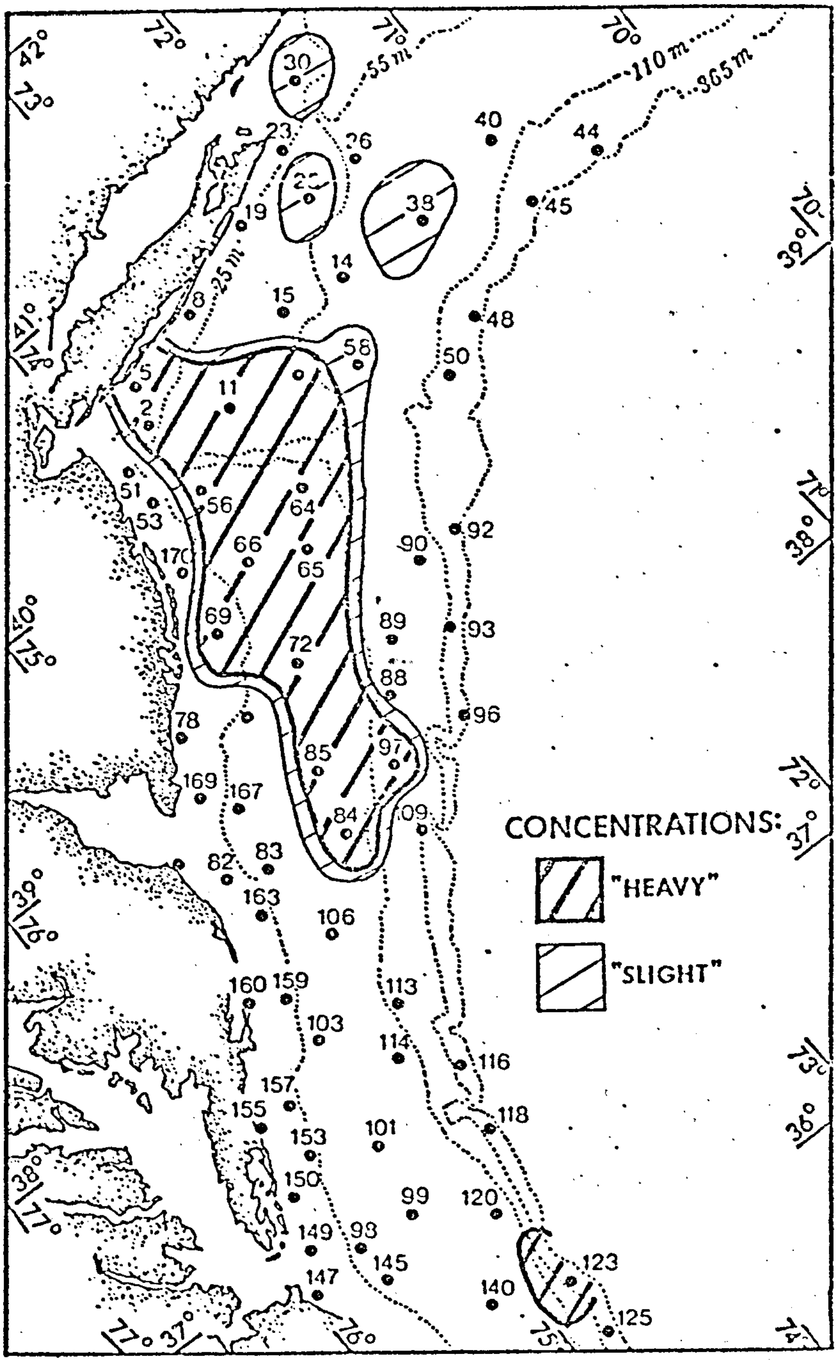


Fig. 9. Distribution and abundance of Ceratium tripos in the Middle Atlantic Bight, March, 1976. (data from NMFS Ichthyoplankton Survey).



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