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# Review of Oxygen Depletion and Associated Mass Mortalities of Shellfish in the Middle Atlantic Bight in 1976

FRANK W. STEIMLE and CARL J. SINDERMANN

*ABSTRACT–In summer and autumn of 1976, mass mortalities of shellfish occurred in a 165-km long corridor of severe oxygen depletion paralleling the New Jersey coast from 5 to 85 km from shore. Mortalities of surf clams,* Spisula solidissima, *the most severely affected species, were estimated in excess of 140,000 t. Alteration of normal migration patterns of lobsters and several species of finfish was also noted. A series of anomalous meteorological and hydrological events (particularly early warming of surface waters resulting in early thermocline development, and a massive shelf-wide phytoplankton bloom) superimposed on an already stressed coastal area, was considered to be responsible. The occurrence is particularly significant because 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.*

## INTRODUCTION

Mass mortalities in the sea are relatively common events and always attract the interest of the scientific community as well as the public. This interest may be based on a concern for the loss of a fishery resource, or the nuisance or health problems created by the decaying animals. Very often it is difficult to identify the cause of mass mortalities because most investigations begin after the fact, so the conditions which lead to the mortalities may have been altered or dissipated by the time studies begin. The majority of mass mortalities are very localized, often confined to a particular bay or estuary, but a few can be widespread, sometimes affecting hundreds of square kilometers of ocean.

The recognized causes of the mass mortalities have been physical (vulcanism, rapid or extreme temperature changes, storms, seaquakes, and strandings), chemical (extreme salinity or pH changes, oxygen depletion, toxic chemicals, and hydrogen sulfide formation), biological (disease and toxic or massive algal blooms), or combinations of the above. Many mass mortalities have been reported in the scientific literature since the 19th century and fossil evidence of mass mortalities exists. Brongersma-Sanders (1957) has compiled the most comprehensive review to date; other reviews include those of Sinderman (1970, 1976).

An environmental event of heroic proportions, leading to mass mortalities of many marine species in a 12,000 km² area of the continental shelf off the Middle Atlantic coast of the United States occurred during July through October 1976. Investigators were able to detect conditions that were lethal to marine life; these conditions were extreme oxygen depletion and hydrogen sulfide formation in bottom waters. First reports of this developing environmental problem reached the scientific community during the weekend of 4 July. Sport divers, lobstermen, and trawler fishermen had observed and reported dead and dying marine organisms, both fish and invertebrates, on fishing reefs and wrecks, and on fishing grounds, off the north-central New Jersey coast, south of New York City. Within a few weeks the mortalities were reported in areas extending southward some 85 km and well out on the continental shelf.

A series of survey cruises was initiated by the National Marine Fisheries Service's Northeast Fisheries Center, Sandy Hook, N.J., to examine the extent of the problem, to assess the damage, and investigate possible causes. Oxygen deficient bottom water, sometimes with zero dissolved oxygen levels, was found for a north-south distance of 165 km in a zone or corridor from 5 to 85 km off the New Jersey coast.

In the central part of this zone, oxygen values were zero, and hydrogen sulfide was detected 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, molluscan shellfish, and other benthic invertebrates 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 percent of the surf clam population off the New Jersey coast, representing some 143,000 t of meats, had been destroyed by October, with significant but lesser mortalities of ocean quahogs and sea scallops. Lobster catches were reduced by 30 percent during the period. The New Jersey coast was declared a resource disaster area in November by the

*Frank W. Steimle and Carl J. Sindermann are with the Sandy Hook Laboratory, Northeast Fisheries Center, National Marine Fisheries Service, NOAA, Highlands, NJ 07732.*

Federal government because of this event.

The problem was complicated by the public's premature conclusion that ocean disposal of pollutants, particularly sewage sludge dumping (over 5 million tons were dumped in 1976), 20 km from the coast, was responsible for this oxygen depletion situation and associated mortalities. Concern was also expressed that this catastrophic event might be repeated, possibly even annually.

The extent and duration of the problem and tremendous impacts on the fisheries and businesses in the area stimulated a massive investigation effort by State, Federal, and private groups or agencies. An interagency group was created to coordinate research efforts and finally to draw all available data together by holding a series of workshops, during November 1976. The results of these workshops, which are for the most part preliminary analyses of available data were published as an interim report (National Marine Fisheries Service, 1977).

From these workshops a large amount of data has been assembled and a causal 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 disturbances 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.

This paper is a review of the situation based partially on the workshop reports and includes subsequent data and assessments.

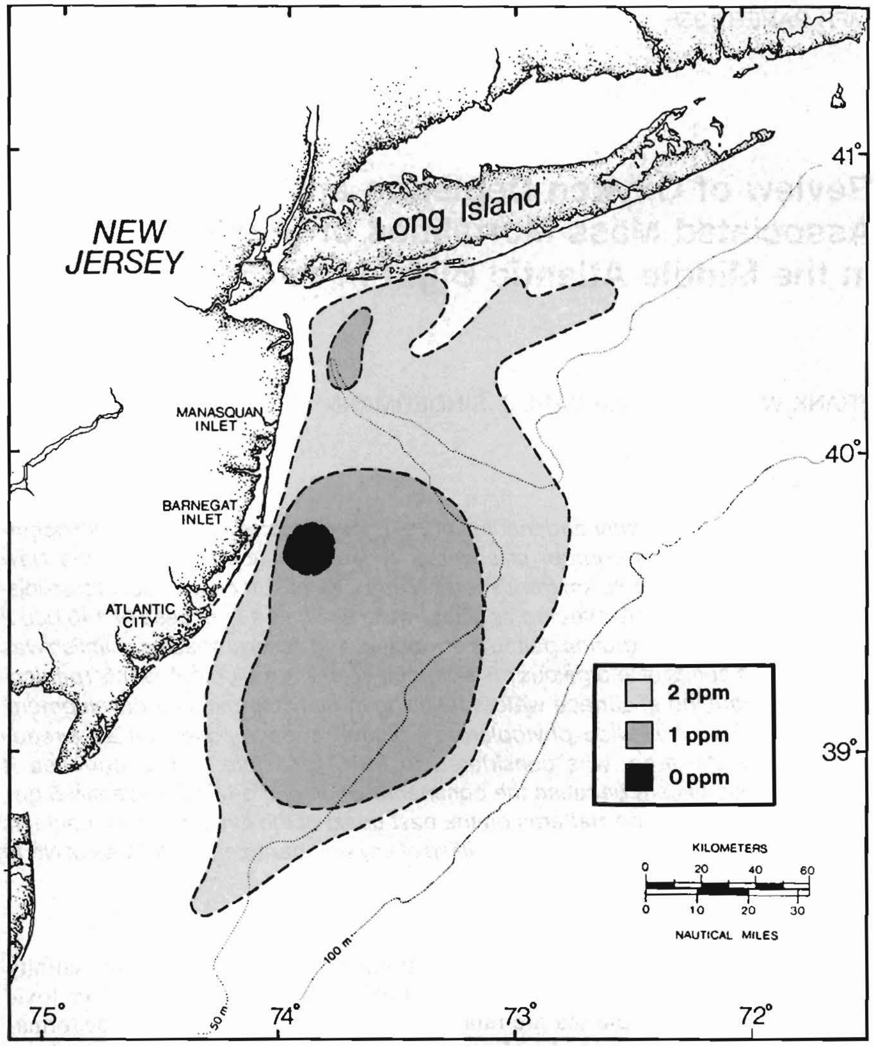

Figure 1.—The bottom oxygen levels in New York Bight at period of greatest distribution, late September 1976.

## EXTENT OF OXYGEN DEPLETION

One major aspect of the 1976 investigation was the monitoring of the levels and distribution of dissolved oxygen in the sub-thermocline bottom waters. Sampling in mid-July found depressed dissolved oxygen (D.O.) values, some below the level of detection by standard Winkler procedure, in an area 3-35 km off Barnegat Inlet, 115 km south of New York City (Fig. 1). Values of less than 2 ppm were found between Long Branch to north of Atlantic City, a coastal distance of 105 km. Trawl surveys collected dead epibenthic invertebrates and stressed surf clams in this zone and noted an absence of the normal finfish population known to inhabit the area in the summer.

By early August, prior to Hurricane Belle, which passed the New Jersey coast on 10 August, 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 km on the central New Jersey coast. Extremely high levels of hydrogen sulfide (to 1.76 mg/l) were also detected near the center of the depleted area. The hydrogen sulfide was present up to 15 m from the bottom (35 m deep), 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, pushing the inshore surface waters offshore, 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 km off the coast to 25 km offshore as the only apparent effect. This was only temporary, because a second resurvey, 5 days later, indicated the anoxic water mass had resumed most of its prehurricane 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. values 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 (Fig. 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 km, were increasing to nonhazardous 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 in the interagency workshops. It was the general conclusion of the workshops (National Marine Fisheries Service, 1977) 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: 1) High February-March temperatures with peak river runoff in February instead of April; 2) reduction of cyclonic storm activity during the summer to less than half the 25-year average; and 3) a period of 4-6 weeks in June-July with persistent south or southwest winds (Diaz, 1976).

Physical oceanographic events included: 1) Early (February-March) warming of surface waters and development of the thermocline (thermal stratification usually begins in April and reaches a maximum in August); and 2) 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 oceanographic events included: 1) A massive bloom of the 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 (Malone, 1977).

Since the Middle Atlantic Bight has been the focus of intensive research by elements of the National Oceanic and Atmospheric Administration for several years, a number of earlier investigations had been conducted. This 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 Jersey coast) 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, particularly surf clams, ocean quahogs, (*Arctica islandica*), and scallops (*Placopecten magellanicus*) 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 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 surveys for surf clams, ocean quahogs, and sea scallops were in April 1976. 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. 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 (Ropes and Chang, 1977). 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 (MacKenzie, 1977).

Finfish species presently of significance in the Middle Atlantic Bight include scup (*Stenotomus chrysops*), summer flounder (*Paralichthys dentatus*), bluefish (*Pomatomus saltatrix*), striped bass (*Morone saxatilis*), mackerel (*Scomber scombrus*), black sea bass (*Centropristis striata*), and weakfish (*Cynoscion regalis*). A number of these species are taken by recreational as well as commercial fishermen, often with the recreational catch predominating. Some of the species exist as year-round local populations, 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 and silver hake, *Merluccius bilinearis*) 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 (McHugh, 1977).

The National Marine Fisheries Service (and its 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 assessment. Additionally, recreational fish surveys have been carried out during the past 3 years. Landing figures for important recreational and commercial species are summarized in Figure 2.

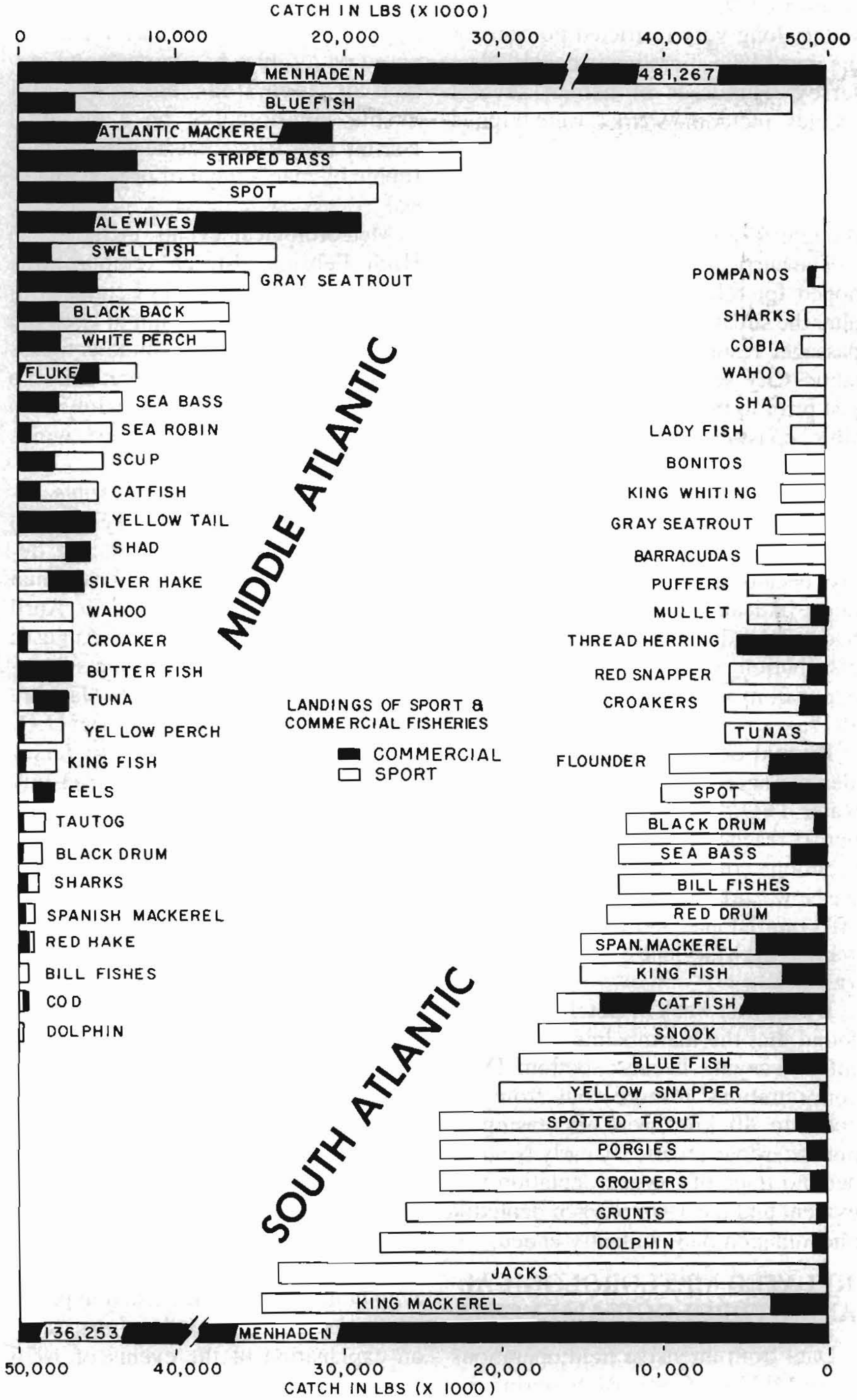

Figure 2.—Landings of recreational and commercial species in the Middle Atlantic Bight in 1970 (National Marine Fisheries Service, 1973).

## EFFECTS ON SHELLFISH AND OTHER BENTHIC POPULATIONS

Begining in late July 1976, assessment of the impact of the anoxic event on the surf clam stocks began. Signs of stressed surf clams were noted by divers as early as the weekend of 4 July. These were clams that were not embedded in the sediment but were lying free on the surface. Several later trawl surveys also found live, but gaping clams. The first specific surf clam dredging survey was completed by the end of July. Mortalities ranging between 0 and 56 percent were found in a restricted area off Barnegat Inlet. A second survey, in early August, found an average mortality of 10 percent in clam stocks in the impacted area. The normal mortality is 2 percent (Ropes and Chang, 1977).

Subsequent expanded resurveys in September and October found that the average mortality had risen to 100 percent at some stations in a 12,000 km$^2$ sector off New Jersey. It was estimated that this represented, by October 1976, a loss of 143,000 t of surf clam meats, or about 69 percent of the offshore surf clam stocks of New Jersey, and 16 percent of the estimated total Middle Atlantic Bight population of the species (Fig. 3). Of the coastal surf clam stocks (those within 5 km of shore) an estimated 1,700 t were killed in an area south of Beach Haven—representing about 5 percent of the total inshore coastal population (Ropes and Chang, 1977). 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, an increasingly 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 percent. Mortalities increased in September to almost 8 percent, with a high of 40 percent at some individual stations. The loss to New Jersey stocks of ocean quahogs was about 6,600 t, or less than 1 percent of the stocks in that sector of the coast (Fig. 4) (Ropes and Chang, 1977).

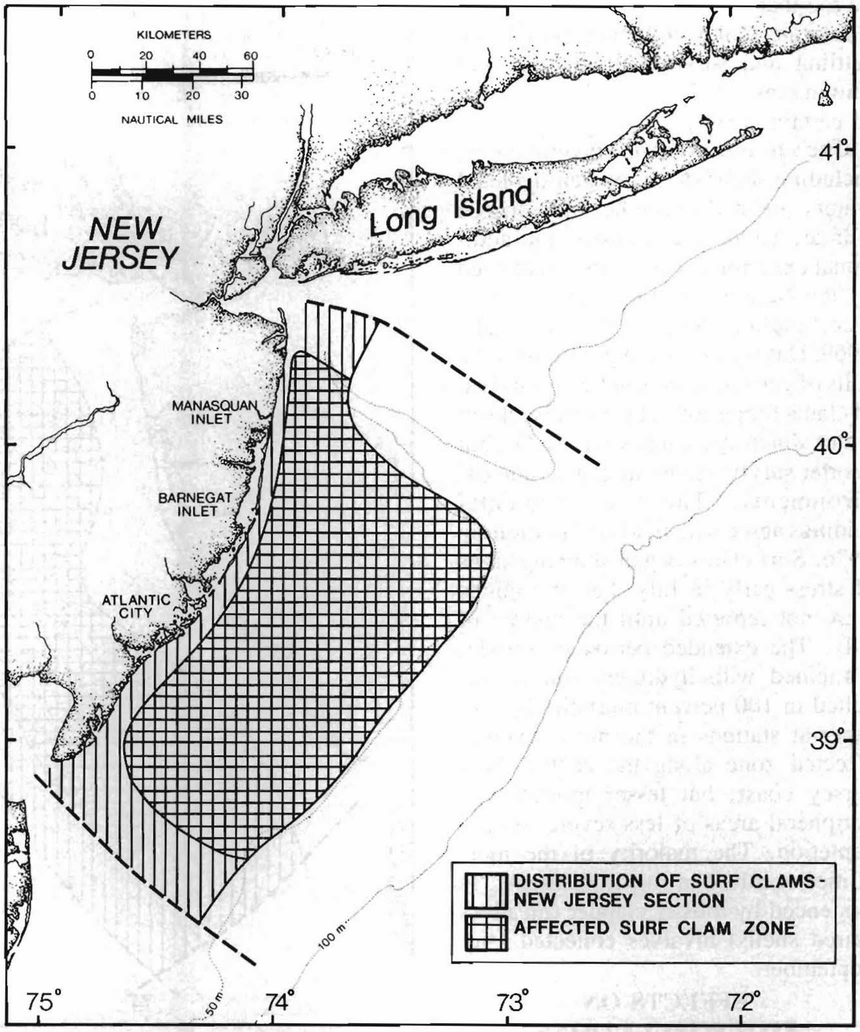

Figure 3.—Distribution of surf clam mortalities in New York Bight.

Sea scallops, which also occur in deeper water than surf clams, were affected by the anoxic event. Scallops occupy an area of 11,500 km$^2$ off the New Jersey coast; of this, 4,300 km$^2$ were within the anoxic zone, and an estimated 10 percent of the population was killed in a zone 35-55 m deep (Fig. 5) (MacKenzie, 1977).

The lobster, *Homarus americanus*, industry off New Jersey suffered. Some of the inshore stocks were killed, and the annual shoreward migration of offshore stocks was interrupted. During the months of June through September, normally the most productive months of the year, landings declined an average 30 percent compared with the same period in 1975. The inshore pot fishery, which operates within 20 km of shore, was most severely affected. Lobstermen stated that few offshore migrants entered the fishery in 1976 (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 reduction 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 (*Platysquilla enodus*), 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 has 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 survival of marine invertebrates, including 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; Davis, 1975) 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 middle of July. The extended period of anoxia, combined with hydrogen sulfide, resulted in 100 percent 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. The majority of the mortalities occurred in July and August, as evidenced by mostly clapper (meatless paired shells) bivalves collected after September.

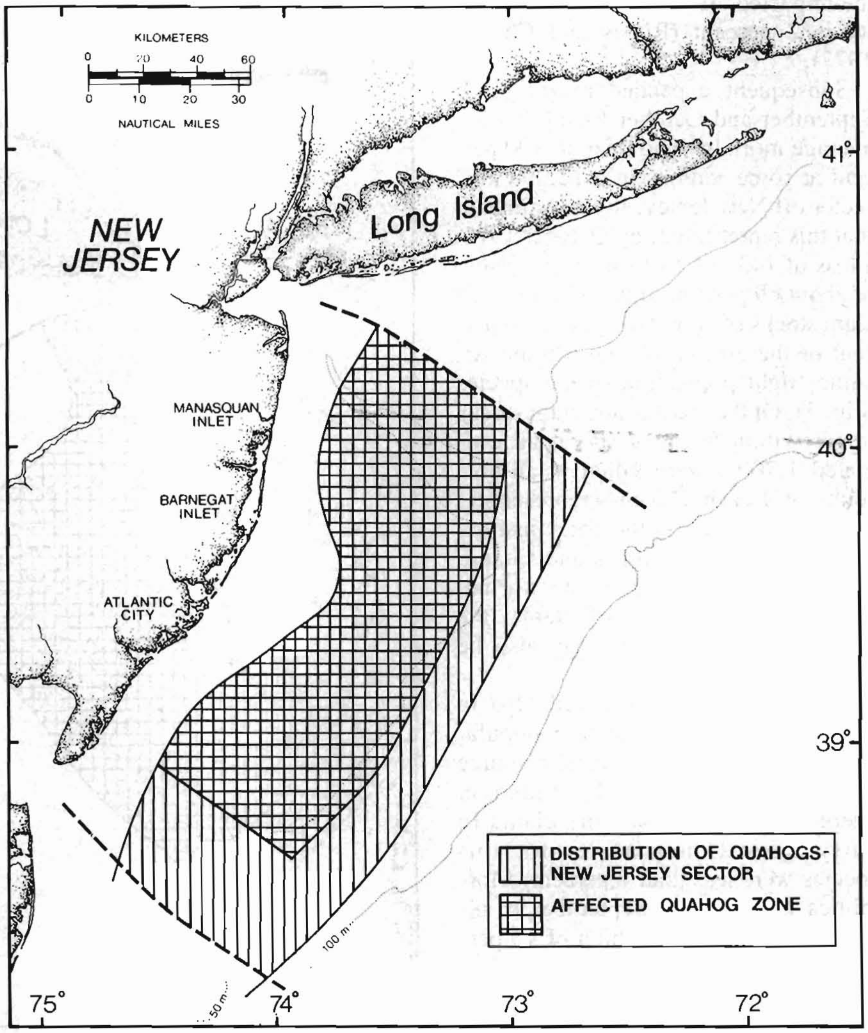

Figure 4.—Distribution of ocean quahog mortalities in New York Bight.

## 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 were crowded within a narrow coastal zone or in estuaries, where they were readily available in large numbers to fishermen. Bluefish, 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 (Smith, pers. commun.[1]).

## DISCUSSION

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 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, 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

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[1] Smith, W. National Marine Fisheries Service, NOAA, Highlands, N.J. Pers. commun.

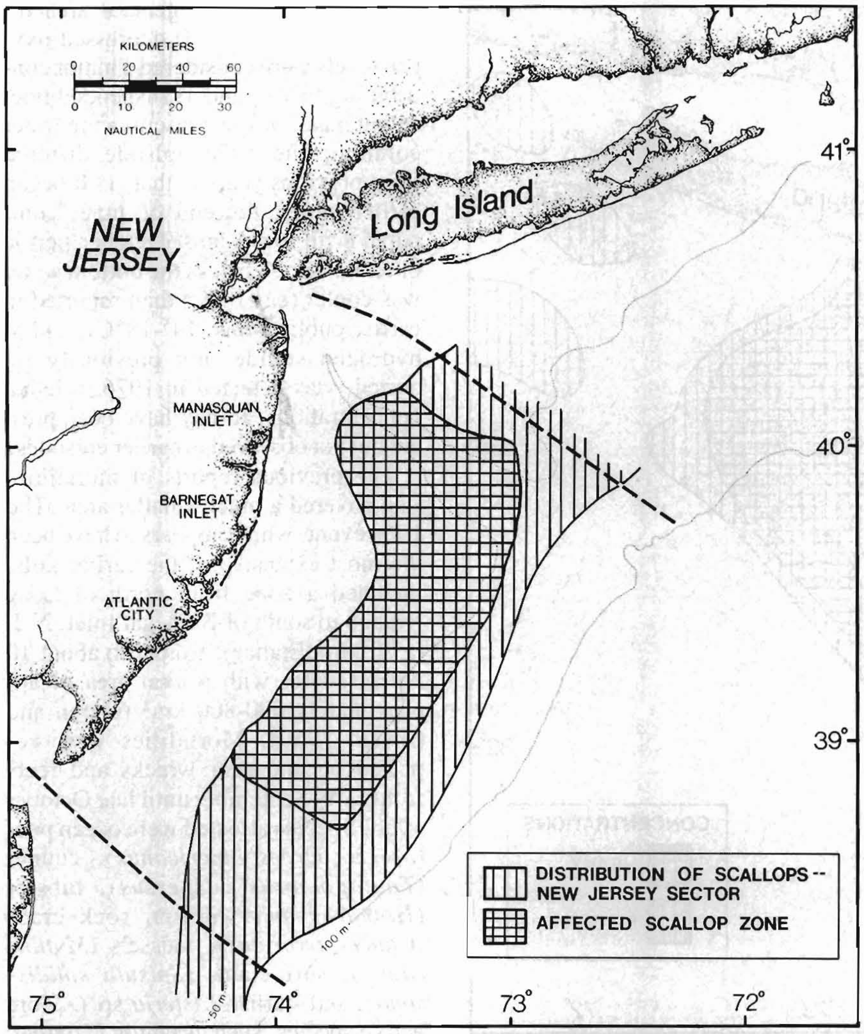

Figure 5.—Distribution of scallop mortalities in New York Bight.

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 lat. 21°S and 25°S. 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 km$^2$, but, interestingly, there is a narrow coastal strip about 5 km wide, extending to a depth of 40 m, where sea life is normal and hydrogen sulfide does not occur (Copenhagen, 1953). 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 4 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 33,000 km$^2$. 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.

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, Ala., 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

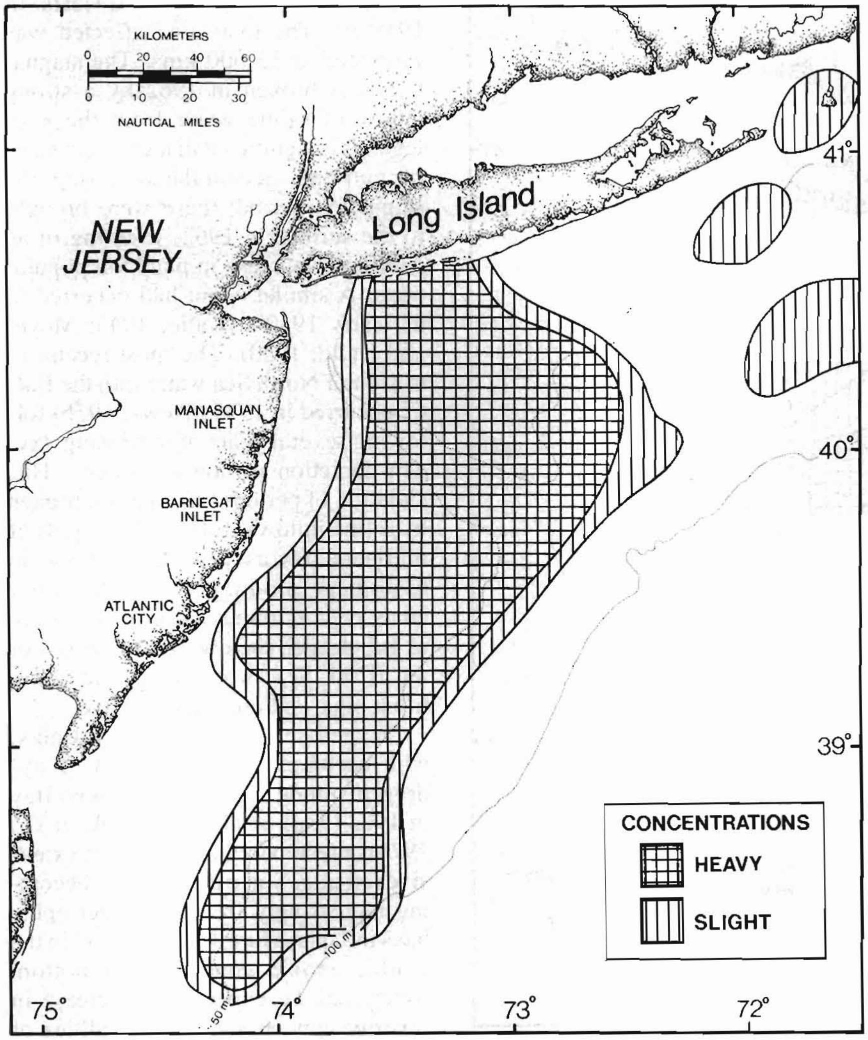

Figure 6.—Distribution and relative abundance of *Ceratium tripos* bloom during early spring 1976.

called a "jubilee." Thirty-five such occurrences were reported by Loesch (1960) between 1946 and 1956, but newspaper accounts go back to the 19th 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.

There have been previous reports of fish kills off New Jersey in 1968, 1971, and 1974 (Ogren, 1969; Ogren and Chess, 1969; Young, 1973, 1974[2]), and there may have been earlier problems that were not observed or reported. 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 off central New Jersey; 3) depressed oxygen levels were considered a major 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 earlier before the end of June, compared with the August-October period of earlier problems; 2) the bottom water was cooler (ca. 10°C) than reported in earlier publications (14°-18°C), 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 north of Long Branch to south of Barnegat Inlet, N.J. (a 70-km distance), from 1 to about 10 km offshore, with a total area of approximately 600-800 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 (*Macrozoarces americanus*), cunner (*Tautogolabrus adspersus*), lobster (*Homarus americanus*), rock crabs (*Cancer irroratus*), mussels (*Mytilus edulis*), surf clams (*Spisula solidissima*), and starfish (*Asteria* sp.). More active species, such as tautog (*Tautoga onitis*), black seabass (*Centropristis striata*), squirrel hake (*Urophycis chuss*), conger eels (*Conger oceanicus*), and round scad (*Decapterus punctatus*), apparently were able to escape and were rarely reported among the mortalities. Fauna on wrecks off Barnegat and Atlantic City, N.J., was normal.

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 km east of Manasquan Inlet in depths of about 30 m, and also at Shark River Inlet, north

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[2] Young, J. S. 1974. Unpublished data. Middle Atlantic Coastal Fisheries Center, National Marine Fisheries Service, NOAA, Highlands, N.J. Pers. commun. to J. B. Pearce.

of Manasquan 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 Manasquan Inlet (Young, footnote 2). 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 south of Manasquan Inlet.

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, 10 km north of Manasquan Inlet, occurred during the summer of 1974. Low D.O. values have been reported previously in the New York Bight dump-site areas (Pearce, Segar and Berberian, 1976). D.O. values in dump-site areas in summer of 1975 were higher than 1974, and above the level considered harmful to most marine life.

## CONCLUSION

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 10 years previous experience of the ichthyoplankton group sampling in this area (Smith, footnote 1) (Fig. 6).

With onset of stratification, the bloom became concentrated in a band at or below the thermocline, within 100 km 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 1 cm 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 100-250 days, and estimated daily chemical inputs from the Hudson River estuary complex alone are 520 t of nitrogen and 138 t of phosphate. Sewage sludge dumping and other human sources of nutrients have been estimated to augment these figures by only minor amounts (<10 percent).

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.

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