Not to be Cited Without Prior Reference to the Authors

International Council for the
Exploration of the Sea
77th Statutory Meeting
The Hague, Netherlands

Marine Environmental
Quality Cttee.
C.M. 1989/E:11
Ref. K, Sess. R

LONG-TERM BIOLOGICAL EFFECTS OF HYPOXIC WATER CONDITIONS OFF NEW JERSEY, USA -- 1976-1989

by

S.A. Murawski, T.R. Azarovitz and D.J. Radosh

National Marine Fisheries Service
Northeast Fisheries Center
Woods Hole, Massachusetts 02543 USA

ABSTRACT

During summer 1976 hypoxic and anoxic water conditions developed in an approximately 8,600 km^2 area off the New Jersey (USA) continental shelf. Local impacts on exploited invertebrate and vertebrate species and supporting animal communities were extensive. Mass mortalities of invertebrates, particularly surf clams, **Spisula solidissima**, and including ocean quahog, **Arctica islandica**, and sea scallop, **Placopecten magellanicus**, caused severe to moderate disruptions in commercial fisheries. Finfish and crustacean resources were influenced primarily through displacement of individuals from the affected area. Benthic infaunal communities were heavily disrupted in areas of maximum hypoxia, with lesser effects at the periphery. This paper examines the status of invertebrate infauna, epifaunal resources, and finfish in this region during 1976-1989. The areal distribution and abundance of these resources before, during and subsequent to the event have been monitored with a variety of sampling programs, including bottom trawl surveys in spring and autumn aimed at finfish and large crustaceans, hydraulic clam dredge surveys for surf clams and ocean quahogs, epibenthic dredge for sea scallop and grab sampling for benthic macrofauna. In addition, commercial landings sampling of fisheries in the area document short- and long-term patterns in the areal extent and productivity of affected fisheries.

The significance of short-term hypoxia/anoxia events on these resources is examined with respect to abundance, life history characteristics, changes in benthic community structure, areal distribution of fishery catches, and the potential fishery management-related aspects associated with the re-occurrence of such an event

INTRODUCTION

During the spring, summer and early autumn of 1976 an hypoxic, and in some areas anoxic, water event occurred on the New Jersey (USA) continental shelf. Although such events had occurred in the affected areas prior to 1976 (Swanson and Sindermann 1979; Sindermann and Swanson 1979), the 1976 event was, as far as can be documented, unique in its duration, geographic extent and severity. Proximal causes of the conditions in 1976 remain some what conjectural. It is likely that the primary causes were natural climatic events that resulted in early and strong density stratification (Falkowski et al. 1980; Swanson and Parker 1988). This, combined with the decay of a massive bloom of the dinoflagellate **Ceratium tripos**, created a large biological oxygen demand below the pycnocline, resulting in anoxic and hypoxic (<2 ml/l) water conditions and the formation of hydrogen sulfide (H_2S). Direct effects on the biota were profound. Commercial and non-commercial species were either killed outright or displaced to other areas with non-lethal water conditions, if the forms were sufficiently mobile (Ropes et al. 1979; Azarovitz et al. 1979; Steimle and Radosh 1979).

A large, directed research effort provided extensive documentation of the short-term effects of the hypoxia on biological resources, and provided integrated analyses of physical, chemical and climatic conditions as explanatory mechanisms (Swanson and Sindermann 1979). Resultingly, the 1976 event off New Jersey is probably the single most extensively documented discrete hypoxic water event yet studied. Investigations of persistent hypoxia conditions have been conducted in other coastal areas of the USA, including Mobile Bay (May 1973), the northern Gulf of Mexico (Boesch 1983), and Chesapeake Bay (Officer et al. 1984). However, results from these semi-persistent hypoxia regions do not necessarily allow for extrapolation of the time sequence of impact and recovery from a discrete hypoxia episode.

In this study we review the status of various invertebrate and finfish resources prior to, during, and subsequent to the 1976 hypoxia. We use the results of directed field sampling programs conducted during and after the hypoxia. Perhaps more importantly, data collected from long-term monitoring studies, primarily for fishery management purposes, are used to present a perspective on the significance of the initial impacts and subsequent recovery of affected resources. Finally, we consider the probability of a recurrence of an event on the scale of that in 1976, in the context of risk-averse fishery management strategies for important commercial resources.

REVIEW OF HYPOXIA EVENT

During early July, 1976, numerous observations of dead and dying finfish, mollusks and crustaceans were reported by commercial and recreational fishermen and sport divers. These reports were centered off the northern New Jersey (USA) coast (Figure 1), but soon spread to cover an extensive offshore area of approximately 150 km along the New Jersey coastline. Some 8,600 km^2 of continental shelf waters were ultimately affected during the 1976 event (Sindermann and Swanson 1979).

Sampling programs conducted aboard commercial fishing and research vessels were either initiated or re-directed to examine the biota and measure ambient environmental conditions to document the geographic extent and severity, and to assess potential causes of these mortalities. Historical records were evaluated to ascertain the degree to which similar events had occurred in the past (Figure 1). The following scenario has emerged from the short-term studies conducted during and just subsequent to the event (Swanson and Sindermann 1979) and from longer-term research spawned as its result.

Several authors conclude that a combination of natural environmental conditions conspired to reduce dissolved oxygen (DO) and build-up H_2S levels in bottom waters (Swanson and Sindermann 1979; Falkowski et al. 1980; Swanson and Parker 1988). However, the area affected is considered significantly degraded by anthropogenic effects including point and non-point source discharges, and direct ocean dumping of materials including sewage sludge (O'Connor 1979). These anthropogenic inputs cannot be completely discounted as contributing factors.

A massive bloom of the dinoflagellate **Ceratium tripos** occurred in the New York Bight area, beginning in January 1976, and peaking in April-June. Because of the geographic extent of this bloom, it is unlikely that nutrient loading from disposal activities was the primary cause. Coincident with the bloom, spring air and surface water temperatures were warmer than average, there was higher river discharge than normal, and an earlier-than-expected shift to summer wind conditions occurred (Swanson et al. 1979; Swanson and Parker 1988). These and other physical factors apparently resulted in early and intense density stratification in shallow continental shelf waters. Development of the density stratification reduced vertical flux of DO from the sea surface. Unusual upwelling of bottom waters occurred along the New Jersey coast due to an early shift to prevailing southerly winds. The upwelling of bottom water apparently stopped or reversed the usual southerly flow of bottom waters on the New Jersey shelf. Respiration of living **Ceratium** decreased DO levels near the pycnocline. Decay of the declining bloom created an organic layer at the bottom, associated with the region of depressed DO.

Dissolved oxygen concentrations in New Jersey coastal waters usually peak in March at c.a. 6 ml/l, and decline to about 3 ml/l in August (Figure 1). During 1976, DO concentrations were lower than normal beginning in early April and were significantly depressed by June. These conditions persisted well into September until surface cooling resulted in the breakdown of thermal/density stratification.

Three other hypoxia episodes resulted in fish/invertebrate mortalities off New Jersey between 1968 and 1974 (Sindermann and Swanson 1979). The 1976 event differed from these earlier events in that the onset of mortalities was earlier (in June rather in August-October), and H_2S was reported during 1976, which was not reported in earlier episodes. The previous events also were confined to a smaller geographic area and mortalities were much less extensive than in 1976.

Extensive monitoring of the biological effects of the hypoxic and anoxic water conditions was undertaken with a variety of sampling schemes. The New Jersey coast supported lucrative commercial and important recreational fisheries for finfish, bivalves, and crustacea. Following is a review of the short-term impacts of the event on various taxa, and subsequent changes in populations and communities as determined from longer-term sampling programs:

LONG TERM EFFECTS -- MACROBENTHOS

The abundance (numbers), species composition, and distribution of benthic macrofauna (as contrasted with 'megafauna', e.g. crabs) was evaluated in a series of research vessel cruises employing 0.1 m^2 Smith-McIntyre grab sampling (Steimle and Radosh 1979; Radosh and Reid ms). These studies were intended to quantify the change in population status of non-commercial species, primarily infauna, and to document patterns of recovery in successive samplings for several years after the event (Figure 2).

Initial grab sampling was conducted between July and November 1976 (Figure 2). A total of 71 stations was sampled, with three replicate grabs at each station location (Radosh and Reid ms). The hypoxia conditions initially had variable effects on the species constituents of the macrobenthos (Steimle and Radosh 1979), probably due to differing exposure times, tolerances to the conditions, and spatial variability in the intensity of the hypoxia. Crustaceans and echinoderms exhibited stress and mortalities over wide geographic areas, while most polychaete species were relatively unaffected. In the region of anoxia (dashed areas in Figure 2) there was a virtual elimination of macrofauna. Most of the tolerant species included polychaetes, while amphipods appeared particularly sensitive to hypoxic conditions and the presence of H_2S.

Recolonization of the heavily impacted areas was detected as early as November 1976, when significantly increased densities of some taxa were observed at several stations within the area of maximal impact (Figure 2). High densities of macrofauna were primarily a result of irruptive populations of four polychaete species: the spionids **Spiophanes bombyx** and **Polydora socialis**, and the ampharetids **Asabellides oculatus** and **Ampharete arctica.** These four species are generally considered to be opportunistic of new habitats (e.g. early colonizers with rapid growth capacities), forming dense 'mats' of tubes across large areas. The elevated faunal densities in the heavily impacted area consisted mostly of these few species, which were persistent through July 1977.

The diversity of species in the zone of maximum impact increased at a much slower rate than did total abundance. Species diversity was relatively low in 1976, declined even more in 1977 with the strong numerical dominance of a few irruptive species, and increased steadily through 1978 as the number of species increased and abundance of individual species stabilized. By late 1978 the density and diversity of macrobenthos had returned to levels thought to reflect the pre-impact stage. Sampling in July 1878 (Figure 2) once again indicated the presence of amphipod species, thought to be sensitive to hypoxia and particularly slow to recover.

Several important conclusions regarding the response of the macrobenthic community to persistent and widespread hypoxia emerge from these long-term monitoring studies: (1) there is considerable variability in tolerance of species to low DO and the presence of H_2S, (2) differing reproductive modes greatly influence the competitive advantages of various taxa resulting in varying rates of recovery from acute hypoxia events, (3) reduced predation pressure by megabenthic crustaceans and fishes may have enhanced the recovery of various species including tube worms, echinoderms and bivalves, and (4) early colonizers may have a significant impact on the benthos, due to their ability to 'out-compete' for space and to inhibit larval settlement of other species. The development of tube worm 'mats' may have significantly inhibited recovery of many benthic forms because of their occupation of broad expanses of bottom habitat, and their potential ingestion of the pelagic larvae of a number of taxa.

Polychaetes **Tharyx spp.** and **Goniadella gracilis**, the tube-dwelling anthozoan **Ceriantheopsis americanus** and the bivalve **Astarte castanea** were among the most tolerant forms. Crustaceans, and in particular amphipods were in contrast very susceptible to the effects of low DO and the presence of H_2S. Benthic forms with planktonic larvae appeared to re-colonize much more quickly than those with limited larval dispersal. For example, the sand dollar **Echinarachinus parma** exhibited strong recruitment in late 1976, which was not apparently subjected to intense predation mortality. In contrast, the peracarid crustaceans exhibited very slow rates of recovery due to their limited larval dispersal.

LONG TERM EFFECTS -- EXPLOITED INVERTEBRATES

Bivalve and crustacean fisheries of the New Jersey continental shelf contribute significantly to regional and national production of various species including surf clam, **Spisula solidissima**, ocean quahog, **Arctica islandica**, sea scallop, **Placopecten magellanicus**, American lobster, **Homarus americanus**, and rock crab, **Cancer irroratus** (Ropes et al. 1979; Azarovitz et al. 1979; Anonymous 1988). Not surprisingly, these species were among the most intensively monitored during the 1976 hypoxia event. The fate of these species in New Jersey shelf waters has had important economic and ecological consequences. Long-term population monitoring programs for these species existed prior to the 1976 event, and have been continued since. Programs of research vessel surveys and commercial catch sampling were developed primarily as input for fishery management, and were supplemented with intensive investigations of a more limited spatial extent in 1976 (Ropes et al. 1979; Azarovitz et al. 1979). Following is a brief overview of the initial impacts and subsequent trends in populations of the five species listed above.

Surf Clam

Throughout the history of the surf clam fishery, the northern New Jersey area had accounted for a significant fraction of the total USA landings of the species prior to 1976 (Murawski and Serchuk 1989). Region-wide surveys of the surf clam resource were initiated in the early 1960s, due to the economic importance of this bivalve. These surveys employed hydraulic dredging equipment similar to that used in the fishery (Murawski and Serchuk 1989).

One such survey was completed in May 1976, serendipitously just prior to the reports of extensive surf clam mortalities off the central New Jersey coast (Figures 3 and 4). This survey in 1976 would provide the benchmark for evaluating the mortality rate of surf clams in the impact area. Several dredge surveys were conducted during the 1976 hypoxia event, aboard commercial dredging vessels (Ropes et al. 1979). Recent mortalities of bivalves could be quantified based on the proportion of articulated paired valves of dead clams ('clappers') taken in dredge samples. By early October 1976 mortality rates averaged >95% in shallow and mid-depth areas off the central New Jersey coast (Figure 3).

Based on re-assessment of the region-wide resource in early 1977, the loss of surf clam biomass in the impact area was estimated to be 85%, with 62% of the entire New Jersey resource killed (Ropes et al. 1979). This amounted to an estimated 147 thousand tons of surf clam meats. Landings of surf clams declined drastically off New Jersey during the event, and there was a significant movement of the surf clam dredging fleet to waters off Delaware, Maryland and Virginia (Murawski and Serchuk 1989). Surf clams were clearly the most severely impacted of the commercial species affected by the hypoxia event.

Resource surveys conducted subsequent to 1977 have documented the presence of a strong year class recruiting to the northern New Jersey region (Figure 4). This and subsequent year classes have rebuilt the standing stock to densities significantly higher than those observed in prior to the hypoxia event (Figure 4). Ageing studies of clams off New Jersey have indicated that the year classes recruiting to the northern New Jersey area are dominated by that spawned in 1976. Currently, the northern New Jersey region supports the bulk of USA surf clam landings; the population size is large and stable (Anonymous 1988).

The presence of a dominant 1976 year class in the area subject to the most intensive and persistent hypoxia presents a compelling case for predation-controlled recruitment in the species. Dominant year classes of surf clams are quite rare (Murawski and Serchuk 1989). Mackenzie et al. (1985) have shown that predation rates on juvenile surf clams are very high, reducing abundant sets rapidly (usually within a few months). This predation is primarily due to various species of crabs. The hypoxic water event during 1976 resulted in considerable mortality and/or displacement of most potential crab predator species (Steimle and Radosh 1979). Given the planktonic larval stage of surf clam, it is likely that larval repopulation of the impact area occurred in autumn 1976. The dominant 1976 year class could have developed in the absence of predators destroyed or displaced by the hypoxia.

Ocean quahog

Unlike surf clams, only a small proportion of the extant New Jersey ocean quahog resource was killed by the hypoxia event (Figure 3). The estimated biomass loss was 7% of that off the New Jersey coast (Ropes et al. 1979). The much less severe population impact on ocean quahog is due to the fact that only the inner margin of the population of the deeper-water dwelling ocean quahog stock was influenced by the hypoxic waters (Figure 3). Additionally, ocean quahogs appear more tolerant to hypoxic water conditions than surf clam (Ropes et al. 1979).

Landings of ocean quahog off New Jersey have increased considerably since 1976 (Anonymous 1976). This is due primarily to diversification of the surf clam fleet to exploit dense quahog populations available off New Jersey (Murawski and Serchuk 1989). Due to the very low recruitment and growth rates of the species (Murawski and Serchuk 1989), it is unlikely that commercial fisheries for ocean quahog will develop in the hypoxia impact area for at least two decades at a minimum.

Sea Scallop

Like the ocean quahog, only the inner margin of the extant sea scallop population was affected by the hypoxic water conditions in 1976 (Figures 5 and 6). Eventhough dead and stressed sea scallops were reported in the area affected by hypoxia, population consequences of these effects were minimal (Ropes et al. 1979; Serchuk and Wigley 1986). Sea scallop landings increased by a factor of four at New Jersey ports during 1976, primarily as a result of high densities of scallops present in the New York Bight (Figure 6). Subsequent scallop dredge surveys have documented a highly dynamic scallop resource, with several dominant year classes occupying the area affected by the hypoxic water conditions in 1976 (Figure 6).

American Lobster

American lobsters were one of the sentinel species indicating abnormal water conditions off New Jersey during 1976. Reports by sport divers indicated that lobsters had congregated on the highest parts of ship wrecks, indicative of stressful but not yet lethal conditions. Later, mortalities of lobsters were documented by sport divers and were collected in resource surveys (Steimle and Radosh 1979). Landings of lobsters and CPUE in the inshore lobster pot fishery declined significantly in 1976, as compared with 1975 (Azarovitz et al. 1979). It is unclear, however, if lobsters avoided and/or were displaced from the hypoxia area, or if they were killed outright. Because of the probable inshore-offshore movement patterns of the stock, it is likely that much of the stock avoided the areas of depressed DO concentrations (Azarovitz et al. 1979).

Landings and populations of lobsters have generally declined in the region (Anonymous 1988), but this is probably attributable primarily to the effects of very intensive fishing. Lobster distribution data presented in Figure 7 indicate no long-term systematic change in the spatial distribution of the stock after the 1976 anoxia event. Trawl survey catches of lobster in two time periods (1968-1975 and 1977-1988) reveal virtually identical distribution patterns before and after the hypoxia event (Figure 7).

Rock Crab

The behavior and mortalities of rock crab were also an early indication of unusual bottom water conditions off New Jersey in 1976 (Steimle and Radosh 1979). Hundreds of dead rock crabs were reported by divers, and reductions in crab abundance were documented in the hypoxic area. Long-term monitoring studies of the abundance and distribution of rock crab indicate no residual effects of the hypoxia event, and as with lobsters, pre- and post-impact distribution patterns as revealed by autumn bottom trawl surveys were identical.

LONG-TERM EFFECTS -- FINFISH

Reports of dead and dying finfish off the New Jersey coast were received beginning in late 1976 (Azarovitz et al. 1979). These reports were primarily again from sport divers and later by commercial trawler captains. A series of trawl surveys was conducted beginning in July 1976 to document the areal extent and severity of finfish mortalities and displacement in the region (Figure 8).

During one such cruise from 6-17 August 1976, a 2,900 km^2 area was found to be devoid of demersal finfishes (Figure 8). Normally, this area would have contained a diverse fish fauna comprised of gadoids, flounders, elasmobranchs and numerous other species (Azarovitz et al. 1979). The lack of demersal finfish in the region can only be attributed to the hypoxic water conditions.

Surveys conducted in early July revealed a few dead finfish, but subsequent trawling did not produce significant numbers of dead fish. Based on these results, there was apparently a rather limited 'fish kill'. Rather, the most profound effects on finfish were limited duration displacements from the area of impact. This displacement of finfish resources is confirmed by a number of independent sampling schemes. Recreational fishery catches in the region were monitored via creel sampling. Catch rates of summer flounder, **Paralichthys dentatus** in 1976 were similar to previous years in early May, but declined to relatively low levels for the rest of May. Summer flounder catch rates then increased considerably, particularly in areas not directly affected by the hypoxic water conditions. Catch rates appeared to be highest at places where hypoxic/anoxic water conditions trapped summer flounder near the coast. Large sized flounders, not usually found nearshore, were taken in bays and inlets (Azarovitz et al. 1979). The distribution of recreational catches of the pelagic bluefish, **Pomatomus saltatrix**, similarly indicated significant avoidance of the most heavily impacted areas.

Re-population of the areas affected by hypoxic water conditions was relatively rapid after the break-up of intense density stratification in the late summer and autumn. The passing of hurricane 'Belle' on August 10 resulted in increased DO levels in shallow waters (<33 m) with a concomitant increase in the population density of finfishes. By late September 1976 (after the breakdown of stratification) the affected areas were again re-populated with demersal and pelagic species seen in previous autumn bottom trawl surveys (Azarovitz et al. 1979).

There is some speculation that reproduction of fish species normally inhabiting the affected area was disrupted (Azarovitz et al. 1979). However, long-term effects on the abundance and distribution of finfishes of the 1976 hypoxia event are not apparent. Most of the finfishes inhabiting the affected areas are migratory species with extensive geographic stock boundaries. Thus, it is unlikely that stock groups unique to the impact area were differentially impacted. In Figures 9 and 10 we present autumn distribution plots of three important and representative demersal fish species, during two time periods: pre-impact -- 1968-1975; and post-impact -- 1977-1988. All three species (i.e. summer flounder, little skate, **Raja erinacea**, and red hake, **Urophysis chuss**), exhibit virtually identical geographic distribution patterns before and after the hypoxic water event in 1976 (Figures 9 and 10). Landings and stock sizes of the red hake and summer flounder have declined recently, but these declines are not related to the 1976 hypoxic water conditions. Little skate abundance has increased greatly during the past two decades (Anonymous 1988).

DISCUSSION

Long-term monitoring programs in place prior to and after the hypoxic water conditions off New Jersey in 1976 provide a unique opportunity to assess the impacts on and recovery of biota from a relatively intense and widespread hypoxia event. The term 'fish kill' was often used to describe this event. However, this term is misleading since the primary short-term effects on finfish were temporary displacements. More realistic terms would be 'clam kill' or 'benthos kill' since these components were subjected to extensive mortalities over a large geographic area.

The time-series of grab sampling for macrobenthos provides a clear picture of the succession of various taxa and the differential rates of re-population. Irruptive species such as tube worms apparently had a clear competitive advantage in the short-term. Species with a competitive dis-advantage included forms that were particularly intolerant of low DO conditions, with relatively immobile larval stages.

The macrobenthic community generally recovered to pre-impact levels of species diversity, abundance and distribution within two years of the hypoxia conditions. Thus, initial competitive advantages by irruptive forms do not necessarily result in their long-term dominance in benthic ecosystems.

An important observation from these studies is the potential for disruption of normal predator-prey relationships among benthic and demersal species, perhaps allowing for the rapid recovery of some species. Predation on juvenile surf clam and sand dollar is thought to be an important determinant of year class strength. Rapid recovery of these decimated populations was coincident with reduced population abundance of their predators, suggesting that normal predator-prey relationships may have been disrupted.

Finfish and megabenthic crustacean populations of the New Jersey shelf generally exhibit strong seasonal inshore-offshore movement patterns, associated with temperature change. The capacity of these populations to avoid low DO and significant H_2S conditions contributed stabilizing these populations and thus permitting their very rapid re-occupation of the impact area following the autumn breakdown of stratification.

The most significant affected demersal resources were bivalve mollusks. Surf clam populations were decimated in the short-term, but have since recovered to levels significantly above those observed prior to the hypoxia event. Little recovery of the ocean quahog resource has occurred in the area, but this species and sea scallop were only marginally affected at the periphery of their nearshore distributions.

Given the apparently very infrequent occurrence of widespread, prolonged hypoxia in this region, should the risk of recurrence of such an event be factored into long-term management strategies for the region's fishery resources? Swanson et al. (1979) argue that fishery managers could incorporate short-term predictions of devastating hypoxia conditions, to intensively harvest those areas likely to be subjected to extensive and widespread mortalities. However, as we have concluded, the long-term effects of the hypoxia event were not problematic to the viability of fisheries or fishermen's income. In fact, it could be argued that the kill enhanced recruitment prospects for at least one commercial bivalve species. More over, the economic impacts on markets for fishery products of enormous quantities of landings over a short time period have not been evaluated. With respect to finfishes, such an adaptive harvesting strategy could in fact do more harm to the resources, than does the hypoxia event, since there was little indication of wide-spread mortalities among the fishes. Although there have been localized hypoxia conditions in the New York Bight since 1976, none compare in severity or extent. Thus, with 13 years since the last such event, it is apparent that the probability of extensive hypoxia conditions in the New York Bight is indeed remote.

Documentation of the long-term biological effects of the New Jersey hypoxia event in 1976 has given us a clearer picture of the population consequences of such short-term environmental disruptions. The challenge remains to evaluate the biological consequences of chronic habitat degradation, particularly for intensively harvested ecosystems.

ACKNOWLEDGMENTS

We thank our many colleagues in the Northeast Fisheries Center who participated on the numerous sampling cruises and provided population data documenting the long-term effects of the 1976 hypoxia event. Fish and crustacean distribution plots from bottom trawl surveys were provided by Brian O'Gorman.

LITERATURE CITED

Anonymous. 1988. Status of the fishery resources off the northeastern United States. NOAA Technical Memorandum NMFS-F/NEC-63. 135 pp.

Armstrong, R.S. 1979. Bottom oxygen and stratification in 1976 and previous years. p. 137-148. **In:** Swanson and Sindermann (1979).

Azarovitz, T.R. 1981. A brief historical review of the Woods Hole Laboratory trawl survey time series, p. 62-67. **In:** W.G. Doubleday and D. Rivard (eds.). Bottom trawl surveys. Canadian Special Publication of Fisheries and Aquatic Science 58.

Azarovitz, T.R., C.J. Byrne, M.J. Silverman, B.L. Freeman, W.G. Smith, S.C. Turner, B.A. Halgren, and P.J. Festa. 1979. Effects on finfish and lobster. p. 295-314. **In:** Swanson and Sindermann (1979).

Boesch, D.F. 1983. Implications of oxygen depletion on the continental shelf of the northern Gulf of Mexico. Coastal Ocean Pollution Assessment News 2(3):25-28.

Falkowski, P.G., T.S. Hopkins, and J.J Walsh. 1980. An analysis of factors affecting oxygen depletion in the New York Bight. Journal of Marine Research 38:479-506.

Mackenzie, C.L., Jr., D.J. Radosh, and R.N. Reid. 1985. Densities, growth and mortalities of juveniles of the surf clam **(Spisula solidissima)** (Dillwyn) in the New York Bight. Journal of Shellfish Research 5(2):81-84.

May, E.B. 1973. Extensive oxygen depletion in Mobile Bay, Ala. Limnology and Oceanography 18(3):353-366.

Murawski, S.A., and F.M. Serchuk. 1989. Mechanized shellfish harvesting and its management: the offshore clam fishery of the Eastern United States. p. 479-506. **In:** J. Caddy (ed.) Marine invertebrate fisheries, their assessment and management. J. Wiley and Sons. New York. 752 pp.

O'Connor, J.S. 1979. A perspective on natural and human factors. **In:** Swanson and Sindermann (1979).

Officer, C.B., R.B. Biggs, J.L. Taft, L.E. Cronin, M.A. Tyler, and W.R. Boynton. 1984. Chesapeake Bay anoxia: origin, development and significance. Science 223:22-27.

Radosh, D.J., and R.N. Reid. (ms). Recovery of benthic macrofauna after widespread hypoxia off New Jersey, 1976. National Marine Fisheries Service, Sandy Hook Laboratory, manuscript report.

Ropes, J.W., A.S. Merrill, S.A. Murawski, S. Chang, and C.L. MacKenzie. 1979. Impact on clams and scallops. p. 263-275 **In:** Swanson and Sindermann (1979).

Serchuk, F.M., and S.E. Wigley. 1986. Abundance, size composition and recruitment of sea scallops in the USA Georges Bank and Mid-Atlantic regions: results of the 1986 USA sea scallop research vessel survey. National Marine Fisheries Service. Woods Hole Laboratory Reference 86-15. 55 pp.

Sindermann, C.J., and R.L. Swanson. 1979. Historical and regional perspective. p. 1-16. **In:** Swanson and Sindermann (1979).

Starr, R.B., and F.W. Steimle. 1979. Temporal development of physical characteristics. p. 17-50. **In:** Swanson and Sindermann 1979.

Steimle, F.W. Jr., and D.J. Radosh. 1979. Effects on the benthic invertebrate community. p. 281-293. **In:** Swanson and Sindermann (1979).

Swanson, R.L., and C.J. Sindermann. 1979. Oxygen depletion and associated benthic mortalities in the New York Bight, 1976. National Oceanic and Atmospheric Administration, Professional Paper 11, Rockville, Maryland, USA.

Swanson, R.L., and C.A. Parker. 1988. Physical environmental factors contributing to recurring hypoxia in the New York Bight. Transactions of the American Fisheries Society 117:37-47.

Swanson, R.L., C.J. Sindermann and G. Han. 1979. Oxygen depletion and the future: an evaluation. **In:** Swanson and Sindermann (1979).

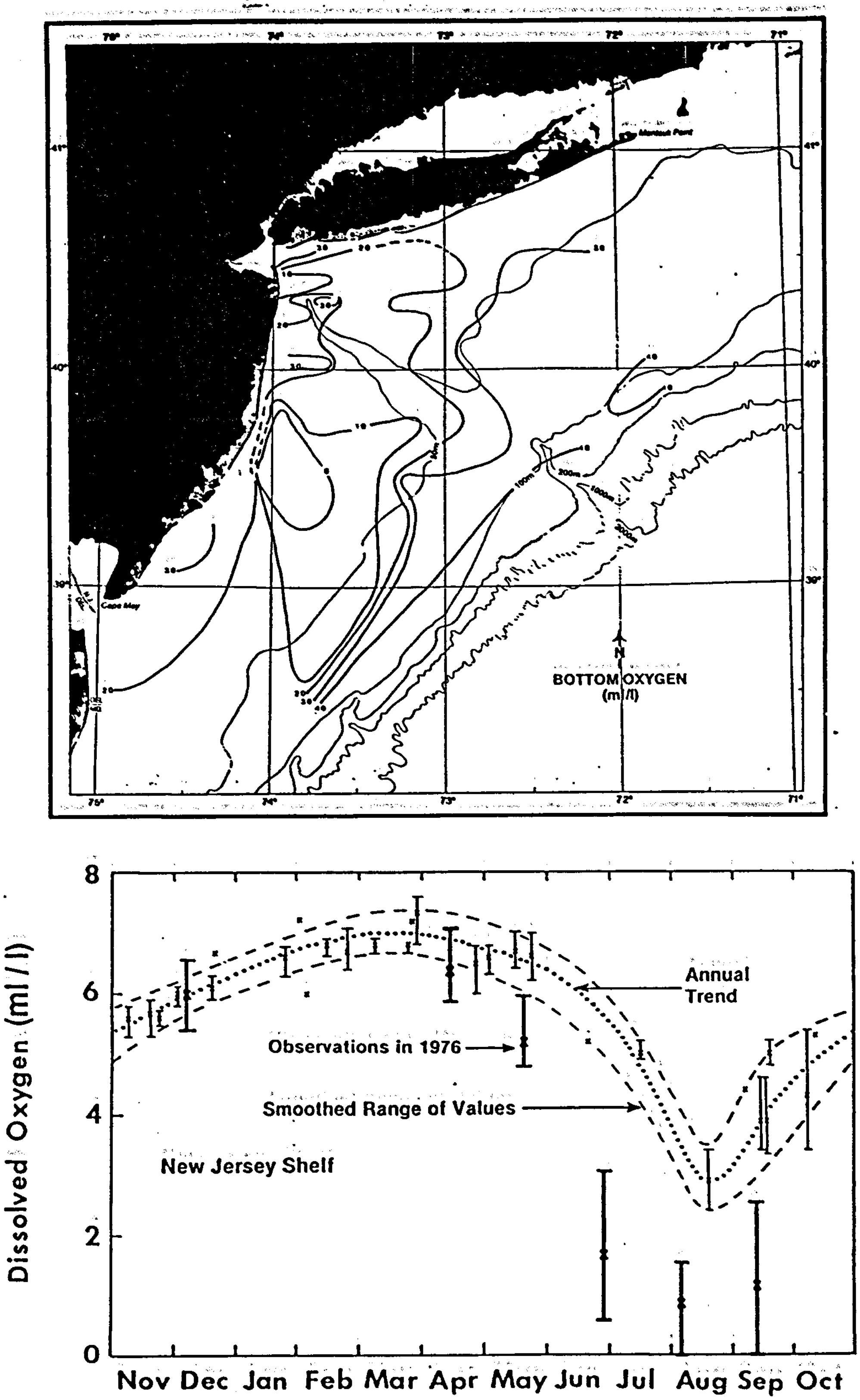

Figure 1. August-September 1976 distribution of bottom dissolved oxygen (ml/l; above), and dissolved oxygen levels of bottom waters (>20 m) off New Jersey, 1976 and historical record (below). Top figure from Starr and Steimle (1979); bottom figure from Armstrong (1979).

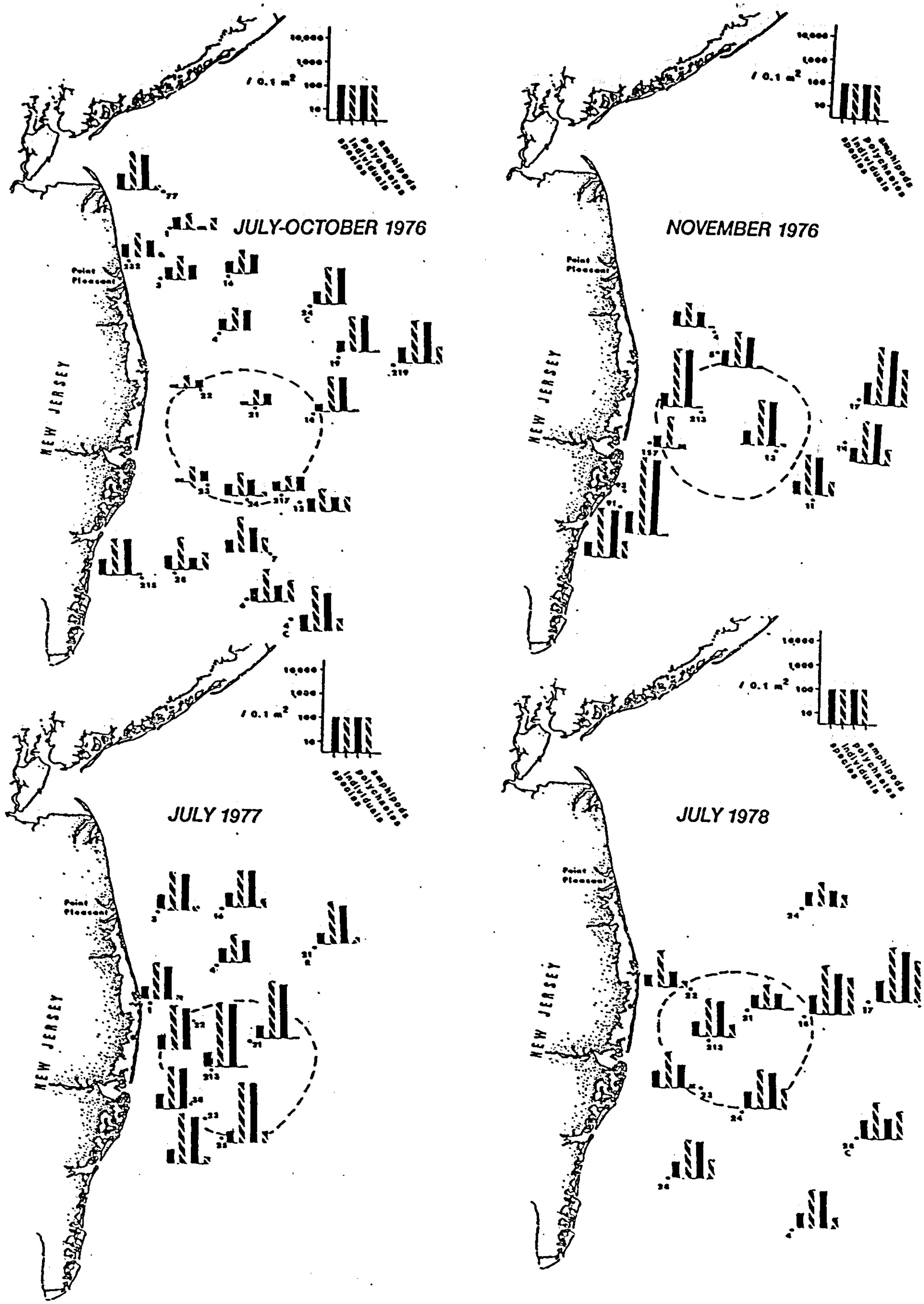

Figure 2. Distribution and abundance of macrobenthic invertebrates sampled from Smith-McIntyre grab stations off the New Jersey coast, 1976 -1978. Histogram components are (left to r:ght): total number of invertebrate species, number of individuals, number of polychaetes, and number of amphipods. Plots are from Radosh and Reid (ms).

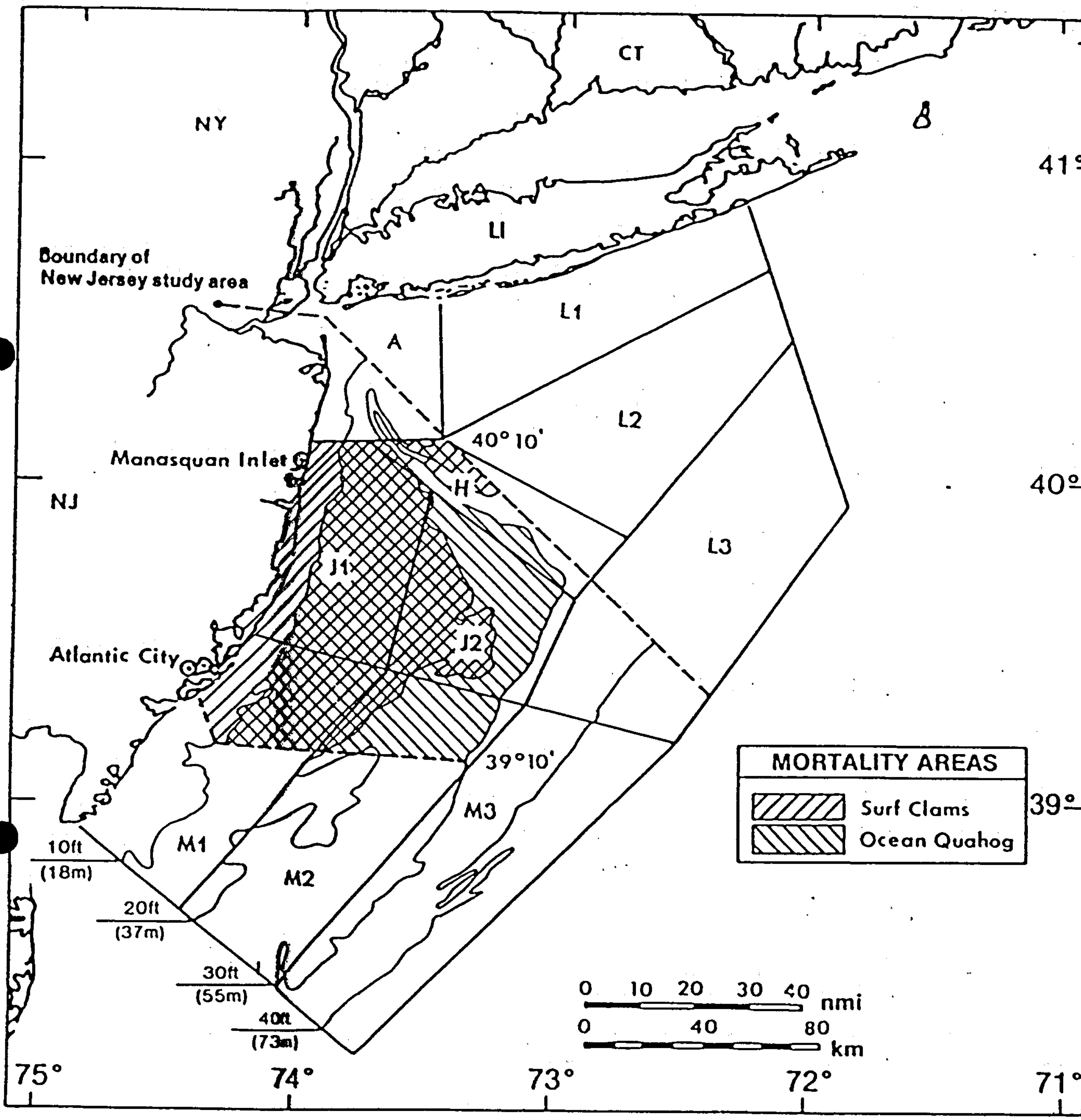

Figure 3. Surf clam and ocean quahog mortality areas off New Jersey (USA), by depth zone. Data are based on the proportion of recently dead clams in dredge surveys, as determined by the presence of articulated paired valves ('clappers'), during a survey conducted in early 1977. Figure is from Ropes et al. (1979).

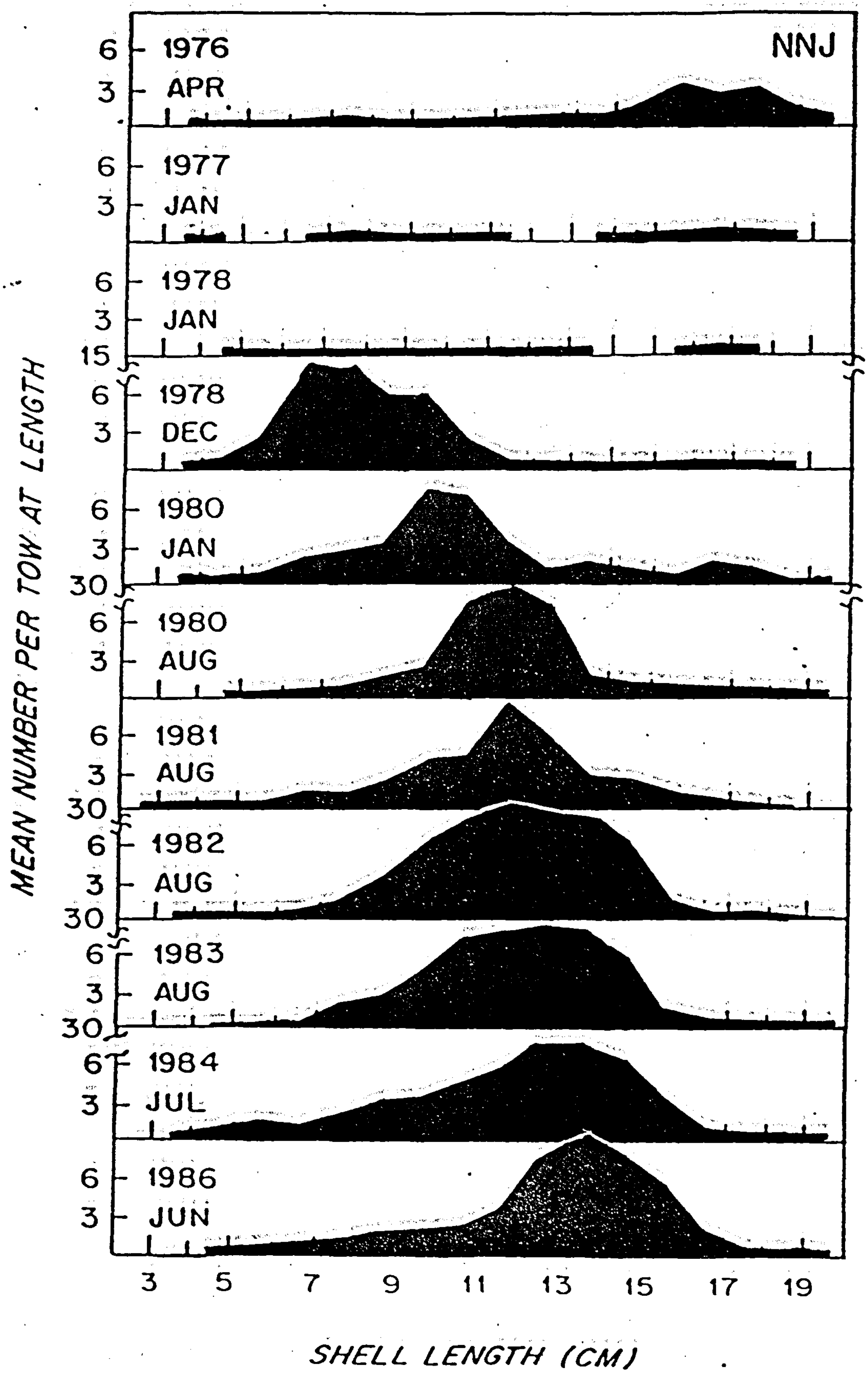

Figure 4. Relative abundance at length of surf clams off northern New Jersey (USA), in clam dredge surveys conducted from 1976-1986. Data are stratified mean numbers per standardized survey tow (Murawski and Serchuk 1989).

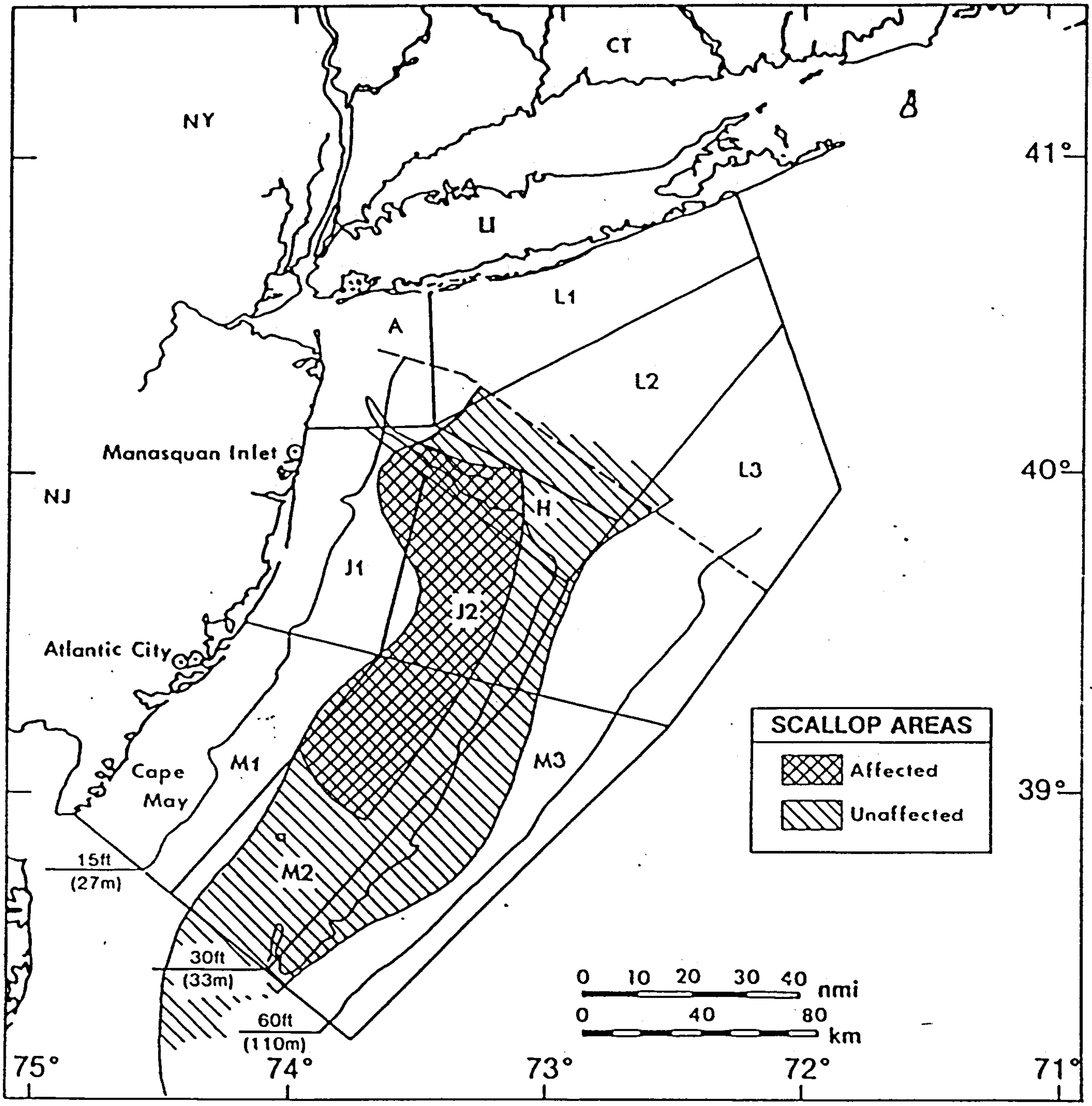

Figure 5. Areas where sea scallops were affected by the hypoxic water conditions off New Jersey (USA) during 1976. Figure is from Ropes et al. (1979).

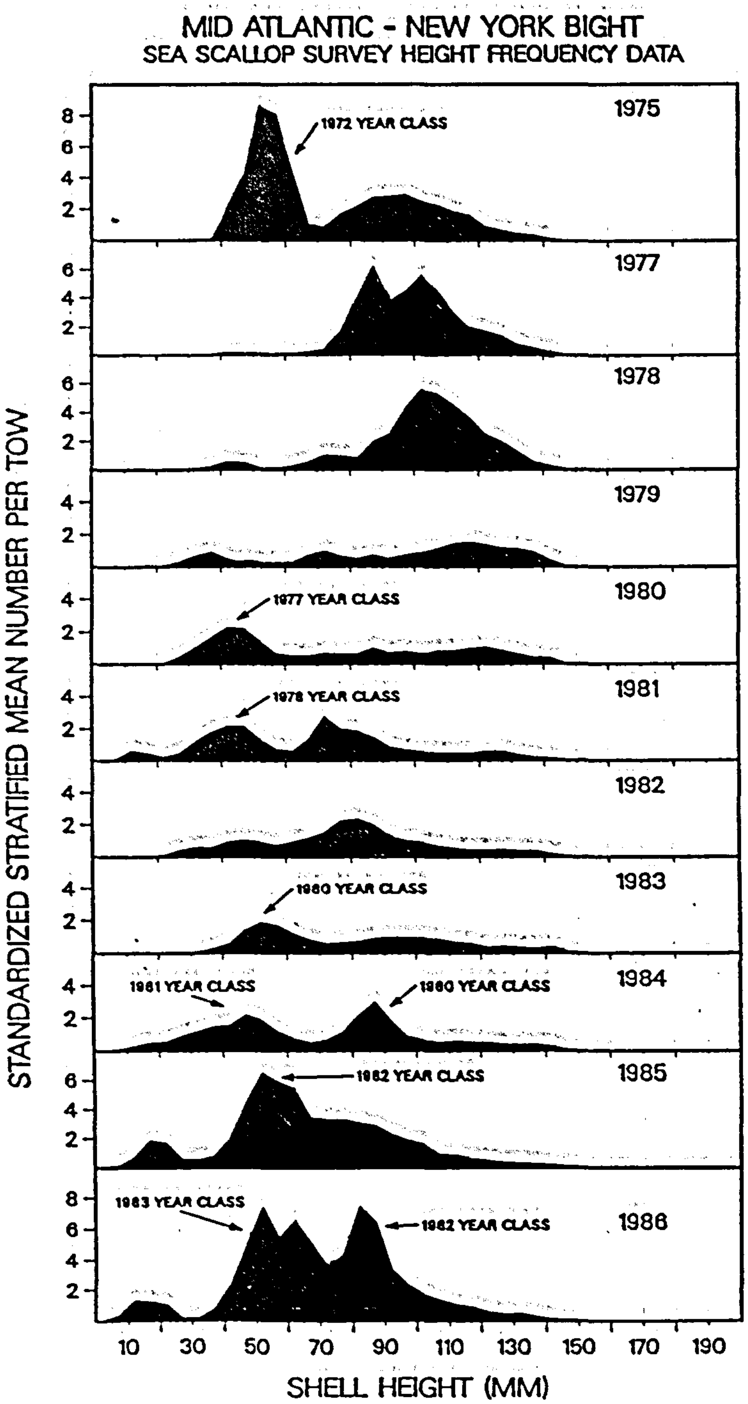

Figure 6. Relative abundance at length of sea scallops in the New York Bight (USA), 1975-1986. Data are based on stratified random scallop dredge surveys (Serchuk and Wigley 1986).

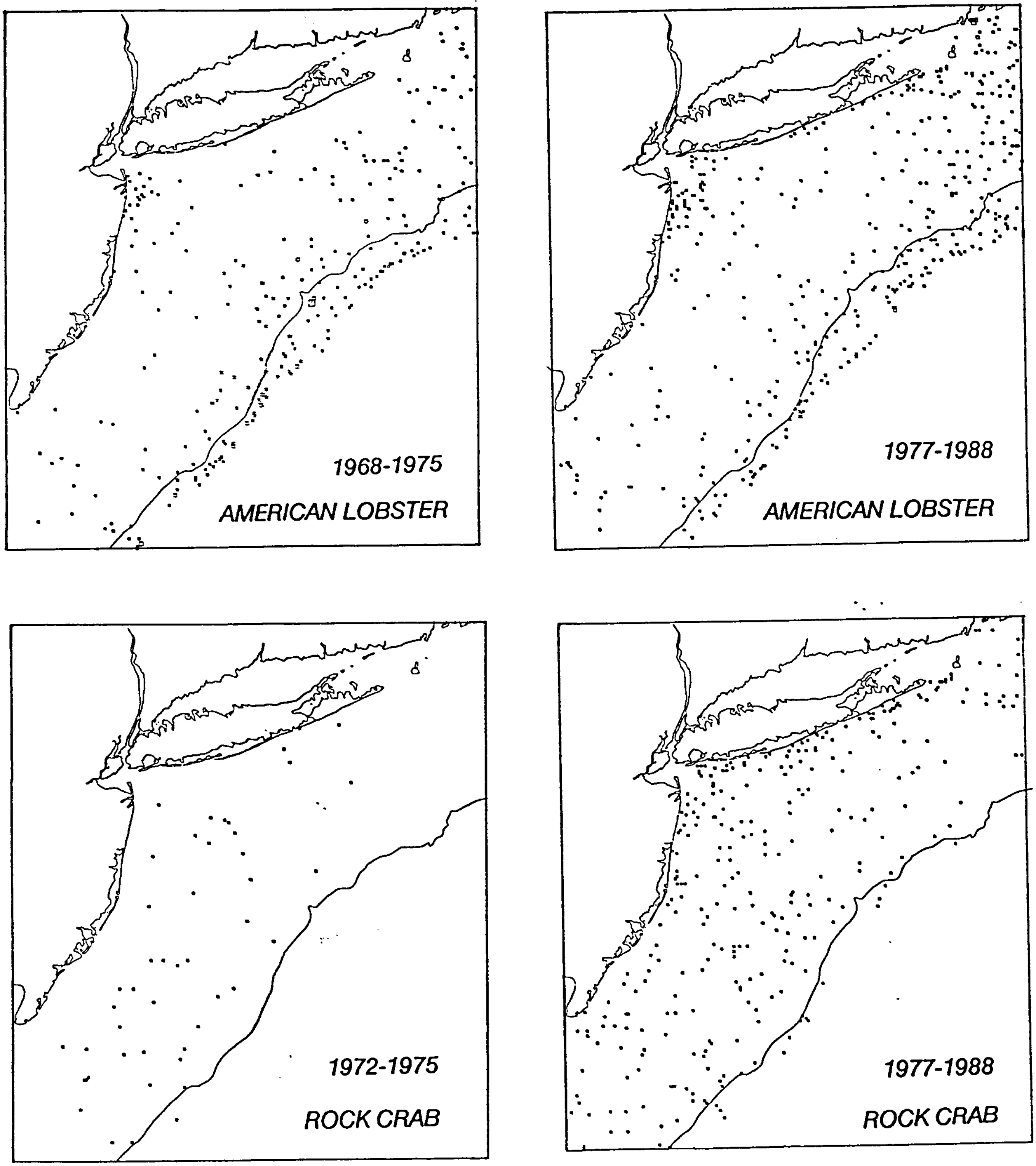

Figure 7. Geographic distribution of catches of American lobster (above) and rock crab (below) during two time periods (1968-1975, 1977-1988). Data are from autumn bottom trawl surveys (Azarovitz 1981). Higher catches nearshore in the recent time period are reflective of greater sampling intensity.

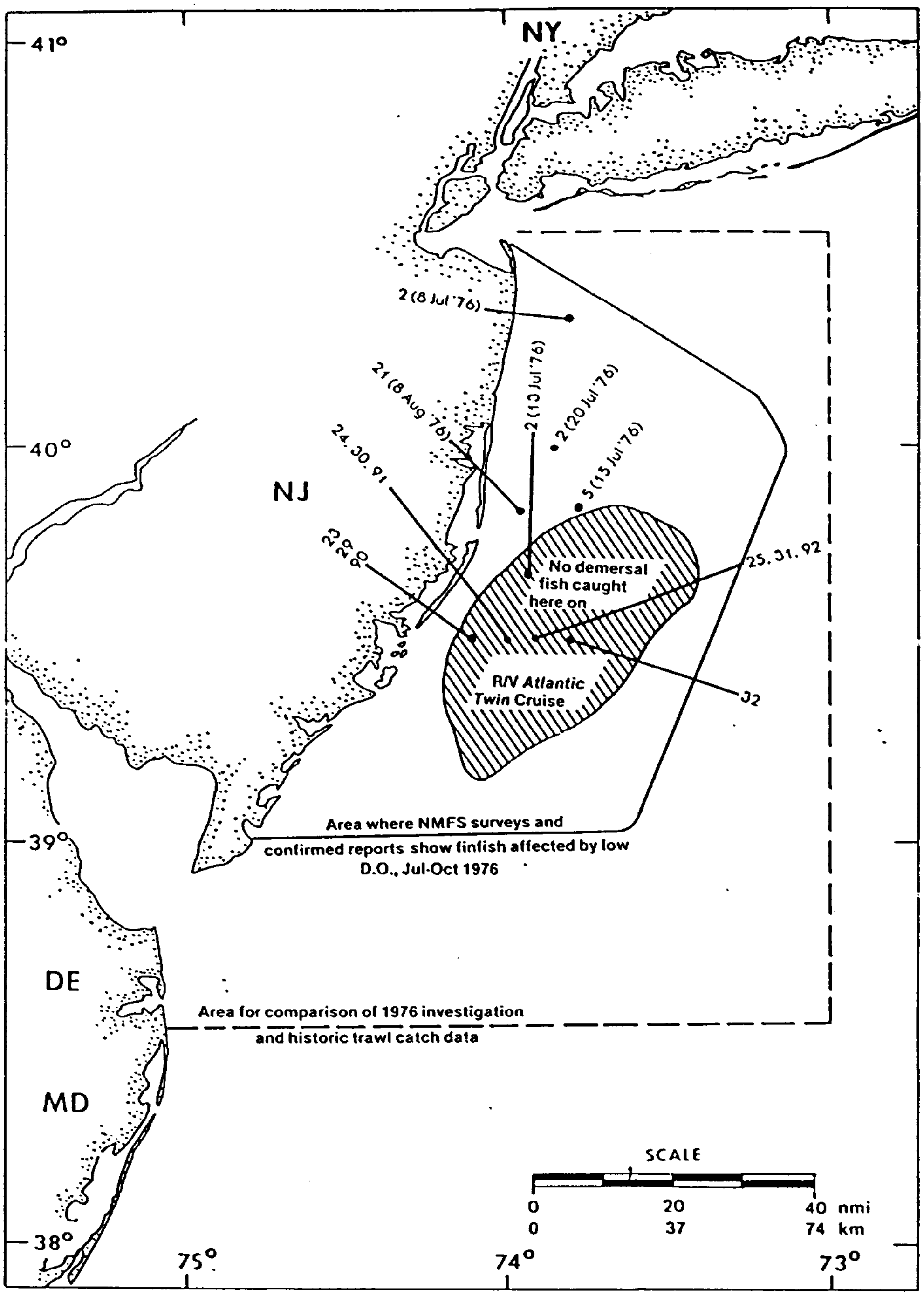

Figure 8. Areas of impact of hypoxic water conditions on finfish, 1976. Shaded area was completely devoid of demersal finfish sampled by bottom trawl during 6-17 August, 1976. Numbers are trawl station locations. Figure is from Azarovitz et al. (1979).

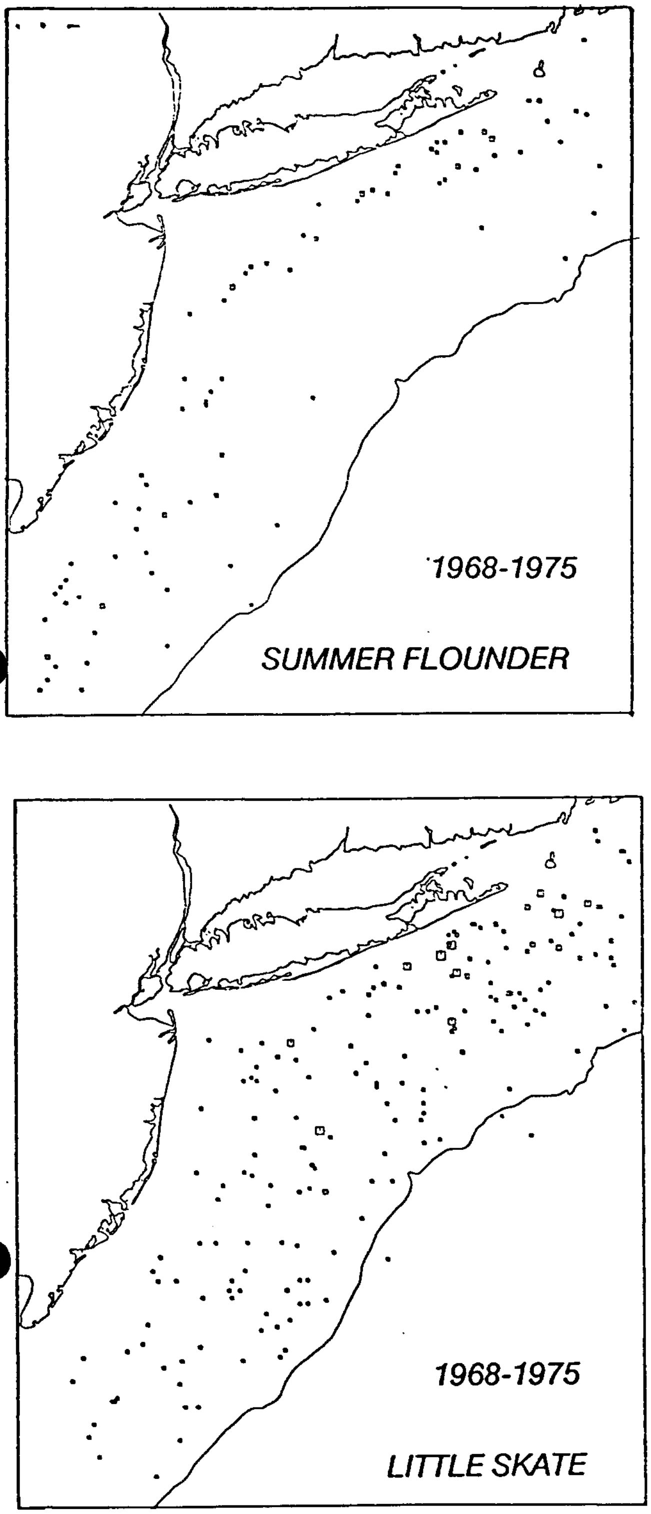

Figure 9. Geographic distribution of catches of summer flounder (above) and little skate (below) during two time periods (1968-1975, 1977 -1988). Data are from autumn bottom trawl surveys (Azarovitz 1981). Higher catches nearshore in the recent time period are reflective of greater sampling intensity.

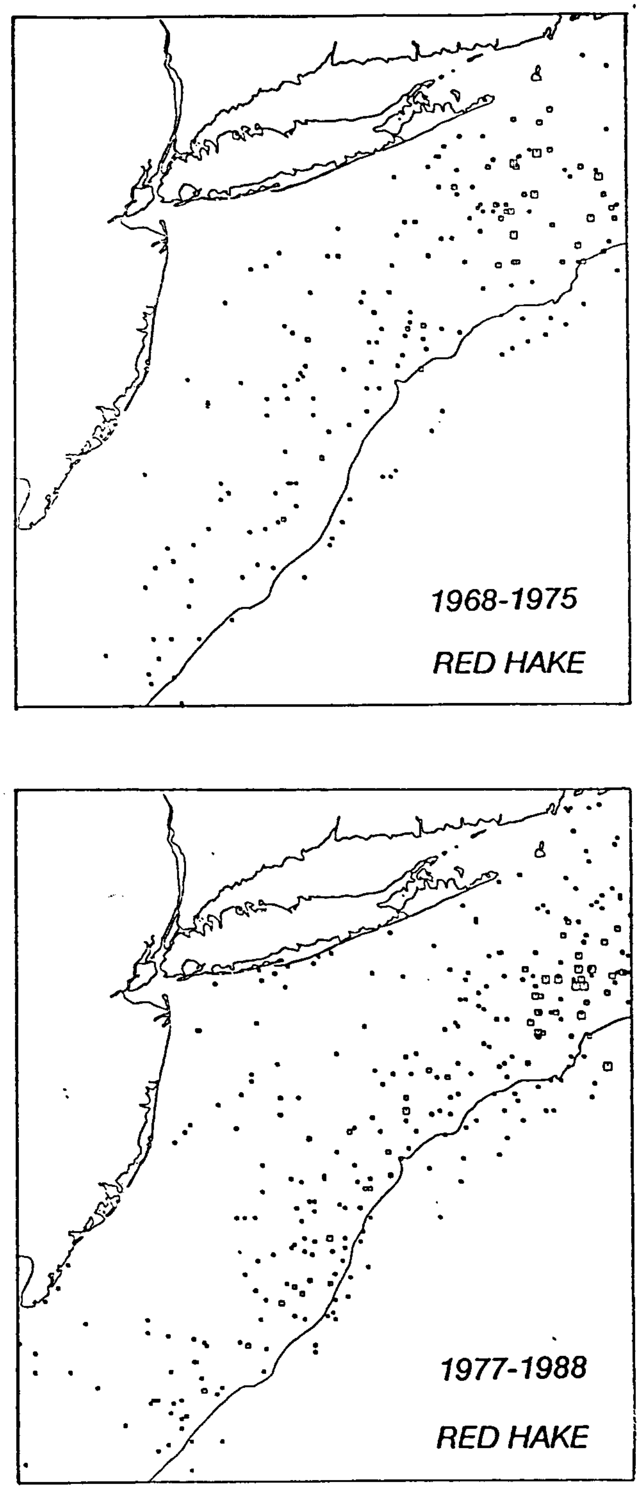

Figure 10. Geographic distribution of catches of red hake during two time periods (1968-1975, 1977-1988). Data are from autumn bottom trawl surveys (Azarovitz 1981). Higher catches nearshore in the recent time period are reflective of greater sampling intensity.