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EFFECTS OF ENERGY-RELATED ACTIVITIES ON THE ATLANTIC CONTINENTAL SHELF

BERNARD MANOWITZ, Editor



MASTER

Conference at

Brookhaven National Laboratory

November 10-12, 1975

Cosponsored by

Energy Research and Development Administration

Brookhaven National Laboratory

Marine Sciences Research Center of the State University of New York

Marine Technology Society, New York Section

BROOKHAVEN NATIONAL LABORATORY
UPTON, NEW YORK 11973

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(Environmental Control Technology
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Under Contract No. E(30-1)-16 with the

United States Energy Research and Development Administration

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Printed in the United States of America
Available from
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price: Printed Copy \$9.00; Microfiche \$2.25

June 1976

750 copies

ACKNOWLEDGMENTS

The Program Chairman is deeply grateful to a number of individuals for extensive and essential help before, during, and after the Conference. Jerry Schubel and Eugene Harlow were instrumental in helping plan the Conference. Walter Tucker, John Walsh, Jon Scott, Kim Kasters, Creighton Wirick, Peter Meier, Steven Howe, and Andrew Stoddard provided extensive help during the meeting, and John R. Craig was responsible for the excellent recording arrangements. Alice Perez provided a detailed and yet rapid editorial review, Everina Wold provided useful editorial assistance, and Trudi Neuhoﬀ was of invaluable aid in expediting the document to its present state of fruition.

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Introductory Remarks

BERNARD MANOWITZ

Brookhaven National Laboratory, Upton, New York 11973

The Atlantic Continental Shelf is a rich and complex ecosystem. Within the next decade the Atlantic coastal zone is also bound to be the scene of ever-increasing activity by man.

The purpose of this Conference is to bring together industrial proponents of energy-related activities proposed for the shelf; members of the oceanographic scientific community who have been trying to understand important coastal oceanographic processes, both of natural and of anthropogenic origin; representatives of regulatory agencies who are attempting to set the standards through which man's activities on the coastal shelf will be controlled; and representatives of the public who will be affected by both the benefits and the risks of coastal enterprises.

Virtually all of man's activities will have some impact on our environment. Some of these activities will result in substantial long-term changes, while others will result in temporary, local, or to some extent reversible changes. We hope that the direct output of this Conference will be a better insight into the degree of change to be anticipated on the coastal shelf as a result of energy-related activities. In a larger sense, however, I view this Conference as the fashioning of a tool that will be of use to those making decisions with regard to coastal activities. It is an imperfect tool. The Conference itself has many omissions. In describing the energy-related activities we will not have an opportunity to present a detailed characterization of all effluents. We have chosen to emphasize a review of important physical, biological, and geological processes rather than to describe the effects of specific pollutants on the biota in the belief that an understanding of the processes and their natural variance is the key to the understanding of the effects of any additional stress. Here too, however, we recognize omissions in the program with regard to shoreline processes. We hope that some of these omissions will be covered in active discussion periods.

The panel discussion on the adequacy of criteria for environmental impact statements will be an experiment in communication. We have gathered together a panel with a spectrum of responsibilities, interests, and concerns with the coastal zone. From this session we hope not only to learn about environmental impact statements and their criteria but also, and perhaps of more importance, to learn more about the public's perception of environmental impacts.

We hope that the experience of meeting together and learning from each other and the publication of the Conference Proceedings will help to identify a balance between what new energy-related objectives can be accomplished intelligently and realistically, and what safeguards are required, without raising hopes in the public that we cannot fulfill or fears that are unwarranted.

If we succeed in playing some role in realizing such a balance in our approach to this one critical national problem, our work will have been well done.

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Session I

Description of Proposed Activities

Chairman: E.H. HARLOW

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Potential Power-Generating Stations on the Atlantic Continental Shelf

ROBERT L. MITTL

Public Service Electric and Gas Company, Newark, New Jersey 07101

The electric utility industry is called upon to provide new generating capacity to meet an ever-increasing demand for electric energy. As recent experience has shown, energy demands grow at slower rates during prolonged periods of economic stress as well as in periods of general public awareness of the importance of conserving natural resources. However, it seems evident that a basic pattern of future load growth is unavoidable. The Public Service Electric and Gas Company's load-growth studies indicate that the Company must install ≈ 500 megawatts of new base-load generation each year over the next 15 years.

Nuclear power has been the choice for new capacity in New Jersey during the past 10 years and remains the choice for the foreseeable future. Favorable economics and minimum environmental impact are important factors in selecting nuclear rather than fossil generation.

Few desirable sites for nuclear generating stations remain in New Jersey, a condition that should come as no surprise in view of population density, steadily decreasing water supplies for cooling, and the State's dedication to preservation of extensive coastal and wetland areas. These siting problems are not unique to Public Service; they are shared to some extent by other utilities serving heavily populated coastal areas.

In an effort to circumvent these siting problems and overcome the trend toward lengthy project schedules, to which construction time and licensing delays have contributed, Public Service undertook 4½ years ago an investigation of the feasibility of siting floating nuclear plants offshore (Figure 1). Consultants were retained to study the parameters for this type of siting.

The concept of offshore floating nuclear plants has some important advantages in addition to site availability and cooling water considerations. These include simplification of the licensing process, reduced overall design and construction time, and enhanced quality control.

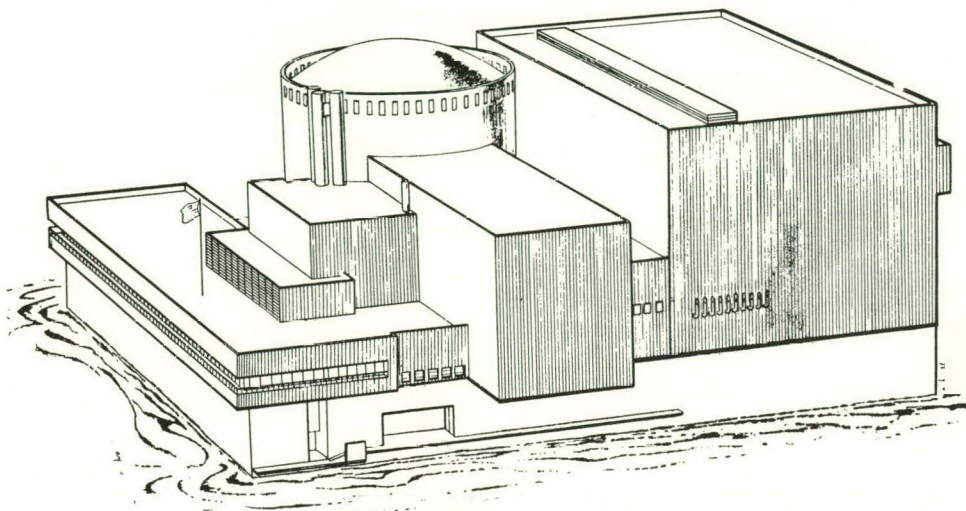


Figure 1 Floating nuclear plant

Site licensing and plant licensing can be handled independently. The plants would be precensored for manufacturing and subsequent operation within a protective breakwater and a specified site envelope. The site licensing process then merely makes reference to the precensored plant and concentrates primarily on details of the site and related structures.

Engineering, design, and construction activities for the plant and site can be carried out simultaneously, which results in a shorter overall project schedule. After the first plant has been completed, subsequent plants or stations need undergo only site-related licensing, engineering, design, and construction. As a point of interest, floating nuclear plants offer an excellent opportunity for more complete realization of the benefits of standardization than is possible with land-based plants. Standardization for the latter has received considerable attention and is progressing slowly. Variations in the characteristics of on-land sites can significantly influence plant configuration and steam cycle design parameters and thus reduce the degree of applicable standardization.

Construction of floating plants in a shipyard-type facility ensures a continuity of experienced personnel in all phases of construction, and this, along with the standardization of design, will lead toward a high degree of overall quality.

As part of the feasibility investigations, meetings were held with interested State and Federal agencies to discuss the licensing feasibility of various conceptual designs. While many comments were received, none were strongly negative.

Public Service proceeded with preliminary design work and site selection. This led to the concept of one or more floating plants moored within a protective breakwater. A significant portion of the preliminary efforts centered on the gathering and analysis of environmental data.

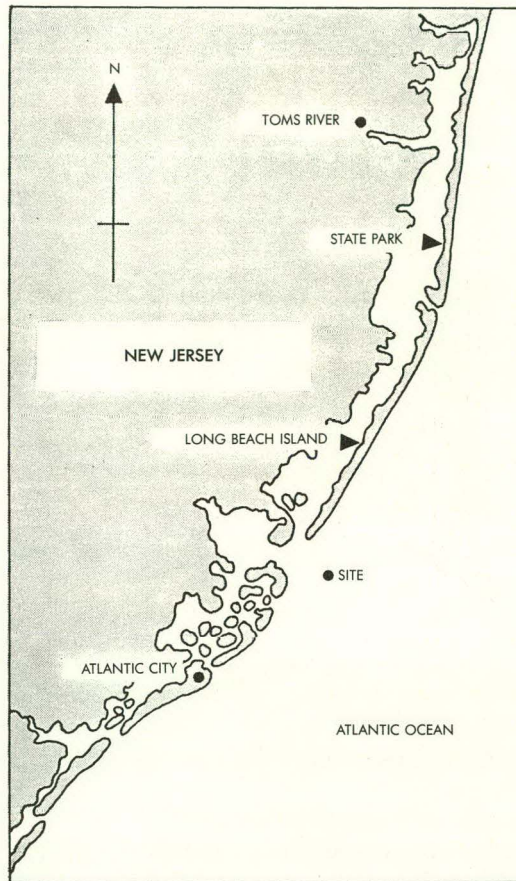


Figure 2. Atlantic Generating Station site off New Jersey Coast.

Once Public Service had established the technical feasibility of floating nuclear plants, the task of finding a practical and economic site was undertaken. A major consideration was the distance from shore, which, along coastal areas, has legal and jurisdictional implications. The three-mile limit was selected for the Atlantic Generating Station site in order to remain within the jurisdiction of federal and state governments.

The water depth at a potential site is important because both excessive dredging and prohibitive breakwater costs should be avoided. It has been concluded that the minimum acceptable depth is ≈ 40 ft, while depths ≥ 70 feet would result in costly breakwaters. The Atlantic site has a 40-ft depth at mean low water.

Other siting considerations include (a) proximity to shipping lanes, (b) available nearby harbor(s) for service vessels during plant operating life and during breakwater construction, (c) suitability of subsoils, and (d) transmission routing.

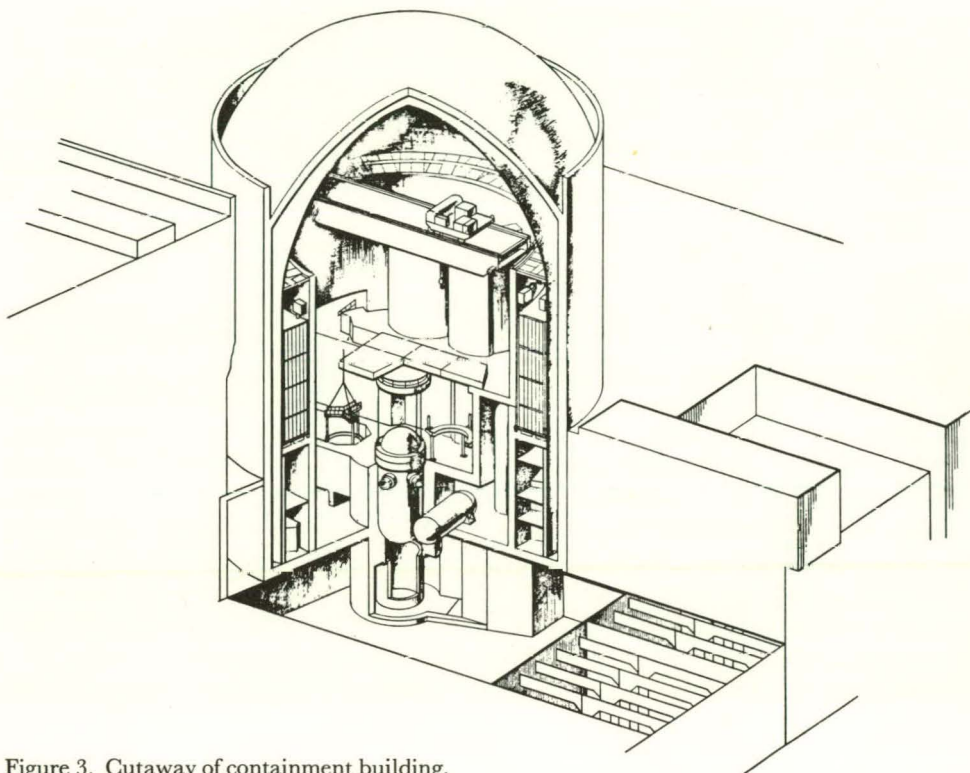


Figure 3. Cutaway of containment building.

The site selected for the world's first two floating nuclear plants is 2.8 miles from the coast, off Little Egg Inlet, and ≈ 12 miles northeast of Atlantic City (Figure 2).

The 1150-MW electric floating plants for the Atlantic Generating Station do not require a pioneering effort in power technology. All the systems and equipment used in the nuclear heat source and steam turbine cycle are commercially available in the power industry and have operated satisfactorily in land-based installations. The maximum motion of platform-mounted plants will be $< 3^\circ$, even during severe storm conditions. Therefore, movement of the floating plant is of no particular concern with regard to equipment operation. The main turbine-generator unit will be provided with slightly enlarged clearances in selected areas in order to tolerate platform-related deflections not present in land-based plants.

The nuclear systems will incorporate standard four-loop pressurized water reactor units virtually identical to some now in operation, others nearing completion, and still others under construction. Each floating plant will have a nuclear system consisting of a single reactor and four steam generators with a total rating of 3425 MW(t) that will produce > 15 million lb/hr of saturated steam at a pressure of ≈ 1000 lb/in.². The reactor and steam generators will be enclosed in a leak-tight containment structure (Figure 3) designed to contain contaminated reactor cooling

water in the event of a loss-of-coolant accident, which is highly unlikely. The nuclear systems will have a full complement of support, auxiliary, and emergency systems equivalent to those in comparable land-based plants. These will include emergency core cooling systems, which have received much attention during the past several years, and radioactive waste treatment systems capable of controlling gaseous and liquid releases, both meeting the same as-high-as-practical standards currently emphasized for land-based plants.

The hull of the floating plant will be a grillage-type structure $\approx 400 \text{ ft}^2$ and 40 ft in depth. It will be compartmented into 60 sections grouped as 39 watertight compartments to produce a virtually unsinkable vessel. The platform will displace 160,000 tons and draw $\approx 31 \text{ ft}$ of water when complete and ready for operation. The highest part of the floating structure will be $\approx 180 \text{ ft}$ above the ocean.

Placing floating nuclear plants offshore is not without challenges. The majority are associated with the ocean environment and relate to maximum wave height, water depth, and potential shipping hazards. One solution is to place such plants inside a "safe harbor." This provides isolation from the effects of severe storms and tends to eliminate chances of ship collision. A safe harbor is obtained by constructing a protective breakwater, illustrated in Figure 4. The shape chosen allows it to resist forces under extreme storm conditions while providing a basin of calm water in which to moor the plants. Important features of a breakwater are a free flow of cooling water, access for vessels transporting personnel and materials, and rapid completion after plant delivery to ensure timely utilization of the protected floating plants.

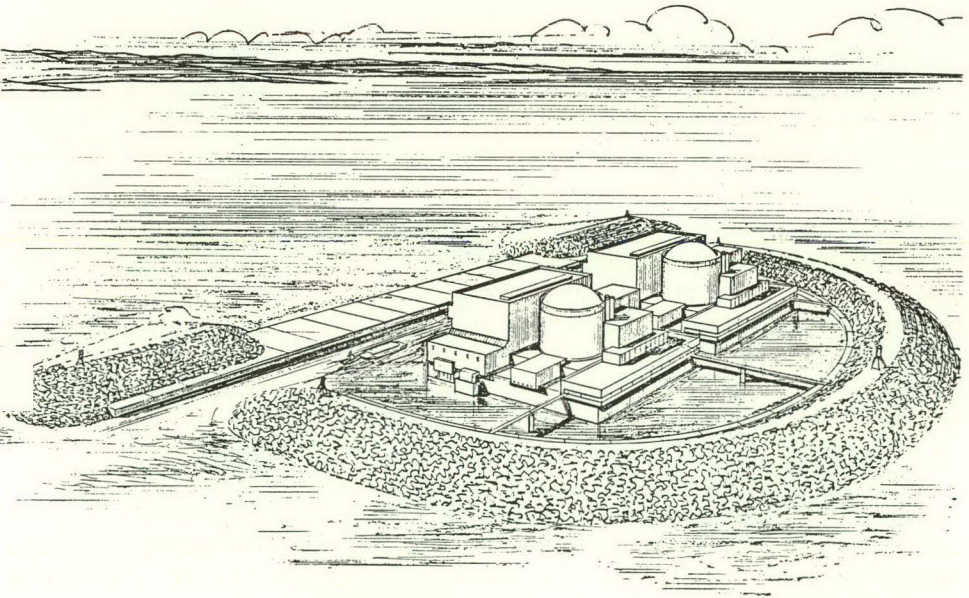


Figure 4. Atlantic Generating Station.

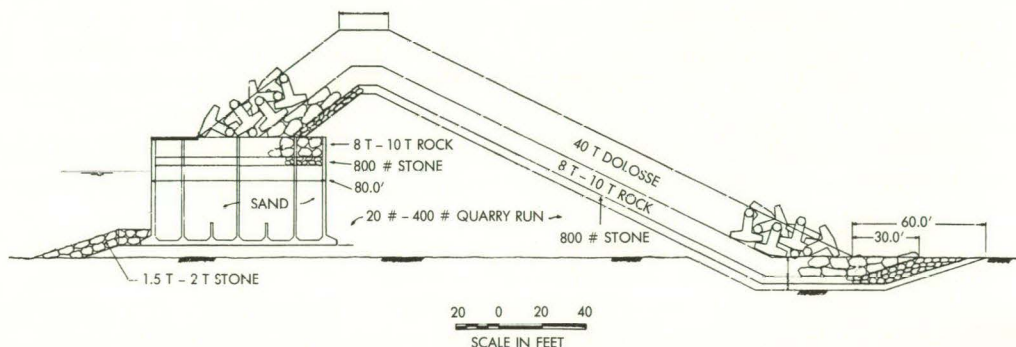


Figure 5. Typical cross section of main breakwater.

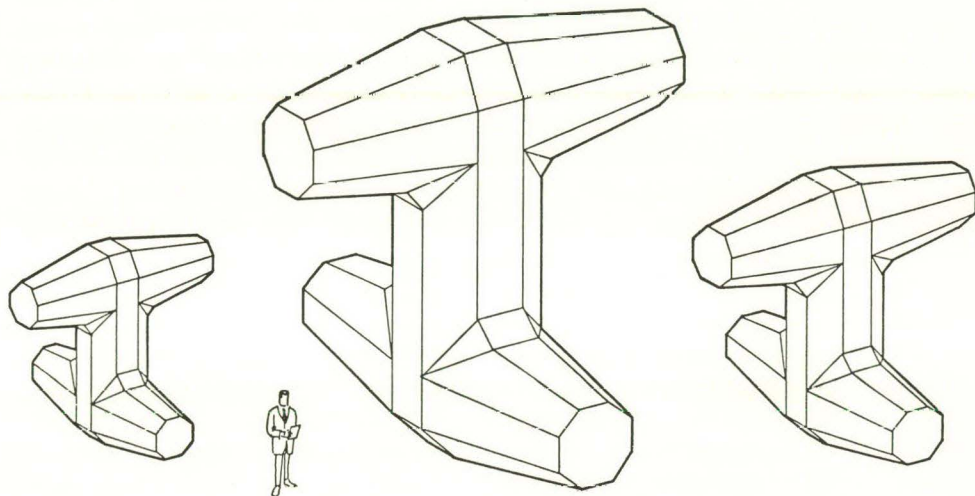


Figure 6. Dolosse.

The horseshoe portion of the breakwater with its open side toward the land eliminates sharp corners and presents a uniform surface within the 180° semicircle facing the ocean, the direction from which maximum-height waves are generated. The straight closure piece on the land side provides sufficient protection against smaller offshore-generated waves and is designed and constructed for rapid closure on completion of the breakwater following delivery of the plants.

The breakwater design prepared by Public Service and its consultants is shown in Figure 5. Its construction will be a formidable job. The breakwater will occupy an area of ≈ 100 acres and will be one of the largest man-made structures ever placed in the ocean, with a width of ≈ 300 ft at the bottom, a width of 30 ft at the top, and a height of 64 ft above the ocean at mean low water. As shown in cross section (Figure 5), the breakwater will have a core of precast concrete caissons filled

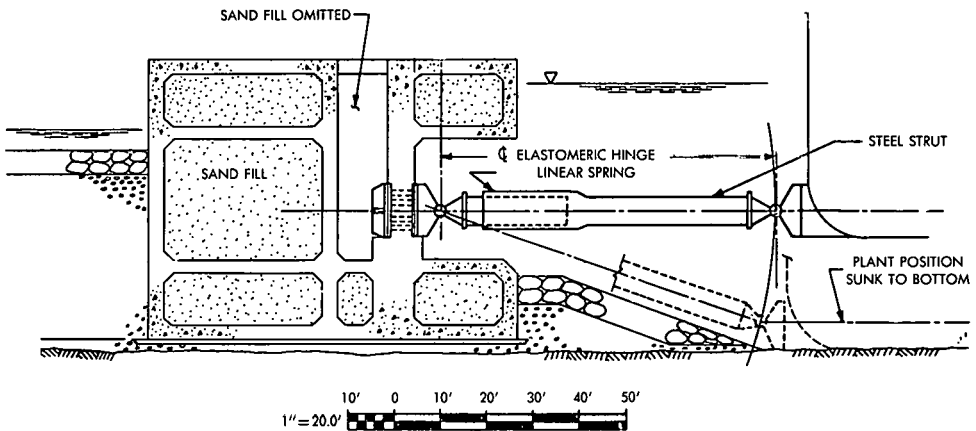


Figure 7. Elevation of typical mooring strut, Atlantic Generating Station.

with rock and material dredged from the ocean bottom. Approximately 1.8 million tons of quarry rock and sand will be placed against the caissons. This breakwater core will be covered by layers of rock and jetty stone and, finally, several layers of precast interlocking concrete armor units called dolosse (Figure 6). At different locations on the breakwater, the weight of the dolosse varies from 40 to 62 tons, and $\approx 17,000$ dolosse units are required in all. The largest dolosse will be used on the "roundheads" at the ends of the breakwater sections.

The design of the breakwater has been supported by experimental verification involving model testing. Models representing sections of the breakwater have been tested at the Waterways Experiment Station in Vicksburg, Mississippi. In addition, tests have been performed on a complete large-scale model at the University of Florida Coastal Engineering Laboratory in Gainesville, Florida. Tests at both facilities have demonstrated the ability of the breakwater to withstand once-in-a-million-year storm conditions. The tests at Gainesville have clearly demonstrated that wave action within the breakwater basin will be at acceptable levels during storm and wind conditions. Tests at the same facility have also verified the ability of the breakwater to protect the plant from ship collision.

Each plant will be moored securely within the breakwater basin to prevent contact with other plants or with the breakwater itself. The mooring system selected for the Atlantic Generating Station consists of a total of eight struts connecting two sides of each of the two plants to massive concrete mooring caissons located within the basin (Figure 7).

Power generated by each floating plant will be transmitted to an on-land switching station by two underground circuits operating at 345,000 V. Each three-cable circuit will extend some 11 miles. For three of these miles, the cables will be buried at least 8 ft beneath the ocean floor. The remaining eight miles will be under land.

Unlike land-based installations, floating plants require a concept of flexible electrical cables capable of conducting power while subjected to vertical movement of the platform due to wind, wave, and tidal conditions, including major storms. For the Atlantic Generating Station, this movement is predicted to be >20 ft. Investigations by cable manufacturers have indicated the feasibility of cabling concepts that can respond without loss of performance through continuous normal and occasional severe differential movement.

In an attempt to ensure that no adverse effects on the environment and marine ecology will result from construction and operation of the Atlantic Project, Public Service is engaged in one of the most comprehensive environmental study programs ever undertaken in this country.

A survey of the existing marine biology and salt marsh ecosystems has been under way since 1971. The work, conducted by Ichthyological Associates, includes a specimen sample program to establish population and species distribution in the adjacent bays, inlets, and salt marshes, as well as in the vicinity of the site.

The marine biology studies also include determination of the water-temperature preferences of selected species of fish, their swimming speeds at different seasons, reproductive patterns, eating habits, migration patterns, and other information needed to understand the ecology of the area and the mutual impact of nuclear plant and ecology, and to ensure satisfactory coexistence. The studies will be continued for a number of years after operation begins in order to make certain that no adverse ecological effects appear.

A potential source of environmental effect on marine organisms is the water used for condenser cooling. By providing a large screened intake area, the approach velocity of this water will be kept low enough to permit fish to escape from cooling water drawn toward and through a floating nuclear plant. Because of the large expanse of the ocean, adverse effects due to warm discharge should not exist. Fish may be attracted to the warmer water of the discharge plume. However, the temperature rise is expected to be $\geq 5^{\circ}\text{F}$ only in the 5-acre area adjacent to the discharge openings.

Thermal hydrology studies have been done at the Massachusetts Institute of Technology Model Laboratory to predict the thermal regions produced by the cooling-water discharge.

The artificial reef effect of the breakwater is expected to enhance the fish population and provide all organisms with a much more favorable environment than the present sand bottom. Fishing around the breakwater should be excellent, since experience has proved that artificial reefs create fish havens.

Studies have been undertaken to determine whether the breakwater will change present beach erosion patterns. One of the most demanding oceanographic studies is the determination of potential bottom erosion and littoral drift. This work consists of detailed surveys of current patterns, tidal influences, waves, temperatures, and related data for the near coastal zone of the plant site. Results from this program will provide other researchers in the field with mass water movement characteristics of the New Jersey Coast.

The offshore location of the Atlantic Generating Station has posed a number of specialized meteorological requirements, none of which are completely defined

by existing conventional data. Information on the general climatic patterns is available, but details of wind, turbulence, and dispersion patterns for the land-sea interface region are virtually nonexistent. These patterns must be established by an elaborate measurement network, involving novel techniques and results.

Environmental radiation monitoring will be conducted by methods similar to those used for land-site investigations, but adapted to the peculiarities of the ocean environment. The natural radiation levels in the ocean water, sediments, and marine biota in the vicinity will be measured. Special attention will be given to radioisotope concentration by marine species, passage to higher trophic levels, and potential critical pathways to human consumption. No assumption is made that the plant, because of its remote offshore location, can operate under relaxed requirements for effluent releases.

The comprehensive program of environmental studies will establish the existing conditions, and continuing studies will determine whether or not offshore nuclear-powered generating stations will have an adverse effect on the environment.

At present, no construction activities are under way for the site and breakwater or for the floating plant. Operation of the first plant is scheduled for the spring of 1985. To meet this date, site work in preparation for breakwater construction must start in 1979. In the same year, work on the first floating plant is expected to begin at the Jacksonville manufacturing facility of Offshore Power Systems.

Project efforts for both site and plant are centered around support of license applications, site studies, model testing, preliminary engineering, and construction

Table 1

Number of Permits Required for the Atlantic Generating Station
From Various Government Agencies

	No.	Total
<u>Federal Government</u>		
Nuclear Regulatory Commission	5	
Federal Environmental Protection Agency	1	
Army Corps of Engineers	7	
Federal Aviation Administration	6	
Coast Guard	2	
Department of the Interior	1	
		22
<u>State of New Jersey</u>		
Department of Environmental Protection	27	
Department of Labor and Industry	2	
Department of Health	1	
		30
<u>Local municipalities</u>		
Little Egg Harbor Township	5	
Ocean County	1	
		6

planning. Public Service's application for a site and breakwater construction permit was submitted to the Atomic Energy Commission (now the Nuclear Regulatory Commission) in December 1973 following approximately two years of preliminary review by the Commission. During the past two years the initial application has been supplemented by numerous documents. It is anticipated that the licensing review will be completed and a site construction permit issued in 1977.

Approval by the Nuclear Regulatory Commission is only one step; more than 50 local, state, and federal permits are required for the Atlantic Generating Station (Table 1).

The Offshore Power Systems' plant license application has been in the Nuclear Regulatory Commission's review process for several years; issuance of a plant manufacturing license is expected in 1976.

To summarize, I have highlighted our progress toward the installation of floating power plants, which represent a beneficial use of the continental shelf. The demonstration of the feasibility of such facilities with existing technology, and the thorough support by safety and environmental reviews, have been made possible by the efforts of engineers and scientists working toward supplying the nation's growing energy needs.

DISCUSSION

FRIEDLANDER: I have heard that the consortium of Westinghouse and Tenneco has been experiencing financial difficulties and there is some question as to whether the project will continue. It is not clear to me whether the facility in Jacksonville is still operational and how this will affect your projected timetable. Has it retarded your program?

MITTL: The program has been retarded several years but the factors involved are not those you mention. About one year ago, Public Service announced that because of a substantially reduced load growth following the energy crisis, we were unable to proceed with prior schedules for installing new generating capacity. The schedules for the Atlantic Generating Station's units were moved up by ≈ 5 years. The units were originally scheduled for operation in the very early 80's, but now we are talking about 1987 for one or two units. The work in Jacksonville had to be rescheduled to match the later dates. Earlier this year, in late January or early February, Tenneco terminated their involvement in the Offshore Power Systems, so that at this point only Westinghouse is involved. It was originally felt that orders for eight floating units would be a prerequisite to moving forward with the full manufacturing facility. It now seems that a facility less extensive than the ultimate development in Jacksonville will be provided and will be justified by the manufacture of four units. In addition to Atlantic One and Two, Public Service has purchased two other floating units from OPS for operation in 1990 and 1992. Thus four units have been ordered, which is a "go" situation for the OPS operation. Some of the manufacturer's facilities exist. Dredging for the slip and the drydock area is under way; some of the buildings are being constructed; and a large crane to span the dredge slip is on site. Construction of the facility seems to be going forward, and a recent meeting between OPS and the Advisory Committee on Reactor Safeguards appears to indicate that the Committee has concluded its review.

STRONGIN: Would you comment on the problem of the increased costs of this facility and what the cost in terms of design capacity would be vis-à-vis that for a land-based fossil-fueled plant?

MITTL: Because of rescheduling the units from the early 1980's to the mid-1980's, the cost of the Atlantic station has gone up, in line with the escalation anticipated during the additional

five years before purchases and various labor-related expenditures can be made. Even so, the electrical capacity and electric energy provided by the Atlantic station will be substantially less expensive than that obtainable from fossil generation in New Jersey and in many other areas along the coast. Our studies have shown that the cost for the plant out in the Atlantic will be lower than the cost of nuclear power from land-based plants built in New Jersey for operation in the same time period.

BLEECKER: Would it have been more desirable from an engineering point of view to site the plant beyond the three-mile limit rather than within the territorial state margin?

MITTL: No, the particular site and the sites available along the shore have a water depth of ≈ 40 ft. To go farther would mean going into deeper water, which would entail much greater costs for the breakwater and a much more costly installation to bring the electrical power in via submarine cables. From the standpoint of either safety or plant operation, we can see no gains. All we can expect from moving out farther is increased costs.

Nature of Potential Oil Industry Operations on the Atlantic Continental Shelf

EDWIN O. BELL

Mobil Oil Corporation, New Orleans, Louisiana 70113

Only in recent years has the general public become aware of the possible effects of some of man's actions on our environment. This Conference, like many others countrywide, is evidence that questions are being raised about public, industrial, and governmental activities that might affect the environment. This questioning attitude has resulted in dissemination of information and provided a basis for sound decisions. To this end I should like to describe the activities involved in offshore operations.

First, a word about our country's energy stake offshore. U.S. oil demand now exceeds domestic supply by 6 million barrels a day – almost 40% of total demand. Unless new reserves are discovered and developed, by 1985 this gap could grow to 15 million barrels of oil a day. Basically, the gap will have to be filled by either increased imports or increased domestic production. In spite of intensified efforts to increase ultimate recovery from known petroleum deposits, the bulk of our new domestic production is expected to come from fields not yet discovered.

We believe that the offshore areas of the Outer Continental Shelf, including the offshore Atlantic, offer the largest and most significant potential.

The Atlantic Continental Shelf stretches 1360 miles from the Canadian border to the tip of Florida and covers some 160,000 square miles. Despite its proximity to the heavily populated and industrialized Eastern United States with its growing energy requirements, this vast area has never been subjected to drilling to determine its oil and gas potential.

Geological and geophysical experts have pinpointed three areas of greatest potential (Figure 1): (1) the Georges Bank Trough, 30 to 120 miles off New England; (2) the Baltimore Canyon Trough, a 150-mile-long deepwater trench centered some 25 to 90 miles from the coastline of the Middle Atlantic States; and (3) the Southeast Georgia Embayment and the Blake Basin extending 150 miles from the coasts of South Carolina, Georgia, and Florida.

All offshore lands are under control of state and federal governments and are therefore subject to offerings or lease sales at the discretion of these governments. This spring the U.S. Department of the Interior called for nominations in the Baltimore Canyon Trough area. The oil industry nominated for lease some 3.2 million acres. The Department has listed 154 tracts totaling 876,750 acres and has tentatively scheduled a lease sale for this area in May 1976. The Department has also called for nominations in the Georges Bank area and has tentatively scheduled a lease sale there for August 1976. On September 12, a call for nominations was published in the Federal Register for the Southeast Georgia Embayment area running from Cape Fear, North Carolina, to Cape Canaveral, Florida. The deadline for nominations was November 3, 1975, and a lease sale for this area is scheduled for November 1976.



Figure 1. Areas of potential oil and gas deposits along the Atlantic Continental Shelf.



Figure 2. Research vessel used in making marine seismic surveys.

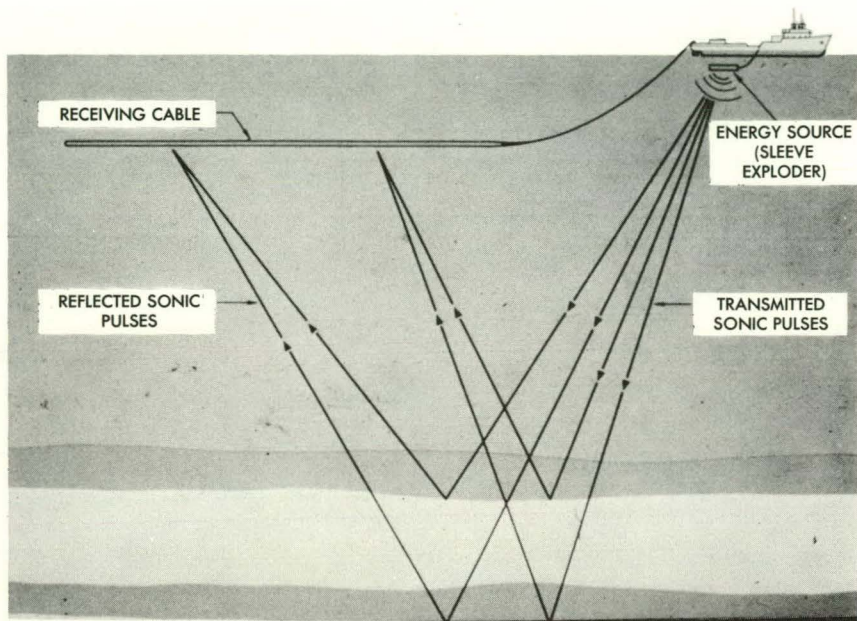


Figure 3. Generation of sound energy to give information about the substrata.

Offshore lease sales usually are made on the basis of competitive bonus bids for specific acreage tracts or blocks. In the past, other bidding procedures have been employed by state governments. The Federal Government, however, has varied only once from the bonus bid method; on that occasion 10 tracts in the Gulf of Mexico were offered on a combination bonus and royalty bid basis.

On the Atlantic Continental Shelf, as in the other offshore areas, interested companies have spent the last few years in geological and geophysical evaluation in order to select the most promising areas for nominations. Once an area has been nominated, the Department of the Interior develops and issues a preliminary environmental impact statement, as required by the National Environmental Policy Act. Open hearings must then be held to give the public an opportunity to express its views. If a favorable final impact statement is issued, a lease sale is held and petroleum companies bid on leases offered. Companies submit sealed bids to the Department of the Interior's Bureau of Land Management, indicating how much per acre they will pay the Government for specific tracts. Later, the Bureau awards leases to the highest bidders.

Since 1966, geophysical contractors have been conducting seismic surveys in the Atlantic. To date, >80,000 seismic miles have been run. In these surveys a research vessel of the type shown in Figure 2 is used; its cost ranges from \$2 to \$5 million. It is designed to provide information about the substrata by generating sound energy and noting through various recording devices the manner in which this energy travels through the ground. In the early years of offshore exploration, this sound was generated by heavy charges of dynamite. Modern-day geophysical operations offer

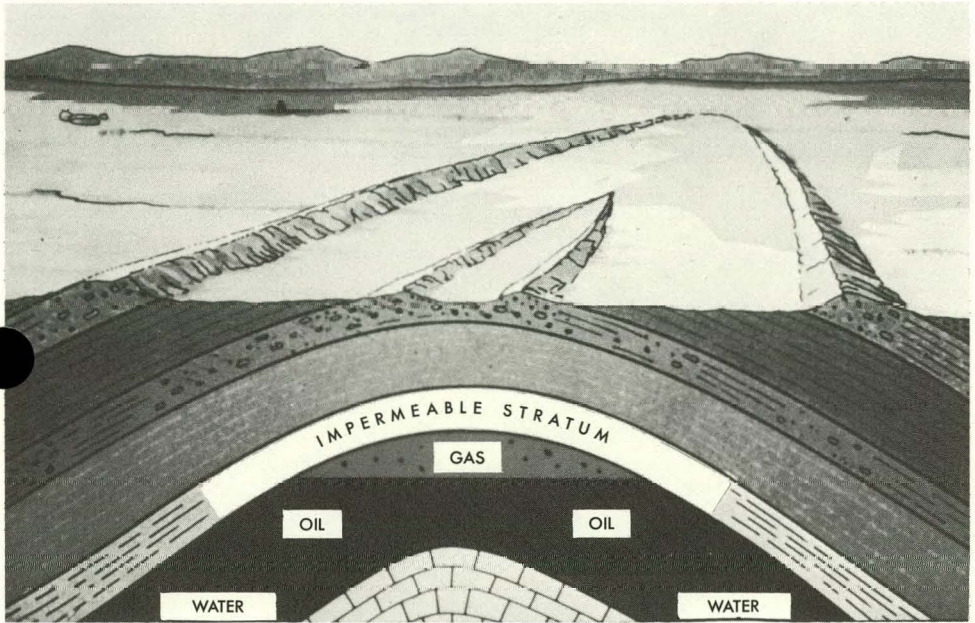


Figure 4. Anticlinal trap.

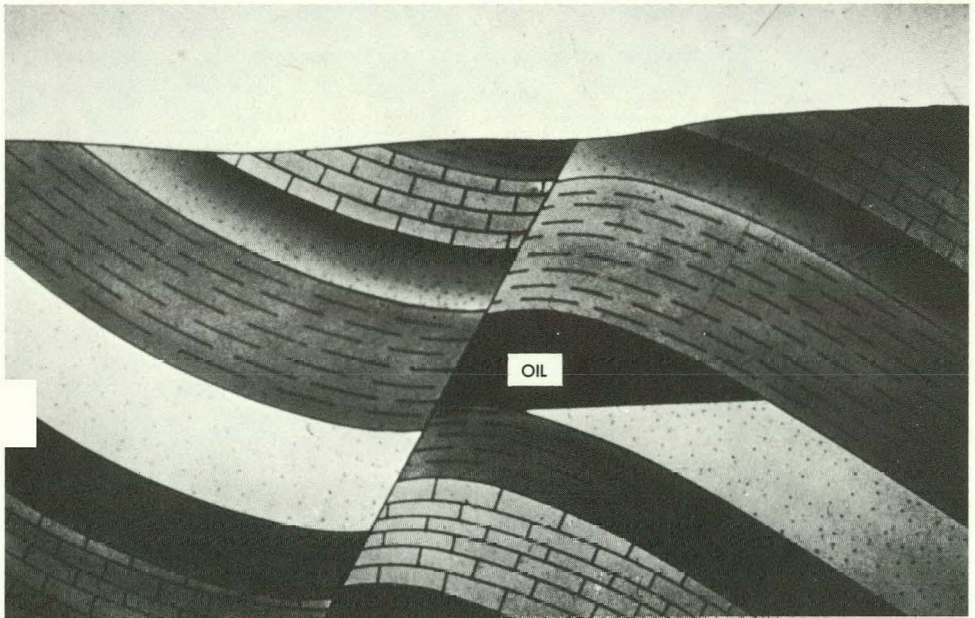


Figure 5. Fault trap.

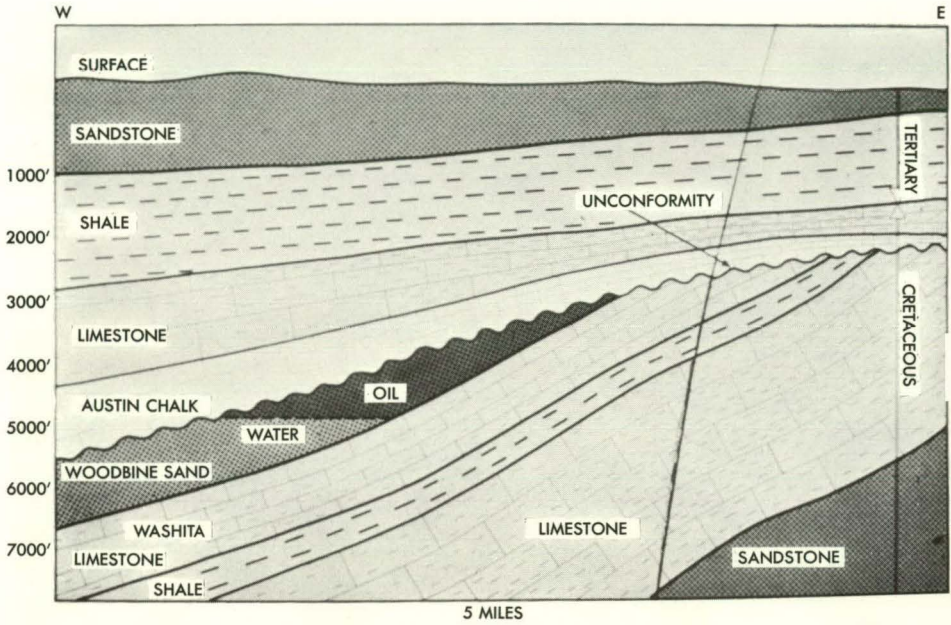


Figure 6. Stratigraphic trap (east-west cross section of East Texas Reservoir).

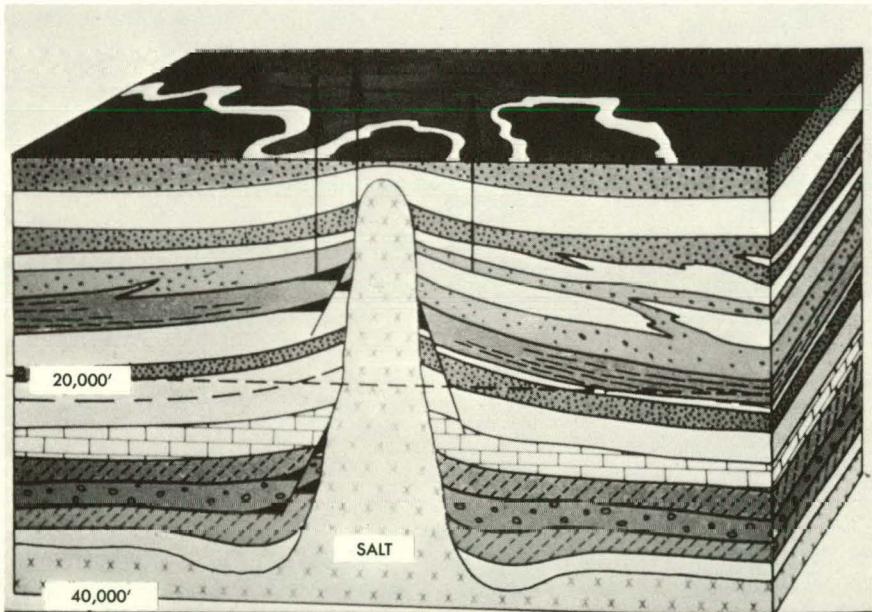


Figure 7. Salt dome.

no hazard to the environment or to other users of the offshore waters. New equipment has radically changed the manner in which exploration is done. Air guns now account for >95% of marine seismic activity. Sound energy generated by these air guns is picked up by trailing hydrophones, as shown in Figure 3.

After leases have been awarded to the highest bidders, detailed seismic shooting is usually conducted over the prospect to select the most favorable location to drill. The prospect may be any one of four types of geologic trap. Anticlinal traps (Figure 4) result from folding of subsurface strata due to the increasing weight of overlying sediment. The oil or gas is lighter than water and moves to the top, where it is trapped. Fault traps (Figure 5) are formed when stresses caused by overlying sediment or movement deep within the earth cause the rock to shear along fault planes.

An impervious section of earth moves across the fault opposite the stratum with oil or gas and keeps the hydrocarbons from moving farther up the stratum. Stratigraphic traps (Figure 6) result when permeable and porous rock is laid down and surrounded by impervious rock. The oil and gas move in the porous rock but are trapped on reaching the impervious strata. Salt domes (Figure 7) are common along the Gulf Coast. They are also present in the Atlantic off eastern Canada. During geologic time large salt deposits have been buried by additional sediments whose weight has forced the flexible salt to flow out and upward through zones of weakness and pierce the overlying rock. Oil and gas migrate to the salt mass but can go no farther. In the Gulf of Mexico some salt masses cover 25,000 to 30,000 acres and rise almost to the sea floor.

Although much is known about the geology of the continental shelves and the types of rocks and structures expected to occur there, exploration of these areas is a costly and unpredictable business. This was demonstrated by the severe losses sustained by the industry in the eastern Gulf of Mexico. In 1973 the industry spent \$1.5 billion for 87 tracts there. After 15 dry holes, costing an estimated \$50 million, no commercial hydrocarbon deposits were found.

Following seismic shooting, a drilling rig is moved to the drill site. The rig may be a semisubmersible, a jack-up, or a drill ship. If the water depth is <300 ft, the exploratory well is usually drilled with a jack-up rig, so called because when it is being towed to location the main buoyant section, or hull, of the rig floats, and the legs are off the bottom (Figure 8). Once the rig is on location, the legs are lowered to the bottom, and the rig is jacked up (Figure 9). These rigs are very stable. Once in position they are like a fixed platform offering very little resistance to wave action, since the main rig section is well above the normal wave action. The capital investment in such a rig can be as much as \$25 to \$30 million, with rental rates as high as \$45,000/day. Normal operating costs for such a rig average \$35,000 to \$45,000/day.

In water depths >300 ft, a semisubmersible rig (Figure 10) is usually chosen. The portion of the rig under the surface of the water (the pontoons) normally floats on the surface while the rig moves to location. Once on location, the pontoons are ballasted and submerged. Anchors and cables from each of the four corners hold the rig in position. Wave action is minimized because of the small number of structural members exposed. The semisubmersible is not as stable as a jack-up but can operate in very rough seas with minimum pitch and roll. The advantage of the semisub-

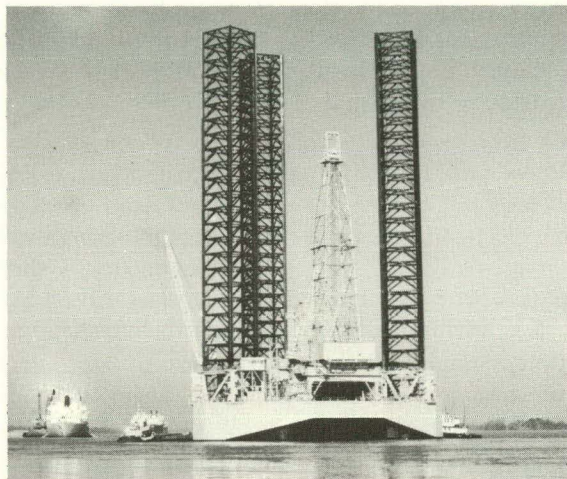


Figure 8. Jack-up rig being towed to location.



Figure 9. Jack-up rig in position.

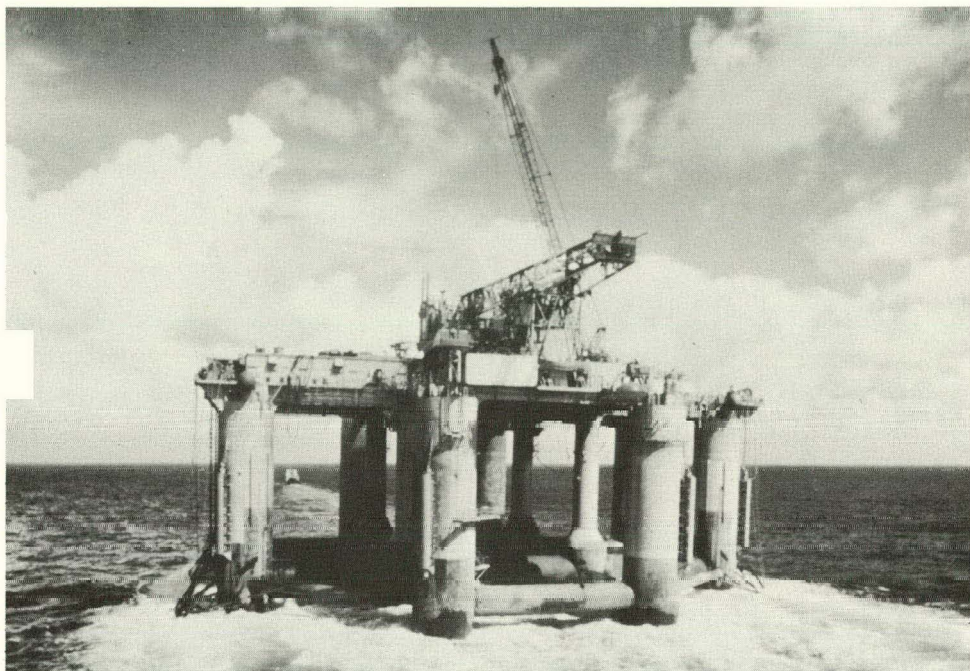


Figure 10. Semisubmersible rig being moved to location.

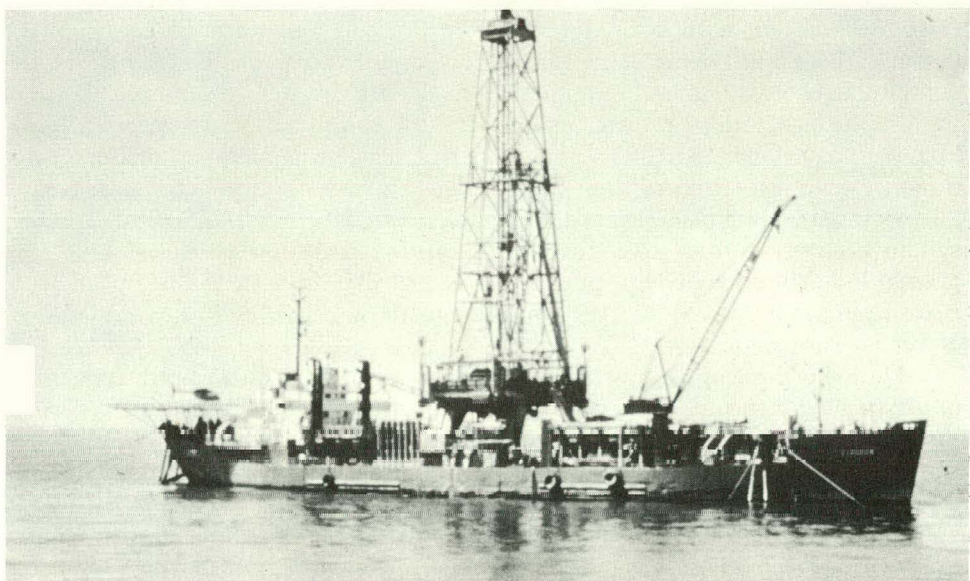


Figure 11. Drill ship.

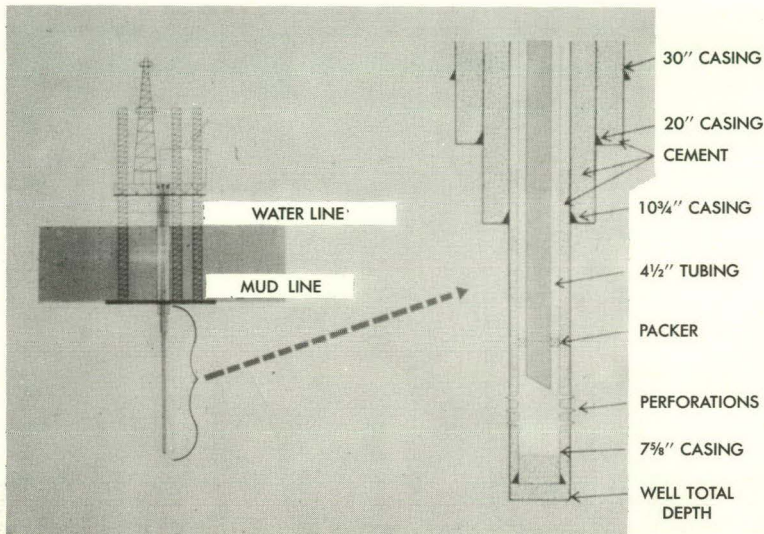


Figure 12. Typical casing program for well.

mersible is the capability to drill in water depths up to 2000 ft. By using computers and dynamic positioning rather than anchors, wells have been drilled in water 3000 ft deep.

Drill ships (Figure 11) are usually used in remote areas of the world, where their large cargo-hauling capacity and speed of movement are advantages. The ships are held on location by anchors from the bow and stern. They are not as stable as the semisubmersible and jack-up rigs but are capable of drilling in water depths of 2000 ft with anchors and up to 6000 ft with dynamic positioning. Costs for some of the larger new semisubmersibles and drill ships are running \$45 to \$50 million, with day rates $\geq$ \$50,000. All drilling rigs, whether jack-up or "floater," must stand rigorous inspection by the U.S. Geological Survey and the U.S. Coast Guard. Sixty-seven items are field-checked, including personnel safety equipment, rig power system, pollution control procedure, casing setting procedures, drilling fluid programs, and drilling safety equipment. Failure to pass inspection on any of these items results in a citation. For certain citations all rig activities are suspended until corrections are made.

During drilling operations, the primary environmental hazard is the possibility of unexpectedly encountering unusually high subsurface pressure, losing control of the well, and experiencing a "blowout." With today's modern technical competence, this possibility is extremely remote. Drilling personnel are trained to respond quickly, should instruments indicate that a so-called kick is coming. A kick is a pressure imbalance that threatens to overcome the weight or pressure of the drilling fluid, or "mud." Considerable technology is involved in the use of this mud, which is a mixture of chemicals, water, and solids that serves a variety of purposes. The mixture is adapted to the characteristics of the area being drilled. Mud is circulated down the well, out

through the drill bit, and back up the outer part of the bore. The mud carries cuttings up out of the hole, lubricates the bit, helps preserve the bore, and helps contain pressure at the bottom of the hole. Should there be warning of a kick, crews respond quickly to increase the weight of the mud and circulate out the oil or gas-cut fluid. As an added precaution, all drilling rigs are equipped with at least three blowout preventers. These are tested to design capacity on installation and frequently thereafter during drilling.

In designing a casing program for each well (Figure 12), all the geological and geophysical information available is used. Successive strings of steel pipe are cemented in the hole from the surface pipe on down. These prevent contamination of the flow-water sands during drilling and provide ultimate control of the drilled well.

Should the initial test well be dry, the hole is plugged with cement, the steel casing is shot off 15 ft below the mud line, all obstructions are removed from the sea floor, and the bottom is dragged to be sure no obstructions have been overlooked. In some cases, several exploratory wells must be drilled on a 5000-acre block before the lease is totally condemned or hydrocarbons are found. Should reserves indicating commercial production be found, it may be necessary to drill several confirmation tests before the company is satisfied that the reserves will economically support the installation of a multimillion-dollar drilling-production platform. The platform location in relation to hydrocarbon deposits must be extremely accurate to minimize the number of platforms installed.

In the early days of offshore exploration in shallow water, wells were drilled and spaced much as they were on land. In deeper water, however, most of today's wells are drilled from a platform constructed onshore and then barged to the offshore well site. The platform is offloaded and set on the sea floor with the assistance of derrick barges like the one in Figure 13. Piling is then driven through the legs to hold the platform securely in place. The actual installation of the jacket section requires only a few hours. Any turbidity from this activity is quickly dispersed before appreciable damage can be done to aquatic life.

Figure 14 is a schematic drawing of a typical platform, showing the main sections. The jacket section is almost entirely under water. The deck section is installed on top of the jacket and welded in place. The drilling rig is placed on the top deck. The well control valves are normally in the lower or cellar deck.

A completed drilling platform, with rig, living quarters, and equipment, is shown in Figure 15. From one such structure, multiple wells can be drilled in various directions. There are numerous structures in the Gulf of Mexico from which 185 wells have been drilled. The various patterns that can be used in drilling directional holes are shown in Figure 16. The angle from vertical can vary up to 65° to 75° , and the bottom of the hole can be 1 to $1\frac{1}{2}$ miles out from vertical, depending on the depth of the particular formation. It costs more to drill a deviated hole, with all the wells being surfaced on the platform. But then there is no need for expensive flow lines between the individual wells and the producing facility, and the density of surface structures is significantly reduced. On completion of the development drilling phase, which usually takes 18 months to 2 years, the drilling rig is removed and production equipment is installed on the drilling platform. In some instances it is in-

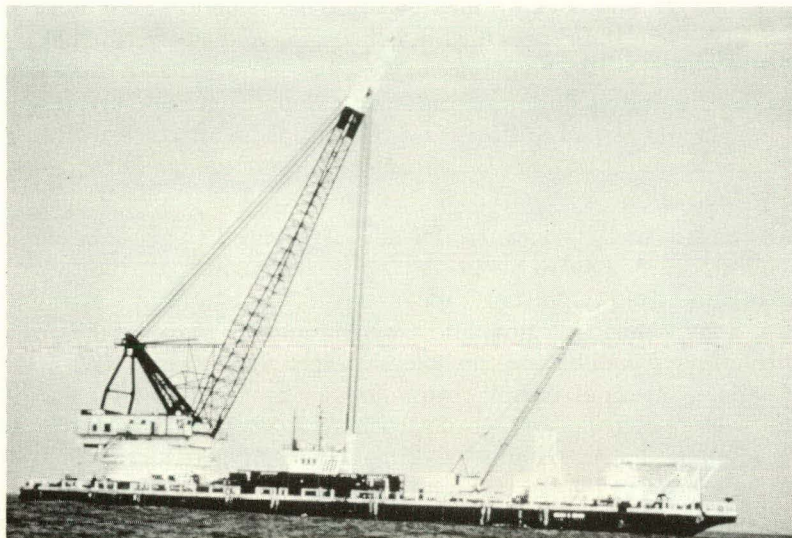


Figure 13. Derrick barge (500-ton) of the type used to install drilling platforms. Such large barges have operating costs of \$35,000 to \$40,000/day.

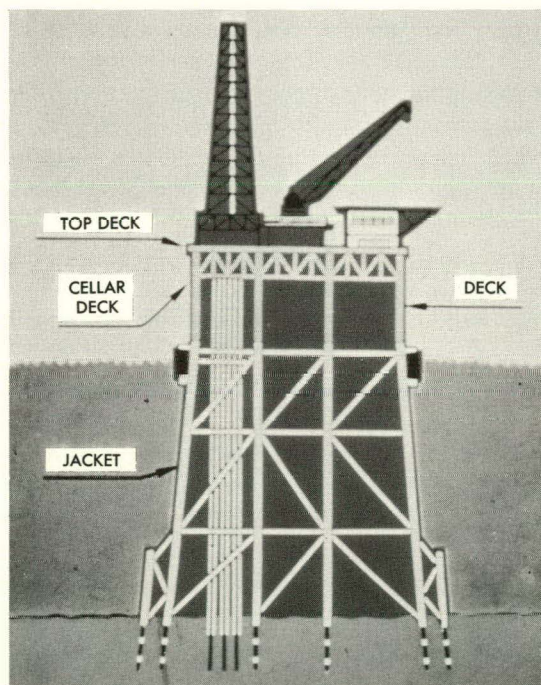


Figure 14. Typical drilling platform installation.

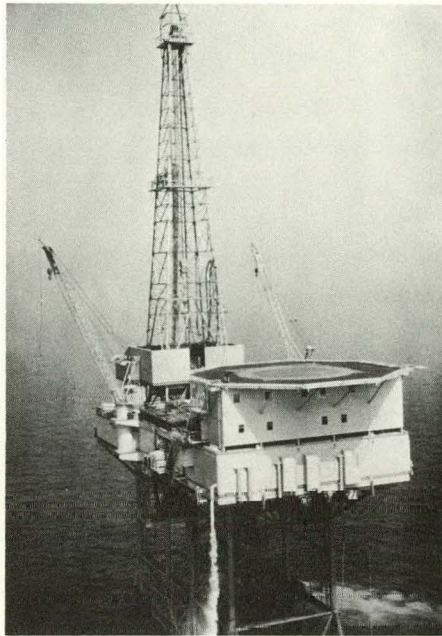


Figure 15. Drilling platform, showing rig, living quarters, and equipment.

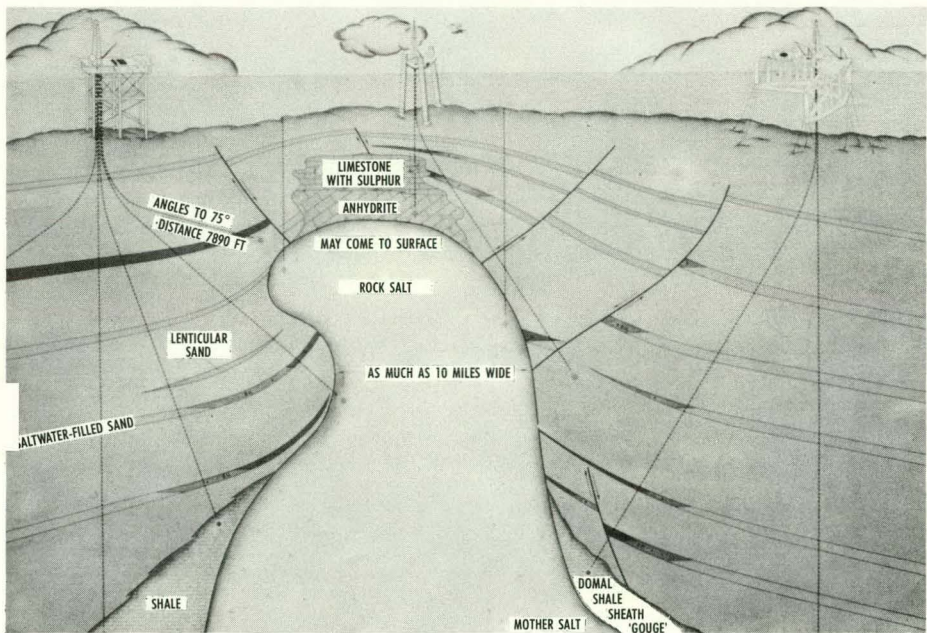


Figure 16. Patterns used in drilling directional holes.



Figure 17. Facility installed in producing field offshore Louisiana.

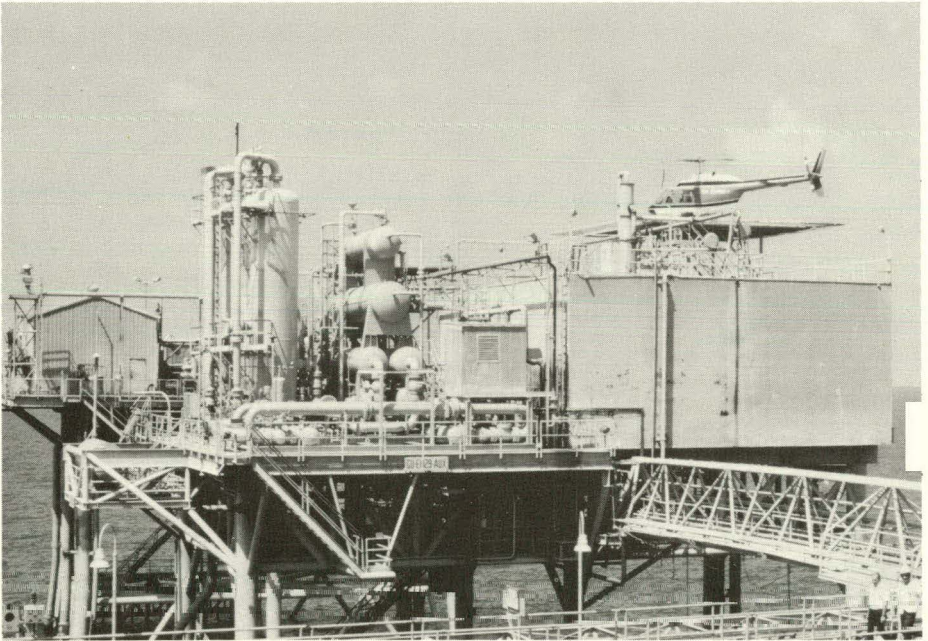


Figure 18. Facility with heliport atop living quarters.

stalled on adjacent structures and bridged back to the drilling platform. The wells are then ready to be placed in production.

Two facilities currently installed in producing fields offshore Louisiana are shown in Figures 17 and 18. A heliport can be seen on top of the living quarters in Figure 18. Living quarters for 36 men currently cost about \$1 million. The men normally work seven days offshore and spend seven days onshore, off the job. The living quarters are maintained like a hotel by cooks and stewards. Recreation rooms are available with color television and pool or other game tables. Walkways connect the living quarters to the other platforms, in this case the wells and the producing equipment that separates the oil, gas, and water produced from the wells.

Like the drilling rig in the initial drilling phase, all equipment placed on the shore lease must be approved by the U.S. Geological Survey. Outer Continental Shelf Orders No. 1 to 13 deal with every phase of the operation and specify such things as the amount of casing to be run; subsurface safety valves; high-low pressure pilots on all flow lines and headers; high-low liquid-level controls on all production vessels and tanks; high-temperature shutdowns on all fired equipment; gas detectors; shielded ignition on all internal combustion engines; and pressure relief systems set to vent through adequate scrubbers well below the critical test pressures. All these instruments are tied into a platform safety system. Should any one of them fail, the well, or in some cases the entire platform, would shut in automatically. In addition, the OCS orders require sewage disposal facilities on all manned platforms.

In some fields, formation water is produced with the oil and gas. This water is separated from the oil or gas and then passed through an elaborate "water polishing" device to further reduce minute traces of oil. An OCS order specifies that the oil content must be ≤ 50 ppm before the water can be discharged into the Gulf.

As with drilling rigs, the U.S. Geological Survey conducts frequent unscheduled inspections on all producing facilities in the Gulf. These inspections cover 135 items relating to safety devices, pollution control, fire-fighting equipment, etc., and in many cases reflect the best practices of the various operators in the Gulf.

Occasionally, even in the best operation, a minor spill will occur. By law all spills – even a cupful – must be reported. The reporting keeps all the offshore operating personnel alert; no one wants to have a spill entered on his platform operating record.

The U.S. Coast Guard has adopted regulations for the installation of aids to navigation to protect the mariner. It has also specified safety equipment and procedures to protect men working on platforms. Each platform is required to display prominently operator identification and location. The platforms have become havens of safety for many Gulf Coast fishermen caught offshore in storms. They have served also as navigation landmarks enabling fishermen to venture farther offshore.

From both the operational and the environmental point of view, pipelines are the most practical means of transporting oil from offshore tracts. Indeed, natural gas can reasonably be moved ashore only by pipeline. The evidence is overwhelmingly clear that the offshore, or underwater, segments of these oil and gas pipelines pose no environmental hazards. Each installation must have the express approval of the U.S. Geological Survey. Each line must be tested to well above its normal operating pres-



Figure 19. Fast-response open-sea and bay skimmer system.

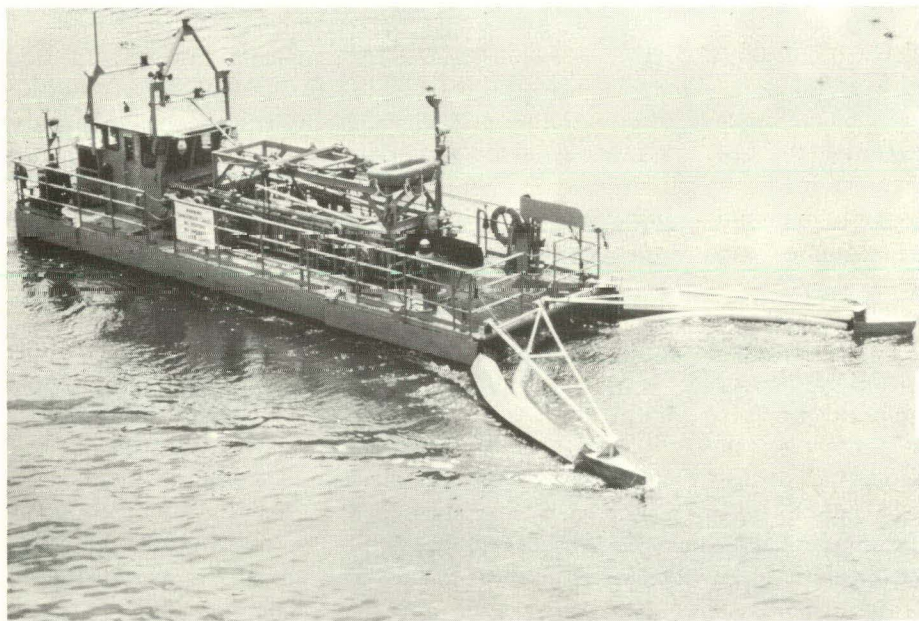


Figure 20. Shallow-water skimmer system.

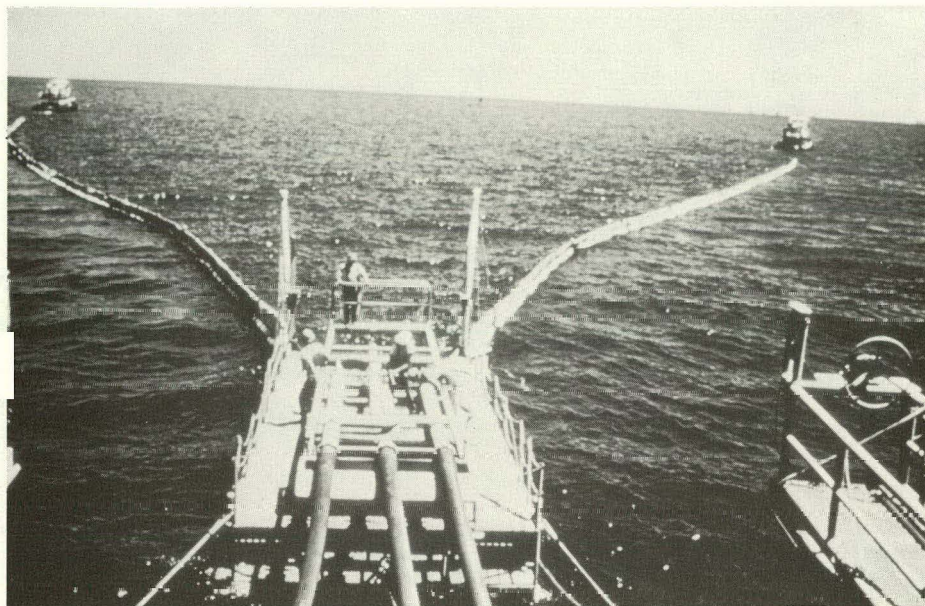


Figure 21. High-volume open-sea skimmer.

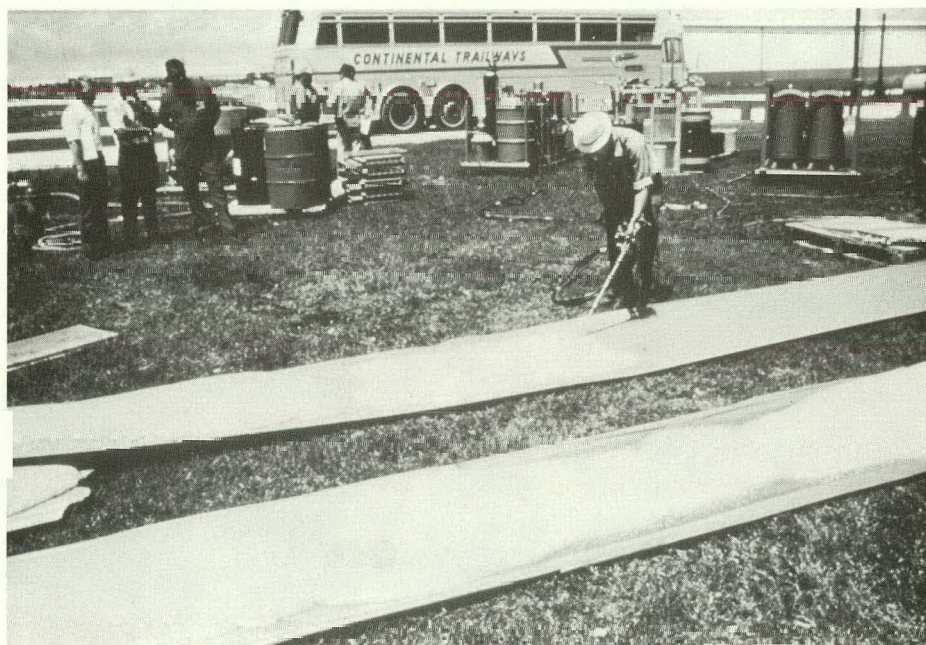


Figure 22. Polyurethane foam pads being formed.

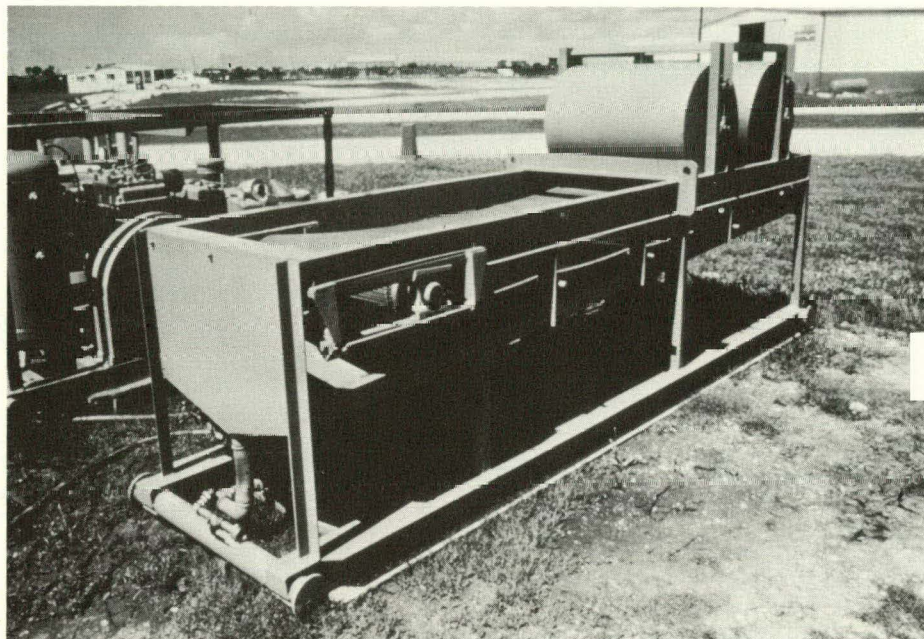


Figure 23. Wringer through which polyurethane foam pads are run to make them reusable.

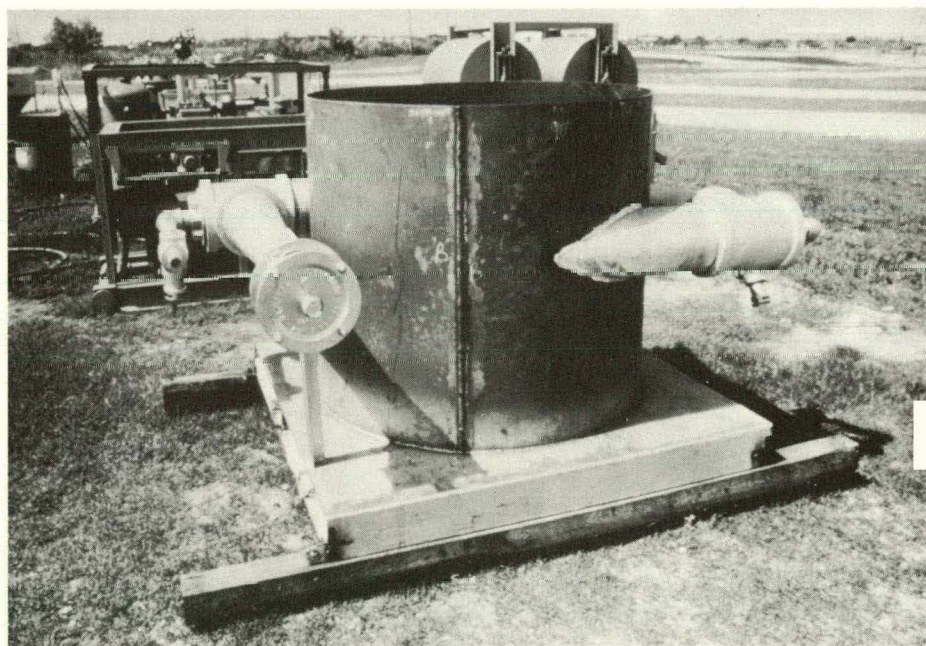


Figure 24. Smokeless incinerator for ultimate disposal of polyurethane foam pads.

sure before it is used. The present OCS administrative procedures require that all new pipelines be buried out to the 200-ft water depth. Pipelines installed in the Gulf of Mexico have not been a problem for the shrimping industry.

In the unlikely event of a serious oil spill, the petroleum industry is prepared to respond in the areas in which it operates. Cooperatives such as the Clean Gulf Associates have been formed. This organization of 43 companies has stockpiled four basic types of equipment for emergency use; (1) fast-response open-sea and bay skimmer systems, (2) shallow-water skimmer systems, (3) a high-volume open-sea system, and (4) auxiliary equipment and beach cleanup systems.

The fast-response units are built to respond quickly to any oil spill. The systems are mounted and designed to fit on the deck of a boat in the 60 to 95-ft class or larger (Figure 19). A fast-response unit can reach a spill 100 miles from its base in < 12 hr. Once on location, the boom and skimmer are deployed and oil pickup is started.

A shallow-water system (Figure 20) is used for spills in bays and calm protected waters close to shore.

The high-volume open-sea skimmer, dubbed the Hoss, is a self-contained system with all equipment, such as the open-sea containment boom, skimmer, separator, storage tanks, pumping, and auxiliary power and lighting equipment, mounted on a 52 × 150-ft barge. In a spill situation, the Hoss is towed to location by a tug. Two other vessels deploy the boom, the skimmer is launched, and recovery is started. Oil on the water is directed to the skimmer by the outstretched booms (Figure 21), and pumps suck the oil from the skimmer to storage tanks on the barge.

Clean Gulf Associates also has many auxiliary items and beach protection equipment. All are packaged for quick deployment, and most can be transported by helicopter.

Figure 22 shows polyurethane foam pads being formed. This very effective sorbent material is used to pick up oil. The foam pads can be run through a wringer (Figure 23) and reused. Afterwards, they can be disposed of in a smokeless incinerator (Figure 24). Three drums of this foam-generating material are the equivalent of about 60 tons of straw.

Although such equipment is not now stockpiled on the Atlantic Coast, similar protection undoubtedly will be provided if offshore drilling and production activities are commenced in this area.

In summary, this has been a brief overview of offshore oil industry activity from the first seismic survey through the exploratory drilling, development drilling, and finally the production phase. The petroleum industry has drilled some 20,000 offshore oil and gas wells in the Gulf of Mexico and offshore California and Alaska with no incident that has resulted in permanent damage to the environment – none. We believe the industry has the work force, the technical skills, the management, and the organization to meet the future needs of the people and to protect the environment at the same time.

DISCUSSION

QUESTION: Would you comment on what you think the odds are of finding oil and gas in the Atlantic Continental Shelf as contrasted to other such areas in the U.S.? How favorable is

the geology out here for oil and gas accumulation, considering that Sable Island up in Canada has been one big bust?

BELL: Sable Island in Canada hasn't been a big bust.

QUESTION: They drilled 80 wells up there and only about three have found anything. It doesn't look commercial, although the sedimentary accumulation seems comparable to what you find in the mid-Atlantic.

BELL: One thing that has made Sable Island uneconomical to date is the 400-ft trench between the find and the mainland of Canada. Once you get on the mainland, there are no refiners' facilities for many, many miles. This would not be the case off the mid-Atlantic here. Mobil has found oil and gas in its wells off Sable Island, but not in amounts that justify bringing it to shore.

QUESTION: What oil reserves would be required off the Atlantic Continental Shelf to make it economical? What would be the size of a field?

BELL: The U.S. Geological Survey has estimated that there could be as much as six billion barrels of oil in the Atlantic offshore region. Industry has run some 88,000 miles of seismic lines out there. There are some very interesting structures and potential traps. In view of the industry's bust in the northeast Gulf of Mexico, we don't want to say that there is a lot of gas out there, but there are good prospects.

Session II

Characteristic Physical Processes of the Atlantic Continental Shelf

Chairman: G.T. CSANADY

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Wind-Driven and Thermohaline Circulation Over the Continental Shelves

G.T. CSANADY

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INTRODUCTION

The principal driving forces of water movements over the continental shelves are the wind stress and the horizontal pressure gradients due to density differences and to tidal waves propagating toward shore from the deep ocean. Tides with their well-defined frequencies constitute a special kind of motion that is better understood than other motions; they are treated elsewhere in this Conference.¹ Here we shall discuss the more chaotic patterns of flow induced by the winds and by the differences in temperature and salinity between different parts of the shelf, which we shall refer to as thermohaline circulation. In attempting to understand these motions many difficult dynamical problems arise, some of them requiring considerable mathematical development. Here I shall discuss the physical properties of water movements over continental shelves, omitting the mathematical arguments necessary for a more rigorous approach.

The most fundamental question in the atmospheric sciences generally is, In what sense can we expect to understand a system as complex as the atmosphere or the ocean? The human mind can appreciate simultaneously only a relatively small number of quantitative parameters. *All* the details of water motions in a given portion of the ocean cannot be described, even in principle, by a finite number of parameters, and even reasonable detail would be beyond our capacity to absorb. It is therefore necessary to distill from experience what might be called distinct phenomena, certain conspicuous features of observed motions that are continuously present or recur regularly, and attempt to understand these phenomena in isolation. It is usually possible to construct a conceptual model for the purpose of such piecemeal understanding, i.e., an imaginary ocean with simple characteristics and subject only to a limited number of external influences, in which calculations reproduce a given

distinct phenomenon qualitatively and, to a degree, quantitatively. Several examples of such conceptual models are given below. For a satisfactory degree of understanding in a given subfield of the atmospheric sciences, many conceptual models are usually required. In the case of continental shelf dynamics we are certainly far from this stage. The number of models is far too few, and what we have is poorly related to observation. Several of these models arose in connection with work on our great inland shallow seas, the North American Great Lakes, especially in the course of efforts related to the International Field Year on the Great Lakes (IFYGL). Most of these models are probably applicable to other shallow seas, especially the continental shelves, but some of the quantitative relationships may be affected by salinity differences and by interaction with tides, two influences absent in the Great Lakes. In addition, the existence of an open boundary at the edge of the shelf poses nontrivial and complex problems. Thus the discussion below is far from complete; in fact, it is only an attempt to piece together the few extant conceptual models I think important, and to speculate on a few other problems.

CHARACTER OF FORCING

At our latitudes winds are quite irregular, although westerlies generally predominate. The stress of the wind on the sea surface is proportional to the square of the wind speed and is therefore dominated by periods of strong wind. Episodes of strong winds (storms) occur with a typical frequency of once in 100 hours and last for 10 hours or so, but there is no regular periodicity involved in either their frequency or their duration. The intermittent nature of forcing has an important influence on the response of a body of shallow water to wind stress. Among other effects, intermittent forcing evokes a number of interesting large-scale wavelike responses, as might be expected on general dynamical principles.

Some aspects of this variable forcing are illustrated by a frequency distribution of wind stress, in categories of magnitude and direction. Saunders² has prepared wind-stress roses of this kind for the eastern seaboard, in 1° latitude-longitude squares; an example is shown in Figure 1. Concentric circles are spaced 1 dyne cm^{-2} apart, and directions are in 45° quadrants. This stress-rose applies to the sea just south of the eastern half of Long Island, for the winter (Dec.-Feb.) period. The average wind stress has components $(0.61, -0.46) \text{ dynes cm}^{-2}$, northward and eastward respectively, while the root-mean-square deviation from the mean is $1.61 \text{ dynes cm}^{-2}$. The high rms-to-mean ratio at once highlights the influence of storms.

If a wind stress of 3 dynes cm^{-2} acted as a uniformly distributed force over water column 100 m deep (a typical depth over continental shelves) for 10 hr, and no other force acted on the water, the impulse of the wind force would generate a velocity of a little over 10 cm sec^{-1} in the water. There are many complications, but this is the correct order of magnitude of wind-driven flow velocities in shallow seas.

Horizontal density contrasts arise from insolation, especially in spring, and from the influx of fresh water at the shore. The shallowest portions of a marginal sea heat up first and thus become lighter (by $\leq 1 \text{ part/1000}$) than the waters farther offshore. Over continental shelves this effect is usually less important than fresh-water inflow at the shore, which similarly lightens nearshore waters, by $\approx 3 \text{ parts/1000}$ in a typi-

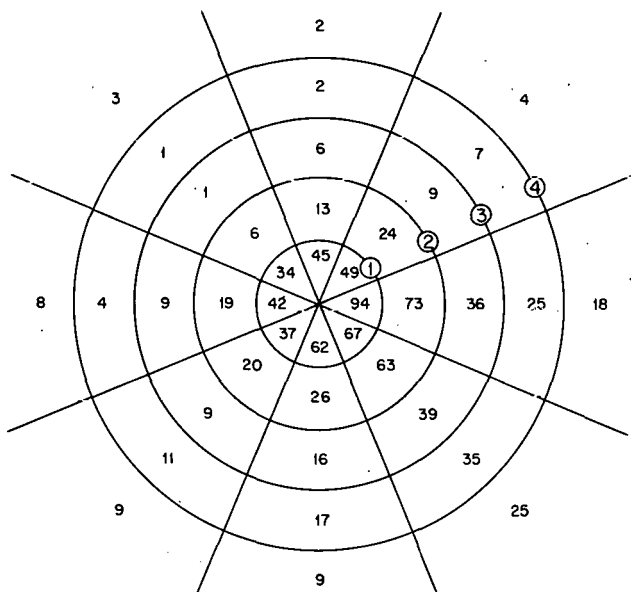


Figure 1. Wind stress frequencies between latitudes 40° to 41° and longitudes 72° to 73° by magnitude (dynes cm^{-2}) and direction (45° sectors). Top sector is stress directed *toward* true north, $\pm 22\frac{1}{2}^{\circ}$. Numbers in each field give frequencies in parts per thousand. Thus, eastward ($\pm 22\frac{1}{2}^{\circ}$) wind stress of magnitude 0 to 1 dyne cm^{-2} occurs for 9.4% of the time.

cal case, in comparison with waters several tens of kilometers offshore. A static fluid cannot sustain such horizontal density differences, and the lighter waters tend to spread out over the top, the heavy waters, to slide in at the bottom. Given the small density differences actually existing, these motions are sufficiently slow to be deflected by the earth's rotation, so that thermohaline motions are more nearly parallel to surfaces of constant density than perpendicular. Therefore the velocity of these motions cannot be calculated in quite so elementary a way as wind-driven flow. Except near zones of concentrated density changes known as fronts, thermohaline velocities are slower than wind-driven ones, their typical magnitude being 3 cm sec^{-1} , as shown in greater detail below. Although there is also a seasonal variability in fresh-water inflow, spring runoff being greatest, thermohaline forcing varies much more drastically than wind forcing.

WIND-DRIVEN COASTAL CURRENTS

Over the continental shelves the depth of water increases gradually and more or less monotonically from zero at the shore to 100 to 200 meters at the shelf break, where it begins to increase a little more abruptly to about 2000 m. The typical bottom slope over the shelf is a few times 10^{-3} , so that within a few kilometers from shore the water depth is still only about 10 m. Our simple calculation of momentum input by a storm would therefore have shown a typical velocity there of 100 cm

sec^{-1} , rather than 10, valid in depths of about 100 m. The shores prevent perpendicular movement of water, so that this calculation is true only for the longshore component of the wind. Also, in water this shallow the frictional drag of the sea floor soon resists further acceleration, so that velocities $>50 \text{ cm sec}^{-1}$ are only rarely reached. Nevertheless, our calculation is basically correct in exposing the dominant influence of depth on wind-generated currents, which are certainly strongest in the coastal zone.

Because of surface-level variations the force of gravity exerts an important influence. Although the sea surface is horizontal in the mean, it is never so instantaneously, not even after the influence of surface waves has been filtered out by averaging over a few minutes and corrections have been made for the phase of the tide to remove any tidal wave. A wind blowing perpendicular to the coast, for example, produces a rise or fall of level sufficient to balance the wind stress, since the water cannot accelerate in a direction normal to the shore. A longshore wind would not be subject to this kind of effect if a shore were very straight and very long, which is never the case. On a real coastline, peninsulae, shoals, and bights all present obstacles to wind-driven flow, and the result is some degree of piling-up or depletion of water. Clearest is the situation in an enclosed basin where, between the upwind and downwind shores, a marked level difference, known as the setup, is established.

When the setup exactly balances the wind stress, the acceleration produced by the force of gravity equals the wind stress divided by the mass of the water column:

$$g \frac{\partial \zeta}{\partial x} = \frac{F}{h} \quad (1)$$

Here g is acceleration of gravity, ζ is the elevation of the free surface above its equilibrium value, and x is the coordinate axis along the direction of the wind. $F = \tau/\rho$ is the "kinematic" wind stress, i.e., the stress τ in dynes cm^{-2} divided by the density of water, the units of F being $\text{cm}^2 \text{ sec}^{-2}$. The mass of the water column is ρh per unit surface area (h = depth), so that F/h is force per unit mass, due to wind stress.

Given the typical values of $\tau = 1 \text{ dyne cm}^{-2}$, i.e., $F = 1 \text{ cm}^2 \text{ sec}^{-2}$, $h = 100 \text{ m} \equiv 10^4 \text{ cm}$, and $g \approx 10^3 \text{ cm sec}^{-2}$, the surface slope, sufficient to balance the wind stress, is seen to be in the range 10^{-7} , or 1 cm in 100 km. Surface slopes of this order are indeed present in shallow seas and are so directed as to balance the wind stress. However, because of irregular variations of depth, Eq. (1) can be satisfied only in a very small fraction of a real basin. Where the depth is greater than necessary for the balance expressed by Eq. (1), the pressure gradient overcomes the wind, whereas in shallow water the wind stress dominates. The distribution of surface elevation over the entire basin is such that the total wind force (over the entire surface area) is more or less balanced by the setup, so that the average gradient $\partial \zeta / \partial x$ is determined by the average basin depth.

In the coastal zone, where the depth is much less than average, the wind stress completely overwhelms the pressure gradient. For example, at a depth of about 10 m, horizontal accelerations due to wind stress of 1 dyne cm^{-2} are in the range $10^{-3} \text{ cm sec}^{-2}$, an order of magnitude larger than $g(\partial \zeta / \partial x)$, which is in the range $10^{-4} \text{ cm sec}^{-2}$, given an average depth of 100 m.

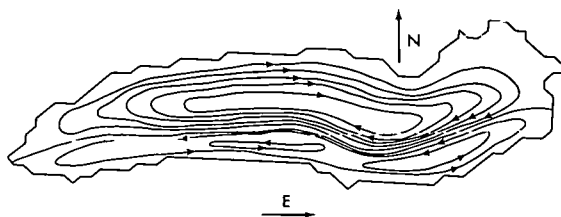


Figure 2. Water transport in Lake Ontario due to an eastward wind stress.
Note downwind flow in shallow water, return flow in deep.

A simple conceptual model of an enclosed shallow sea may now be envisaged which the wind stress is partly balanced by a certain distribution of surface level, with the difference between the wind-stress force and the gravity force accelerating the water. The wind is assumed to be "switched on" at time zero and the flow pattern to be calculated for some realistic time t , e.g., 6 to 10 hr, during which the wind is assumed to be constant and other complications absent. An arbitrary depth distribution may be handled with the aid of a computer. Patterns of depth-integrated transport (average velocity times depth) calculated in this way by Rao and Murty³ for Lake Ontario are shown in Figure 2.

Patterns of this sort are always characterized by at least two closed gyres that are related to the depth distribution, i.e., to the topography of the sea floor, and are therefore called topographic gyres. Their downwind legs coincide with shallow water along both shores, while return flow occurs over the deepest portions of the basin. In a cross section perpendicular to the wind, flow is *with* the wind where the depth is less than the average for that section, and *against* the wind in deeper water. As already pointed out, the physical explanation is that the pressure gradient opposing the wind stress balances the latter exactly where the water depth is average, but "wins" over the wind in deep water (the gravity force being proportional to mass and therefore depth) and "loses" in shallow water, the wind stress being the same everywhere.

The transport pattern is slightly misleading because it does not show the high velocities in shallow water. The spacing of transport streamlines is proportional to transport, and, when this is roughly constant, velocities vary as h^{-1} . The details near shore also depend on friction and on the density distribution in the vertical, but it is basically true that high-speed currents occur near shore.

The application of similar conceptual models to the continental shelves presents a problem because it is difficult to predict the longshore pressure gradient. Along a straight, infinite shore no permanent longshore gradients can exist, whereas in a closed basin the gradient is determined by the average depth in a section perpendicular to the wind. Neither of these ideas is useful on a real shelf, with an open boundary seaward. In the conceptual models so far proposed for shelf circulation, the longshore gradient appears as an arbitrary external parameter, a *deus ex machina*. In the actual physical case this gradient is determined by shelf topography and by the nature of the forcing, but at present we do not know how to estimate its magnitude in a given location under given conditions.

TOPOGRAPHIC WAVES

Another important influence on water motions of reasonably large scale is the deflecting force (Coriolis force) due to the rotation of the earth. A coastal current of the kind under consideration would tend to be deflected to its right (in the Northern Hemisphere) within a few hours of its establishment. The shore prevents actual massive deflection, but a small quantity of water moves in or out from shore just enough to establish an elevation gradient in the *offshore* direction, which then balances the Coriolis force acting on the *longshore* flow. This equilibrium condition is known in meteorology and oceanography as geostrophic balance. A coastal current a few kilometers wide requires at the shore a rise (when the current leaves the shore to the right) or drop (shore to the left) in elevation of only a few centimeters for geostrophic balance. However, a broad current over a wide shelf (e.g., off the Gulf of Mexico produced by a longish storm) can lead to considerable buildup and depletion of water levels at the coast, amounting to ± 50 cm.

In a closed basin the wind-induced coastal current along the right-hand shore (looking along the wind) produces a *rise* in level as geostrophic balance is established, and a *fall* on the left-hand shore. Thus a pressure difference acts across the upwind and downwind ends of the basin. This pressure gradient may be small, but it is not opposed by the wind or any other force and gradually accelerates the water in a longshore direction. Gradually the downwind-flowing right-hand jet is extended across the downwind end of the basin, and the left-hand jet across the upwind end. In other words, the stagnation points of the flow pattern characterizing the topographic gyres move around the basin in a counterclockwise sense. This movement is quite slow, covering about 40 km day^{-1} in Lake Ontario, but nevertheless has striking observable effects. After passage of the stagnation point at some nearshore location, the coastal current spontaneously *reverses* direction. Thus, during a quiescent period following a storm, in some locations coastal currents are still moving in the direction of the wind that started them, while in other places the current is already moving in the opposite direction.

The flow structure started by a storm may be described as a wave propagating at a given speed in a given direction. Further analysis of the problem shows that depth variations are essential for the existence of this type of wave, which is therefore known as a topographic wave. A simple conceptual model of a shore zone in which such a wave may be produced is shown in Figure 3. The distribution of longshore velocity calculated for the idealized case is illustrated in Figure 4. The amplitude of this wave reduces to zero where depth variations vanish. The calculated speed of propagation agrees closely with observations in Lake Ontario. Note that significant motion is confined essentially to < 15 km from shore, so that waters farther offshore are not affected by this phenomenon. The wave may be said to be trapped at the shore.

The existence of topographic waves on continental *slopes* (outside the shelf break) has been postulated by theoreticians for some time, and some evidence on slow, wavelike progression of small-amplitude variations in sea level has been interpreted as a "signature" of such waves. Some direct evidence on longshore velocities along the slopes also supports such an interpretation. However, a conclusive demon-

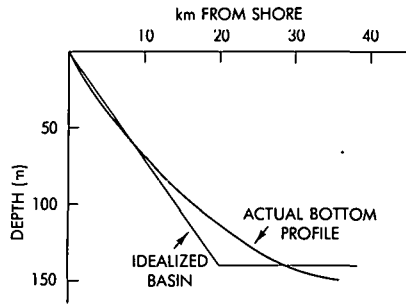


Figure 3. Idealized shore zone with beach of constant slope.

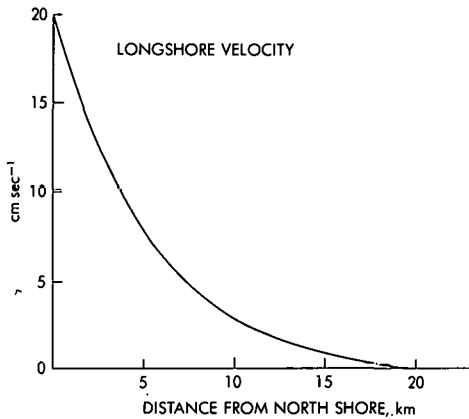


Figure 4. Distribution of longshore velocity in a topographic wave of 1-cm elevation amplitude at shore, in idealized shore zone of Figure 3.

stration that any given flow episode over the continental slope was a topographic wave has yet to be made. The principal signature of such a wave resides in its characteristic velocity field, associated surface elevations being small and subject to alternative interpretation. To observe the velocity structure over the continental slope sufficient detail would require considerable expenditure. However, the demonstration of topographic waves in the shore zone of Lake Ontario, added to the other available evidence, makes it very likely that such waves will frequently occur over other strongly sloping parts of the continental shelf, i.e., beyond the shelf break.

The depth distribution across the continental shelf south of Long Island (at Tiana Beach, where our experimental work is proceeding) is shown in Figure 8 (discussed later). One may surmise from the character of this distribution that different natural modes of topographic waves will exist with concentrations of longshore velocity over the shore zone and over the slope, and that probably no part of the shelf will escape their influence. Flow structures of this sort are remarkable: one

finds flow velocities of up to a knot, extending over a massive body of water, which possess no obvious driving force analogous to wind stress in a wind-driven current. We have seen some apparent instances of topographic wave flow off Long Island, but our data are not yet complete enough for confirmation.

Note that although topographic waves are free modes of motion, their generation is due to wind-stress impulses. In this sense they are part of the picture of the total wind-driven circulation, with variable winds producing a complex pattern of topographic waves.

COASTAL JETS

The discussion so far has ignored any density variations in the water column. In summer a seasonal thermocline exists over the continental shelves, at a depth of some 30 m, separating a top, light layer from a bottom layer that is heavier because of higher salinity and lower temperature. The thermocline itself is a region of rapid density variation in the vertical. The density difference between top and bottom layers is a few parts in 1000, and most of this is concentrated in the few meters of the thermocline thickness. Wherever the density of a fluid decreases this strongly upward, the arrangement of fluid layers is markedly stable, sufficiently so to suppress turbulence. With turbulence absent, the force of the wind cannot be communicated directly to the bottom layer, and our ideas on wind-driven coastal currents must be modified.

A simple conceptual model is a two-layer fluid. The thermocline is compressed into a single plane, in which the density change takes place jumpwise. This interface between two fluids of slightly differing density is assumed to be frictionless. In the simplest approach, the total depth of water is taken as constant, and the shoreline as long and straight.

As a longshore wind is "switched on" over such a shore zone, the wind stress acts on the top layer alone and accelerates it downwind, which produces higher velocities than if the momentum were distributed over the entire water column. The deflecting force of the earth's rotation now produces some peculiar effects: the top layer may glide freely offshore over the frictionless thermocline (if the wind blows so as to leave the shore to the *left*); the bottom layer then must move onshore to compensate for the loss of water in the shore zone. In this manner a considerable thermocline tilt may develop near shore. If the process continues long enough, the thermocline may intersect the surface, producing upwelling of cold water at the shore. The inclination of the thermocline creates horizontal pressure gradients in the offshore direction that are in geostrophic balance with the strong current in the top layer. This current has many properties in common with the atmospheric jet stream and is therefore known as a coastal jet. A schematic illustration of coastal jet development based on the two-layer conceptual model is shown in Figure 5.

The characteristic width of coastal jets is the internal radius of deformation, $R = c_i/f$, where c_i is the speed of propagation of long waves on the thermocline and f is the Coriolis parameter. Typical magnitudes are $c_i = 50 \text{ cm sec}^{-1}$ and $f = 10^{-4} \text{ sec}^{-1}$, so that R is about 5 km. Within a nearshore band of this width, the wind-imparted momentum is concentrated in the top layer. Farther from shore the long-

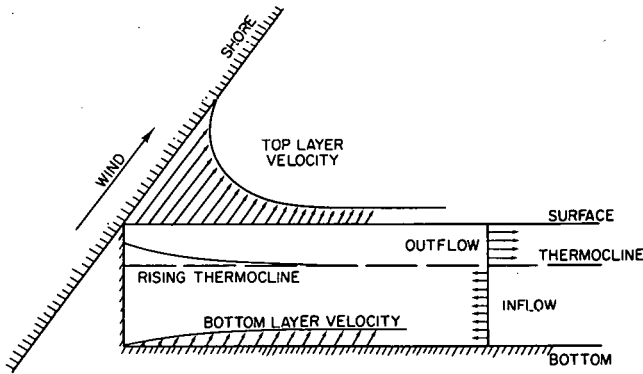


Figure 5. Schematic illustration of coastal jet flow structure in two-layer fluid of constant depth. The onshore-offshore velocities have constant amplitude, while the longshore velocity and thermocline elevation grow linearly with time.

shore momentum is more or less evenly distributed over the two layers, much as in a homogeneous water column, in spite of the isolation of the bottom layer by a frictionless thermocline. In this offshore region the Coriolis force transfers the momentum vertically downward. The equation of motion for the bottom layer, in the absence of longshore pressure gradients and friction, is

$$\frac{du}{dt} = f\bar{v}, \quad (2)$$

i.e., acceleration equals Coriolis force per unit mass.

Integrating with respect to time we find

$$u = f\eta, \quad (3)$$

where η is offshore displacement of the fluid. As noted, such displacements occur in the bottom layer as the coastal jet develops. A quantitative treatment shows that they are just sufficient to equalize the longshore velocity between top and bottom layers outside a band of scale-width R .

A wind leaving the coast to the right produces a downward movement (downwelling) of the thermocline and an associated coastal jet in geostrophic equilibrium with that thermocline structure. The amplitude of thermocline movements in the core zone is quite large, as may be inferred from Margules' equation expressing geostrophic balance across an inclined frontal surface. If $\epsilon = \Delta\rho/\rho$ is the proportionate density defect and ζ' is the elevation of the thermocline above equilibrium, the velocity jump across the front is

$$u - u' = \frac{\epsilon g}{f} \frac{\partial \zeta'}{\partial y}. \quad (4)$$

A velocity jump of 20 cm sec^{-1} , with $\epsilon = 2 \times 10^{-3}$, thus requires a thermocline slope of 10^{-3} , or 1 m/km , or a total elevation amplitude of about 5 m (given $R = 5$

km, the scale-width of the upwelling-downwelling). As already mentioned, the thermocline may intersect the free surface after a strong wind episode, corresponding to a displacement amplitude equal to the top layer thickness of 20 to 30 m.

Episodes of opposing storms cause episodes of thermocline upwelling-downwelling near shore, accompanied by corresponding coastal jets. These are fascinating phenomena, and the massive onshore-offshore water movements that take place as one or the other develops are important in that they renew the coastal waters. Coasts subject to frequently alternating upwellings and downwellings can thus be kept remarkably clean in spite of considerable pollutant discharges, as the Chicago water-front, for example, demonstrates.

KELVIN WAVES

The Coriolis force is again implicated in the generation of coastal jets and results in an upwelling on a left-hand shore (looking along the wind), a downwelling on the right. In a closed basin, the situation is similar to that for topographic waves: across the upwind and downwind ends of the basin thermocline elevation gradients develop, implying unbalanced longshore pressure gradients. These gradients again accelerate fluid across the original stagnation points of the initial coastal jet flow pattern, extending the right-hand jet across the downwind end, the left-hand jet across the upwind end. The analogy with topographic waves is strong; the pattern again propagates in a counterclockwise (cyclonic) sense around the basin. The speed of propagation is the velocity of long waves on the thermocline, which, as already noted, is typically 50 cm sec^{-1} (40 km day^{-1}). At a fixed location on shore, the coastal jet reverses direction as the wave passes, and the thermocline slope changes appropriately, from upwelling to downwelling or vice versa. This type of flow structure is known as a Kelvin wave.

The idealized shore zone containing a two-layer fluid is again an appropriate model. Kelvin waves of arbitrary wave form may propagate along such a shore, but always so as to leave the shore to the *right*. The main signature of the wave is now the relatively large-amplitude thermocline movement, associated with a considerable longshore velocity *difference* between top and bottom layers [given by Eq. (4)]. The amplitude of the wave decreases exponentially with distance from shore, with an e -folding scale of R ($R \cong 5 \text{ km}$). Particle movements are everywhere alongshore, and those in the surface layer can be of quite large amplitude; long Kelvin waves could theoretically (i.e., in the absence of friction) lead to longshore excursions of about 100 km. Even if this is scaled down to, say, 30 km, it is clear that motions accompanying Kelvin waves on the thermocline make important contributions to circulation of shallow seas. The progression of a Kelvin wave around Lake Michigan has been demonstrated by water intake temperatures.⁴ Such Kelvin wave progression episodes have been documented more recently and in greater detail in Lake Ontario.⁵

In Lake Ontario the speeds of propagation of a topographic wave and an internal Kelvin wave are very close, so that the two travel almost in phase. The wave speeds are, however, determined by different physical factors (e.g., the slope of the shore zone and the density defect of the top layer) and, while they are likely to be of

the same order of magnitude in shallow seas of similar depth, in general they are easily distinguishable. The progression of an internal Kelvin wave along a seacoast does not seem to have been demonstrated so far, no doubt because so little attention has been paid to the 0 to 10-km range from shore. Note that such Kelvin waves are also "trapped" at the shore, within the first 10 km or so.

THE COASTAL BOUNDARY LAYER

We have so far discussed four distinct phenomena and corresponding simple conceptual models: wind-driven coastal currents (the experimentally verifiable part of topographic gyres), topographic waves, coastal jets, and Kelvin waves. All these exist primarily in a coastal zone some 10 km in width, and their combined effect is to generate a current "climate" within this zone which differs markedly from the climate farther offshore. We may regard this difference in climate as a distinct phenomenon, perhaps belonging to a class of phenomena different from waves and jets. The physical factors leading to shore-trapped flow structures are all connected with the presence of the boundary, in close analogy with the case of the well-known boundary layers over aeroplane wings, and it is therefore appropriate to refer to the special coastal zone as the coastal boundary layer, CBL.

Experimentally, the differences between CBL and "offshore" (outside CBL) are best exhibited by current spectra, extracted from long time series of current measurements at fixed locations. The most complete evidence, which again comes from Lake Ontario, is summarized by Blanton.⁶ Within the CBL, currents are usually parallel to the shore and more or less persistent. Outside the CBL, water movements in all directions occur with similar frequencies and are dominated by relatively short-period oscillations. In the Great Lakes the "offshore" current regime in the summer features predominant near-inertial oscillations known as Poincaré waves. These have not been observed over the continental shelves, but tidal oscillations are prominent and provide the main velocity signal. Density effects and the influence of storms are superimposed on this "carrier signal" almost in the manner of an amplitude-modulated radio transmission.

The width of the CBL may be determined empirically as the extent of the region within which shore-parallel flow dominates. On the north shore of Lake Ontario this was found to be 7 km. In other places around the Great Lakes it is similar, but varying distances can be expected elsewhere. Along the New Jersey coast, for example, the existence of a CBL has been demonstrated on an empirical basis, but its width is unknown.

In discussing the continental shelves, the question arises whether there is a second boundary layer at the shelf break, i.e., at the open boundary of the shelf. There is some evidence to suggest that there is, and that it is connected with the existence of a semipermanent front near the shelf break, an inclined surface of rapid density change, separating shelf water from slope water. Within the shelf-break zone currents would be expected to flow parallel to this frontal surface, much as they flow parallel to shore within the CBL. However, a systematic experimental study of the shelf-break zone has not yet been carried out.

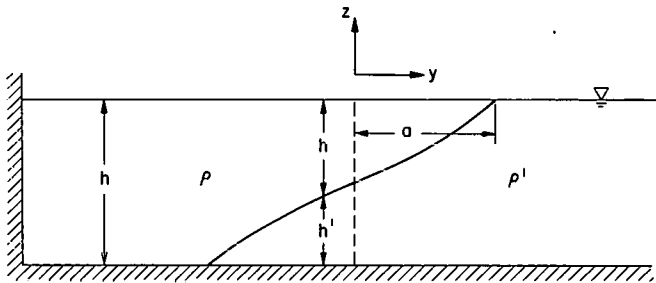


Figure 6. Adjustment of an initially vertical front (dashed line) separating light nearshore waters of density ρ from heavier offshore waters, density ρ' , to an inclined position in geostrophic balance (solid curve).

FRONTAL ADJUSTMENT

We now consider some flow phenomena connected with horizontal density gradients, arising from freshening or heating of nearshore waters. As mentioned above, a semipermanent inclined surface, with a relatively rapid density variation across it, separates shelf water from slope water at the edge of the continental shelf. A similar spring thermocline separates nearshore waters in the Great Lakes from the cold central mass early in the season, after the shallow coastal waters have warmed up. Although this thermocline, with a typical lifetime of 6 weeks, is ephemeral compared with the shelf-edge front, it is clearly maintained by similar dynamical factors. The behavior of the spring thermocline was documented in considerable detail during IFYGL, and this provides some clues for gaining an understanding of the shelf-edge front.

We consider first the simple conceptual model illustrated in Figure 6. In a constant-depth shore zone (straight, infinite shore along the x -axis), at $t=0$ the waters between the shore and $y=0$ are somewhat lighter than those beyond. In an idealized experiment a thin wall coinciding with the dotted line could be suddenly removed. In a real ocean a storm might mix the water column vertically, with some freshwater addition at shore. Left to itself, the system shown in Figure 6 begins a readjustment of mass, the light fluid moving offshore at the top, the heavy fluid onshore at the bottom. The Coriolis force deflects both, so that longshore motions develop, of a velocity given by Eq. (3), that are proportional to the offshore displacement of water particles. During such an adjustment process following a sudden change, some oscillations develop at the inertial frequency f (Coriolis parameter), which proceed about an equilibrium configuration of the front separating lighter and heavier waters. Ignoring friction and any mixing of the waters across the front, the equilibrium configuration can be calculated from the postulates of geostrophic equilibrium after adjustment and the conservation of potential vorticity during it. The latter principle may be expressed by the condition

$$\frac{f - \partial u / \partial y}{h} = \text{const}, \quad (5)$$

where h is the depth of the water column. This equation is applied separately to light and heavy fluid columns. The result in a typical case is also illustrated in Figure 6: a wedge of light water moves to overlie a wedge of heavier water. The half-width a of the wedges is $R = f^{-1} \sqrt{g\epsilon h}$, where ϵ is the proportionate density defect of the light water. This again ranges from a few kilometers for the nearshore zone of the Great Lakes (and other shallow seas) to 10 km or so for the shelf-edge front. The light water moves so as to leave the shore to the right, the heavy water in the opposite direction. The slope of the inclined front is h/R , so that [according to Eq. (4)] the velocity difference across the front is $\sqrt{g\epsilon h}$, or 30 to 100 cm sec⁻¹ in the two typical cases mentioned. In the coastal zone the longshore velocities generated by frontal adjustment are thus comparable with wind-driven flow velocities, whereas they dominate the latter near the shelf edge.

Given the large velocity differences across the inclined front, friction cannot be negligible even if the flow is laminar in the region of the steepest density gradient. Very little is known about boundary layer processes within such frontal zones, but the example of the sea surface (where the density contrast between air and water is extreme) suggests that a quadratic friction law prevails even in the presence of stable stratification. Friction at the interface in Figure 6 would gradually destroy geostrophic equilibrium and require further offshore movement of light water, with compensating inflow of heavy fluid, to reestablish the balance. Eventually, therefore, the inclined front should "relax" toward a more nearly horizontal position. In the Great Lakes coastal zone, a frontal zone under quiescent conditions doubles its width in a few days.

Yet it is wind-induced mixing, not such gradual decay, that usually destroys a frontal structure like that in Figure 6. Strong wind acting over shallow water breaks down the stratification of the water column and reestablishes a situation similar to that prevailing in our model *before* adjustment, in which density differences occur only in a horizontal direction. Surface cooling in a cold outbreak further enhances vertical mixing.

Weaker winds, which occur more frequently, produce less drastic effects on a frontal structure of the type shown in Figure 6. Such winds, if acting in the longshore direction, preferentially impart longshore momentum to the light fluid, which occupies more of the surface. If the wind leaves the shore to the *right*, this effect enhances the velocity contrast between light and heavy fluid and, in accordance with Eq. (4), steepens the gradient of the interface, making the angle of the wedges (light and heavy fluid) more obtuse. On the other hand, when the wind impulse opposes the direction of flow of the light fluid necessary for geostrophic balance, an offshore displacement of the light fluid must take place, much as in the case of frictional decay. Given a strong enough wind (leaving the shore to the left) the warm body of fluid might separate completely from the shore. These possibilities may be explored with the aid of our model (Figure 6), by adding an arbitrary longshore wind-stress impulse to the light fluid alone. One possible consequence is a lens-shaped thermocline (see Figure 7). In the outer portion of such a light lens, the velocity contrast [according to Eq. (4)] is like that over a wedge-shaped front, but it is reversed over the inner portion. The latter is a direct consequence of the wind-stress impulse, the former, of

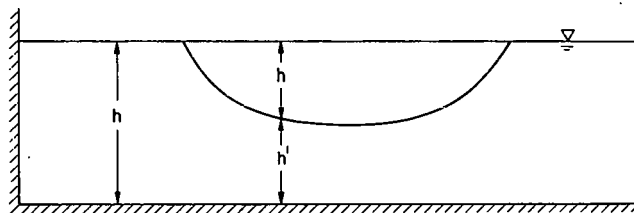


Figure 7. Lens of light water that develops when longshore wind (leaving the shore to the *left*) acts on nearshore band of light water.

an offshore displacement more than large enough to compensate for wind-imparted momentum. The heavy fluid moves in this case everywhere in the direction of the wind.

Some examples of wedge-shaped and lens-shaped thermoclines from the shore zone of Lake Ontario and associated longshore flow patterns have been given by Csanady.⁷ Similar frontal structures (the wedge type frequently, separated "bubbles" occasionally) have been observed near the edge of the continental shelf, although little is known about the associated flow patterns. Given rather complex differences (subject to seasonal variations) in salinity as well as temperature between shelf water and slope water, it is certain that the behavior of the shelf-edge front is more complex than the above simple ideas would suggest. However, it is reasonable to suppose that under suitable conditions the phenomena described above will play an important role in determining the flow pattern prevailing in the shelf-break zone.

FRICTIONAL CIRCULATION

In the above discussion of conceptual models, no account has been taken of the velocity *differences* arising in a water column as the latter is subjected to wind or bottom *stress*. Although turbulent friction is subject to more complex laws than viscous friction, it is still generally true that vertical transfer of momentum requires a velocity gradient down which the momentum is transferred. Thus, as the wind stress is applied at the surface, the near-surface layers of the water column must move faster than those below, in order to effect momentum transfer. The Coriolis force acting on the faster near-surface flow also deflects it more (this force being proportional to velocity) and produces a complex velocity distribution involving variations of both horizontal velocity components, in the vertical direction.

Simple conceptual models for the understanding of similar phenomena were proposed as early as 1905 by Ekman and are now well known. The simplest such model, applying to a deep ocean far from coasts, results in the celebrated Ekman spiral. In shallow water near coasts, both bottom friction and the condition of no net onshore-offshore flow must be taken into account (under steady conditions), and a more complex conceptual model is required. Suppose the wind to be parallel to a straight long coast and to blow with constant force. Longshore currents are produced, strong enough so that bottom friction exactly balances the longshore wind

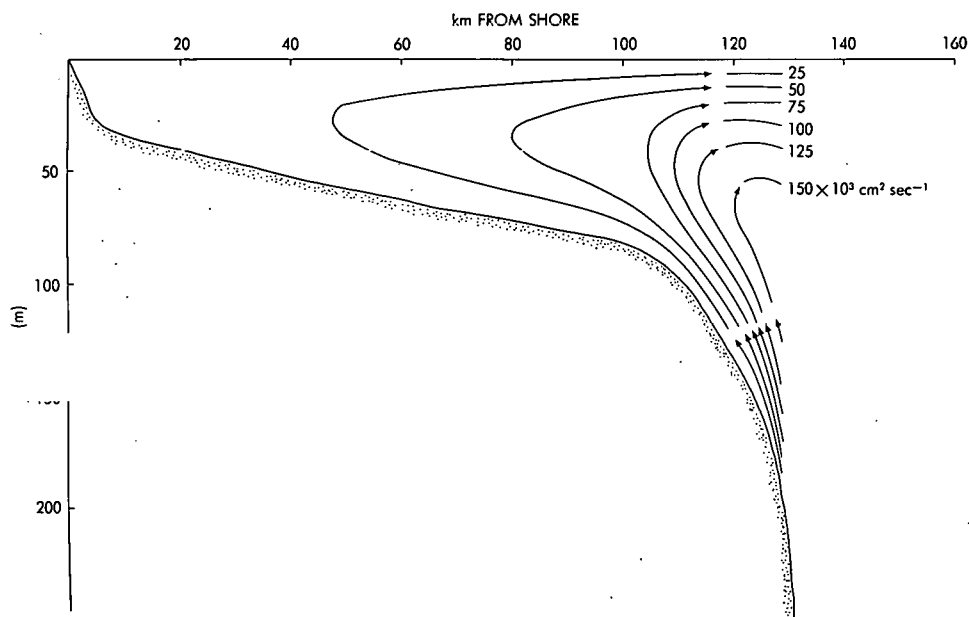


Figure 8. Calculated frictional secondary circulation in a plane normal to the coast over the continental shelf south of Long Island, caused by a strong eastward gale.

stress. A pressure gradient is established in the offshore direction in order to eliminate any net onshore-offshore flow. When the wind blows so as to leave the shore to the *left*, the top layers move offshore, the bottom layers onshore; the reverse occurs with an opposite wind. An example of such calculated frictional-equilibrium flow in a plane normal to the coast, using the depth distribution off Tiana Beach and realistic friction parameters, is shown in Figure 8. The wind was assumed to be very strong, exerting a stress of 10 dynes cm^{-2} . A much weaker wind produces a less intense circulation, similar in character but closing much nearer shore. The water column in such models is assumed to be homogeneous, and therefore similar circulations can be expected only under winter conditions.

Another classical model of this type is relevant to the thermohaline circulation inter over the continental shelves. Although the water column is vertically well mixed, horizontal density gradients due to freshwater influx are present. Under frictionless geostrophic equilibrium conditions a southwestward current would be present in this situation, increasing in velocity linearly with vertical distance from the bottom. With vigorous turbulence present, this implies a certain rate of vertical momentum transfer. At the surface, in the absence of wind, the stress must reduce to zero, so that something akin to an Ekman spiral again forms, within which some offshore flow takes place. Return flow occurs in a bottom boundary layer. The velocity structure of such frictionally controlled thermohaline circulation is illustrated in Figure 9.

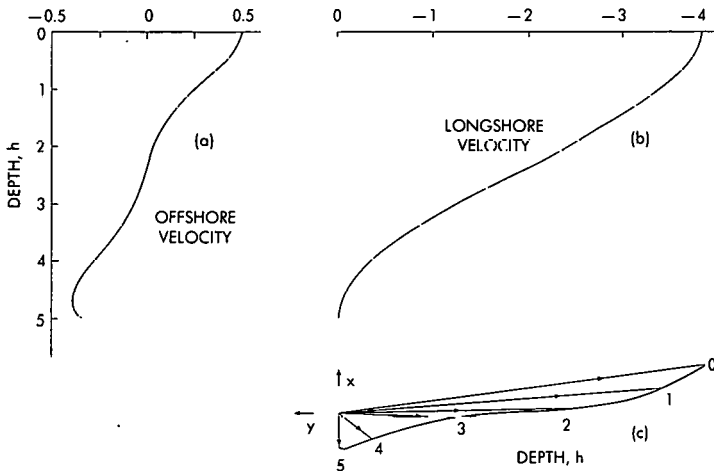


Figure 9. Velocity distribution: (a) offshore, (b) longshore component, (c) hodograph, in steady density driven flow due to horizontal salinity gradient over the continental shelf in winter. Depths are marked in units of Ekman depth (typically 15 m); velocities are in cm sec^{-1} , positive offshore and eastward.

Although these classical models are widely accepted as realistic, nowhere have they been satisfactorily related to observation. Part of the reason is no doubt the absence of suitable instrumentation; current meters have to be quite efficient to describe accurately the secondary-flow type of circulation in a vertical plane normal to the coast, where the dominant velocity component is longshore. Another problem is that any steady-state model is suspect, given the variable nature of forcing. Perhaps there are frictionally induced circulations such as those shown in Figures 8 and 9, but whether they can be identified as distinct phenomena is not certain, given the many transient forces and impulses affecting the coastal zone.

CONCLUSION

Even this brief and incomplete review shows the impressive complexity of flow phenomena over continental shelves. We have not even touched upon such questions as how different distinct phenomena (e.g., tides and wind-driven currents) may interact, or what a long-term (seasonal) "mean" circulation might look like. A great deal of empirical input will be needed to develop a satisfactory understanding of water motions over continental shelves. It is equally important, however, that our observational efforts be guided by realistic conceptual models; random survey work over such a vast area as the continental shelves, which are subject to such complex physical influences, is likely to be very wasteful.

To draw one specific conclusion, much of the "action" seems to take place in a coastal zone about 10 km in width, and this zone should receive special attention in any large-scale observation program. A deployment of current meters on an even grid (of, say, 20-km spacing) is likely to miss this zone almost entirely, a resolution

of 1 to 2 km being necessary near shore. Much the same goes for the frontal zone at the shelf break, where a resolution of 3 to 5 km would appear to be necessary in the cross-isobath direction. We have begun to work on these important boundary layers, but it will probably take a decade or two of solid effort to achieve a scientific understanding of continental shelf circulation.

Acknowledgment: This work was supported by Brookhaven National Laboratory under its coastal shelf transport and diffusion program, sponsored by the United States Energy Research and Development Administration.

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Tidal Water Movements

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INTRODUCTION

Tides on a continental shelf are largely excited by deep-ocean tides, with direct astronomical forcing playing a minor role. The principles of the excitation, and appropriate matching conditions between shelf and ocean, are described. The type data necessary for development of a numerical model of tides in a shelf region is discussed.

Observations and models of tides on the Atlantic Continental Shelf are summarized, and the different roles that will be played in the future by further observations and by numerical models are outlined.

The tides account not only for purely oscillatory currents but also, through a variety of nonlinear rectification processes, for steady transport, both Eulerian and Lagrangian, with both horizontal and vertical variations. Some examples of rectified tidal flows are given.

Mixing and dispersion processes due to surface tides and to the large-amplitude internal tides generated at the continental slope are outlined.

Tidal currents at the sea floor play an important role in sediment transport; they also, because of the quadratic nature of bottom friction, interact strongly with currents due to other forces.

Quite apart from the effect of tides on offshore development, the influence of large-scale engineering projects on the tides themselves must often be examined. This point is illustrated by a discussion of the surprising effects that tidal power development in the Bay of Fundy is predicted to have on the tides of the Gulf of Maine.

TIDE GENERATION

Laplace's Tidal Equations

The simplest form of Laplace's tidal equations (LTE) is

$$\begin{aligned}\partial \mathbf{u} / \partial t + g \nabla (\zeta - \zeta_e) + \mathbf{F}_b &= 0 ; \\ \partial \zeta / \partial t + \nabla \cdot (h \mathbf{u}) &= 0 .\end{aligned}\tag{2}$$

$\mathbf{u}(\mathbf{x}, t)$ is the vertically averaged horizontal current vector at position $\mathbf{x}$ and time t in water of mean depth $h(\mathbf{x})$. $\mathbf{F}_b(\mathbf{x}, t)$ represents bottom friction. $\zeta(\mathbf{x}, t)$ is the elevation of the free surface, and $\zeta_e(\mathbf{x}, t)$ is the so-called equilibrium tide, with tide-generating force $\nabla \zeta_e$.

Hendershott^{1,2} discusses the complications arising from the non-rigidity of the earth and the gravitational self-attraction of different bodies of water. Briefly, the

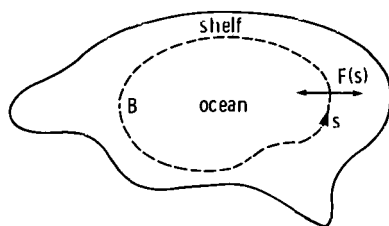


Figure 1. Solutions of the tidal equations are matched across the shelf break B separating the continental shelf and the ocean.

response of the elastic earth to direct tidal forces leads to a reduction of ζ_e (by about 31% for the semidiurnal tides), but the deformation of the earth under the weight of the ocean tides, and ocean self-attraction, render LTE integrodifferential rather than differential. Hendershott¹ suggests an iterative solution of the resulting equations, in which Eqs. (1) and (2) apply at each iteration, with $\nabla\zeta_e$ modified by the previous solution.

Hendershott² has also discussed the difficulties associated with solving LTE for the world ocean and suggests that, in view of the change in depth by a factor of 30 or so from the continental shelves to the deep ocean (with a consequent change in grid scales required for adequate spatial resolution), continental shelves and other marginal seas should be treated in separate models, to be added to a deep ocean model in some appropriate way.

Matching Conditions

The formalism of Garrett³ for matching tides in a gulf to the deep ocean is readily applied to the matching of shelf and deep-ocean regions. Figure 1 is a schematic of a deep ocean surrounded by shelf areas and marginal seas. For a particular tidal frequency ω let $\text{Re}u(\mathbf{x})e^{i\omega t}$, $\text{Re}\zeta(\mathbf{x})e^{i\omega t}$ be the solutions of LTE, with subscripts c and o referring to shelf and ocean regions. Let $u^{(1)}(\mathbf{x})$ and $\zeta^{(1)}(\mathbf{x})$ be solutions of LTE with zero mass flux across the shelf break. In general $\zeta_c^{(1)}(s) \neq \zeta_o^{(1)}(s)$ at position s along the shelf break, so that a mass flux $hu \cdot \mathbf{n} = F(s)$ across the shelf break is generated where $F(s)$ is the solution of the integral equation

$$\zeta_c^{(1)}(s) + \int_B K_c(s, \sigma) F(\sigma) d\sigma = \zeta_o^{(1)}(s) - \int_B K_o(s, \sigma) F(\sigma) d\sigma = \zeta_B(s). \quad (3)$$

$K_c(s, \sigma)$, $-K_o(s, \sigma)$ are the elevations at position s on the shelf break B produced by unit mass flux across B at position σ .

Hendershott² discusses the importance of this for models of deep-sea tides. In practice $\zeta_c^{(1)}(s)$ is negligible because of the small size of the shelf, so that Eq. (3) becomes

$$\int_B K_c(s, \sigma) F(\sigma) d\sigma = \zeta_B(s). \quad (4)$$

Under some circumstances (requiring further investigation) a local approximation,

$$K_c F(s) = \zeta_B(s), \quad (5)$$

which is the type of boundary condition proposed by Proudman,⁴ may be adequate.

Numerical Models of Shelf Regions

The tides in any coastal region may be described in a numerical model with boundary conditions of zero normal velocity at the coastline and observed elevations on the seaward boundaries. In the absence of adequate input data, the prescribed elevations at the seaward boundary are usually adjusted to optimize the agreement between computed elevations and observations at the coastline.

It is clear, though, from the precise formulation above, that $\zeta_B(s)$ is not a boundary condition imposed independently of the shelf, but is itself partly determined by the shelf. This is particularly important in discussing resonances of gulf or shelf regions³ and in considering the effects on the tides of large engineering projects (see below = effect of offshore development on the tides).

OBSERVATIONS AND MODELS

Elevation and Current Data

Data on tidal elevations are available for many coastal locations and, by a process of extrapolation for each tidal frequency, are used to prepare tide tables. Offshore data are still very limited, although Swanson⁵ has used data from recent experiments by the Environmental Protection Agency, the National Oceanic and Atmospheric Administration, and the Massachusetts Institute of Technology to prepare a cotidal chart of the New York Bight. Data on surface tidal currents are incorporated in National Ocean Survey hydrographic charts to show the magnitude and direction of the tidal current at different stages of the tide, and predictions for inshore areas are also available in tidal current tables.

Models

A simple analytical model of tides on the Atlantic Continental Shelf of the U.S. was used by Redfield⁶ to extrapolate from tidal elevations at the coast to those at the edge of the shelf. He concluded that both range and time of high water should more uniform at the shelf break than at the coast.

While analytical models of this sort are useful in adding to one's physical understanding of the phenomenon, they are inevitably idealized, and it is clear that only a numerical model can provide the detailed predictions that are sometimes necessary. A numerical tidal model, such as Greenberg's⁷ for the Bay of Fundy and Gulf of Maine, generally provides excellent agreement with tidal elevation data (partly by being forced to do so), but agreement with tidal current data can be unreliable. This may be due partly to internal tides (see below) but is largely due to sub-grid-scale variations in bottom topography.

The implication is that, if the tidal current at a precise location is required, the output of a numerical model is inadequate and direct measurement is necessary. On the other hand, if a large-scale average of tidal currents is required for transport studies, a numerical model may be a more convenient source of information than the large number of observations needed to average out local irregularities.

A numerical model of the surface tide on the Atlantic Continental Shelf could certainly be developed, and, with the advent of commercially available offshore tide gauges as well as those developed by individual institutions, there is no reason why adequate input data could not be obtained along the outer boundary of the region to be modeled.

MIXING AND DISPERSION

Vertical Profiles of Tidal Currents

Because of friction at the sea bed, the horizontal tidal current shows considerable vertical variation. Within one or two meters of the bottom the profile is logarithmic,⁸ with current u at height z above the bottom given by

$$u(z) = (1/k_0)(F_b/\rho)^{1/2} \ln(z/z_0). \quad (6)$$

By fitting data on $u(z)$ to this form the bottom stress F_b and roughness length z_0 can be determined, assuming von Karman's constant k_0 to be 0.4. This is equivalent to an eddy viscosity that increases linearly with height as $A(z) = k_0(F_b/\rho)^{1/2}z$. Bowden et al.⁸ found that the bottom stress was related to the current u_1 at 1 m above the bottom by the formula $F_b = 3.5 \times 10^{-3} u_1^2$, and to the depth-mean current $\bar{u}$ by $F_b = 2.1 \times 10^{-3} \bar{u}^2$.

From current measurements at other depths, Bowden et al.⁸ were able to estimate the vertical eddy viscosity $A(z)$ as a function of depth z and stage of the tide. They found it to be somewhat larger at mid-depth than near the surface or bottom and to reach maximum values at times of maximum current. The mid-depth value of $A(z)$ can be parametrized reasonably well⁹ by $A_{\max} = 2.5 \times 10^{-3} \bar{u}h$ in water of depth h with depth-mean current $\bar{u}$.

Vertical Mixing

In the absence of a vertical density gradient it is thought that the same turbulent eddies that mix momentum will also mix any passive scalar, so that the vertical eddy diffusivity $K(z)$ equals the eddy viscosity $A(z)$. However, stable stratification

will tend to suppress the turbulence and reduce both $A(z)$ and $K(z)$. $K(z)$ is reduced more than $A(z)$ because of the presence of internal waves, which can transport momentum but not heat or any other scalar. A number of recent reviews¹⁰⁻¹³ discuss this problem and the way in which both $A(z)$ and $K(z)$ depend on the density gradient $\partial\rho/\partial z$, nondimensionalized with the current shear to form the Richardson number $Ri = g(\partial\rho/\partial z)/(\partial u/\partial z)^2$. Suitable parametrization may be used in depth-dependent numerical models of estuaries or shallow seas.^{10,11,13}

In summary, we may think of a tidal current as sliding over a thin, rather slippery, bottom boundary layer (Figure 2) that exerts a quadratic stress on the fluid

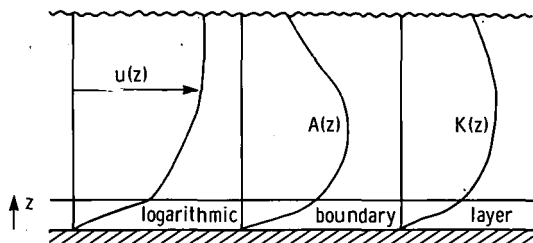


Figure 2. Vertical profiles of horizontal tidal current $u(z)$, eddy viscosity $A(z)$, and eddy diffusivity $K(z)$.

above it, in which the eddy viscosity and diffusivity may be functions of current speed, depth, and Richardson number.

Horizontal Mixing and Dispersion

Horizontal transfer of momentum and scalars may occur through the action of turbulent eddies with vertical axes, but frequently the combination of vertical mixing and vertical shear of the horizontal current is more important. This is discussed by Fischer elsewhere in this Conference.

TIDAL RECTIFICATION

Stokes Drift

The total mass transport at any location is

$$\mathbf{T} = \left\langle \int_0^{h+\zeta} \mathbf{u} dz \right\rangle, \quad (7)$$

where $\mathbf{u}$ is the horizontal current, ζ is the elevation above mean sea level at $z=h$, h is the water depth, and $\langle \rangle$ denotes the average over a tidal cycle. $\mathbf{T}$ may be written approximately as

$$\mathbf{T} = \int_0^h \langle \mathbf{u} \rangle dz + \langle \mathbf{u}_s \zeta \rangle, \quad (8)$$

where $\mathbf{u}_s$ is the fluctuating part of the velocity at the surface. Thus the total transport depends not only on the average current $\langle \mathbf{u} \rangle$ but also on the Stokes drift $\langle \mathbf{u}_s \zeta \rangle$. If $\mathbf{u}_s = \mathbf{u}_0 \cos \omega t$ and $\zeta = \zeta_0 \cos(\omega t + \phi)$ this becomes $\frac{1}{2} \mathbf{u}_0 \zeta_0 \cos \phi$.

For a progressive tidal wave $\phi=0$, and in some cases (such as the Straits of Dover in the English Channel¹⁴) the total transport can be in the opposite direction to the mean Eulerian current $\langle \mathbf{u} \rangle$, an important consideration in considering movement of fish stocks and pollutants. The Stokes drift is unlikely to be important for the small tides of the Atlantic Continental Shelf of the U.S., but it should certainly be evaluated as soon as data, or numerical model output, are available.

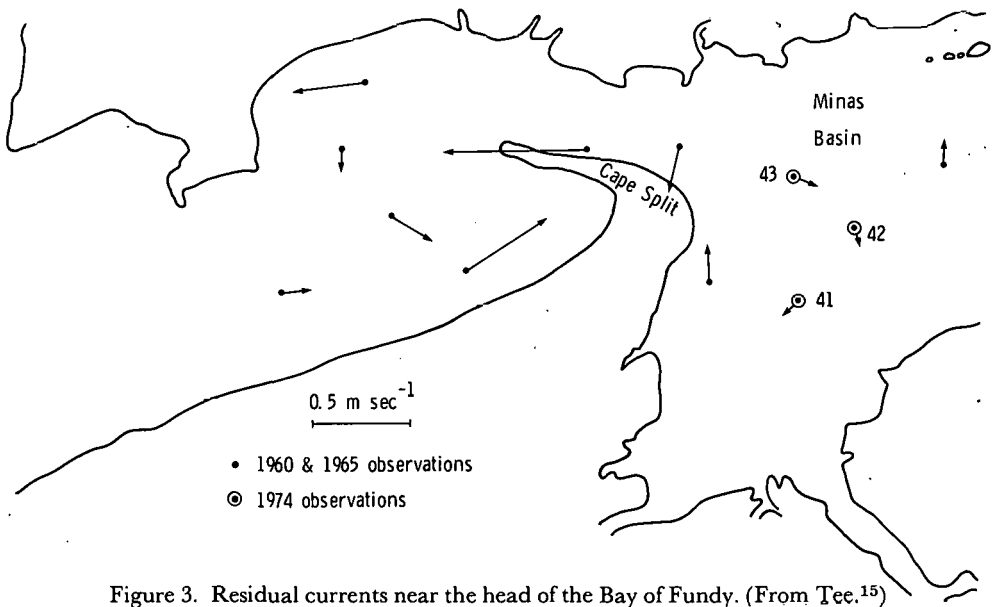


Figure 3. Residual currents near the head of the Bay of Fundy. (From Tee.¹⁵)

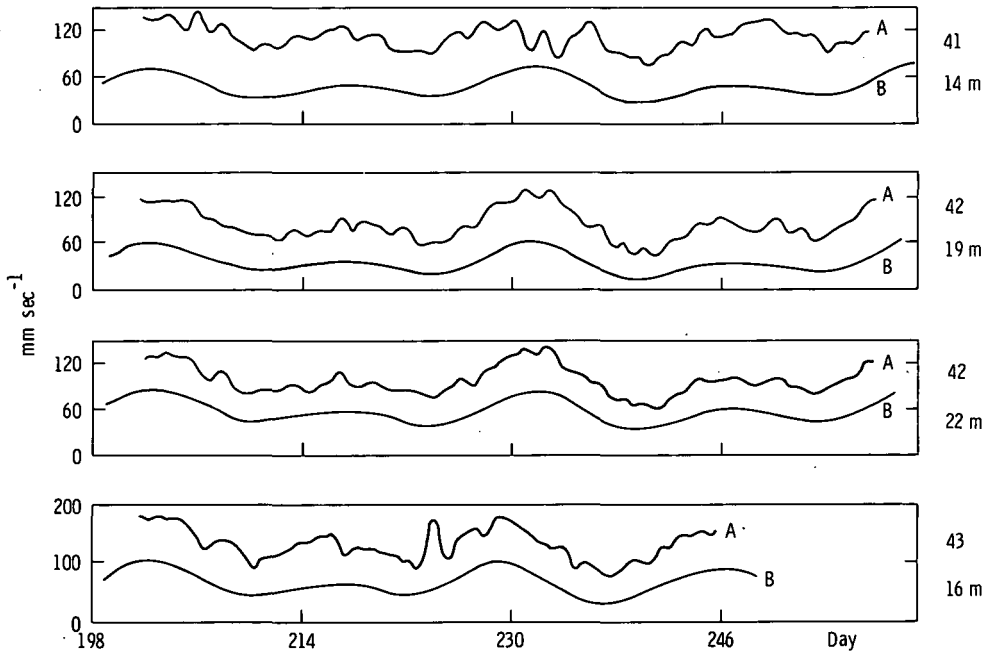


Figure 4. *A* is the low-pass filtered speed at moorings (shown in Figure 3) and depths below the mean sea level indicated. *B* is the modulation of the oscillatory part of the tidal current in the same location. (From Tee.¹⁵)

Depth-Independent Rectification

In a number of localities with strong tidal currents and an irregular coastline, a steady component of the current may be generated from oscillatory tidal forces, through the action of the nonlinear terms in the equations of motion. A good example occurs in the upper reaches of the Bay of Fundy (Figure 3), where large residual eddies, with residual currents of $\geq 0.5 \text{ m sec}^{-1}$, are observed. The cause of these eddies is that the flood tide enters Minas Basin as a jet, but the ebb tide leaves as a more uniform, sink-like flow.¹⁵ The average of this asymmetry is the observed eddy, with a similar eddy the other side of Cape Split. This pattern is well reproduced in a numerical model by Tee¹⁵ of the full nonlinear tidal equations. Further evidence that the residual current is tide induced appears in current meter data (Figure 4) showing a modulation of the low-pass filtered current in accordance with variations of strength of the periodic part of the tidal current.

While Tee's model¹⁵ averages the output from a fully nonlinear numerical model, as is essential in an area of strong tide-induced residuals, Nihoul and Roday¹⁶ have argued that a perturbation approach is more appropriate in an area of weak residuals. They have evaluated the "tidal stress," essentially the Reynolds stress associated with a solution of the linear equations, for the North Sea and have used this as an input force in a model of residual circulations. This is probably the best approach for the Atlantic Continental Shelf.

Tide-induced residual currents can occur not only near coastlines but also over offshore variations in topography. Huthnance¹⁷ found in an analytical model that a combination of the advective terms with bottom friction and the Coriolis effect could lead to steady currents, and he attempted to relate the theory to a steady clockwise circulation observed around the Norfolk sand banks in the North Sea.

Depth-Varying Residual Currents

It was shown by Longuet-Higgins¹⁸ that viscous boundary layer effects at the sea floor beneath periodic water waves lead to a mean Eulerian current of $(3\omega a^2 k)/(4 \sinh^2 kh)$ at the top of the boundary layer, and a mean Lagrangian current $5/3$ times this. ω , a , and k are the wave frequency, amplitude, and wave number, and h is the depth of water. Hunt and Johns¹⁹ applied a similar analysis to tidal currents in shallow seas, and Johns and Dyke²⁰ extended this with turbulent mixing parametrized as a depth-dependent viscosity. They found that a residual current of 0.03 m sec^{-1} within 1 m of the sea floor could be accounted for under conditions applicable to Liverpool Bay, where the amplitude of M_2 (the principal lunar semi-diurnal tidal component) is 2.8 m and the water depth 30 m.

In a more general study, Bowen²¹ has found that the magnitude and structure of these near-bottom streaming velocities are very dependent on the model of turbulent mixing used. Further effort is clearly required to elucidate this important phenomenon before it can be used in estimates of sediment transport.

Garrett and Loucks²² have suggested another way in which the tides may produce significant residual flow near the bottom; they point out that as strong tidal currents flow around a curved coastline, the onshore pressure gradient developed to balance the centrifugal force of the curved flow will be unbalanced near the bottom

where the tidal current is reduced by friction. This will lead to an onshore flow (for a convex coastline) in the same way that bottom flow is generated toward the inside bank of a river going around a corner. A crude estimate²² for the southwestern shore of Nova Scotia appears to account for the persistent onshore movement of bottom drifters²³ and consequent upwelling, but further modeling is required.

Heaps²⁴ has investigated the circulation resulting from a density gradient normal to the coast, produced by the combination of freshwater discharge and strong tidal mixing. Geostrophic currents are induced by both the setup of the sea surface near the coast and the density field, and again boundary layer effects produce a steady onshore flow at the bottom.

Density-driven currents may also occur in offshore regions due to vertical mixing by the tides, in one locality, of an otherwise stratified water mass. In particular, it seems possible that the clockwise circulation around Georges Bank observed in summer²⁵ is the partly geostrophic response to horizontal density gradients set up by tidal mixing.

INTERNAL TIDES

A density-stratified ocean can support internal waves, those of tidal period being known as internal tides. It is now generally believed that internal tides are generated by the interaction of surface tides and bottom topography, principally that of the continental shelf.²⁶ As the ocean moves to and fro with the surface tide, the bottom topography is effectively moving to and fro relative to the water, and thus internal waves of tidal period are generated. In practice these internal tides have wavelengths of tens of kilometers and amplitudes of up to 40 m or so. In a recent review²⁶ Wunsch concluded that internal tides are not a significant sink of energy for the surface tide, although Bell²⁷ has argued that they may be a significant source of energy for mixing in the deep ocean.

Internal tides generated at the shelf break should propagate on to the shelf as well as seaward, and Petrie²⁸ has argued, on the basis of data from the Scotian Shelf, that the input of energy to the shelf by internal tides may be as great in some locations as that lost by the surface tide (which loses most of its energy in extensive shallow seas rather than on typical continental shelves). Also, from observations of the rapid shoreward decay of the internal tide, possibly because of shear instability, Petrie has suggested that the internal tide may be causing significant mixing on the outer shelf, where he estimated a rough upper bound of $0.01 \text{ m}^2 \text{ sec}^{-1}$ for the resulting eddy diffusivity.

There are undoubtedly areas in which internal tides play a significant role, but much more work is required before the effects can be parametrized with any confidence.

BOTTOM PROCESSES

Sediment Transport

The complex role of tidal currents in sediment transport is dealt with elsewhere in this Conference.³⁵ There is a definite need for a satisfactory parametrization of bed load and suspended load transport in terms of quantities that can be determined from numerical models of tidal and other currents.

Effect of Quadratic Friction

The bottom stress is generally parametrized as being proportional to $-u|u|$, where u is either the current at some small distance above the bottom or the depth-averaged current. As $u|u|$ is a nonlinear function of u , the presence of an oscillatory tidal current u_t will affect the stress felt by a steady current u_0 . If $u = u_0 + u_t$,

$$\langle u|u| \rangle \simeq \langle (u_t \cdot u_0) u_t / |u_t| \rangle + \langle |u_t| \rangle u_0 \quad (9)$$

if $|u_t| \gg u_0$. We see that the average stress is proportional to the magnitude of the steady current and the average magnitude of the tidal current, and that its direction depends on the relative directions of steady and tidal currents. This modification of the bottom stress by the tides must be taken into account in any theory of steady circulation driven by density gradients or wind.

OFFSHORE DEVELOPMENT

Effect of the Tides

Tidal currents can play an important role in advection and dispersion of oil spills or toxic wastes, and tidal effects must be incorporated into any predictive models. To cite just one example, Loucks et al.^{29,30} have estimated the spread of a potential oil spill in Canadian waters from a tanker approaching the oil refinery at Eastport, Maine, proposed by the Pittston Company. They assume that a spill would be advected with the purely tidal component of the current and dispersed by the higher frequency currents, which are probably due to eddies generated by the tide. The actual estimation of dispersion rate is based on certain statistical properties of current meter data with the tidal velocities removed.

Effect on the Tides

A large-scale energy development rather different from those discussed at this Conference is the proposed tidal power project in the upper reaches of the Bay of Fundy. Here a central problem has been that of predicting changes that would be brought about in the tides themselves by construction of a barrier.

Until recently it has been assumed that the way to predict changes in tidal regime is to adjust a numerical model to the natural regime, then rerun it with the tidal power plant in place, but with the same tidal elevation as before at the open boundary of the model. This led to predictions³¹ of decreases of 5 to 10% in tidal amplitude at the barrier, depending on the location and type of power plant.

The assumption of fixed elevation at the entrance to the bay is obviously incorrect. If the tide consists of an incident wave and a reflected wave, the latter, and hence the amplitude at the open boundary, is obviously changed by the presence of a barrier. Recent progress in our understanding of the reasons for the large tides in the Bay of Fundy^{32,33} has made it clear that a tidal model must extend to the edge of the continental shelf (rather than just to the mouth of the Bay of Fundy), where the assumption of prescribed elevation is better, although still not perfect.³

Heaps and Greenberg³⁴ have developed a numerical model of the tides of the Bay of Fundy and Gulf of Maine and predicted changes in tidal regime that would

be caused by tidal power development. It is still uncertain whether tides at a dam site would increase or decrease slightly, but it has been shown that the tidal range over the southern part of the Gulf of Maine would increase, with an increase of $\approx 25\%$ at Boston being forecast for the most ambitious tidal power scheme considered. An increase of this order was also predicted roughly³³ on the basis of an approach to resonance of the Bay of Fundy and Gulf of Maine system, together with a change in the fundamental mode of oscillation.

Further work is in progress to increase the reliability of these predictions. Tidal power may never be developed, but whatever predictions are made should be made from a model based on valid assumptions. An understanding of basic processes is fundamental to any attempt to predict the results of man's intervention.

Acknowledgment: I thank Professor Anthony J. Bowen for information on and discussion of many of the topics of this paper.

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Turbulence and Vertical Mixing

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Analysis of data obtained by towing high-frequency-response velocity and temperature sensors in the upper layers of the ocean shows evidence that turbulence is generally absent or very weak. Spectra of horizontal velocity fluctuations may serve as a useful criterion to distinguish between turbulent and internal wave motions, since the evidence is that they exhibit distinct subranges at small and large scales, respectively, separated by a buoyancy scale $L_R = (\epsilon/N^3)^{1/2}$, where ϵ is the viscous dissipation rate and N is the Vaisailla frequency of the layer. For wavelengths $\lambda = 2\pi/k$ smaller than about $\frac{1}{2} L_R$, spectra may exhibit the universal similarity shape, but for larger scales a buoyancy subrange proportional to $N^2 k^{-3}$ appears, where k is the horizontal wave number. When the oceanic region is sufficiently active for a turbulence spectrum to appear the buoyancy spectrum increases to a saturated level, with a proportionality constant of $\lambda_T = L_R/2$. Oceanic temperature fluctuations frequently fail to exhibit the universal spectral forms expected for the dissipation rates suggested by the velocity measurements. Vega (Ph.D. dissertation, AMES Department, University of California at San Diego, 1975) finds that the cutoff wave number is proportional to $(N/D)^{1/2}$ rather than $[(\epsilon/\nu)^{1/2}/D]^{1/2}$, and that subranges $\sim k^{-1}$ appear for smaller scales such that $\Gamma = 0.3\chi/Nk$, where Γ is the horizontal temperature spectrum and χ is the dissipation rate of temperature variance. The present (speculative) interpretation is that internal wave motions strain nonturbulent "fossils" of previous turbulent mixing events at a rate $\sim N$. The resulting Γ level increases above $\Gamma = 2\chi/k(\epsilon/\nu)^{1/2}$ (the universal viscous-convective subrange of Batchelor) because N is less than the turbulent rate of strain $(\epsilon/\nu)^{1/2}$ and appears in the denominator of the expression for Γ . An equilibrium is established between the turbulent and nonturbulent portions of a layer and the turbulent portion is rapidly damped by radiating energy as internal waves; this radiated energy keeps the nonturbulent portion in a state of nearly saturated small-scale internal wave motion. Thus ocean layers may be separated into three classes: turbulent, nonturbulent, and equilibrium. Turbulent layers have the property that $\epsilon > 100 N^2$, nonturbulent layers have $\epsilon < 100 \nu N^2$, and for equilibrium layers it appears that $\epsilon \approx 100 \nu N^2$ (note the cgs thumb rule, $\epsilon_{\text{equilibrium}} = N^2$). It is suggested that a substantial fraction of the ocean may be in the equilibrium state and that an important parameter of vertical mixing in the ocean may be the volume fraction turbulence of an equilibrium layer.

DISCUSSION

MANOWITZ: Do you care to say anything about our state of knowledge of mixing processes at the thermocline?

GIBSON, C.H.: At least two major oceanic expeditions are being planned to try to get some data for comparison with numerous models that have been proposed. One is the JASIN program being planned in Great Britain (joint air-sea interaction experiment), and the other is a similar experiment off the California coast. The direct answer is that little is known of the actual mixing processes at the base of the thermocline.

An Introduction to Shear Flow Dispersion and Its Relevance to Dispersion on the Continental Shelf

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INTRODUCTION

The purpose of this paper is to introduce the shear effect, to describe how shear dispersion occurs in rivers and estuaries, and to offer some thoughts on why the process is important on the continental shelf. The author's work has been primarily with rivers and estuaries; no familiarity with the hydrodynamics of the shelf is claimed, and no conclusions are offered. Nevertheless, it seems apparent that shear flow dispersion is an important mechanism on the shelf and that those working on shelf studies ought to be familiar with it. For anyone wishing to study mixing in rivers and estuaries in greater detail, reasonably complete and up-to-date lists of references are given in two recent review papers.^{1,2}

THE SHEAR EFFECT IN TURBULENT FLOW

The concept of longitudinal dispersion by the shear effect was introduced by G.I. Taylor in two classical papers.^{3,4} Taylor analyzed the dispersion of marked fluid particles in flow in a long, straight pipe. He noted that a cloud of marked particles equally distributed over the cross section of the flow will be dispersed because the particles in the center of the pipe will be moving downstream faster than those near the sides. On the other hand, turbulent diffusion provides a means for particles to move from the sides to the center, and vice versa. The faster the rate of turbulent diffusion, the more nearly equal will be the downstream velocity of all the particles, and the less the cloud will disperse. Consequently, turbulent diffusion acts as a brake to longitudinal dispersion. Less cross-sectional diffusion, on the other hand, causes the particles to have different velocities longer and to spread farther apart. Taylor showed quantitatively that the longitudinal dispersion coefficient is inversely proportional to the turbulent diffusion coefficient.

Taylor's quantitative result is based on a hypothesis of a balance between cross-sectional diffusion and longitudinal advection. His method of approach can be applied to any bounded cross section; Elder⁵ applied it to a two-dimensional open-channel flow, and Fischer,⁶ to a cross section typical of a natural stream. In both cases it was possible to derive analytically a value of the longitudinal dispersion coefficient. The approach, however, has two significant limitations: (1) for the diffusion-advection balance to occur, there must be sufficient time for the marked particles to distribute themselves over the cross section; and (2) velocities must be uniform in the direction of flow (i.e., the pipe or channel must have a constant cross section). In practice, it is probably more reasonable to say that the velocity distribu-

tion must remain constant for longer than the time required for cross-sectional mixing, which is of the order of l^2/e , where l is a typical cross-sectional dimension and e is a typical diffusion coefficient.

HYDROLOGIC APPLICATIONS

Most of the dispersion observed in rivers, lakes, and estuaries can be interpreted as a generalized form of the shear effect. Mass transport occurs in two ways, by advection along streamlines and by diffusion along and between streamlines. In almost all hydrologic applications, diffusion along streamlines is negligible compared with the joint effect of the velocity difference and diffusion between streamlines. The Taylor's basic concept of the combination of velocity distribution with cross-sectional diffusion is relevant, even though the asymptotic balance he postulated may not occur.

As an example, rivers usually have one deeper section in which the velocity is faster than in the rest of the cross section. Taylor's analysis may be applied directly to rivers, taking the balance between downstream advection and diffusion across the river. In many cases, however, the cross-sectional mixing time l^2/e is sufficiently long that before a cloud of marked particles can be well distributed across the river, the velocity distribution has undergone a significant change. Also, many rivers have indentations along the sides which act as storing basins for material; the effect of these basins can be included in a Taylor-type analysis, but this greatly increases the cross-sectional mixing time. Consequently, it can be said that the shear effect is the major mechanism for longitudinal dispersion in rivers, but the results of a straightforward application of Taylor's technique may not be exactly correct.

In estuaries the flow is substantially more complex, but the shear effect remains. Usually the flow oscillates with a period much shorter than the time required for cross-sectional mixing, and this greatly reduces the importance of the velocity distribution. It is possible, however, to average over the tidal cycle and apply a Taylor-type analysis to the time-averaged velocity distribution. The result is complicated by the interaction of the tidal wave with embayments and branching channels, which produces a separate mechanism for dispersion. The results of the shear effect and the other mechanisms are, however, additive, as discussed at some length in the review paper already mentioned.²

APPLICATION TO DISPERSION ON THE CONTINENTAL SHELF

On the continental shelf, just as in estuaries, a large number of scales of motion are undoubtedly present. Motion on each of these scales has its associated shear effect (in fact, small-scale turbulent diffusion may be looked on as the result of a laminar velocity gradient and molecular diffusion, a sort of shear effect). Presumably the direction as well as the magnitude of the velocity vector varies with depth. The variation in direction leads to an apparent transverse dispersion, i.e., a spreading in the horizontal direction perpendicular to the mean velocity vector. Csanady⁷ has given an analysis of the effect of a skewed velocity distribution in Lake Huron, a

situation probably similar to that for currents on the shelf. Okubo and Karweit⁸ have shown how the combination of velocity variations can lead to an oval distribution of a dispersing cloud.

Application of the shear-effect analysis to dispersion on the shelf requires two types of data. First, it is essential to know the distribution of velocity, in both time and space, because the advective velocity is the primary determinant of where a pollutant will go. Second, the rate of turbulent diffusion between streamlines must be known because this rate determines how much of a diffusing cloud will migrate from streamlines of one velocity and direction to streamlines of another. With sufficient data it is a relatively simple matter to construct a numerical model of dispersion and pollutant transport. The concept of the model will be the same as the concept of shear-flow dispersion in a pipe, although the simple results of Taylor and others for bounded flows cannot be applied because the mixing is usually unbounded.

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Review of Oil Spreading on the Sea

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INTRODUCTION

The spread of oil on the sea is important for a number of reasons. Historically, the subject first gained practical importance after the Torrey Canyon incident.¹ The first studies^{2,3} were used to estimate the required response time if an oil boom is put around a massive spill in the open ocean. Such an approach no longer is promising because of difficulties in preventing the rapid spread of oil (discussed below) and because most biological damage occurs when the oil reaches the inshore area.⁴

At present, the main application of oil-spreading and drift calculations is the evaluation of environmental hazards associated with oil production and transport.⁴ The practical approach to oil spills appears to be rigorous prevention of accidents. Since my last review of this subject⁵ the spill rate in the United States has decreased.

The phenomena to be dealt with in gaining an understanding of oil spread include the inertia and buoyancy of the oil and the drag of the water under the oil slick. These factors influence the rate at which an oil spill initially spreads and the effect of currents on its drift. Surface tension controls the rate at which some oil slicks become thin films, as well as the formation of droplets. The different boiling-point fractions found in most oils determine, in part, the rate of aging of spilled oil and perhaps the surface tension of various fractions. Finally, the drift of oil slicks is controlled by the complex interaction of wind, waves, currents, and the properties of the oil slick.

OIL SPREADING IN TEMPERATE WATERS

It is now well known⁵ that in calm water three mechanisms control the rate of spreading of oil slicks. For a large volume of oil V released at $t=0$, initially there is a balance between the forces of gravity (buoyancy), which tend to cause the oil to spread, and inertia, which retards the motion. If l is the radius of the pool,

$$l \cong (g\Delta V)^{1/4} t^{1/2}. \quad (1)$$

Here g is the acceleration due to gravity, and Δ is the difference in specific gravity between oil and water.

At later times the balance is between gravity and the drag caused by the oil sliding over the water. If ν is the kinematic viscosity of the water, the law is

$$l \cong \nu^{-1/12} (g\Delta)^{1/6} V^{1/3} t^{1/4}. \quad (2)$$

Both these laws are well supported by theory and experiment.

Note, however, that the theory that yields Eq. (1) as a similarity solution is analogous to that for a compressible liquid with a speed of sound α , given by⁵

$$\alpha = \sqrt{g\Delta h}, \quad (3)$$

where h is the local thickness of the oil slick. This theory predicts a thickness profile $h(r, t)$ ($r \leq l$ being the distance from the point of release) which is far from correct, although there are choices of boundary conditions⁶ that yield the correct coefficient in Eq. (1). Another important prediction of this theory has to do with the maximum rate at which oil can be swept up by a skimmer operating in a pool of oil.⁷ Here the theory is known to yield correct results both on the laboratory scale⁸ and in practice. The reason the theory does not yield the correct thickness profile is that the under-surface of a thick pool of oil is unstable, a point to which we shall return.

Equation (2) is well supported by experiment.⁵ Since 1972 a similarity solution to the Navier-Stokes equations that yielded such a flow has been known to exist. However, the proper construction of this solution was first achieved in 1974.⁹ The difficulty is that the boundary layer under the oil has a thickness that scales in one way near the leading edge of the slick and in a different way near the center portion of the slick. At present there is excellent agreement between experiment and theory for viscous-gravitational spread, as the law given by Eq. (2) is known.

The final phase of spread represents a balance between surface tension, with a net spreading coefficient σ , and viscous drag. The law is

$$l \cong \sigma^{1/2} \nu^{-1/4} t^{3/4}. \quad (4)$$

Again since 1972, it has been known that there is a similarity solution of the Navier-Stokes equations that has a form giving Eq. (4). To date, however, reasonable agreement between theory and experiment has not been obtained.

This surface tension law is also controversial and important in its application. It is important because small spills, which are the most frequent, spread entirely according to Eq. (4). It is controversial for several reasons: (1) Eq. (4) implies that the net surface tension σ of the oil is constant with time; (2) it implies that the oil consists of only one component, which has one value of σ ; and (3) it is not modified by wind, waves, and currents.

Taking the last point first, many authors have noted that the final phase is much more complex than Eq. (4) indicates. The simplest reason is that the dispersion rates due to wind, waves, and currents are of the same order of magnitude as Eq. (4) a few days after release. [On the other hand, it is not commonly appreciated¹⁰ that Eqs. (1) and (2) are modified only slightly by waves and wind; the reason is that both the fluctuating vertical acceleration due to waves and the stress due to winds are small compared with the forces involved in the derivation of these laws.]

We shall return later to the fact that oils consist generally of multicomponent mixtures, whose properties change with time.

Although Eqs. (1) and (2) do not depend much on the water temperature, Eq. (3) does; at arctic seawater temperatures near 29°F, $\sigma \cong 0$, and hence the oil does not spread to a thin film.¹¹

ARCTIC OIL SPREAD

The main modification to the above spreading laws, when ice is not present, is that $\sigma = 0$, as previously mentioned. When ice and open seawater are both present,

another consideration arises. Suppose a pool of oil floats on seawater surrounded by ice. Suppose next that the lead closes, which causes the oil layer to become thicker. Eventually the oil will either stick to the ice, flow over the ice, or flow under the ice. The stickiness of oil has been measured,¹² and it is known that a layer about 2 mm thick can adhere to the porous undersurface of the ice.

Sea ice varies in density between 0.70 and 0.91 g/cm³, the latter being pure ice and the former, ice with a porous brine structure. Generally, the older the ice is, the higher its density. On the other hand, North Slope crude has a density of 0.89 fresh out of the ground, and of >0.91 after 10 days to 2 weeks of exposure in the arctic winter, or a few days' exposure in the summer. Since in most cases we expect the oil to be more dense than the sea ice, we are forced to conclude that in general, as the lead closes, the oil is forced *under* the ice rather than over it.¹³ As sea ice in the arctic winter is 3 m thick, it is clear that just locating such a spill is a major task.

However, the undersurface of the sea ice pack is very rough. Calculations¹⁴ show that even a massive spill, larger than Torrey Canyon, would be contained in the "pockets" under the ice in an area of several square kilometers. Contrast this to the hundreds of square kilometers covered by the Torrey Canyon spill at its largest.

As the oil spreads over or under a rough ice surface, the spreading law is controlled by gravity and the drag of the rough surface.

Our present best estimate of the spreading law is

$$l \cong \left(\frac{gQ^2\Delta}{\langle h^- \rangle} \right)^{1/6} t^{2/3}. \quad (5)$$

Here Q is the rate of spread and $\langle h^- \rangle$ is the mean depth of the pockets. Equation (5) matches both laboratory experiments¹⁵ on random rough surfaces ($\Delta = 1$ when oil spreads over the ice) and small-scale observations of spills carried out in the high arctic in both summer and winter.^{11,16}

OTHER TOPICS

From a practical point of view, it has long been assumed that the oil drifts at 3% of the wind speed.⁵ However, the results of careful laboratory experiments¹⁷ yield drift speeds ranging from 2.5 to 4% of the wind speed. In assessing the drift problem, it is important to realize that there is a Stokes drift due to waves alone, a drift due to wind blowing over a smooth water surface (which is possible when the fetch is short), and modifications of both effects due to the surface properties of the oil slick. The present laboratory experiments¹⁷ separate drift due to wind from drift due to waves and thereby show that the two effects are not simply additive. But it seems unlikely that laboratory-scale experiments can simulate the building up of a sea under the action of a wind and the modifications of this process by the presence of an oil slick. I think that great progress in this area is unlikely. Rather, one should recognize that the drift calculations done in the standard way are uncertain by a factor of ≈ 2 .

A second practical matter is how oil ages in the sea. This aging process affects both the oil density and the surface-tension spreading coefficient, and hence all as-

pects of the oil spreading. For variations, some theory has been developed,^{18,19} the most recent result being that the characteristic time for changes in density due to evaporation, τ , is

$$\tau = \frac{1}{\frac{\lambda U^* p A}{RT} \exp \left[5.0 \left(\frac{T - T_B}{T} \right) \right]} \quad (6)$$

Here T_B is the boiling temperature of the fraction of the oil considered, A is the exposed area, p is the atmospheric pressure, R is the gas constant, and T is the absolute ambient temperature. U^* is the friction velocity of the air blowing over the oil slick. Equation (6) shows that as T decreases, the aging time increases exponentially, and at the aging time decreases with increasing exposed area and with increasing wind speed (which causes U^* to increase). Such a theory predicts fairly well how oil ages in the arctic.²⁰

Surface-tension variations due to aging are not well understood. The surfactants that determine the value of σ are a small fraction of the bulk oil. One cannot determine how σ varies with time by studying the bulk properties of the oil. The chemistry of the surfactants in the oil, even before aging, is known to vary greatly with the type and source of the oil.

Finally, there is the plague of practical devices to prevent oil spread by barriers: at currents above $U \cong 1.5$ ft/sec, the undersurface of a pool of oil held by some floating barrier becomes unstable,²⁰ and drops of oil are torn from the pool by the turbulent water flow. Let the pressure fluctuation in the current be

$$\Delta p \cong \rho U' U, \quad (7)$$

where U' is the fluctuating velocity component, typically about $0.10 U$. If the oil-water surface tension is σ' , then, for a drop to form with diameter D ,

$$\rho U' U \cong \sigma' / D. \quad (8)$$

On the other hand, the stable size of a drop is determined by a balance between surface tension and buoyancy:

$$\rho g \Delta D \cong \sigma' / D. \quad (9)$$

Equations (7) to (9) may be combined to estimate the Weber number of the drops formed:

$$We = \frac{\rho U^2 D}{\sigma'} \cong 10, \quad (10)$$

which is close to the range observed (from 5.5 to 7.5).²¹

As the size of the drop is about

$$D = \left(\frac{\sigma'}{\rho g \Delta D} \right)^{1/2}, \quad (11)$$

the critical current velocity for droplet formation is

$$U_c = 3 \left(\frac{\sigma'}{\rho} g \Delta \right)^{1/4}. \quad (12)$$

Using nominal values of $\sigma' = 10$ dynes/cm and $\Delta = 0.10$ gives $U_c = 0.7$ ft/sec, which is within a factor of 2 of the observed critical current and very close to the water velocity observed 2 in. below the oil pool.

This argument makes it clear that droplets, and the corresponding oil leakage, are an inevitable part of oil boom operations at even modest currents or towing speeds.

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DISCUSSION

MANOWITZ: Have you any estimates of what fraction of either crudes or distillates dissolves in the water column? Also, what fractions are dispersed in some way other than being dissolved, so that they act as though they are part of the water column rather than part of a surface film?

HOULT: Broadly speaking, most hydrocarbons are insoluble in water, so that in terms of molecular diffusion of the components going into the surface waters from the film, a much larger fraction must be evaporated than is dissolved. On the other hand, if the current is >1 knot, droplets are swept off the underside of the oil slick and dispersed in the water column. And if the characteristic shear velocities in a turbulence region are $>\approx 1$ knot, the oil can be dispersed in the water column. It is believed that these two mechanisms are necessary to get appreciable amounts of oil in the water column. If that process occurs, it can occur very rapidly because the power available goes with the cube of the wind speed. I think it can be said in general that, if it is assumed that spills are equally likely in all sea states, this mixing in the water column is not expected to be a pervasive phenomenon, but if oil is spilled in a hurricane, it certainly would occur.

Session III

Characteristic Biological Processes of the Atlantic Continental Shelf

Chairman: GORDON RILEY

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Plankton Processes in Mid-Atlantic Nearshore and Shelf Waters and Energy-Related Activities*

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INTRODUCTION

The occurrence of seasonal and regional differences in phytoplankton dynamics is well documented. Parsons and de Lange Boom¹ listed 15 physical, chemical, and biological components of the marine pelagic ecosystem which can interact to regulate plankton dynamics. Advection, temperature, nutrient regeneration, phytoplankton production, and food-chain stability are examples of these controlling factors and processes. To this list should be added a component that includes perturbants resulting from human activities. Energy-related activities may release into the sea petroleum hydrocarbons, chlorinaceous compounds, thermal effluent, and trace metals and may also influence the transparency of the recipient waters. The potential impact of these and other energy-related perturbants on plankton dynamics will obviously be influenced by the "natural" factors and processes characteristic of the stressed area. Moreover, seasonal and regional differences in effect are to be expected. This paper therefore emphasizes the general characteristics of the plankton processes in the Mid-Atlantic nearshore and offshore waters to put into perspective their natural dynamics subject to potential impact and modification, rather than presenting a detailed exposition. Chesapeake Bay is excluded from consideration. The phytoplankton dynamics in this region and in the coastal waters from Cape Hatteras to Nantucket have recently been reviewed in detail.²

The potential effects of temperature and petroleum hydrocarbons on key plankton processes and events are also considered, based on phytoplankton physiology. As for natural processes, only some general aspects are considered, without reference to a specific region. Nearshore waters are more likely to be affected by calefaction and

*Work supported in part by National Science Foundation Grant GA 31319X and Environmental Protection Agency Grant R803902010.

chlorine discharge from nuclear power generating plants; on the continental shelf, oil release is a more likely source of contamination. However, shore-based activities of the petrochemical industry may also stress recipient waters, as would discharge from tankers that collide on shipping lanes or discharges from tankers in port.

This overview is an attempt to provide some orientation and insight into plankton processes for those employed by energy-related corporations and regulatory agencies, and environmental groups.

GENERAL FEATURES

Plankton processes in the nearshore and shelf waters of the Mid-Atlantic region lectively exhibit the following characteristics:

1. There are seasonal cycles in phytoplankton abundance and productivity; these vary regionally.

2. Phytoplankton growth is influenced by the same factors throughout this region, but the relative importance (solely and in combination) of temperature, light intensity, nutrients, "water quality," grazers, etc. in regulating growth varies seasonally and regionally.

3. Considerable annual variations in phytoplankton dynamics may occur within a given area.

4. The species composition of the plankton communities varies seasonally and regionally, exclusive of certain cosmopolitan and eurytolerant species.

5. Environmental modification has altered phytoplankton composition and dynamics in certain areas.

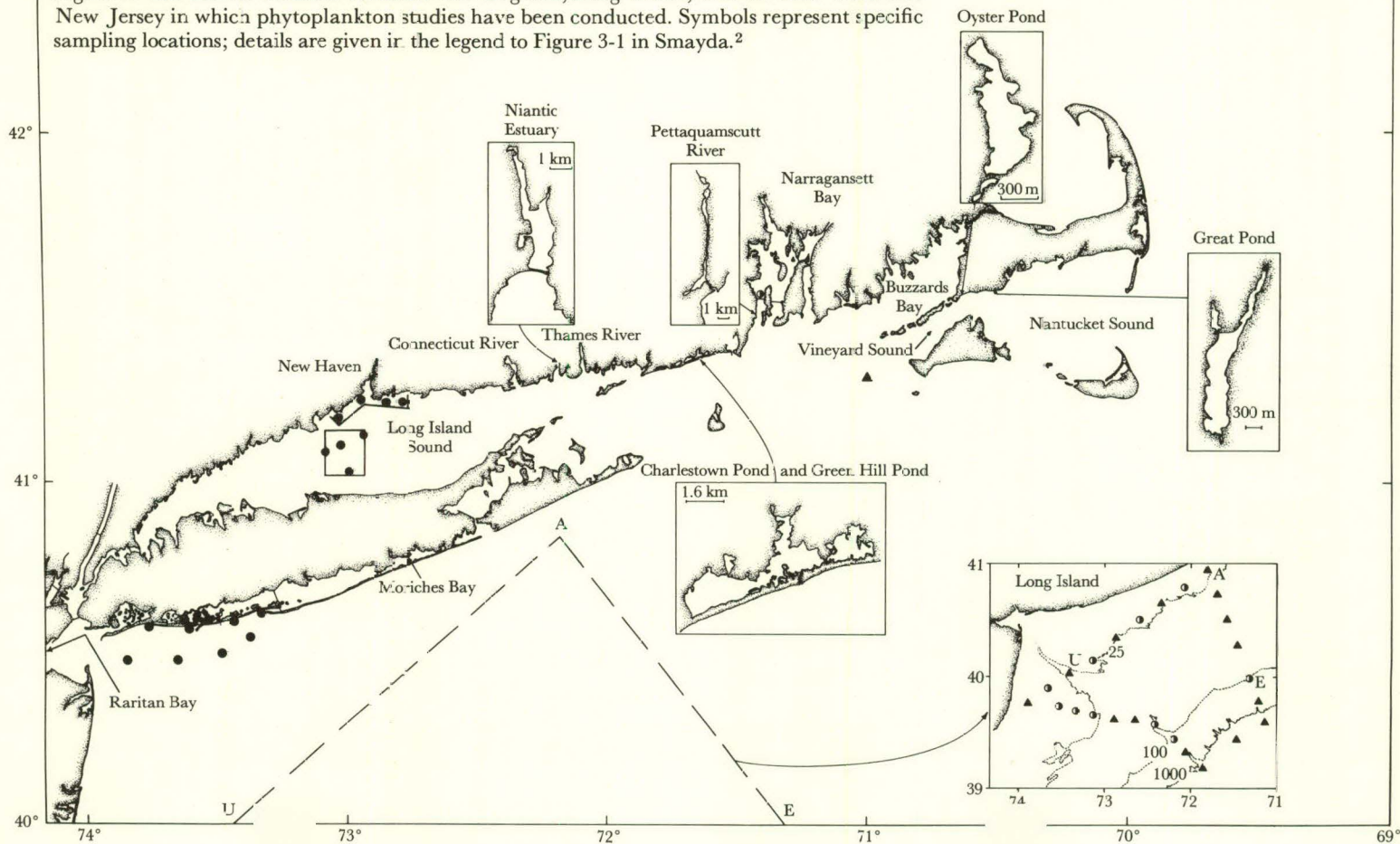
These characteristics are documented by selected examples. A detailed documentation can be found in Smayda.²

Regional Variations in Abundance and Productivity

Figure 1 shows some of the areas discussed. The mean standing stock of phytoplankton numerical abundance in Mid-Atlantic coastal and shelf waters varies over 6 orders of magnitude, from about 10^3 to $>10^8$ cells liter⁻¹ (Figure 2). It is generally much higher (sometimes it is enormous) in coastal salt ponds than in estuaries such as Narragansett Bay and in semiencloded sounds such as Long Island Sound. The average abundance also decreases progressively and significantly with increasing distance offshore. This onshore-offshore gradient persists when the greater depths of the euphotic zone in the shelf and deeper waters are taken into account and standing stock per unit area is calculated. The data are too scanty to determine whether a latitudinal gradient in phytoplankton abundance occurs. The mean of about 1.7×10^6 cells liter⁻¹ reported for Cape Fear Estuary, North Carolina,³ is similar to that for western Long Island Sound (Figure 2).

It is well known that nearshore waters are generally more productive than deeper waters. The annual carbon production in the different environments (Figure 3) also varies with depth, possibly latitudinally, and in the proportion of the total carbon production fixed by macrophytes [seaweeds, sea grasses (*Zostera*)]. The progressive decrease in carbon production along the onshore-offshore gradient (similar

Figure 1. The coastal waters of southern New England, Long Island, and off New York and New Jersey in which phytoplankton studies have been conducted. Symbols represent specific sampling locations; details are given in the legend to Figure 3-1 in Smayda.²



to that for mean phytoplankton abundance) is vividly demonstrated in the transect between Long Island and the Sargasso Sea. Annual production along this gradient decreases about 10-fold from a maximum of $\approx 500 \text{ g C m}^{-2}$ in waters shallower than 10 m. A decrease is also evident in the series extending from Narragansett Bay (310 g C m^{-2} to Georges Bank (150 g C m^{-2}). Block Island Sound and Long Island Sound exhibit intermediate levels of production.

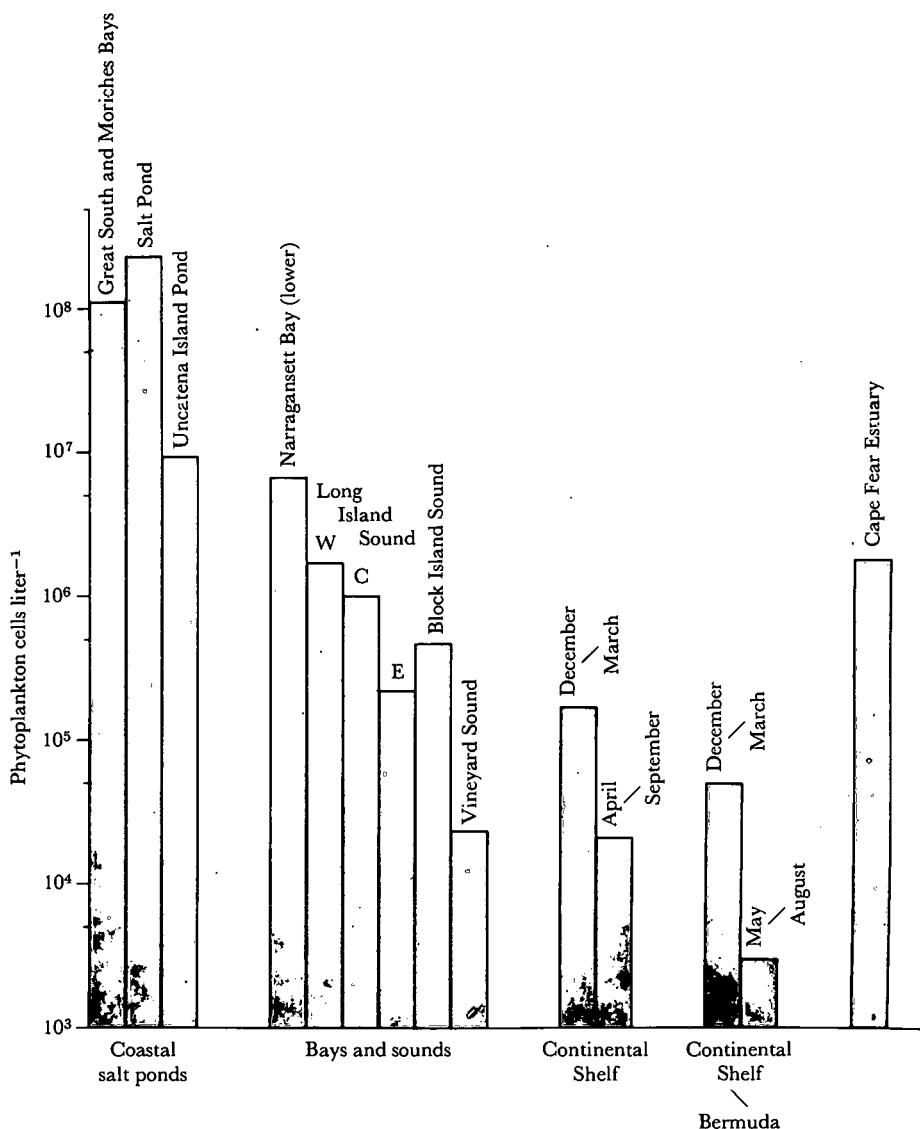


Figure 2. Mean standing stock of phytoplankton in selected areas as presented in Table 1 in Smayda.² Cape Fear Estuary datum is taken from Carpenter.³

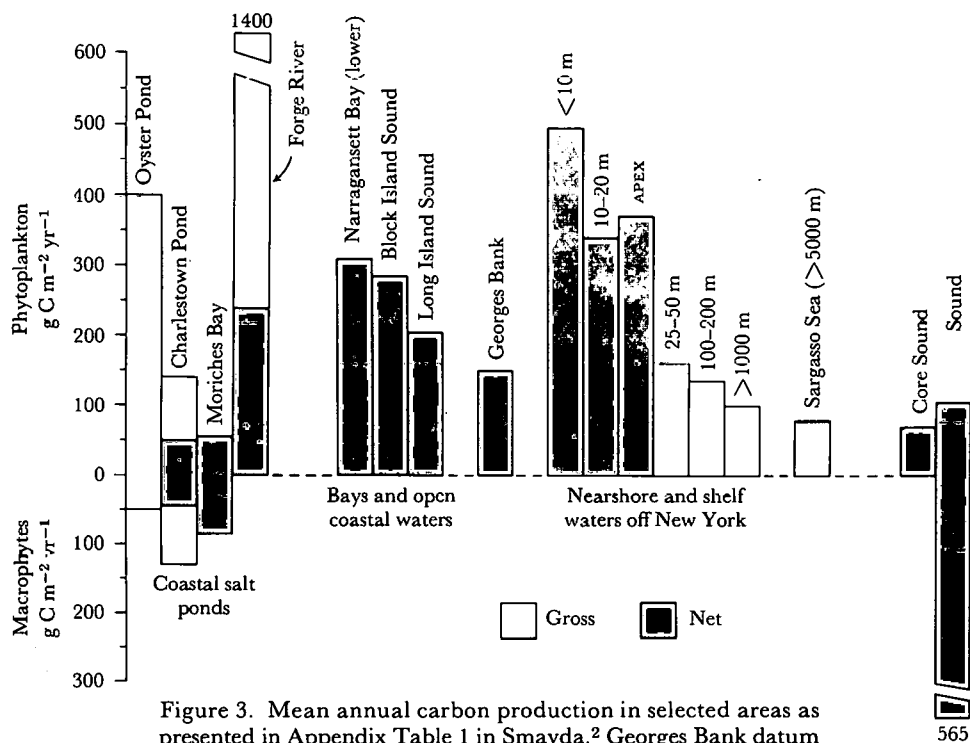


Figure 3. Mean annual carbon production in selected areas as presented in Appendix Table 1 in Smayda.² Georges Bank datum is from Riley⁴; APEX datum is from T.C. Malone (unpublished).

The evidence that a latitudinal gradient in annual carbon production occurs in Mid-Atlantic coastal waters is restricted to observations made in Pamlico Sound (North Carolina), which represent some of the few data sets for the area south of the New York Bight. The annual phytoplankton carbon production (70 to 105 g C m^{-2}) in the warmer, nutrient-poorer⁵ Core and Bogue Sounds is 4 to 7-fold less than that in northerly estuarine and coastal waters of equivalent depth. However, evaluation of this regional difference is complicated by another major feature that these shallow sounds have in common with coastal salt ponds: significant carbon production by attached macrophytes. Macrophytes accounted for 84% of the total annual carbon production of 670 g C m^{-2} in Bogue Sound.⁶ In Charlestown Pond (Rhode Island) production by *Zostera marina* (eelgrass) equaled that by phytoplankton ($51 \text{ g C m}^{-2} \text{ yr}^{-1}$), and in Moriches Bay (Long Island) it exceeded ($83 \text{ g C m}^{-2} \text{ yr}^{-1}$) phytoplankton production by 50% (Figure 3).

These few, incomplete measurements suggest that where sufficient light penetrates to the bottom in very shallow areas the annual production of carbon by attached macrophytes will probably exceed that by phytoplankton. Carbon production by the benthic microflora will also be stimulated.⁷ This community produced $90 \text{ g C m}^{-2} \text{ yr}^{-1}$ in some Rhode Island coastal salt ponds; in the Niantic Estuary (Connecticut) its annual production of 80 g C m^{-2} was 2-fold greater than phytoplankton carbon production.

Clearly, the phytoplankton are not the only carbon producers in the shallow nearshore waters, which are important as fish nurseries; in fact, they may be the least important of the primary producers, with carbon production by macrophytes $>$ benthic microflora $>$ phytoplankton. This is relevant in evaluating the potential impact of energy-related activities on marine ecosystems. Consider shore-based nuclear power generating plants. An evaluation of the effects of thermal discharge and chlorination treatment should not consider only phytoplankton responses, since this component may be of secondary importance. Macrophyte and benthic microflora dynamics may be equally, if not more significantly, affected by these perturbants. In contrast, assessment of the potential impact that drilling for oil on the continental shelf would have on plant growth need consider only phytoplankton responses.

The potential disruption of a commercial fishery following changes in magnitude of primary production caused by energy-related stresses is not easily predictable. While a high level of phytoplankton production is necessary, it is not in itself sufficient to support a thriving fishery.⁴ Annual phytoplankton carbon production and commercial fish yields are not closely correlated. For example, the annual net production in Block Island Sound of 285 g C m^{-2} is about twice that on Georges Bank (Figure 3). However, the annual fish production, as carbon, is similar in both areas; it amounts to between 0.4 and 0.8% of the net phytoplankton production. Riley⁴ believed that the lower fish yields in Block Island Sound reflected the loss of about $135 \text{ g C m}^{-2} \text{ yr}^{-1}$ (i.e., 47% of the annual production) through horizontal dispersal into outer coastal areas. Since this made available only $150 \text{ g C m}^{-2} \text{ yr}^{-1}$ for fish production, both areas were about equally efficient in food chain conversion, even though Block Island was twice as productive in the absolute sense.

The efficiency in food chain conversion also influences the relationship between phytoplankton and fish production. For example, phytoplankton production in Long Island Sound ($205 \text{ g C m}^{-2} \text{ yr}^{-1}$) is about 40% greater than in the open coastal and bank (shelf) waters off New England, and twice as productive as in the English Channel.⁴ However, the commercial fish catches are significantly lower in the Sound; Riley attributes this to the dominance of certain zooplankton species (*Acartia*). While these relatively inefficient feeders influence community dynamics in several ways, the overall consequence is that a food base adequate to support a thriving fishery does not develop. Thus, although Long Island Sound is productive in an absolute sense, the trophic structure is relatively inefficient in food chain conversions. Optimal efficiency seems to be more nearly approached in coastal and shelf waters of moderate depth and ≥ 30 ‰ salinity than in deeper waters or more enclosed sounds and bays.⁴

Causes of Regional Variations in Abundance and Productivity

The annual yield of phytoplankton carbon has been demonstrated to vary regionally; moreover, it tends to decrease with distance offshore. This latter trend raises the question of to what extent the yield may be regulated by onshore-offshore gradients in nutrients and/or depth of the water column. The increased fertility of inshore waters has been generally attributed to enrichment by freshwater drainage. However, Riley⁸ concluded that runoff is a minor source of nutrients in this region,

except in some local semienclosed areas such as Long Island Sound. In fact, enrichment of this sound from oceanic waters appears to be about equal to that derived from runoff. Hale⁹ calculated that drainage and rainfall contributed about 13% of the daily nitrogen input into Narragansett Bay during the summer (August) – a minor input. Nonetheless, nutrient concentrations in the nearshore waters of this region are higher than in offshore waters (see Kester and Courant¹⁰). The maximum concentrations of inorganic nitrogen in the unpolluted waters of lower Narragansett Bay (30 μM) and Long Island Sound (25 μM) are about 4-fold greater than that in the New York Bight and about 20 times that in the very shallow Core Sound (Table 1). Competition for nitrogen by the prolific macrophyte stands in the shallow North Carolina estuaries (Figure 3) probably accounts for the latter levels.

Riley's mathematical model⁸ of nutrient dynamics in local coastal waters supports his view that the usual pattern of exchange between inshore and offshore waters tends to enrich the coastal zone irrespective of enrichment by freshwater drainage. This suggests that the region must be treated as a unit despite the observed variations in carbon production and nutrient levels. Modifications or perturbations in offshore waters may ultimately influence nearshore processes because of exchange processes. This holistic view is reinforced by Marshall's demonstration¹¹ that the Niantic River estuary is an effective concentration system which utilizes the production of contiguous Long Island Sound. In fact, coastal lagoons generally may function as a nutrient sink not only through nutrient uptake by plants but also by the efficient grazing of the phytoplankton produced in offshore waters and introduced with the tidal prism.²

Despite similar onshore-offshore trends in carbon production and nutrient levels, the evidence is not convincing that nutrient concentrations *per se* are respon-

Table 1

Annual Production of Carbon and of Nitrogen (N_p) per m^2 , Maximum Concentration of $\text{NO}_3 + \text{NO}_2 + \text{NH}_3$ (ΣN), and Number of Times That ΣN Must Be Replenished Annually ($N_p/\Sigma N$) to Support N_p in Selected Areas

Region	Carbon production		N_p (g-atom)	ΣN ($\mu\text{g-atom liter}^{-1}$)	Euphotic zone (m)	ΣN (mg-atom m^{-2})	$N_p/\Sigma N$
	g C	g-atom					
Lower Narragansett Bay ^a	310	25.8	3.9	30	8	240	1
Long Island Sound	205 ^b	17.1	2.6	25 ^c	12.5 ^b	313	8
New York Bight (25 to 200 m)	150 ^d	12.5	1.9	7 ^e	50	350	5
Core Sound ^f	67	5.6	0.8	1.5	1.2	2	400

^aFrom Smayda, unpublished data.

^bFrom Riley.¹²

^cFrom Harris.¹³

^dMean reported by Ryther and Yentsch.¹⁴

^eFrom Vaccaro.¹⁵

^fFrom Thayer.⁵

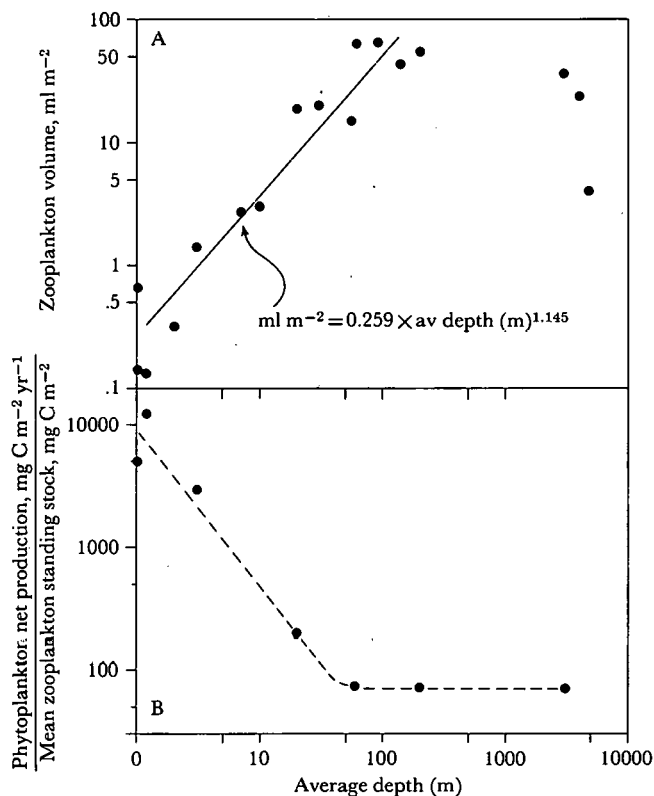


Figure 4. A: Relationship between average zooplankton standing stock and average depth of the water column sampled in various areas. B: Ratio of annual net carbon production by phytoplankton to the average zooplankton carbon standing stock, compared with the average depth of the water in various areas. Both modified from Figures 3 and 4 in Williams et al.¹⁶

sible for the regional variations in production. Table 1 indicates that inorganic nitrogen must be replenished 5 to 16 times annually in the waters off southern New England and New York to support the observed production. Daily replacement is necessary in Core Sound. [Nitrogen production was calculated assuming that the stoichiometric ratio for C:N:P is 100:15:1 (by atoms).] These calculations indicate that remineralization processes are also a factor in the regulation of regional productivity, specifically the excretion of nutrients by the zooplankton and benthos, now commonly acknowledged to be important sources.

This focuses attention on the role of water column depth in regional production, since depth influences zooplankton abundance and the extent to which pelagic processes are influenced by benthic processes. Figure 4A, based on data from the region of interest,¹⁶ indicates that while shallow waters support a lower average standing stock of zooplankton than do deeper waters, the biomass increases with depth to about 200 meters and can be approximated by the equation

$$\text{Zooplankton volume (ml m}^{-2}\text{)} = 0.259 \times \text{av depth water column (m)}^{1.145},$$

for which $r=0.96$, significant at the 0.01 level. The standing stocks at depths >1000 m do not fit the regression.

The influence of water column depth on the ratio of net carbon production by phytoplankton to mean zooplankton standing stock (as carbon) is presented in Figure 4B. Williams and co-workers¹⁶ interpreted this plot to indicate that the zooplankton become more important as grazers in waters deeper than about 100 m, and become steadily less important with decreasing depth. It is not possible to define precisely the depth at which pelagic processes become uncoupled from benthic influence, but it is evident that there is an onshore-offshore gradient in the relative contributions of zooplankton and benthic excretion. Benthic activities can be expected to predominate in shallow waters, with the contribution by zooplankton progressively increasing with water column depth. At depths >100 m zooplankton probably become preeminent and pelagic processes more or less uncoupled from benthic influence (grazing and nutrient excretion).

Some estimations of benthic and zooplankton activity in Narragansett Bay and Long Island Sound can put these relationships into perspective. The average depths are about 10 m for Narragansett Bay and 20 m for Long Island Sound. Based on an annual carbon production of 310 g C m^{-2} in lower Narragansett Bay (Figure 3) and a benthic respiration rate⁹ of $38 \text{ mg O}_2 \text{ m}^{-2} \text{ hr}^{-1}$, which equals $3.2 \text{ kcal m}^{-2} \text{ day}^{-1}$, about 38% of the net phytoplankton carbon production is utilized annually by the benthos. In Long Island Sound, where this amounts to 31%,¹² Harris¹³ estimated that the zooplankton excreted about 50% of the daily phytoplankton nitrogen needs, and the benthos only 10%. The remainder was derived from other sources. In Narragansett Bay benthic excretion appears to be more important than zooplankton excretion.^{9,17,18} During the summer (August) benthic communities contributed 64% of the daily nitrogen inputs into this bay and zooplankton only 7%.⁹ Furnas et al.,¹⁷ on the basis of uptake experiments, estimated that only 3% of the daily phytoplankton nitrogen needs were excreted by zooplankton during the summer of 1974, whereas benthic excretion averaged 34%.

Whatever the mechanisms responsible for the generally increased concentrations of nutrients and fertility in nearshore waters, it is clear that excretion by the zooplankton and benthos is very important in recycling nutrients to sustain the observed production and its regional variations. Moreover, the extent to which pelagic processes are generally coupled to benthic processes is inversely related to depth.

The significance of these features for energy-related activities is clear. Perturbants that have only a modest *direct* effect on primary production may have a major *indirect* effect if they are deleterious to the zooplankton or benthic components. For example, petroleum hydrocarbons form particles of various sizes¹⁹ and in this form they are grazed by zooplankton.²⁰ However, at this trophic level uptake predominates over assimilation, and most of the particles pass through the gut and are voided as fecal pellets, which sink to the sediments. The large copepod *Calanus finmarchicus*, for example, removes up to $150 \text{ } \mu\text{g}$ of oil per day under optimal conditions. For dense populations this could amount to $300 \text{ mg m}^{-3} \text{ day}^{-1}$ or, at 1.5 ppm of oil, $3 \text{ tons km}^{-2} \text{ day}^{-1}$.²¹ While such activity may help to detoxify the water column and render it favorable to phytoplankton growth, the deposition of fecal pellets would lead to a buildup of hydrocarbons in the sediments. This may be potentially deleterious.

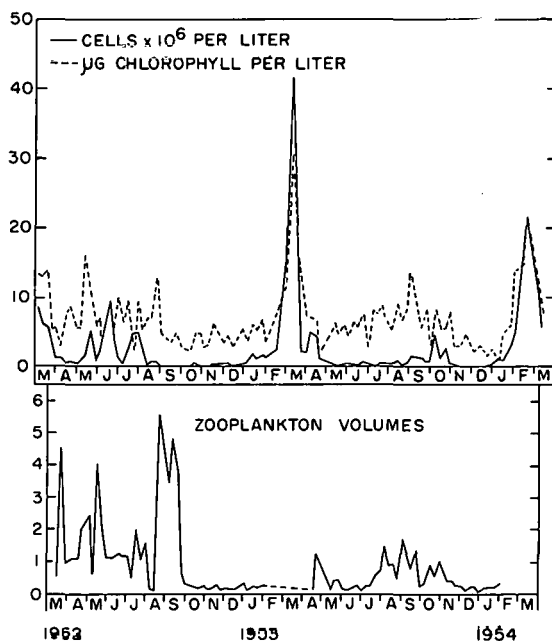


Figure 5. Average phytoplankton cell numbers and chlorophyll concentrations at the surface, and zooplankton volumes (ml m^{-3}) obtained by oblique tows with a No. 10 net in Long Island Sound at inshore stations 1, 6, 7, and 8 located near New Haven (see Figure 1). Modified from Riley.⁴

rious to benthic processes and, through these, to phytoplankton growth, depending on the extent to which it is coupled with the benthos in the stressed area.

Seasonal Cycles

The annual range of daily carbon production (0.10 to $1.70 \text{ g C m}^{-2} \text{ day}^{-1}$) is about the same from Long Island Sound across the adjacent continental shelf to the slope waters, and even in the oligotrophic Sargasso Sea.¹⁴ This indicates that phytoplankton production is independent of location when suitable nutrient enrichment occurs. Nonetheless, regional variations in plankton abundance and production occur (Figures 2 to 4). These characteristics and the variation in daily carbon production rates indicate that the intensity and duration of active phytoplankton growth must vary locally, regionally, and seasonally. That is, annual (seasonal) cycles occur which are regulated by environmental conditions rather than by plankton life cycles.

Temperate waters exclusive of shallow embayments (Narragansett Bay, for example) are characterized by the classical phytoplankton cycle. This consists of a major bloom sometime between January and March, and a smaller bloom usually sometime during late summer to autumn. This cycle is found in Long Island (Figure 5),²² Block Island,²³ and Vineyard²⁴ Sounds. The winter-spring bloom generally develops first in inshore waters and gradually moves offshore. This characteristic is also detectable in the waters over the continental shelf off New York (Figure 6), where

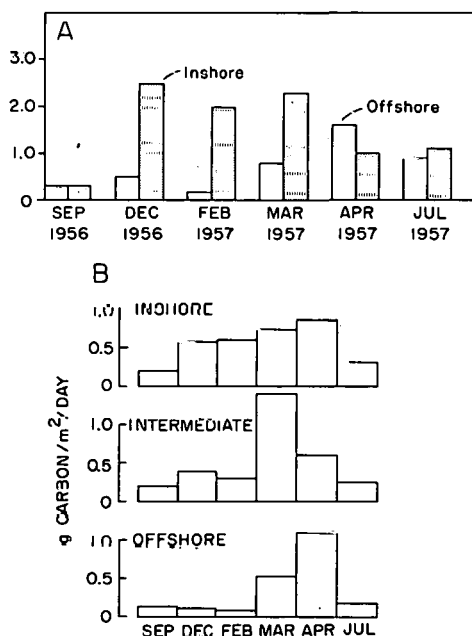


Figure 6. *A*: Summary of the average chlorophyll *a* content, in $\mu\text{g liter}^{-1}$; *B*: the mean daily primary production per square meter of sea surface at 5 shallow (<50 m), 5 intermediate (100 to 200 m), and 5 deep (>1000 m) stations in the continental shelf waters off New York and New Jersey as depicted in Figure 1. *A* is modified from Yentsch,⁷⁷ and *B* from Ryther and Yentsch.¹⁴

bloom inception began in December at depths of <50 m, in March at depths of 100 to 200 m, and in April in deeper waters. On Georges Bank, when the 1940 bloom was in progress during March, the surface population in water <50 m deep was 3 times as great as that in depths of 50 to 100 m and 6 times as great as that in deeper waters.²⁵

The annual phytoplankton cycles in the shallower inshore waters of Narragansett Bay²⁶⁻²⁹ and North Carolina estuaries^{3,5} differ somewhat from the classical type. In Narragansett Bay the cycle (Figure 7) is characterized by a bloom that often begins in early winter (December), with logarithmic growth continuing thereafter for as long as a month, followed by a series of pulses and eventual termination of the bloom in May-June. The summer period is usually characterized by a series of secondary phytoplankton pulses. Fundamentally, this estuary is characterized by series of blooms throughout the year rather than the major-minor bloom cycle characteristic of deeper coastal waters.

A more relevant aspect of the Narragansett Bay data is the extraordinary year-to-year variation in important features of the phytoplankton cycle, based on weekly monitoring over a 15-year period (Figure 7). Some highlights of this natural variability include the following. The winter bloom usually begins in December but has started as early as November (1968), and as late as February (1965). While maximum abundance frequently occurs in January, it has been as late as March (1964,

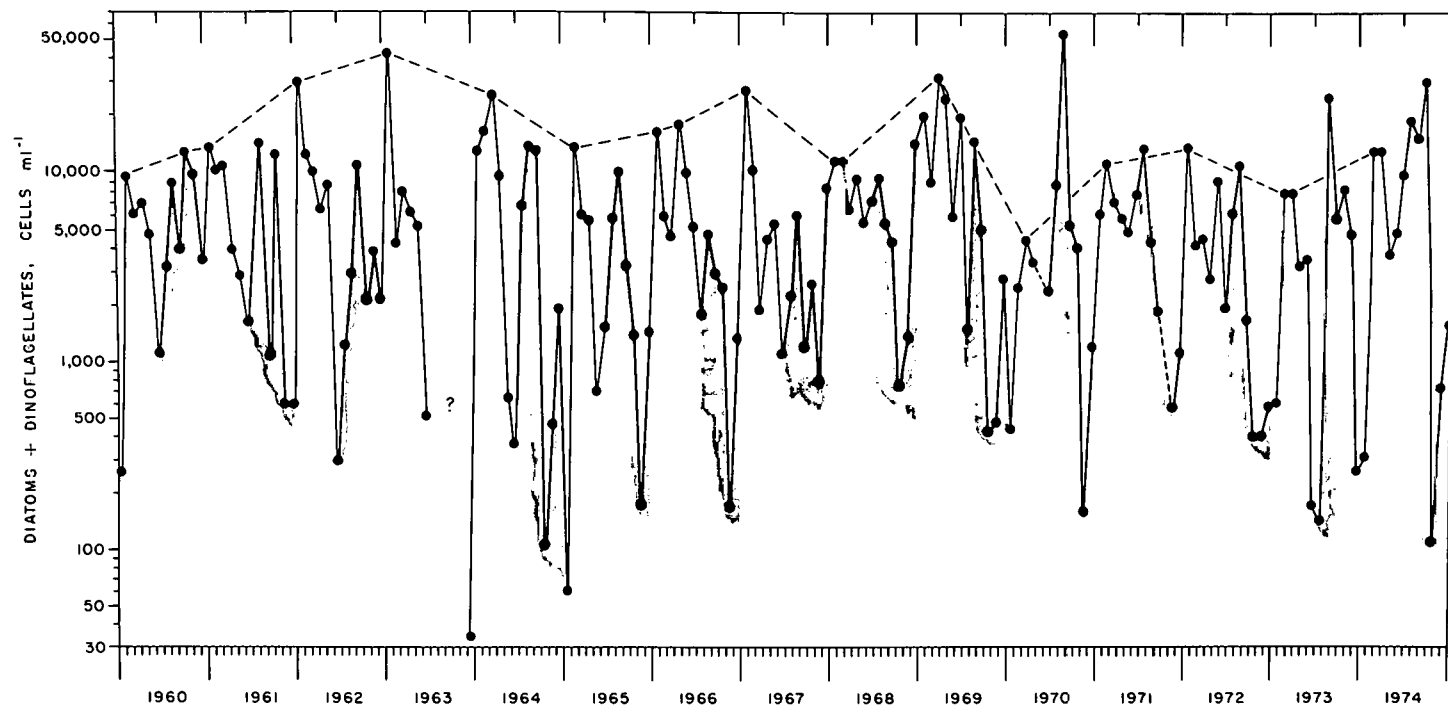


Figure 7. Maximum monthly abundance of the diatom and dinoflagellate populations in the surface waters of lower Narragansett Bay from 1960 through 1974.

1969) and April (1966). The maximum abundance has ranged from 4500 cells ml^{-1} (1970) to 42,000 cells ml^{-1} (1963).

The series of secondary phytoplankton pulses that characterizes the summer period also exhibits considerable annual variations in time of occurrence, bloom duration, maximum abundance, and dominant species (Smayda, unpublished). Maximum abundance has ranged from 7000 cells ml^{-1} (1967) to 59,000 cells ml^{-1} (1975); initiation of this seasonal bloom has ranged from a couple of weeks in August (1969) to an almost continuous period from July through September (1968). The most extraordinary finding, however, is that in four of the last six years (1970, 1973-1975) the annual maximum has occurred in mid-August rather than during the winter-spring period. The reasons for this shift are unknown but are under study. The 2-year cycle for Long Island Sound (Figure 5) is also characterized by annual variations in magnitude and time of maximum abundance. Riley³⁰ has demonstrated that such variability over a 6-year cycle was related to the prevailing light, temperature, stability, and grazing conditions.

Thus, natural populations exhibit considerable annual variations in their cycles, probably in response to environmental regulation. A local year-to-year variability undoubtedly also occurs within the mosaic of regional variations in phytoplankton production described earlier, and this might cause significant deviations from the patterns summarized here. Therefore, in dealing with the impact of energy-related activities on plankton processes, the simultaneous occurrence of natural variability in response to short-term and long-term *natural* environmental perturbations cannot be ignored.

Factors Regulating Seasonal Plankton Cycles and Their Regional Variation

The inception and termination of phytoplankton blooms in the survey area is considered only generally to put into perspective the regulatory factors that apparently govern the cycles. (A detailed treatment of the events specific to the individual regions is considered elsewhere.²) The winter-spring and summer-autumn blooms are emphasized.

Role of Light, Turbulence, and Depth. The regional variations in the time of inception of the winter-spring bloom are not related to nutrient availability or grazing pressure. Nutrient levels are then usually at maximal concentrations, the zooplankton standing stock is low, and benthic metabolism is suppressed by low temperatures.⁹ The evidence is overwhelming that inception of this bloom is governed by the light available for photosynthesis and by the residence time of the phytoplankton within the euphotic zone. The light available for photosynthesis is obviously influenced by incident radiation levels (I_0) and the transparency, or extinction coefficient (K), of the water mass. Residence time within the euphotic zone is influenced by the rate of mixing and depth of the mixed layer (Z), and water column depth. Obviously, the two aspects are interrelated, and several mathematical relationships expressing this interdependence have been formulated. The key aspect, however, is the average amount of light incident on the phytoplankton cells, which will determine the time at which photosynthesis begins to exceed respiration, allowing the population

to increase. The average daily radiation ($\bar{I}$) received by the phytoplankton cell *in situ* in a well-mixed water column (z) can be calculated from Riley's equation³¹

$$\bar{I} = \frac{I_0}{kz} (1 - e^{-kz}),$$

where $\bar{I}$ is in Ly day^{-1} ; z is the depth of the mixed layer in meters; k is the extinction coefficient, m^{-1} ; and I_0 is the incident radiation. On the basis of an analysis of Long Island Sound dynamics, Riley³⁰ suggested that $\bar{I}$ equal to 40 Ly day^{-1} is the "critical intensity", required for inception of the winter-spring bloom in temperate coastal waters. This has been confirmed in a recent study in Narragansett Bay.³² This critical intensity is not a physiological constant expressing the relationship between photosynthesis and light intensity. Rather, it is the intensity at which growth begins to exceed population losses due to advection, sinking, grazing, lysis, etc.

The influence of depth on the time of inception of winter-spring bloom in temperate coastal waters can be demonstrated by events in Narragansett Bay. Although the incident radiation on this bay is similar to that on contiguous Long Island Sound, the bloom usually begins several months later in the latter area. However, since well-mixed Narragansett Bay has an average depth of about 10 m compared with 20 m for Long Island Sound, the critical intensity of 40 Ly day^{-1} is reached earlier. The importance of depth on bloom size over Georges Bank²⁵ was mentioned earlier.

The transparency of the water column is also important. For example, the flowering in the shelf waters off New York (Figure 6 and Ref. 14) began earlier (December) than is usual in Long Island Sound (Figure 5 and Ref. 30) despite similar or greater depths and similar mixing characteristics. However, since the transparency of these offshore waters is greater, the depth of the euphotic zone is also greater, which favors earlier attainment of the critical intensity. Thus, although there are regional variations in the factors that determine the amount of light received by the phytoplankton population, light is the major parameter influencing time of inception of the winter-spring bloom in temperate waters. It may not be in the warmer, shallow North Carolina estuaries.^{5,33,34}

This is very relevant to energy-related activities such as offshore drilling or related processes which might affect turbidity. Should the extinction coefficient increase during such activities, the accompanying reduction in light intensity could influence the time of inception and the duration and magnitude of phytoplankton blooms. Obviously, the depth of operations and hydrographic conditions would also influence the impact.

Temperature. Since population growth requires that photosynthesis exceed respiration, temperature, through its effect on respiration, is an important factor in regulating inception of the winter-spring bloom. It also influences assimilation number, maximum potential growth rate, and species composition. The effect of temperature on respiration is expressed in general form by³⁵

$$r_T = 0.0175e^{0.069T},$$

where r_T is g C respired per g phytoplankton C per day and T is temperature in $^{\circ}\text{C}$. Although the respiratory coefficient is known only approximately and a Q_{10} of 2 is

used, the lowered respiration rates predictable at winter-spring temperatures would favor a net phytoplankton growth. However, photosynthesis is also influenced by temperature, as is evident from its effect on the assimilation number (mg C produced mg chl⁻¹ hr⁻¹) at saturating light intensities (for photosynthesis) (Figure 8). From this index and a knowledge of the C:chl ratio, the rate of carbon growth can be estimated. This dependence of the assimilation number (A_n) on temperature (T) for natural populations in Narragansett Bay³⁶ is essentially identical to that reported for a shallow North Carolina estuary.³⁴ It can be expressed by

$$A_n = 1.43e^{0.080T},$$

with a Q_{10} of 2.23.

Temperature seemingly also regulates the maximum growth rate of phytoplankton. Eppley,³⁷ on the basis of a literature review, fitted an enveloping curve that defined the upper limit of growth of ≈ 200 species grown in laboratory batch culture. This relationship between maximum potential growth rate, μ , as doublings day⁻¹, and temperature ($< 40^\circ\text{C}$) (Figure 9B) is defined by

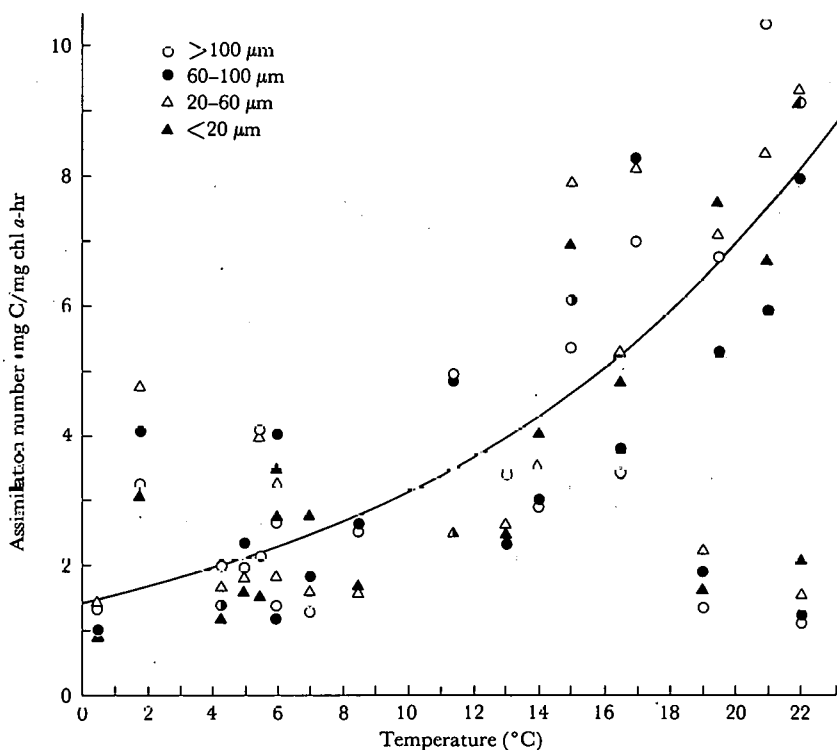


Figure 8. Assimilation number versus temperature for different size fractions of phytoplankton in lower Narragansett Bay over an annual cycle from November 1972 to October 1973. Modified from Durbin et al.³⁶

$$\mu = 0.85e^{0.063T},$$

where T is in $^{\circ}\text{C}$; Q_{10} equals 1.88.

Clearly, at the community level temperature influences the rate of photosynthesis per unit chlorophyll, the rate of respiration, and the potential growth rate. But aside from Riley's examination³⁰ of its effect on plankton processes in Long Island Sound, and Pratt's conclusion²⁹ that there was no consistent relationship between temperature and the time of inception of the 1960 to 1963 winter-spring blooms in Narragansett Bay (Figure 7), little attention has been directed toward its effects on natural community dynamics.

Temperature also has an effect at the species level, since tolerance to temperature and its effect on growth rate varies between species (Figure 9). (Species characteristic of Mid-Atlantic nearshore and shelf waters were selected preferentially.) Extrapolation of these laboratory results to *in situ* situations is risky because of interactions with other parameters. Nonetheless, thermal regulation of the dynamics of natural populations of a given species, as well as species selection and community

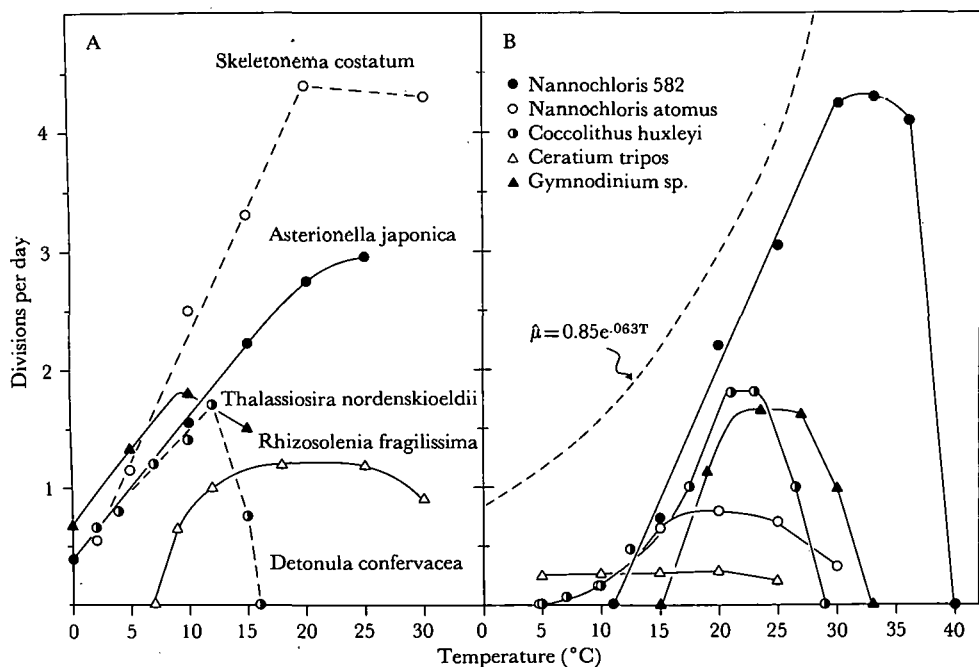


Figure 9. Relationship between cell division rate and temperature for various diatoms (A) and flagellates (B). Data sources for A: *Asterionella japonica*, Teng (unpublished); *Detonula confervacea*, Smayda⁴⁴; *Rhizosolenia fragilissima*, Ignatiades and Smayda⁴⁵; *Skeletonema costatum*, Smayda²⁷; *Thalassiosira nordenskiöldii*, Durbin.⁴⁶ In B, the general relationship between cell division rate (μ) and temperature is from Eppley³⁷; *Ceratium tripos*, Nordli⁴⁷; *Coccolithus huxleyi*, Paasche⁴⁸ and Mjaaland⁴⁹; *Gymnodinium sp.*, Thomas⁵⁰; *Nannochloris atomus*, Ryther⁵¹; *Nannochloris 582*, Thomas.⁵⁰

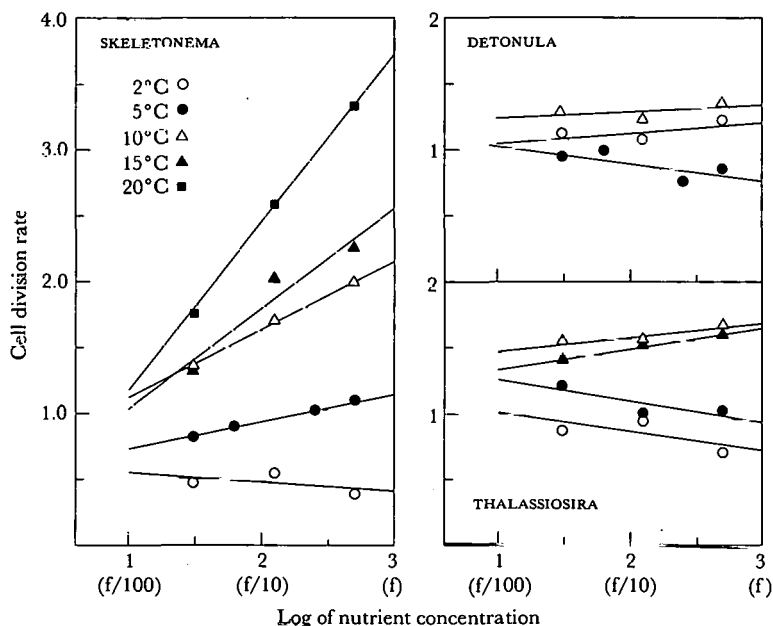


Figure 10. Relationship between cell division rate, temperature, and nutrient enrichment for the diatoms *Skeletonema costatum*, *Detonula confervacea*, and *Thalassiosira nordenskiöldii*. Modified from Yoder.³⁹

composition, is anticipated and has been observed. For example, temperature influenced the responses of *Skeletonema costatum* during a winter-spring bloom in Narragansett Bay²⁷ and species selection in entrained populations collected from a North Carolina estuary.³⁸

The effect of temperature on growth is also influenced by nutrient levels, as demonstrated by Yoder³⁹ and illustrated in Figure 10. While the differing responses between species preclude a general statement, Goldman and Carpenter⁴⁰ have recently proposed a model for phytoplankton growth rate based on the combined effects of temperature and nutrient limitation.

With regard to energy-related activities, it is apparent that an increase in water temperature during discharge of heated effluents can change phytoplankton growth rates at the species and community levels and thereby influence plankton cycles and dynamics. In response to a temperature increase the growth of a particular species may increase, or decrease, or even terminate; this will induce changes in composition of the community and cause species succession. It is not possible at present to arrive at a general statement of the most probable overall impact of thermal pollution *in situ*. Its consequences will vary with local ambient nutrient and temperature levels (Figures 8 to 10), with the degree to which macrophyte production is important (Figure 3), and with water column depth (Figures 4 and 6), exclusive of the local hydrographic conditions and characteristics of the nuclear power plant. Impact will also be influenced by the magnitude of the deleterious effects that chlorination of

the cooling water and elevated temperatures have on entrained phytoplankton and zooplankton populations.⁴¹⁻⁴³

Nutrients. Numerous surveys suggest that the high levels of nutrients in temperate waters following winter mixing do not influence the initiation of the winter-spring bloom, except possibly in some shallow North Carolina estuaries that are not light limited.⁵ However, the concentrations of nutrients present at the beginning of rapid growth can determine the magnitude of the bloom maximum, as shown for Narragansett Bay.²⁹ The need for a continuous supply of nutrients to sustain plant growth through microbial regeneration, animal excretion, and other sources is self-evident; some representative annual recycling times are given in Table 1. Nonetheless, phytoplankton demand for nutrients during the winter-spring bloom eventually exceeds the rate of supply; growth then becomes limited by one or more nutrients; the population (also under grazing pressure) begins to decline, and finally the bloom terminates. While the bloom duration and timing of this sequence of events vary regionally and annually within a given area (Figures 5 to 7), the evidence is overwhelming that growth eventually becomes nitrogen limited throughout the Mid-Atlantic region: Narragansett Bay,^{27,29} Long Island Sound,¹³ Moriches Bay,⁵¹ Vineyard Sound,^{15,24} North Carolina estuaries,⁵ and continental shelf waters.^{15,52} There is also evidence of multiple nutrient limitation. Silica and nitrogen can concurrently limit the bloom in Narragansett Bay,^{27,29} where a seasonal succession in the types and combinations of limiting nutrients was also found in some bioassay experiments carried out over an annual cycle.⁵³

With regard to energy-related activities, phytoplankton growth may be influenced by offshore drilling through modification of the nutrient and "water quality" characteristics in the overlying waters during such operations. Nutrient-rich bottom water (depending on depth) admixed into the euphotic zone could increase nutrient levels there and favor growth. The roiling up of sediments into the water column, however, may also introduce trace metals or elevate them to toxic concentrations, or introduce growth-regulating organic compounds, including chelators. For example, heavy metals tend to concentrate in bottom sediments, depending on the organic content.⁵⁴ If released into the water column, the concentrations of those trace metals required by the phytoplankton may be elevated to toxic levels, as has been demonstrated experimentally for zinc⁵⁵ and copper.⁵⁶

Water quality modification is a more subtle aspect and is difficult to quantify because experimental artifacts are easily introduced into the monitoring procedure. Smayda⁵³ found that in Narragansett Bay adverse water quality affects individual species' growth as a consequence of total phytoplankton growth; this could be overcome by the addition of the chelator EDTA. Young and Barber⁵⁷ found that the addition of sediments from the New York Bight to inshore water samples collected from the New York Bight, off Woods Hole, and off Beaufort, North Carolina, inhibited phytoplankton growth temporarily and to varying degrees. The evidence suggests that this was attributable to unknown organic compounds rather than to heavy metals.

One practical problem in evaluating the impacts of energy-related activities cannot be overemphasized: dilution of the pollutants and/or advection of plankton

populations throughout the stressed area may be so rapid that the conditions locally may not appear to be toxic or have negative population effects. However, harmful effects may be manifested downstream of the toxic source, or eventually as a lag effect in population cycles and processes, perhaps similar to natural variability (Figures 5 and 7). Therefore, careful consideration must be given to the design of the sampling and monitoring program in space and in time and to the choice of processes to be measured. The natural variability, response times, and trophic relationships characteristic of plankton dynamics should also be kept in mind.

Grazing. Historically, grazing of phytoplankton by zooplankton has been emphasized. There is little quantitative data on benthic herbivory, and virtually none on grazing by fish. Since benthic metabolism utilizes 30 to 40% of the annual carbon production in Long Island Sound and Narragansett Bay,^{9,12} phytoplankton dynamics are obviously influenced by benthic processes. Durbin and Durbin⁵⁸ have demonstrated that the commercially important fish menhaden (*Brevoortia tyrannus*), widely distributed along the eastern U.S., can be a significant grazer of phytoplankton. Predation of *Skeletonema costatum* and other diatoms in Narragansett Bay by an amoeboid flagellate has been reported.²⁷ However, since the extent to which benthic and fish grazing regulates phytoplankton cycles remains unclear, the role of zooplankton is emphasized. Jeffries and Johnson⁵⁹ have summarized the data on zooplankton standing stocks in the coastal waters from Cape Hatteras to Nantucket Shoals. Riley³⁰ has suggested that possibly the most common and significant difference between estuarine and open ocean zooplankton populations is the relatively large summer estuarine populations (Figure 5).

Zooplankton predation has two effects. The phytoplankton population is grazed down, but its growth may also be stimulated by excreted nutrients. Thus, exclusive of the grazing and growth constants, the overall impact of the zooplankton on phytoplankton dynamics reflects the ratio of phytoplankton to zooplankton biomass, nutrient availability, and the extent to which the pelagic processes are coupled to benthic metabolism. Estuarine zooplankton species (*Acartia*) are less efficient in catching and utilizing phytoplankton than offshore species³⁰; this results in a considerable carbon flux to the benthos in shallower areas. Thus, while phytoplankton blooms in offshore waters are frequently terminated by zooplankton grazing, in nearshore waters termination may be nutrient- and/or zooplankton-induced.

In Long Island Sound, for example, the vernal increase in zooplankton comes well after the phytoplankton bloom (Figure 5). Termination of this bloom appears to be the result of depletion of nutrients, specifically nitrogen.³⁰ As mentioned earlier, bloom inception here is light dependent.

Pratt²⁹ and Martin^{60,61} believe that inception of the winter-spring bloom in Narragansett Bay is triggered by the release of grazing pressure, although in 1972-73 its inception was light regulated.³² Wild populations of zooplankton excrete only a small fraction of the daily nitrogen and phosphorus requirements of the phytoplankton during their periods of abundance.^{18,27,62} Experimental manipulation of the winter-spring bloom in 1972 revealed that its collapse in May resulted primarily from a combination of increased zooplankton grazing, reduced nutrient excretion, and depleted nutrient supplies available to the nitrogen and silicate-limited phyto-

plankton.²⁷ Thus, the extent to which bloom termination is grazing-regulated or nutrient-regulated in coastal waters varies regionally and reflects local characteristics.

Post Winter-Spring Bloom Characteristics

Phytoplankton dynamics subsequent to the winter-spring bloom in the Mid-Atlantic nearshore and shelf waters have been less rigorously investigated. The phytoplankton pulses then are usually of lesser magnitude, are often a series of erratic peaks, and are generally thought to reflect nutrient limitation. Hence, it is commonly held that the late summer or early autumn pulse accompanies increased nutrient levels and that its subsequent termination is regulated by grazing and nutrient limitation. However, while this may be true for shelf waters, the situation is considerably more complex in coastal waters. The recent trend toward displacement of the annual phytoplankton maximum in Narragansett Bay to the summer (Figure 7) has been pointed out. In 1974, 42% of the annual production of 310 g C m^{-2} occurred during July and August¹⁷ when nitrogen remained at very low concentrations. Rapid nutrient recycling was necessary to sustain this production. That it must have occurred is consistent with the elevated assimilation numbers found during the summer despite very low ambient nutrient concentrations (Figure 8). Phytoplankton dynamics during the summer in this bay, however, are not clearly limited physiologically by nutrient limitation or by grazing.¹⁷ While nutrient levels and the recycling rate may set the magnitude (yield) of the population pulses, the underlying factors regulating the fluctuations in abundance remain unknown.

Riley's perceptive evaluation of the autumn flowering in Long Island Sound³⁰ revealed that inception of this bloom depends on a preliminary slight increase in nitrogen concentrations and, surprisingly, in stability of the water column. The seemingly paradoxical situation that light is limiting during the autumn (at levels 4 to 5 times as great as during inception of the winter-spring bloom) is attributable to the higher temperatures then. Temperature elevates phytoplankton respiration and zooplankton grazing rates, and increased rates of light-dependent photosynthesis are required then to offset population losses due to respiration, grazing, advection, and sinking. When this happens, the autumn flowering begins.

Phytoplankton Communities and Environmental Modification of Their Species Composition

Have previous and/or ongoing (but not energy-related) human activities modified the composition (and hence the dynamics) of phytoplankton communities? Brief consideration of this may put into perspective the potential impact of energy-related activities on species selection and community structure. The phytoplankton composition in the Mid-Atlantic region has been summarized by Smayda.² Detailed observations are available for Narragansett Bay,^{26,28} Long Island Sound,^{22,30} the continental shelf,⁶³ and Cape Fear Estuary.³ The communities in these areas are diatom-dominated, with a clear tendency for certain species, notably *Skeletonema costatum*, to become particularly abundant. The species composition of the coastal lagoons and certain estuaries differs (possibly because of the reduced salinity) from that of more open waters,⁶³ where species composition tends to be essentially similar, although

the relative importance of the different species may vary regionally and seasonally. There are no apparent indicator species or communities.

Despite this apparent regional uniformity in species composition, unpredictable species blooms occur. In Narragansett Bay, for example, the diatom *Asterionella japonica* blooms unpredictably during certain years (called *Asterionella* years), which alters the ensuing pattern of species succession and community dynamics.⁶⁴ In 1970 an enormous, prolonged bloom of *Chaetoceros diadema* initiated the winter-spring flowering and likewise modified the phytoplankton cycle. This species had been absent or unimportant during the previous 17 years! These examples illustrate that significant, unpredictable annual differences in composition of the dominant species may occur, analogous to certain red-tide outbreaks. A recent example of the latter was the unexpected and financially devastating red-tide bloom of the toxic dinoflagellate *Gonyaulax tamarensis* in New England coastal waters.⁶⁵ In 1972 there were 33 instances of human illness, but no deaths, and shellfishing was banned in three states, with an economic loss of \$1 million per week.²

The significance of these observations for energy-related activities is that data analysis to date has not demonstrated that indicator species or communities exist for the different water types or growth conditions in the Mid-Atlantic region. Moreover, there is some unpredictable variation, similar to population cycles (Figures 5 and 7), in species occurrence and dominance. Finally, there is also evidence that considerable community alteration can indeed occur in response to environmental modification associated with human activities. The classical example is Moriches Bay, where, because of heavy fertilization by duck-farm wastes, the phytoplankton composition and abundance were altered, to the detriment of the shellfish industry.^{2,51,52} Raritan Bay also has a modified phytoplankton community,^{52,66} possibly in response to domestic and industrial pollutants. It is at present impossible, on the basis of field and experimental data, to predict the most probable type of community reorganization (if any) in response to an anthropogenic perturbant, the levels that would induce such changes, when they would occur, and the speed of recovery to normal conditions upon alleviation of the stress.

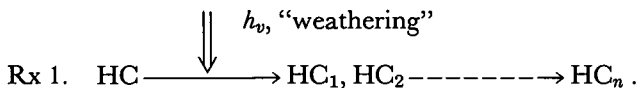
SOME GENERAL CONSIDERATIONS OF PETROLEUM HYDROCARBONS

The environmental impact of thermal discharge and the use of chlorinaceous biocides as antifoulants during nuclear power plant operations is of obvious concern. There is even greater concern about the need to elucidate the potential impact on ecosystems of drilling for oil on the outer continental shelf, including the effects of oil spills at the drill sites, in the shipping lanes, and in ports and of the effluent from shore-based activities of the petrochemical industry. It seems fitting, therefore, to conclude with some general considerations of hydrocarbon perturbants.

In assessments of the impact that such perturbants may have on a given trophic level or species, one must distinguish between direct and indirect effects. Hydrocarbon species and concentration may directly affect phytoplankton growth or photosynthesis and hence community structure. Modification of the phytoplankton community through changed bacterial, zooplankton, or benthic behavior caused by the oil would be an indirect effect.

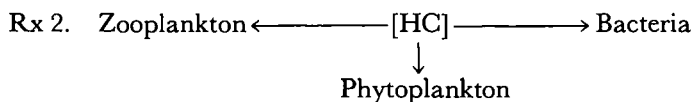
The schematic presentation and synopsis presented below attempt to elucidate some key hydrocarbon-organism relationships in order to put into perspective most probable direct and indirect effects on the phytoplankton.

Rule 1. Hydrocarbons (HC) Speciate (HC_n), Emulsify, and Degrade in Sea Water



The consequences of this reaction are that photochemical (h_v) changes and those used by nonbiological factors (weathering) such as temperature decrease the overall concentration and speciate the hydrocarbon mixture (see Ref. 21). These changes undoubtedly affect the potency and type of biological effect, but such effects *in situ* are difficult to monitor and to assess routinely. Particle formation occurs during the above, with the result that nonbiological deposition of the oil to the benthos occurs.

Rule 2. Hydrocarbons Are a Substrate, []



The uptake (U) and assimilation (A) of hydrocarbons by bacteria in the laboratory and *in situ* after oil spills is well established, e.g. 21,67,68 Under favorable conditions bacteria appear capable of degrading practically any hydrocarbon, from methane to the heaviest residues. This uptake probably follows Michaelis-Menten kinetics:

$$U = \frac{U_{\max} S}{K_S + S},$$

where $U_{\max}$ is the maximum uptake velocity, S is hydrocarbon concentration, and K_S is the concentration at which uptake is $U_{\max}/2$.

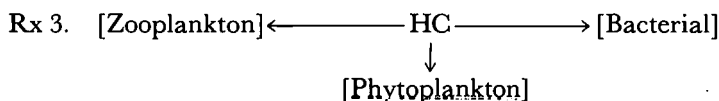
The potential importance of bacterial degradation is easily calculated. Zobell (see Ref. 21) estimates that 5×10^{-12} mg hr⁻¹ is the average rate of oil oxidation by one bacterial cell at 25°C. Using Sieburth's estimate⁶⁹ of 10^7 to 10^9 bacteria per liter in Narragansett Bay yields a daily bacterial degradation of 1.2 to 120 µg. Bacteria have an average generation time of ≈ 2 hr. Thus, within one day there would be 64×10^7 to 64×10^9 bacteria per liter capable of degrading oil at a rate of about 0.8 to 7.7 mg liter⁻¹ day⁻¹. Since this decomposition rate is temperature dependent (decreasing by about 70% at 15°C and 90% at 5°C), seasonal changes in the importance of bacterial degradation of the hydrocarbons are anticipated.

Hydrocarbons form particles of various sizes⁷⁰ which are grazed by zooplankton.²⁰ However, at this trophic level uptake predominates over assimilation, since most of the particles pass through the gut and are voided as fecal pellets that sink to the sediments. The significance of zooplankton uptake (grazing) of oil particles is that this activity may represent an important natural clean-up mechanism that removes oil from the water column; i.e., zooplankton grazing (1) decreases the partic-

ulate oil concentration and (2) packages oil droplets into fecal pellets, which may hasten bacterial degradation upon deposition. In fact, Conover²⁰, p. 1330 concluded that "... zooplankton may be the single most important natural agent leading to eventual dispersal and degradation of oil spills, at least in the open sea."

While such activity may help to detoxify the water column and render it favorable to phytoplankton growth, the deposition of fecal pellets leads to a buildup of hydrocarbons in the sediments. This may be potentially deleterious to benthic processes and may, depending on the depth and the degree of coupling, influence phytoplankton processes.

Rule 3. Hydrocarbons Are Toxicants or Inhibitors



Surprisingly, certain oils in low concentrations have been found to stimulate the photosynthesis of natural phytoplankton populations⁷¹ and cultured species,⁷² probably because of low molecular weight aromatic compounds.⁷³ But, depending on the hydrocarbon species, its concentration, and the stressed organisms, oil may also be a toxicant, narcotic, or inhibitor. It is this aspect of oil spills that particularly requires elucidation, with specific reference to the overall impact on marine communities.

By means of chemoreception, marine bacteria are attracted to organic compounds and particulate matter, which they then degrade.⁷⁴ However, Mitchel et al.⁷⁴ report that the ability of certain bacteria to detect living and nonliving substrates was reversibly inhibited by certain hydrocarbons. For example, the diatom *Skeletonema costatum*, the dominant diatom in the Mid-Atlantic region,² was spared from bacterial attack and degradation in the presence of phenol, toluene, and Kuwait crude oil, which immobilized the bacteria. This effect is significant; it suggests that phytoplankton growth may be regulated indirectly by hydrocarbon-regulated bacterial predation on phytoplankton, in addition to the use (Rule 1) of hydrocarbons by bacteria as a carbon substrate, which detoxifies oil concentrations.

Certain oil products are generally toxic to phytoplankton and zooplankton, but differences (by 4 orders of magnitude) in sensitivity occur between species.⁷⁵ Extrapolation of LD₅₀ toxicity data^{6,8, 76} to natural communities is of dubious value. But such information is helpful in revealing the relative sensitivities of species to hydrocarbons, which in turn may help to determine the reasons for species changes under an oil stress. Therefore an increased knowledge of the effect of hydrocarbons on the rates of photosynthesis, chlorophyll synthesis, and growth of key phytoplankton species at various concentrations and under varying light and temperature combinations is needed.

Rule 4. Physical, Chemical, and Biological Events Cleanse the Water Column of Hydrocarbons by Promoting Transport to the Sediments

Two general processes regulate the concentration of hydrocarbons in the water column exclusive of nonbiological decomposition (Figure 11). The first, which might

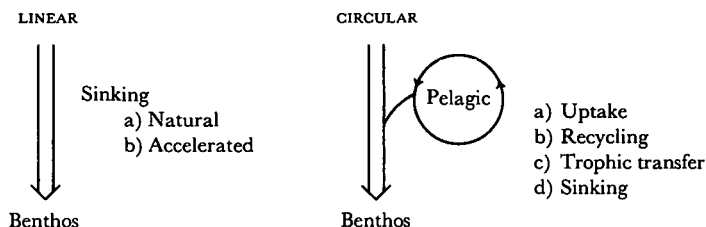


Figure 11. Schematic representation of some general processes regulating the concentration of petroleum hydrocarbons in the water column.

termed *linear*, is the sinking of oil particles onto the sediments through gravitational forces or, as mentioned earlier, after grazing by zooplankton and elimination as fecal pellets. Deposition is accelerated in the latter pathway, which may be the more important one.

The second general process, which might be termed *circular*, represents the classical pelagic food web. Uptake, assimilation, and transfer of hydrocarbons occur. But this process tends only to delay transfer of the hydrocarbons to the sediments. Eventually, through grazing and deposition of waste products, the material is transferred there.

An oil spill may have an immediate effect on the benthic community, or a pulsed input may occur, depending on whether the linear or circular route predominates. This in turn depends on the ratio of bacteria:autotrophs:heterotrophs in the water column. If nutrients (nitrogen) remain low, for example, then the bacteria may not be able to utilize effectively the carbon substrate.⁶⁷ If temperatures are too low (e.g., $<4^{\circ}\text{C}$ in coastal waters), then zooplankton (*Acartia*) activity is reduced, and the accelerated linear route is suppressed. Thus, the time needed for the pelagic communities to recover to prestress conditions cannot be predicted; it depends on the trophic interrelationships, including the extent to which pelagic and benthic processes are coupled, as well as the "normal" environmental conditions, with which most of this paper has dealt. Nonetheless, the model predicts that a key pathway of hydrocarbon stress is to the benthos, where a maximum impact on community dynamics is to be expected. This also will be influenced by the depth of the water column, which in turn will influence the concentration of hydrocarbons in the circular phase and the duration of its recycling pelagically.

The significance of this proposed flux to the sediments is that short-term, transitory effects on pelagic communities are also predicted. The phytoplankton probably will recover rapidly to prestress conditions, unless the benthic sink is minimized and/or there are significant indirect effects on phytoplankton growth.

Acknowledgments: Much of our knowledge of, insight into, and quantification of plankton processes in the Mid-Atlantic coastal and shelf waters is attributable to the remarkable efforts of Gordon A. Riley. Without these contributions there would be little of substance that could be synthesized in this overview. Ms. Blanche Coyne typed the manuscript and drafted the figures.

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DISCUSSION

ADAMS: In the area of environmental assessment, it is very difficult to separate natural temporal variations from those resulting from operation of nuclear power plants. In many cases, all ... have is several years of base-line data, which we compare with one or two years of operating data from a nuclear power plant. Would you care to comment on any methods or procedures that are now known to be effective in separating natural variations from man-made perturbations due to operation of power plants?

SMAYDA: All I can suggest is that one has to take into consideration life cycles, the nature of the stress, and what process in the life cycle the stress is particularly effective against or stimulates. Right now I think there are very few data that would be useful in sorting out natural variability and environmental stress.

Petroleum, Temperature, and Toxicants: Examples of Suspected Responses by Plankton and Benthos on the Continental Shelf

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INTRODUCTION

Birth rate and death rate are a population's most fundamental attributes. If cause these rates are so difficult to measure in nature, we often observe their expression as standing crop, without knowing which rate may have been responsible for a population's rise or fall. Nevertheless, causal relations involving both natural and artificial stressors are identified for more refined study. In this paper, gross population changes carefully enumerated over time in natural communities of the New York Bight and nearby areas are examined. From such comparisons a basic appreciation of sensitivity within natural systems can be obtained.

GENERALITIES ON RESPONSES TO ENERGY-RELATED ACTIVITIES

Although fewer energy-related studies have been made on holoplanktonic copepods than on other components in the plankton, present knowledge allows a general assessment of effect. Responses among the copepods to man's activities range from unimportant to significant. In no case, however, is there sufficient evidence to show

Table 1

Major Holoplanktonic Copepod Populations in Various Habitats of the New York Bight Area

Species	Seasonal occurrence	Ecological classification
<i>Acartia clausi</i>	Winter-spring	Estuarine and marine
<i>Acartia tonsa</i>	Summer-fall	Estuarine and marine
<i>Calanus finmarchicus</i>	Year-round	Stenohaline marine
<i>Centropages hamatus</i>	Year-round	Euryhaline and marine
<i>Centropages typicus</i>	Summer-fall	Stenohaline marine
<i>Eurytemora affinis</i>	Winter-spring	True estuarine
<i>Oithona colcarva</i> *	Summer-fall	Estuarine and marine
<i>Oithona similis</i>	Winter-spring	Euryhaline marine
<i>Pseudocalanus minutus</i>	Winter-spring	Euryhaline marine
<i>Temora longicornis</i>	Winter-spring	Euryhaline marine

*Incorrectly reported as *Oithona brevicornis* in studies on the Gulf of Mexico and Atlantic Coast south of Cape Cod.⁴

altered structure or abnormal function of the copepod fauna beyond spatially limited areas. Diversity and abundance are, therefore, still controlled naturally, even in such heavily used areas as the New York Bight.

Ecology

The list of copepod species found in the Mid-Atlantic Bight runs into the hundreds, but only a few widely distributed populations are abundant and then only seasonally. The major species, their control by temperature and salinity, and the way abundances are coordinated with events in the phytoplankton are all reasonably well known throughout the area, which makes possible the simple classification shown in Table 1.^{1,2} Stenohaline-marine and euryhaline-marine species reveal gross patterns of circulation, sometimes with greater clarity than salinity does.³ Because reproductive tolerances are narrower than the annual temperature range and generation times are shorter than seasons, competition between species is chiefly temporal and not spatial as in the larger, longer-lived benthic fauna.⁵

Temperature and Power Generation: Direct vs Indirect Effects

1. Copepods die when drawn through a power plant's cooling system: mortality ranges from 30 to 100% and tends to be most severe in summer. Total kill is often assumed for assessment purposes. Survivors sink 2 to 3 times faster than usual, and they do not reproduce as fast.^{6,7} But copepods have generation times usually only 4 to 8 weeks long, much shorter than the seasonally based variables controlling abundances in nature, so a population has considerable capacity to recover from short-term perturbation. Open-water populations probably experience no adverse influence if power-plant flow is kept small in relation to volume available for dilution.

2. In the near-field zone surrounding a hot-water discharge, copepod nauplii are killed by thermal diffusion and mixing.⁸ Direct entrainment plus the potentially greater indirect influence in a hot-water plume can be expressed quantitatively in relation to mixing processes, recruitment, and biological stability. Simulation models should soon become sufficiently inclusive and routine in application for management purposes.⁸⁻¹⁰ Because these models express stochastic relationships derived from information specific to the area being assessed, they are a step beyond broad-scale application of statistical water-quality criteria.

3. Through the plankton, effects on benthos associated with slightly increased water temperature may be mediated and perhaps amplified. A hypothetical explanation derived from observations on fishes of Narragansett Bay, R.I., is considered later.

Petroleum Discharges: Little Effect on Copepods; Benthos Threatened

1. Large-scale integrative phenomena among copepod populations in an estuary chronically affected by low-level petroleum pollution result in "normal" behavior, comparable with that in unpolluted estuaries. In the meroplankton, however, delayed appearance of molluscan species and aberrant orders of dominance among polychaetes and barnacles probably arise from the effects of various pollutants.¹¹

2. Following a major oil spill, pelagic copepod populations show little if any adverse response.¹² Indeed, *Calanus finmarchicus* ingests huge quantities of spilled oil, grazing apparently without harm up to 20% of Bunker C globules <1 mm in diameter.^{13,14} *Calanus helgolandicus* females, in bioassay experiments on 10 ppm Kuwait crude plus 2 ppm dispersant, reduce their rate of fecal pellet production but recover well a week later.¹⁵

3. Copepods pack oil into sheathed fecal pellets which sink rapidly and are eaten by benthic molluscs. Because they are sedentary, grow more slowly, and have a method of digestion entirely different from that of crustacean holoplankton, molluscs are more susceptible to chronic effects of oil pollution.

Bivalve filter-feeders were once thought to rely chiefly on intracellular digestion by amoebocytes. More recently, extensive extracellular enzymatic activities have been demonstrated,¹⁶ but it is still clear that molluscs process foods in an altogether different manner than do representatives of most other phyla comprising the macrobenthos. Amoebocytes are apparently able to remove hydrocarbons as well as plankton brought into the mantle cavity by the feeding current – either by engulfing particles or by absorbing dissolved fractions directly (pinocytosis) – but the process has limits. In hard clams (*Mercenaria mercenaria*) chronically exposed in nature to hydrocarbon pollution, laden amoebocytes move in exceptionally high numbers to the renal sac, which becomes plugged with a black polymeric substance that is resistant to common lipid solvents at room temperature. There follows a syndrome of behavioral, morphological, histological, and biochemical responses that culminate in early death.¹⁷

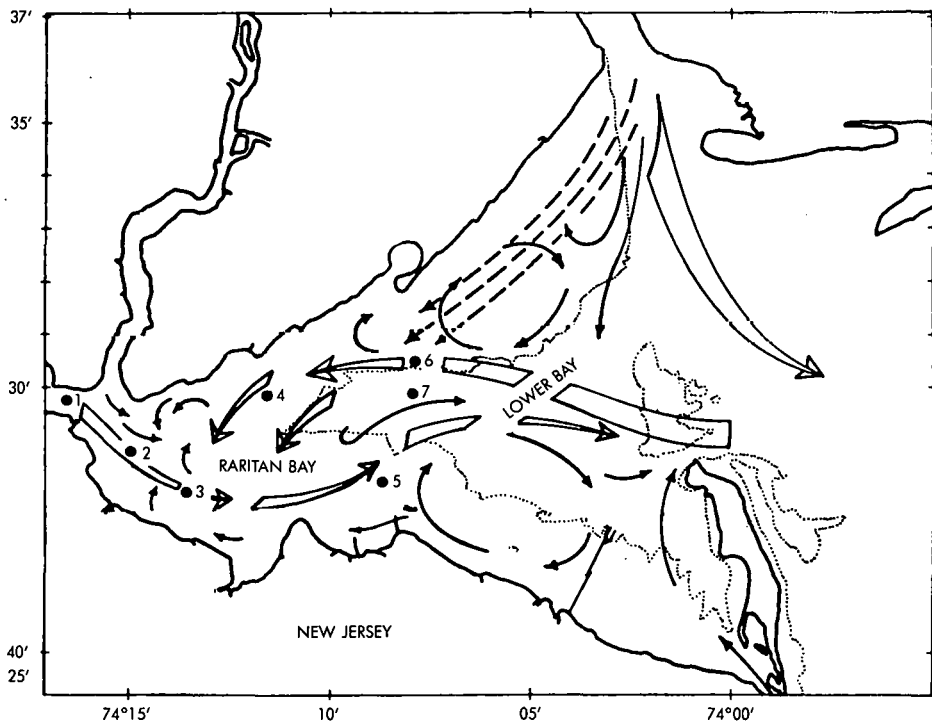
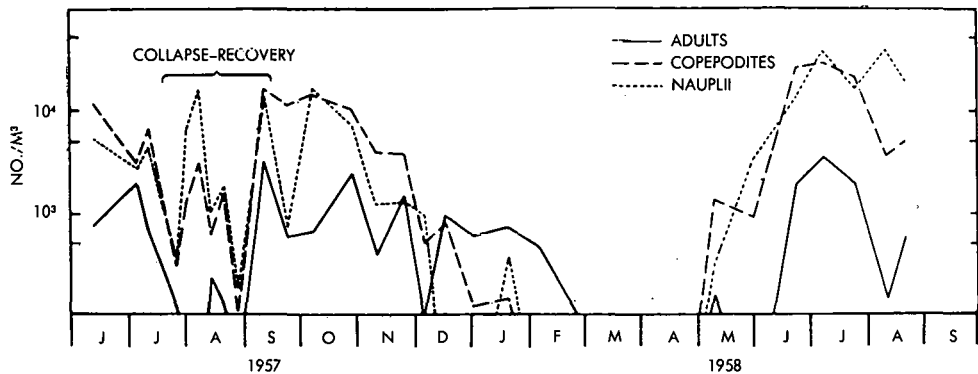
4. Although copepods are unable to degrade aromatic hydrocarbons in petroleum, 90% of the uptake accumulated under experimental conditions is purged after 14 days in clean water¹⁸; conversely, metabolic processes in oysters (*Crassostrea virginica*) may react irreversibly with petroleum products.¹⁹

5. Paraffinic and saturated isoprenoid hydrocarbons are degraded in the crustacean hepatopancreas. Several unsaturated isoprenoids synthesized by copepods from dietary phytol offer unique opportunities for research on feeding relationships.²⁰ Associated isoprenoid fatty acids are equally interesting as natural “markers” in trophic relationships.²¹

COLLAPSE AND RECOVERY OF A PLANKTONIC COMMUNITY

To the best of our knowledge, collapse and recovery of an entire planktonic community during a normally productive season have not been described. We will give one example, which may have resulted from poisons released into an estuary. Our intent is not to speculate on causes but rather to emphasize the rapidity with which a destroyed planktonic community reestablishes itself.

Prior to 1958, the huge industrial-social complex in the Raritan Valley, New Jersey, drained much of its waste into rivers that become the chief fresh-water supply for Raritan-Lower New York Bay. As in other estuaries bordering the New York Bight, the copepod *Acartia tonsa* dominated the zooplankton throughout the summer and fall. Six generations reaching concentrations of >100,000 individuals/m³ were produced here, much the same as in neighboring, unpolluted areas.²²



1957		Chlorophyll ($\mu\text{g}/\text{liter}$)	Diversity, $\bar{H}$ (bits/liter)	Redundancy	$\text{PO}_4\text{-P}$ ($\mu\text{g-atoms}/\text{liter}$)	T ($^{\circ}\text{C}$)	Salinity ‰
ly	26	71.3	0.14	0.04	2.4	23.2	27.3
g.	1	41.3	0.53	0.16	1.6	26.2	27.1
	8	0.0	2.15	0.53	2.1	25.1	26.8
	15	97.0	—	—	2.0	22.6	26.7
	21	89.1	0.91	0.23	1.0	23.5	26.4
	29	64.7	0.65	0.19	3.5	21.7	25.9
Sept.	12	20.5	0.69	0.23	—	22.4	27.7

Figure 1. *Top*: Collapse and recovery of the *Acartia tonsa* population in Raritan Bay, station 5.22 *Middle*: Schematic diagram of net currents in Raritan Bay, showing the ebb flow from the Raritan River (station 1) and head of the bay along the southern shore to station 5.22 *Bottom*: Collapse and recovery of the phytoplankton at station 5 and environmental characteristics during period.

On Aug. 1, 1957, before a large sewer system went into operation, second-generation adults actually disappeared (Figure 1). Third-generation nauplii dropped from abundances $>4000/\text{m}^3$ to $<500/\text{m}^3$, while immature copepodites decreased by an order of magnitude from $\approx 6000/\text{m}^3$. By mid-August the survivors matured and produced concentrations of nauplii $\gg 10,000/\text{m}^3$, but in late August adults again disappeared at two stations. A week later fourth-generation nauplii and copepodites declined precipitously and almost disappeared.

Irregularities were greatest in the mouth of the Raritan River and at other stations along the bay's southern shore. Across the bay in an area hydrographically isolated from ebb flows along the southern shore (station 6, Figure 1), adults disappeared only during the first collapse, but even then the concentration of developmental stages increased.

The phytoplankton also behaved in a most unusual manner. Surface and bottom chlorophyll dropped from $>40 \mu\text{g}/\text{liter}$ on Aug. 1 to unmeasurable on Aug. 8 (according to the colorimetric method used for typically high bay concentrations^{23,24}), an event rarely, if ever, observed in characteristically rich estuarine habitats. Chlorophyll disappeared at all stations except the hydrographically isolated area in which *A. tonsa* maintained reproductive activities at usual levels throughout August.

Representative data for phytoplankton and environmental characteristics are shown in Figure 1. Mean diversity of net phytoplankton (No. 20 mesh, 0.076-mm aperture) increased during the disappearance of chlorophyll. Throughout the entire period, phosphate, temperature, and salinity did not appear to diverge markedly from seasonal trends, and surface dissolved oxygen remained near saturation. It follows that domestic sewage was probably not responsible for irregularities in the plankton during August. The patterns suggest that causative agents, perhaps a chemical toxicant, emanating from the head of the bay during late July and mid-August, killed *A. tonsa* and the phytoplankton.

The point to be made is the rapidity of recovery. The planktonic community was functionally intact shortly after successive collapses during a normally productive period. Upset nutritional relationships may have hastened the copepods' decline but they did not start it, because *A. tonsa* adults disappeared a week earlier than the phytoplankton. Nor was there evidence that predation was the cause of depletion, even though both *Aurelia aurita* (white jellyfish) and *Mnemiopsis leidyi* (comb jelly) commonly reduce zooplankton in Mid-Atlantic Bight estuaries to low levels in late spring and early summer. Indeed, *M. leidyi* has all but eliminated the summer zooplankton in Narragansett Bay for short periods, on one occasion in 1955 sparing (in No. 2 mesh net samples) only the long-spined zoeae of *Polydora macrocheles*, which were presumably too large to ingest. In Raritan Bay during 1957, however, comb jellies never approached the abundances found in Narragansett Bay. Furthermore, predation would seem to be somewhat size-selective, yet death rates among nauplii, immature copepodites, and adults appeared comparable.

The zooplankton finally recovered in mid-September to a comparatively stable situation resembling the pattern observed in 1958, after sewer operation commenced. Indigenous production, not recruitment from outside the estuary, replenished the populations.

Perspective. From the above we may generalize that for open-coastal areas in the Mid-Atlantic Bight, the direct effect of energy-related activities on copepod populations, by far the major component in the zooplankton, is at present not a concern. Limited, short-term effects are seen only at point discharges. Lasting damage to the benthos, however, is another matter. Experience suggests that on the bottom persistent, small-scale environmental changes have cumulative effects that are enhanced, rather than dissipated as in the plankton, by ecosystem processes. An example is given below.

FISH: SIGNIFICANCE OF INTERACTIONS POSSIBLY MEDIATED THROUGH THE PLANKTON; CATCH IN RELATION TO SUBTLE CLIMATIC CHANGE

The abundance of winter flounder (*Pseudopleuronectes americanus*) in Narragansett Bay increased from 1966 to 1968 and then decreased through 1972, undergoing a 78% drop from the peak year.²⁵ During the entire study, 76% of the variation

Table 2

Air Temperature From Average Degree Days (Degree Heating Minus Degree Cooling, Centered on 65°F) and Corresponding Surface-Water Predictions, Calculated From Relationships Between Degree Days and Monthly Means of Weekly Water Temperature Measurements, 1966-1973

Period ^c	No. days	Air, °C (°F) ^a			Predicted water, °C ^b		
		Low	High	Range	Low	High	Range
A29	30	6.67 (44.0)	10.06 (50.1)	3.39 (6.1)	5.10	7.63	2.53
T29	883 (884) ^d	11.39 (52.5)	12.39 (54.3)	1.0 (1.8)	11.84	12.64	0.80
T30	913 (914) ^d	11.22 (52.2)	12.28 (34.1)	1.06 (1.9)	11.71	12.55	0.85
Total degree days ^e							
		High	Low	Range			
* 29		630	447	183			
29		11,091	9,438	1,653			
30		11,721	10,004	1,717			

^a U.S. Department of Commerce Weather Bureau, *Local Climatological Data, T.F. Green Airport, 1964-1973*, Govt. Printing Office, Washington, D.C.

^b A29 water temperature = $13.82 - 0.42$ (daily av °days for April): $r = -0.85$.

T29 water temperature = $17.42 - 0.45$ (daily av °days for the interval): $r = -0.96$.

^c See Table 3 for definition of periods.

^d Leap years taken into consideration.

^e Degree days decrease with increasing temperature.

in catch was statistically attributable to factors associated with air temperature. Comparisons were based on monthly averages of daily determinations of air-degree heating minus degree-cooling days centered on 65°F, for which the U.S. Weather Bureau serving the Narragansett Bay area keeps detailed records and which, in turn, were highly correlated with monthly averages of weekly water temperature

Table 3

Tests Showing That a Bivariate Model (III) Relating Winter Flounder Abundance in Narragansett Bay to Temperature (1966-1973) Is Significantly Better Than Univariate Models (I and II)

Model	Catch related to	Degrees of freedom (d.f.)	Sum of squares (SS)
I	April °days, 29 months prior to catch $y = a_1 + b_1x_1$	1	5,892,625 (SS ₁)
II	Total °days, during 29 months prior to catch $y = a_2 + b_2x_2$	1	5,812,275 (SS ₂)
III	Bivariate model, combining I and II $y = a_3 + b'_1x_1 + b'_2x_2$ Deviation (total - SS ₃)	1 5	9,730,144 (SS ₃) 1,654,215 (SS _D)

Equation

$$(1) \quad y = -5,037.6 + 13.7(A29) \quad r = 0.72^*$$

$$(2) \quad y = -16,570.1 + 1.8(T29) \quad r = 0.72^*$$

$$(3) \quad y = -19,526.4 + 11.4(A29) + 1.5(T29) \quad r = 0.92^*$$

Test, model III vs I:

$$F = \frac{SS_3 - SS_1}{d.f.} \div \frac{SS_D}{d.f.} = 11.60^*$$

Test, model III vs II:

$$F = \frac{SS_3 - SS_2}{d.f.} \div \frac{SS_D}{d.f.} = 11.84^*$$

where

x_1 = A29: April °days 29 months prior to beginning of year of catch.

x_2 = T29: total °days for 29 months prior to beginning of year of catch.

y = Total catch, flounder year (Sept. - Aug.).

Therefore:

1. The correlation coefficient between x_1 and x_2 is 0.203; April temperature (x_1) is not a predictor of the temperature record for the following 29 months (x_2).
2. The multivariate model (III) is significantly better at the 95% level than either of the univariate models (I and II).

*Significant at $p < 0.05$.

measurements ($r=0.966$). The degree-day unit (increasing temperature $\rightarrow$ decreasing degree days) was adopted as a more accurate measure than surface-water temperatures and for computational convenience; it is simply a linear transformation of $^{\circ}\text{F}$.

Equivalent ranges of mean air temperature and their corresponding expression on surface-water temperatures, as calculated from weekly observations, are shown in Table 2. Predicted water temperature for the entire 1966-1973 period varied by 2.53°C for April (A29), but over any $2\frac{1}{2}$ years (the age at capture for the majority of the catch) the range was only 0.85°C . These ranges reflect a general trend of warmer late winter-early spring periods and slightly cooler summers.

For catch, Table 3 shows that the totals during flounder years (Sept. 1-Aug.) may be statistically expressed in terms of three equations:

(1) April degree days 29 months prior to the start of a flounder year (A29), or
(2) Total degree days over a 29-month period prior to the flounder year, a summation of the population's thermal history (T29).

(3) With data now available, we can advance a bivariate model [Eq. (3), Table 3] relating catch to thermal history and temperature during spawning-metamorphosis for the following 29 months.

As indicated previously,²⁵ the temperature range experienced by the flounder population throughout the entire study would seem too small to be ecologically significant. The two periods evaluated in Eq. (3) (T29 and A29) are statistically independent ($r=0.203$). Their regression coefficients show that temperature at spawning as well as environmental temperature during growth and maturation are important, so it is to be expected that a bivariate model relating both periods would account better for catch variation than either source alone. The new model is intended not as a statistically better expression than the univariate models but as a step leading to biological explanations for population responses to subtle environmental change.

We speculate that interactive processes in a community magnify the effect of a minor temperature change that is well within reproductive and survival tolerances of the component species. Warmer Aprils bring about significantly shorter hatching and development times. Larvae would then metamorphose and settle to the bottom earlier each spring than previously, going through the especially critical stage when the left eye moves to the right side of the head and pigment fades from the blind side. A foreshortened planktonic existence means that young flounder may encounter a new set of predators. Predator-prey periodicities once well separated begin to

merge, and an additional toll is taken on the flounder population. Indeed, the winter under's success in the New York Bight appears to result from avoidance; success is the product of a coordinated reproductive-migratory strategy that successfully reduces predation by other species during critical life-history stages.²⁵ In such cases, the consequences of a minor physiological response by one species may lead to major changes in community structure.

There is no direct way at present to confirm or deny biological hypotheses arising from the statistics in Table 3; correlation does not prove causation. Wind direction and cloud cover, for example, may be interrelated variables important in the timing and intensity of migration. More indirectly, sun, wind, and clouds modify the

Table 4

Changes in Various Aspects of Species Populations Predicted From a 1°C Increase in the Grand Mean Air Temperature

Species	% Change	Aspect	Basis of annual comparison, aspect relative to mean temperature	Observation period	r
Winter flounder (<i>Pseudopleuronectes americanus</i>)					
Jeffries and Johnson ²⁵	-100	catch	T30 ^a	1966-1972	0.
Jeffries and Johnson bivariate model	-67	catch	A29 and T29 ^b	1966-1973	0.92
Yellowtail flounder (<i>Limanda ferruginea</i>)					
Sissenwine ²⁹	-88	recruitment/egg	temperature, spawning year	1944-1965	-
Sissenwine ²⁹	-47	individual growth rate	same year	1944-1965	-

^aT30 represents total ° days for 30 months prior to beginning of year of catch.

^bA29 represents total ° days for April 29 months prior to beginning of year of catch; T29 represents total ° days for 29 months prior to beginning of year of catch.

start, amplitude, and duration of the algal productive cycle, which in turn modifies year-class variabilities in plaice and haddock.²⁶ The winter-spring diatom bloom in Narragansett Bay is known to be erratic in timing, intensity, and successional pattern, but just what bearing the bloom's characteristics may have on flounder reproduction and early survival is not known. Zooplankton biomass, in the form of adult copepods and late copepodite stages during April, is ≈ 60 mg/m³ dry weight,²⁷ which seems adequate for supporting larval densities usually $< 1/\text{m}^3$.

Our findings agree with records for a variety of commercially important fishes and invertebrates reported by others. Taylor²⁸ has calculated for cod (*Cadus morhua*) that a 1°C increase in average annual surface temperature produces a 29-cm decrease in maximum length attained and an 18-year decrease in life span. In Table 4 we have calculated other changes that would accompany a 1°C increase in annual mean air temperature. (The range of observed values may not include the displacement used here for purposes that are chiefly comparative, not predictive.) From Sissenwine's data,²⁹ growth of individual yellowtails would be expected to decrease by about one-half, while the rate of recruitment per egg in the fishery would decrease two-thirds. For the winter flounder, the bivariate model predicts a two-thirds reduction in catch. The correspondence is fortuitous, but it does lend credibility to statistical inference: two species having similar roles in different habitats respond similarly to the same climatic change.

Further comparisons based on the data of Dow³⁰ and of Flowers and Saila³¹ are shown in Table 5. As would be predicted from Hutchins's conceptual model,³²

Table 5

Changes in Abundance of Several Species Predicted From a 1°C Increase
in the Grand Mean Annual Sea-Surface Temperature (Maine)

Species	% Change	Basis of annual comparison, total yield rela- tive to mean temperature	Average catch (metric T)	Observ- ation period	r^a	Effect
Univariate Models (Dow ³⁰)						
Hard clam (<i>Mercenaria mercenaria</i>)	+ 73.4	same year	83.3	1939-1967	0.770** ^b	Winter survival, near N limit
Oyster (<i>Crassostrea virginica</i>)	+ 51.0	3 yr later	1.2	1951-1967	0.822**	Winter survival, near N limit
Lobster (<i>Homarus americanus</i>)	+ 15.2	same year	8.3×10^3	1939-1967	0.627**	Molting, recruitment
Shrimp (<i>Pandalus borealis</i>)	- 75.0	4 yr later	139	1939-1949 1954-1967	-0.505* ^c	Spawning, early survival, near S limit
Scallop (<i>Placopecten magellanicus</i>)	- 37.5	6 yr later	135	1941-1965	-0.743**	Spawning, early survival, near S limit
Soft clam (<i>Mya arenaria</i>)	- 36.8	5 yr later	1.9×10^3	1940-1966	-0.643**	Predation on spat
Sand worm (<i>Nereis virens</i>)	- 32.5	same year	239.2	1949-1967	-0.812**	Spawning, early survival
Bloodworm (<i>Glycera dibranchiata</i>)	- 22.4	same year	179.7	1949-1967	-0.669**	Spawning, early survival
Bivariate model (Flowers and Saila ³¹)						
Lobster (<i>Homarus americanus</i>)	+ 14.6	T_0 and T_{-678}^d	9.4 ^a	1947-1967	0.889**	T_0 : molting, recruitment; T_{-678} : early winter mortality

^a Calculated from data presented by Dow.³⁰

^b ** indicates significant at the 99% level of probability.

^c * indicates significant at the 95% level of probability.

^d T_0 is the mean annual sea-surface temperature of the present year; T_{-678} is the sum of the mean annual sea-surface temperatures for 6, 7, and 8 years previous to T_0 .

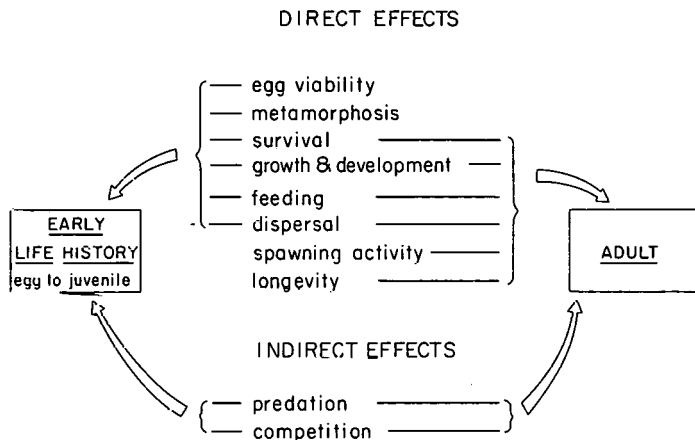


Figure 2. Biological evaluation of a bivariate statistical model explaining abundance in terms of climatic change.

warming benefits certain species and harms others, depending on where within its range a species is living. The hard clam, for example, is near its northern limit in Maine, and population density is apparently controlled by winter survival.³⁰ If mean water temperature increased 1°C , catch would increase 73%. Conversely, *Pandalus borealis* catch in Maine is limited by temperatures approaching the maxima for spawning and early survival. A 75% reduction in catch predicted for a 1°C increase in annual mean water temperature is in the direction expected, but the magnitude of change here, as in all other examples, is not certain because of the kinds of data that are available.

Despite the statistical significance of the relation between temperature and less catch shown in Table 3, we cannot predict a smaller flounder catch even if the warming trend continues. To do so would ignore the complexities of control in nature. An example is the hard clam–green crab (*Carcinus maenas*) problem in Maine. Warming reduces winter clam kill, and the population increases. If the trend includes summer, green crabs and other predators previously excluded from the area move in. Later, fish may bring these predators under control, which will allow hard clam stocks to increase once again. In short, predators also have predators.

The bivariate statistical model (Table 3) helps to establish outlines for research on communities responding to subtle climatic change. There is little indication, for example, that short-term extremes arithmetically diminishing to insignificance in an annual mean control the bay's flounder population. Indeed, the time-series suggests that such events as summer "heat waves" have moderated recently.

The bivariate model also indicates conceptual difficulties at the community level. When the components of investigation are viewed as outlined in Figure 2, the flounder problem appears too complex for solution by traditional means. Requirements may be met by field experimentation, a technique that marine ecologists are just beginning to develop.³³

Field experimentation calls for holding constant the variable being examined and allowing all others to vary naturally, whereas in laboratory experimentation all variables except the one of interest are held constant. Experimental control in nature is a problem, but as facilities become available and experience accumulates, we can expect to understand organization at the ecosystem level more clearly and, from such fundamental information, be able to predict permissible loadings due to energy-related activities.

Perhaps then we will have broken the stalemate well-stated by Emery³⁴: "In a way, debates about the environmental and political controls on oil and gas production are akin to the medieval debates about how many angels can dance upon the head of a pin."

Acknowledgments: These studies were supported by the State of Rhode Island, the Office of Sea Grant Programs, PHS Grants RG-7003 and RG-5278, and FWPCA Grants WP-00858 and 18050TDX. Drs. David M. Pratt, Candace A. Oviatt, Nelson Marshall, and Michael P. Sissenwine read the manuscript and offered helpful criticism. We are also indebted to Evelyn Dyer for maintaining the data file on fishes and to Capt. Stanley Spink for trawling.

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DISCUSSION

MICHAEL: I am curious about the graphs on the flounder. Do you have enough benthic information in Narragansett Bay to look for possible effects of predation on the benthos?

JEFFRIES: No, we didn't look at predation. We did look at some species that we suspected of competing, but species data were difficult to interpret and it was not clear that any particular pattern was being set up.

MULLIGAN: How were you able to zero in on temperature in the long-term 1966 to 1973 data? Weren't there also long-term rainfall differences in that period? I think that 1966 and thereabouts were very dry years and rainfall has since been going up.

JOHNSON: We presented some of these data informally at an EPA laboratory, and someone suggested that we should have taken 50 physical variables and plugged them all into a stepwise regression to see which variables would have had the most effect. One must be wary of using too many variables because of the increased possibility of spurious correlation. We considered temperature important, perhaps not directly, but in relationship to day length, amount of light intensity, etc. But searching for many physical variables had certain drawbacks, and I think one can lose credibility by searching too systematically. We observed a progressive decrease in catch, but it was not clearly associated with salinity variation.

HENNEMUTH: You seem to have overlooked one predator that may be involved in this phenomenon, and that is man. Two comments: First, you seem to be measuring abundance in terms of catch, a notoriously poor measure of abundance, particularly in these sought-after populations. Second, the time series for both yellowtails and flounders tend to coincide with more and more catch. Certainly over the period of your correlation the fishing pressure has built up greatly.

JOHNSON: We are aware of the catch-abundance problem and we should have emphasized that our station in Narragansett Bay was purposely selected on a migratory route. We think have a good census station. We did not discuss abundances in Rhode Island Sound in similar detail because there the conditions for an accurate census obviously do not exist.

JEFFRIES: We examined the data on commercial catch to see whether it was having an effect, but none was apparent. There was an indication that our catch in the bay was a predictor of offshore catch by the commercial fleet two years later, the time required for small bay flounder to grow and enter the offshore fishery. Thus, the data available suggest that fishing pressure is not important at present; rather, natural factors varying in an estuarine nursery area have future consequences for the winter flounder fishery offshore. Others have shown the considerable effect of climatic variation on yellowtails over long periods. Of course, our data are short term; we do not have 50 years' worth of trawl data.

Structure and Stability in Three Marine Benthic Communities in Southern New England

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INTRODUCTION

The pressure to exploit a variety of resources in the marine environment presents the ecologist with the problem of monitoring ecosystems to evaluate the impact of such activities. The fundamental issue of what should be measured and how the measurements should be made remains unanswered or at least in dispute. Benthic ecology is not a well-developed science since it has not received much attention in the past. In many areas a benthic monitoring project must start with the fundamentals of describing the species that exist in the region and their approximate abundances. The data available are insufficient for developing a firm theoretical basis to explain the distribution and abundances of the benthic fauna. Community processes such as energy transfer or nutrient cycling within the benthos are not understood. We do not know which parameters of marine benthic communities can be most accurately measured, or what the controlling factors are, although we may extrapolate from other areas of marine ecology. It is obvious that both physical and biological factors affect species distributions, but their relative importance in various situations is not understood.

In attempting to monitor a benthic community, should one measure community parameters such as diversity, species richness, equitability, etc. or should one concentrate on documenting individual species responses? Could this time-consuming work of identification and sorting be avoided by simply estimating rates of various processes such as oxygen uptake, nitrogen regeneration, etc? The literature is much too scant in the latter area for any evaluation of its potential for monitoring purposes. Even the basic numerical data that exist for the benthos may not be sufficient for a clear statement. In spite of all these problems, some significant advances have been made in the last few years. I will discuss some of these in an overview of some recent data from three nearshore areas, Long Island Sound, Buzzards Bay, and Cape Cod Bay.

BACKGROUND

Relatively little information has been published on the benthos of the outer continental shelf. Two transect studies^{1,2} give data on the types of species at a few isolated stations on the shelf. Wigley and McIntyre³ made some quantitative comparisons between macro- and meiobenthos at depths from 40 to 567 m off Martha's Vineyard. Qualitative observations – some estimates of biomass and the role of the benthos as fish food – have been provided for the Georges Bank area by Wigley.⁴⁻⁶ The National Marine Fisheries Service at Woods Hole, Massachusetts, has collected hundreds of benthic samples from the Gulf of Maine to Cape Hatteras during the last decade. These data, which will be published soon, will provide a much more

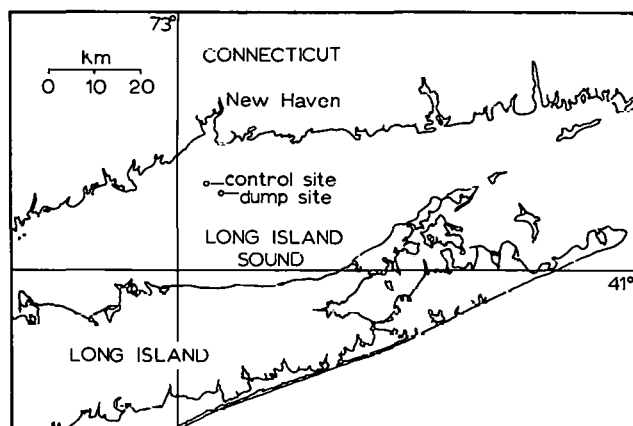


Figure 1. New Haven dredge spoil dump site in central Long Island Sound.

comprehensive statement on the shelf benthos. The problems in monitoring offshore benthic communities are similar to those for the nearshore environment, and since many more data are available in the latter case it seems appropriate to use these for the purposes of discussion.

LONG ISLAND SOUND

Previous studies in Long Island Sound have been conducted by Burkenroad,⁷ Sanders,⁸ Carey,⁹ and Richards and Riley.¹⁰ These studies give a fairly complete description of the fauna and provide some insight into the biological factors in operation. The benthos was initially described by Sanders, who recognized the basic community types and related feeding habits to the substrate. Carey demonstrated a seasonal cycle in oxygen consumption but found that the dominant macrofauna accounted for only a small part of the uptake. Richards and Riley estimated epifaunal abundances and standing crops of a variety of infaunal and epifaunal species. They concluded that Long Island Sound supported only a small population of demersal fish because of competition from the starfish *Asterias forbesi*, the muddy nature of the substrate, the inefficiency of zooplankton feeding, and the abundance of the indigenous meiofauna. In spite of large discrepancies between results obtained with differing sampling gear, they suggested that the benthic fauna remained fairly stable central Long Island Sound over the period 1953–1961.

In July 1972 studies were initiated to evaluate the effects of dumping dredge spoils from New Haven Harbor into the Sound. Samples were collected at a site that had been used for dumping some years previously. A control site 5.5 km to the northwest (Figure 1) was selected. A grid was established at each site and samples were collected with a 1.6-m² Van Veen grab and sieved through a 1-mm screen. Table 1 lists the fauna found at these sites during the initial sampling. For comparison, the results of Sanders for station 3 are listed in Table 2.

Table 1
Benthic Fauna in Long Island Sound, Summer 1972
(Mean number of individuals per m²)

	Dump site	Control site		Dump site	Control site
POLYCHAETA			MOLLUSCA		
<i>Nephtys incisa</i>	41.8	164.3	<i>Nassarius trivittatus</i>	23.9	45.9
<i>Maldanopsis elongata</i>	7.7	12.1	<i>Retusa</i> sp.	50.6	50.9
<i>Praxillella praeterrimissa</i>	25.1		<i>Mitrella lunata</i>	1.5	
<i>Clymenella torquata</i>	0.5		<i>Toldia limatula</i>	60.0	52.3
<i>Vichomache lumbricalis</i>	3.0		<i>Nucula annulata</i>	52.5	678.2
<i>Aelina cristata</i>	67.9	36.1	<i>Pitar morrhuana</i>	410.8	45.2
<i>Ampharete arctica</i>	9.3	2.6	<i>Mulinia lateralis</i>	3134.4	1.5
<i>A. acutifrons</i>	1.0		<i>Tellina agilis</i>	11.2	3.3
<i>Asabellides oculata</i>	18.2	0.5	<i>Petricola pholadiformis</i>	10.9	
<i>Streblospio benedicti</i>	156.7		<i>Periploma papyratum</i>	0.5	0.5
<i>Scolecopsis squamata</i>	8.7		<i>Macoma tenta</i>	7.4	4.9
<i>Polydora ligni</i>	43.4	4.1	<i>Pandora gouldiana</i>	109.9	10.5
<i>Pherusa affinis</i>	54.5	7.9	<i>Lyonsia hyalina</i>	8.3	
<i>Pherusa plumosa</i>	0.3		<i>Ensis directus</i>	1.0	
<i>Brada villosa</i>	6.8		<i>Anadara notabilis</i>	0.7	
<i>Mediomastus ambiseta</i>	5.6		<i>A. transversa</i>	0.3	
<i>Paraonis gracilis</i>	3.6		OTHERS		
<i>Tharyx acutus</i>	1.5		<i>Ampelisca abdita</i>	18.0	3.4
<i>Cirratulus grandis</i>	1.5		<i>Cancer irroratus</i>	2.2	2.9
<i>Pectinaria gouldii</i>	10.4	0.5	<i>Pinnixa sayana</i>	2.9	1.1
<i>Phyllodoce maculata</i>	0.5		<i>Leptocheirus pinguis</i>	2.5	1.4
<i>P. mucosa</i>	1.3		<i>Pagurus longicarpus</i>		0.2
<i>Sigambra tentaculata</i>	22.7	7.4	<i>Crangon septemspinus</i>	0.8	1.4
<i>Harmothoe imbricata</i>	0.5		<i>Pagurus pollicaris</i>		0.2
<i>Lepidonatus squamata</i>	0.3		<i>Diastylis polita</i>	2.9	
<i>Pholoe minuta</i>	0.5	0.5	<i>Grapsidae</i>	0.5	
<i>Cossura longicirrata</i>	0.3		<i>Unciola</i> sp.	0.3	
<i>Glycera americana</i>	0.3	0.5	<i>Cumacea</i>	1.5	
<i>Owenia fusiformis</i>	19.4	12.1	<i>Copepoda</i>	0.5	
<i>Ninoe nigripes</i>	2.6		<i>Mysidacea</i>	0.3	
<i>Spiochaetopterus oculatus</i>	0.8	2.7	<i>Heteromysis formosa</i>	0.3	
<i>Terebellidae</i>	0.3	0.5			

Table 2
Benthic Data (From Sanders⁸)

	Station 3, Feb. 19, 1974, No./m ²		Station 3, Feb. 19, 1974, No./m ²
<i>Cerianthus americanus</i>	30	<i>Nucula proxima</i>	1984
<i>Nephtys incisa</i>	106	<i>Toldia limatula</i>	61
<i>Lumbrineris tenuis</i>	23	<i>Pandora gouldiana</i>	8
<i>Cistenoides gouldii</i>	15	<i>Pitar morrhuana</i>	8
Unidentified polychaete	213	<i>Mulinia lateralis</i>	8
<i>Ampelisca B</i>	46	<i>Retusa canaliculata</i>	167

The control site has fauna similar to that found by Sanders at station 3 almost 20 years earlier. The fauna in both cases is dominated by the protobranch bivalve *Nucula* and the polychaete *Nephtys incisa*. The species list for the dump site varies greatly from this. The dominant species is *Mulinia lateralis*, and among the other bivalves *Pitar morrhuana* and *Pandora gouldiana* are more abundant than *Nucula*. The most striking difference is in the polychaetes. Among the most abundant species are the small, opportunistic species *Streblospio benedicti* and *Polydora ligni*. Densities of these and other small polychaetes are probably underestimated because of the use of 1-mm sieving. Overall, the dump site had many more species and individuals than the control site. In spite of this, biomass determinations on bivalves (decalcified dry weight) were lower, which indicated that the average size was much smaller. (Most of the individuals at the dump site are opportunists, as defined by Grassle and Grassle.¹¹) The combined evidence suggests that the dump site was at some stage of faunal succession and not near the equilibrium condition found at the control site.

This type of faunal composition has not been recorded in previous work from Long Island Sound. Physical disturbance can probably be ruled out, since it does not seem possible that one particular 1.8-km² area in central Long Island Sound would be affected and not another some 5 km removed. It is not probable that physical changes due to dumping (compaction, erosion) were in effect, since the material had been dumped nine years earlier. The sediment transported from the harbor during dredging is heavily contaminated with a variety of pollutants, including heavy metals, sewage wastes, and petroleum hydrocarbons. High levels of copper and zinc have been recorded,¹² and fuel oil components are visible in sediments at the dump site. The fauna is similar to that described at West Falmouth following a spill of No. 2 fuel oil.^{13,14} The presence of such contaminants in the sediments appears to be the best explanation for the stress over a localized area.

Samples were collected at the same sites some 6 and 12 months later (Table 3). In subsequent sampling a smaller Van Veen grab (0.04 m²) was used and replicates were collected at each station. The dump site averaged 29 species and >4000 indi-

Table 3
Numbers of Species and Individuals at Dump and Control Sites

	August 1972		January 1973		August 1973	
	n = 31	S.E.	n = 21	S.E.	n = 21	S.E.
Control site						
Species/sample	14.7	0.91	10.4	0.58	3.1	0.36
Individuals/m ²	1226	213	1916	367	177	38
	n = 27	S.E.	n = 21	S.E.	n = 21	S.E.
Dump site						
Species/sample	29.2	1.2	14.1	2.9	2.1	0.25
Individuals/m ²	4684	566	1266	283	85	14

viduals/m² in the summer of 1972 but declined to 14 species and 1276 individuals/m² over the winter. The control area was much more stable. The infauna at both sites apparently suffered heavy mortality between January and July 1973, since numbers of species and individuals were extremely low in the summer of 1973. The spring and summer larval set apparently failed, since densities remained low for the following 12 months. Our subsequent data show that the fauna had not recovered to original levels by the spring of 1974.

The decline in the benthic fauna over this period was also documented by workers from Sandy Hook¹⁵ and by McCall,¹⁶ but the cause remains unknown. The decline cannot be related to any pollution event. A major physical disturbance remains a possibility, since a wide area of central Long Island Sound was affected. In more studies, Rhoads (personal communication) has found discrete layers of bivalve shells at irregular intervals, which suggests that similar massive mortalities have occurred in the past. McCall¹⁶ produced direct evidence of storm layers.

In summary, although the benthic infauna seemed rather stable between 1953 and 1961, an atypical situation was found at a dredge spoil dump site in 1972. In 1973 there was large-scale mortality of benthic invertebrates over a wide area of central Long Island Sound, and equilibrium conditions were not reached for at least 18 months.

BUZZARDS BAY

Sanders^{17,18} recognized two major communities in Buzzards Bay. One was the *Nucula-Nephtys* association, as in Long Island Sound; the other, found in sandier sediments, was dominated by *Ampelisca*. The distribution of feeding types was related to sediment. Following this, Rhoads and Young¹⁹ developed the trophic group amensalism hypothesis with additional studies in the bay. The separation of deposit and suspension-feeding benthos was attributed to biological factors. Reworking of the upper few centimeters of mud bottom by deposit feeders produces an unstable surface, which discourages the settlement and survival of suspension feeders. In 1969, a small spill of No. 2 fuel oil occurred at West Falmouth and in follow-up studies samples have been taken at selected sites for six years. Grassle and Grassle¹¹ applied the concept of opportunism to field and biochemical studies of species from the spill area. Structural changes in the communities due to the presence of oil were demonstrated for the period 1969–1974.^{13,14}

The fauna was severely depleted as a result of the spill, and in nearshore areas around Wild Harbor there was a complete kill. This provided an opportunity to evaluate the response of the benthos to the initial severe stress and a lower stress over a longer period of time. The area was first colonized by opportunistic species such as *Capitella capitata*. Densities of this species reached 200,000/m² three months after the spill in the Wild Harbor marsh. Using these data and some experimental results, Grassle and Grassle reexamined the concept of opportunism. Initial response to disturbed conditions, ability to increase rapidly, large population size, early maturation, and high mortality were suggested as features of opportunistic species. They proposed using mortality as the best single measure of opportunism. The short-term

Table 4
Dominant Species at Two Sites in Buzzards Bay

Station 20		Station 35	
Species	%	Species	%
March 1973			
<i>Mediomastus ambiseta</i>	25	<i>Mediomastus ambiseta</i>	60
<i>Exogone verugera</i>	8	<i>Ampelisca vadorum</i>	16
<i>Sphaerosyllis hystrix</i>	8	<i>Sphaerosyllis hystrix</i>	
<i>Aricidea jeffreysii</i>	6		
Total individuals: 20,200		Total individuals: 52,275	
March 1974			
<i>Parapionosyllis longicirrata</i>	22	<i>Ampelisca abdita</i>	15
<i>Aricidea jeffreysii</i>	13	<i>Ampelisca verrilli</i>	15
<i>Sphaerosyllis hystrix</i>	12	<i>Ampelisca juv.</i>	10
<i>Protodorvillea minuta</i>	12	<i>Sphaerosyllis hystrix</i>	9
<i>Exogone dispar</i>	7	<i>Byblis serrata</i>	7
<i>Byblis serrata</i>	6	<i>Brania wellfleetensis</i>	6
<i>Exogone verugera</i>	6		
Total individuals: 14,650		Total individuals: 7,275	
May 1973			
<i>Mediomastus ambiseta</i>	28	<i>Mediomastus ambiseta</i>	87
<i>Parapionosyllis longicirrata</i>	13		
<i>Aricidea jeffreysii</i>	10		
<i>Ampelisca vadorum</i>	6		
<i>Sphaerosyllis hystrix</i>	6		
<i>Exogone verugera</i>	5		
Total individuals: 23,775		Total individuals: 35,325	
May 1974			
<i>Parapionosyllis longicirrata</i>	21	<i>Mediomastus ambiseta</i>	23
<i>Mediomastus ambiseta</i>	18	<i>Sphaerosyllis hystrix</i>	15
<i>Aricidea jeffreysii</i>	11	<i>Aricidea jeffreysii</i>	8
<i>Terebellidea juv.</i>	10	<i>Praxillella sp.</i>	5
<i>Exogone dispar</i>	10	<i>Nucula annulata</i>	5
<i>Sphaerosyllis hystrix</i>	5		
Total individuals: 28,250		Total individuals: 12,675	
July 1973			
<i>Mediomastus ambiseta</i>	27	<i>Mediomastus ambiseta</i>	60
<i>Aricidea jeffreysii</i>	15	<i>Ampelisca juv.</i>	9
<i>Parapionosyllis longicirrata</i>	15		
<i>Byblis serrata</i>	9		
<i>Exogone verugera</i>	9		
<i>Sphaerosyllis hystrix</i>	5		
Total individuals: 31,275		Total individuals: 23,675	

Table 4 (Continued)

Dominant Species at Two Sites in Buzzards Bay

Station 20		Station 35	
Species	%	Species	%
July 1974			
<i>Parapionosyllis longicirrata</i>	27	<i>Minuspio</i> sp.	34
<i>Aricidea jeffreysii</i>	24	<i>Mediomastus ambiseta</i>	18
<i>Exogone dispar</i>	14	<i>Nucula annulata</i>	8
<i>Protodorvillea minuta</i>	11	<i>Cerastoderma pinnulatum</i>	6
<i>Byblis serrata</i>	6	<i>Leptocheirus pinguis</i>	6
Total individuals: 25,875		Total individuals: 4,775	
September 1973			
<i>Protodorvillea minuta</i>	12	<i>Mediomastus ambiseta</i>	23
<i>Aricidea jeffreysii</i>	12	<i>Ampelisca verrilli</i>	18
<i>Mediomastus ambiseta</i>	9	<i>Ampelisca</i> juv.	10
<i>Parapionosyllis longicirrata</i>	7	<i>Sphaerosyllis hystrix</i>	6
<i>Macoma tenta</i>	6	<i>Tellina agilis</i>	5
Total individuals: 11,950		Total individuals: 6,425	
September 1974			
<i>Aricidea jeffreysii</i>	22	<i>Mediomastus ambiseta</i>	32
<i>Parapionosyllis longicirrata</i>	16	<i>Nucula annulata</i>	12
<i>Exogone verufera</i>	14	<i>Ampelisca</i> juv.	11
<i>Protodorvillea minuta</i>	8	<i>Ampelisca verrilli</i>	7
<i>Brania wellfleetensis</i>	6	<i>Sphaerosyllis hystrix</i>	6
<i>Sphaerosyllis hystrix</i>	5	<i>Byblis serrata</i>	5
Total individuals: 17,750		Total individuals: 9,850	
November 1973			
<i>Parapionosyllis longicirrata</i>	19	<i>Ampelisca</i> juv.	11
<i>Sphaerosyllis hystrix</i>	19	<i>Pitar morrhua</i>	11
<i>Exogone verufera</i>	13	<i>Ampelisca verrilli</i>	10
<i>Protodorvillea minuta</i>	12	<i>Sphaerosyllis hystrix</i>	9
<i>Brania wellfleetensis</i>	7	<i>Goniadella gracilis</i>	7
<i>Aricidea jeffreysii</i>	7	<i>Aricidea jeffreysii</i>	5
Total individuals: 23,700		Total individuals: 5,325	
November 1974			
<i>Parapionosyllis longicirrata</i>	28	<i>Mediomastus ambiseta</i>	23
<i>Brania wellfleetensis</i>	22	<i>Ampelisca</i> spp.	17
<i>Protodorvillea minuta</i>	12	<i>Sphaerosyllis hystrix</i>	13
<i>Aricidea jeffreysii</i>	9	<i>Protodorvillea minuta</i>	8
<i>Sphaerosyllis hystrix</i>	8	<i>Exogone dispar</i>	7
Total individuals: 21,700		Total individuals: 10,950	

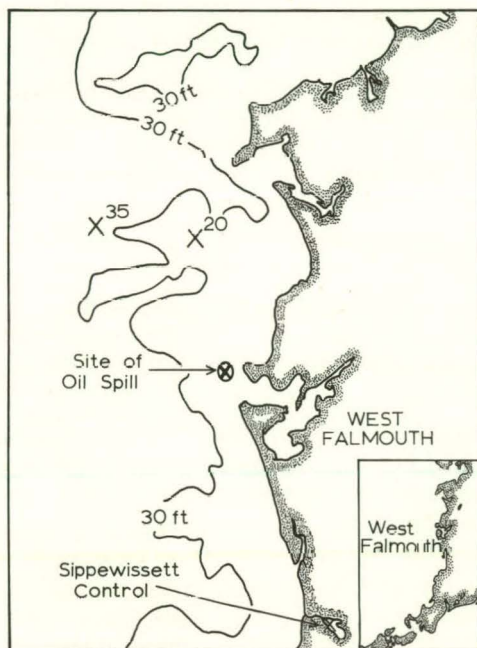


Figure 2. Location of oil spill control sites in Buzzards Bay.

selection for a single genotype in *Capitella capitata* following the spill was presented as evidence of the role of genetic variation in adaptation to unpredictable environments.

In the areas in which oil persisted some four years later, community changes observed were (1) reduction in numbers of species, (2) reduced faunal densities, and (3) greater proportion of opportunistic species and individuals.¹⁴ One of the benefits of this study is that the fauna at some stations has been sampled at regular intervals for a period of several years. This provides information on the problems of natural variation which must be taken into account in any monitoring studies. Table 4 lists the dominant fauna of the two control sites used in the West Falmouth study. These stations were located at 11-m depth and quite close to shore, so that accuracy in sampling at the same sites was high (Figure 2). The total number of individuals per m² is reported (0.297-mm sieve), as are the species comprising 5% or more of the total. The fauna at station 20 is dominated by polychaetes such as *Mediomastus ambiseta* and *Aricidea jeffreysii*. The two dominant species from each sample include from 24 to 51% of the total individuals. Station 35 is not as predictable as station 20, and dominance is pronounced in some samples. The indication of seasonality is primarily qualitative since the results are based on single 0.04-m² Van Veen grab samples. At station 20 two of the dominant species, *Mediomastus ambiseta* and *Parapionosyllis longicirrata*, do not appear as a major component of the fauna in some samples. A similar situation is found at station 35, where *Mediomastus ambiseta* and *Ampelisca* spp., although quite dominant overall, are not present in significant numbers in every

case. The total number of specimens caught varies by a factor of 2.6 at station 20 and of 7.4 at 35. Even allowing for normal sampling error it is obvious that major changes are occurring seasonally and yearly. Such data raise questions of the type: (1) To what extent are the changes attributable to physical or biological factors? (2) What sampling scheme is necessary to provide a statistically valid description of the changes? (3) What is the relationship between work invested and precision of the data? Monitoring programs for the benthos will be limited to superficial qualitative statements until these questions are addressed.

CAPE COD BAY

From 1966 to 1969, 446 0.1-m² Smith McIntyre grab samples were collected in Cape Cod Bay. The sampling pattern was based on a grid (Figure 3) and each numbered quadrat was sampled once. A single grab was taken from the center and four corners of the quadrats. The major results of this study will be presented elsewhere, but some information is included here for comparison with data collected by Young and Rhoads.²⁰ Young and Rhoads collected samples from seven of the same stations in July 1969. The sites formed a transect between stations 2318 and 0918. A single sample was collected for faunal analysis at the center of each of the selected stations. Young and Rhoads found high faunal densities ($\bar{x}$ = 15,410 individuals/m²) and dominance by five species of polychaetes: *Euchone incolor*, *Capitella capitata*, *Spio limicola*, *Ninoe nigripes*, and *Asabellides oculata*. Specimens identified as *Capitella capitata* were probably *Mediomastus ambiseta*. In the major survey of the bay, *Mediomastus ambiseta* was the second most abundant organism. *Capitella capitata* occurred much less frequently. *Mediomastus ambiseta* is absent from Young and Rhoads' species list. Table 5 lists the total numbers of individuals and species collected in the two studies. The dominant species are listed in Table 6.

Table 5

Faunal Parameters Reported in Two Cape Cod Bay Benthic Studies

Station	No. of species		No. of individuals		Date ^c
	Pa ^a	Y + R ^b	P	Y + R	
2318	21	40	2,400	16,000	10/66
2118	56	44	6,140	11,190	10/68
1918	20	56	3,790	30,150	8/66
1718	52	43	7,560	15,820	10/68
1518	42	43	9,230	14,230	1/68
1118	43	43	3,870	12,540	9/68
0918	46	34	8,640	7,870	1/68

^aPresent study.

^bY + R = Young and Rhoads.²⁰

^cDate refers to present study; all Young and Rhoads samples were collected in July 1969.

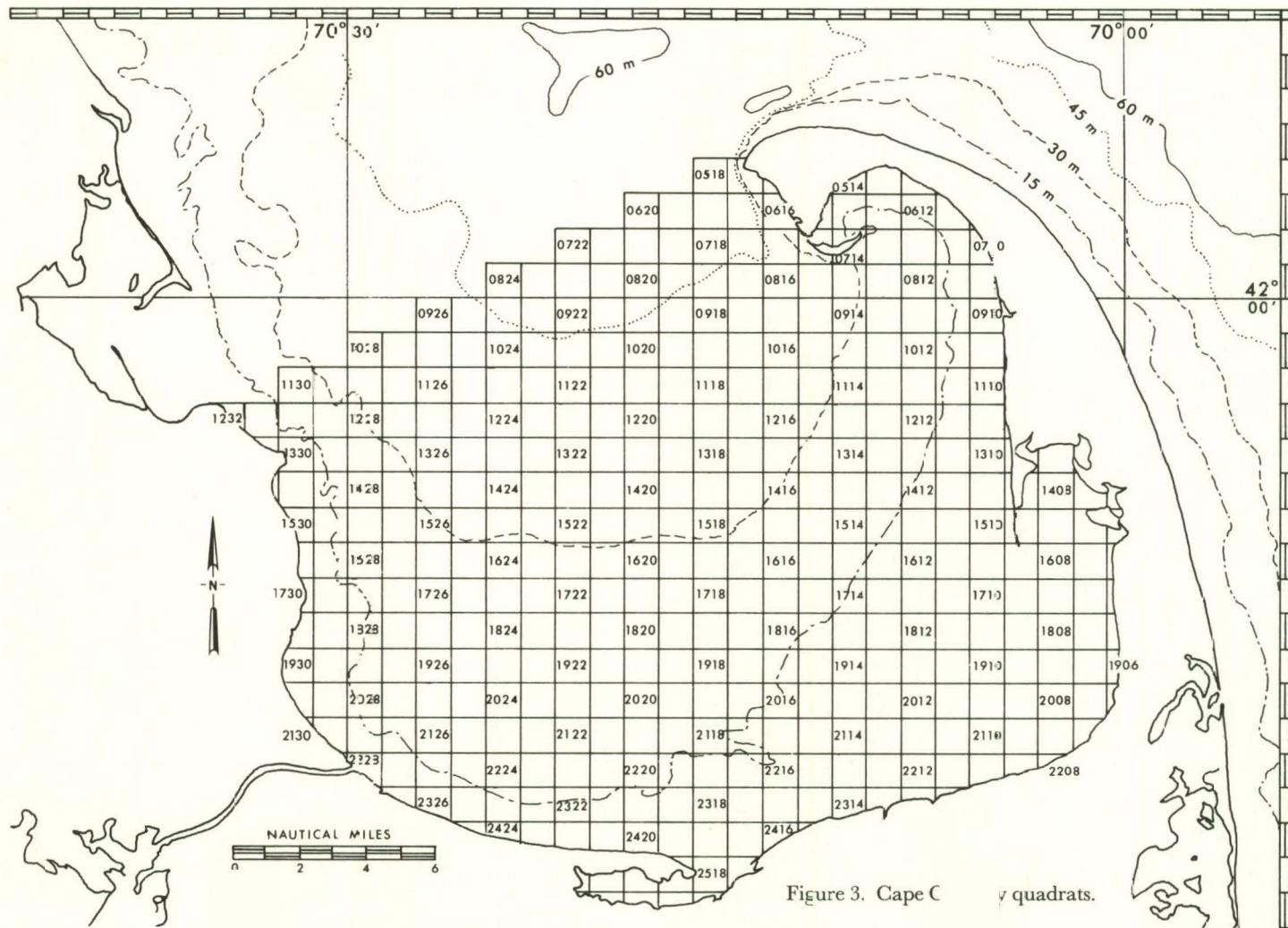


Figure 3. Cape C quadrats.

The data show marked differences, the most obvious being the greater dominance by small polychaetes in 1969. Samples were collected from the same vessel and the same equipment (grab, etc.) was used. A few of the same personnel were involved in field work for both collections; hence the dramatic difference cannot be attributed solely to sampling error or bias. In other samples of the major survey, faunal densities of up to 34,330 animals/m² were found, and there was a significant number of samples of *Euchone incolor* with high densities (>5000/m²). It appears that the benthos of Cape Cod Bay, an area of some 1600 km² and depths to 57 m, is subject to significant changes in faunal densities and composition; we have recorded similar findings in Long Island Sound and Buzzards Bay.

To evaluate the stability of the Cape Cod Bay benthos, the results of >400 iniment analyses were plotted as histograms (Figure 4). Using either mean or median grain size the resulting histogram is trimodal. One group centers around 1 ϕ (0.5 mm) and represents the clean sands of shallow areas at <15-m depth. A second peak occurs near 4 ϕ (0.062 mm) and these are the silty sediments of medium depths (15 to 30 m). A final group occurs at the 6 ϕ (0.016 mm) range representing the clay sediments of the deep central portions of the bay. Three size groups were chosen from these data. Group 1 included samples with a median particle size of 0 to 2 ϕ . Group 2 contained those in the 2.5 to 4.5 ϕ range. The final group consisted of samples with a median particle size of 5.5 to 7.5 ϕ . By excluding other samples the boundaries between groups can be sharpened to emphasize differences. An additional separation was made on a seasonal basis. Summer samples (July–September) were separated from those taken in winter (January–March). In Table 7 the total numbers of species and individuals found in these restricted categories are compared.

Group 1 averages about 34 species per sample, with faunal densities of 6000 to 7000 animals/m² and no significant change between winter and summer seasons. Very little change between seasons is evident for group 3, and the values for these two community parameters are much more predictable, as indicated by the range and standard error of the mean. Values for group 2 are similar to those for the other groups in the summer season, but there is a marked difference in winter: the numbers of both species and individuals are much higher. The depth range (15 to 30 m) for group 2 encompasses the summer thermocline. In addition to the temperature change, there is an increase in resuspended sediment below the thermocline. These two factors operating over the same area present an unstable environment which may reduce species diversity in summer. An alternative explanation is that deeper water species are able to penetrate into the shallow areas during the winter and the higher species number represents an overlap of the fauna. The composition of the fauna indicates that the 15 to 30-m depth area is characterized by elements of the other two depths rather than its own discrete fauna. The increased densities on a short-term basis are probably due to the presence of greater numbers of small opportunistic species.

The results in Table 7 are based on 184 grab samples taken within the specified seasons over a 4-year period. The range and standard error of the mean values show a great deal of variance in the data. There appears to be a gradient of predictability with depth, the deeper areas being more stable. These data, in themselves, and in

Table 6
Dominant Species in Cape Cod Bay
(Comparison of 1969 data with previous data)

Station	% of Total individuals		% of Total individuals
October 1966		July 1969	
2318			
<i>Praxillella</i> sp.	30	<i>Protodrilus</i> sp.	40
<i>Crenella glandula</i>	17	<i>Polydora</i> sp.	15
<i>Unciola irrorata</i>	9	<i>Unciola irrorata</i>	14
<i>Goniadella gracilis</i>	14	<i>Glycera capitata</i>	6
<i>Polygordius triestinus</i>	7	<i>Clymenella</i> sp.	6
<i>Euchone elegans</i>	7		
<i>Aricidea jeffreysii</i>	6		
<i>Asabellides oculata</i>	5		
October 1960			
2118			
<i>Asabellides oculata</i>	23	<i>Capitella capitata</i>	40
<i>Mediomastus ambiseta</i>	12	<i>Asabellides oculata</i>	9
<i>Terebellides stroemi</i>	8	<i>Nucula proxima</i>	6
<i>Syrhoe crenulata</i>	7	<i>Euchone incolor</i>	5
<i>Prionospio streenstrupi</i>	6		
August 1966			
1918			
<i>Leptocheirus pinguis</i>	20	<i>Capitella capitata</i>	35
<i>Orchomene minuta</i>	16	<i>Euchone incolor</i>	13
<i>Phoxocephalus holbolii</i>	15	<i>Spio limicola</i>	10
<i>Eudorella emarginata</i>	12	<i>Asabellides oculata</i>	8
<i>Ninoe nigripes</i>	9	<i>Ninoe nigripes</i>	5
<i>Mediomastus ambiseta</i>	9		
<i>Anonyx lilljeborgi</i>	6		
October 1968			
1718			
<i>Euchone incolor</i>	16	<i>Euchone incolor</i>	35
<i>Mediomastus ambiseta</i>	13	<i>Capitella capitata</i>	28
<i>Spio limicola</i>	11	<i>Apistobranchus tulbergi</i>	5
<i>Asabellides oculata</i>	9		
<i>Ninoe nigripes</i>	8		
<i>Apistobranchus tulbergi</i>	5		
January 1968			
1518			
<i>Euchone incolor</i>	30	<i>Euchone incolor</i>	49
<i>Spio limicola</i>	14	<i>Capitella capitata</i>	18
<i>Mediomastus ambiseta</i>	9		
<i>Asabellides oculata</i>	9		
<i>Tharyx acutus</i>	6		

Table 6 (Continued)

Dominant Species in Cape Cod Bay
(Comparison of 1969 data with previous data)

Station	% of Total individuals		% of Total individuals
September 1968			
1118			
<i>Euchone incolor</i>	17	<i>Euchone incolor</i>	58
<i>Ninoe nigripes</i>	11	<i>Spio limicola</i>	9
<i>Spio limicola</i>	11		
<i>Tharyx acutus</i>	7		
<i>Scoloplos acutus</i>	7		
<i>Paraonis gracilis</i>	5		
January 1968			
0918			
<i>Spio limicola</i>	49	<i>Euchone incolor</i>	40
<i>Limnodriloides medioporus</i>	8	<i>Capitella capitata</i>	18
<i>Paraonis gracilis</i>	6	<i>Ninoe nigripes</i>	8
<i>Euchone incolor</i>	6	<i>Spio limicola</i>	6

Table 7

Community Parameters for Groups Based on Sediment Size and Season

Group	Number of species			Number of individuals		
	$\bar{x}$	Range	S.E.	$\bar{x}$	Range	S.E.
1 [0-2 ϕ]						
Winter (19)*	33.4	10-74	3.5	6,950	290-23,220	1,390
Summer (34)	34.4	11-80	2.4	5,640	510-34,330	1,190
2 [2.5-4.5 ϕ]						
Winter (50)	45.9	23-69	1.52	10,690	1,330-21,990	860
Summer (27)	32.7	17-56	1.98	5,390	1,330-11,090	590
3 [5.5-7.5 ϕ]						
Winter (30)	36.6	17-58	1.61	4,710	1,270-15,830	644
Summer (27)	38.9	25-49	1.17	4,480	1,319-13,270	501

*Numbers in parentheses are the number of samples.

comparison with those of Young and Rhoads,²⁰ emphasize the spatial and temporal heterogeneity of the Cape Cod Bay benthos.

In addition to the transect work, Rhoads and Young²¹ studied the effect of reworking by the holothurian *Molpadia oolitica*. This species occurs in silt-clay muds in densities of 2 to 6/m². Reworking by this species produces vertical sediment sorting,

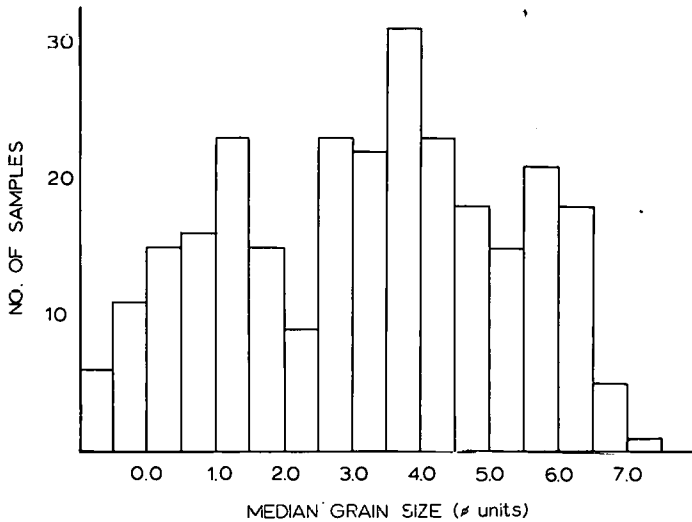


Figure 4. Median particle size in Cape Cod Bay sediments.

high sediment-water content, and topographic relief of the sea floor. Fecal cones offer a relatively stable surface for the settlement and growth of suspension feeders such as *Euchone incolor*. Uncompacted feces in the depressions between the mounds discourage suspension feeders, and so there is small-scale spatial separation of suspension-feeding organisms affected by the activities of a larger species. Both biological and physical factors influence the distribution patterns.

DISCUSSION

The significance of processes within the benthos is not well understood, and our knowledge of the role of the benthic fauna in larger-scale ecosystem processes is scant. Measurements of oxygen consumption on the sea floor have been made, e.g.,²²⁻²⁶ More recently, evidence that the benthos contributes to regeneration of nutrients has been provided by Rowe et al.²⁷ Studies such as these are of primary importance in understanding the significance of changes in benthic populations and communities. Determinations of oxygen uptake show considerable variance,²⁸ from ≈ 1 to >100 $\text{ml m}^{-2} \text{ hr}^{-1}$, but the effects of faunal composition, which itself shows great spatial and temporal variation, on such measurements are not clearly defined. Macrofauna is responsible for only a small fraction of the total oxygen consumption.⁹ We question whether we can expect to reach firm conclusions about the role of the benthos in community processes if only a small portion of the total fauna is considered.

The number of specimens caught is proportional to the size of the sieve. Megabenthos typically number 1 to 10 adult individuals/ m^2 in coastal waters. Macrobenthos, caught on a 1-mm sieve, usually total 1000 to 10,000/ m^2 , whereas meiobenthos caught on screens of $\approx 100 \mu$ are found in densities of 100,000 to 1 million.

Bacteria are much more numerous. The larger forms account for a greater proportion of the biomass, but the smaller forms are more important in processes such as oxygen consumption and, perhaps, nutrient regeneration. The system is a continuum in all aspects, and it seems obvious that studies should not be restricted to a particular segment of the benthos if its role as a unit is to be understood. Most benthic studies are based on 1-mm sieving. This arbitrary spectrum does not effectively sample the megabenthos, some of which may have a dominant effect on the whole structure of the macrofaunal community.²¹ The meiobenthos is completely ignored in such sampling. Community structural changes due to stress have been found in Long Island Sound and Buzzards Bay. In both cases faunal composition changed with increased numbers of smaller polychaetes which probably were not sampled adequately with a 1-mm sieve. We have no data on the effects of such structural shifts on benthic community processes. It is possible that such changes could affect the food chain. Smaller organisms, even though more numerous, may not constitute a suitable food source for demersal fish.

Data provided herein are of no assistance in solving the basic questions involved in monitoring. Numerical data such as species numbers, numbers of individuals, and faunal composition are but one approach in monitoring communities. The limits of precision in various numerical estimates have not been established because of the effort involved in processing the very large number of samples necessary. The literature on processes is much too scant and has not been related to faunal data in a way suitable for monitoring. A third approach is that of using community parameters such as diversity, equitability, etc. Use of diversity in monitoring studies has developed from Sanders' time-stability hypothesis.²⁹ Less stable environments tend to have lower diversity than more stable areas. Sanders' original concept was applied to communities at equilibrium. While any community under severe stress will have few species, there are many examples in which significant faunal changes in stress situations are not reflected in differing diversity values. At the New Haven dump site, where mixtures of the late successional and equilibrium species were present in the same samples, diversity values were the same as or higher than those at the control site. One must be careful to distinguish transient diversity from equilibrium diversity.³⁰ The mathematical form of diversity indices makes them insensitive to small changes in the data, such as the replacement of one species by another. This takes no account of the biology involved. Such indices may be used as supplemental information but not as sole indicators of the "condition" of any one community.

Data from nearshore areas show that the benthos undergoes both spatial and temporal changes. I have reported a major change in the case of Long Island Sound. The causes of these changes have not been demonstrated, but both biological and physical factors are involved. Deeper areas such as Cape Cod Bay at depths >30 m seem to be somewhat more stable. The time-stability hypothesis suggests that the shallow areas are more physically controlled. Studies have been made on biological and physical factors as controlling elements in community structure, but most of them are intertidal or shallow subtidal investigations.³¹⁻³⁶ At this point no data are available on the relative importance of physical versus biological factors (competition, predation, etc.) in controlling the distribution and abundance of the benthos

on the continental shelf. If the shelf benthos is more stable than the communities discussed herein, it will be more susceptible to any physical or chemical stress imposed by exploitation activities. Equilibrium communities of stable areas are not preadapted to respond to sudden changes.

Although information on the shelf benthos is scant, we do know what types of species are present and their approximate abundances (within an order of magnitude). There is a high degree of overlap between the benthos of large open embayments such as Cape Cod Bay and the adjacent continental shelf. The major change in benthic fauna occurs on the lower continental slope.¹ In spite of the scant information available for the shelf benthos and the inadequacies of inshore data, some significant advances have recently been made. The more numerous data from inshore areas make us more cognizant of the sampling problems and the spatial and temporal variation in benthic communities. The application of the concept of opportunism and data from communities responding to stress in Long Island Sound and Buzzards Bay has improved our understanding of the biology of these systems. A particularly promising area is the recent work on processes and direct evidence of a link between benthic and pelagic systems in nutrient cycling. The most effective way to resolve the issues in monitoring and to advance the science of benthic ecology would be to initiate comprehensive studies in which the several approaches are used concomitantly.

Acknowledgments: Results from Long Island Sound were collected under a U.S. Army Corps of Engineers Contract (DACW-74-M-0035) to Donald C. Rhoads at Yale University. Contracts from the American Petroleum Institute and the United States Environmental Protection Agency supported work by the author in Buzzards Bay and Cape Cod Bay respectively.

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DISCUSSION

SCOTT: I was interested in your cluster analysis. First I would like to know why you chose similarity index, and second, have you used cluster and ordination in combination?

MICHAEL: I have used cluster and ordination, and in my experience in Cape Cod Bay I found ordination to be relatively ineffectual with highly heterogeneous data. If you partition the data first, you get the same sort of results as with the cluster analysis, but if you do ordination on the total set of data you just get into a shambles.

O'CONNOR: I realize that there haven't been measurements of benthic productivity off our coast, at least all across the shelf, but do you have any information from the worldwide literature on changes in productivity with distance off the shelf?

MICHAEL: I would expect the productivity of the benthos to decrease in general with distance from shore. There is no question that it is obviously high in the shallower areas out in George's Bank and similar places.

Patterns of Larval Fish Distributions in the Middle Atlantic Bight

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In this paper I will briefly describe the early life history of marine fishes, explain the utility of studying young stages of fish relative to fisheries and oceanographic problems, and illustrate the present state of knowledge of ichthyoplankton studies in the Northwest Atlantic Ocean. With this background, needs for future studies, particularly in relation to man's activities in the Middle Atlantic Bight, will be evident.

The early life history of nearly all marine fishes includes a planktonic larval stage.¹ Among east coast fishes some species (e.g., sand lance) lay demersal eggs and others (e.g., redfish) bear live young, but most species spawn pelagic eggs. Regardless of the site of egg development, most young fishes pass through a planktonic larval stage (Figure 1). Although the adults are disparate in size, the planktonic eggs are generally 0.7 to 2.0 mm in diameter. The larvae hatch at about 3 mm, and by 30 mm most have transformed into juveniles. On the east coast this pattern is seen in small pelagic fish such as anchovies as well as large pelagic fish such as tunas. Demersal and semidemersal fishes such as cod, cunner, and most flounders have the same pattern. After larval development at sea, the juveniles of some fish migrate to estuarine nursery areas. Of the juveniles that remain at sea, some become part of the neuston at the surface of the sea, while some take up demersal habits. A few juvenile fish (e.g., red hake) establish commensal relationships with other organisms (e.g., scallops). After the juvenile stage all these fish take up the habits of their parents, spawn at sea, and start the cycle anew.

The ubiquity of the larval stage among marine fishes offers the opportunity to use a single type of collecting device – the plankton net – to sample many kinds of fishes at once. Adult fish occupy a variety of habitats and are so varied in size and behavior that no single device can be used to sample them all adequately. For some fish not presently exploited we have little information on distribution and relative abundance. Some schooling, migrating fishes such as bluefish and tunas have such complicated distributions as adults that estimates of population size are difficult to derive. For some species we must rely on commercial catch statistics, which are highly biased, for estimates of biological parameters. The contrasting habits and economic importance and the variety of sampling gears and techniques used to study adults are in stark contrast to the uniform environment of eggs and larvae and the relative ease of sampling them. With an adequate number of quantitative plankton samples we can determine the numbers of eggs spawned and in turn estimate the size of the adult spawning population. From data on numbers of late larvae we can estimate the size of the year-class resulting from the spawning.

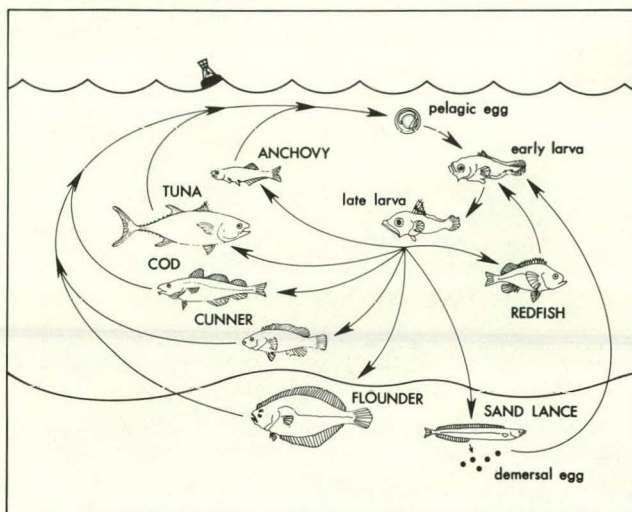


Figure 1. Diagrammatic representation of the early life history stages of east coast marine fishes.

Fish with planktonic early stages produce enormous numbers of young. Individual females usually produce 10^5 to 10^7 eggs annually. To retain stable populations, few of these eggs can survive to adulthood. Most of the tremendous mortality occurs during the egg and larval stages, but its causes are varied and not well understood. Starvation and predation are of primary importance, but drift from essential environments may also be important. It is generally assumed that the ultimate size of year-classes of fish is determined by annual differences in mortality during the larval period. Little or no relationship exists between number of eggs spawned and year-class strength, but surveys of early juveniles usually provide good estimates of year-class strength. Thus the differential mortality must occur between the egg and juvenile stages. Monitoring the abundance of larval fish and understanding the causes of mortality are important areas of fisheries research.²

To understand the influence of natural and man-induced changes in the environment on fishes, we must understand their early life history. We need to know the time and place of spawning and larval development. We need to know the predator-prey relationships of larval fishes. We must investigate the transport and migration of larvae from spawning areas to nursery grounds. We need to understand the stimuli inducing spawning of adults and movements of larvae. The effects of density-dependent mortality of larvae resulting from cannibalism and intraspecific competition need to be investigated. Only with this type of information can we hope to understand causes of mortality and to predict year-class strength from larval fish studies. Even without full comprehension of these factors, we can form and test hypotheses that may lead to estimates of year-class strength. Environmental conditions related to weather and food supply have been correlated with year-class strength in several cases.²

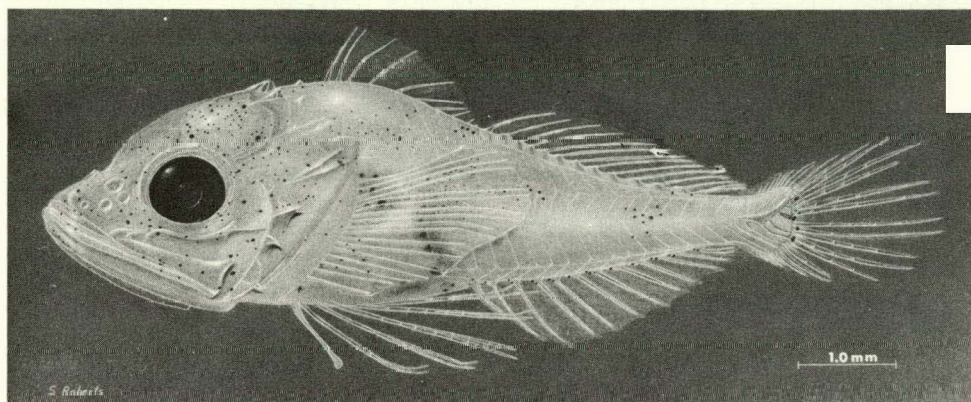
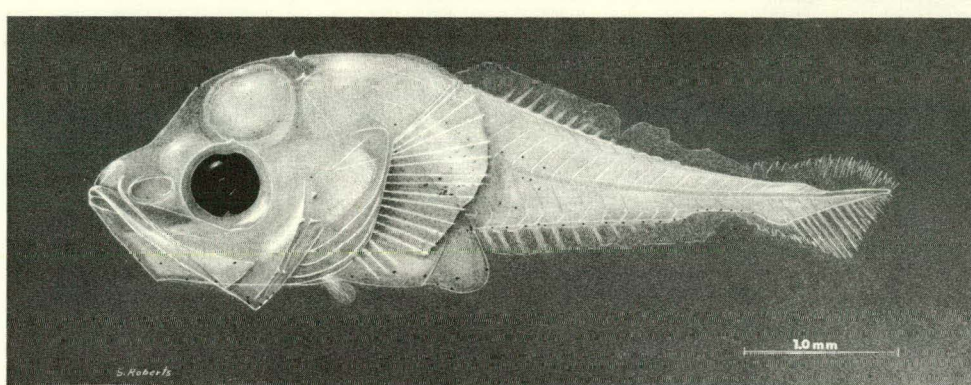


Figure 2. Northern sea robin (*Prionotus carolinus*) larvae, drawn by Susan C. Roberts.

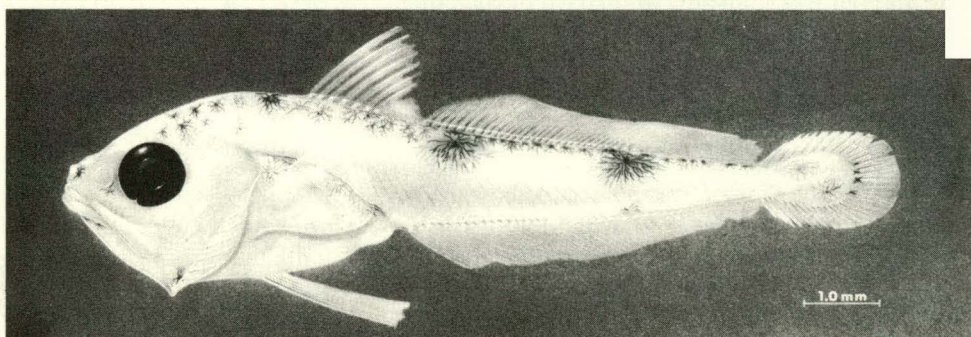
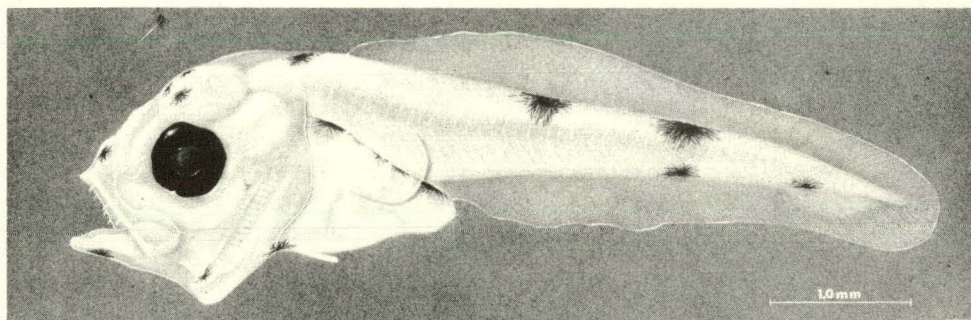


Figure 3. Silver hake (*Merluccius bilinearis*) larvae, drawn by Michael P. Fahay.

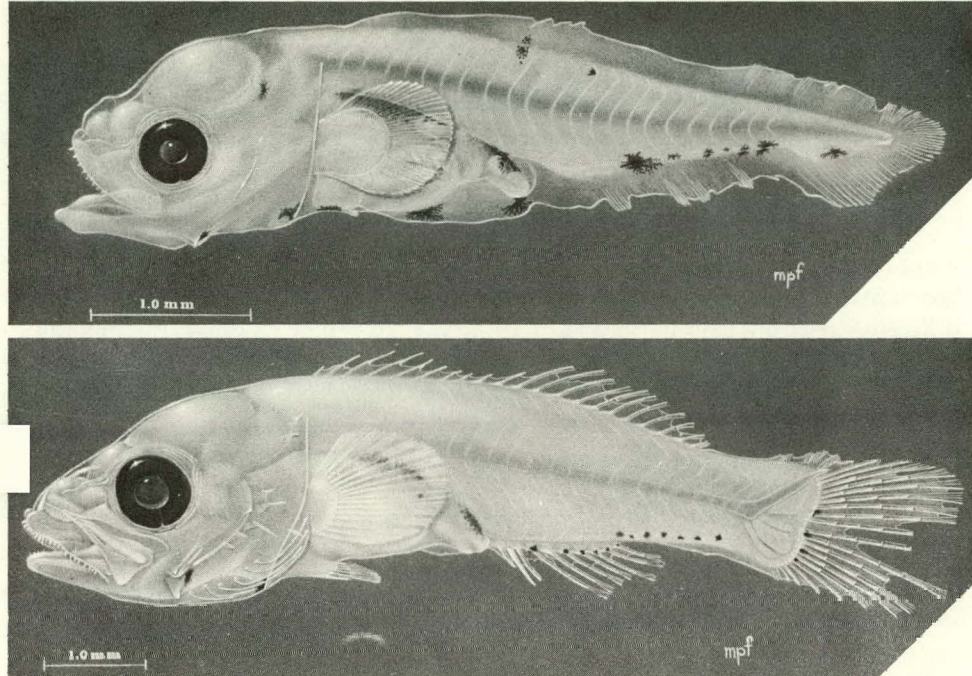


Figure 4. Black sea bass (*Centropristis striata*) larvae, drawn by Michael P. Fahay.

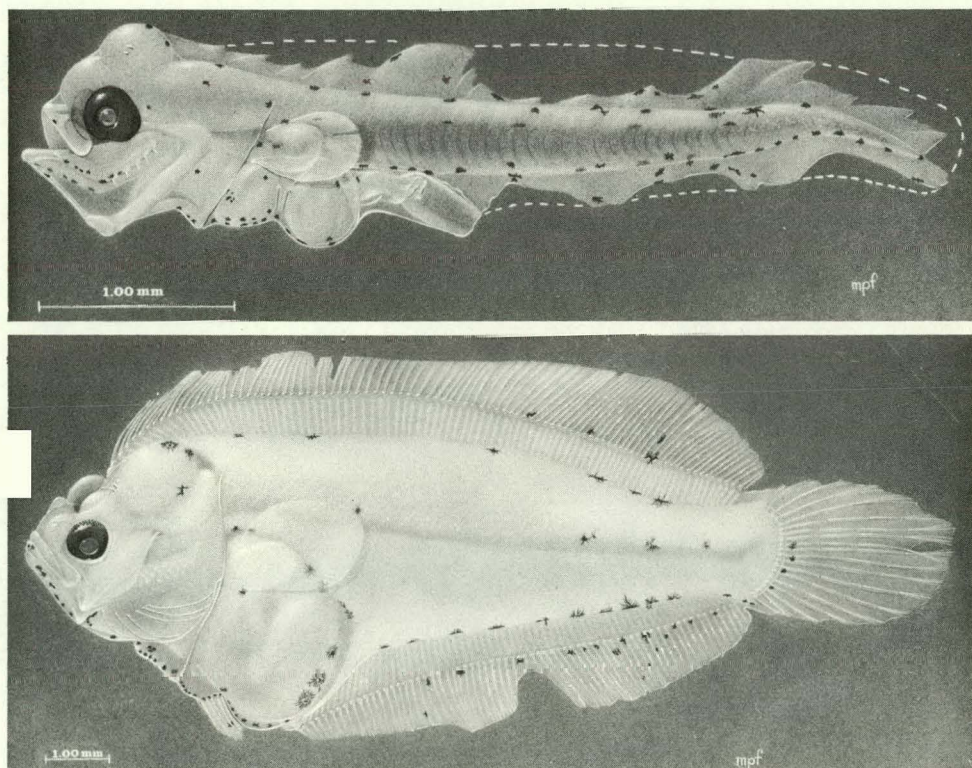


Figure 5. Summer flounder (*Paralichthys dentatus*) larvae, drawn by Michael P. Fahay.

Our knowledge of the early life histories of east coast fishes is rather limited. The eggs of many have not been described, and even the larvae of some common species are not known. Larval fish do not look like adults and have few diagnostic characteristics of adults. Literature on larval fish identification is scattered among a variety of sources, and some common species are erroneously or poorly described, if at all. Since few marine fish have been reared in the laboratory, identification of larval fish depends primarily on accumulating series of similar-appearing larvae of different sizes from field samples. Larger larvae have some characteristics of adults, while retaining the pigment patterns and body shape of smaller larvae. As examples of the variety and similarities of fish larvae, drawings of black sea bass, northern sea robin, summer flounder, and silver hake larvae are included here (Figures 2 to 5).

Most field studies on the east coast have been of a survey nature – attempts learn what species are spawning, where, and when. Notable among these studies are Sette's work³ on Atlantic mackerel, Pearson's work⁴ near the mouth of Chesapeake Bay, the Virginia Institute of Marine Science's work⁵ off the coast of Virginia from 1959 to 1961, and Colton and St. Onge's compilation of data⁶ from Nova Scotia to Long Island.



Figure 6. RV *Dolphin*, used for ichthyoplankton survey of Middle Atlantic Bight.



Figure 7. Gulf V plankton sampler.

With the background of limited information on time and place of spawning and larval development of Middle Atlantic Bight fishes, personnel of Sandy Hook Laboratory conducted the most extensive ichthyoplankton survey yet completed in this area. This survey involved eight cruises aboard the RV *Dolphin* (Figure 6) from December 1965 through December 1966.⁷ During each cruise, 92 stations situated on 14 transects from Cape Cod, Mass., to Cape Lookout, N.C., were occupied. The transects ran from within 2 km of the shore to the edge of the continental shelf – the 200-m isobath. Stations were closely spaced inshore and farther apart offshore. At each station, temperature and salinity were measured with depth and plankton tows. Step oblique tows were made with Gulf V plankton samplers (Figure 7). The

nets were towed for 5 min at two sets of six 3-m depth increments, one from the surface to 15 m and the other from 18 to 33 m, when water depths permitted. In shallower water fewer steps were sampled for longer periods, the total tow time always being 0.5 hr. Samples were preserved in dilute buffered formaldehyde and returned to the laboratory for removal of fish eggs and larvae. Major taxonomic groups of fish larvae were then assigned to several biologists for further identification and analysis. A number of papers dealing with descriptions and distributions of several species from this survey have been published.⁸⁻¹⁵

As individual species were identified, counted, and measured, the data were accessioned in an ADP file. We now have larval fish and ancillary data from each station and can make comparisons of catches at different stations for different seasons and cruises.

By compiling the data from our ichthyoplankton survey we can determine which species occur together as larvae. This is of interest because larvae occurring together could compete for food or feed on each other and thus influence each other's survival. Several statistical methods are available, and we plan to compare the results of different methods to see which is most useful in larval fish studies. We have begun by using a method designed by Fager called REGROUP.¹⁶ An index of affinity is computed for each pair of species, and the species are then grouped according to their affinities. The index, which ranges from 1 for complete co-occurrence to 0 for no co-occurrence, is based only on occurrences and does not consider abundances. For our initial test we used the 39 species that we found in >27 tows during the survey. Of these, 28 possessed an index of affinity with at least one other species of ≥ 0.4 . Initial results indicate that there are four recurring groups of larvae in the Middle Atlantic Bight (Figure 8). A group composed of four species, including Atlantic mackerel and yellowtail flounder, dominates the spring ichthyoplankton assemblage. Silver hake is a ubiquitous species occurring with members of three groups, including the spring group. It has its greatest affinities with the summer group of five species, including red hake and butterfish. In fall a group of three species, Atlantic menhaden, summer flounder, and windowpane, is prevalent. The fourth group occurs mainly in the offshore waters of the southern part of the bight. Two lantern fishes and three flounders dominate this group. Their centers of spawning activity are probably south of Cape Hatteras. Bluefish and bonita, confined to our summer collections, showed affinities with each other, but with no other species. Several species occurred with some member of each group, and some were present with members of two groups. The winter ichthyoplankton assemblage, composed in part of Atlantic herring, cod, and sand lance, showed affinity levels below those used for this analysis. These are encouraging preliminary results and we hope to amplify this work, using other methods such as cluster analysis and factor analysis.

The geographic and seasonal distributions of three fish, Atlantic menhaden (*Brevoortia tyrannus*), northern sea robin (*Prionotus carolinus*), and summer flounder (*Paralichthys dentatus*), illustrate several features of larval fish distribution. The adults of these fish have quite different habits. Menhaden, a plankton-feeding, schooling pelagic fish, migrates seasonally along the coast, north in spring and south in

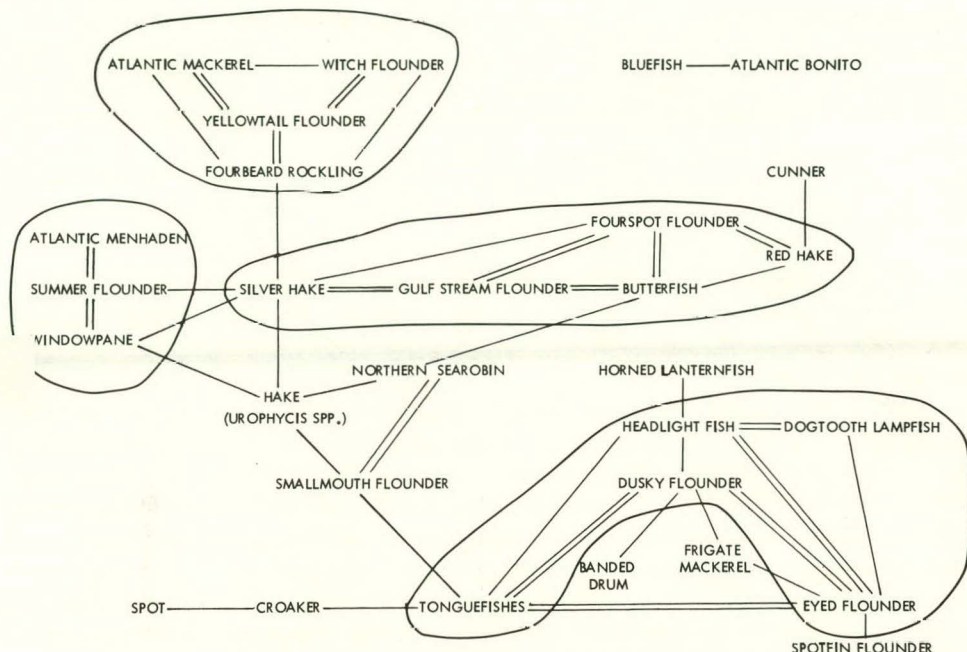


Figure 8. Recurrent groups of fish larvae in the Middle Atlantic Bight. Single lines connect species with affinity indices 0.4 to 0.5. Double lines connect species with indices >0.5 . Species within balloons form groups with indices >0.5 between members.

fall. It accounts for more biomass than any other fish caught by American fishermen on the east coast. After early development at sea, the late larvae migrate to estuaries, where they transform into juveniles and grow during their first summer of life. Northern sea robin has its center of abundance in the Middle Atlantic Bight. It migrates inshore in summer and offshore in winter and is of little economic value. Pelagic eggs develop and hatch into larvae at sea, and, after a fairly short larval period, juveniles become demersal in the same habitat occupied by adults. Summer flounder is an important commercial and recreational fish of the Middle Atlantic Bight. It migrates to coastal waters in summer and offshore to near the edge of the continental shelf in winter. Its early life history includes use of estuaries by juveniles after egg and larval development offshore. Despite these differences in life history, all three species have similar patterns of distribution as larvae.

Seasonally, northern sea robin and Atlantic menhaden larvae were first seen in June, when sea robins occurred from Cape Lookout to New Jersey. Menhaden were present only near Delaware Bay (Figure 9). In August sea robins were widespread in the Middle Atlantic Bight while menhaden were confined to nearshore areas of the New York Bight (Figure 10). October was the month of maximum abundance for all three species, with the centers of abundance corresponding closely (Figure 11). A band of high concentrations extended from Chesapeake Bay to Long Island,

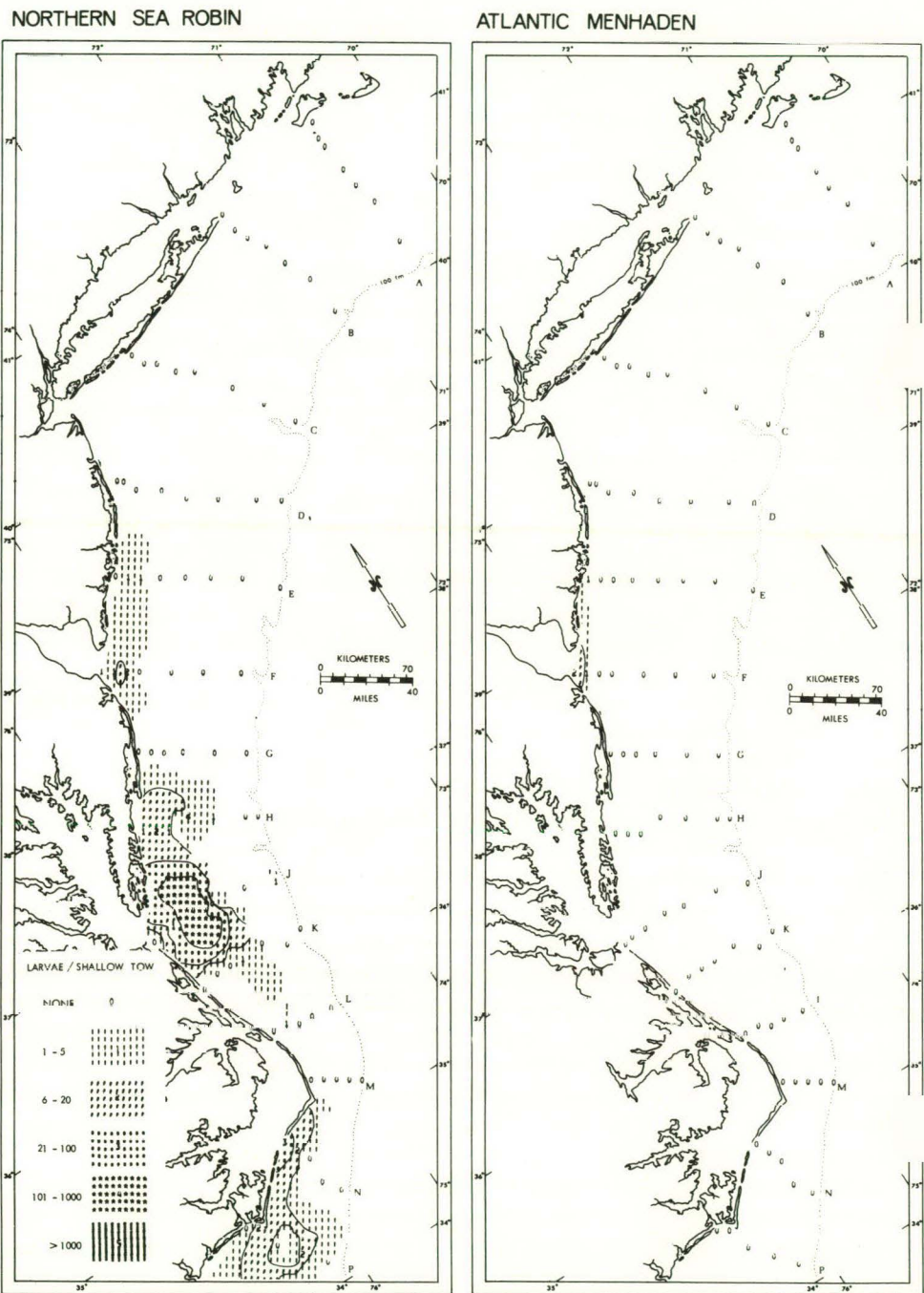
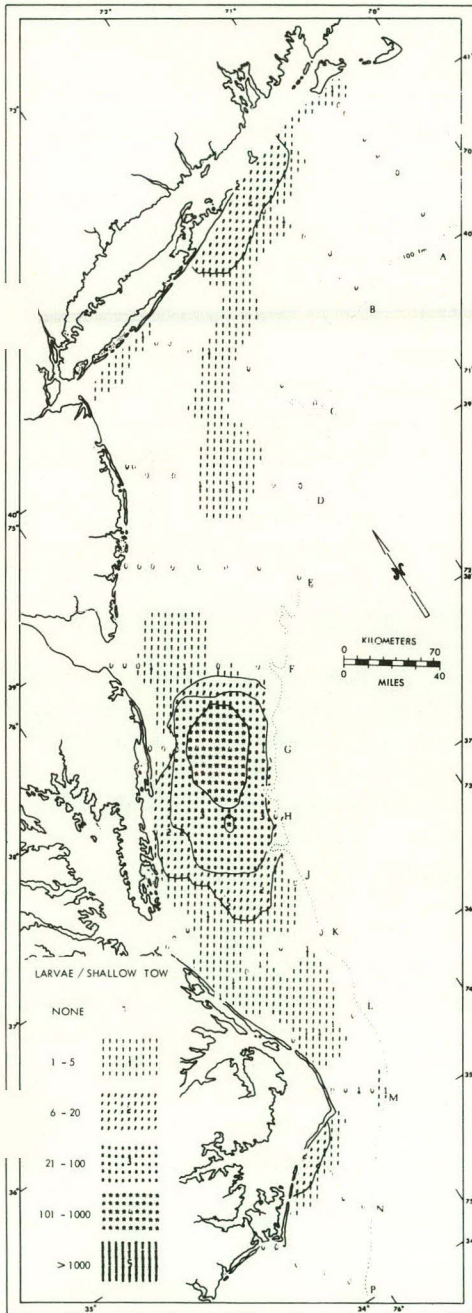


Figure 9. June distribution of northern sea robin and Atlantic menhaden larvae.

NORTHERN SEA ROBIN



ATLANTIC MENHADEN

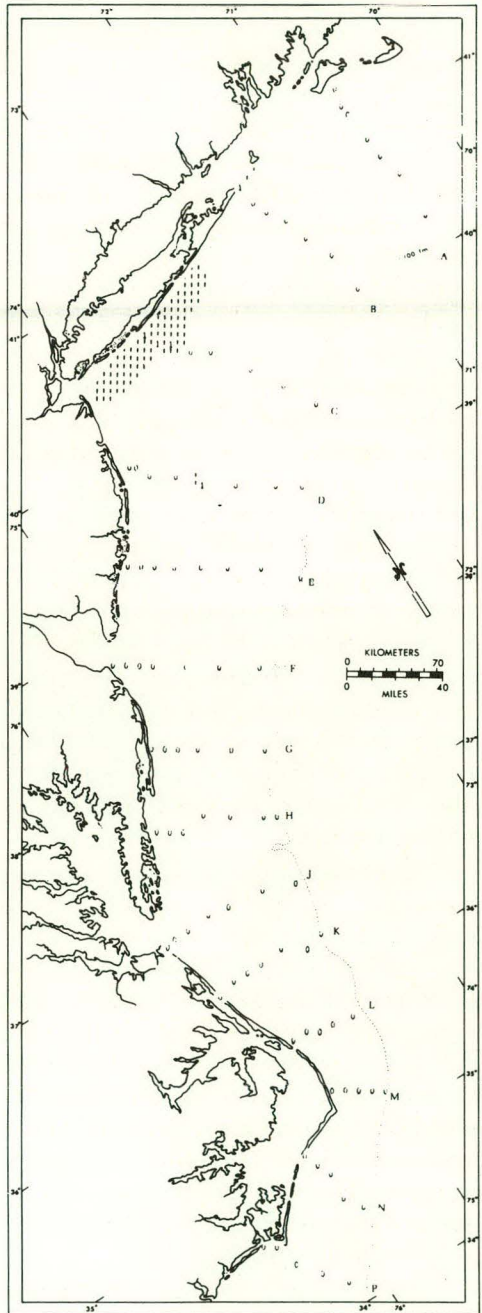


Figure 10. August distribution of northern sea robin and Atlantic menhaden larvae.

mainly over the middle of the continental shelf. Seasonally, October was the first occurrence of summer flounder, although they were present on an abbreviated cruise in September when the northern four transects were occupied. By November, sea robins were much less abundant and were found mainly in the southern part of the bight (Figure 12). Menhaden were also mainly south of their October location. Summer flounder were present fairly uniformly throughout the bight. In December the distribution patterns were farther south than in November, with sea robins confined to waters off North Carolina, menhaden mostly south of Delaware Bay, and summer flounder widespread south of Long Island (Figure 13). January saw further reductions in numbers and area of larvae, with all three species primarily in the southern part of the bight (Figure 14). In April and May remnants of earlier spawnings were present mainly off North Carolina (Figures 15 and 16.)

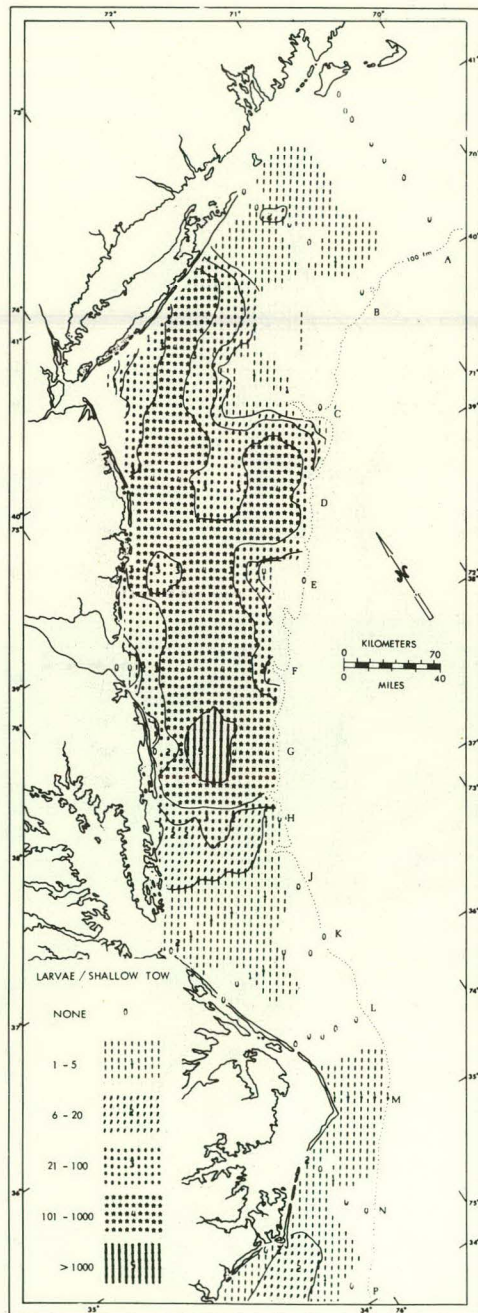
Some conclusions can be drawn from the distributions of these species which are substantiated by similar analyses of other species. Most species are present for a few to several months annually, although not in the same areas at all times. Larvae of most species are quite widespread geographically in the bight. Species that spawn primarily in late summer and fall start spawning in the northern part of the bight, and spawning moves south with the season. Species spawning in spring start in the southern part of their range and move north with the season. Fish larvae found in the northern part of the bight in the winter are generally the southern extent of spawning of fishes found primarily north of the bight. Larvae of many species that also spawn south of the bight are found in the summer.

In an effort to determine the vertical and diel distribution of larval fishes, we have conducted a series of cruises at different seasons, each with a particular target species. In this way we are beginning to understand how several species of fish can use the water column simultaneously, yet have minimal adverse effects on each other. One such cruise was conducted during the summer of 1974, with bluefish as the target species.

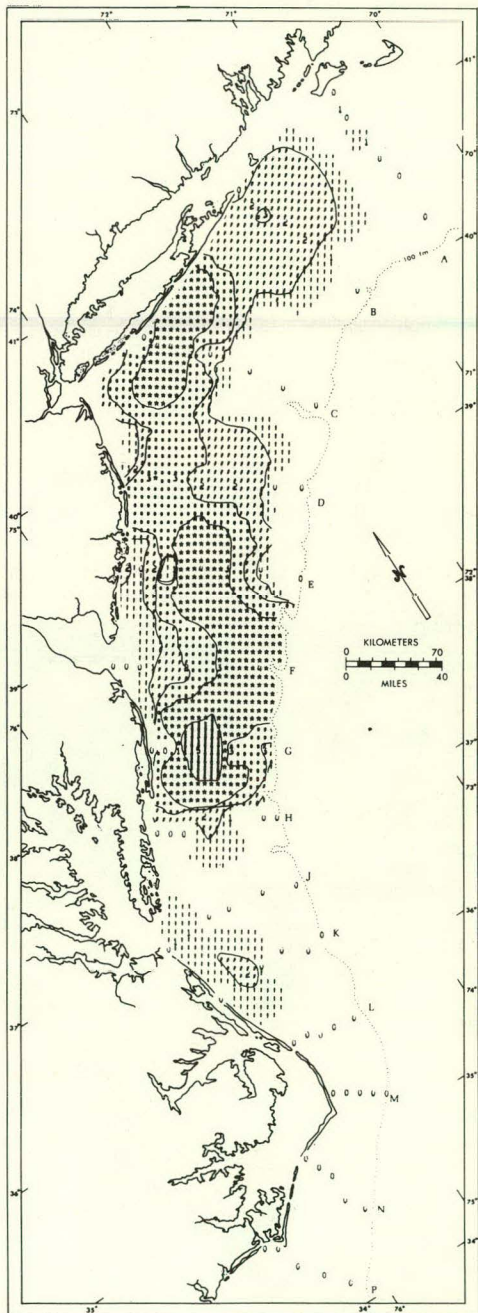
Using data from past collections and information on recent catches of adult bluefish, we searched for a concentration of larval bluefish. After several exploratory tows, bluefish larvae were located on July 18, 1974, about 95 km off Ocean City, Md., in 57 m of water (Figure 17). A parachute drogue with a lighted staff buoy was deployed and plankton was sampled at 3-hr intervals for 72 hr. An array of four 20-cm bongo plankton samplers fitted with 0.505-mm mesh nets was fished at depths of 0, 4, 15, and 30 m. A series of six tows was made at 2 and 6 m to further define the near-surface distribution of larvae. Temperature and salinity profiles were obtained before each tow. All fish eggs and larvae were sorted from these samples. The larvae have been identified and counted, and the bluefish larvae have been measured. The eggs have been identified as far as possible and counted. The catches were adjusted to account for differences in the amounts of water filtered, as indicated by flowmeters in the nets.

Six species of larvae were abundant enough to warrant an analysis of variance. All species showed significant differences in abundance with depth (Figure 18). Bluefish and frigate mackerel were most abundant 6 m below the surface. The other four species, fourspot and Gulf Stream flounders, butterfish, and hakes, were most abun-

NORTHERN SEA ROBIN



ATLANTIC MENHADEN



SUMMER FLOUNDER

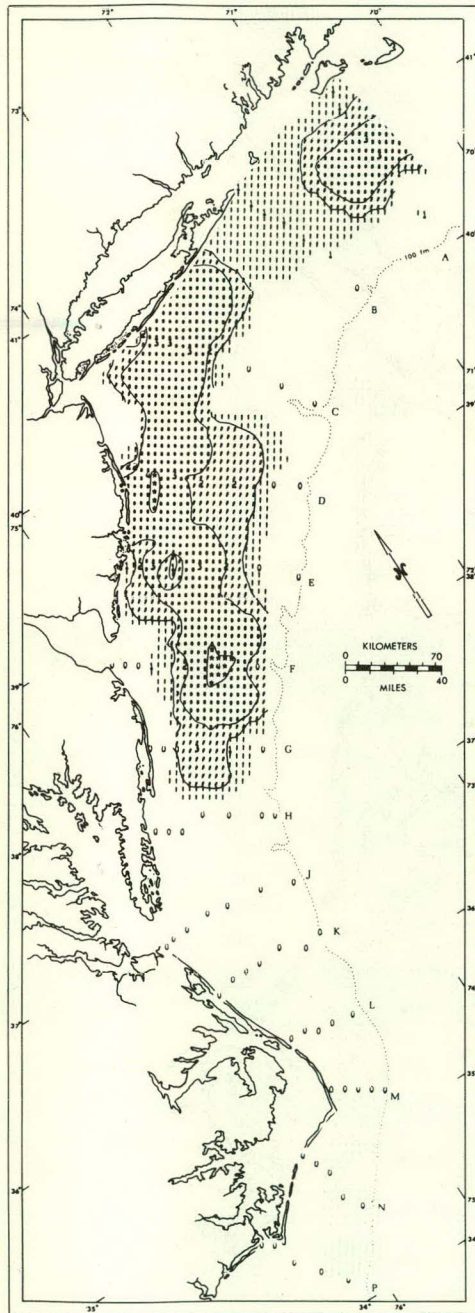
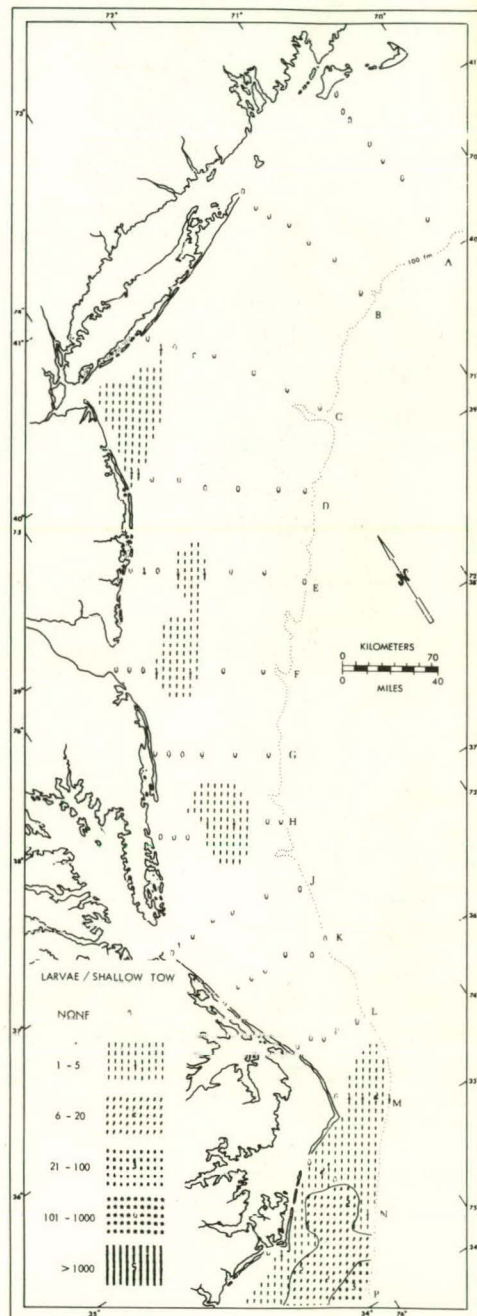
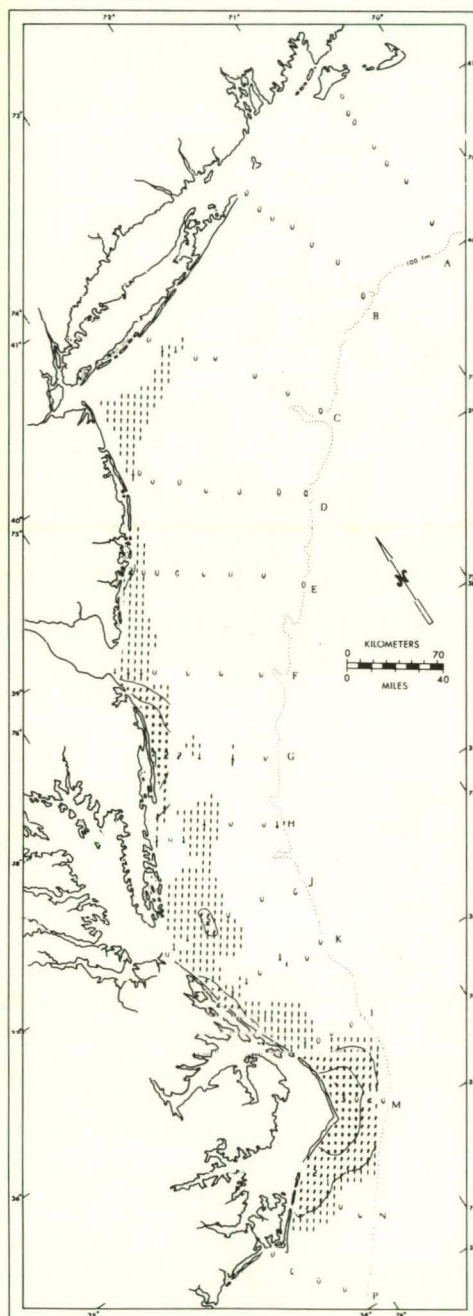


Figure 11. October distribution of northern sea robin, Atlantic menhaden, and summer flounder larvae.

NORTHERN SEA ROBIN



ATLANTIC MENHADEN



SUMMER FLOUNDER

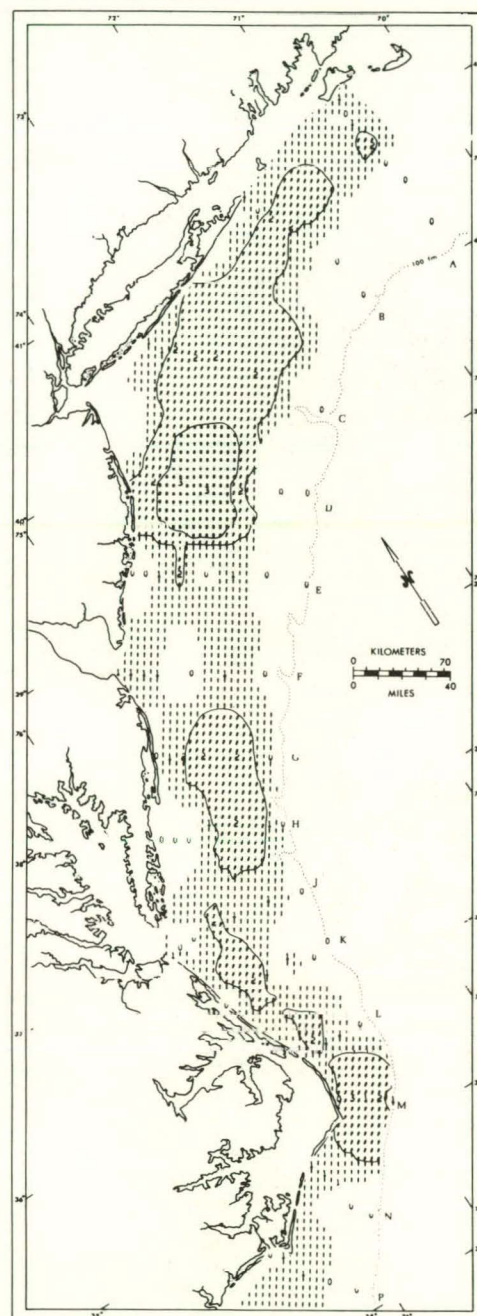


Figure 12. November distribution of northern sea robin, Atlantic menhaden, and summer flounder larvae.

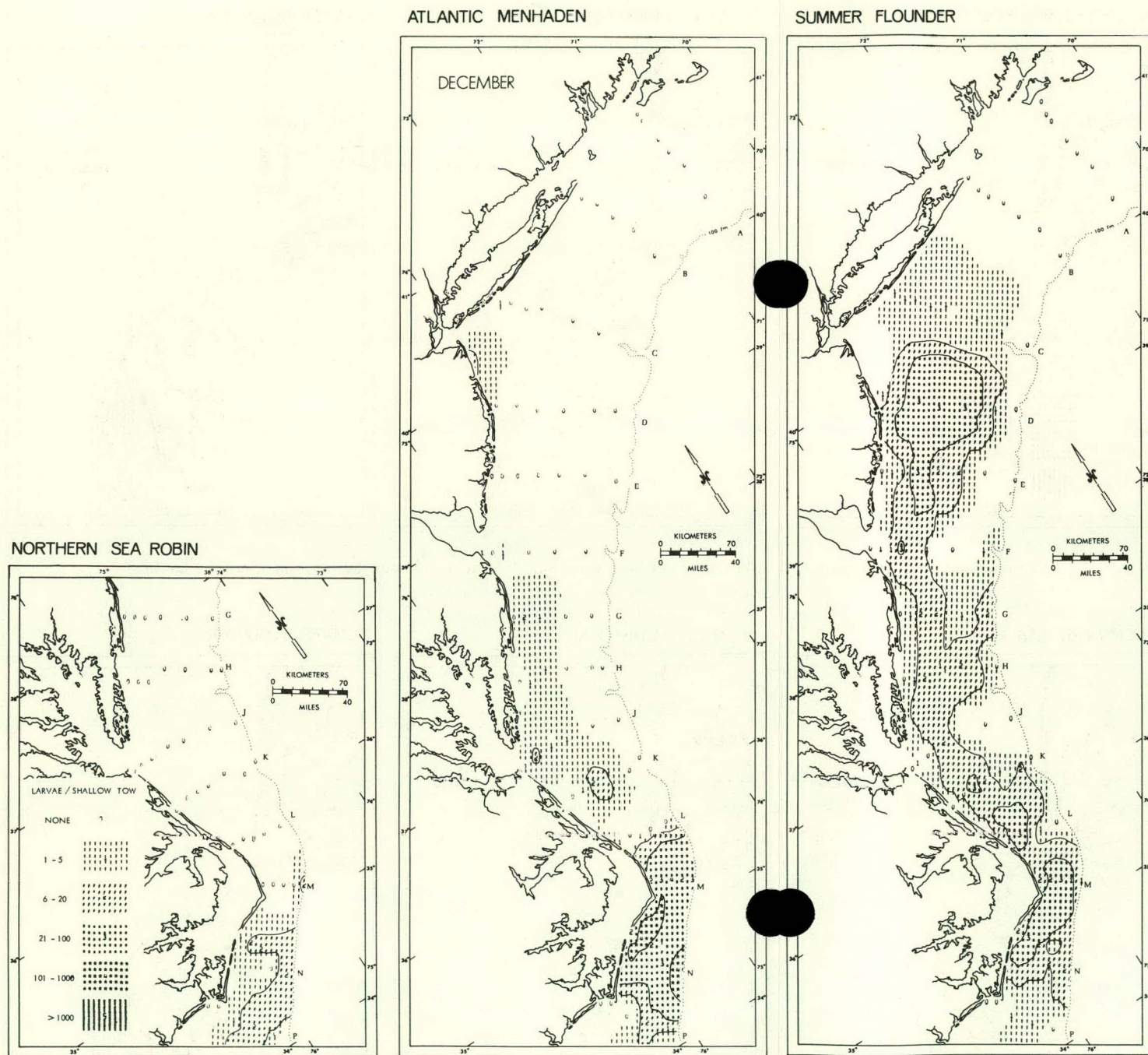
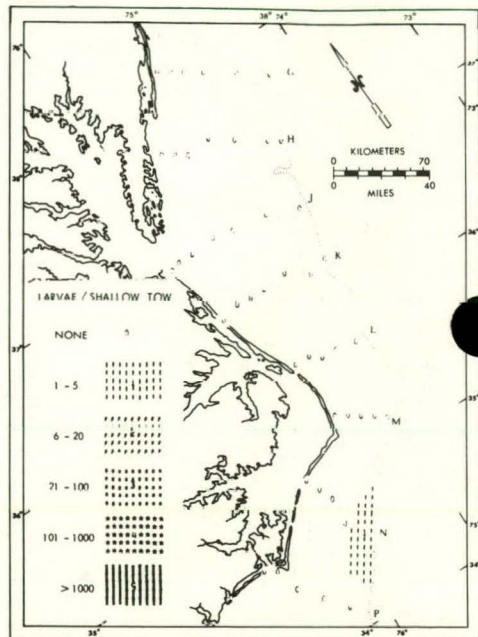
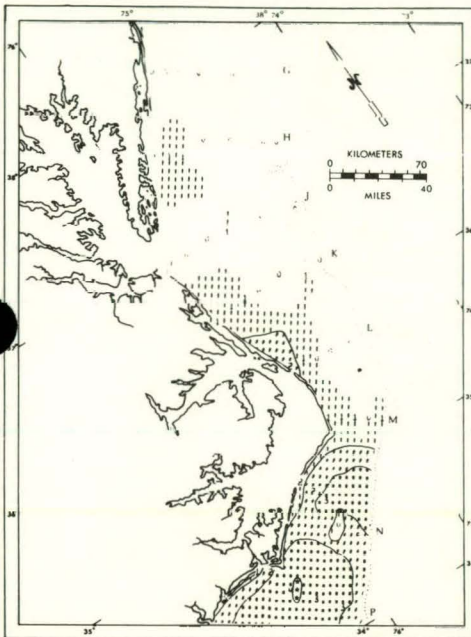


Figure 13. December distribution of northern sea robin, Atlantic menhaden, and summer flounder larvae.

NORTHERN SEA ROBIN



ATLANTIC MENHADEN



SUMMER FLOUNDER

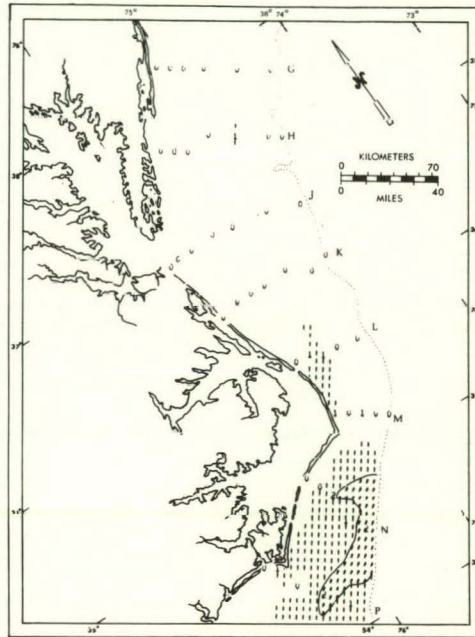
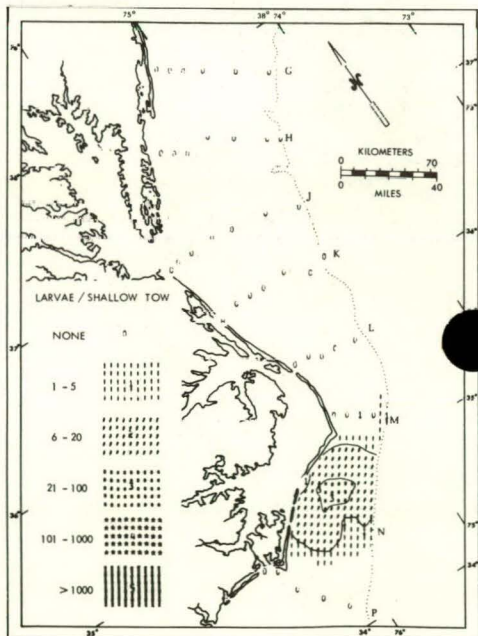
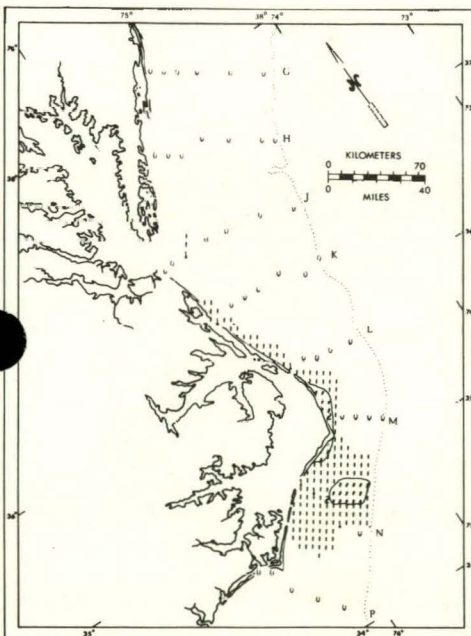


Figure 14. January-February distribution of northern sea robin, Atlantic menhaden, and summer flounder larvae.

NORTHERN SEA ROBIN



ATLANTIC MENHADEN



SUMMER FLOUNDER

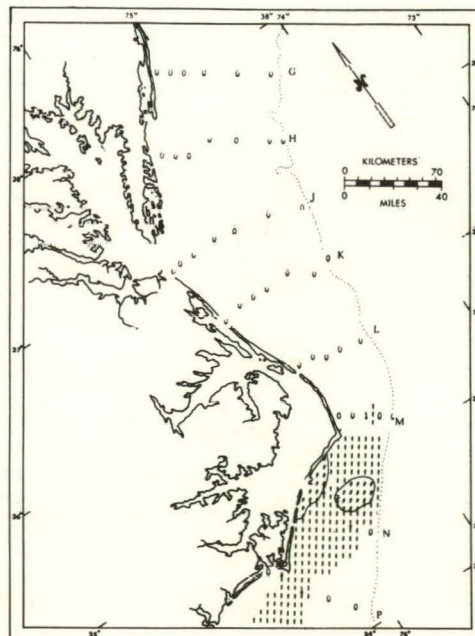
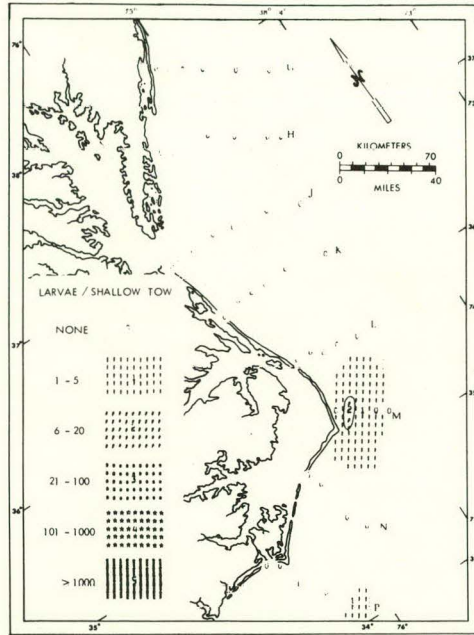
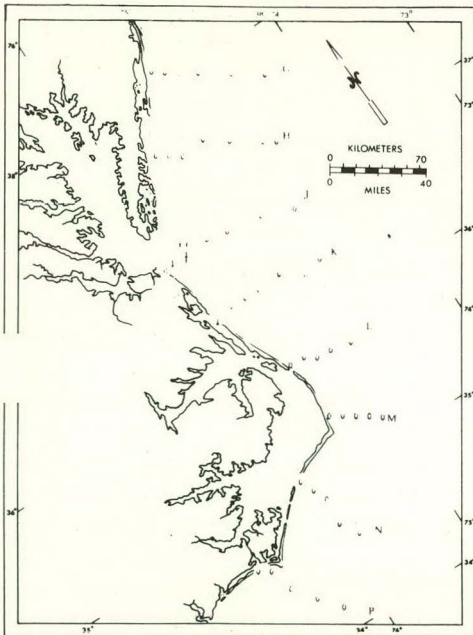


Figure 15. April distribution of northern sea robin, Atlantic menhaden, and summer flounder larvae.

NORTHERN SEA ROBIN



ATLANTIC MENHADEN



SUMMER FLOUNDER

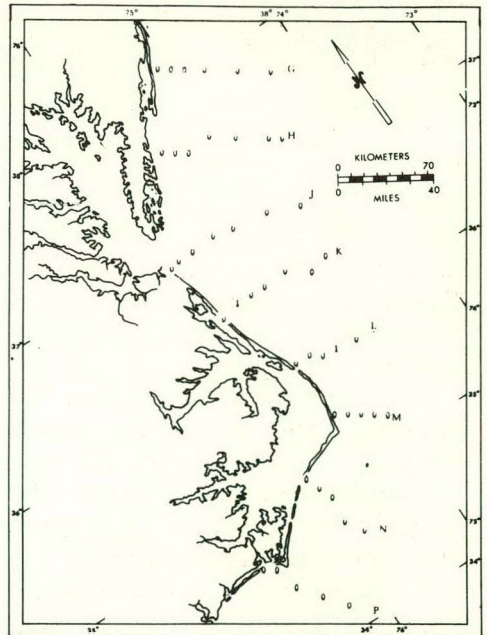


Figure 16. May distribution of northern sea robin, Atlantic menhaden, and summer flounder larvae.

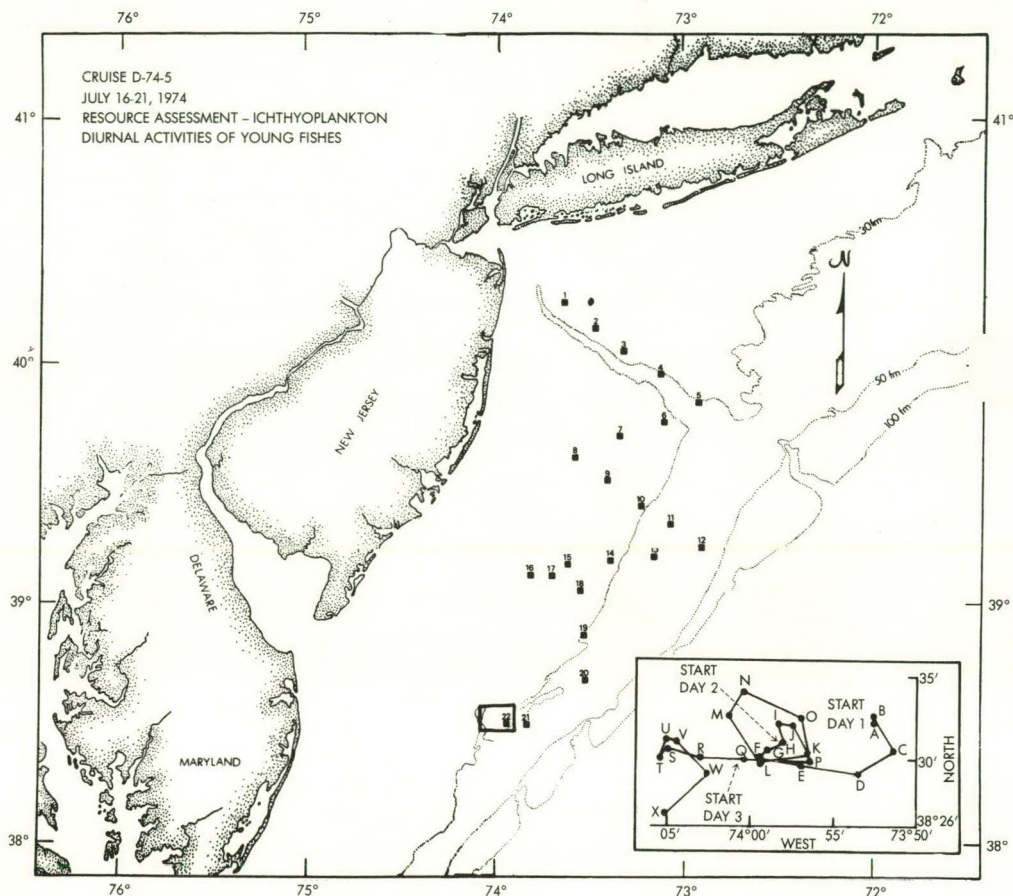


Figure 17. Search and drogue stations during vertical distribution study of bluefish (*Pomatomus saltatrix*) larvae, July 1974.

dant 15 m below the surface. The catches of bluefish, frigate mackerel, and fourspot flounder were different on the three days of the cruise. The diel-depth interaction was significant for all species, an indication that their vertical distribution varied with day and night.

It appears that these species, which occur as larvae in the same geographic areas at the same time of year, separate themselves vertically in the water column. All species undertake diel-vertical migration and occur closer to the surface at night than during the day. They apparently move horizontally at different rates and possibly in different directions, since the overall abundance of half the species changed during the 3-day sampling period.

Further studies on these larvae, and on others taken on similar cruises, are planned to show the role that types of food and time of feeding play in determining

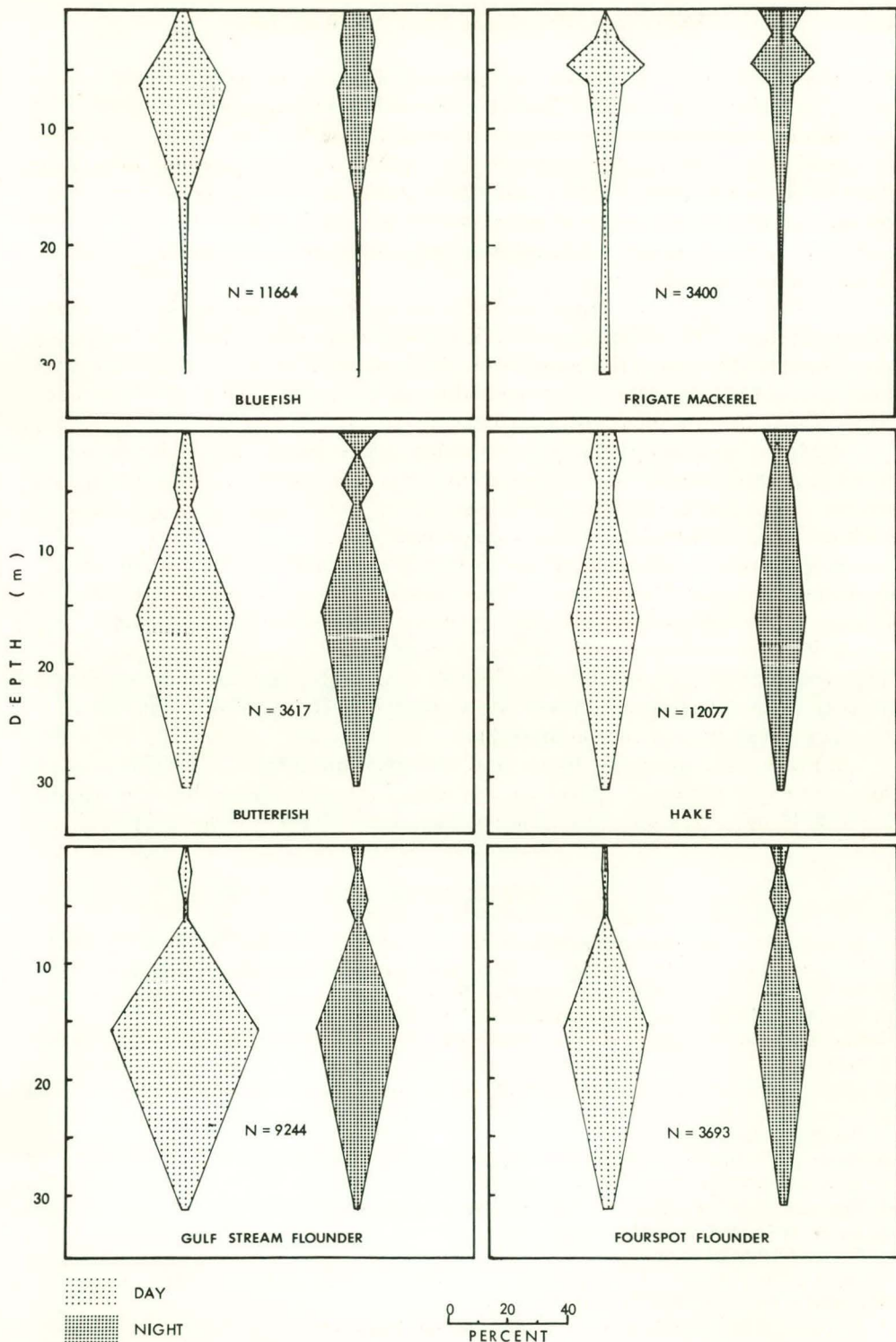


Figure 18. Day-night vertical distribution of bluefish and associated larvae collected during July 1974 study.

the vertical distribution of fish larvae. Although different species occur in the same area, it is anticipated that their feeding habits will limit competition for food.

As has been shown, we are still far from understanding the biology of a single species of fish in the Middle Atlantic Bight during its early stages. We cannot predict year-class strength or evaluate the effects of various environmental parameters on success of spawning. Nevertheless, at our present level of understanding, we can offer some generalizations that seem relatively important in measuring the impact of man's activities in this area:

1. There is no place or time not used by some fish in the Middle Atlantic Bight for spawning and larval development. Eggs and larvae of fish are found from the shore zone to the edge of the continental shelf and beyond. Several species center their area of early development in the bight, while others use the bight as southern or northern extents of their spawning areas.

2. Most marine fish probably do not seek a specific geographic site for spawning at sea. Rather, they seem to be influenced by temperature and other factors to spawn wherever they find themselves within broad geographic areas. Spawning areas for each species generally shift along the coast seasonally.

3. The sizes of year-classes of fish are largely determined by differential mortality during the egg and larval stages. These stages are quite vulnerable and sensitive to many forms of environmental stress, even conditions lasting only a few days.

4. Enormous quantities of planktonic eggs and larvae are produced over fairly large areas and long periods of time. To maintain stable populations, most of these must die before reaching adulthood. Man-induced mortality must be considered in light of the high level of natural mortality.

5. Fishes with dissimilar habits and economic importance as adults may be competitors or predators as larvae and thus influence each others' year-class strength. Density-dependent mortality may also occur during the larval period.

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DISCUSSION

GIBSON, C.I.: Would you speculate on the possible effect of a single power plant, or even ten power plants pumping at their own rate, on a fish population, given their distribution as you have shown it and their density in the water? Could you extrapolate this to a major oil spill covering several hundred square miles?

KENDALL: I have estimated the effect of a single plant off Long Island and I came out with essentially an insignificant mortality in terms of adult fish. I think that we might be able to say that ten such plants or insults would also have little effect. Indirect effects besides outright killing of the larvae present in the water column need to be considered, and I really don't know how we can even guess what those effects might be.

Fisheries and Renewable Resources of the Northwest Atlantic Shelf

RICHARD C. HENNEMUTH

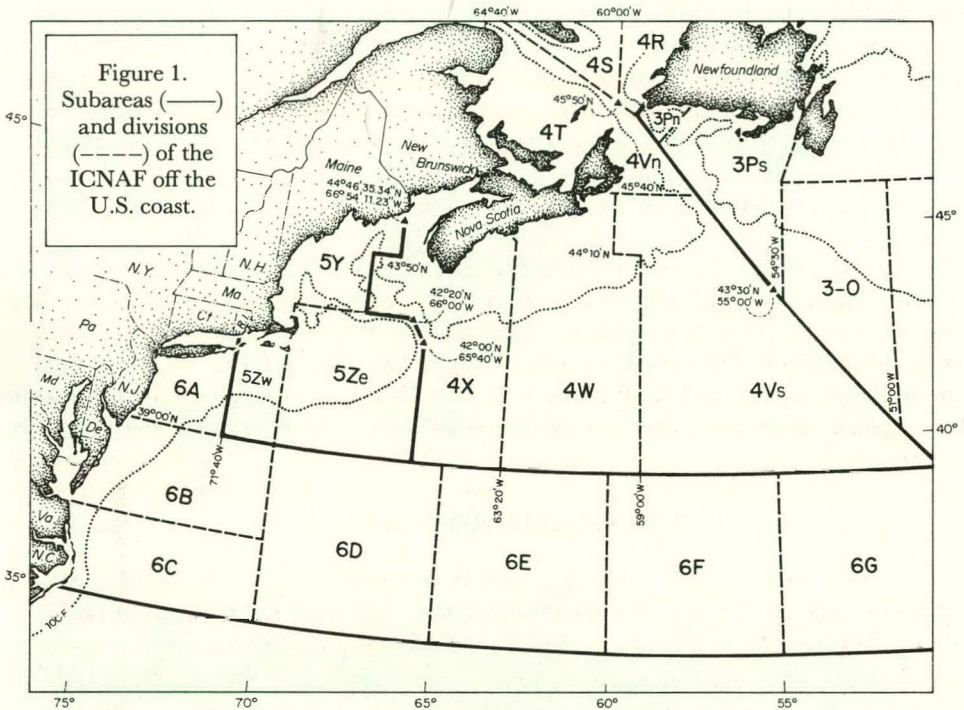
*Northeast Fisheries Center, National Marine Fisheries Service,
Woods Hole, Massachusetts 02543*

INTRODUCTION

The fishery resources of the Northwest Atlantic Continental Shelf are rich and varied. They are among the world's most productive. The United States and many other nations have a long and continuing tradition of development and management of fisheries based on this resource. The development of East Coast communities has been based on these renewable resources and is still dependent on them. More recently, the ever-expanding world requirements for protein and recreational opportunities have escalated the rate of use of these resources and the dependence on them. It is now generally accepted that the traditional fishery resources of the world's oceans are fully exploited; indeed, cutbacks and curtailment are the order of the day. The world's fishery planners are now looking toward nontraditional forms to supply the needs, mostly in the trophic levels below the traditional fish populations. Biologists are becoming concerned with evaluating the effects of such development, just as they were 30 years ago when the potential and effects of the rapid development of the now traditional finfish fisheries needed evaluation. Scientific research fell well behind fishery development then. In fact, adequate assessment of the effects of fishing on individual fish populations has approached reality only in recent years. We need now to significantly change our approach to include considerations of total biomass and interspecific effects. It has been well documented that not to do so means that an adequate biological basis for managing fisheries will not be developed.⁴

The development of nonrenewable resource extraction presents an even more difficult and challenging problem. Hitherto, the sea environment was taken for granted. It was assumed that only natural changes that were random or long-term, and to which the living resource was conditioned to respond to preserve itself, were involved, and that these effects were at least implicitly included in our models. Apparently that is not now the case. Man can now intercede in the natural system in a significant and rapid manner and is planning to do so. The effects of dumping, dredging, drilling, and spilling noxious substances are now becoming intertwined with natural changes and the effects of fishing. Ecosystem dynamics is difficult enough in the experimental, natural mode; faced with natural-unnatural interactions, I am sure that we will not be prepared for some years to provide the information and firm advice heretofore demanded.

Man so far has merely interceded in the natural way of things. Most of the actions (exploitation and regulation) are but tactics for short-term human realizations (gains, minimizing of losses). There is no underlying strategy in the current approach to utilizing our natural resources which reflects the necessity to understand and ac-



commodate nature's strategy. We are really hoping that the adverse things we have done can be undone, and that those that cannot be undone will not make much difference. The ecosystem is relatively fragile with respect to man. The feedback loops within the ecosystem which serve as adequate controls for the reactions of the elements in the system do not seem useful for controlling man. They are either very long-term or masked by our technology.

Man is part of the ecosystem, but I am sure we do not want to wait for the inevitable natural feedback before we correct the effects of our development. I am reasonably certain we do not have to. We must, however, build the basis of understanding before taking significant actions if we are to circumvent such consequences.

We are only now determining the requirements for redressing the effects of overexploitation in the fisheries. We are not yet sure of the success of the remedial actions. But we are reasonably certain of one thing: The severity and time span of corrective measures as we see them now makes correction almost more than anyone is willing to undertake.

GEOGRAPHICAL AREA

This paper covers fisheries and resources in the region from Georges Bank and the Gulf of Maine southwest to Cape Hatteras (Figure 1). This region encompasses subarea 5 and statistical area 6 of the International Commission for the Northwest

Atlantic Fisheries (ICNAF). It is thus convenient for statistical purposes, but more importantly it represents an ecosystem within which the resources are rather well integrated. Much of what happens in one part of the area will affect the whole. There is some intermix of stocks across the southern border (menhaden, sea basses) and to the north, three significant stocks that migrate and are mixed (mackerel, pollock, and probably *Illex* squid). However, all the fish stocks, including the above, depend on sustained biological phases (spawning, feeding, etc.) within the region's waters.

The fishery and the resource are distributed primarily within the 300-m depth contour. This is well within 200 miles of the coast. The descriptions in this paper are based primarily on the area seaward of the 30-m contour to 300 m. This region covers $\approx 263,000 \text{ km}^2$. The nearshore area is important to the productivity and utilization of the resources, as I shall point out later. However, because of the data base the emphasis is on the outer continental shelf area, the primary concern of this meeting.

THE RENEWABLE RESOURCE BASE

It is convenient to divide the resources into two subgroups – the finfish (including squid), and the benthic macroinvertebrates. This is useful primarily because of fishery interests, but is also a natural division within the ecosystem.

Table 1

Species Harvested From ICNAF Subareas 5 and 6, 1973* (10^3 metric tons)

<u>Finfish</u>			
Mackerel	380	Skates	8
Menhaden	331	Angler	8
Herring	234	Sculpins	8
Silver hake	136	Haddock	6
Red hake	67	Sea robins	6
Cod	35	Squeteague	5
Yellowtail flounder	30	Striped bass	5
Butterfish	19	Summer flounder	1
Redfish	17	Argentines	3
Alcwife	16	Witch flounder	3
Dogfish	14	Bluefish	3
Pollock	13	White hake	3
Winter flounder	10		
Ocean pout	9	Other species (44)	< 3 ea.
<u>Invertebrates</u>			
Crabs	33	Sea scallops	55
Surf clams	196	Lobster	10
Squid	57	Shrimp	9

*ICNAF Stat. Bull. 23, 24-5 (1975).

Finfish

There are >200 species of fish in the region. Of these, ≈ 70 are routinely recorded in the commercial catch. In 1973 the reported landings of each of 26 species exceeded 3000 metric tons (Table 1). The landings do not necessarily reflect relative population magnitude and will change from year to year, depending on fishery objectives. Nonetheless, the relatively large amounts of a great number of species reflect the variety and diversity of the fish resource.

The variety provides an important element of choice for fishery endeavors, and also some problems, to be mentioned later. It also provides for a stable productivity over the years. Natural variations of the environment will not affect all species in the same way; indeed, what reduces the productivity of one may increase that of another.

The variety of species has developed because of the variety of niches in the region. This leads to a productivity that is not only stable but also rich (Table 2). Georges Bank undoubtedly provides one of the world's richest harvests at about 11 metric tons/km². However, because some of the fish caught there represent production from other areas, a fairer estimate for comparative purposes is one taken over the whole region, or from 3 to 4 tons/km². On this basis the North Sea would rate somewhat higher and the northeast Arctic and Grand Banks somewhat lower. The large harvest of menhaden has been excluded because it is restricted to the southernmost portion of the area. However, some part of its production is obtained from within the region. Adding this to the total yield would increase the rate to >5 metric tons/km². This calculation also excludes the recreational yield, which would increase the rate, perhaps by 50% or more.

The geographic distribution of the fish illustrates several important aspects. First, although some species, e.g., redfish and haddock, have a restricted distribution within the region, many of the major species are distributed throughout the entire

Table 2
Relative Yields From Atlantic Ocean Areas

Region	Area (10 ³ km ²)	Landings		Metric tons/km ²
		Period	Annual total	
Northeast Arctic ^a	1,300	1968	2,730,000	2.1
North Sea ^a	600	1968	3,360,000	5.6
Grand Bank ^a	290	1968	783,000	2.7
Georges Bank	70	1973	818,056 ^b	11.6
ICNAF subareas 5+6	263	1973	1,154,000 ^b	4.4
ICNAF subareas 5+6	263	MSY ^c	1,000,000 ^b	3.0

^aFrom L.M. Dickie.³

^bFinfish and squid, exclusive of menhaden (300,000 tons).

^cMSY = maximum sustainable yield.

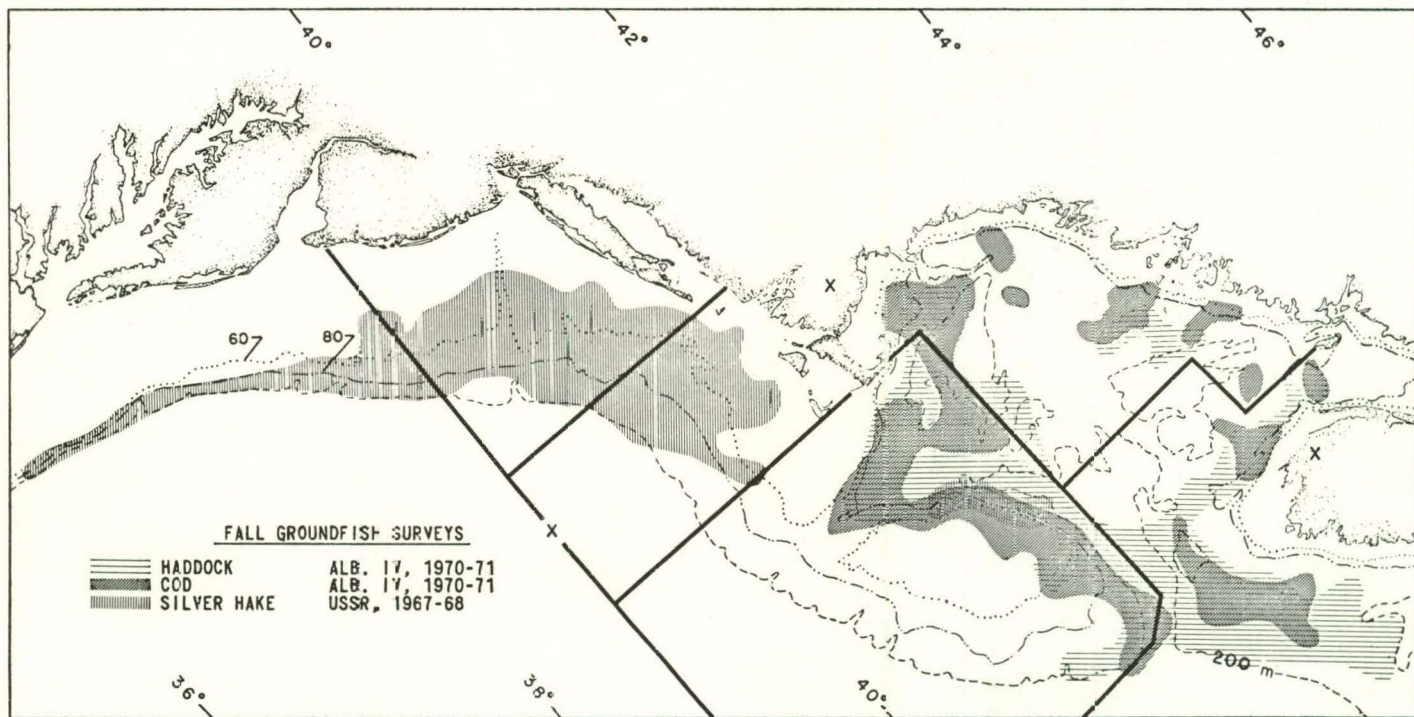


Figure 2. Geographical distribution of haddock, cod, and silver hake – spring.

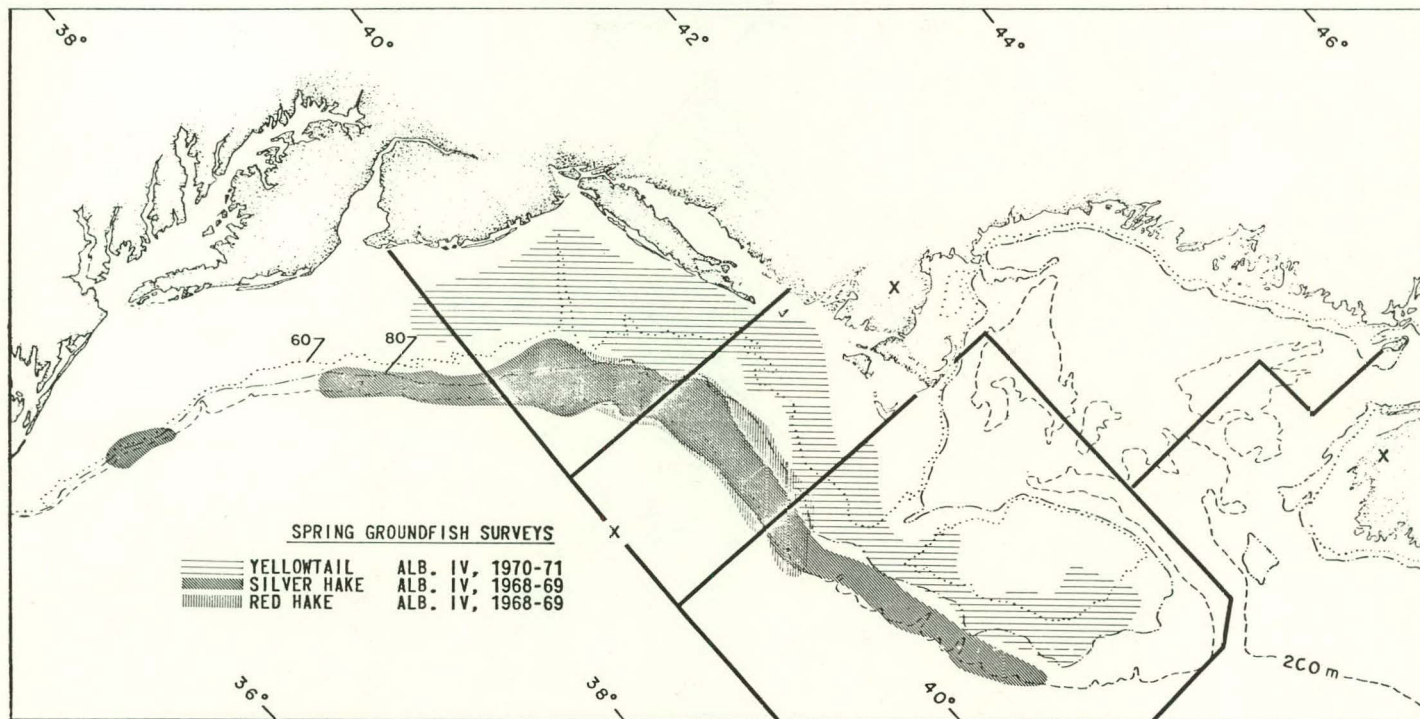


Figure 3. Geographical distribution of yellowtail, mackerel, and sea herring – spring.

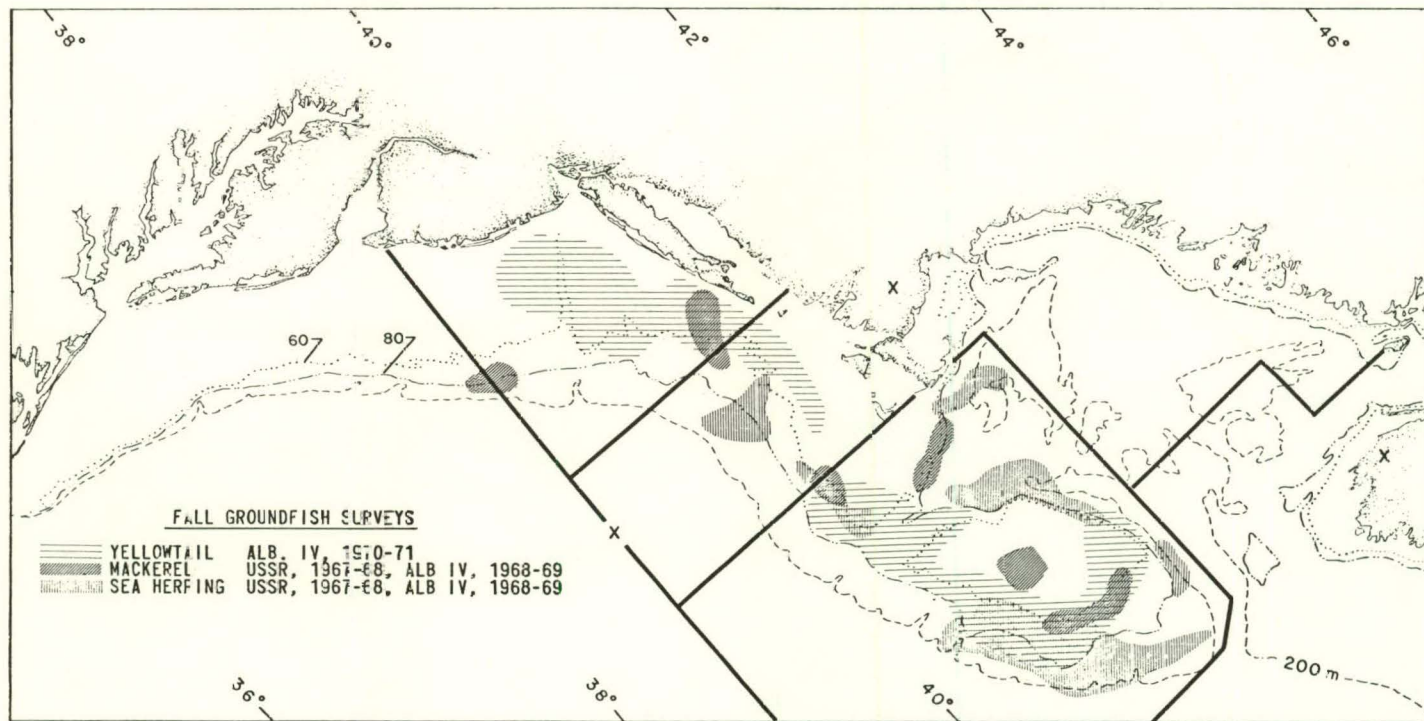


Figure 4. Geographical distribution of yellowtail, mackerel and sea herring – autumn.

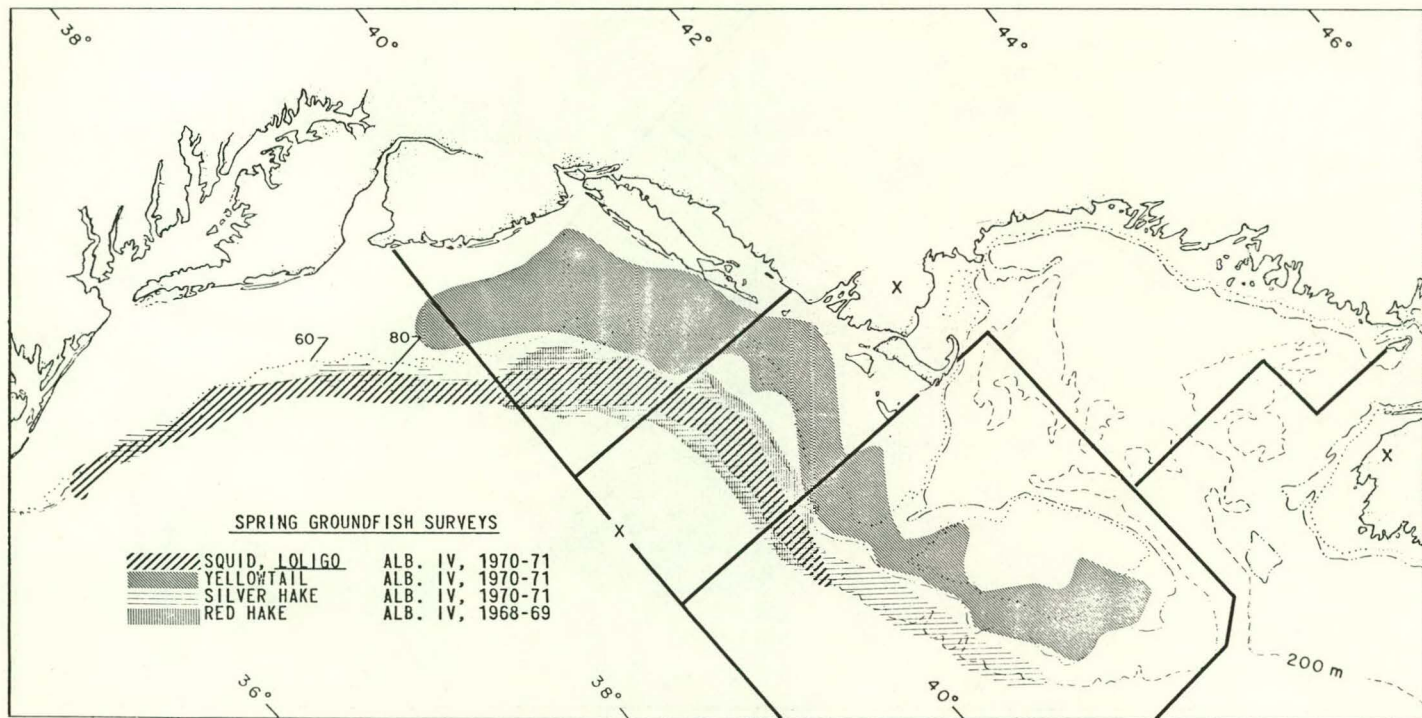


Figure 5. Geographical distribution of squid, yellowtail, silver hake, and red hake – spring.

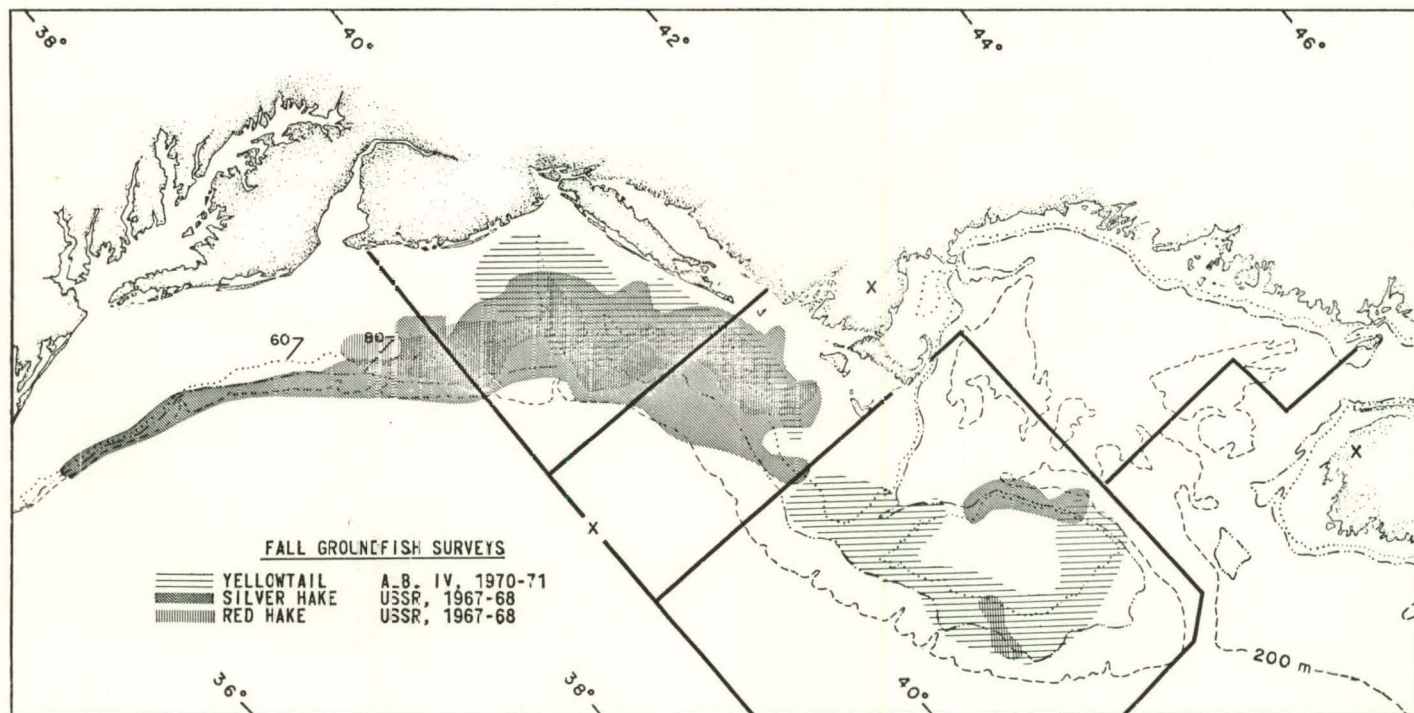


Figure 6 Geographical distribution of yellowtail, silver hake, and red hake – autumn.

region. This is due in some cases to mass movements, both coastwise and inshore-offshore, associated with spawning and feeding. Yellowtail flounder are found throughout the region at all times of year. Some species such as silver hake and red hake move from winter grounds near the 200-m isobath to nearshore depths of 30 to 50 m in the summer and autumn. Others, such as summer and winter flounders and the anadromous species, move farther inshore into rivers and estuaries.

The distribution of species such as mackerel, pollock, and probably *Illex* squid is even more extensive and includes areas outside the region. Part of the region's mackerel stocks appear to migrate as far north as the Gulf of St. Lawrence. Bluefin tuna are renowned for their extensive movements around the entire North and Mid-Atlantic.

Another important aspect is the mixture and overlap of species within the region. Some are actually intermixed, and many are separate but exist in close proximity. This leads to both biological and fishery-related dependencies which must be taken into account. These distributional aspects are illustrated in Figures 2 to 6, which are based on *Albatross IV* seasonal trawl surveys.^{5,6}

Benthic Invertebrates

The biomass of macrobenthic invertebrates on the continental shelf is also extremely varied and rich. The density is generally highest inshore and in shallow depths (0 to 20 m), decreasing by a factor of ≈ 100 at depths of 2000 m.

The standing crop is of the order of tens of millions of metric tons. Bivalves (shell weight) are the largest component, followed by echinoids and holothurians.¹⁰

At this time, estimates of productivity are not available but, as shown later, the benthic invertebrates produce a large proportion of the food eaten by fish.

Currently, only shrimp, lobsters, and scallops are harvested to any extent offshore.^{7,9} Exploitation of crabs (*Geryon*) is just beginning.¹¹ The geographical distributions of these animals are shown in Figures 7 and 8. The fishery closely follows this distribution. Blue crabs, clams, and oysters are exploited near shore in large quantities.

RECREATIONAL FISHING

The marine recreational fishery is conducted primarily from the beach, estuaries, or within a few miles of shore. No stretch along the coast is lacking in activity. Several species, such as striped bass and bluefish, are restricted in their distribution to the nearshore area and are harvested primarily by recreational fishermen. Many other fish of interest to sports fishermen, such as flounders, mackerel, and scup, are harvested by both sport and commercial fishermen. The seasonal inshore migrations of these latter species provide the sports fishing opportunity.

The magnitude of the noncommercial, inshore species is not well established, nor is the recreational catch. The available estimates indicate that this is about one million metric tons, or nearly the same as the commercial catch. Recreational fishing activity in the region is increasing rapidly. Fishermen now travel farther offshore in pursuit of large sharks, bluefin tuna, and, to a lesser extent, billfish. This is also a fast-growing segment of the fishery.

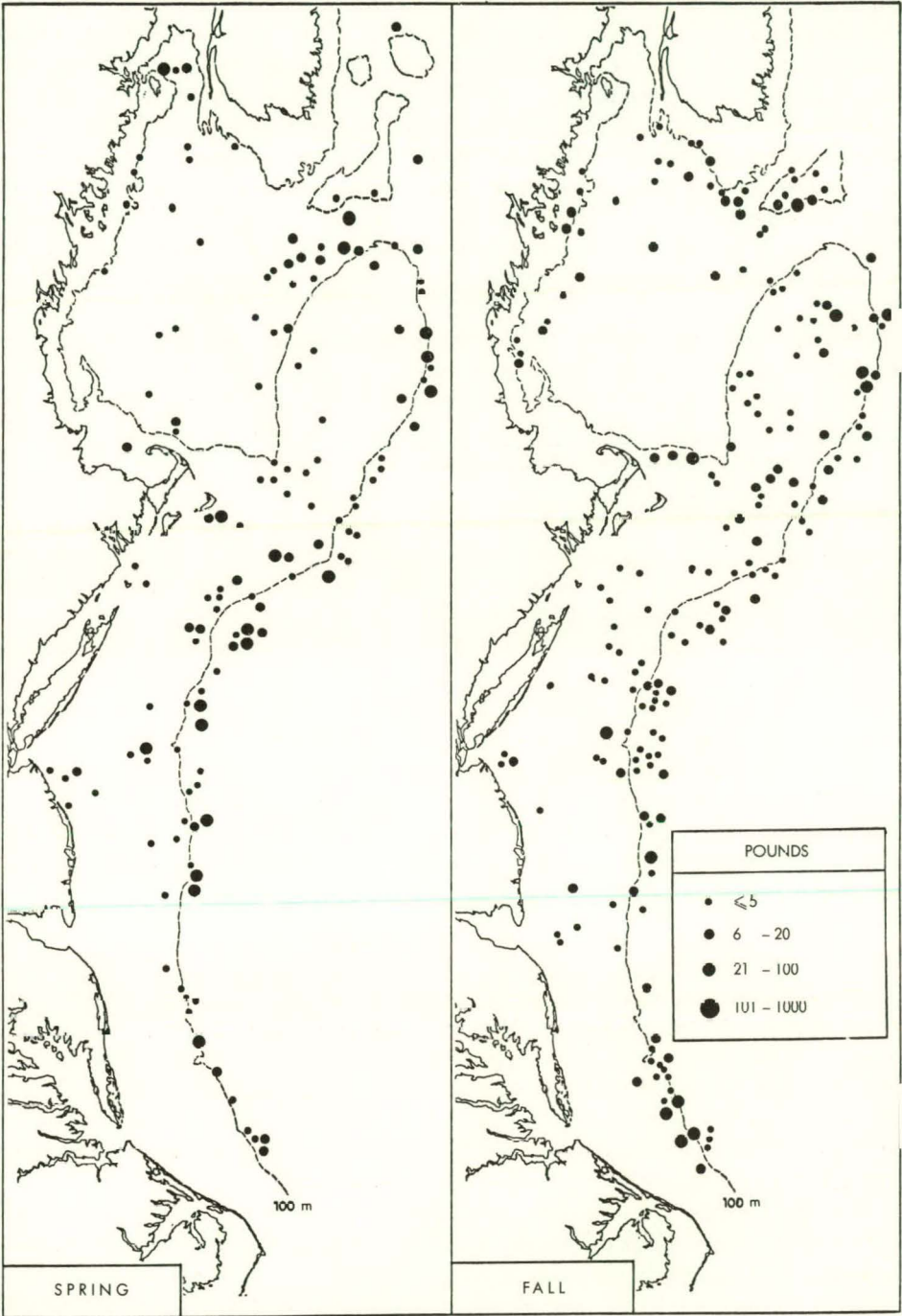


Figure 7. Geographical distribution of lobsters, 1973 and 1974.

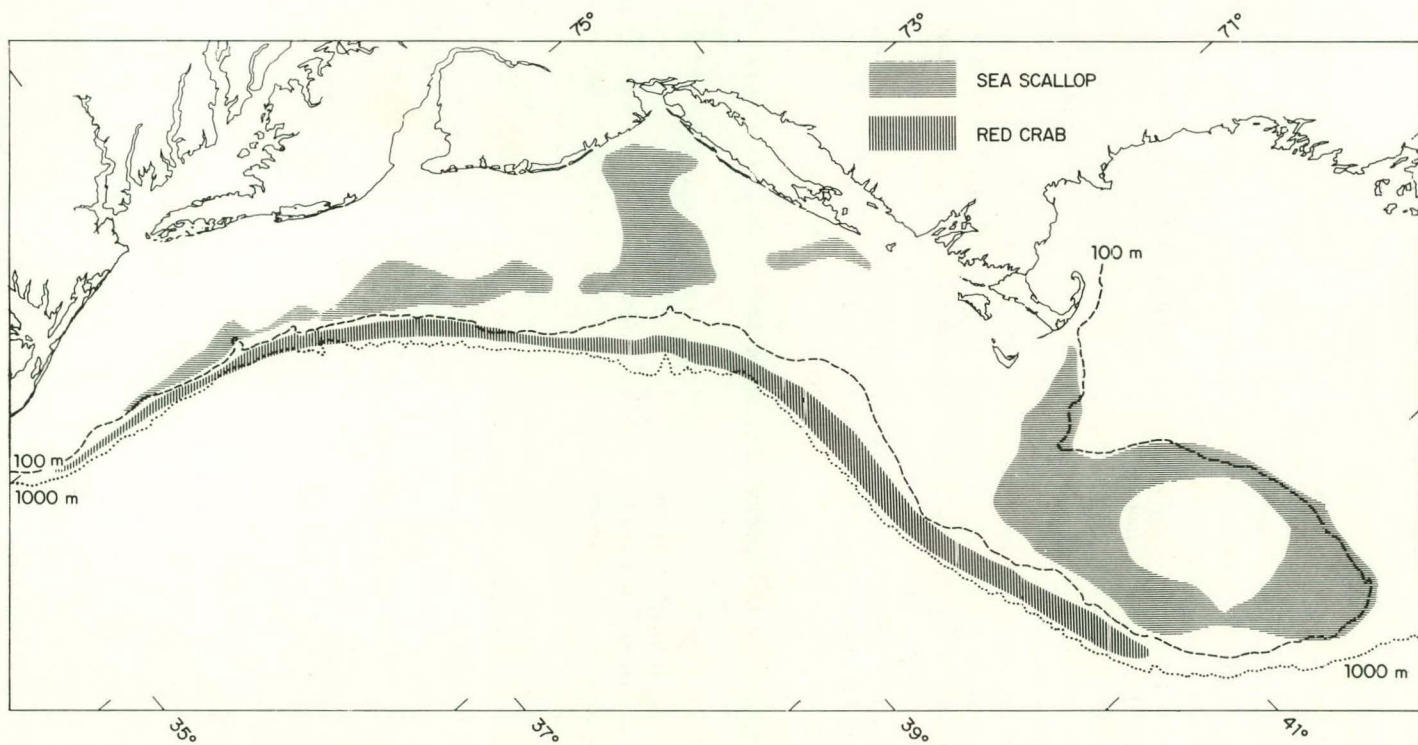


Figure 8. Geographical distribution of sea scallops and red crab.

THE COMMERCIAL FISHERY

Commercial fishing is by far the greatest activity on the outer continental shelf off the East Coast. From the mid-1800's, when a large mackerel fishery existed and the cod fishery began, until 1960, U.S. fishermen had the region almost entirely to themselves. Only a few Canadian vessels ventured into the area. Beginning in 1961, a few U.S.S.R. vessels were observed fishing, primarily for herring. The U.S.S.R. fleet expanded rapidly in the next few years and was joined by vessels from Poland, the United Kingdom, Romania, the Federal Republic of Germany, the German Democratic Republic, Spain, Japan, and several others (Table 3).

The total yield of finfish increased rapidly from 336,000 metric tons in 1960 to more than a million by 1971, and stabilized thereafter. The U.S. catch decreased 140% over the period.

The U.S. fishery was based primarily on the demersal species (cod, haddock, flounders), with an inshore herring fishery (Maine sardines). The long-distance fleet initially developed fisheries for herring and hake but also caught the other demersal species incidentally and directly when opportunity arose (Table 4). The haddock in 1965-1966 and yellowtail in 1969 were subjected to large pulses of fishing effort – a major factor in the severe and still existing decrease in stock abundance. Mackerel again became a major fishery in 1968, this time for the long-distance fleets. A squid fishery was initiated in the late 1960's by Japan, and now several countries are directing effort toward this species. The stock became fully exploited within three years.

Many other species entered the landings in large amounts for the first time because the long-distance fleets, unlike the U.S. fleets, did not discard them and even directed effort toward them as the fleets increased and the initially sought species became less abundant. Thus, dogfish sharks (22,000 tons in 1972), sea robins (9000

Table 3

Total Finfish and Squid Catches, Subareas 5 and 6, 1970-1973 (10³ metric tons)

Country	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	1971	1972	1973
Bulgaria										5.8	7.3	44.8	39.7	36.8
Canada	2.8	0.8	7.0	17.9	22.5	29.3	42.1	37.5	50.1	22.9	12.2	36.7	17.4	16.8
France													0.3	3.6
Germany (FRG)								20.3	71.5	73.8	92.8	60.0	32.9	38.3
Germany (GDR)							2.2	22.9	71.7	66.9	44.3	106.9	139.7	150.0
Iceland									0.3	12.8				
Italy													4.0	3.0
Japan								0.3	7.2	16.3	288.0	27.7	288.0	32.0
Norway										1.2				
Poland			0.5			3.4	16.1	41.3	92.5	76.0	147.1	219.8	206.7	190.5
Romania						2.0	3.4	1.8	2.9	0.6	2.7	8.7	5.3	7.1
Spain							9.5	16.2	18.0	15.5	8.1	13.3	19.7	22.2
U.S.S.R.		68.5	201.2	238.8	358.2	535.2	579.6	312.6	330.6	477.8	262.1	392.3	464.7	447.6
U.K.					9.2	5.0								
U.S.	333.8	284.9	378.2	394.1	395.4	379.2	335.4	298.8	289.7	259.0	234.6	213.5	183.0	203.0
Others					1.1	0.8	0.2	0.2	0.3	0.7	0.1	1.3	2.4	
Total	336.6	354.2	586.9	650.8	786.3	954.8	988.6	759.9	942.8	1029.3	840.3	1124.9	1144.6	1153.9

Table 4

Total Landings of Finfish and Squid From ICNAF Subareas 5 and 6, All Countries, 1960-1973
(10³ metric tons)

Year	Cod	Haddock	Silver hake	Herring	Mack- erel	Flounders	Squid	Red hake	Other fish	Total
1960	16.4	45.8	52.7	60.2	1.0	34.3	0.7	8.0	117.5	336.6
1961	19.6	51.9	24.5	94.1	1.1	35.8	0.5	12.3	114.4	354.2
1962	27.8	59.1	70.1	224.0	0.9	45.1	1.1	14.8	144.0	586.9
1963	31.0	59.7	153.6	171.5	2.5	55.3	2.1	8.1	167.0	650.8
1964	28.8	69.6	240.3	172.0	2.3	63.7	0.9	37.1	171.6	786.3
1965	42.5	154.7	344.3	87.7	4.5	64.6	1.3	84.4	170.8	954.8
1966	57.5	127.1	258.3	172.4	9.4	63.4	1.6	113.5	185.4	988.6
1967	42.7	57.0	124.1	255.2	22.9	61.3	2.6	60.7	133.4	759.9
1968	49.6	44.5	99.2	438.6	60.0	61.8	4.9	20.8	163.4	942.8
1969	46.6	25.0	99.0	365.2	113.2	87.6	9.9	55.0	227.8	1029.3
1970	34.0	12.9	54.6	291.0	209.6	64.2	15.4	12.5	145.5	840.3
1971	35.8	12.2	107.9	318.3	384.7	58.9	22.2	39.9	180.7	1112.5
1972	32.0	6.7	115.5	236.5	387.4	62.0	48.7	76.2	179.6	1144.6
1973	35.1	5.9	136.2	233.5	381.2	52.3	56.8	66.6	186.3	1153.9

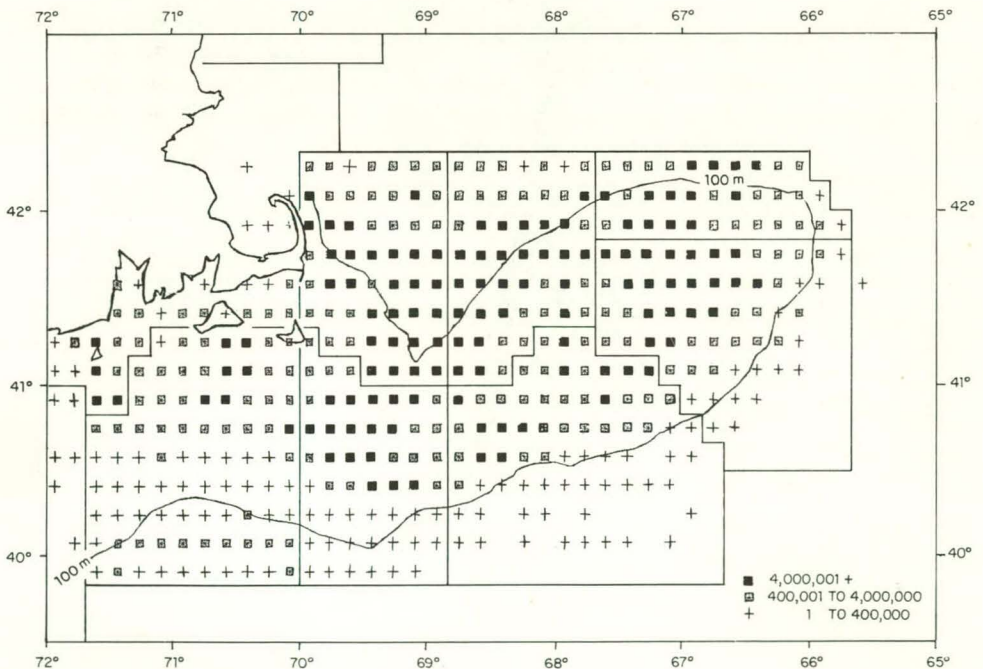


Figure 9. U.S. fishing activity, 1965-1974 (symbols indicate total haul, in pounds).

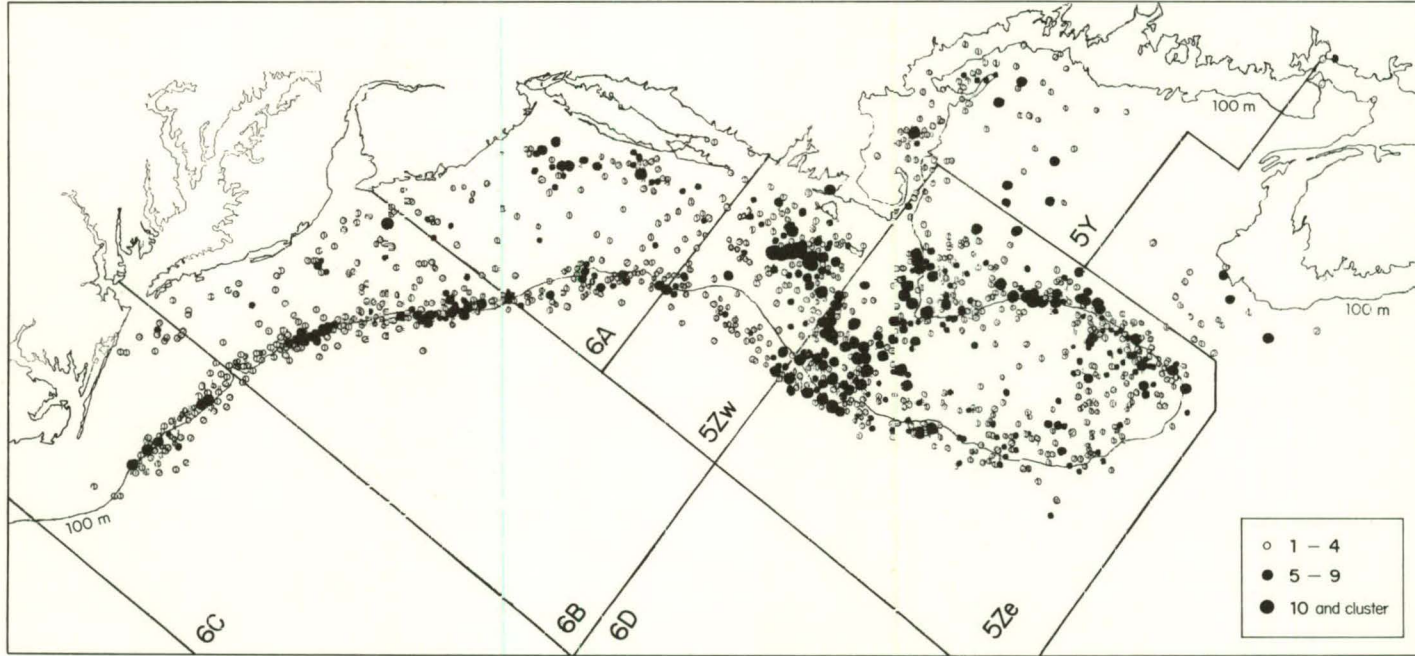


Figure 10. Activity of all foreign fleets, 1974, as observed in surveillance flights.

tons in 1968), argentines (33,000 tons in 1968 and 1972), and other "exotics" were reported in the foreign landings. The effects of the blanket of effort laid over the total region were thus becoming apparent even without comprehensive analysis.

The distribution of U.S. fishing effort in the northern part of the region (Figure 9) reflects the geographical ubiquity of fish and shellfish in the region. This pattern of fishing has not changed much from year to year for the last 25 years. The offshore lobster fishery has developed more effort along the 300-m depth zone in recent years, and the areas more distant from port have become less fished as the size of the fleet has decreased. The records of fishing effort to the south are not complete enough to provide such detailed distribution patterns. Much the same picture would be presented, but in lesser density.

What may be the peak of long-distance fleet activity is illustrated by the fishing locations in 1974 observed on surveillance overflights (Figure 10). Regulations and changes in fishery objectives (e.g., more directed fishing for squid) have changed the pattern to some extent compared with that of previous years, but the scope of activities in recent years is fairly well depicted.

The actual magnitude of fishing activity is given by national reports to ICNAF of days fished for 1973 (Table 5). A total of >90,000 days were spent fishing by all kinds of vessels. The days fished were just about evenly split between the U.S. and long-distance fleets, with $\approx 90\%$ spent in subarea 5.

A day fished by a 3000-GRT vessel is different from a day fished by a 150-GRT vessel, for various reasons. One of these is the fishing mortality imposed on the fish population. The efforts of various types of vessels have been standardized in terms of a U.S. 50 to 150-GRT vessel.¹ From 1961 to 1973 (Table 6 and Figure 11) the

Table 5
Fishing Activity* in Number of Days Fished in 1973

	Subarea 5	Subarea 6	Total	%
Bulgaria	809	184	996	1
Canada	9,449	-	9,449	10
France	81	47	128	<0.5
Germany (FRG)	690	169	859	1
Germany (GDR)	3,379	1,002	4,381	5
Italy (est.)		90	90	<0.5
Japan (est.)	446	1,032	1,478	2
land	5,378	658	6,036	7
omania	61	272	333	<0.5
Spain	1,710	735	2,445	3
U.S.S.R.	18,336	3,550	21,886	24
Subtotal	40,339	7,739	48,078	53
U.S.	41,146	1,393	42,539	47
Total	81,485	9,132	90,617	100

*As reported to ICNAF.

standardized total days fished have increased nearly sixfold, with the U.S. effort increasing in the early 1960's but decreasing by 1973 to less than the 1961 level.

MANAGEMENT

Regulation of the fisheries outside of U.S. jurisdiction, i.e., beyond 12 miles except for creatures of the shelf, at the present time is under the aegis of ICNAF. En-

Table 6
Standardized Effort for 1961-1973 (with adjustment for learning)

Year	U.S.	All others combined	Total
1961	47,054	3,272	50,326
1962	62,355	47,946	110,301
1963	65,121	40,905	106,026
1964	71,451	91,088	162,539
1965	70,523	95,488	166,011
1966	66,395	126,200	192,595
1967	56,972	88,794	145,766
1968	54,722	130,573	185,295
1969	51,600	174,794	226,394
1970	50,121	137,198	187,319
1971	47,120	211,982	259,102
1972	45,408	276,467	321,875
1973	45,403	232,959	278,362

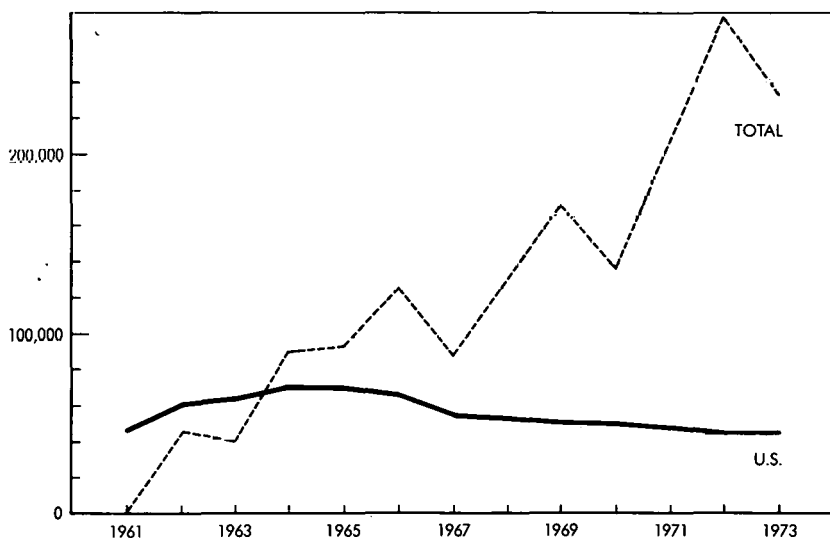


Figure 11. Total standardized days fished in subareas 5 and 6, 1961-1973.

Table 7
ICNAF Total Allowable Catch Limitations (TAC) in Subareas 5 and 6, 1976

Species (first tier)	TAC
Cod	43
Haddock	6
Silver hake	103
Red hake	42
Herring	68
Mackerel	254
Squid	74
Pollock	17
Yellowtail flounder	20
Redfish	17
Other flounder	20
Other fish	150
Total	814
All species (second tier)	650

forcement is the responsibility of each flag state. There are now 17 nations in ICNAF – all the major fishing countries except Cuba, which is expected to join soon.

The regulatory measures imposed on the countries fishing in the region are now the most extensive in the world. Regulations include minimum mesh size in trawls, minimum length of fish caught, restriction of fishing by large vessels to pelagic trawls over large areas, seasonal closures of certain areas and seasons for certain species, species catch quotas and total finfish catch quotas, both nationally allocated, an international inspection scheme, comprehensive record-keeping and reporting, and now proposals for registration of national vessels and direct effort regulation. Most of these regulations have become effective within the last four years.

Most significant from both the biological and the fishery viewpoint is the imposition of a total finfish and squid catch limitation. For the first time the yield, and hence the productivity, of an entire biomass is being regulated. This catch limitation system may be defined as two tiers (Table 7). The first tier is composed of the individual stock catch limitations. Each species or group of species is assessed independently to determine the appropriate yield, "appropriate" being defined in terms of maximization of yield on either a short or long-term basis (in some cases the catch is set low to provide for increases in stock size).

The total catch limit for all species is the second tier, which is now set at less than the sum of the species catch limits for two reasons. First, the mortality generated as by-catch must somehow be accounted for. Any given trawl haul anywhere on the shelf will generate mortality of more than one species. The sum of the effort associated with individual species assessments will not include the effort generated as by-catch. In 1971, for example, 38% of the total fishing mortality was estimated to

Table 8

Status of Finfish and Squid and Fisheries Biomass in Subareas 5 and 6
(10³ metric tons)

	Population (standing crop)		Catch	
	1975	MSY*	MSY	1976 TAC**
Cod	98	153	45	43
Haddock	53	267	50	6
Silver hake	330	580	150	103
Red hake	117	222	65	42
Herring	374	620	250	68
Mackerel	876	1104	250	254
Squid	200	229	75	74
Pollock	40	53	20	17
Yellowtail flounder	22	84	32	20
Other fish	391	604	187	187
Total	2501	3916	1124	814

*Maximum sustainable yield.

**Total allowable catch.

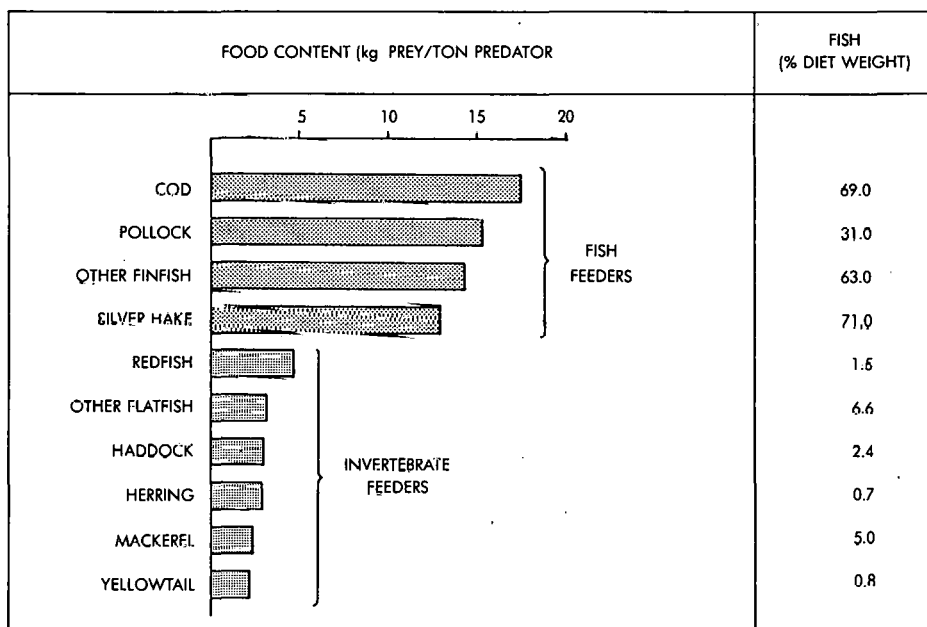


Figure 12. Consumption of selected stocks of fish by predator groups in the Northwest Atlantic off the U.S. Coast.

have been generated as by-catch. Linear programming techniques provide estimates of the reduction required to ensure that the by-catch mortality is accounted for.²

Second, the evidence available on species interactions (competition, predation) indicates that the total yield will be less than that estimated from the sum of independently assessed stocks. Admittedly, we do not have sufficient information to evaluate this effect in terms of tons of fish, but the alternative hypothesis is less likely in terms of general or specific biological knowledge. Assessment of the total yields, using the techniques applied to single stocks, has produced yield curves indicating a potential total smaller than the sum from species yield curves.¹ Interspecific effects are assumed to be included because they should be reflected in the data used to measure abundance changes and mortality.

The total catch limit of 650,000 metric tons (to begin in 1976) is the best estimate of yield that will allow the biomass to increase in subsequent years (at least seven will be required) to a level that can provide maximum yields on the average and in the long run.

The total finfish and squid population is now estimated at about 2.5 million metric tons, with the largest components being hake and mackerel (Table 8). The target is a population of ≈ 4 million metric tons, with proportionately more demersal species than at present. The total allowable catch in 1976, which represents replacement yield, is between 650,000 and 815,000 metric tons, with severely reduced catches of herring, haddock, and yellowtail flounder. At the target level, the maximum total catch will average about one million metric tons per year.

ECOLOGY

One approach to investigating the results of interspecific effects is to determine the food consumption pattern of the fish population. A first analysis⁸ indicates two distinct groupings based on fish and invertebrate consumers (Figure 12). The food consumption is expressed in kilograms per ton of consumer per feeding. This will underestimate the amounts consumed because some of the original stomach contents have been digested.

An analysis using these data and the biomass estimates in Table 8 indicates that about equal weights of fish and invertebrates are consumed. A 3.6-million-ton fish biomass consumes at least 19 million tons. The amount of fish consumed is about ten times the maximum average catch. These estimates, particularly with respect to absolute magnitudes, must be taken as only illustrative of the approach, but they do say two things: the fish eat much more fish than can be caught, and they depend heavily on the benthic invertebrates for food. Everybody knows this. We can only quantify our knowledge, so that the magnitude and importance of interactions can be applied to determine the effects of man's intervention.

SUMMARY

I hope that I have provided some basis for the following conclusions:

1. The shelf and waters off the New England and Middle Atlantic states must be considered as a well-integrated ecosystem. Small, selected areas cannot be considered independently in terms of evaluating effects of proposed or ongoing activities.

2. The rapid imposition on this ecosystem of massive activities and substances foreign to the natural course of events will produce persistent disequilibria. Severe and long-lasting actions will be required for a return to a previous state.

3. The effects cannot be predicted with any degree of certainty. The possible courses of events are almost infinite in relation to our ability to define and evaluate them.

4. Almost any activity of any scope on the shelf will create conflicts with fishing activities and with the objective of maximizing catch. It is only a matter of degree. The present information can define only what the conflicts could be, not what they will be.

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DISCUSSION

GIBSON, C.I.: Have you any historical data to indicate what is happening to fisheries activities off the Gulf of Mexico?

HENNEMUTH: That's a little out of my area. The fish catch itself has gone up over the period. What that means I don't know, but I think it means that they are fishing harder. It is difficult to interpret that particular fishery because the by-catch problem in the Gulf is estimated to be even more severe than it is in our area, and some estimates for the shrimp fishery indicate that they catch ten times as many finfish as shrimp and throw them away without reporting them. The data are not good enough in the long run to evaluate the population terms in that area. I know of no specific studies that indicate whether there might be an interaction with the oil.

Session IV

Characteristic Geological Processes of the Atlantic Continental Shelf

Chairman: J.R. SCHUBEL

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Some Aspects of Bottom Sediment Transport Mechanics on the Continental Shelf

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The general subject is much too large and too poorly understood to be comprehensively reviewed in the space of a few pages. On the other hand, the best time for a review is when a subject is under active study. Ample evidence in this case is found in the recent compilation of papers on sediment transport on the continental shelf, edited by Swift et al.¹ More than 20 investigators reviewed various aspects of the topic. In May 1975 the Office of Naval Research sponsored a one-day informal conference in Boston on the benthic boundary layer. It became apparent during the discussion that much remains to be learned about the benthic boundary layer and that the boundary layer on the continental shelf is even less well known.

Accordingly, in the present paper attention is focused on the structure of the boundary layer on the continental shelf and its role in the prediction of initial sediment motion. The well-known C_{100} prediction scheme of Sternberg² and his colleagues and the analytic studies of Smith and Hopkins³ are reviewed elsewhere and hence are not discussed here.

A brief discussion of initial sediment motion in uniform flow is given below by way of introduction.

Because of their practical importance in rivers and canals, initial scour or initial motion criteria have been under consideration for several centuries. The earliest approach utilized the idea of a critical velocity, above which sediment initially at rest on the bottom begins to move. One of the first proponents was Brahms.⁴ A well-known recent form is that due to Hjølström.⁵ The basic difficulty with this approach lies in the lack of a suitable definition for the bottom velocity U_b and the undefined relationship between the average velocity $\bar{U}$ and the bottom velocity (Graf⁶). The difficulty is emphasized when a turbulent boundary layer overlies the sediment.

The use of the bottom shear stress to provide a critical scour criterion is physically more meaningful. Modern usage is to express the shear stress in terms of $U_* \equiv (\tau_0/\rho)^{1/2}$, which has the dimensions of velocity. Although a number of propositions for predicting initial scour have been made, the most widely accepted appears to incorporate some form of the Shields function. According to Shields,⁷ the ratio between the critical shear stress and the resisting force of the sediment weight is a function of a Reynolds number referred to as the shear Reynolds number.

$$\frac{(\tau_0)_{\text{crit}}}{(\gamma_s - \gamma)d} = F \left(\frac{dU_*}{\nu} \right). \quad (1)$$

This functional relationship was experimentally verified by Shields and subsequent by many others, as indicated in the well-known Shields diagram (Figure 1). It may be stated that in general for smaller grain sizes the critical tractive force is less than for larger grain sizes, although considerable discrepancy is found among the various proposed relationships (Figure 2).

The discussion so far has dealt with noncohesive sediments such as sand or gravel, consisting of separable, identifiable particles. Typically fine-grained sediments, such as muds, are also found on river bottoms. Predominant constituents of these "cohesive" sediments are the clay minerals. The basic differences between cohesive and noncohesive sediments are listed below.

1. The predominant resisting forces in cohesive sediments are electrochemical; in noncohesive sediments the predominant force is gravity.

2. Unlike the predominant gravity force in noncohesive sediments, the electrochemical forces in cohesive sediments vary as a function of flow disturbance, water chemistry (including salinity), and thixotropy, which is time dependent.

3. Rather than individual particles, clusters of particles called flocs may be the basic units in the suspension mode of cohesive sediments. The size and settling velocity of the flocs depend on local turbulence intensity, sediment concentration, and salinity. Kranck⁸ shows experimentally that in a well-flocculated suspension grains larger than the mode settle as individual grains, whereas grains smaller than the mode settle as parts of flocs.

4. Water content may be important in determining resistance to scour, but its role is not clear. Small changes in water content correlate with large differences in erosion velocity.⁹⁻¹¹

Cohesive sediments form a major portion of the benthic region and are widespread over much of the continental shelf. In comparison with the noncohesive sediments, the mechanics of the transport of cohesive sediments are not well understood partly because of the complications described above.

An important complication with respect to both cohesive and noncohesive sediments is the presence of organic material, which may be a major constituent in the superficial layers. Organic material appears to have a dual effect. It may act as an adhesive material between the inorganic grains. On the other hand, long-chain molecules (polymers) may inhibit the onset of turbulence in the boundary layer.¹² The importance of organic material in sediment transport mechanics has only recently been recognized.^{13,14} Other factors may be locally important. An example is

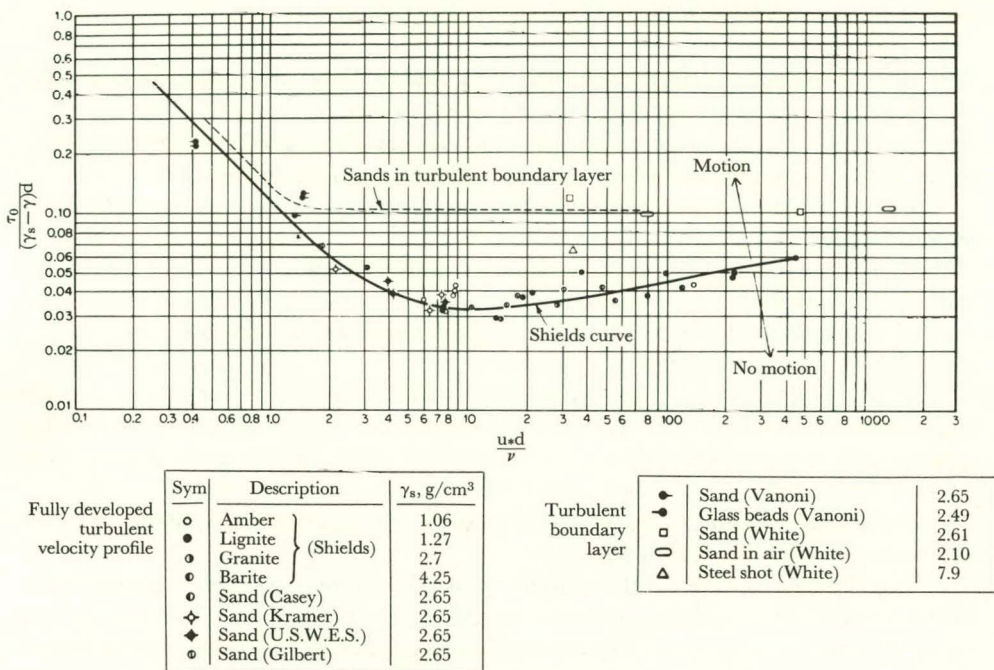


Figure 1. Shields diagram: dimensionless critical shear stress vs shear Reynolds number. (From Graf.⁶)

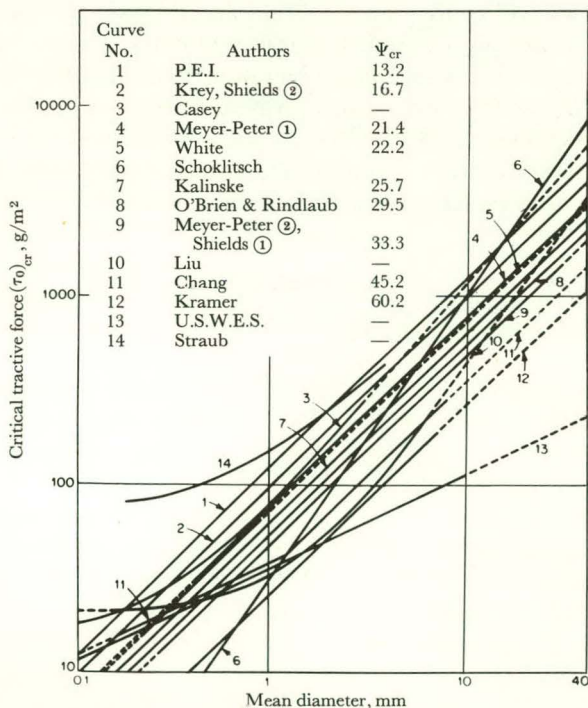


Figure 2. Critical shear stress as a function of grain diameter: a comparison. (From Graf.⁶)

“armoring”: sustained scour leaves behind a “lag deposit,” or residue, of coarser or denser particles, which form a surface layer, resistant to further erosion.

It is evident from the preceding discussion that reliable prediction of initial scour in rivers has not yet been achieved and that further study is needed.

If we turn our attention to the continental shelf, several significant differences should be noted.

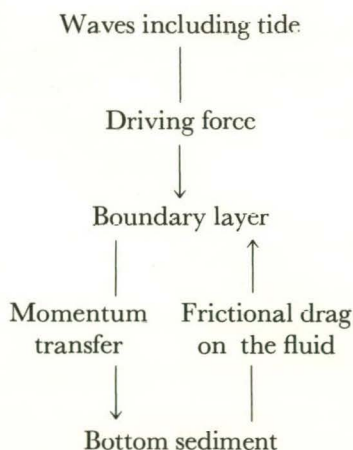
1. Approximations based on studies of channel flow are to some degree unsatisfactory. The confining walls in channels introduce a unidirectional effect that is absent on the open continental shelf. In contrast, the Coriolis force is significant over much of the continental shelf.

2. The assumption of uniform flow, implicit in most channel studies, cannot be made for flow on the continental shelf. As emphasized later, the bottom flow is primarily modulated by the tide with a period of ≈ 12 hr, and by wind waves with a period of ≈ 15 sec.

3. The salinity of the water on the continental shelf is an important factor in the transport of cohesive sediments.

It will be convenient in this paper to consider those aspects of sediment transport mechanics that are characteristic of the continental shelf. Attention will be focused on the manner in which momentum is transferred from the moving fluid to the bottom sediment.

Just above the bottom is a relatively thin, distinct region of fluid flow where viscous forces are important. This region is called the boundary layer. As will be shown later, the bottom boundary layer on most of the ocean floor is turbulent rather than laminar, and we will confine our attention to this case. The turbulent boundary layer is a special case of geophysically important flows, the quasi-parallel turbulent shear flows. The bottom boundary layer on the continental shelf is primarily driven by waves, ranging from tide to wind waves. An analysis of these yields a scaling and hence an expectation for the free stream velocity just above the boundary layer. Momentum is transferred through the boundary layer to the sediment, and under certain circumstances the sediment will begin to move. A flow chart of this sequence is shown below.



THE DRIVING FORCES: WAVES

Figure 3 is a representation of the energy distribution of the surface waves of the ocean in the form of a power spectrum.¹⁵ The spectrum is not computed from real data but represents an educated guess. In the present context we are concerned with the waves that contribute near-bottom velocities most of the time. Occasional large storm surges and tsunamis are excluded. The two energy peaks of interest are the astronomically forced tide waves with a period of ≈ 12 hr and the wind waves with periods from 1 to 20 sec. Evidence from the few field studies available indicates that these two frequency bands are of primary importance in driving the ocean boundary layer.

THE BOUNDARY LAYER ON THE CONTINENTAL SHELF

For the outer continental shelf, the flow just above the ocean floor may be described as a time-dependent, turbulent, Ekman-like boundary layer, analogous to the benthic boundary layer as described by Weatherly¹⁶ and by Wimbush and Munk.¹⁷ It may be described as Ekman-like since the expectation is that the Coriolis force is dynamically significant. As indicated earlier, waves contribute important driving forces. Thus the outer shelf boundary layer is time dependent principally with respect to tidal modulations of ≈ 6 hr. On the inner continental shelf the Coriolis force becomes dynamically of little significance, especially in the region near

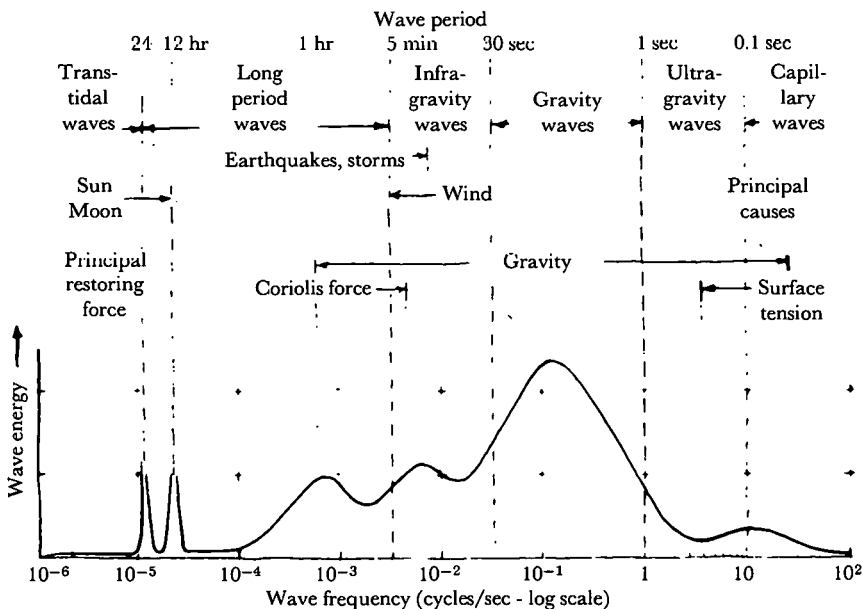


Figure 3. Schematic representation of the relative amounts of energy in waves of different periods. (After Kinsman.¹⁵)

the surf zone, where a second scale of time dependence of ≈ 10 sec becomes important as the wind waves increasingly affect the boundary layer.

A detailed description (and theory) for a nonstationary planetary boundary layer is not available. Therefore the stationary boundary layer is used to illustrate the basic structure. Modifications due to superimposed wave modulations will be indicated later. An example on a planetary scale of the stationary case is the atmospheric boundary layer. For a review of this relatively well-studied case, see Monin.¹⁸

The present state of knowledge about the boundary layer on the continental shelf is summarized in Table 1. Details of the ocean-bottom boundary layer (excluding nonuniform effects) are sketched in Figure 4 (a) to illustrate some of the properties listed in Table 1.

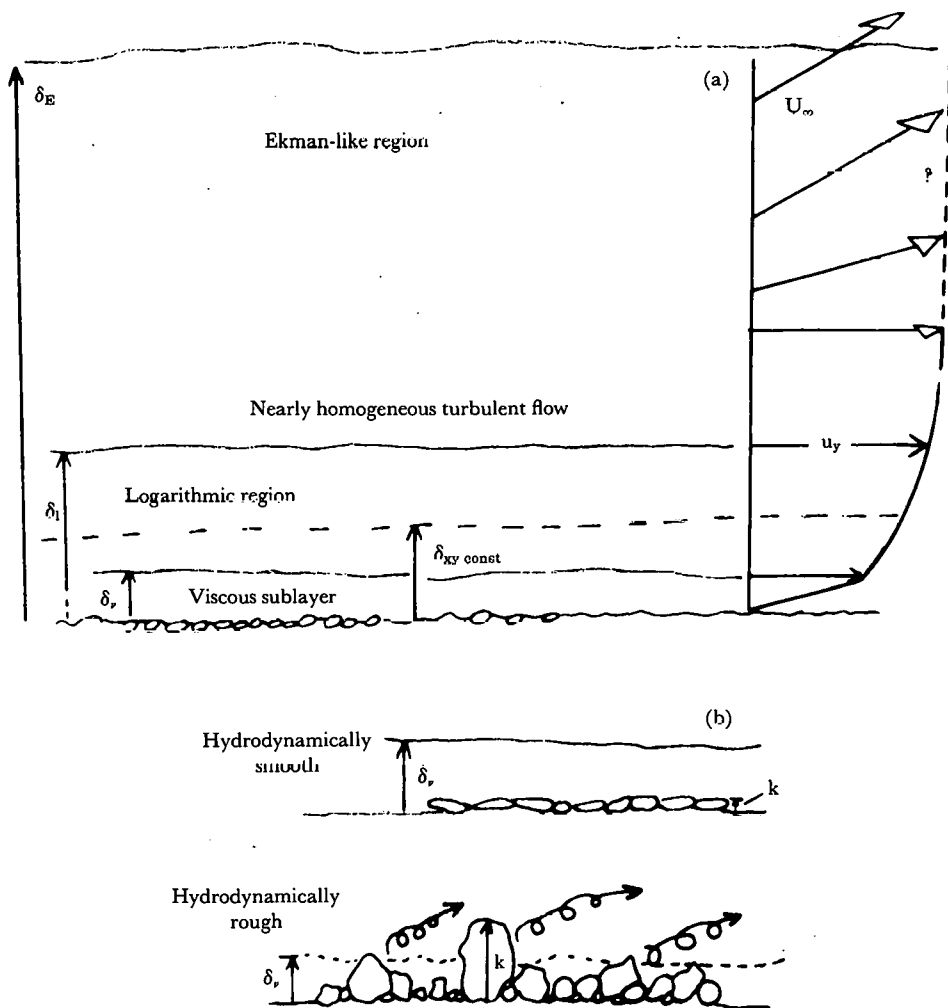


Figure 4. (a) Sketch of ocean-bottom boundary layer; (b) hydrodynamics of boundary layer.

Table 1
Representative Scales for the Boundary Layer

Physical property	Representative scale term	Typical value			
		Deep ocean	Outer shelf		Inner shelf
VELOCITY					
Free stream or geostrophic velocity (as appropriate)	V_g, U_∞, U_0	3.0 cm sec ⁻¹ (obs)	30 cm sec ⁻¹		40 cm sec ⁻¹
At 100 cm above bottom:					
A. Tide (max), linearized longwave	$a(g)^{1/2}/d^{1/2}$	1.43 cm sec ⁻¹ at $a=25$ cm $d=3$ km	10.1 cm sec ⁻¹ at $a=46$ cm $d=200$ m		27 cm sec ⁻¹ { at $a=61$ cm $d=50$ m { 20 cm sec ⁻¹ , local topography effect ²⁶
B. Wind waves		$d/L \gg 1$	$d/L=0.553, d=250$ m		$d/L=0.15$ $d/L=0.08$ $d=50$ m $d=20$ m 159 367
Storm wave	Stokes 3rd order, nonlinear	$U_{c,t} \approx 0$	$U_{crest}=10$		
$H \cong 9.14$ m; $T=17$ sec; $L_0 \cong 450$ m; calc at $z=1$ m			$U_{trough} = -10$ $\Delta(U_c - U_t)=0$		-144 -167 (15) (200)
Medium wave			$d/L=0.502, d=50$		$d/L=-0.14$ $d/L=0.09$ $d=10$ m $d=5$ m 64 120 -58 -70 (6) (50)
$H \cong 1.5$ m; $T=8$ sec; $L_0=100$ m; U , cm sec ⁻¹ ; d , meters; calc at $z=1$ m		$U_{c,t} \approx 0$	$U_{crest}=5$ $U_{trough} = -5$ $\Delta(U_c - U_t)=0$		
U_*	$(\tau_0/\rho)^{1/2}$	0.1 to 0.2 cm sec ⁻¹ (obs)	smooth 0.5	rough 1.3	3.0
LENGTH					
δ_ν , thickness of viscous sublayer	$12\nu/U_*$	2 cm	0.3 cm	0.1 cm	0.05 cm
$\delta_{\tau, const}$, thickness of constant stress layer	$0.2U_*^2/U_\infty f$	7 cm at 40° lat.	smooth 4 cm	rough 9 cm	?
Thickness of Ekman layer	$\delta_{E\ lam} \approx (\nu/\frac{1}{2}f)^{1/2}$ $\delta_{E\ tot} \approx k(U_*/f)$	2 cm 5 cm	17 cm 21 m 55 m		? ?
Thickness of logarithmic layer	$\delta_l = \bar{U}/U_\infty \approx 0.99$	1 m (obs) to 4 m (obs)	?		??
Bottom roughness (k =sand diameter)	smooth: $k < \frac{1}{3}(12\nu/U_*)$ critical: $k = \frac{1}{3}(12\nu/U_\infty)$ rough: $k > \frac{1}{3}(12\nu/U_*)$	$k < 0.7$ cm, e.g., clay, mud $k \approx 0.7$ cm, organic mounds, tracks $k > 0.7$ cm, manganese modules	$k < 0.1$ cm, coarse sand, mud	$k < 0.1$ cm, fine sand, mud	$k < 0.05$ cm, very fine sand, mud $k > 0.05$ cm, fine sand, sand, gravel

Table 1 (Cont'd)

Representative Scales for the Boundary Layer

Physical property	Representative scale term	Typical value		
		Deep ocean	Outer shelf	Inner shelf
TIME				
Entire Ekman layer	$2\pi/f$	$\frac{1}{2}$ day	$\frac{1}{2}$ day	
Logarithmic layer	z/U_*	at $z = 1$ m, $U_* = 0.2$ cm sec ⁻¹ , 8.3 minutes	200 - 75 sec	30 sec
Wind waves	1. $(U_c - U_t/L) \cdot \sigma^{-2}$ 2. T	≈ 0	≈ 0 2 - 20 sec	large wave 0.3-6 sec medium wave 0.14-2 sec 2-20 sec
MISCELLANEOUS				
Steady-state total veering in Ekman layer*	$\sin^2 \phi_0 = A c_f$	13° at $A = 25$	?	??
Turbulence criterion for Ekman layer	$Re_{crit} = U_\infty \delta_{E\text{lam}}/\nu \approx 100$	$Re = 3 \times 10^3$, turbulent	turbulent	turbulent
Friction coefficient	$c_f = (U_*/U_\infty)^2$	1×10^{-3} at $U_\infty = 3$	2×10^{-4} (sm); 2×10^{-3} (rgh)	6×10^{-3}
τ_0 , Bottom shear stress	ρU_*^2	0.2 dyne cm ⁻²	$\tau_{rough} = 2.65$ obs (1.69 calc) $\tau_{smooth} = 0.8$ obs (0.25 calc)	(9.0 calc)
Coriolis parameter	$f = 2\Omega \sin \phi$ Ω = av velocity, daily rotation of Earth $= 7.29 \times 10^{-5}$ rad sec ⁻¹	Lat. $\phi = 25^\circ$, $f = 6.162 \times 10^{-5}$ rad sec ⁻¹ Lat. $\phi = 40^\circ$, $f = 9.372 \times 10^{-5}$ rad sec ⁻¹ Lat. $\phi = 45^\circ$, $f = 10.31 \times 10^{-5}$ rad sec ⁻¹		
Molecular viscosity	ν varies with temp. at salinity 35 ‰	at 0°C , $\approx 1.9 \times 10^{-2}$ cm ² sec ⁻¹	at 10° , ≈ 1.4	at 15° , ≈ 1.2
Eddy viscosity	$K = U_* Z$ in constant stress region of bottom layer	at $\kappa = 0.4$, $U_* = 0.1$, $Z = 1$ m, $K \approx 3.2$	?	??
Ellipticity of fluid particle trajectory in x-y plane	$\frac{\text{transv. axis}}{\text{long. axis}} = \frac{f}{\text{tidal freq.}}$	0.64 at lat. 40°	0.64 at lat. 40°	??
Rossby number	$R_0 = U_\infty/\Omega L$	at $L \gg 10$ km, $R_0 \ll 1.0$ Coriolis force important	at $L > 10$ km, $R < 1.0$ Coriolis force present	at $L \approx 1$ km, $R > 1.0$ Coriolis force insignificant

*A = experimental constant.

DISCUSSION OF TABLE

Velocity

Values for the free stream velocities U_0 and U_∞ or the geostrophic velocity V_θ in the context of the present paper represent the velocity just above the boundary layer. Since we are ultimately concerned with sediment transport, the appropriate velocity is that just above the logarithmic region in Figure 4(a), i.e., at the base of the Ekman region. In shelf areas in which the bottom Ekman layer is well developed, the velocity at the base is expected to be less than that at the top. However, an expression for the velocity decrease is not available for the time-dependent case.¹⁶ The relation between the Ekman layer and the logarithmic layer is discussed by Csanady.¹⁹

In any case, the representative velocities must be obtained from actual measurement. This is difficult to do in the field since the velocity at the top of the boundary layer asymptotically approaches U_∞ . In Table 1 the value of 3 cm sec⁻¹ for U_∞ is taken from observations by Wimbush and Munk.¹⁷ Although Weatherly¹⁶ reports 10 to 20 cm sec⁻¹ for the Straits of Florida in the vicinity of the Florida Current, Sternberg²⁰ finds an average of 3 cm sec⁻¹ off the California coast at depths of ≈ 3.5 km.

It appears that the nature of the bottom topography and the presence or absence of deep currents must be specified to obtain meaningful representative values of U_∞ for the benthic region.

The outer shelf and inner shelf values are somewhat arbitrary but are close to those observed by Lesht et al.,²¹ Heathershaw,²² and Kachel and Sternberg.²³

The friction velocity $U_* = (\tau_0/\rho)^{1/2}$ is the fundamental velocity scale for the boundary layer. Values for U_* are usually obtained through application of the Karman-Prandtl equation,

$$\frac{\bar{U}}{U_*} = \frac{1}{\kappa} \ln \frac{Z}{Z_0},$$

to the logarithmic portion of the boundary layer. Simultaneous measurements of velocity, $\bar{U}$, are taken from the top of the boundary layer (U_∞) to very near the bottom. Inferred values for U_* are gotten by using graphic methods to obtain Z_0 from the intercept of the straight lines in the $\ln Z$ speed profiles. Weatherly¹⁶ used a numerical least-squares fit to replace tedious data plotting. He also suggested a method for estimating U_* directly from the spectra of the velocity meter data.

Values for U_* obtained from calculations based on observed velocity profiles are ≈ 0.2 cm sec⁻¹ for the benthic boundary layer.^{17,20} In the presence of the Florida Current, Weatherly¹⁶ reports $U_* \approx 0.4$. Values for the outer shelf for U_* are taken from Lesser,²⁴ who gives an array for both smooth and rough categories in each of three sediment types. The inner shelf value is from observations by Kachel and Sternberg,²³ with an average of ≈ 3.0 . The benthic boundary layer is primarily driven by the semidiurnal tide in the regions where deep currents are absent.¹⁷ Even in the presence of a strong current, the tide is dynamically significant.¹⁶ On the continental shelf the tide is supplemented by the wind-wave orbital velocities that extend significantly to the boundary layer. Just seaward of the surf zone, the wind-

wave orbital velocities may dominate, but even here tide velocities may be significant. A first approximation to the maximum tide velocity just above the boundary layer is obtained by utilizing the linearized small-amplitude long-wave equation for the horizontal component of the orbital velocity. It is assumed that the envelope of the orbits is as in a shallow water wave (longitudinal axis $\simeq$ constant surface to bottom). The horizontal component of the orbital velocity is

$$U = \frac{a\sigma}{kd} \cos(kx - \sigma t), \quad (2)$$

and under crest,

$$U_{\max} = \frac{a\sigma}{kd} = \frac{a}{\sqrt{d}} \frac{\sqrt{g}}{c} \quad \text{for } \sigma = ck, \quad c = \sqrt{gd}. \quad (3)$$

Rearrangement of the above indicates that the ratio of the orbital velocity to the phase velocity is equal to the ratio of the depth to the wave amplitude. Calculations given in Table 1 show reasonable agreement with observed values except for the inner shelf. Values for the tidal amplitude were taken from Pekeris and Accad²⁵ for the open Atlantic and from Redfield²⁶ for the North Atlantic Continental Shelf. In the inner shelf region the dominant influence of local topography renders the first approximation ineffective.

Within the orbit of the tidal wave the fluid particle does not simply oscillate in the x - z plane; it also moves in an ellipse in the x - y plane, parallel to the bottom. This introduces an additional component for consideration of the near-bottom fluid motion.

The contribution of the relatively high frequency wind waves ($T < 20$ sec) to the bottom flow cannot be properly evaluated through the linearized small amplitude theory. This is partly because the excess of maximum forward velocity under the crest over the maximum return velocity under the trough does not appear in small amplitude theory. Realistic estimates of the maximum orbital velocities in the vicinity of the boundary layer require nonlinear finite amplitude theory. Over most of the continental shelf ($d/L > 0.05$) the Stokes finite amplitude theory is appropriate. In the region just seaward of the surf zone ($d/L < 0.05$), cnoidal theory appears to yield more satisfactory results.²⁷ The table of representative scales gives calculated values for $U_{\max \text{ crest}}$ and $U_{\max \text{ trough}}$. Two representative waves are chosen: a very large storm wave and a medium wave.

For third-order-approximation Stokes finite amplitude waves, the expression for the horizontal component of the particle velocity may be written as

$$U = C \left(F_1 \cosh \frac{2\pi S}{L} \cos \theta + F_2 \cosh \frac{4\pi S}{L} \cos 2\theta + F_3 \cosh \frac{6\pi S}{L} \cos 3\theta \right), \quad (3)$$

where F_1 , F_2 , and F_3 are functions of d/L and a/L and are tabulated by Skjelbreia,²⁸ $\theta = (kx - \sigma t)$, $S = y + d$, and d = still water level. For maximum forward velocity under the crest, $\theta = 0$; for maximum return velocity under the trough, $\theta = 180^\circ$. The values given in Table 1, this paper, were obtained with use of the tables of functions computed by Skjelbreia.²⁸

Length

Values for δ_v , the thickness of the viscous sublayer, $\delta_{\tau \text{ const}}$, the thickness of the constant stress layer, and $\delta_{E \text{ lam}}$, $\delta_{E \text{ turb}}$, thickness of the laminar and of the turbulent Ekman layer, were all calculated from the appropriate magnitudes of U_∞ , U_* , f , and ν given in Table 1.

As indicated earlier, the thickness of the logarithmic layer must be estimated from analysis of the near-bottom velocity profile. The criterion is that value $\ln Z$ where $\bar{U}/U_\infty \cong 0.99$. This may be interpreted as requiring a gradual departure from a straight line in the plot of an observed $\ln Z$ speed profile. Wimbush and Munk¹⁷ plotted U_* estimates at a given height against U_* estimates at a much lower height, presumably within the logarithmic layer. If the points fitted well to a 45° line, both heights were considered to satisfy the $\ln Z$ criterion. If the plot showed a consistent departure from the 45° line, the upper height was considered to be above the logarithmic layer.

When the diameter (k) of the sediment particles on the bottom is $< 1/3$ the thickness δ_v of the viscous sublayer, the boundary layer is considered hydrodynamically smooth. When the roughness elements approach the thickness of the viscous sublayer, or protrude above it, eddies and turbulent wakes will form (Figure 4b). Mixing occurs and the viscous sublayer is dissipated. The boundary layer is then fully turbulent for this hydrodynamically rough case. The typical values in Table 1 were calculated by using the appropriate value for U_* in the term $12\nu/U_*$. It can be seen that the admissible roughness height k for a hydrodynamically smooth bottom decreases in the direction of shallower water. Examples of sediment types are given to illustrate the roughness criteria.

Miscellaneous

The Ekman layer may be either laminar or turbulent. For the laminar case $\delta_{E \text{ lam}} \approx (2\nu/f)^{1/2}$ is a thickness scale. Thus the relevant Reynolds number for transition from laminar to turbulent is $Re = U_\infty \delta_{E \text{ lam}}/\nu$. Experimental studies by Fallér²⁹ and by Fallér and Kaylor³⁰ indicated the existence of inviscid instability waves (type I) at critical Reynolds number 125 and sporadic viscous instability (type II) at critical Reynolds number 70. These values are verified by Tatro and Mollo-Christensen.³¹ We thus can take $Re_{\text{crit}} = (U_\infty \delta_{E \text{ lam}}/\nu)_{\text{crit}} \approx 100$ as the turbulence criterion following Weatherly¹⁶ and Wimbush and Munk.¹⁷ Examination of Table 1 indicates that the Reynolds numbers for deep ocean and outer shelf significantly exceed the critical value and the boundary layer is clearly turbulent.

The bottom shear stress τ_0 is found from the relation $\tau_0 = \rho U_*^2$. τ_0 may also be obtained through measurements of the Reynolds stress ($\rho \overline{u'w'}$ and $\rho \overline{v'w'}$) taken within the "constant stress layer." It is assumed (with some experimental verification) that within this region the shear stress τ_{xy} is nearly independent of z and equal to τ_0 at the bottom. The thickness of the constant stress region is defined as that height at which $\tau_{xz} = 0.8\tau_0$. The thickness $\delta_{\tau \text{ const}}$ is given by Monin and Obukhov³² as $\approx 0.2(c_f)^{1/2} U_*/f$. In boundary layer scale terms $c_f \stackrel{\text{def}}{=} (U_*/U_\infty)^2$, so $\delta_{\tau \text{ const}}$ may be written as $0.2 U_*^2 / U_\infty f$.

Evaluation of the importance of the Coriolis force by use of the Rossby number is included in the scaling table. The numerical value is strongly dependent on the choice of a characteristic length scale, L , within which a significant velocity change is expected to occur. This rather subjective approach is reinforced by the following argument. The earth's rotation is of importance to wave motion if the period of the wave approximates the length of half a pendulum day (inertia period). Examples: at latitude 30° , ≈ 24 hr; at latitude 45° , ≈ 17.4 hr. This criterion excludes all but tidal and very long waves from consideration for the important Coriolis effect.

INTERMITTENT FLOW IN THE TURBULENT BOUNDARY LAYER

In a recent review, Mollo-Christensen³³ discusses the physics of intermittent generation of turbulence in large-scale flows, including geophysical flows such as convectively driven flows, shear flows, and planetary boundary layer flows. He points out that in these cases a burst of turbulence implies a burst of stress or momentum transfer by Reynolds stress, which may result in destruction of part of the boundary: for example, destruction of a forest or erosion of a sand bed. Kovasznay,³⁴ in summarizing his review of the structure of the turbulent boundary layer, asks what mechanism is responsible for connecting the seemingly independent regions [Figure 4(a)]. He indicates that "the single feature that seems to be present in controlling all regions is the system of large-scale eddies." He visualizes a random sequence of eruptions, or "bursts," in the outer part of the viscous sublayer (Figure 5). At the outer region of the boundary layer, similar but larger bursts are observed. They appear to be highly correlated with the interior eddies. Kovasznay surmises that there exists a "reverse cascade" of eddies, beginning with the small frequent bursts near the wall and, either by growth or coalescence, producing progressively larger and less frequent eddies as a last step before reaching the outer edge of the boundary layer and becoming visible as turbulent bulges [Figure 4(a)].

It appears that the relatively new and very active study of the bursting phenomenon is bringing important insight into the nature of the turbulent boundary layer. Bursting may be a very important factor in the initial motion mechanics of sediment transport. A brief review of the subject is given here. An example in the atmospheric boundary layer is given by Durman and Mollo-Christensen.³⁵

Laboratory Studies of Bursting in the Turbulent Boundary Layer

The phenomenon of bursting, or ejection, and its converse, inrush or sweep, attracted considerable attention since the descriptive papers of Kline et al.,³⁶ Cor and Brudky,³⁷ Kim et al.,³⁸ and others using various flow visualization techniques. The general theoretical concept, however, is found earlier in Townsend³⁹ and in Grant,⁴⁰ among others.

In the region consisting of the upper part of the viscous sublayer and the buffer layer, that is, $5 < zU_*/\nu < 30$, streaks of slow-moving fluid are carried as sudden bursts or ejections from the vicinity of the wall into the faster turbulent zone (Figure 5). A second well-defined mode called inrushing occurs in the form of the transport of high-momentum fluid inward toward the wall. Both inrush and ejection sequences

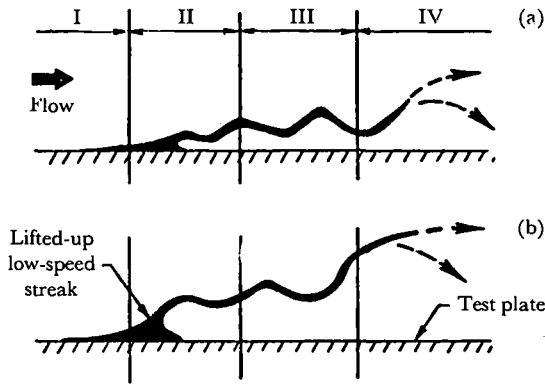


Figure 5. Bursting process in or near viscous sublayer: (a) occurring close to wall; (b) occurring farther out from wall. (From Kovasznay.⁴⁴)

correlate with an extremely high contribution to Reynolds stress.⁴¹ Specific experiments by Wallace et al.⁴² and by Willmarth and Lu⁴³ verify that the largest contribution to Reynolds stress and turbulent energy occurs during the bursting or ejection process and much of the remainder can be attributed to the inrush or sweep phase.

The eruptions are three dimensional and occur at random. According to Kline et al.³⁶ the rate of burst* per unit time and per unit width depends on friction velocity and pressure gradient (Kovasznay⁴⁴):

$$F = F_0 \frac{U_*^3}{\nu^2} (K - K_0)^2,$$

where F is burst frequency, U_* is friction velocity, and K is the nondimensional pressure gradient.³⁶

$$K = \frac{\nu}{U_\infty^2} \frac{dU_\infty}{dx} = -\frac{\nu}{\rho U_\infty^3} \frac{dP}{dx}.$$

Kline et al.³⁶ found that a positive (adverse) pressure gradient makes the bursting more frequent and more violent, whereas a negative (favorable) pressure gradient reduces the bursting rate. In sufficiently accelerated flow the bursting ceases entirely. These observations are utilized in several field studies discussed later. The magnitude of the Reynolds stress during bursting may be as much as 30 times as great as the mean value.⁴⁶ The effect of wall roughness such as may be encountered in nature was examined by Grass⁴¹ in the laboratory. He found that the inrush phase decelerates more rapidly in rough flow because of form drag of the roughness ele-

*Field observations in an estuary⁴⁵ give a burst frequency of ≈ 1 per 25 sec; in the Irish Sea,²² of 20 to 100 sec, with a duration of ≈ 5 to 10 sec.

ments. He also observed rapid response of the inner layer to sudden changes in boundary roughness.*

Field Observations

Although direct observation of bursting and inrush has not been made in the ocean, several studies have simultaneously recorded u and v to obtain Reynolds stress and infer bursting and inrush from these data. The consensus of the laboratory studies reviewed above indicates that this procedure is valid. Gordon^{45,47} has measured the Reynolds stress in a tidal estuary at a depth of ≈ 10 m, and Heathershaw,²² in the Irish Sea at depths of 10 to 60 m. In both cases the measurements were taken in the vicinity of the boundary layer. The Reynolds stress records are interpreted as evidence of bursting, and the magnitude and frequency of the burst-sweep cycles were found to increase greatly during the decelerating tidal phases (Figure 6). This is in agreement with the laboratory observations of Kline et al.³⁶ and others. Gordon suggests that because of the direct relationship between bursting Reynolds stress and horizontal pressure gradient, inferences may be drawn regarding sediment transport, e.g., increased sediment transport during decelerating tidal phases.

Laboratory Studies Relating Sediment Transport to Bursting

Gordon, in a brief review,⁴⁷ indicates that the interaction of turbulent velocity fluctuations and intermittent sediment transport has been recognized since at least 1940. Only recently, however, have sediment transport experiments been described which imply, but do not actually measure, the bursting process, e.g., those of Sutherland⁴⁸ and Grass⁴¹ on noncohesive sediments, and Southard et al.⁹ on calcareous ooze. In these three important studies attention is focused primarily on initial motion.

SUMMARY AND CONCLUSIONS

It seems evident from recent investigations that the bursting phenomenon is of fundamental importance. With reference to sediment transport there is the strong suggestion that scour may be initiated by intermittent bursts of relatively large Reynolds stress, even though the average velocity $\bar{U}$, or U_* calculated from $\bar{U}$, may be well below the critical value. This raises serious questions with respect to the practice of averaging the velocities in obtaining estimates of U_* and hence of τ_0 . The process of smoothing may mask the basic process in sediment transport mechanics. A vigorous program of experimental study is needed to establish the relation between intermittent Reynolds stress generation and the mechanics of transport, for both non cohesive and cohesive sediments.

The introductory section of this paper has illustrated some of the fundamental difficulties that still remain, especially in the area of sediment transport mechanics. These difficulties are compounded when the bottom boundary layer is influenced by oscillatory motions, especially those in the higher frequency range, e.g., wind-gener-

* Analogues on the ocean bottom may include manganese nodules, irregularities created by organisms, and, on a larger scale, ripple bedforms.

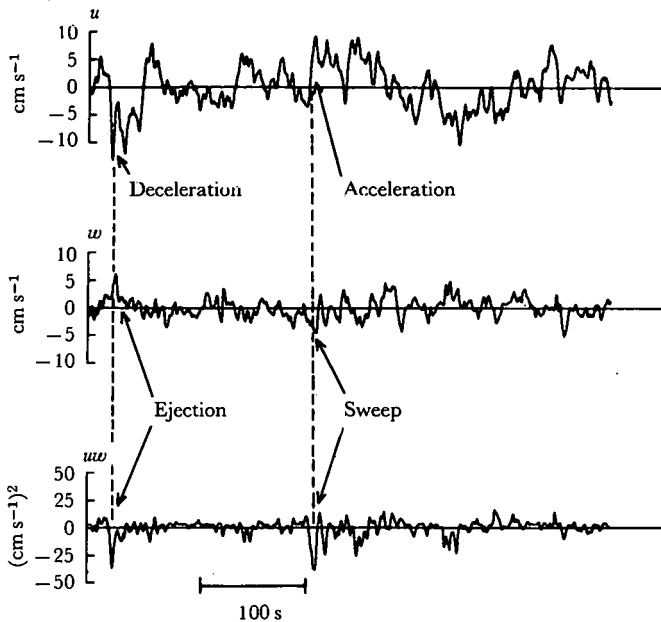


Figure 6. bottom turbulence record 2/14, station 2, depth of water 15 m. Analogues of u , w , and uw at a height of 1 m above the seabed in a mean current of 22 cm sec^{-1} and a Reynolds stress of $2.69 \text{ dynes cm}^{-2}$, showing ejection and sweep phases. (From Heathershaw.²²)

ated waves. Space does not permit treatment of this important topic here. Reviews are given by Jonsson⁴⁹ and by Teleki.⁵⁰

An attempt has been made to gather together the scaling and related properties of the bottom boundary layer on the continental shelf, following the approach of Wimbush and Munk¹⁷ for the deep sea. Particular attention is paid to the aspects that relate directly to sediment transport. It is evident that gaps appear and that a systematic program of field measurements is needed, especially to establish typical values for U_∞ , U_* , and the thickness of the logarithmic region of the boundary layer. The scaling chart should serve as necessary background for the proper design of instruments for field measurements and as a basis for selection of appropriate boundary conditions and general criteria for proper construction of numerical prediction models. The scaling chart is undoubtedly incomplete and subjective in some areas and requires further thought and input. However, the author considers it a necessary and long-overdue component in the rapidly expanding study of the continental shelf.

Acknowledgments: This study was supported in part by the Office of Naval Research, Geography Programs, N00014-67-A-0825-0018, and in part by NOAA, AOML-MESA Project 03-3-022-111. My thanks for helpful discussions are extended to G.W. Platzman and L.F. McGoldrick of the University of Chicago and to G.T. Csanady of Woods Hole Oceanographic Institution.

NOTATION

a	= wave amplitude, $H/2$
c_f	= friction coefficient
k	= diameter of sediment particle
d	= depth
f	= Coriolis parameter
g	= gravitational acceleration
H	= wave height, crest to trough
k	= wave number, $2\pi/L$
k	= roughness parameter
K	= eddy viscosity
L	= wave length
L_0	= deepwater wavelength
Re	= Reynolds number
Re_{crit}	= critical Reynolds number
T	= wave period
u'	= horizontal velocity component
v'	= vertical velocity component
U_c	= horizontal component of orbital velocity under wave crest
U_t	= horizontal component of orbital velocity under wave trough
U_0	= free stream velocity
U_∞	= free stream velocity
U_b	= bottom velocity
$\bar{U}$	= average horizontal velocity component
U_*	= $(\tau_0/\rho)^{1/2}$, the friction velocity
V_g	= geostrophic velocity
x, y, z	= Cartesian coordinates
Z	= vertical coordinate, vertical distance
Z_0	= roughness length
γ	= ρg , weight of fluid
γ_s	= weight of sediment
δ	= thickness
δ_v	= thickness of viscous sublayer
$\delta_{E\text{turb}}$	= thickness of turbulent Ekman layer
$\delta_{E\text{lam}}$	= thickness of laminar Ekman layer
$\delta_{E\text{tot}}$	= thickness of total Ekman layer
δ_l	= thickness of logarithmic layer
κ	= Karman constant ($=0.4$)
ν	= kinematic viscosity
ρ	= density
σ	= $2\pi/T$
τ_0	= horizontal shear stress on bottom
Ω	= average angular velocity of Earth's rotation

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Bedforms on the U.S. Atlantic Continental Shelf: A Review

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INTRODUCTION

Utilization of the continental shelf to improve the activities associated with energy production in the United States implies a variety of operations, each with its own scenario. In each case a structure of some type or a conduit of some form for transferring the energy or raw material to the land may be placed upon the sea floor or at shallow depth under it.

The land surface is easily seen, and its processes of formation and change are rather readily comprehended in the context of design and construction. In contrast, the sea floor cannot be easily seen, and processes of its formation and change are much less clearly understood. In order to design and construct an object to be placed on the sea floor, and do it at minimum total cost with a sufficient margin for safety, it is necessary to know as much about the sea bed surface as about land surface.

The earliest seafarers knew that the sea bed, or at least parts of it, was comprised of reefs, shoals, and deep channels. It was not until the discovery, development, and use of acoustic hydrographic surveying techniques that marine scientists and engineers became aware of its irregular form. Veatch and Smith¹ pioneered the analysis of the topography of the Atlantic Continental Shelf off the United States. Work by others^{e.g. 2-7} clearly indicated that the sea floor comprised a variety of morphologic features, that these features were on a variety of scales, and that the form and location of these features varied in space and probably time. More recent studies^{e.g. 8-11} are directed toward more quantitative understanding of the processes and rates of formation and change of some of the forms of the sea bed.

Knowledge of the sea bed is not sufficient to answer all the questions that might be posed relative to its use. The basic questions that those seeking to utilize or protect the marine environment need to ask are

What is the form of the sea bed?

What is the distribution of these forms in space?

What processes produced or are producing these forms?

What is the stability (or instability) of these forms in time?

What are the implications of these processes and the response of the sea bed for engineering and design?

The existing body of knowledge concerning the shape of the sea floor stands as a base line of the state of the art. In addition, many studies of both a theoretical (numerical model) and empirical (laboratory and field) nature are under way. The state of understanding on which to base responses to the above questions is the subject of the following paragraphs.

Table 1

Morphological Elements of the Atlantic Continental Shelf

Small-scale elements

Ripples

Sand waves

Large-scale elements

First order: Linear ridges and shoals

Shoreface-connected and isolated

Second order: Arcuate shoals

Inlet and cape associated

Ridge fields

Third order: Shoal retreat massifs

Cross-shelf valleys

Cuestas

Deltas

Scarps

WHAT IS THE FORM OF THE SEA BED?

General

The morphology of the sea takes on a variety of shapes and scales. The main interest here is the continental shelf off the Atlantic seaboard; hence discussion will be limited to the area landward from the edge of the shelf (water depth < 200 meters) but seaward of the base of the shoreface (the point at which the relatively steep slope descending from the low waterline or inshore terrace changes to the less steep slope of the continental shelf, usually about 10 meters⁶). Features of the continental shelf sea bed vary in size (relief) by a factor of 50,000 (1-mm-high ripples to 50-m relief in cross-shelf valleys). In this discussion, the various forms of the shelf will be considered in the hierarchical context of Swift et al.⁷ in Table 1 and schematically illustrated in Figure 1.

Studies of sea floor morphology based on site-specific requirements can be in such detail as to require and permit development of a more narrowly defined bed-form classification scheme. Nevertheless, a general hierarchical scheme such as that in Table 1 is suited to systems analysis and conceptual design considerations.

Small-Scale Elements

This group comprises ripples and sand waves (Figure 1). Ripples are small bed-forms about 3 cm high with wavelengths less than ≈ 30 cm¹² and are the smallest of a gradation of bedforms that develop in unconsolidated noncohesive sediment under the action of waves or currents. Ripples may be symmetrical or asymmetrical in cross section, implying formation by oscillatory or directional motion, respectively. Sand waves are large wavelike features of unconsolidated sediment having wavelengths from 10 to 1000 m and heights from ≈ 0.5 to 30 m.

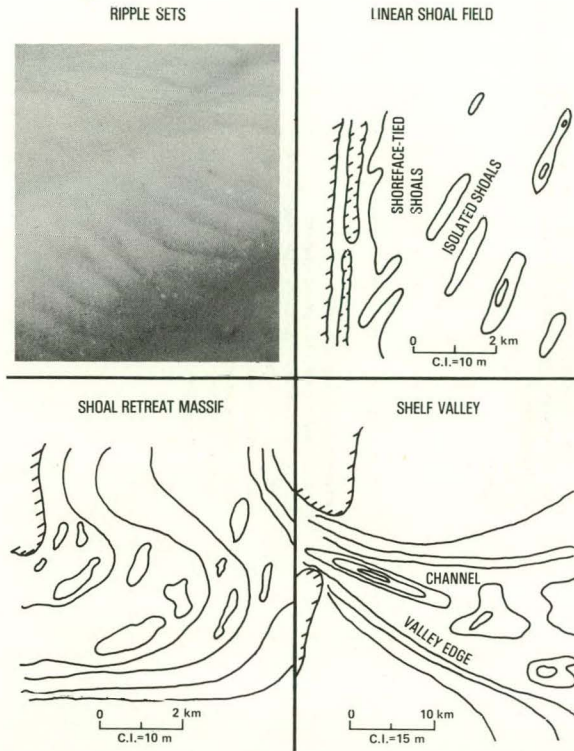


Figure 1. Four morphological elements of the U.S. Atlantic Continental Shelf. Ripple sets were photographed in water 18 m deep off New Jersey (photograph courtesy of D. J.P. Swift). Large-scale elements are schematized to show salient features and size.

Sand waves are characteristically asymmetrical. Forefront or down-current slopes are the short, steep side, sometimes approaching the limiting angle of repose. Sand waves in the Chesapeake Bay entrance have foreslopes averaging 1.5° and back slopes of $<1^\circ$.¹³ Because of the variability in the size and shape of sand waves occurring in a region, it is difficult to adequately characterize their shape with a single number. Ludwick¹³ analyzed the Chesapeake Bay entrance sand waves with a spectral density analysis technique. Divided into two regions separated by a topographic high, the seaward field had a spectrum peak at a wavelength of 274 m, with mean of 211 m; in contrast the landward field spectrum peaked at 86 m, with a mean of 93 m. Average height of the seaward waves was 1.9 m, slightly greater than the average of 1.4 m for the landward field.

Using data on the morphology of the central New Jersey continental shelf, McKinney et al.¹⁹ have described a bedform, current lineations, mid-scale between ripples and sand waves. Somewhat similar to sand ribbons in the North Sea,¹⁴ the current lineations from the central New Jersey shelf are low relief (to 1.5 m), extremely long (up to 1000 m), and occur as zones of textural contrast about 10 to 50 m wide.

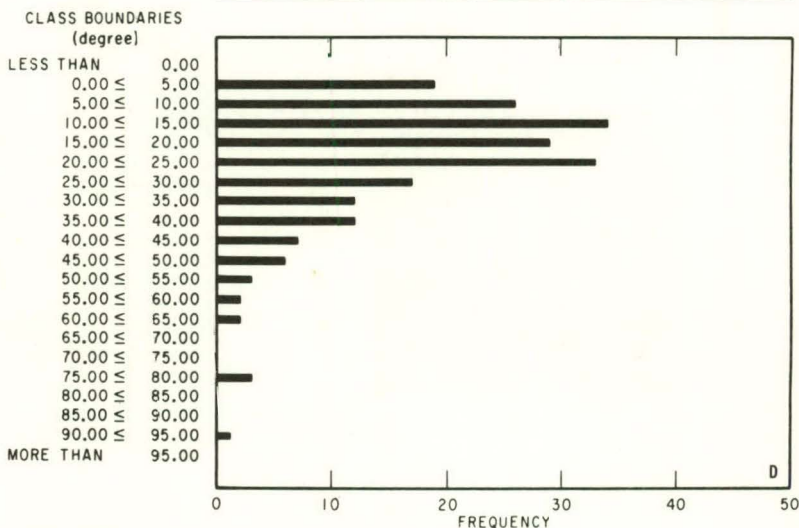
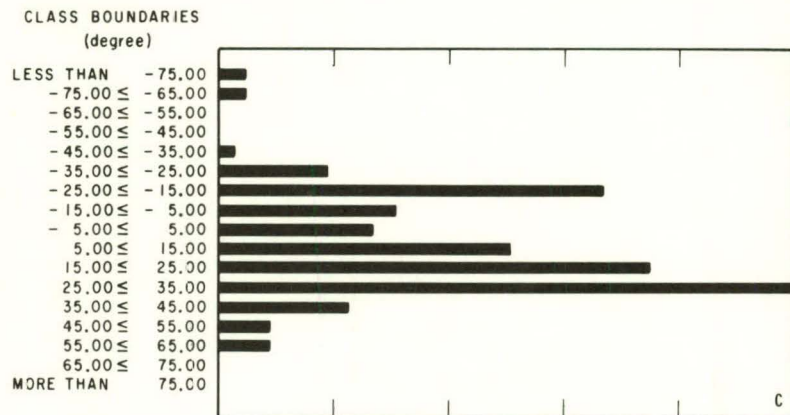
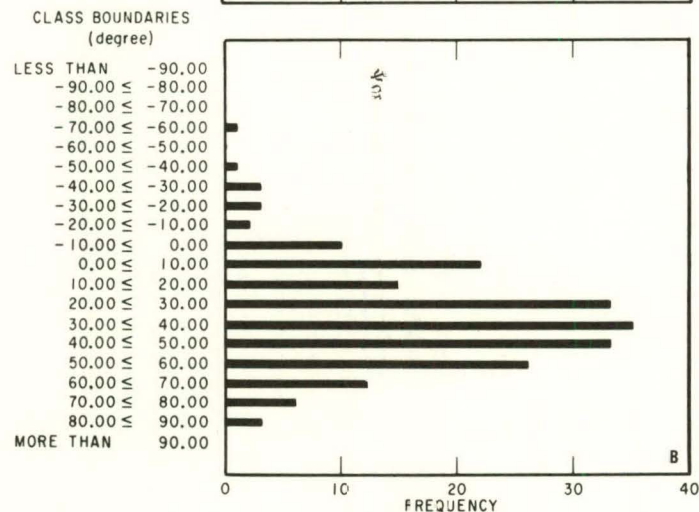
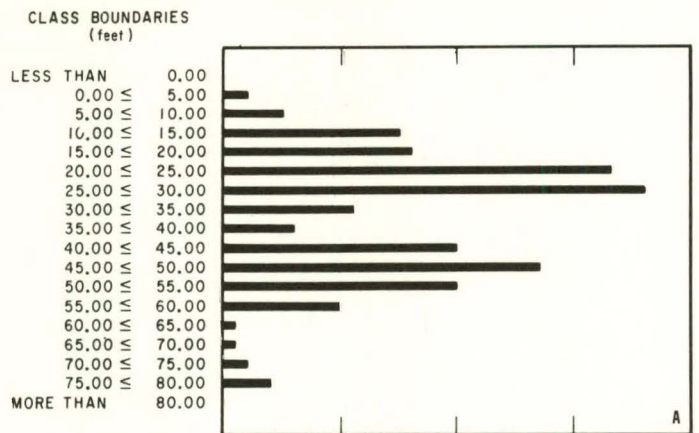


Figure 2. Group characteristics of more than 200 linear shoals on the U.S. Atlantic Inner Continental Shelf. Parameters plotted by frequency of occurrence are (A) water depth over shoal crest; (B) azimuth of shoal axis; (C) azimuths of shore line adjacent to shoals; and (D) angular deviation of shoal axis trend with coastline and.

Large-Scale Elements

Several of the large-scale morphologic elements in Table 1 are schematized in Figure 1. Linear ridges and shoals are positive features with heights ≥ 3 m between the crest and surrounding surface and lengths ≥ 1000 m. Heights range from 3 to 15 m, lengths from 1 to 15 km, and side slopes are of only a few degrees, but considerably less than the limiting angle of repose. Two primary classes are recognized⁶: shoreface-connected shoals, defined by a seaward excursion of the 10-m water depth contour; and isolated shoals, lying on the continental shelf and displaying no topographic ties to the shoreface. Duane et al.⁶ analyzed more than 200 shoals on the inner shelf and summarized four characteristics in the form of histograms (Figure 2).

Their study indicated that the linear shoals form a small acute angle with the coast, open northward, and cluster about water depths of 6 to 9 m and 12 to 15 m, and possibly 24 m. Continuous seismic reflection profiles across the shoals show them to be plano-convex in section. Cores show these bedforms to consist of granular, noncohesive sediment that differs markedly from the underlying clayey substrate.^{6,8,9}

A typical area of linear shoals occurs off the Delmarva Peninsula (Figure 3). The large number of shoals in this area constitute a shoal field, a feature more common north of Cape Hatteras than south of it. In a detailed study of the shoals of this region, Field¹⁸ found the following "typical" values: relief, 6 to 9 m; length, 8 to 13 km; width, 1.3 to 2.3 km; mean coast intersect angle, 17.5° ; and side slopes, $< 1.2^\circ$.

Most shoals associated with capes and inlets in this category of second-order size are arcuate in plan view (Figure 1). Typical of the arcuate shoals at inlets are those off Chesapeake Bay,¹³ and typical of those off capes are those found off Cape Canaveral, Florida.¹⁵ Although arcuate shoals differ in location and plan view from linear shoals, the two classes have many similar characteristics. As is true for linear shoals, arcuate shoals at estuary entrances¹⁶ and capes¹⁵ are plano-convex in section and composed of granular sediments resting on a clay or silt substrate.

Arcuate shoals occur in large numbers seaward of present capes and estuary inlets. They are superimposed on low, poorly defined, large-scale topographic features termed massifs,⁷ which are a third-order morphologic element (Table 1, Figure 1). The Middle Atlantic Bight exhibits several other third-order morphologic features: valleys that completely (or nearly) traverse the shelf, notably the Hudson and the Delaware,⁷ and features interpreted as deltas, scarps, and cuestas.⁷

All morphological elements on the sea floor can be construed as active bedforms. However, the term bedform was originally associated with forms (deviating from a flat bed) occurring in unconsolidated sediments in alluvial channels. The shelf valleys, scarps, and cuestas, although formed as a result of erosion due most significantly to hydraulic processes, are essentially land forms and will not be mentioned further.

Differences of opinion exist about the origin of the large-scale elements. As herein used, the term bedform implies that the feature of interest is hydraulically active under present conditions. The degree of hydraulic activity of large-scale bedforms on the continental shelf is not yet agreed upon.

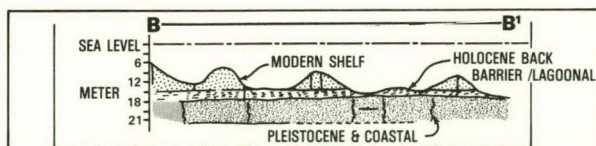
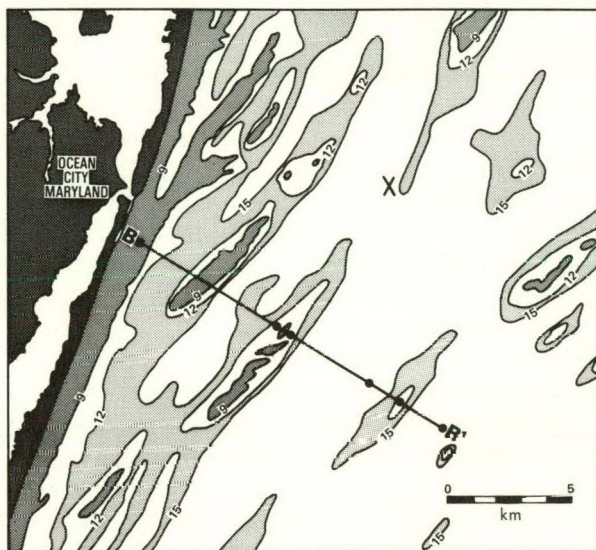
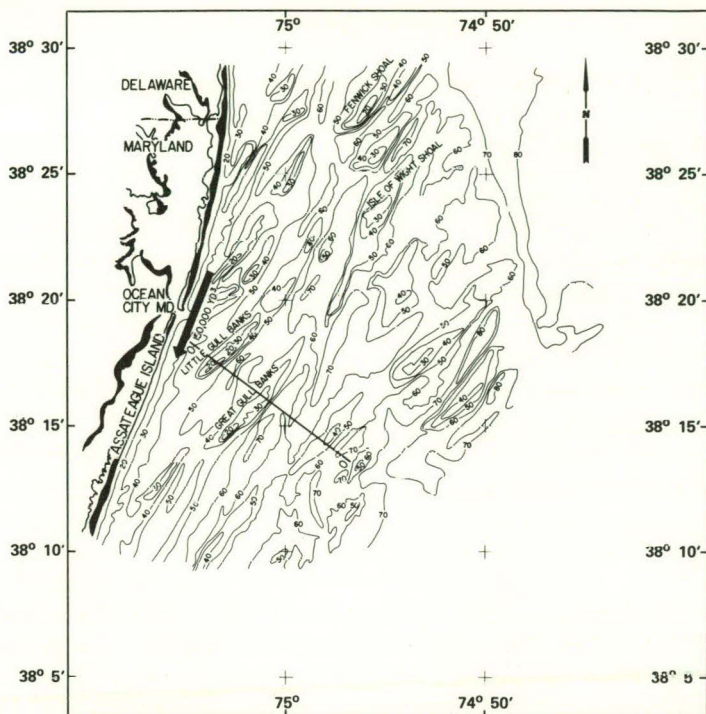


Figure 3. Linear shoal field off the Delmarva peninsula. *Top*: Shelf bathymetry contoured to depict a field of linear shoals; C.I. = 10 ft.⁶ *Bottom*: Enlarged portion of the Ocean City area, showing in greater detail the morphology of elements in the shoal field both in plan view and in section; C.I. = 3 m.¹⁶

WHAT IS THE DISTRIBUTION OF BEDFORMS ON THE CONTINENTAL SHELF?

General

The scale of the bedform determines to a considerable degree what is known about its distribution. Small-scale elements cannot be detected by normal bathymetric surveying techniques, which were widely used in the studies conducted in the 1960's and early 1970's and provided much of the base-line information on the distributional characteristics of large-scale morphological elements. Until the recent development and rapidly increasing use of side-scan sonar techniques (which can detect small-scale bedforms), direct observation of small-scale bedforms on the floor of the continental shelf was limited to the results of surveys made with scuba, submersibles, or deep-sea cameras.

Small-Scale Elements

Virtually every reported *in situ* observation of the sea floor mentions ripples, sand waves, or both. Observations by the author from submersible dives in the inner New York Bight indicated active oscillation ripples in sandy sediments in several regions. They have been reported at other locations in the Bight as well.¹⁷

Using side-scan sonar and submersibles while studying the shelf off central New Jersey, McKinney et al.¹⁹ found widespread occurrence of ripples and current lineations on the scale of sand waves. The current lineations occurred in troughs between ridges, as well as at the sides and crests of large-scale ridges. Field¹⁸ carried out a detailed study of the shoals off Delmarva Peninsula and reported that ripples were widespread on ridges and in troughs. Features similar to the current lineations described by McKinney et al.¹⁹ off New Jersey have been observed in calcareous sand on the North Carolina shelf by MacIntyre and Pilkey.²⁰

Milliman²¹ indicates that unconsolidated sediment with a modal size class ≥ 125 microns exists everywhere on the shelf from Long Island to Florida. Therefore, because ripples and sand waves occur in unconsolidated noncohesive sand and sandy sediments ($\geq 62\text{-}\mu$ diameter), bedforms can be expected to occur everywhere on the shelf when bottom current velocity and shear exceed critical values, and indeed, despite the relatively small numbers of *in situ* observations on the shelf, ripples and sand waves seem to be widespread.

Large-Scale Elements

Maps prepared by Uchupi⁴ from his work on the Atlantic shelf and slope clearly show ridges and intervening troughs to be the dominant topographic features across the entire shelf to the break in slope, which commonly occurs at 150 m. Duane et al.⁶ made a detailed study and analysis of shoals on the inner shelf. More than 200 large linear shoals occur between Florida and Long Island. Actual occurrence is related to the character of the adjacent coastline and previous geologic events.¹⁶ Offshore from headlands, shoals are either absent or scarce. In contrast, well-developed fields of linear shoals occur seaward of the long, convex barrier spits of the Middle Atlantic Bight (Figure 3) off the sea islands of northern Florida,

Georgia, and the Carolinas. South of Cape Hatteras linear shoals are absent or subdued, although several characteristic sets occur off central Florida. Where fields of shoals occur off the convex barrier splits, they can be traced offshore to water depths ≥ 100 ft (Figure 3).

Inlet and cape-associated shoals occur, as their names imply, off inlets or capes. Typically they occur in fields analogous to those of linear shoals. Particularly well developed are those off the entrance to Delaware Bay,⁷ and an excellent example of cape-associated shoals lies off Cape Canaveral.¹⁵ Because of the large numbers of individual shoals associated with the "fields" and the large areal extent, Swift et al.⁷ referred to them as massifs. Cape and inlet-associated massifs can be easily traced at least halfway across the Atlantic shelf. Those north of Cape Hatteras are shown in Figure 4.

Capes, of which Hatteras and Lookout are excellent examples, occur at the intersection of lines drawn parallel to coastal segments on each of their sides. If lines extending east from Long Island and south from Cape Cod are drawn, a vast area of shoals (Nantucket Shoals) is seen within the landward side of these two lines. The seaward-most occurrence of these shoals begins at approximately the intersection of these imaginary north to south and west to east lines. In a sense, therefore, these shoals are cape associated and mark the retreat path of that cape. Whether they can be considered to have formed as the "cape" retreated completely across Georges Bank is at this stage of knowledge problematical.

WHAT PROCESSES PRODUCE THESE FORMS?

General

Bedforms were first observed and studied with respect to unidirectional steady flow in rivers. In these early studies it was observed that when hydrodynamic forces acting upon noncohesive sediments exceeded a critical value, the bed shape was altered and sediment underwent transport. Much of the early theory and experimental work resulting from research is summarized by Hjulström²² and by Shields,²³ who present diagrams of the relation of factors such as flow velocity and sediment characteristics to the state of sediment motion.

Unidirectional steady flow occurs in the marine environment in several realms and on several scales: major current systems, wind-generated currents, and tidal flows. On a much smaller time scale are the oscillatory, unsteady currents induced by the passage of waves. The theory of wave-generated sediment motion, together with experimental results, is well summarized by Bagnold,²⁴ who presents a diagram analogous to those of Hjulström²² and Shields.²³ All three diagrams are usually termed competency diagrams, i.e., the competency of flow at a given time to induce sediment transport, and are much referred to in the literature of sedimentology.

The existence of bedforms on the sea floor unequivocally demonstrates that fluid forces act on the sea floor in strength sufficient to deform the bed and produce sediment transport. Competency diagrams indicate that near-bed velocities necessary to erode sediment from the bed are generally an order of magnitude greater than observed ambient velocities of shelf tidal currents and prevailing cir-

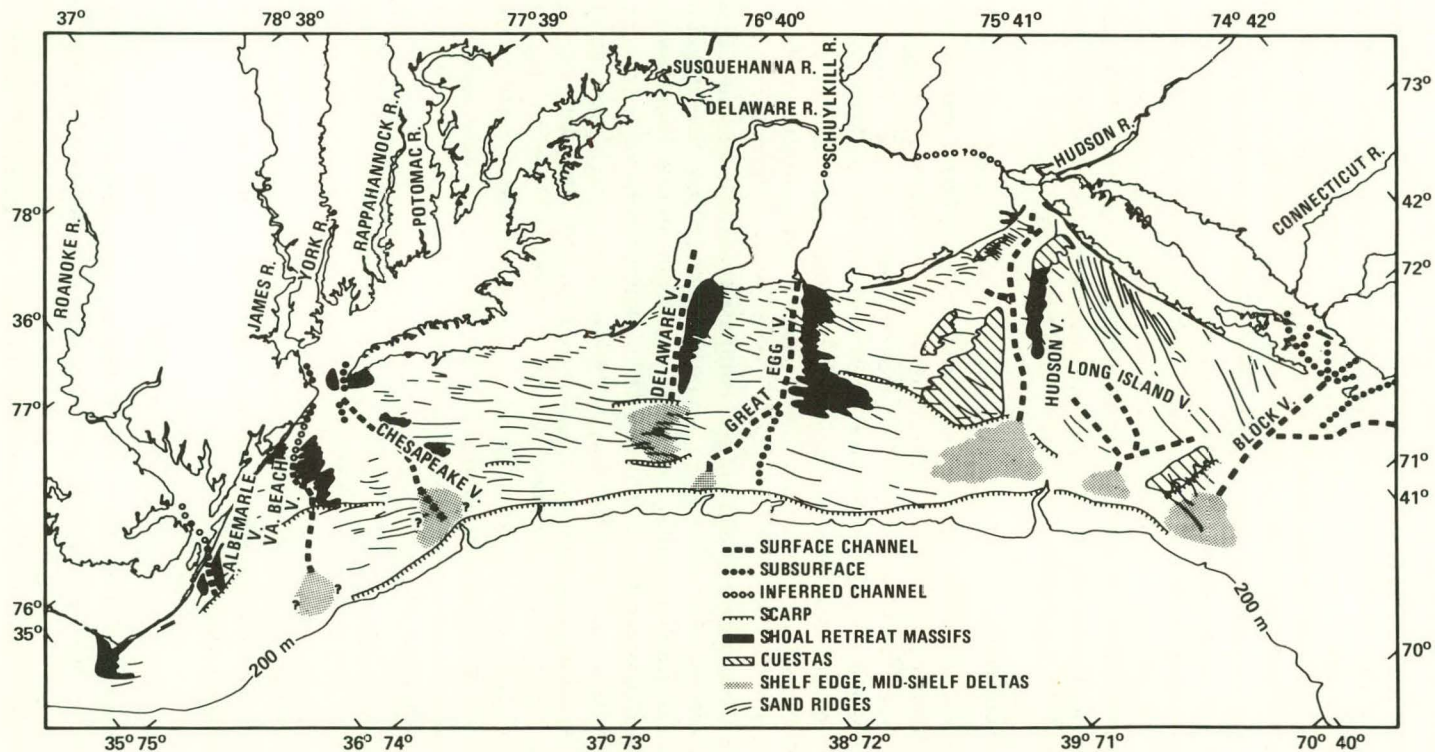


Figure 4. Distribution of large-scale morphologic elements on the Atlantic Continental Shelf of the Middle Atlantic Bight.⁴⁷

ulation patterns. However, instantaneous velocities sufficiently high to deform the bed and entrain sediment in the fluid column occur from the passage of wind waves. Such currents, when purely oscillatory (i.e., when the orbits are closed) do not result in sediment transport. From the standpoint of sediment transport on the shelf, the transport process can be considered a two-step phenomenon: entrainment and translation. Entrainment is the process of moving sediment from the bed (often for an infinitely small period of time) some finite distance into the water column; translation is the net motion imparted to the grain while suspended in the water column.

Data presented in the competency curves²²⁻²⁴ are primarily from laboratory investigations. Experiments to verify these results under field conditions have understandably been slow in coming. Recent advances in instrumentation are remedying the situation and providing new empirical relationships concerning the transport of sediment and the generation and movement of bedforms.

Small-Scale Elements

Several empirical criteria for determining the onset of sediment movement and the generation of ripples under oscillatory unsteady flow have been established from laboratory experiments such as that reported by Carstens et al.²⁵ This experiment, while proposing an equation as a universal determinant for incipient motion, is similar to many other laboratory experiments²⁶⁻²⁸ in that the range of experimental variables, particularly wave conditions and sediment size, is restricted. Relationships are thus usually limited to the range of experimental conditions from which they were derived. Silvester and Mogridge²⁹ compared results from some 13 such relationships, noting considerable scatter. Komar and Miller³⁰ concluded that use of the Shields criterion for determining the initiation of sediment movement under oscillating flow led to considerable imprecision due to differences in forces between oscillatory unsteady flow and unidirectional steady flow. Komar and Miller³⁰ and Komar³¹ suggest using a threshold parameter, θ_t , which does not require determining bottom shear stress. More recently, however, Grant and Madsen³² reevaluated the experimental results of others^{28,33-36} and found good agreement among these experiments and the Shields competency diagram when the wave friction factor was employed in the calculation of maximum bottom shear stress³⁷ ((Figure 5). The Shields parameter (after Grant and Madsen³²) is

$$\psi = \frac{\tau_{0m}}{(\rho_s - \rho)gd},$$

where τ_{0m} = maximum bottom shear stress, ρ_s = density of sediment, ρ = density of water, g = acceleration of gravity, and d = grain diameter in centimeters. The evaluation of τ_{0m} (from Jonnson³⁷) is

$$\tau_{0m} = \frac{1}{2} f_w \rho u_b^2,$$

where f_w = wave friction factor, ρ = fluid density, and u_b = maximum fluid velocity just outside the boundary layer. f_w can be found from a diagram prepared by Jonnson and by using the grain diameter as the boundary roughness (given also the near-bottom velocity, displacement of near-bottom wave orbit, and kinematic viscosity).

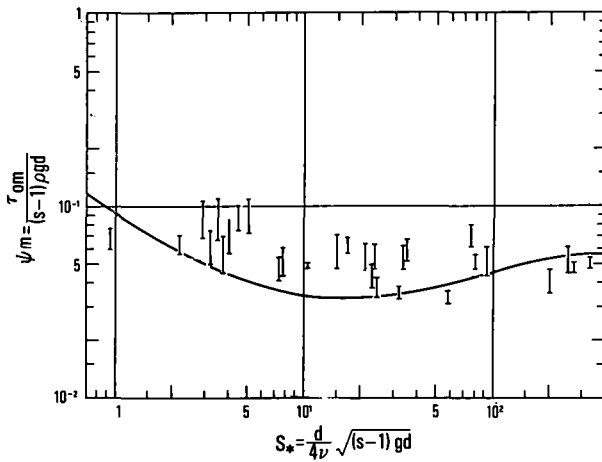


Figure 5. Results of experimental studies on the initiation of sediment movement in which Jonnson's wave friction factor was used in determining the Shield's function, ψ . Solid line is the Shield's curve. (Data from Madsen.³²)

This work of Grant and Madsen³² implies that the Shields criterion is valid (and perhaps conservative) for oscillatory unsteady flows. On the basis of the above-mentioned studies, the minimum fluid velocity at the bed required to induce transport of noncohesive sediment is generally accepted as ≈ 20 cm/sec, although it is possible to evaluate that velocity for every case.

All methods of evaluating the threshold of grain movement require determination of the bottom or near-bottom velocity. Linear wave theory permits a computation of maximum bottom orbital velocity,

$$U_{0m} = \frac{\pi H}{T \sinh(2\pi h/L)},$$

where H = wave height, T = wave period, h = water depth, and L = wavelength. From this relationship a family of curves may be constructed which permit determination of U_{0m} if water depth and wave height and period are known (Figure 6).

Tidal flow is oscillatory, but the period of oscillation is such that the flow varies slowly. Consequently at a given instant in an estuary entrance or on the continental shelf, the flow may be considered as steady unidirectional. The same holds true for wind-generated storm currents. In the field it is difficult to measure the near-bottom velocity or the boundary shear stress. Therefore use is made of the quadratic shear stress law,

$$\tau_s = C_D \rho \bar{U}^2,$$

where C_D = dimensionless drag coefficient, ρ = fluid density, and $\bar{U}$ = mean flow velocity, which has been modified to

$$\tau_s = C_{100} \rho U_{100}^2,$$

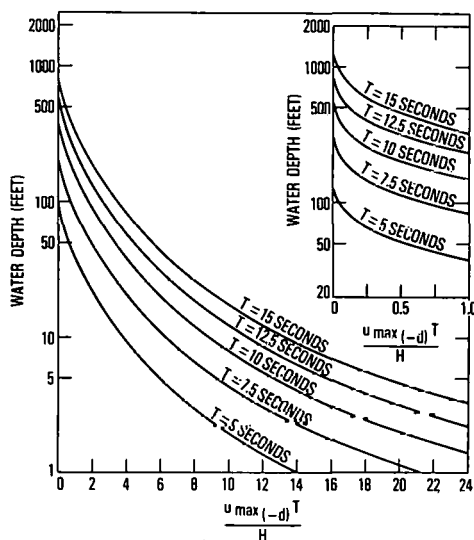


Figure 6. Computed maximum bottom velocity ($U_{\max}$) based on small amplitude wave theory.^{6,9}

where C and U are evaluated for a standard elevation, say, 100 cm, above the sea floor. As pointed out by Ludwick,³⁸ when only U_{100} is measured, C_{100} must be assumed, and the proper values for C_{100} are not well known. From a large number of determinations of C_{100} in the Chesapeake Bay entrance, Ludwick³⁸ found variations through four orders of magnitude and determined a mean value that differed significantly from that established for tidal channels in Puget Sound.³⁹ A variety of bedforms occur in the Chesapeake Bay entrance, differing in all dimensions as well as in position through space and time, with a hierarchy of forms ranging from a few millimeters to meters in height and tens of meters in length.¹³ With flow variable through time, a movable bed, and a size hierarchy of bedforms, Ludwick concludes that it is extremely difficult to arrive at a meaningful value of C_{100} , and therefore the usefulness of the modified quadratic shear stress law for predicting sediment motion is severely limited.

Velocities associated with tidal flow in the Chesapeake Bay entrance vary with the stage of tide. The corrected maximum velocity at U_{100} exceeded 24 cm/sec at 11 stations, sufficiently in excess of 20 cm to induce sediment motion.⁴⁰

On the basis of bathymetric and continuous seismic-reflection profiling data,⁶³ the shoals south of Cape Cod and Nantucket are very similar in shape and section to those of the Chesapeake Bay entrance¹³ and the North Sea.⁴¹ The current regimes extant may thus be interpreted as similar to those of Chesapeake Bay, complicated by wave-induced currents produced as a result of refraction and as a consequence of wave trains focused by the capelike change in coastal orientation.

Measured current speeds on the shelf exhibit marked variations directly correlatable with storm systems. Non-storm flow has been determined on the basis of a variety of studies over the years to be southerly at ≈ 5 cm/sec from Cape Cod to Cape Hatteras.⁴² Velocities of that magnitude will not produce bedforms or transport of bed material. However, during storms in which winds reach velocities ≥ 11 to 15 m/sec for 24 hr, water velocities can be quite high. Boicourt and Hacker⁴² show 59-hr means of ≈ 30 cm/sec near the surface at four stations across the shelf, and near-bottom (at 3 m) velocities of 18 cm/sec in water ≈ 18 m deep, 27 cm/sec in water ≈ 30 m deep, and ≈ 50 cm/sec nearshore in 10 m of water. McClennon⁴³ reports sustained storm-generated current velocities of ≈ 35 cm/sec 100 cm above the bed on the New Jersey shelf. McClennon applied the Shields criterion to the data and concluded that bottom sediment was moved by these currents. Currents of the same magnitude were reported by Swift et al.⁸ for a Savonius rotor current meter stationed 37 cm above the sea floor at a 20-m depth off Virginia Beach. Although these studies provide a strong basis for predicting sediment transport, studies of sand movement south of Long Island are being undertaken using radioactively tagged sand. That program, still under way, unequivocally documents the movement of sand on the shelf under conditions of a northeaster.⁴⁴

At present, direct measurements of near-bottom current velocities on the continental shelf are sparse. However, investigations are under way to collect, interpret, and report on shelf currents off Massachusetts, the inner New York Bight, the inner New Jersey shelf, the Maryland inner shelf offshore Assateague Island, Virginia, and North Carolina.

Superimposed on sustained flows are high-frequency pulses of high-velocity flow associated with the passage of surface waves. Therefore, if the measured storm current is at, or even below, the threshold for movement, the coupling of wave and storm-induced bottom flow can be expected to induce transport of bed material. Proof of such activity lies in the existence of small-scale bedforms.

Large-Scale Elements

The formation of the large-scale morphologic elements existing across the shelf appears to be a combination of short-term hydraulic phenomena and long-term geologic processes. The linear shoals (shore-tied and isolated) and shoal retreat massifs (cape or estuary-associated) originate near shore in response to hydraulic processes associated both with fair weather and with storm conditions.^{6,7,45} The occurrence of these forms across the shelf in varying water depths is attributed to the retreat of the shoreline through geologic time in response to a rising sea level.

Study of a small beach ridge system in Delaware⁴⁵ suggested that the linear shoals had been generated by nearshore processes. The idea was reinforced and supported by Duane et al.,⁶ who reported apparent evolutionary sequences in several areas: off Long Island, New Jersey, Delmarva (south of and including Bethany Beach), and North Carolina. The shoal field off Ocean City, Maryland (Figure 3) is considered representative of the evolutionary sequence (schematized in Figure 7) from shoreface-connected shoals to individual shoals isolated out on the shelf. The *en echelon* nature of shoal peaks and the stepwise trend of crestlines suggest that a

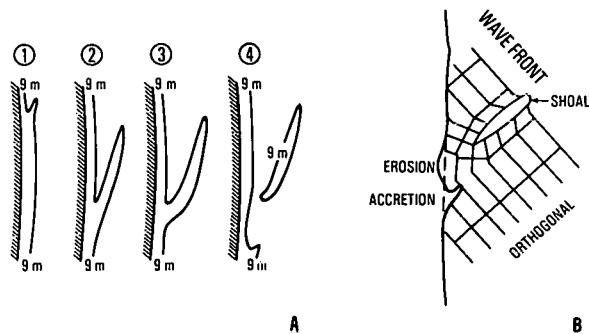


Figure 7. Schematic of conceptual model for sequence of shoal evolution. (A) Evolution, stages 1 to 4. Movement in stages 1 and 2 is primarily shoal extension; in stage 3, a combination of shoal extension and coastal retreat (primarily the latter); in stage 4 (and subsequently), coastal retreat. (Modified from ref. 6.) (B) A possible mechanism for isolating a shoal and generating a daughter is wave refraction caused by the shoal. (Modified from ref. 46.) A more probable mechanism is a combination of wave action and wind-induced nearshore currents.

shoreface-connected ridge develops by headward erosion and continued deepening of its landward trough, possibly with concomitant crestal aggradation, until a critical threshold is reached. The base of the ridge is then severed, and a new ridge begins to form inshore and downdrift from the initial segment. A mechanism has been presented⁴⁶ for generation of a new "daughter shoal" downdrift by wave refraction around the updrift parent (Figure 7). It may well be that the same process, which serves to concentrate wave energy at the foot of the shoal and induce development of a daughter, could also serve to sever the parent shoal from the shoreline.

Once isolated from the shoreface, the shoals are "relict," having been abandoned as the shore retreated in response to sea level rise. Orientation of the shoals and correlation with the shoreline (Figure 2) suggest that the shoreline has retained essentially the same orientation for the past 10,000 years.

The argument that the linear shoals on the continental shelf are wave generated, as are shore-parallel offshore bars, was considered by Duane et al.⁶ While there is some evidence to support this idea for shoals in water depths < 8 m, the vast majority of shoals would require combinations of wave height and period that are unrealistic for the Atlantic coast. Consequently the idea was rejected.

The existence of linear shoals across the shelf supports the idea that shoals extending seaward from capes^{7,15,47} and estuary entrances⁷ mark the retreat path that coastal landform through geologic time. Capes on barrier islands (such as Hatteras and Lookout, North Carolina; Canaveral, Florida; May, New Jersey; and Henlopen, Delaware) are depositional centers for sediment transported along shore as littoral drift. As noted by Swift et al.⁷ the morphology of the nearshore portions of these shoals is shaped by nearshore hydraulic processes, while the outer portions become isolated from these processes.

Shoal retreat massifs offshore of capes and estuary entrances consist of smaller-scale elements of the type discussed previously. The size, scale, and hierarchy of

these forms at estuary entrances are described in detail by Ludwick¹³ and by Boothroyd and Hubbard.⁴⁸

Conceptual models for the formation of shoal retreat massifs and linear shoals have been developed. The mechanism of formation of the shoal retreat massifs is more clearly understood than that for the linear shoals and shoal fields. In all cases, however, once the large-scale elements are formed, hydraulic processes active on the shelf act upon them to modify their shape and size.^{8-10,17}

WHAT IS THE STABILITY OF THE BEDFORMS IN TIME?

General

The stability of bedforms is a function of the occurrence and duration of the processes (wind, waves, and water currents) producing them and may be considered in terms of creation of the form and persistence in place through time, translation (advection) of the form through space, or a combination of the two. Translation of the form implies mass transport of noncohesive sediment, usually $Q_{in} \neq Q_{out}$, although the movement may take place with no net change in sediment flux, i.e., $Q_{in} = Q_{out}$.

Small-Scale Elements

Because of their size, small-scale elements can be modeled and studied in flumes and wave tanks. On the basis of laboratory studies, relationships have been developed relating migration rate of ripples to one or more physical characteristics of the flow and bed material. Rates of propagation of ripples have been determined in laboratory studies with oscillatory flow,^{e.g. 25} but such studies have characteristic limitations. Field verification of predictive equations for ripple migration is difficult. At best, empirical relationships may be developed for limited geographical areas in which currents can be measured and migration of the bedform observed. A method for computing bed load transport from time-lapse stereophotography of rippled beds has been described.⁴⁹ Using that technique, Kachel and Sternberg⁵⁰ measured bed load transport during ebb-tide flow in Puget Sound.

However, when suspended material occurs in concentrations that make photography impossible, other measurements techniques are required. Ludwick¹³ reported results of field studies of sand wave migration at the entrance to Chesapeake Bay, where scuba divers reported a cloud of moving sediment 1 m thick above, but in contact with, the bed. The basic tool of Ludwick's study was time-lapse data, provided by bathymetric profiling rather than photography. Sand waves were observed to move at the rate of tens of meters per year, but direction and rate varied with location in the bay entrance. Ludwick explained the movement of the sand waves as the combined effect of the migration of smaller forms (ripples) upon the larger sand waves. He approximated the relationship of small-bedform migration speed C_r to fluid flow velocity as

$$C_r = K_2(U_f - U_c)^n \quad \text{when} \quad U_f \geq U_c,$$

where K_2 = empirically determined constant depending on the numerical value of n ; n = empirically determined constant depending on the size of bedforms, particle size, and probably other factors; U_f = fluid velocity near the bed, and U_c = critical velocity for sediment motion.

Large-Scale Elements

Determination of the migration rate of large bedforms such as shoals is based on time-lapse studies, i.e., comparison of successive hydrographic surveys. Many factors enter into the precision and accuracy of the results of such comparisons. Among them are the method and accuracy of position and depth determination, scales of the chart, and complexity of the bottom morphology. Two recent studies^{51,52} detail the source and magnitude of errors introduced into these studies and methods for reducing them. It is important to be cognizant of these sources of error when making comparative profile studies and when evaluating reports of studies in which such techniques are employed.

The magnitude of the computed length of displacement between successive surveys of some of the linear shoals on the Atlantic shelf is such that the reality of the movement cannot be denied. A number of studies indicate that movement of the crest position, or a particular depth contour, is such as to indicate general movement southward, but at varying rates. Moody⁴⁵ studied the nearshore linear shoals at Bethany Beach, Delaware, and found that the ridges had migrated at an average annual rate of 9 m/yr over a 42-yr period (≈ 380 m net). Moody's studies were under way when the Ash Wednesday storm of 1962 struck the east coast. Surveys before and after that storm established shoal migration of ≈ 80 m southeastward. Blackfish Bank Shoal, offshore of Chincoteague Inlet, Virginia (90 km south of Bethany), has been shown to have lengthened ≈ 4000 m to the south in 53 years, an average annual rate of ≈ 80 m.⁶ Other evidence for migration of shoals off the Delmarva coast is provided by Field,¹⁸ who noted a net southerly motion but observed shoreward and offshore movement as well. Much the same apparent behavior has been observed for shoals offshore of False Cape, Virginia.⁷

While the discussion above deals primarily with translation of the form in the horizontal plane, there is evidence that the shoals also show changes in the vertical plane. Aggradation of crests has been reported, as well as deepening of the adjacent trough.⁵³

Time-lapse bathymetric surveys provide a means of quantifying the lateral movement of the large-scale bedform elements. Stubblefield et al.⁹ computed a volume transport rate for a mild summer storm that was reported by McClennon⁴³ to have produced U_{100} of ≈ 35 cm/sec. Stubblefield et al.⁹ concluded that "ten transport events of that magnitude per year would be able within several decades to transport, over the surface area of a ridge, an amount of sediment equal to the volume of the ridge [which suggests that possibly] the flow field has been structured in such a way as to maintain the ridges; otherwise they would have been degraded and flattened." Additional evidence to support McClennon's idea that the hydraulic environment helps to maintain the forms is found in the creation of "ridges" through activities of man.

Williams and Duane⁵⁴ document the creation, off the entrance to New York Harbor, of a shoal ≈ 15 m high, 15 km long, and 5.6 km wide, composed of waste material dumped in that area beginning in the late 19th century. The dumped material, similar to ambient sediment, has remained relatively stable over the years. Farther to the south off Long Branch, New Jersey, the U.S. Army Corps of Engineers placed sand offshore in water 12 m deep in an experiment on "natural" nourishment of the beach. Over a 4-year period, comparative bathymetric surveys showed slight modification of the sand, but it was still a prominent anomaly.⁵⁵ More recently, the Corps began an experiment involving offshore storage of sand for potential use, by rehandling, as beach nourishment material. Placed in nearly 15 m of

er offshore of Virginia Beach, this "shoal," after three years of sequential bathymetric profiling, shows only slight modification. Detailed examination of the shoal and its surrounding hydraulic environment is now in progress under a contract between Old Dominion University and the Norfolk District, Corps of Engineers.⁵⁶

Without question movement of shoals occurs, as does change in their size and shape. The magnitude of the change is difficult to predict at present, except to say that during northeast or tropical storms, when enough energy is coupled to the continental shelf water mass to produce currents exceeding the critical velocity for sediment movement, the bedforms will move or be otherwise modified.

WHAT ARE THE IMPLICATIONS OF THESE PROCESSES AND BEDFORMS FOR ENGINEERING AND DESIGN?

General

Bedforms are a manifestation of the movement of sediment. The presence of bedforms implies two basic facts: (a) energy exists to move the noncohesive sediment (for fine-grained sand this energy is ≥ 1.7 dynes/cm² at the sea floor⁴⁰); and (b) sediment exists to be moved. The effect of the force can be handled in conventional methods of design in the sense of stress analysis resulting from movement of the water column. Resolving problems of the consequences of the transport of sediments is more complex, since the sea bottom at a given time may not be where it was, or where it will be, at another. A few of the various scenarios relating to offshore activities and the effect of bedforms are discussed below.

Small-Scale Elements

Impacts of small-scale bedforms are most direct on small-scale structures. Such inereed objects as pipelines, electrical cables, and bottom-sited "christmas trees" (oil-well completion valve systems) will be affected differently when on the sea floor, buried, or suspended above the surface. If a conduit is buried, it must be negatively buoyant with respect to the sediment ($\rho_c > \rho_s$) to keep it from working its way to the surface. Furthermore, it should be designed to have considerable rigidity. If bedforms develop, the conduit can be excavated at the troughs and theoretically suspended at crests of sand waves of $\bar{H} = 1.9$ m and $\bar{L} = 210$ m. In addition to the bending moment created by gravity, the conduit would be subjected to loading from wave- and current-induced forces. Similarly, producing oil- or gas-well completion hardware,

when installed, could be above the sea floor. When necessary to service the wells or otherwise work with the device, it could be buried. Cooling water intakes, consisting of up to 2-m-diam pipes, if placed with their lower surface resting upon the sea floor, could also become closed by burial in a sand wave or shoal.

Large-Scale Elements

Because of their size and their elevation above the surrounding sea floor, these features could play a major role in the placement of large-scale facilities. Both gravity-type artificial islands and pile-supported oil-drilling platform structures could use the shoal as a foundation. In either case, movement of the shoal would undermine the facility and cause instability, damage, and possibly destruction. Closer shore, the tendency might be to use the shoal as a natural submerged breakwater and site a major facility "behind" it. Evidence of movement of shoals toward the southeast suggests that "behind" means on the northwesterly side of the shoal, away from the direction of movement. However, in so placing a structure, consideration must be given to the possibility of increased flow velocities due to the focusing of

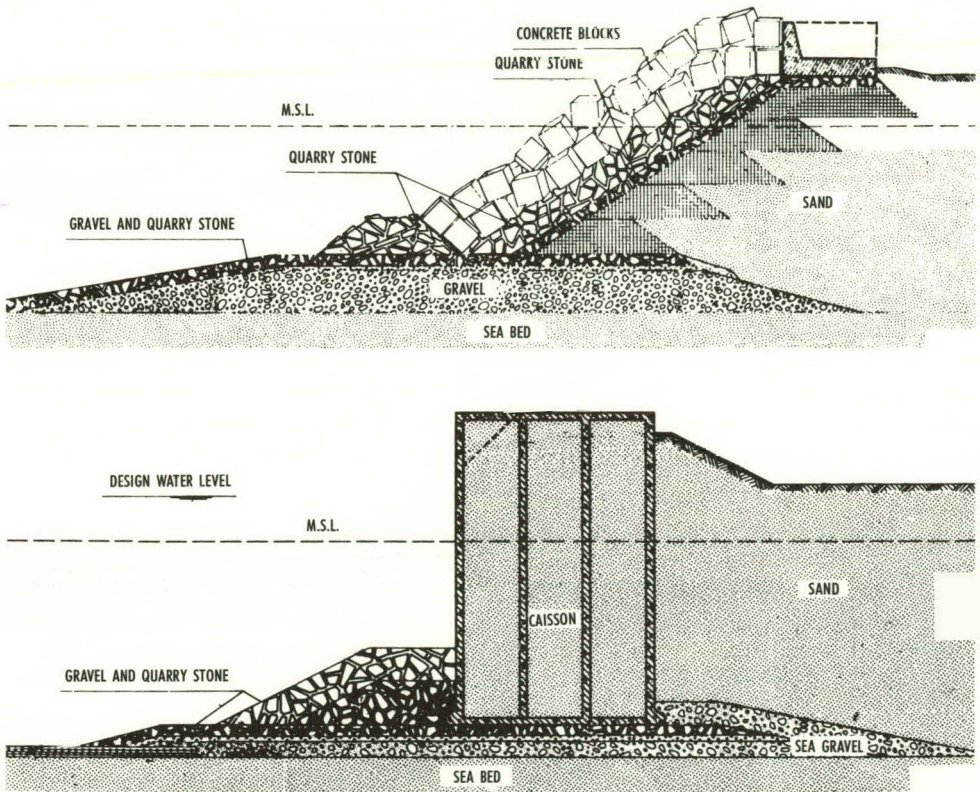


Figure 8. Two possible design profiles for a shelf-sited man-made island.
(Courtesy of *Ocean Industry Magazine*.)

water currents in troughs during northeast storms. Furthermore, the role the shoals would play in refraction of incident waves would need to be considered in siting a structure.

The sediment comprising the shoals is potential building material. Some designs for offshore islands call for large volumes of sand or other granular seabed material as the principal constituent of the island body. For example, Kelly⁵⁷ notes that the New York Bight is the possible site of several such islands in water ≈ 24 m deep. Assuming a top elevation of 10 m and a profile similar to those in Figure 8, an island of 50 hectares (1 hectare = 1×10^4 m², or 2.5 acres) would require $\approx 1.7 \times 10^7$ m³ of fill material. A 1200-hectare island would require $\approx 4.8 \times 10^8$ m³ of fill.

Large volumes of sand (and gravel) suited for fill exist on the U.S. Continental shelf, particularly the Atlantic shelf, as a presently exploitable resource.⁵⁸ Surveys conducted to date⁵⁹ show that 1.1×10^{10} m³ of sand exist. Of that number, 1×10^{10} m³ occur from Miami to Portland, Maine. Much of this sand occurs in shoals, the potential location of structures associated with energy production. Another potential use of large volumes of this sand is for beach nourishment.^{15,60-62} Consequently, competing demands for the same resource would need to be taken into consideration.

CONCLUDING REMARKS

The marine environment of the North Sea is more severe than that of the U.S. Atlantic Continental Shelf. Therefore, experience gained by companies engaged in energy production activities in the North Sea would be directly applicable to analogous activities on the Atlantic shelf. Although identical structures would certainly function as well here as there, they would probably be overdesigned rather than optimum. This would be somewhat uneconomical.

As long as offshore conditions, such as waves, can be measured only statistically, any structure will suffer damage sooner or later. For optimum design, the structure

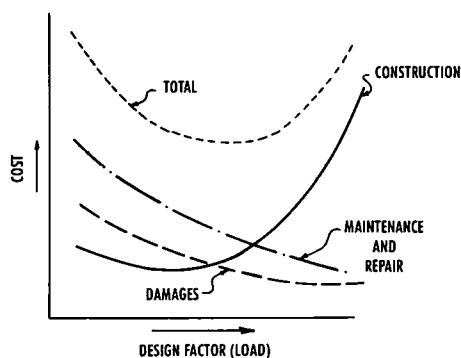


Figure 9. Schematic showing how various cost-design factors affect the total cost of a project. If the design factor (load) is small, construction costs will be low but damage and maintenance costs will be commensurately higher. As the design factor is increased, construction costs rise but damage and maintenance costs decrease.

or activity should meet requirements at minimum total cost commensurate with risks. To establish the proper relationships (Figure 9) requires knowledge of the cost of construction and the behavior of the structure, anticipated damage, and characteristics of the sea and sea floor.

The sea floor comprises a variety of forms, varying in scale through many orders of magnitude. Many of the forms are mobile, although at varying rates, responding in some measure to the energy imparted to the sediment through movement of the water mass. While factors relating motion of the water mass to movement of sediments and bedforms on the sea floor are not yet known with great accuracy, good estimates based on reasonable assumptions can be made which lead to optimum design characteristics. Continued research will lead to increased understanding and improved design.

Acknowledgements: This paper benefited from comments by Dr. John C. Ludwick (ODU), Prof. Ole S. Madsen (MIT), Dr. Thomas F. McKinney (Dames and Moore), and Dr. Harold O. Palmer (Westinghouse), and by Dr. Donald J.P. Swift (NOAA), who reviewed an earlier version. The author is responsible for omission of possibly major pertinent papers and for possible misinterpretation of the papers discussed.

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Distribution and Transportation of Suspended Sediment*

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INTRODUCTION

Suspended matter in the waters overlying the continental shelf constitutes a potential vehicle for the accumulation and dispersal of contaminants that would be generated by energy-related activities proposed for shelf regions. The effectiveness of this vehicle as a transport mechanism depends on the concentration and character of the suspended material and on the routes and rates of transport.

The primary purposes of this paper are (1) to briefly review the literature on the suspended matter of the waters overlying the Atlantic shelf of the United States, (2) to assess the significance of suspended matter as a mechanism for transporting oil and radionuclides back to the coast and therefore to man, and (3) to determine whether additional studies of suspended-matter dispersal systems are required for preparation of environmental impact statements that would be associated with siting of nuclear power plants and oil drilling on the Atlantic shelf. The paper is largely a review paper, but some new data are presented.

Throughout the discussion, the terms suspended sediment, suspended matter, and total suspended solids are used interchangeably.

SOURCES OF SUSPENDED MATTER

Suspended matter is added to continental shelf waters by discharge from estuaries, erosion of the contiguous coast, the atmosphere, the resuspension of bottom sediments by tidal currents and waves, transport from more seaward areas, chemical precipitation, and by primary productivity. The particles are inorganic (both naturally occurring and anthropogenic) and organic (both living and dead).

The relative importance of the several sources of suspended matter varies not only spatially over the shelf at any given time, but also temporally. There have been few attempts to assess the relative importance of the several sources. Meade et al.¹ attempted to evaluate, at a number of stations on the Atlantic shelf, the relative contributions from three generic "sources" of suspended sediment - sediments discharged by rivers and estuaries; sediments resuspended from the bottom by waves, tides, and benthic organisms; and organic particulate matter produced in shelf waters. Their assessment was based entirely on the vertical distribution of total suspended matter at each station and the partitioning of this total between the organic and inorganic particulate fractions.

*Contribution 143 of the Marine Sciences Research Center of the State University of New York.

Meade et al.¹ in their study of the distribution of suspended matter between Cape Cod and Cape Hatteras, found that in September 1969 only off the mouth of Delaware Bay did a high near-surface concentration of predominantly inorganic suspended matter indicate estuarine discharge as the predominant source of suspended matter. Stations southeast of New York Harbor were characterized by relatively high surface and near-bottom concentrations separated by lower values at intermediate depths. Meade et al.¹ point out that if these high surface values are produced by discharge from the Hudson River they probably reflect increased organic production under the influence of river-borne nutrients, since the material was mostly organic ($>75\%$ by mass). According to them, "Where bottom sediment is fine grained, where the water is shallow, or where benthic organisms are actively resuspending the sediment, bottom sediments may be an important constituent of the suspended matter; where bottom sediment is coarser and the water is deeper, bottom sediments do not contribute as much suspended matter under usual conditions." Meade et al.¹ reported that the greatest concentrations of suspended matter over the shelf southeast of Long Island were near the bottom, and they attributed this to the local resuspension of relict silty sand and mud that blankets this segment of the shelf. The near-bottom concentrations they observed are similar to those reported by Spencer and Sachs² in near-bottom water overlying muddy areas of the Gulf of Maine.

Meade et al.¹ found that over most of the shelf between Cape Cod and Cape Hatteras in September 1969 the suspended matter was predominantly organic matter produced by primary production. In surface waters over the shelf and upper slope, combustible organic matter averaged about 80% of the total concentrations of suspended matter, and in near-bottom waters it averaged about 40% of the total concentrations. They estimated that in the whole area from Cape Hatteras to Cape Cod in September 1969 there were about 2.8×10^6 metric tons of particulate matter in suspension, of which about 1.2×10^6 tons were inorganic.

There are no reliable estimates of the absolute strengths of the various "ultimate" sources of inorganic suspended matter to the waters overlying the shelf. Probably the most readily determinable source is fluvial input, but not even estimates exist of the discharges of fluvial sediment to the sea. The suspended-sediment discharge data for the rivers of the eastern seaboard of the United States³⁻⁵ are of little use in predicting the discharges from the estuaries of these rivers to the ocean. Indeed, there is evidence that estuaries may be sinks rather than sources of suspended sediment to the ocean. A simple, single-segment mathematical model recently developed by Schubel and Carter⁶ to estimate the exchange of suspended sediment between the ocean and Chesapeake Bay indicates that the Chesapeake Bay acts as a sink for sediment suspended in shelf waters, rather than a sediment source.

The resuspension of shelf sediment is an extremely inconstant source of suspended sediment to the waters overlying the shelf. Its strength is a function of the intensity of scour, the texture and fabric of the sediment, and the activity of benthic organisms. The intensity of scour is determined largely by the wave and current action and by the water depth. Since most of the Atlantic shelf is covered with relatively coarse-grained relict sands, resuspension is a significant source of suspended

sediment only locally where fines predominate, or very near the bottom during storms when sand is resuspended.

DISTRIBUTIONS OF SUSPENDED MATTER IN TIME AND SPACE

Normal Range of Conditions

Prior to the late 1960's there were few observations of the suspended matter in the waters overlying the Atlantic Shelf, and no systematic studies to document the variations of the distribution of suspended matter in either time or space over any substantial segment of the shelf.

The paucity of suspended-matter data is due in large part to the difficulty and expense associated with making measurements of suspended matter in the ocean. Since concentrations in shelf waters are low – generally not more than a few milligrams per liter on the inner shelf and a few tenths of a milligram per liter on the outer shelf – relatively large (1 to 10-liter) volumes of water must be processed to separate enough material for precise and accurate determinations of the concentration of suspended matter. Extreme care is required in sampling and analysis to avoid contamination by ship dirt, and particularly by sea salt. Manheim et al.⁷ and Meade et al.¹ recently discussed problems of sea salt contamination resulting from insufficient rinsing of filters. For chemical and mineralogical studies of the suspended particles, even larger (10 to 50-liter) volumes of water must normally be processed to recover sufficient material for analysis.

Suspended matter can be removed from the water either by high-speed centrifugation or by filtration of the water through membrane filters with small ($\leq 0.8 \mu\text{m}$) mean pore diameters. The water can be collected for shipboard analysis with submersible pumps, with any one of a variety of water bottles, or with special *in situ* filtering devices.^{2,8}

Two recent reviews of methods and instruments used in studying suspended matter in water^{9,10} can be consulted for additional information. In my opinion, at present the most effective way of determining concentrations of suspended matter in shelf waters is by shipboard filtration of water samples collected in water bottles of the Niskin or Van Dorn type. On the inner shelf, pumped water samples are acceptable if adequate precautions are taken to purge the lines between samples. I recommend pore sizes of 0.4 to 0.6 μm and favor polycarbonate filters over cellulose membrane filters for gravimetric analysis because of their greater stability.

Optical devices have also been used to study suspended matter, but are not salt with here. At present, such devices probably have their greatest use in suspended sediment studies of shelf waters in selecting locations for collection of samples of suspended matter by filtration. In a recent study, Meade et al.¹ compared gravimetrically determined suspended sediment concentrations in shelf and slope waters with light-scattering measurements made with a laser nephelometer at the same sample sites. They reported that the correlation was satisfactory in slope waters but poor on the shelf. The concentration of suspended sediment corresponding to a given nephelometer reading in shelf waters varied by as much as a factor of 2.5. The investigators were unable to satisfactorily explain the poor correlation and con-

cluded that "The nephelometer apparently cannot resolve differences in suspended concentrations within the narrow range that was measured at these stations – 50 to 200 μg per liter, except where the nephelometer went off scale."

The most comprehensive studies, at least geographically, of suspended matter in the waters overlying the Atlantic Continental Shelf that have been reported in

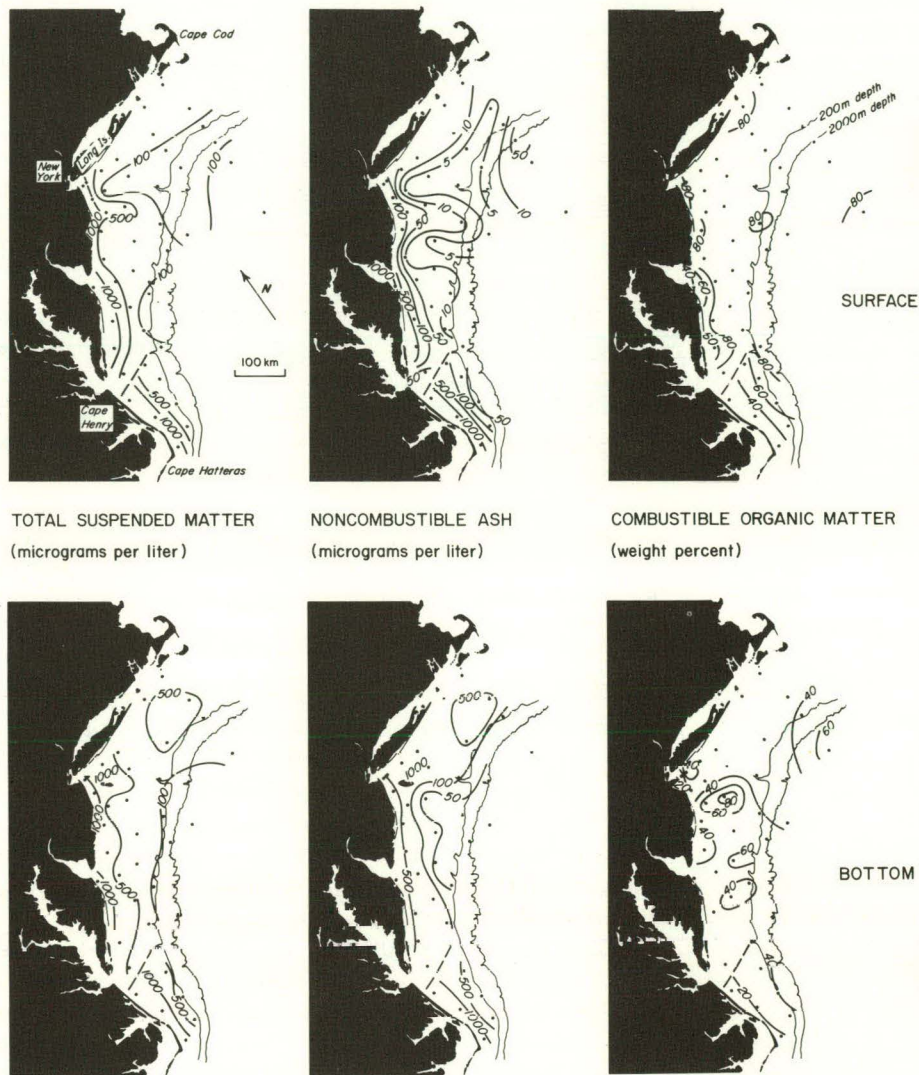


Figure 1. Maps showing distribution and composition of suspended matter in near-surface and near-bottom waters of the Middle Atlantic Bight, September 1969. Surface samples from 5 to 6-m depth; bottom samples taken within 2 to 5 m of bottom. Dashed line across continental shelf near Cape Henry separates storm-affected sampling area (south of dashed line) from non-storm-affected area (northeast of line). (From Meade et al.¹)

the literature are those of Manheim et al.⁷ and Meade et al.¹ The latter reported the results of observations of suspended matter in the Middle Atlantic Bight (Cape Cod to Cape Hatteras) made in September 1969. These investigators gravimetrically determined the vertical distribution of the concentration of total suspended matter at about 50 stations. They also made measurements of particulate carbon, combustible organic content and mineralogy of the suspended particulate matter, and, with a laser nephelometer, the light-scattering character of the suspended particles.

The general spatial distributions of total suspended matter, noncombustible ash, and combustible organic suspended matter in the surface and near-bottom (≈ 2 m above the bottom) waters in September 1969 determined by Meade et al.¹ are shown in Figure 1. The concentrations of total suspended matter and noncombustible ash in both surface and near-bottom waters generally decreased seaward. Concentrations of total suspended matter in the waters over the inner shelf ranged from $< 500 \mu\text{g/liter}$ (0.5 mg/liter) to $> 1000 \mu\text{g/liter}$ (1.0 mg/liter), while concentrations over the middle and outer shelf typically ranged from < 100 to $500 \mu\text{g/liter}$ (0.1 to 0.5 mg/liter). Between Cape Henry and Cape Hatteras concentrations of total suspended matter and of noncombustible ash over the middle and outer shelf were greater than farther north. The cross-shelf gradient in the concentration of noncombustible ash in near-bottom waters was less than that near the surface. Figure 1 clearly shows that organic matter constituted a greater fraction of the total suspended matter in surface waters than near the bottom; the combustible organic fraction averaged about 80% by mass in surface waters and only 40% in near-bottom waters.

The results reported by Manheim et al.⁷ for the distribution of total suspended matter in surface waters in the same region in May and June 1965 are in agreement with those determined by Meade et al.¹ in September 1969. Manheim et al. reported determinations of the concentration of total suspended matter for about 600 surface samples collected at stations from Cape Cod to the Florida Keys in May and June of 1965. They also estimated the percent of the total concentrations accounted for by combustible organic matter, and microscopically measured the sizes of suspended mineral particles. They reported that "Waters containing more than 1 mg/liter of suspended matter are generally restricted to river mouths, estuaries, and a narrow nearshore zone less than 10 km wide. Surface waters over the continental shelf and slope generally contained less than 0.125 mg/liter of total suspended matter, most of which (60 to 90 percent) consisted of combustible organic matter. Local increases in concentrations of terrigenous suspended matter were noted offshore from promontories such as Capes Hatteras, Lookout, and Fear, from the discharge areas off the mouths of the Pee Dee, Santee-Cooper, Savannah, and Altamaha rivers, and off the mouth of Long Island Sound."

The studies by Manheim et al.⁷ and Meade et al.¹ are the only published regional observations of the suspended matter in the waters overlying the Atlantic Continental Shelf. There have been a number of more local studies.^{2,11-14}

Drake¹⁴ initiated an intensive sampling program to document the distribution of total suspended matter in both time and space in the New York Bight. Observations were also made of the size distribution of the inorganic particles and of the

combustible organic matter. The program is being continued and expanded by Robert Young of the Atlantic Oceanographic and Meteorological Laboratory (Miami) of NOAA.

Spencer and Sachs² made suspended-sediment sampling cruises in September 1966, March 1967, and October 1967 to the Gulf of Maine, a partially enclosed basin of glacial origin. The bottom sediments of the gulf are characterized by soft muds of Recent age in the depressions and by sands and gravels of Pleistocene age on the ridges separating the individual basins. Spencer and Sachs found that the concentration of total suspended matter normally decreased from the surface to about 50 m and then increased exponentially as the bottom was approached. The

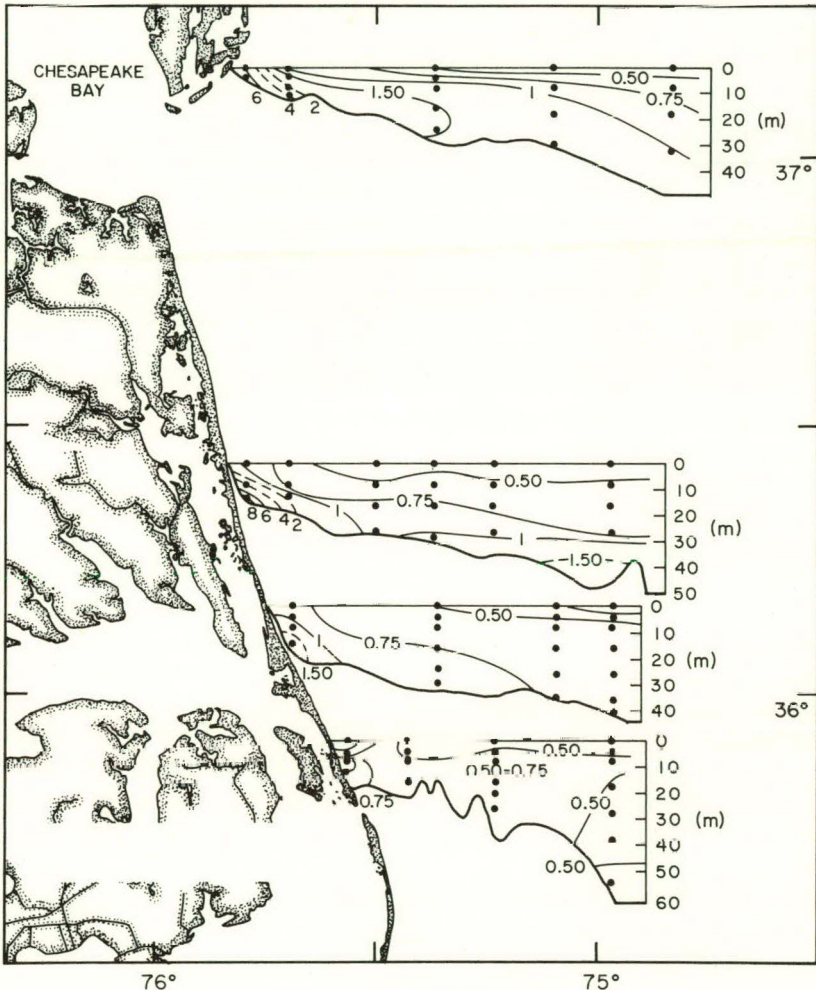


Figure 2. Distribution of total suspended solids (mg/liter) on cross-shelf sections between Chesapeake Bay and Cape Hatteras, May 10-19, 1971.

total concentrations ranged from <0.05 mg/liter to >1 mg/liter, and averaged ≈ 0.30 mg/liter in the upper 50 m and ≈ 0.43 mg/liter in deeper waters. Surface concentrations of total suspended matter reported by Spencer and Sachs for the Gulf of Maine are in the range reported by Manheim et al.⁷ and Meade et al.¹ for the open Atlantic Shelf. The relative abundance of organic suspended matter is also comparable – 60 to 90% of surface suspended matter is combustible. Spencer and

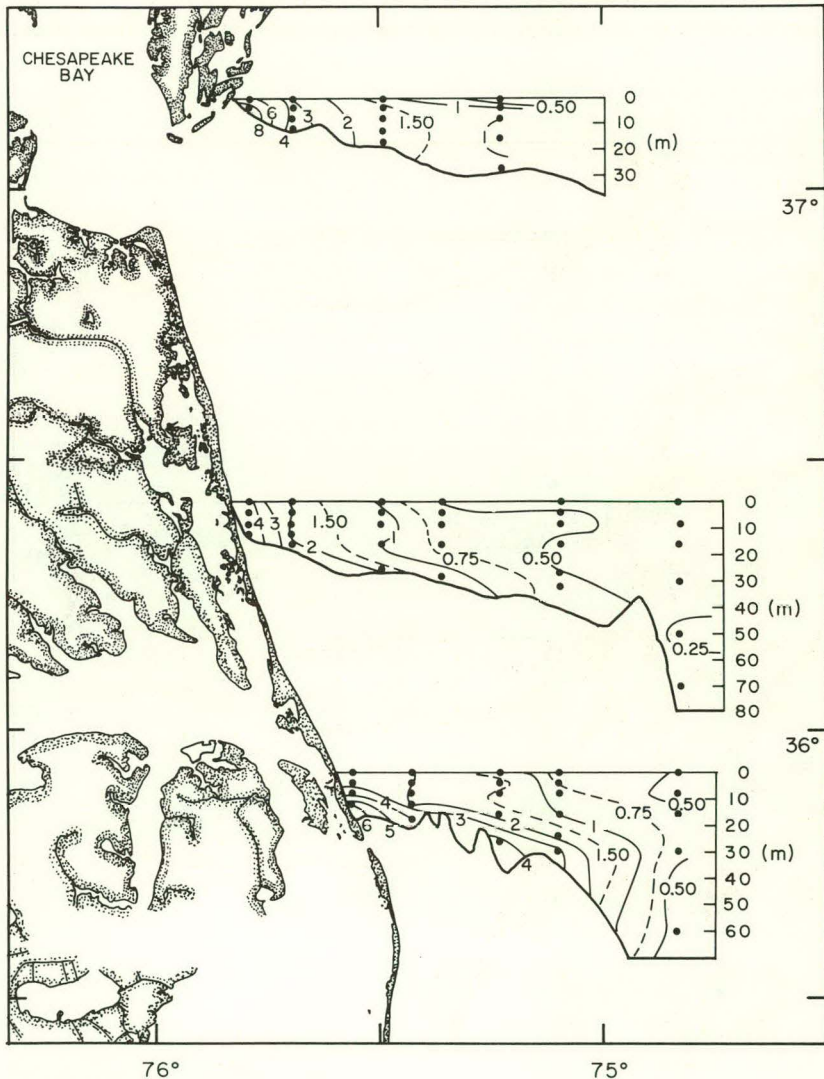


Figure 3. Distribution of total suspended solids (mg/liter) on cross-shelf sections between Chesapeake Bay and Cape Hatteras, Nov. 14-24, 1971.

Sachs reported exponential increases in suspended matter very near the sea floor, which they ascribed to the resuspension of fine bottom sediments.

Spencer and Sachs² considered that resuspension, biological and physical, was the dominant process in determining the distribution of inorganic suspended sediment in the Gulf of Maine. They based their conclusion on the vertical distribution of inorganic suspended matter and on the total mass of inorganic material in suspension. They estimated the total amount of inorganic suspended matter in the Gulf of Maine as $\approx 3.7 \times 10^{10}$ kg. While this value appears to this investigator to be too high on the basis of an examination of their data, the amount of inorganic material in suspension is almost certainly higher than can be accounted for by the fluvial inputs.

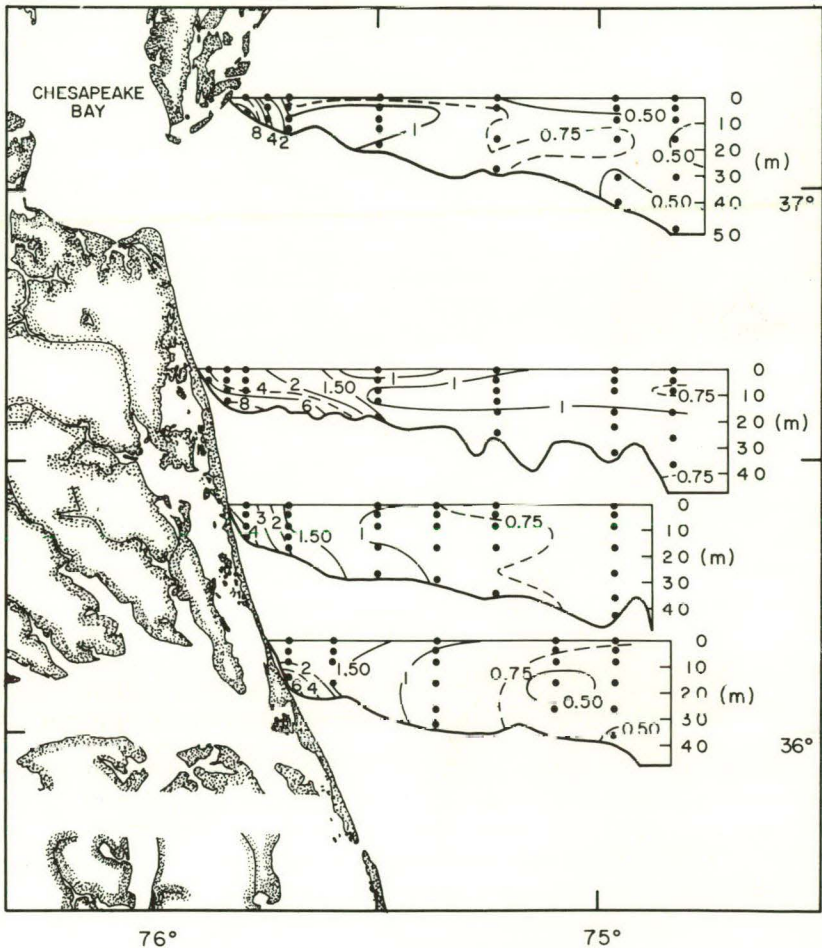


Figure 4. Distribution of total suspended solids (mg/liter) on cross-shelf sections between Chesapeake Bay and Cape Hatteras, Jan. 26–Feb. 2, 1972.

Schubel¹⁵ studied the distribution and character of suspended matter between $37^{\circ} 20' \text{ N}$ ($\approx 15 \text{ km}$ north of the entrance to Chesapeake Bay) and $35^{\circ} 25' \text{ N}$, Cape Hatteras. Nine cruises were made at about 1 to 2-month intervals between February 1971 and July 1972. This is the only study to systematically document the distribution and character of the suspended matter in time, as well as in space, over a substantial segment of the Atlantic shelf. Suspended sediment samples were collected from the surface and from a series of depths to within $\approx 2 \text{ m}$ of the bottom by filtration of 2 to 10-liter water samples through $0.4\text{-}\mu\text{m}$ APD polycarbonate filters.

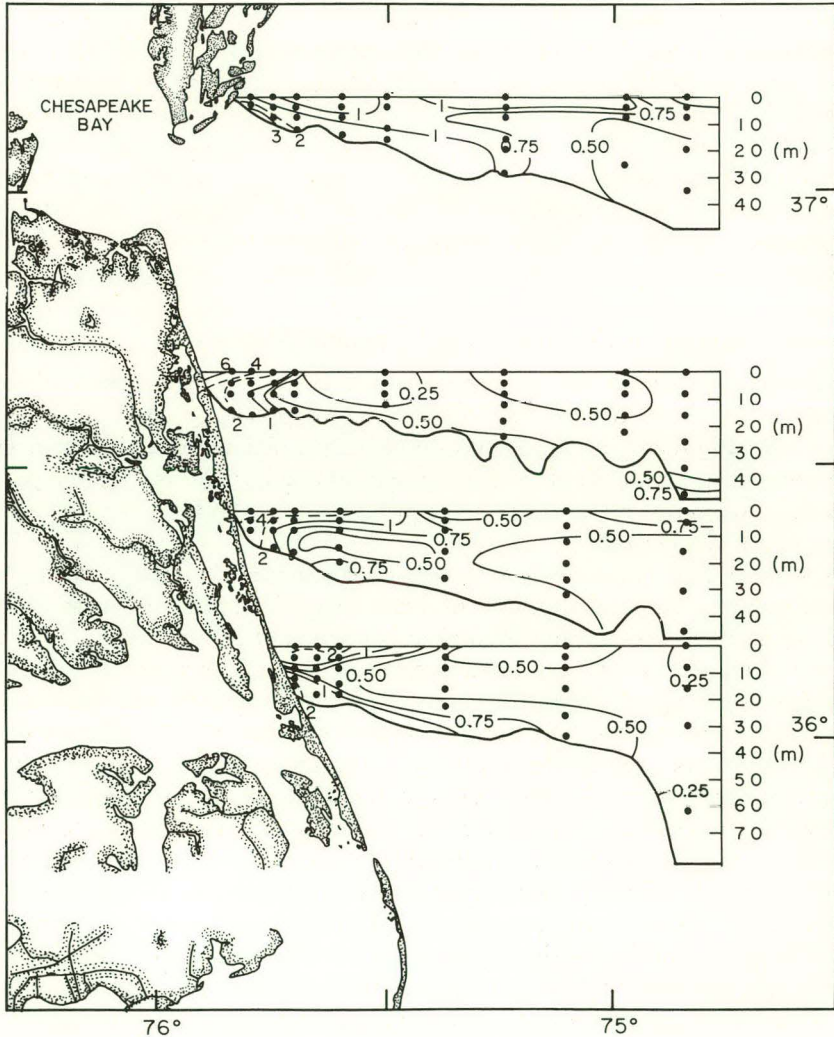


Figure 5. Distribution of total suspended solids (mg/liter) on cross-shelf sections between Chesapeake Bay and Cape Hatteras, July 30–Aug. 2, 1972.

The distributions of total suspended matter observed on several cross sections on four different cruises are shown in Figures 2 to 5. The values are not discordant with those reported by other investigators^{1,7} for this same shelf segment for similar times of the year. Concentrations of total suspended matter over the inner shelf ranged from <1 to >10 mg/liter. The distributions over the inner shelf appear to have been dominated primarily by resuspension and, to a lesser extent, by discharge from estuaries and erosion of coastal marshes. Vertical gradients of the concentration of total suspended matter are highly variable.

In the waters overlying the middle and outer shelf concentrations of total suspended matter are lower and less variable than farther inshore. The range in concentration over the outer shelf was ≈ 0.25 to 1.5 mg/liter. In the waters overlying the middle shelf, it was ≈ 0.25 to 2 mg/liter, except near the bottom, where concentrations reached values as high as 4 mg/liter during a period of rough seas in November 1971 (Figure 3). The effects of the major flood following Tropical Storm Agnes in late June 1972 can be clearly seen in the near-surface waters south of the entrance to Chesapeake Bay in July 1972 (Figure 5). The effects of Agnes are briefly discussed in a later section of this report, and a complete discussion of the data presented in Figures 2 to 5, and of other data in this series, is now being prepared.

Effects of Events on the Distribution of Suspended Matter

Most observations of suspended matter in shelf waters are representative of the "typical" range of conditions. Few observations have been made of the effects of severe storms and floods on the distribution of suspended matter in waters overlying the Atlantic Continental Shelf. The infrequency of such events makes the likelihood of fortuitous observations small, and sampling during episodes is generally difficult and frequently dangerous.

Rodolfo et al.¹³ reported the effects of Hurricane Gerda in September 1969 on the distribution of suspended matter in shelf waters off Cape Lookout, North Carolina. They made determinations of total suspended matter at a series of stations on a transect extending from shore out to a distance of nearly 80 km before and after passage of Gerda through the area. Maximum wind speeds near the center of the storm off the North Carolina coast were ≈ 130 km/hr. All samples were collected from the Cape Lookout suspended-sediment plume that extends over the shelf from the Cape and can be clearly seen in satellite photographs. During the first sampling period, the week prior to Gerda, winds were gentle and seas calm. During the second, which began 36 hr after Gerda's nearest approach to Cape Lookout, winds averaged about 40 km/hr, and the investigators reported that rough seas hampered and limited their work. During the third sampling period, of stations farthest offshore, 5 to 6 days after passage of the hurricane, winds were <20 km/hr, and "the sea was correspondingly calmer." Before passage of Gerda, typical concentrations of total suspended matter in surface waters were 0.5 mg/liter within 2 km of the shore, between 0.2 and 0.3 mg/liter at 2 to 30 km from shore, and 0.1 mg/liter, or less, farther offshore. Mid-depth concentrations were slightly lower, and there was frequently a secondary maximum near bottom. Shortly after the storm, surface concentrations 2

km offshore had increased by about 40%, and at 10 km offshore in depths of about 15 m both near-surface and near-bottom values had increased by more than an order of magnitude, from ≈ 0.2 mg/liter to > 2 mg/liter. At 20 km offshore in depths of about 23 m, maximum concentrations were observed near the bottom, where increases of more than an order of magnitude were reported. At 60 km offshore in depths of from 48 to 60 m, the concentrations of total suspended matter increased by as much as a factor of two over pre-storm levels. On reoccupation of the outer shelf stations 5 to 6 days after the storm, the concentrations were found to have dropped to pre-hurricane levels.

It is clear that the increases in the concentration of suspended sediment following the passage of Gerda were produced largely by the resuspension of bottom sediments and that the high values did not persist. The effect of Gerda on the transport of fine sediment is obscure, but, according to Rodolfo et al.,¹³ "Transport of inner shelf sediment to the outer Carolina shelf may be accomplished mainly by such storms."

Drake¹⁴ estimated that moderate storms with 1 to 2-m seas increased the concentrations of total suspended matter throughout the water column in the New York Bight by an average of about 0.5 mg/liter – an increase of 10 to 80% of pre-storm values. Pierce et al.¹⁶ reported that on the shelf off the southeastern U.S. near-bottom concentrations of suspended matter were increased by an order of magnitude during rough seas (October) relative to those observed during calm seas (August).

Meade et al.¹ reported a number of observations made on the inner shelf southeast of the entrance to Chesapeake Bay near the end of a three-day northeaster. They found relatively high concentrations of suspended sediment (predominantly inorganic) throughout the water column, with values increasing near the bottom. Maximum concentrations reached 3 mg/liter. No pre-storm concentrations were available for comparison.

The primary effect of wind storms on the distribution of suspended matter is to increase the concentrations of suspended matter, particularly near the bottom, by the resuspension of bottom sediments. For given wave conditions, the amount of resuspension will be determined largely by the water depth, the texture and fabric of the sediment, and the activity of the benthic organisms.

Flooding can also significantly affect the distribution of suspended matter in shelf waters. The only published observations of the effects of a major flood on the suspended matter of the Atlantic shelf are those made following Tropical Storm Gnes (June 1972). Flooding of the major tributary rivers to the Chesapeake Bay following this storm was of such magnitude that it had an estimated recurrence interval of 200 years, and Schubel¹⁷ reported that in the 10-day period following passage of the storm the Susquehanna River discharged more than 25 times as much suspended sediment into the upper Chesapeake Bay as it had during the entire previous year. Most of this sediment, and most of that discharged by the other tributary rivers, was deposited within the Chesapeake Bay, but significant amounts did reach the sea.

One cruise was made on the continental shelf between July 28 and Aug. 2, 1972, about one month after the Susquehanna had crested at its mouth near the

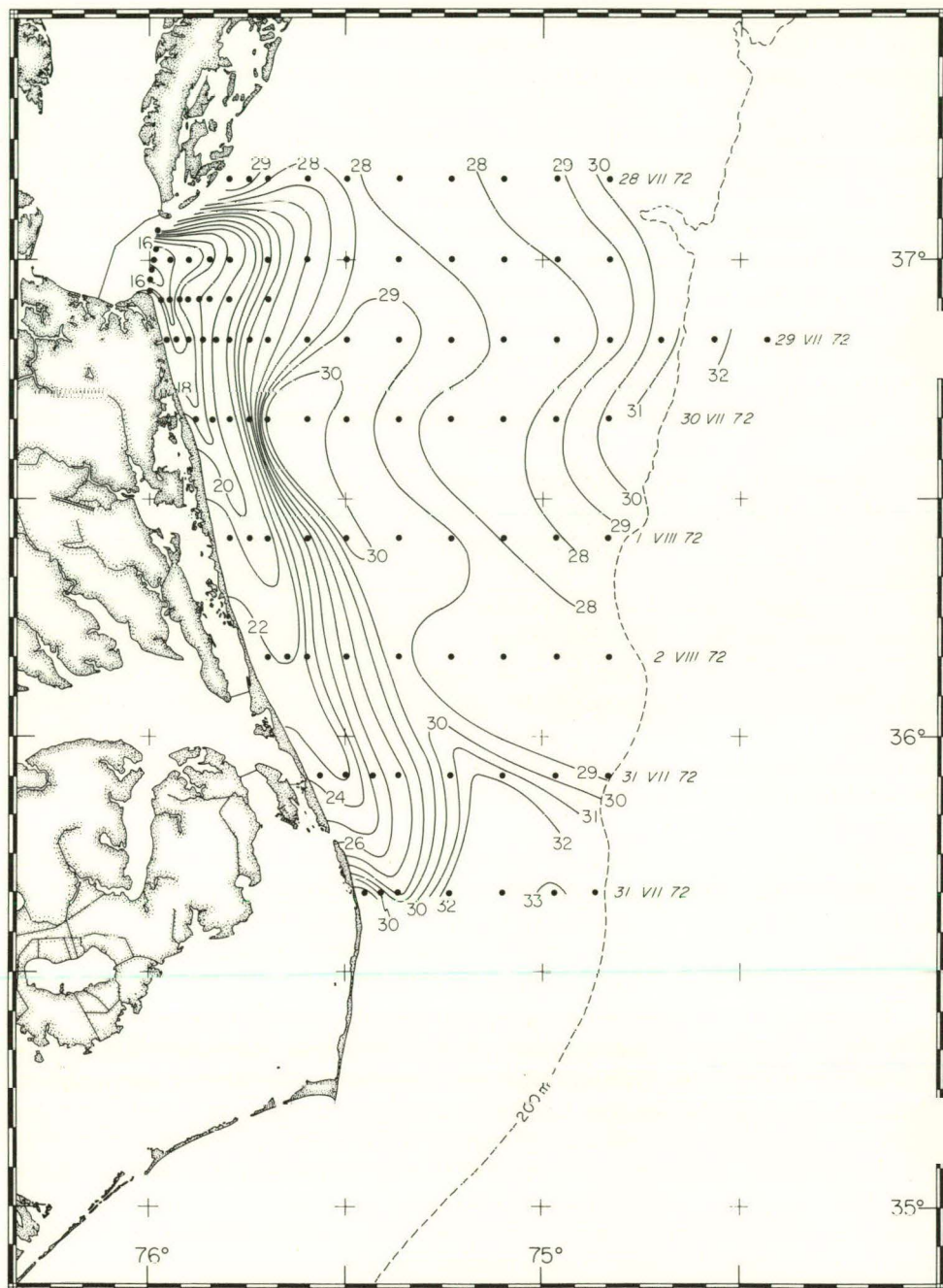


Figure 6. Distribution of surface salinity (‰) in the waters overlying the continental shelf between Chesapeake Bay and Cape Hatteras, July 28-Aug. 2, 1972, following Tropical Storm Agnes.

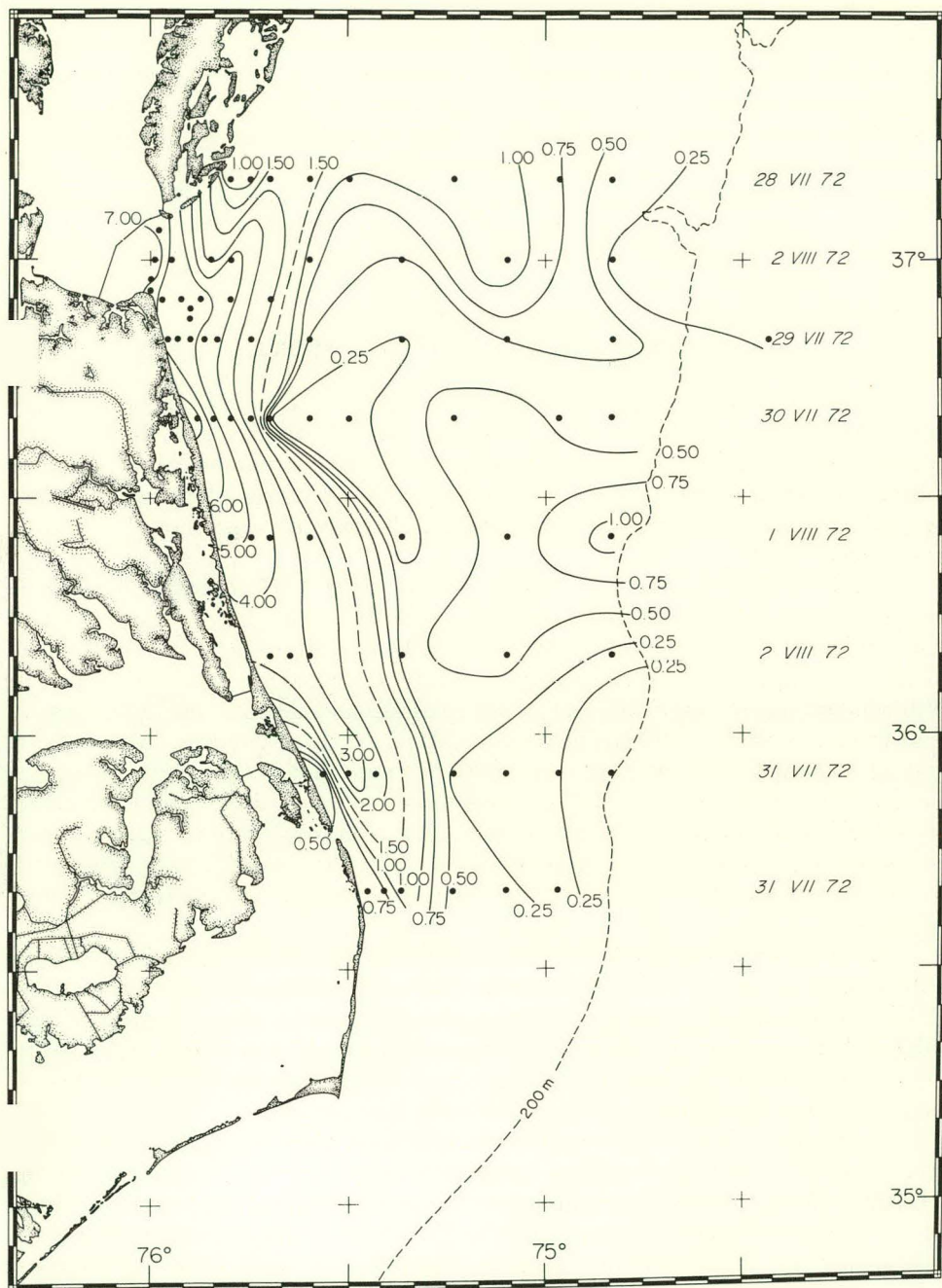


Figure 7. Distribution of total suspended solids (mg/liter) in the surface waters overlying the continental shelf between Chesapeake Bay and Cape Hatteras, July 28–Aug. 2, 1972, following Tropical Storm Agnes.

head of the bay, and at about the time minimum salinities were observed in the mouth of the bay. The outflow from the bay at that time could be traced as a band of low-salinity water that turned south after leaving the bay and moved along the Virginia and Carolina coasts (Figure 6). This band was also characterized by relatively high concentrations of suspended sediment, higher than any previously reported for this segment of the shelf (Figure 7). There was little apparent effect on the suspended matter in the waters overlying the middle and outer shelf. The ultimate fate of the suspended sediment discharged from the bay during Agnes is obscure, but it appears likely that a significant fraction crossed the shelf off Cape Hatteras.

ROUTES AND RATES OF TRANSPORT

It is obvious that fine-grained suspended matter is transported by both advection and diffusion, and that in order to establish the prevailing routes, and particularly the rates of transport, relatively long-term physical observations are required in addition to determinations of the concentrations and settling velocities of the suspended particles. It is surprising that there is such a paucity of data on the circulation of shelf waters.

In 1955 Iselin¹⁸ summarized, primarily in the context of application to fisheries problems, what was then known concerning shelf circulation. Iselin considered that the circulation of Atlantic shelf waters off the United States between Nantucket Shoals and Cape Hatteras was primarily density driven as a result of river inflow, with wind serving to modify normal current patterns and to supply energy for small-scale mixing processes. This concept was based primarily on available temperature and salinity data, which at the time were widely separated in both time and space. Iselin concluded his review with the observation that only a limited understanding of shelf circulation would be possible until continuous observations were made at well-selected points over the continental shelf. In his view, such observations would provide the means of evaluating the influences of runoff, local winds, and offshore currents.

The foregoing concepts of shelf circulation had been little modified by 1969, in spite of the large amount of drift-bottle and seabed drifter data acquired during the 1960's, when Carter¹⁹ reviewed the status of our knowledge of the mean shelf circulation between Nantucket Shoals and Cape Hatteras. Carter considered as mean motion flows that were shelfwide in extent and seasonal in persistence, and his review was primarily from the standpoint of waste management.

A somewhat different picture has emerged since 1969 as a result of the development and deployment of current meter arrays capable of sensing and recording measurements of current speed and direction over relatively long periods of time, say, 30 days. However, even as recently as 1972 Stommel and Leetmaa²⁰ verified their wintertime shelf circulation model by inferring net flows from the recovery data for surface and bottom drifters because no representative current meter records were available to them.

In the past several years the number of direct current meter measurements made and reported for Atlantic shelf waters has increased dramatically.^{21,22} These

data show that, although the seasonally varying salinity and temperature patterns are *often* reflected in the circulation, the strongest flows are highly variable in time, that they are wind driven, that they are well correlated in the along-shore direction during both high and low flow conditions, and that cross-shelf flows are less well correlated except for high flows.

Boicourt and Hacker's measurements²¹ reveal periodic exchanges of shelf and slope water in the middle Atlantic Bight as a result of southerly wind events which drive an offshore motion in the upper Ekman layer and a return flow of high-salinity slope water; a return flow in the bottom Ekman layer during unstratified conditions (winter); and a return flow in mid-depth waters during stratified conditions (summer). Beardsley and Butman²² also reported circulation patterns dominated by *ort*, intense wind events.

These studies and others currently in progress (see Niiler²³ for an up-to-date review) strongly suggest that the major signal in the current meter records may be predictable with a time-dependent wind-driven circulation model. One such model was given by Hopkins.²⁴ These large transient flows should be extractable from the total record to permit examination of the low-frequency (seasonal) density-driven flows.

In the shelf waters between Cape Cod and Chesapeake Bay there is a small net (residual) transport of water from the shore to the ocean. This net seaward flow must exist because the supply of fresh water from rivers is about five times as great as the excess of evaporation over precipitation along this stretch of the continental shelf.²⁵ There is still little direct information concerning the long-term residual flow pattern. The few investigations published indicate a prevailing offshore component of the surface flow.²⁵⁻²⁷ The data also indicate a residual landward flow near the bottom on approximately the inner third of the shelf, and a seaward flow across the remainder. Estimates of the rate of residual bottom flow, based on seabed drifters, range from about 0.4 to 1.0 cm/sec. Currents inferred from the movement of drifters include both advection and diffusion. Schubel and Okubo²⁸ estimated that throughout a water column of the shelf between Cape Cod and the Chesapeake Bay one might expect, on the average, a long-term offshore advective flow of very small velocity, probably ≤ 0.1 cm/sec, except on the inner shelf where there is a net landward flow. The offshore "diffusive velocity" may be about 1 cm/sec.

It is not clear whether the transport of fine suspended matter is dominated by short, intense wind-driven events or by the large-scale residual, seasonal density-driven flows. The relative effectiveness of these mechanisms probably varies over the shelf, but in view of the fine-grained character of the suspended matter in the Atlantic shelf waters, the lack of any large inputs of inorganic terrigenous sediment, and the coarse relict sediments that blanket most of the shelf, it appears likely that the more persistent density-driven flows may control long-term dispersal of fine suspended sediment over most of the shelf. Locally, where the shelf is narrow or the bottom is covered with fine sediments, transport during storms may dominate.¹³

A recent review²⁹ on shelf-sediment transport clearly revealed the paucity of data on the dispersal of suspended sediment on the world's continental shelves. Only one model has been proposed for the transport of fine-grained suspended sediment in the waters overlying the Atlantic shelf.²⁸ Schubel and Okubo²⁸ constructed a sim-

ple steady-state, two-dimensional mathematical model to predict the long-term average distribution of suspended sediment in shelf waters. They applied the model to a section across the shelf off the entrance to Chesapeake Bay and used the results to estimate the flux of fine-grained particulate matter across the shelf to the deep sea. Their calculations indicated that the cross-shelf flux of sediment associated with the mean (residual) flow could account for most of the mass of sediment that is estimated from erosion rates to reach the ocean basin. The model was not designed to describe temporal variations in the distribution of suspended matter, local features such as plumes of turbid water off promontories of the coast, or nearshore events. The formulation of their model and the preliminary results are not in conflict with the irrefutable evidence that the preponderance of inorganic terrigenous sediment trapped in estuaries and marshes. The model does indicate that sediment that ultimately escapes the coastal zone and reaches the middle shelf will probably "bypass" the remainder of the shelf and be deposited on the continental slope and rise.²⁸ Their model should be applied to the inorganic fraction, rather than to the concentrations of total suspended matter, and should be refined to allow the diffusive and advective fluxes of sediment to be independently assessed. Such a refinement requires data on the flux of sediment through the inshore boundary, and these data unfortunately are not available.

SOME COMMENTS ON SUSPENDED SEDIMENT AND ENERGY-RELATED CONTAMINANTS

Suspended Sediment and Oil

The movement and dispersal of oil may be affected by the incorporation of suspended particles, which increase its density. Oil sinks after its density exceeds that of the surrounding water. The density of oil is increased not only by inclusion of particulate matter but also by evaporation of the oil's more volatile fractions and by oxidation.³⁰⁻³² The effectiveness of suspended matter in a particular region as a dispersive vehicle depends largely on its concentration and physical character, particularly its density. Oils readily take up suspended particles, and the incorporation of sufficient inorganic material with densities typically ranging from 2.2 to 2.8 g/cm³ will increase the density of the mixture to the point that it sinks.^{30,32-34} Following the Santa Barbara spill, suspended sediment apparently played a major role in the sinking of large quantities of crude oil.³⁵ The concentrations of suspended matter were very high, probably thousands of milligrams per liter, as a result of extreme flooding. Powdered chalk was intentionally added to oil from the Torrey Canyon spill to facilitate sinking. According to Bone and Holme³⁶ the French claimed to have sunk at least 20,000 tons of Torrey Canyon oil in the Bay of Biscay by using 3000 tons of steartated chalk. Whether the intentional sinking of spilled oil is a desirable practice depends upon the location of the spill and on the character of the bottom and its flora and fauna.

It is of interest, and perhaps useful, to ask whether the levels of particulate matter typically suspended in the waters overlying the middle and outer Atlantic Continental Shelf might have a significant effect on the sinking of spilled oil. Consider

the case in which crude oil with a density of 1.0 g/cm^3 forms a layer 0.003 cm ($30 \text{ }\mu\text{m}$) thick at the surface over a segment of the middle and outer Atlantic shelf. It is unlikely that the concentration of total suspended matter in the surface layers would reach 1 mg/liter , but let us use this value to assess the greatest effect that suspended matter might have on accelerating the sinking of spilled oil. Let us further assume that 50% (by mass) of the total suspended matter is organic, with a mean density of 1.01 g/cm^3 , and that 50% is inorganic material with a mean density of 2.65 g/cm^3 . Since the relative abundance of organic matter is probably closer to 75 to 90% of the total suspended matter on the middle and outer shelf, our estimate of the mean density of the total suspended matter will be exaggerated. Next, assume that *all* the suspended matter in the upper 1 m of water is incorporated into the overlying oil layer. Under these conditions, what is the effect of the suspended matter on the density of the oil? We are assuming that no other processes affect the density.

On making the appropriate calculations, the density of the oil-sediment mixture turns out to be $\approx 1.015 \text{ g/cm}^3$. If we assume an efficiency of removal of particulate matter of 10% instead of 100%, the increase in ρ resulting from removal of 10% of the mass of suspended matter in the upper 1 m would be only 0.0015 g/cm^3 . If we assume a thinner film, the effect of the suspended matter would of course be greater. At thicknesses $\leq 0.00025 \text{ cm}$ ($2.5 \text{ }\mu\text{m}$) and a mean concentration of suspended matter of 1 mg/liter (50% organic and 50% inorganic), 100% removal of particulate matter from a 1-m column would increase the density of the slick to a value greater than the mean density of sea water.

It appears unlikely that the concentrations of suspended matter typically found in the waters overlying the middle and outer Atlantic shelf of the United States would have a significant direct effect on the density and therefore the settling of surface slicks. This conclusion agrees with that of Knebel³⁷: "The concentrations and compositions that have been observed indicate that suspended matter is not likely to have an appreciable effect on the movement and dispersion of oil that may be spilled over the Baltimore Canyon Trough area Moreover, because of the lack of terrigenous sediments and the predominance of biogenic detritus, the average density of the suspended matter in this area is probably quite low. Thus, even with greater concentrations, the suspended matter would probably not have a pronounced effect on the sinking rate of spilled oil."

Severe storms can dramatically increase the concentration of inorganic suspended matter locally and the intensity of mixing – two factors that increase the likelihood of removal of oil by sediment. Resuspension is important, however, only where there is a "suitable" supply of fine-grained material (silt and clay) or where water depths are shallow.

The ingestion of oil particles by filter-feeding zooplankton and the incorporation of that oil into fecal pellets increase the effective density of the oil and may play an important role in the removal of oil from the water column.³⁸

Suspended Sediment and Radioactivity

Radionuclides introduced into the aquatic environment in solution may be sorbed to particulate matter. The rate of sorption depends on the particular radionuclide; on the concentration, composition, and character of the suspended matter;

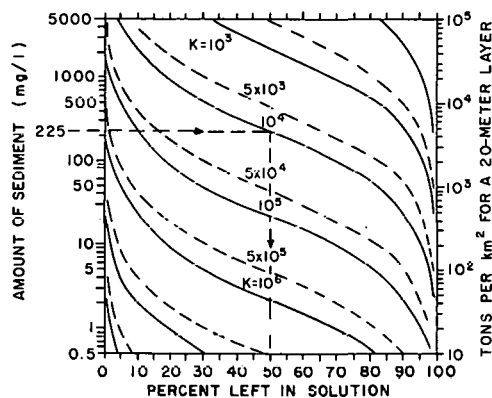


Figure 8. Predicted relationship between the fraction of the original radionuclide concentration remaining in solution as a function of the amount of sediment that has settled out of suspension, for different distribution coefficients. The assumed dry sediment density is 2.27 g/ml. (From Duursma and Gross.³⁹)

and on the physical, chemical, and biological character of the environment. Duursma and Gross³⁹ reported that the sorption capacity for a particular radionuclide "did not, on the average, differ by more than a factor of four between the sediments with extremely high and extremely low cation exchange capacities."

The sorption capacity for radionuclides is commonly expressed as a distribution coefficient, which can be defined as a dimensionless ratio of the amount of bound radionuclide per unit volume of dry sediment to the amount of radionuclide per unit volume of sea water. The larger the distribution coefficient, the stronger the binding or sorption of the radionuclide to the sediment.* Fine particles sorb radionuclides more readily than coarser particles of the same mineralogy.

In areas where the concentrations of fine-grained suspended matter are relatively high (tens to hundreds of milligrams per liter) and where there is a continual supply of new material, either by periodic resuspension of bottom sediment or by new additions from external sources, scavenging of radionuclides by suspended matter is an important process for the removal of radionuclides from solution and their eventual incorporation into the bottom sediments. As long as the radionuclides remain sorbed to the suspended particles, their movement and accumulation in the environment depend on the fine-particle dispersal system.

Duursma and Gross³⁹ calculated the scavenging effect of a given concentration of fine suspended sediment settling through a layer of sea water contaminated by one of a variety of radionuclides (Figures 8 and 9). Their data indicate that for a single scavenging with a distribution coefficient of 10^4 , less than 50% of the radioactivity would be removed at concentrations of inorganic suspended matter of less than

*Some investigators express distribution coefficients in terms of the amount of radionuclide per mass rather than per volume. Values used here are apparent-equilibrium values and, according to Duursma and Gross,³⁹ are about 0.4 to 0.5 the value of similar coefficients defined on a mass basis.

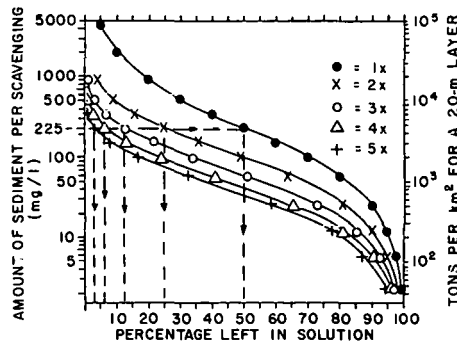


Figure 9. The effect of five successive scavengings by equal amounts of sediment with a density (dry) of 2.27 g/ml for a radionuclide with a distribution coefficient of 10^4 . (From Duursma and Gross.³⁹)

≈ 50 mg/liter. At concentrations of less than ≈ 15 mg/liter and $K = 10^4$, less than 5% of the radionuclide would be removed by a single scavenging, and even after five successive scavengings with "new" sediment, about 90% would still be left in solution. Since equilibrium distributions between the solution of most radionuclides in sea water and their sorption onto suspended particles occur relatively rapidly (in hours), repeated exposures of low concentrations of the same suspended particles to a contaminated solution are relatively ineffective in increasing the fractions of radionuclides removed from solution. Removal is largely a function of the availability of new material. Successive exposures of a contaminated solution to moderate levels of new suspended sediment are more effective in removing radionuclides than a single exposure to a concentration equal to the sum of the concentrations of the successive exposures. The periodic resuspension of fine-grained bottom sediments in estuaries, other coastal basins, and the tidal reaches of rivers constitutes a very effective scavenging mechanism because of the essentially infinite supply of new sediment.

A significant fraction of an accidental release of radioactivity might already be in particulate form at the time of introduction. In such cases, the distribution, transportation, and ultimate fate of the radionuclides depend upon the fine-sediment dispersal system. Because of our lack of understanding of the routes and rates of fine-sediment dispersal on the Atlantic shelf, reliable *a priori* predictions of the fate of that material are not possible. Radionuclides introduced into the environment at known points provide a valuable potential tracer for sediment movement.

It is of interest to ask whether the suspended matter in the waters overlying the inner and middle Atlantic Continental Shelf would be an effective mechanism for scavenging radionuclides that might be introduced in solution into these waters by an accidental release from a nuclear power plant. Offshore nuclear power plants will probably be located in the zone 5 to 20 km from shore. Let us assume a mean concentration of total suspended solids of 2 mg/liter for these waters, with 50% inorganic. This is a reasonable value, based on the data presented in Figures 1 to 5 and on other observations by the author. If a large accidental release of radioactivity

were to occur, it would almost certainly be discharged into the bottom waters, where resuspension might appreciably raise the concentration of suspended sediment. Since the predominant sediments in this band are medium-to-coarse sand and their sorptive capacities are low, the value of 2 mg/liter appears reasonable even close to the bottom on most of the Atlantic shelf in the 5 to 20-km offshore zone.

Let

C = concentration of total suspended matter (mg/liter),
 S = concentration of radionuclide at point of discharge (curies/liter),
 ρ = mean density of suspended particles (g/cm³),
 K = distribution coefficient

$$\begin{aligned} &\equiv \frac{\text{Amount of radionuclide bound per unit volume of dry sediment}}{\text{Amount of radionuclide in solution per unit volume of sea water}} \\ &\equiv \frac{C_B}{C_S} \end{aligned}$$

At $t=0$, $C_B=0$ and $C_S=S$. After some time $t=t'$, $C_B/C_S=K$. With an average concentration of suspended sediment of 2 mg/liter, each cm³ of water contains $10^{-3} C$ mg of suspended sediment, the equivalent of a sediment volume of $C/\rho \times 10^{-6}$ cm³. We can define

$$r \equiv \frac{\begin{array}{c} \text{Amount of radionuclide bound to dry sediment} \\ \text{per unit volume of water, } C/\rho \times 10^{-6} \end{array}}{\begin{array}{c} \text{Amount of radionuclide in solution} \\ \text{per unit volume of sea water} \end{array}} \equiv \frac{C'_B}{C_S},$$

which expresses the partitioning of a radionuclide in a unit volume of water between that which is bound to the suspended sediment and that which is free (in solution). We can also express r as

$$r = \frac{\begin{array}{c} \text{Amount of radionuclide bound} \\ \text{per unit volume of dry sediment} \times C/\rho \times 10^{-6} \end{array}}{\begin{array}{c} \text{Amount of radionuclide in solution} \\ \text{per unit volume of sea water} \end{array}},$$

which is equivalent to

$$r = \frac{C_B}{C_S} \times \frac{C}{\rho} \times 10^{-6}$$

and therefore we can write

$$r = K \times \frac{C}{\rho} \times 10^{-6}.$$

The fraction of radionuclide bound to particulate matter, β , can be expressed as

$$\beta \equiv \frac{C'_B}{C'_B + C_S} = \frac{C'_B/C_S}{1 + C'_B/C_S} = \frac{r}{1 + r},$$

and the fraction of free radionuclide, σ , is defined by

$$\sigma \equiv 1 - \frac{r}{1+r},$$

$$\sigma = \frac{1}{1+r}.$$

This is actually the fraction of a radionuclide remaining after the first scavenging, so let us designate it as σ_1 . For the second scavenging, σ_2 , we can write

$$\sigma_2 = \sigma_1 \times \sigma_1 = \sigma_1^2,$$

and so on for successive scavengings. Thus for the m th scavenging

$$\sigma_m = \sigma_1^m = \left(\frac{1}{1+r} \right)^m.$$

As an example, consider the following: If

$C = 2 \text{ mg/liter}$	(concentration of total suspended matter)
$\rho = 2 \text{ g/cm}^3$	(mean density of the suspended matter)
$K = 10^5$	(distribution coefficient)

then $\sigma_1 = 0.91$ and $\beta = 0.09$. This means that after the first scavenging about 91% of a radionuclide will still remain in solution, and it will take about seven scavengings with "new" sediment to sorb about 50% of a radionuclide. With a K of 10^4 it would take nearly 70 scavengings to remove 50% of a radionuclide from a solution.

Given the low concentrations of suspended matter on the inner and middle shelf, and the general absence of any significant sources of new inorganic sediment, it is not likely that suspended matter would be an effective scavenging vehicle for radionuclides in the 5 to 20-km offshore zone. Relatively rapid scavenging might be favored if the release occurred in one of the few areas of the shelf covered with fine bottom sediments and if these sediments were actively being resuspended; or if at the time of release, or soon afterward, a strong onshore flow carried the radionuclides into coastal areas characterized by high suspended sediment levels and a continual supply of new sediment, where scavenging would be promoted. This is not to suggest that fine suspended particles would not play an important role in the long-term removal (over periods of years, or perhaps decades) of radionuclides originally introduced into shelf waters; clearly they would. It does indicate, however, that the particles suspended *within* shelf waters are not likely to be the controlling scavenging agent. It also suggests that only a small fraction of the original release of radioactivity would be incorporated into the sediments blanketing the shelf.

SUMMARY

Suspended matter is added to the waters overlying the continental shelf by runoff, coastal erosion, the atmosphere, resuspension of bottom sediments by tidal scour

and wind waves, and by primary productivity. The sources are thus external, internal, and marginal. The particles are inorganic (naturally occurring and anthropogenic) and organic (living and dead).

Concentrations of total suspended matter typically decrease with distance from shore, whereas the relative abundance of the organic fraction typically increases in an offshore direction. At any station, the vertical distribution of total suspended matter is frequently characterized by a maximum in the concentration near the sea floor, produced by the resuspension of bottom sediments and to a lesser extent by settling, and a secondary maximum in the surface layer, produced by primary productivity. There may be other layers at intermediate depths with relatively high concentrations of suspended matter; such layers are more common on the middle and outer shelf than on the inner shelf.

The concentration of total suspended matter in the surface waters typically ranges from a few milligrams per liter on the inner shelf to a few tenths of a milligram per liter on the outer shelf. Organic matter may range from $<50\%$ of the concentration of total suspended matter in the surface layer of the inner shelf to $>90\%$ in the surface waters overlying the middle and outer shelf. Near the bottom, the concentration of total suspended matter is greater than in the surface waters, but the percent that is organic matter normally decreases.

The size range of inorganic suspended particles away from the bottom is very narrow; mean (by number) particle diameters vary only from a few tenths of a micrometer to a few micrometers.

There are no large inputs of fluvial suspended sediment to the Atlantic shelf of the United States. All the rivers debouch into estuaries, where the bulk of the fluvial sediment is entrapped. Some estuaries, for example, the Chesapeake Bay, even appear to be sinks for sediment suspended in shelf waters.

A number of studies of the distribution and character of suspended matter in the waters of the Atlantic shelf have documented the variations in the concentration of total suspended matter in both time and space. Very little is known, however, about the ultimate sources of inorganic suspended matter, and even less is known about the routes and rates of suspended sediment transport in shelf waters.

Suspended particulate matter constitutes a potential vehicle for the transfer of energy-associated contaminants – radionuclides and oil – back to the coast and therefore to man. The concentrations of total suspended matter in shelf waters are typically so low, however, that the mechanism is ineffective. Studies of suspended particulate matter have a high scientific priority, but in this investigator's opinion the state of knowledge is adequate for preparation of the environmental impact statements that would be required for siting of offshore nuclear power plants and for oil drilling on the Atlantic Continental Shelf.

Acknowledgments: Preparation of this report was supported by the Marine Sciences Research Center of the State University of New York and the New York Sea Grant Program. The author's studies of suspended sediment in shelf waters have been supported by the National Science Foundation through Grants GA-28276 and GA-40803, and by Brookhaven National Laboratory. I thank T. Kana, W. Cronin, and K. Kastens for their assistance both in the field and in the laboratory. I am par-

ticularly indebted to H.H. Carter, A. Okubo, E.W. Baylor, and D. Hirschberg for discussions and advice on sections of this manuscript.

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Session V

Panel Discussion

Chairman: C.G. GUNNERSON

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Panel Discussion on Adequacy of Criteria for Environmental Impact Statements

C.G. GUNNERSON, C.S. RUSSELL, D.W. PRITCHARD, R.W. HANMER,
F.J. CLARK, JR., G. HILL, C. STERN, AND J.L. KELLY

OPENING REMARKS

GUNNERSON: It is almost six years since the President signed the National Environmental Policy Act of 1969 (NEPA). Since then, the 1972 Stockholm Conference on the Human Environment and the United Nations Environment Program have been developed, similar legislation has been adopted by a number of states, and private as well as public actions are included within the purview of these policies. Each participant in this Conference, as well as most of our associates and neighbors, has been consciously affected by this legislation, which is a way of saying that NEPA is a powerful tool.

The instrument through which NEPA works is the environmental impact statement (EIS) in which, under the provisions of Section 102 of the Act, the agency or person proposing to do something is required to include in every recommendation or report on proposals for legislation and other major Federal actions significantly affecting the quality of the human environment, a detailed statement by the responsible official on (1) the environmental impact of the proposed action, (2) any adverse environmental effects that cannot be avoided should the proposal be implemented, (3) alternatives to the proposed action, (4) the relationship between local short-term uses of man's environment and the maintenance and enhancement of long-term productivity, and (5) any irreversible and irretrievable commitments of resources which would be involved in the proposed action should it be implemented.

There will be more on disclosure and communication later; the point here is that the wording of Section 102 is so broad that each agency has found it necessary to promulgate its own criteria for preparation of EIS's. This approach ensures variety and color, has encouraged competition between Federal, state, and local agencies to see which one was the most demanding in environmental affairs and hence the most virtuous, and has occasionally resulted in overkill so that desirable or essential projects have been abandoned. Fortunately, others have been built. On the other

hand, a number of projects that neither could nor should have withstood the light of disclosure have also been shelved, which was an intent of the bill.

To repeat, NEPA is a powerful tool. Like all powerful tools, it can be used for more things than its inventors had in mind. These range from using NEPA as an instrument for social change to highlighting engineering and other professional liability for environmental impacts of public works or services design, operation, and regulation.¹ Of more interest to me is the Act's role in compelling communications between government agencies, industries, universities, and public institutions and individuals.

The communications theme is particularly important. A recent international symposium featured an opening paper by a British Member of Parliament. The paper was devoted to the political realities of research sponsorship and support. The need for the political link between the "scientific elite" represented by that Symposium and the scientific public who pays the bills was emphasized by her remark² that "scientists do not try as hard to tell us what we want to know as we try to understand what they are trying to tell us." (That is why science fiction is so successful, although scientific fact is more fun.) Having accepted the idea of objectivity and discipline in scientific decision-making of the sort required by the EIS process, there is public concern when it appears that the full disclosure provisions of NEPA are not being met. Some industries have expressed concern over keeping proprietary information confidential. A firm that reports impacts of possible actions may reveal its plans and put itself at a competitive disadvantage. However, full disclosure is the best assurance against delays in the EIS process.

All these lead to the need for developing integrated environmental information programs that include the whole spectrum of technical documentation; reports quality control; technical information storage, retrieval, and exchange; media relations (including government); education at all levels; public participation; and institutional support.

The theme of this Conference, Effects of Energy-Related Activities on the Atlantic Continental Shelf, concerns only one of many activities in which EIS criteria are developed, but one that is most visible and involves disclosure. To this end, today's panel presentations are arranged, in order, on energy resource development, environmental assessment, regulatory aspects, and public information and participation, with the conviction that the last is essential to the success of any of the first three.

Panel members include representatives of governments, industry, academic and industrial research, environmental protectionist groups, and communications. Most of the panelists have had qualifying experience with more than one of the disciplines and sets of issues. With the assistance of the other participants in this Conference this panel session will highlight both problems and solutions in environmental assessment of energy needs, benefits, and costs.

RESOURCE DEVELOPMENT

RUSSELL: In addressing the subject of this panel everyone starts from some idea, however vague, of the purpose of the National Environmental Policy Act and the

place within that purpose of the environmental impact statement. It should not surprise us that there is no consensus on these basic questions, that our ideas are not so vague that they cannot be seen to be diverse. For example, the organizer of this session, in a letter to one of the panel members, mentioned three possible ways of viewing NEPA: (1) as "an instrument for social change"; (2) as a technical exercise "highlighting engineering and other professional liability in environmental aspects of public works design, operations, and regulation"; (3) as a means of "compelling communications between government agencies, industry, universities, and public institutions and individuals."

While we each might choose different words, we can see here three broad ways looking at NEPA, each with its own implications for the development of EIS criteria. We might call these ways, for brevity: (1) changing things (a lot or a little); (2) creating a technical record; (3) getting the public discussion started. In practice, all these aims are intermixed, since, to the extent that anything has been changed, it has usually happened in response to law suits from outside the government. These have rested on flaws in the technical record and have usually provided the focus for such public discussion as has actually occurred. But it is still useful to realize that some people view the process *itself* of EIS preparation and review as likely to lead to social change, and that others see "public discussion" of proposed actions as an end in itself.

To hold the first of these ideas, one has to believe that by providing suitable methodological instructions for preparation of the statement, for review within government and in public forums, it will be possible to lead the executive agency planners to make the "right" decisions. There is, I think, a utopian cast to this approach which connects process and result, even though we are dealing with questions in which some of the most important variables are precisely those that defy our existing (and potential) methodologies for quantification and comparison.

The third view, on the other hand, focuses on one aspect of the process – public discussion. There may be two important, but perhaps cynical, views here: one counting on wide discussion to defuse the issues by providing a forum for the discontented, the other perhaps counting on a kind of town meeting approach to bring out the "silent majority" and to give new legitimacy to traditional projects and ways of doing things. In any event, if one sincerely holds this basic view, one should prefer criteria for the EIS that stress completeness and inclusiveness. The more information made available, the more likely that the public debate will be informed and useful (although it is by no means clear that more information increases the chance of finding a consensus position.) The implications of the record-building idea seem clear enough.

My own view of the role of the EIS lies somewhere in the neighborhood of the third set of ideas – the stimulation of public discussion. But the ideas of public debate and discussion most often mentioned in this connection present some problems. For example, at the risk of oversimplification, let us briefly consider the problems and solutions that seem to be evolving in this area. First, for a given project one faces the questions: What public should be involved in the debate? In what forum should the debate take place? How long can it go on? (And, as a corollary, who gets

to use that scarce resource, time, to make his or her ideas heard?) What is to be the "product" of the debate? Merely a transcript? A resolution? Binding or nonbinding? And so forth. It is not stretching a point very much to say that these are all tremendously important *constitutional* questions. That they are being answered by officers in the U.S. Army Corps of Engineers, officials of the Department of the Interior, etc., is in itself a comment on NEPA and our political system.

What do the answers look like? With apologies for the impressionistic nature of my reply, I would say that the forums being developed are generally of the public-hearing variety; that the public from whom views are sought varies, as one would expect, with the nature of the project involved (although I think there is a tendency to emphasize the projects' physical neighborhoods and to look on Washington as the place to find "the national public"); that the active participants are most often chosen by the agency involved as "representatives" of interest groups (or else are self-selected on the same basis); that the product is highly variable in its practical import, depending, as one would expect, on the political pressures involved rather than on the force of rhetoric or argument actually heard at the hearing.

My problems with this evolving system begin where that last observation ends; that is, environmental problems are (almost always) political problems. Granted that there are technical questions, many still unanswered, about the effect of this action on that species or system; even if we knew the answers we would not know whether or not it was "right" or "best" to take the action or build the project. We are dealing here with public goods, in the economist's jargon, such as clean (or dirty) air, landscapes, and phytoplankton populations in the New York Bight. There is no market for these goods (or "bads") because there is no way to prevent access, no way to ration. If the air over Washington is made cleaner, I enjoy the benefits just as surely as does Gerald Ford, and one of us cannot exclude the other from the benefits (short of forcible relocation). On the other hand, only one of us may *pay* for the improvement, for example, through higher electric and gas bills or increased inconvenience due to traffic bans. And the system does not provide for the persons or groups who pay to be compensated out of the benefits of those who benefit. (This simplifies the problem greatly, since there are spatial variations in quality over the city itself; individual valuations of air quality will differ; and the payors may or may not be the benefactors, in whole or in part.) All this adds up to *politics*, a word that has a dirty connotation in this country, but which ought to denote one of our most important professions.

The first implication of this view is that no process, however carefully spelled out, can ever lead executive agencies to the "right" answers. The right answers are those that come out of the right process, and in this country that process is, or ought to be, representative democracy. Thus, all these forums and hearings seem to me to be in the nature of sideshows, with the legislatures, local, state, or Federal, serving as the big tent.

What, then, is the role of the EIS? First, legislatures cannot and should not have to look into and decide every detailed controversy about the environment. Many decisions must be left to the agencies. The EIS in this view is a declaration of what is about to be done that gives the public a chance to react before it is done. If the pro-

posed action creates too much political heat, the NEPA procedures ought to be designed to make it impossible for the agency to go ahead without explicit direction from the legislature. My model for this view would be the Alaska pipeline dispute, in which environmental suits tied the project in knots and created a situation that the Congress felt obliged to resolve.

With the above as prologue, I suggest the following as useful criteria for the EIS:

a. It should be short and crisp, with boiler plate and padding discouraged. More information is not always useful; indeed, the current tendency to produce a four-foot shelf of books about each project probably guarantees that they will be read by very few.

b. It should look at real alternatives, not straw men. One form of challenge ought to be the definition and costing of realistic alternatives not considered by the EIS.

c. It should cost the project and the alternatives in economically meaningful ways and give the results in useful form. (For example, total undiscounted dollar costs over a project's lifetime are a *useless* and meaningless measure. The present value of these costs at several interest rates is a valuable datum.) This will tell us what it costs to buy environmentally less harmful alternatives.

d. It should make use of the best methodology available. For example, water quality models should be used wherever possible in preference to impressionistic statements about effects.

Then, with the potential battle lines drawn clearly, the process can go forward within the context of the existing set of institutions, and without the necessity of creating a parallel set of quasi legislatures or trying to legitimize unelected interest-group spokesmen. Hearings can be seen as exercises in taking the political temperature. And the legislatures will have to assume the responsibility for acting on the tough disputes.

ENVIRONMENTAL ASSESSMENT

PRITCHARD: I note that I am the only participant listed under the subheading Environmental Assessment for this panel discussion. I presume that this allotment of panel time was made, not because of the lack of appreciation of the importance of the subject area, but rather because any two investigators of the coastal marine environment are likely to produce conflicting statements on the adequacy of knowledge in this area.

I interpret my assignment to be to discuss the adequacy of existing knowledge of the continental shelf environment and of the processes that might be pertinent to the impact of energy-related activities on this environment. My remarks reflect my own views and do not necessarily reflect a consensus on the marine environment.

From the papers given here and from other sources, including my own work, I conclude that (1) we know quite a lot; (2) this knowledge is still inadequate in many respects; and (3) the priorities assigned to the environmental research efforts are not consistent with the potential for adverse environmental impact of energy-related activities.

This last conclusion is important because the manpower, facilities, resources, and funds available for environmental studies are not infinite. To be cost effective, research efforts should be allotted among the areas most pertinent to the probable impact of man's activities on the environment. To do this, some assessment of the potential for impact must be made.

I believe such assessment of the possible environmental consequences of energy-related activities on the Atlantic Continental Shelf can be made, at least to the extent of identifying the research areas most needed for detailed assessment. This is in spite of the inadequacy of knowledge in a number of subject areas.

Consider first the activities that alter the energy content of the coastal and continental shelf waters, that is, the potential, kinetic, and heat energy. Not included are changes in chemical and/or biological energy. An activity that obviously would result in changes in the energy content of the coastal marine waters is the proposed tidal power project in the Bay of Fundy. This project would significantly alter the potential and kinetic energy associated with tidal motions over a large area of the coast, extending far beyond the immediate area of the proposed tidal basins. The most obvious impact is on man's use of the coastal waters for navigation. Knowledge is sufficient to develop numerical predicting models capable of computing the probable temporal and spatial changes in tidal heights and tidal velocities resulting from such a project. Additional data, particularly for the edge of the continental shelf, are required to serve as boundary conditions for such models.

The construction of structures required for such tidal power projects, and the resulting changes in tidal energy, would certainly lead to spatial and temporal changes in the biota of the local coastal waters. There is sufficient biological information so that, for a given proposed project, studies to obtain needed additional local data can be effectively planned and conducted.

Offshore structures, such as artificial harbors and artificial islands for offshore power plants or oil drilling, will result in changes in the energy content of the adjacent continental shelf waters. The breaking of surface wind waves on such structures, the changes in direction and speed of the local currents, and similar physical processes will result in temporal and spatial changes in the local marine biota. The biological consequences are likely to include both beneficial and undesirable changes. The probable number and size of such offshore structures, and the purely local nature of the impact of each structure, suggest that the biological impact of offshore structures will not be very significant.

The discharge of condenser cooling water from shore-based and offshore power plants will change the heat content of the coastal marine environment. Criteria for siting of power plants and design of once-through cooling systems are adequate to ensure a negligible adverse impact of the purely thermal aspects of the problem. There are, however, potentially adverse effects of once-through cooling systems related to factors other than temperature rise. These are entrainment of small organisms in the condenser cooling water inflow, with subsequent passage through the pumps, condenser tubes, and discharge structure; and entrapment of larger organisms in the intake forebay and subsequent impingement on the intake screens. The organisms entrained in the condenser cooling water inflow are subject to mechanical damage

in the pumps and to biocide kills during periods when chlorine or another antifouling agent is being used. Studies conducted at existing power plants indicate that primarily the larger zooplankton and fish eggs and larvae are mechanically damaged. The fraction of the zooplankton killed or subjected to shock leading to death varies widely from plant to plant. Several plants have produced annual average deaths, with little variation about the mean, of about 7% of the zooplankton passing through the plant. Research should be undertaken to determine criteria for pump design to minimize loss of entrained organisms due to mechanical effects.

The potential for loss of fish eggs and larvae entrained in the condenser cooling water inflow may also be significantly reduced by proper design of pumps and other features of the once-through cooling systems. However, siting of power plants away from spawning areas, particularly those of anadromous fish, which tend to be concentrated in a restrictive reach of the inshore tidal waterways, would eliminate the need to assess this impact.

The problem of entrapment of adult fish and impingement on the intake screens can be solved by proper design of the intake structure. Most existing intakes are funnel-shaped traps. Intakes should be designed to be flush with the shore-hill or with the offshore structure, to eliminate cul-de-sacs capable of acting as traps. The design and development of horizontal moving intake screens to replace the vertical screens now used would further minimize impingement losses.

Chlorine is the major biocide used to reduce fouling of intake piping and condenser tubes. It is an indiscriminate killer of organisms carried through the plant as well as of the target fouling organism. Regulatory limits on the amount of free chlorine that can be discharged confine the effects of free chlorine to the entrained organisms prior to discharge. However, research should be continued on the effects of chloramines, which are produced by the interaction of chlorine with ammonia or other nitrogenous compounds. These compounds may have adverse effects over a sizable area of the receiving waterway. The prime need here, however, is not for environmental research but rather for studies of methods to eliminate biocide kills from the list of environmental problems requiring more than cursory evaluation. Mechanical systems, such as AMERTAP, have eliminated the need for the use of chlorine in the condenser tubes; however, chlorine or another biocide is still required for the intake piping.

An alternative to the use of chlorine to reduce fouling in the intake is the use of overheated condenser cooling water to backwash the intake piping. This mode of operation should be studied to determine possible environmental effects. Also, research should be pursued to find a biocide that acts specifically on the target fouling organisms and does not lead to the death of other organisms.

The environment can have an impact on energy-related activities on the continental shelf, just as these activities can have an impact on the environment. Thus offshore structures associated with power plants or oil drilling are subject to damage due to wind and to storm waves. Such damage could lead to discharge of oil or other contaminants, with serious environmental consequences. There is probably adequate knowledge to develop specifications for design and construction of offshore and shore-based structures to safeguard against significant damage by wind waves and storm surges.

Many of the offshore structures will be built on the unconsolidated sediments that cover most of the bottom of the Atlantic Continental Shelf. Despite the considerable knowledge concerning the stability of large-scale linear features of the bottom topography, intensive site-specific studies will be required to determine the movement and stability of the bottom sediments on which these offshore structures will rest.

Radioactive substances constitute one of three categories of substances that might be released into the coastal and continental shelf waters as a result of energy-related activities. The possibility of adverse environmental effects of the release of radioactive materials to the continental shelf waters has been overrated. Certainly the release of radioisotopes from shore-based and offshore nuclear power plants under conditions of normal operation can and will be kept at levels low enough to be no concern from the standpoint of impact on the marine biota or on public health. Even with a "worst case" design accidental release, there is little likelihood of ecological disruption; consequently public health concerns become the controlling factor. From the standpoints of both theory and practice, our ability to predict the physical movement and mixing of the waterborne components of radioactive substances that might be released to the coastal environment is reasonably adequate. We do need field data on currents and field tracer experiments to establish mixing coefficients to serve as inputs to the predicting models. Our knowledge of the non-conservative processes acting to modify the predicted conservative distribution is not adequate. Much of the radioactivity will be released in particulate form or will become attached to naturally occurring suspended particles. Hence studies on the fate of suspended materials on the continental shelf are needed.

Essentially the same comments can be made for the other two categories, chemical pollutants and oil, except for the comment on the potential for causing significant ecological damage. Certain possible chemical pollutants, for example, chloramines and, to a greater extent, oil, should at the present level of knowledge be viewed as potentially disruptive to the coastal and continental shelf ecosystems. However, the greatest lack of knowledge lies in the subject area – that is, the biological consequences of a given distribution of oil or other chemical pollutant. Research on the ecological consequences of the release of chemical pollutants or oil to the coastal and continental shelf waters resulting from energy-related activities is urgently needed. Existing knowledge is in general inadequate for assessment of the environmental impact of such activities.

REGULATORY

HANMER*: Under Section 309 of the Clean Air Act, the Environmental Protection Agency routinely reviews environmental impact statements (EIS's), as well as regulations, legislation, and administrative actions proposed by any department or agency of the Federal Government. EPA review and commenting procedures involve two independent forms of analysis, one evaluating the environmental impact

*Remarks prepared in collaboration with L.S. Leonhart, Staff Geologist, U.S. Environmental Protection Agency.

of the proposed action and the other assessing the adequacy of the impact statement. In assessing the adequacy of criteria for EIS's with respect to offshore energy development, an appraisal of past reviews performed by EPA is useful in identifying the major shortcomings of past EIS preparation efforts and in formulating recommendations for improving the quality of future statements.

To date, oil and gas leasing and development proposals have constituted almost the entire volume of EIS's on offshore energy activities. Various EIS's, such as the Coast Guard's statement on a deepwater port program, have involved activities related peripherally to offshore energy development. It is expected that soon EIS's will be prepared on individual deepwater port proposals as well as offshore nuclear power plants and perhaps offshore refineries. In assessing the adequacy of EIS criteria for these activities, it is logical to first examine past EIS's for OCS oil and gas proposals, since many of the impacts are analogous. For example, transportation and landing of oil from offshore terminals and platforms can display similar hazard and risk probabilities. Likewise, biological base-line data can be applied to virtually any type of development.

Perhaps the most significant among recent EIS reviews of OCS oil and gas leasing and development proposals are those performed for the Mississippi, Alabama, and Florida (MAFLA) Sale No. 32, the proposed plan of development for the Santa Ynez Unit in Santa Barbara Channel, the programmatic EIS for Increased OCS Acreage, the Southern California Sale No. 35, and the Northern Gulf of Alaska Sale No. 39.

In examination of these reviews, the following areas of deficiency have been isolated: (1) development considerations such as support facilities and transportation systems; (2) risk probabilities of development and transportation; (3) compatibility between proposed lease offerings and state-of-the-art recovery technologies; (4) environmental base-line information, such as identification of fragile ecosystems, migratory patterns, food chain relationships – transfer and bio-accumulation of leaked petroleum; (5) toxicity of hydrocarbons to marine organisms, especially long-term chronic effects; and (6) assessment of probable onshore (secondary) impacts, including land requirements, population influxes, and other socioeconomic impacts.

Development Considerations

In order to ensure full consideration of development-level environmental impacts that may be poorly understood at the leasing stage, EPA and others have asked the Department of the Interior to consider establishment of a "dual-EIS" system. The first EIS would be issued following a call for nomination for each area, but prior to tract selection. It would address the potential impacts arising from exploration activities and describe the biological and physical environment. The second EIS would be issued prior to approval of plans for development and would focus on development considerations such as support facilities, transportation systems, recovery technology, and onshore impacts. This EIS could serve not only Federal actions, but state and local decision-making on support facilities as well.

The Department of the Interior, to date, has turned out only two EIS's on development-level proposals: the unitization plan for the Santa Ynez Unit in Santa

Barbara Channel, and the programmatic statement for the Santa Barbara Channel OCS. It has also proposed a 60-day review period for affected states prior to approval of development plans.

The need for state and local scrutiny of development plans is becoming increasingly evident, particularly for states that have not experienced previous OCS development off their coasts. Onshore support facilities are a good illustration of this need. For example, depending on whether platforms are to be constructed onshore or transported from other locations, the environmental impact on an area can vary significantly. Similarly, transportation impacts can vary widely.

Risk Probabilities

EPA's reviews of the impact statements for the Southern California Sale No. 35 and the Gulf of Alaska Sale No. 39 revealed informational gaps with respect to hazard probabilities of development and transportation of petroleum resources in those areas.

In consideration of the marine bird and mammal sanctuaries, esthetic resources of the Channel Islands area, and the risk of offering deepwater tracts for development, EPA contracted two risk analyses: (1) Risk and Cost Analysis of Transporting Southern California Outer Continental Shelf Oil and (2) Estimates of Spill Trajectory Likelihoods for the Southern California OCS.

The situation in the Gulf of Alaska also involves high risk. In addition to supporting a fragile ecosystem and in general being characterized by a low potential for recoverability from a spill, the Gulf of Alaska is subject to geologic hazards and severe meteorological conditions. At best, the only risk figures that have been assigned to OCS development in the Gulf of Alaska involve extrapolations from the North Sea analogy.

Resource Recovery Technology

Also associated with risk probability is the inherent risk of pioneering technology. The leasing of deepwater tracts, as in the case of the Southern Californian sale, represents a critical departure from traditional operating technologies, since it would involve subsea production systems and/or nonconventional platforms. To date, the U.S. Geological Survey has been unable to write operating orders for these advanced recovery systems, largely because they have not been tested. EPA's recommendations have suggested a reflection of this risk in designing lease offerings. It would be better from an environmental risk standpoint to attempt a gradual progression into higher risk areas as experience with the requisite technology is assimilated and to gradually develop operating orders based on such experience.

Environmental Base-Line Information

The significance of gathering environmental base-line data for the OCS is harbored in the directive of the National Environmental Policy Act to assess "the relationship between local short-term uses of man's environment and the maintenance and enhancement of long-term productivity." Without establishing a reference information base, one cannot fully pursue this directive. Yet the question remains of

how to weigh the long-range resources of fishery, recreational, and esthetic values against the finite and relatively short span of demands for petroleum.

Perhaps the "kickoff" example of base-line data-gathering is the MAFLA Sale (No. 32), which involved breaking into a virgin area of the OCS for which few base-line data existed. In consideration of this, EPA recommended as a condition of the sale that base-line data be gathered prior to initiation of offshore development. As a result, an *ad hoc* interagency effort was launched to offer scientific and technical assistance to the Bureau of Land Management. These efforts have since evolved into a federally chartered advisory group which also involves state membership and participation.

Onshore Impacts

In commenting on the EIS for Increased OCS Acreage, EPA recommended that states should be provided with the following information as a minimum to assist in their proper coastal zone planning: (1) data regarding the location and magnitude of potential offshore oil and gas resources; (2) data and plans for OCS development, including estimates of the number of facilities needed for production, refining, and transportation; and (3) a projection of types and numbers of municipal facilities required to service the population and industry to be affected by OCS development.

The Department of the Interior's proposal to provide states with a 60-day review of development plans is a step in this direction, but its utility could be augmented through the issuance of an EIS on the proposed plans.

The potential onshore impacts are evident: land acquisition, siting of facilities (including offshore support, landing, and refining), population influxes, construction activity, increased harbor traffic, local petroleum surpluses, onshore transportation, etc. What is needed is a quantification in terms of economics and degree of environmental impact. The EIS is a good vehicle for providing this assessment, and particularly for linking the environmental considerations not only for Interior's action but also for EPA's actions such as issuing discharge permits for platforms and onshore facilities, and state and local regulatory actions.

Regulatory Authorities

Aside from Section 309 and NEPA responsibilities, EPA is involved in many other ways in the entire gamut of OCS operations. It is not possible here to define all these interests or responsibilities; however, some limited examples may be of interest. Section 104 (N) of the Federal Water Pollution Control Act Amendments of 1972

(FWPCA) mandates the EPA Administrator to concern himself with the nation's estuarine areas; EPA is concerned with ocean disposal; the Narragansett Environmental Research Laboratory has the mission of supplying a scientific basis for establishing marine water quality standards for petroleum; and Gulf Breeze Environmental Research Laboratory conducts research on the ecological effects of man-produced organic compounds in marine/estuarine ecosystems.

Specific regulatory responsibilities arising from legislative requirements are contained in Sections 311, 316, 402, and 404 of FWPCA and in the Marine Protection, Research, and Sanctuaries Act of 1972.

Section 311 relates to contingency planning for spill events in the contiguous zone and to oil spill prevention within the three-mile limit. Oil spill prevention regulations under Parts 112 and 114 of Title 40 of the Code of Federal Regulations were implemented in January 1975 and to date have resulted in 1600 enforcement actions stemming from some 8000 inspections.

Section 316 is applicable to offshore nuclear power developments since it involves provisions for issuance of variances for thermal discharges into navigable waters.

Discharges from platforms and similar facilities require permitting under the National Pollutant Discharge Elimination System under Section 402 of FWPCA. Dredging and filling operations on the OCS are subject to permitting procedures under Section 404. This would include artificial islands as well as platforms. (In addition, many support facilities in territorial waters or discharging to waters from shore facilities would require Section 402 and possibly 404 permits.)

Finally, under the Marine Protection, Research, and Sanctuaries Act, EPA conducts research and sets standards for ocean dumping.

Atlantic OCS

As energy development progresses to the Atlantic OCS, a review of past OCS leasing and development proposals for the Gulf of Mexico, Southern California, and Alaska areas has afforded a needed overview of the broad spectrum of issues. In summary, we have learned that environmentally safe development on the OCS involves greatly increased levels of information gathering and exchange. We know that, as a minimum, we must improve our reference data base, monitoring and enforcement capabilities, knowledge of the affected ecosystems, understanding of the endemic risks, recovery technologies, coastal zone planning, and predictive capabilities for secondary developments. Yet we have seen that endemic hazards and impacts vary widely among OCS areas, as do the assimilative capacities of the affected communities. Regulatory authority exists, but enforcement capabilities are limited.

The Atlantic OCS also supports a broad spectrum of resources, including fisheries, recreational and scenic areas, wildlife habitats, and great industrial centers. Without proper advance planning, the development of offshore energy resources could be disastrous.

The EIS is a planning document that is also providing "multichannel" communications among Federal, state, and local entities, industry, and the public. As a vehicle for examining alternatives and establishing trade-offs between local short-term uses of man's environment and the maintenance and enhancement of long-term productivity, the EIS can be most effective, particularly if properly timed. It allows all regulatory agencies to evaluate offshore energy developments as a whole, not just piece by piece, and early enough in the process to ensure that environmental problems are prevented.

CLARK, F. J.: A major effort within the U.S. Nuclear Regulatory Commission which relates to activities on the Atlantic Continental Shelf is the overall technical review of the floating nuclear plant (FNP) concept and the specific aspects of licensing FNP's for water-based electric generating stations. Since this is a first-of-a-kind

activity as far as power plant siting is concerned, several new licensing considerations have been formulated to account for some of the new and unique aspects.

First, a new type of license – a manufacturing license – provides for the manufacture of a given number of completed nuclear power plants (less nuclear fuel) at locations other than those at which they will be used as generating stations. The establishment of the manufacturing license and several aspects of manufacturing standardized nuclear power plants are covered in a relatively new Commission regulation: Appendix M to Title 10 CFR Part 50.

The standards for FNP's require that potential sites meet certain criteria to avoid exposing the plant to conditions for which it has not been designed. Appendix M requires applicants for a manufacturing license to provide an envelope of site parameters and evidence demonstrating that proposed plants can be located and operated at sites falling within the envelope of site parameters without undue risk to the health and safety of the public. Appendix M also requires that a detailed review be made of each individual site during *construction permit* proceedings to ascertain that the site does fall within the site parameters specified at the *manufacturing license* stage.

The licensing process for FNP's therefore involves three separate and distinct licenses or permits from NRC:

1. *Manufacturing license* (for a given number of plants of a standardized design, manufactured at a location other than the final location).
2. *Construction permit* (required of an owner/operator of FNP's to construct the water-based generating station using the previously licensed design of FNP's). A construction permit is necessary before an FNP can be moved from its point of manufacture.
3. *Operating license* (required before nuclear fuel can be placed in the reactor and operation of the nuclear station can commence).

The construction permit and operating license stages are essentially no different from those for land-based nuclear power plants.

With respect to the environmental review associated with the current licensing proceedings for the proposed issuance of a manufacturing license to Offshore Power Systems, there is also a new consideration. The environmental review consists of two parts, each resulting in the preparation of a draft environmental statement and a final environmental statement. The first element of the review concerns the action proposed – the manufacture of a given number of FNP's at a large shipyard-like manufacturing facility in Jacksonville, Florida. Accordingly, this statement (Part I) covers the operation of the manufacturing facility and the resulting impacts on the city of Jacksonville and environs (final statement issued as NUREG 75/091, October 1975). The second part of the review centers around the environmental aspects of siting and operating the FNP's. This statement, issued as a draft environmental statement (NUREG 75/113, November 1975), is commonly referred to as the generic statement, Part II. It addresses, on a generalized basis, the siting of FNP's in the coastal regions of the Atlantic Ocean and the Gulf of Mexico, including riverine and estuarine locations. The generic statement will be supplemented with a special study comparing the consequences of accidental releases of radioactivity through liquid pathways for a spectrum of releases at several types of land-based and water-based

plant siting environments. This supplement is scheduled for issuance in the spring of 1976.

Finally, I will briefly discuss a recent coordinating effort in the licensing of nuclear plants involving the U.S. Army Corps of Engineers and the Nuclear Regulatory Commission. NRC and the Corps have executed a memorandum of understanding on the regulation of nuclear power plants on navigable waters. Both NRC and the Corps have responsibilities for ensuring that nuclear power plants on coastal and inland navigable waters and at offshore sites are built and operated safely and with minimum impact on the environment. The new memorandum of understanding is designed to allow each agency to take full advantage of the other's capabilities and to avoid unnecessary duplication of regulatory functions.

Covered by the agreement are floating nuclear power plants and associate structures, as well as inland plants on navigable waters. Structures associated with floating plants include the electrical transmission lines from the plant to a land-based substation, the protective breakwater and mooring systems, and other supporting facilities.

The principal provision of the NRC-Corps agreement emphasizes the "lead agency" concept by providing for a single coordinated NEPA environmental review, to be accepted by each agency as a part of its action leading to the NRC construction permit and the Department of the Army permit – both required of an applicant to commence construction of a nuclear power station. The Corps will provide information on the elements of the review falling within its area of expertise, such as shoreline changes, siltation and sedimentation, dredging and filling effects, and location of structures in navigable waters. The agreement calls for simultaneous issuance of the permits by each agency, once both agencies have approved them. This has eliminated a major duplicative effort and is expected to result in a more closely coordinated review process.

PUBLIC PARTICIPATION

HILL, GLADWIN: In talking about public perceptions of coastal issues, I think we should take it as axiomatic that people, because they are human, are directed both by emotions and by reason. Emotions have a proper place in coastal affairs; they relate to esthetic values that cannot be quantified but are undeniable. A promontory adorned by trees is, by esthetic consensus, preferable to a promontory dominated by an oil refinery.

At the same time, people are reasonable. They will trade esthetic values for utilitarian values if the latter seem necessary or desirable. Nobody argued during World War II about the many coastal disruptions attendant on military shipping. People willingly tore up attractive lawns and parks to plant victory gardens.

The crux of effective public decision-making is to avoid entangling emotional valuations with utilitarian valuations and provoking a dispute that may defy resolution indefinitely. When emotional and practical considerations become entangled, it is usually because of lack of information, or of information conveyed lucidly.

The U.S. Army Corps of Engineers is involved in a dispute over a proposed industrial development in a pristine natural area on the coast at Hilton Head, South Carolina. The current corporate applicant has been less than candid about exactly what its manufacturing intentions are. Just what the environmental impacts would be is unclear, despite the preparation of reams of purported impact assessments. There is a wide disagreement on economic costs and benefits. A conclusive factual basis is lacking. So emotion – sentimental valuations that cannot be quantified or effectively refuted – holds the field. The argument has been going on for several years and seems likely to go on for some time.

The whole question of oil development on the outer continental shelf, which epitomizes the environmental issues involved in all sorts of coastal energy development, has been similarly obfuscated. The public has not been given firm, precise information on how necessary or desirable such development is. While the Federal energy people have been saying in effect that we should pump oil as fast as we can wherever it can be found, the Senate's Ocean Policy Study staff, for one, has suggested that sound long-term energy strategy may dictate husbanding OCS oil, even at the cost of importing oil at quasi-extortionate prices.³

Lacking a coherent measure of urgency, the public does not have a basis for a sensible judgment of what sacrifices in coastal integrity might be warranted. Nor does it have a lucid exposition of what sacrifices are called for. To the average citizen, the possibilities of oil spills and related damage are vague, as are the prospective impacts on communities of construction, processing and storage facilities, new burdens on housing, highways, schools, law enforcement, etc.

Granted, great efforts manifestly have been made to quantify many of these factors in environmental impact statements. But a single EIS will be a stack of paper several feet high. Does anyone seriously think a single ordinary citizen is going to look at one of these?

Yet efforts by government, the oil industry, and the media to convey to the public the factual essence of impact assessments have seemed at best perfunctory, sketchy, and inadequate. This may represent a deficiency on the part of the news media. But the onus rests mainly with the Federal government and the oil industry, who are the proponents. The addresses of both government and industry have tended to be on the emotional level – strident cries that "We must achieve energy independence," and "We must produce more oil." Inevitably the public response is on the emotional level too: "Preserve our coasts!"

Much public resistance could have been averted if two things had been done at the outset: provision made for state sharing in Federal OCS revenues, to ameliorate prospective community dislocations; and a forthright commitment made to at least the principle of undersea completions. The specter of forests of oil platforms and towers ruining the seascape is a major psychological block in the public mind; and, specious or not, what people can't see bothers them less.

Both government and industry ducked these questions until public resistance already had started to harden. Since then there has been grudging concession on revenue-sharing. But there still is little to be heard from the industry on undersea completions.

Meanwhile there has been the Department of the Interior's nonsensical and suspicious haste about saving a few weeks in the leasing portion of a development program whose time-frame is more like ten years. This has been both implausible and an egregious insult by the Executive branch to the people's elected representatives who have been trying to fashion needed revisions in OCS development legislation.

To summarize the public perception of this problem, it is marked by the same perplexities and apprehensions that were precipitated by the Santa Barbara blow-out in 1969. In terms of meaningful communication between government and the people we are right where we were six years ago, but confronted with making far more pressing decisions.

Up to now the public has not been given a convincing story as to why *any* environmental risks are worthwhile to produce a relatively small fraction of presumed oil needs ten years hence, to avoid burdening an unfavorable trade balance by an indeterminate amount. Consequently people have no rational basis for judging whether the hoped-for results would warrant one big oil spill a year or five spills; whether the results would warrant jeopardizing benthic organisms over 10,000 square miles as against, say, 2000 square miles; whether the results would warrant destroying 20 miles of recreational beach for pipelines and processing and storage facilities as against five miles or one mile; or what monetary compensation would be appropriate for the loss of, for instance, an indeterminate amount of tourist business.

In other words, the viable criteria for impact assessment on OCS development or any other sort of coastal development are not *absolute*s; they are *relative* matters. The relativity is between environmental impacts and the public purpose served and the necessity of serving it. If an atomic power plant demonstrably is needed, and if demonstrably there is no alternative to a coastal site, then the criteria acceptable to the public will be the minimal environmental disruption possible under the circumstances. But if a coastal site is picked simply because it is the easiest or cheapest for the developers, then they had better gird themselves for an emphatic public reaction that the project is not worth disturbing the tranquility of six seagulls. What the public instinctively insists on is the factual ingredients with which it can make, in each instance, its own cost-benefit reckoning.

The EIS process was designed primarily to be a policy-making tool and guide for governmental agencies. It was not designed as an after-the-fact mustard plaster to justify to the public decisions already made. It is hoped that EIS's will yield the grist for public discussion. But production of an EIS, however massive, does not exempt government or industry from their traditional obligation of marshaling citizen support for major undertakings.

The answer to the question of how the public perceives problems of coastal development at present is, I think: Dimly. And the dimness can be dispelled only if proponents of development make a quantum leap in making environmental impact assessment meet not only legal requirements but the dimensions of common sense, which the public considers the ultimate criterion.

STERN: As the only representative of a public interest organization on the panel, I will speak for the concerns of the varied "user" public, as well as for organized en-

vironmentalists. I cannot represent all segments of the public, but we do try to speak for the public interest in our lobbying efforts. We might define the public interest as that which affects the health and safety of all people and is not directed by the prime concern of profit-making. The motivation for our activities is a perception that man's technological genius has degraded the quality of the air, water, and land to a degree that poses far-reaching threats to this region, the nation, and indeed the world. The changes are so severe that nature, which can correct itself, does not have time left to rectify man's changes.

Industry, labor, and other vested interest groups have always had their spokesmen in the halls of the legislatures of the states and the Congress. At last, environmentalists have established themselves as a constituent segment of society who also try to influence the outcome of legislation. Recognized and known groups on the national scene such as the Sierra Club, the Audubon Society, and the Wilderness Society have professional staffs in Washington who have learned the art of providing informed opinion to the Congress and the White House. The Environmental Defense Fund and the Natural Resources Defense Council are two special groups combining scientists and lawyers who monitor the interpretation and implementation of environmental laws.

The Long Island Environmental Council is different from these organizations. It is a coalition of more than 100 organizations – conservation, environmental, educational, and municipal groups, unions, profit-making corporations, and local chapters of public interest groups such as the American Association of University Women. We therefore have a working knowledge of how groups with various and sometimes conflicting agendas nonetheless can join together for the common goal of protecting and enhancing the environmental quality of the whole Long Island region.

I stress the potential for participation through broad coalitions because the tasks associated with influencing public policy in an open democratic society are complicated and frustrating. *Ad hoc* coalitions on specific issues are a useful device for effective action. More structured coalitions have a greater potential for maintaining a basis for education and action. For the organized public, for *their* self-interest, the job must also be done by professionals on a full-time basis. Specific user groups, such as sportsmen, commercial fishermen, marina operators, and builders, have long been organized, but until recently they did not recognize that their self-interest included a knowledge of environmental laws as a *benefit*. They, too, breathe the air, swim in the water. And there is no escape. Many still do not accept the notion that NEPA is a planning tool, a means of acting thoughtfully. Even Luke, in the *New Testament*, admonishes, "For which of you, desiring to build a tower, does not first sit down and count the cost, whether he has enough to complete it?" (Luke 14:28). At first most groups did not understand the significance of NEPA, especially if they stumbled over the Act only when it interfered with some project they wished to undertake. Hence, frustration and confrontation.

So it has been left to the environmental groups to watch over NEPA as a fierce parent protecting the health and well-being of a child while the statute grows strong enough to take care of itself. Sometimes this self-assigned watchdog role is a bit too much for the citizen advocate:

"Self-government is a very demanding and time-consuming business, and when the organs of government are decentralized so as to maximize participation, it will inevitably become more demanding still. Ultimately, it may well require almost continuous activity, and life will become a succession of meetings. When will there be time for the cultivation of personal creativity or the free-association of like-minded friends? In the world of the meeting, when will there be time for the tête-à-tête?"⁴

We have used the provisions of the Act, especially the requirement of an EIS, as an invaluable tool for intelligent planning. A well-executed EIS is the means by which decisions can be made – not in private, and not by agreement between a public agency and the industry, but in full view, exposed to the scrutiny of an informed public. Final decisions in this country should be made by political leadership, as they are, but, thanks to NEPA, with adequate information from the scientific and user communities. The deficiencies of impact statements usually stem from the lack of fully examined alternatives. Unfortunately the EIS has been used as a self-serving document for a decision already made rather than as an analytical weighing of alternatives.

Environmentalists have interfered with projects considered to be ill conceived or not for the greatest community use within the provisions of the EIS. We have testified, commented, conferred, cajoled, explained, and finally sued, to ensure compliance with the law. The impact statement has been the tool for examining the need for such major projects as a bridge across Long Island Sound, the landing of the SST, bringing oil and gas from frontier areas, development at Fire Island National Seashore, and installation of sewage facilities. We have defended and will continue to defend this statute from destruction by congressional amendments offered in desperation by some who object to the primary goal of the Act – to improve decision-making in an atmosphere of recognizing our responsibility as "trustees of the environment" for this and "succeeding generations" [Sec. 101 (b) (1)].

Thoughtful people are not sure that our society has the ability and flexibility to deal with the complex issues created by man-made technology. Writers such as Robert Heilbroner have asked, Are our institutions strong enough, are the people sufficiently informed for democracy to flourish? In his book, *An Inquiry Into the Human Prospect*, Heilbroner says NO.

I am less pessimistic than Heilbroner about our ability to learn to reconcile conflicting pressures. But if this society is to be successful as a government of the people, we cannot continue to view the problems of resource use and reuse from a narrow, selfish perspective. We must grow up as a thinking society and learn more about sharing our resources with one another. We must shift our attitude that land is a commodity to be used solely for profit toward the ethic of stewardship, of serving as caretakers. To accomplish these environmental goals, we must use the revolutionary tool of NEPA as our national response to the challenge of the future, in a quiet, rational revolution, which is already under way.

KELLY: The National Environmental Policy Act has surely become the key-stone of the ecological or environmental quality concerns of the past few years. It was spawned of a national crusade demanding the prevention or elimination of damage to ecological systems and natural resources, to the end that man's enjoyment and productive use of his environment might be enhanced.

NEPA is the full disclosure act, rightfully demanding that all actions affecting the natural environment be planned, designed, and implemented with full regard for its preservation. NEPA set a policy for a productive and enjoyable harmony between man and his environment. It addressed the prevention or elimination of damage to the environment in the interest of mankind's health and welfare and directed the development of a better understanding of ecological systems and natural resources. In NEPA, Congress also established the Council on Environmental Quality for the purpose of guiding the attainment of these policies.

The most public aspect of NEPA is the environmental impact statement, which displays the environmental impacts of projected plans or projects and details possible alternatives to the proposed action. In providing this full disclosure, the EIS emphasizes the adverse environmental effects that cannot be avoided if the plan or project is implemented. In this respect, the EIS displays one of its limitations.

The EIS has become an assessment of the impacts of an action on the natural environment, but often does not adequately address people impacts. When I say people impacts, I am referring to the crucial and specific impacts on people that are created by not proceeding with a plan or project. This focusing of attention on natural environmental effects such as the adverse impacts on rivers, streams, lakes, wetlands, and coastal shorelines, does not provide for the balance needed in weighing the true benefits of an action.

The impacts of not proceeding are often much more negative or adverse than the environmental impacts. The "do-nothing alternative" often has an impact on national economic goals, regional resource requirements, man's ability to protect himself from floods and to provide himself with adequate water supplies, required energy sources, or employment.

Another limitation of the EIS is that it is prepared after completion of the lengthy planning process that goes into the development of a plan or project. The planning process of the U.S. Army Corps of Engineers involves an evaluation of a variety of needs, economic and social as well as environmental, and develops a diversity of alternative means of meeting these needs. Inputs from a wide range of individuals, organizations, and agencies are sought and incorporated into the planning process. This procedure provides a large volume of data to the decision makers for their consideration in selecting the most feasible plan or project. When this selection is made, then the EIS is prepared.

And therein lies the limitation, because at this point a new group of people get involved in the planning process, seemingly all opponents. They are often people who were asked to participate in the planning and decision-making processes, but chose not to do so. After reviewing the EIS, they conclude that the adverse environmental impacts make the proposed action unjustified. The needs or requirements that were to be met by the plan are never understood or quickly forgotten. In explaining their position, they often cite alternatives not selected as the best means of satisfying the people's needs - flood control, water supply, power, recreation. But they didn't come forward to defend the other alternatives during the planning process in the hope of improving the plan or project.

Perhaps planning should incorporate "environmental impact statements" at all critical stages throughout the process and thus negate the need for an "after-the-action" EIS. That might involve the dyed-in-the-wool opponents in the process and direct their often great abilities and energies toward working to perfect a more acceptable project, rather than toward killing an action and benefiting no one.

A discussion of NEPA as the full disclosure act, the environmental impact statement as a public communication medium, and the public's role in the planning process, brings me to a topic that embraces everything discussed at this Conference, namely, public participation, or public involvement. Call it what you may, it still boils down to the same thing – getting all concerned and interested organizations and individuals involved as participants in planning for public works and projects. We must recognize that public participation is not an end in itself; to be successful must result in an improved solution, acceptable to the majority.

Speaking for the Corps of Engineers, it has long been a policy of the Chief of Engineers to conduct the Corps' civil works program in an atmosphere of public understanding, trust, and mutual cooperation. Under this policy, we who operate in the field have been directed that all interested individuals and agencies are to be informed and afforded the opportunity to be fully heard and to have their views considered in arriving at conclusions, decisions, and recommendations in the formulation of civil works proposals, plans, and projects and in regulating the proposed uses of navigable waters. These two programs are the Corps' major environmentally sensitive decision-making areas and also the areas most frequently requiring environmental impact statements.

Federal resources agencies can be assured of active and quite successful public participation activity for small projects. A good example would be a local flood protection project, involving a localized public with vested and direct interests. They must trade their river view for flood protection, or their potential for growth for flood plain zoning. However, the story is quite different for larger-scale projects such as Tocks Island Lake, the Passaic River Basin flood control plan, or potential offshore deepwater petroleum port development. Because these larger-scope projects or proposals affect such diversified interests and often span widespread geographic and political subdivisions, generating *constructive* public involvement is a difficult task not yet fully mastered.

Our experience has been that the generation of public interest leading to responsible inputs in regard to these larger efforts is very much a political process. In many instances a state, region, or other political subdivision or organization may be better able to develop public participation programs than a Federal agency, as in the recent case of the Tocks Island Lake Project.

This very controversial project on the Delaware River near the Delaware Water Gap was subjected to a year-long restudy by the Congress. In its authorization of the \$1.5-million study, Congress directed my office to conduct the study in cooperation with the Delaware River Basin Commission. The entire study effort – from formulation of the plan of study and contract scope of work, to monitoring the consultant's progress, to review of the final report – was coordinated with the states and other interested individuals and organizations through the DRBC. As a matter

of fact, all public contacts and public participation activities were coordinated by the Commission under a contractual agreement with the Corps. The contacts were extensive; progress reports were issued through the news media and at hearings, and completed drafts of portions of the study report were regularly and routinely made public. In short, the public dissemination of information was excellent and the solicitation of public input was extensive.

What was the result of this effort? We found that during the year-long study the inputs received and attitudes expressed were basically the same that we had heard for some years. We had launched a comprehensive restudy of Tocks Island Lake, being careful to analyze all aspects of the project and all alternative proposals, with special emphasis on distributing all available data to the public, only to find no changes in attitudes or position. Those who had been against the project were still resolutely opposed. They did not want the Tocks Island Lake Project. And the Tocks Island proponents were the same individuals and organizations who had supported it in the past.

But in the end, the governors of the Basin States each made his decision based on inputs from his constituents. Three of the four governors concluded that Tocks Island should not proceed to construction, and I recommended deauthorization based on the desires of the affected states. In the meantime, water supply, flood control, hydropower, and the other needs to be met by the Tocks Island Lake will have to be restudied and new planning initiated for their resolution.

Basically the same problems are being encountered with respect to flood control in the highly developed Passaic River Basin. Extensive effort at all levels has been expended toward developing possible solutions, but when each plan is advanced, the opponents cite adverse environmental impacts and recommend further study, and the decision-making process is delayed. The people of the Passaic Basin still must live with a serious flooding hazard and the resultant mental anguish and economic loss. Here again, resolution is obviously a political process involving a number of trade-offs; perhaps the implementation of public participation activities at the state and county levels would resolve conflicts and allow for action.

The Corps' 1973 report on potential sites for deepwater port facilities along the Atlantic Coast was met with opposition on environmental grounds – basically, possible oil spills and secondary land use. The result was the passage of laws by two states, New Jersey and Delaware, prohibiting such construction along their shorelines. These states did not propose to reduce their consumption but assumed some other area should accept the environmental risks. The recent petroleum crises stimulated new interest in the entire Northeast, but no actions have been initiated to reopen the discussion.

The issues of public participation and the environment are clearly linked in the planning process. Planning efforts will be more successful once meaningful public participation is achieved early in the process, enabling planners to more fully identify, address, and display the full range of concerns of the public. This early consideration of views would definitely be preferable to dealing with these same concerns later in our work after some basic decisions have been made.

Both the environmental impact statement and public participation are important to the success of public works planning and resource development. I wish I could offer some better answers for resolving their more controversial aspects. I hope that my brief presentation will lead to some meaningful discussions by the panel and assist us in their resolution.

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DISCUSSION

STRONGIN: An arbitrator or mediation panel would arrive at a decision faster than the legislative process.

KELLY: Mediation presumes that everyone is interested in a solution. That is not always the case. The best approach to avoiding delays is to unify the government agency approach.

SCOTT: The long-range environmental impact is in the noise level of the measurement, and it is well below the noise level of our ability to predict the impact. How are we going to incorporate an evaluation of these subtle environmental and social effects into EIS?

HILL, GLADWIN: In situations where we will not have all the adequate information within a reasonable time and yet are confronted with a GO or DON'T GO question, a decision still has to be made on the basis of alternatives.

STERN: The diversity of people weighing the alternatives by the political process at best provides an answer that people are willing to live with.

HARLOW: One of the alternatives whose impact must be evaluated early is that of doing nothing.

KELLY: I agree that in the political arena the tendency is to find a solution unsatisfactory, but not to face the fact that some solution must be made. Maybe public pressure would help to avoid such an impasse.

TIMLOFF: EIS's could be made more concise if anonymity were replaced with identified reviewers.

JENSEN: How can we be assured that in the political arena we are going to get a good or best decision?

RUSSELL: That's the way we chose to govern ourselves; I prefer representative to executive government.

KELLY: Many of the benefits in long-range problems will not come to fruition for 10 or 15 years, and the man who makes a tough decision will get little or no credit for it. On the other hand, whatever benefits exist in a decision to preclude a construction accrue rapidly. The politician is faced with a tough decision and it is difficult for the public to make an evaluation.

PROIOS: When dealing with environmental quality, certain absolutes exist, such as the protection of endangered species, which should not be violated by either cost effectiveness or local legislative decision.

RUSSELL: I do not agree that there are absolutes that cannot be violated, except for scientific absolutes such as the law of gravity. Scientists cannot tell us what is the socially right thing to do. They can only describe the consequences of alternative decisions.

PERSHING: Jurisdiction in the coastal zone is more Federal than local. I question whether representatives on a Federal level adequately express the concerns of affected local communities.

RUSSELL: There ought to be better ways of drawing jurisdictional lines.

JACOBS: What would be the nature of a national energy policy? Are there any historical analogies?

GUNNERSON: One analogy is the Act that created the national highway system.

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