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Offshore Mariculture in the Gulf of Mexico: A Feasibility Report

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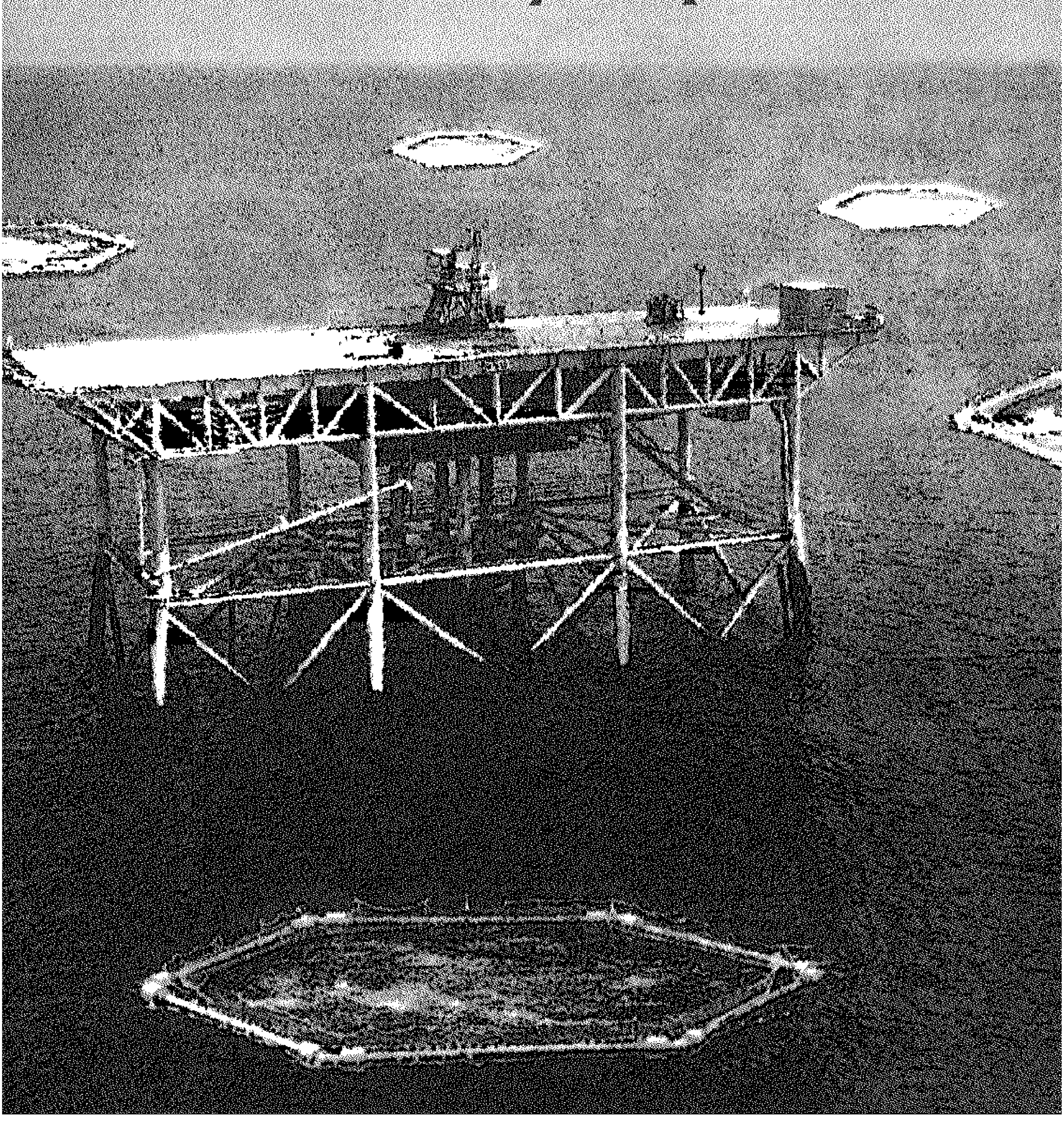

Offshore Mariculture in the Gulf of Mexico: A Feasibility Report

Waldemar Nelson International Inc.

Produced by

Louisiana Sea Grant College Program

Louisiana State University

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To obtain additional copies of this report, contact:

Communications Office
Louisiana Sea Grant College Program
Sea Grant Building
Louisiana State University
Baton Rouge, LA 70803

(225) 578-6448 or 578-6449

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Preface

Offshore mariculture in the Gulf of Mexico region holds much attraction for both public and private entities, but its feasibility remains untested. A major hindrance to such development is the lack of easily accessible information about the environment of the northern gulf and the conditions surrounding offshore platform operations. Louisiana Sea Grant decided to republish this report, originally produced by Waldemar Nelson International, both to fill some of the knowledge gaps and to serve as a point of departure for those who want to investigate mariculture opportunities more thoroughly. It is by no means an exhaustive treatment of the subject but can be considered an incremental step toward the implementation of offshore mariculture.

Louisiana Sea Grant College Program

Acknowledgments

A project team was assembled by Waldemar Nelson International Inc. to conduct a study on the feasibility of establishing offshore finfish mariculture operations in the Northern Gulf of Mexico. This report, originally published by Waldemar Nelson, presents the results of that study. In addition to staff of Waldemar Nelson International Inc., a number of individuals and institutions contributed to the conducting of the study and preparation of the document. Grateful appreciation for these efforts is extended to the following:

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Russell Raulston

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Disclaimer

In order to develop certain portions of this feasibility study, it was necessary for the project team to select classes of certain components of equipment. The mention or use of any particular type of equipment in this report is not intended to be an endorsement of that particular type of equipment. It is merely a means of assessing overall feasibility of offshore mariculture in the Northern Gulf of Mexico.

Executive Summary

This report evaluates the feasibility of establishing offshore finfish mariculture operations in the northern Gulf of Mexico. A component of this analysis was an evaluation of what has transpired in the last two or three decades in other countries around the world. Extensive literature reviews on many aspects of these operations were performed.

It became obvious in the early phases of our analysis that a truly offshore finfish farming operation would almost necessarily be on a rather large scale in order to be economically attractive. Our analysis covered a private operation with no significant federal or state subsidies. The project team developed a "base case" senario which was used subsequently in many types of analysis, i.e., economic, enviromental, regulatory, etc. The derivation of the base case also assumed that the farming operation was based on an oil and gas production platform which has ended its useful life of hydrocarbon extraction. Following is a summary of the pertinent conclusions reached.

The establishment of an offshore mariculture industry in the northern Gulf of Mexico is certainly practicable with the use of existing technology. Chapter 1 of this report details the available systems for cages, mooring systems, feeding systems, and other support functions and concludes that the technology for these systems is well established in other countries around the world and could be easily adapted to installation in the northern Gulf of Mexico.

The project team evaluated a number of different finfish species for Gulf mariculture and concluded that two of these species (red drum and striped bass) are currently suitable for extensive farming operations in the Gulf of Mexico, particularly when associated with a marine hatchery. A number of other species were evaluated and conclusions reached that some degree of development either in the hatchery or grow-out phases would have to be realized in order to make these other species suitable for farming at production scale.

An adequate number of platforms are available in the northern Gulf of Mexico for potential use as centers of farming operations. Chapter 3 of this report gives detailed information on the locations, numbers, sizes, and ages of these platforms. There is also considerable discussion in that chapter about the concerns of platform owners regarding transfer of these structures to a start-up mariculture company. Oil and gas company owners have legitimate concerns that will have to be addressed in detail by a prospective mariculture enterprise.

The project team evaluated the current status of the regulatory environment for mariculture in the northern Gulf. Chapter 4 presents a discussion of the status of projects previously proposed and also a detailed discussion of all the necessary permits and authorizations for operation that need to be acquired by a mariculture company. The project team does not believe that these regulatory constraints will impede development of mariculture operations in the Gulf in the long-term; however, some suggestions are made in that chapter regarding necessary statutory and regulatory revisions that should be made in order to foster the establishment of a mariculture industry.

The costs for establishing and operating an offshore farm will be substantial. In Chapter 5 of this report we indicate that for an independent mariculture operation, i.e. not operating in concert with oil and gas production, capital costs for such an operation could be about $6 million with annualized costs of about $3 million. For this reason, the establishment of truly offshore mariculture operations in the Gulf will probably be by well- funded, relatively large companies. Chapter 5 also presents data that can be used by prospective mariculture operators in the development of their own cost and revenue projections for their respective operations.

Chapter 6 in this feasibility study is an assessment of the environmental impact of establishing the base case operation in the Gulf of Mexico. Items reviewed as part of that analysis include water quality issues, impact on native fish stocks, impact on protected species, and a summary evaluation of socioeconomic impact analyses. It was concluded that a single, large mariculture operation such as described in the base case analysis should not create significant adverse impacts to any of these areas. A relatively detailed water quality impact analysis was conducted and it was determined that the water quality surrounding a well-operated offshore farm should not be adversely affected. Effective monitoring of these operations in the future is important as this will verify use of certain assumptions and ensure that individual operators work in close concert with regulatory agencies.

Disease management, market analysis, cage systems, and water quality data are practical considerations discussed in chapters 7-11. A bibliography offers additional resources.

In summary, the project team concludes that the establishment of offshore finfish mariculture operations in the northern Gulf of Mexico is likely to occur in the next several years. Given the national trend toward more conservative fisheries management and worldwide increasing demand for seafood, we believe it will prove to be a necessary and valuable supplement to marine finfish harvested by the commercial fishing industry.

WALDEMAR NELSON INTERNATIONAL INC.

Chapter 1

Introduction

The concept for an offshore finfish mariculture operation in the Northern Gulf of Mexico and the basis for this feasibility study includes use of the numerous oil, gas and/or sulfur production platforms located there. It has been estimated that there are more than four thousand platforms in the Northern Gulf off the coasts of Texas through Alabama. Although the majority of these are still in mineral production, approximately one hundred (on the average) are decommissioned each year. Decommissioning means the producing company does one of three things with the structure after its production service is completed: (1) remove the platform and transport to shore to sell as scrap; (2) remove the platform and place within a state-approved "rigs to reef" area to serve as marine habitat; or (3) if the platform still has useful life, it can be moved to another production area for service either by the original owner or another. The first two options above typically incur significant costs to the platform owner.

The study team evaluating a Northern Gulf mariculture operation believes that a platform owner should have a fourth option available. That option would include the use of the platform, after all remaining wells are properly plugged and abandoned and production equipment removed, as a center of operations of a mariculture operation. It is known that some previously proposed and currently planned offshore mariculture operations have contemplated using still operating platforms. The authors of this feasibility report believe that the complications arising from such joint use of the platform outweigh any potential benefits. First there is a requirement for a fairly significant amount of space required for mariculture equipment (feed storage and delivery systems) which is typically not available on a still producing platform, fish cages surrounding the platform would obviously interfere with well workover or other activities, and both operations require routine access to the platform by marine vessels which would have to be closely coordinated.

The comprehensive, large-scale mariculture installation as envisioned in this report is composed of six basic components:

1) Fish Cage Systems
2) Cage Mooring systems
3) Fish Feeding Systems
4) Offshore Support Systems (Platform Operations & Maintenance)
5) Onshore Operations
6) Product Transportation Systems

In addition to these six components, offshore processing of raised finfish is a possibility and will be discussed in Chapter 5.

The system envisioned, as described herein, is a highly mechanized and automated one. Mechanization and automation is deemed necessary for the type system contemplated in this study because, for such a venture to be economically successful, the scale of the operation would require storage and distribution of large quantities of fish feed, efficient and high capacity product handling, electronic monitoring and control of grow-out facilities, up to date disease control and prevention technology, mass harvesting methods, and, sophisticated fish husbandry accounting procedures. Such a system would be generally arranged as follows:

> Fish grow-out containment cage systems, either floating or submerged, will be moored to the sea floor around an abandoned minerals production platform, spaced at distances from one another and the platform as determined by depth, wind, current and wave conditions at the site. The mooring systems will consist of arrays of dead weight anchors on the sea floor, connected to the cages by tensioned systems of cables and/or chains, arranged to hold the cages in position under specified design storm conditions. Cages will be provided with navigational aids and warning markers in compliance with U.S. Coast Guard Regulations.
>
> Fish fingerlings will be transferred to grow-out cages from hatchery(ies) located onshore in a specially constructed transfer tank installed on a tender/transport boat owned or leased by the mariculture company. Size of the fingerlings introduced into the offshore cages will be species dependent.
>
> A mariculture operations and maintenance crew will man an operations center located on the platform on a full time basis to monitor and control fish feeding, fish health and growth, net maintenance, and installation security. When the fish reach target harvest weight or size they will be harvested by the crew, which may be augmented by additional personnel to assist in the operation.
>
> Fish feeding will be accomplished by an automated feeding system, controlled by a PC-type computer. Specially prepared feed will be brought in bulk by tender boat to the platform, where it will be stored in hoppers or bulk containers, which in turn will supply – through a conveying system – an automatic feed distributor. For floating, or surface cage systems, dry feed will be conveyed to drop lines or blown pneumatically through flexible tubing from the distributor to the cages, where the feed will be discharged onto the surface of the water in the cages by spreader nozzles mounted on the cage flotation structure. For submerged cage systems, wet feed will be pumped by the distributor through flexible tubing down to the fish through discharge nozzles located inside the submerged containment cages. Feeding will take place automatically, multiple times per day in order to achieve optimum feeding efficiency. Feed quantity for each feeding will be calculated to ensure that a minimum of feed is lost through the net without being consumed by the fish. The number and timing of the feedings will be

determined to ensure that the fish consume enough feed each day to promote optimum growth rates. Carefully controlled feeding will allow the operation to reach optimum feed conversion ratios, that is, produce the maximum edible fish meat for the minimum quantity of feed.

The cages will be constantly monitored by underwater, remotely operated video systems in order to spot and treat possible diseases or other threats to the fish, to locate general and routine wear-and-tear damage to the nets, predator intrusion, etc. The operations and maintenance crew will have diving capabilities and all accessory equipment required to maintain and repair damage to nets and other equipment. The crew should be provided with a small boat for routine or daily use in maintaining equipment, observation of fish, minor repairs to cages, etc.

Depending upon species and size of fish, harvesting by operations in other countries is accomplished in two ways:

1) In large-sized surface cages fish are separated using a mini seine net which is gradually pulled in to crowd fish into a harvest space adjacent to the side of the harvest vessel. Fish are then either brailed using a large hydraulically driven winch system or, in the case of smaller fish, directly pumped aboard into an ice slurry.

2) In submersible cages the bottom of the net is attached to a winching system which enables the space within the net to be reduced. A harvesting cage is then attached to an opening in the main culture net below water level and then fish are herded into the harvesting cage in controlled numbers. These fish can then be brailed, pumped or lifted onto the harvest vessel.

Harvest rates of 30 tons per hour can be achieved with either of these two systems.

Grading at sea is undertaken for fish species up to 5 kg by a fish pump coupled directly to a grading unit. Using the vessel's wet holds, fish can then be pumped back over the side into a new cage or transported to a different site.

Fish Cage Systems

There are two general types of mariculture cage systems: the floating or surface type and the submersible type. Each of these types is available in a wide variety of types, configurations and materials of construction. A typical surface cage system consists of a floating structure which is directly connected to the mooring and anchoring system, and supports underwater fish containment and predator net systems; an overhead bird predator net; personnel access and walkways; feeding accessories and/or control; and monitoring or navigational aid equipment. Submersible cage systems consist of a net system support structure, also directly connected to a mooring and anchoring system which, upon command, can be fully or partially submerged to a given controlled depth beneath the surface by means of various types of ballasting and floatation control systems. Many submersible-type cage systems could also be used as surface floating systems.

Surface Cage Systems

Floating cage systems are manufactured in a variety of shapes, sizes and material configurations. Smaller sized cages (up to approximately 20 m^2) or pens are generally rectangular in shape, and are often installed as group, in rectangular arrays of four or more cages interconnected by walkways and intermediate platforms. Larger cages are usually circular, hexagonal or octagonal in shape and, though moored to a common system of anchors and interconnected by tension lines, are spaced at some distance apart in the open sea. Many of the circular or hexagonal/octagonal types are provided with walkways or access platforms along the side or top of the flotation structure. Materials of construction of the rectangular-shaped cage system float structures vary by manufacturer, from metal tubing, sheet metal and reinforced rubber hose tubing with metal couplings, to pin-coupled solid high density polyethylene (HDPE) blocks. Octagonal and hexagonal cages are generally built of pressurized, reinforced flexible rubber hose tubing (hose of the type used for pumping petroleum products from oil tankers to pipeline transfer buoys at sea) connected by heavy metal couplings to form the octagon or hexagon. Circular cages are usually constructed of heavy wall (50 mm) HDPE heat-fused pipe lengths filled with polyurethane foam. The circular HDPE cage flotation systems are manufactured in either a single or double pipe configuration, with heavy-duty plastic or metal stanchions installed at intervals to reinforce the pipe structures as well as net support systems, handrails, and walkways. All cage control, monitoring, accessory and navigational aid equipment is supported directly by the flotation structure.

In floating cage systems, the fish are contained within a net which hangs from the flotation structure to a desired depth beneath the water surface. When site water depth is not a limiting factor, net bottoms can reach a depth of up to 20 meters. Nets are weighted and stiffened in order to prevent the net from becoming greatly distorted by lateral currents or wave action. Fish containment nets are generally made of nylon or other synthetic materials, though natural fiber is used in some instances. Containment nets may be treated with various types of non-toxic chemical compounds for the prevention or retardation of marine growth. Marine growth can become a factor in blocking water passage, which in turn can cause severe drag on nets, thereby exacerbating subsurface distortion and stress from water current and wave action. Fish containment nets often incorporate zip-closure-type access openings near or in the bottom mesh for mortality removal and other access purposes.

Offshore marine cage systems are usually provided with a heavy gauge net called a "predator net" around the outside of the fish containment net or nets. Depending upon the location of the installation and the type of predators common to the area, the nets may be constructed of more or less heavy gauge metal or synthetic fiber material of a mesh size gauged to prevent access by sharks, seals, otters, etc. Predator nets are supported directly by the flotation structure, and are not attached to the fish containment nets.

Bird predator nets covering the fish containment nets are commonly installed as well, and are supported from the flotation structure and above the water surface by stanchions or purpose built stays. These nets are generally made of light gauge synthetic fiber material and are of a mesh size designed to deny access to all but the smallest birds.

Submersible Cage Systems

Submersible cage systems differ from the floating type in that the containment and predator nets must totally surround the fish being grown out in the system. The cages must also have a mechanical system for submerging and rising to the surface. These systems are also available in a variety of configurations. The most common material used in the construction of submersible systems is lightweight metal, such as aluminum or titanium alloy tubing. Predator netting is attached to the outside of the cage structure and fish containment netting is supported on the inside of the structure. The structures themselves are usually supported by or built around a hollow central vertical spar, which can serve as ballast-flotation chamber, feeding conduit, personnel support spar, etc. Some submersible systems utilize slip rings and exterior net-support rings that allow the shape of the containment net to be altered in order to drive the fish inside into a smaller volume area for harvesting or transfer to another net. Nets are provided with zipper-type access ports for harvesting, inspection, mortality removal, etc. The cage structure is connected to a stationary anchoring and mooring system by adjustable cable and chain arrangements which maintain controlled tension on the cage at variable depths.

Submersion and re-surfacing of the system is accomplished either by mechanically producing positive or negative buoyancy through the introduction of water and/or air into ballast chambers located in the cage support structure, as in a submarine, or, by a system of cables and pulleys which pull a zero buoyancy cage up or down in the water.

Cage Mooring Systems

Cages are moored to the sea floor using single or multi-point arrays of anchors and a system of cables and/or chains and buoys to maintain tension on the anchoring and positioning lines, which keep the cage system moored in position while allowing in situ movement due to wave and/or wind action.

Many types and sizes of anchors are available commercially and some dead weight-types may be easily manufactured using concrete and rebar, scrap iron, etc. Generally, the anchors are positioned in evenly spaced arrays around the cage systems, attaching the cage structure(s) to the anchors with cables and/or chains.

The cages, cable systems and anchors may be interconnected in various configurations designed to hold the cage position steady while allowing an appropriate amount of vertical movement due to wave action and some surface translation due to changes in current and wind direction. The cables and chains are maintained under tension by use of flotation buoys.

Anchor type and sizing, mooring configurations and cable tensioning arrangements depend upon site weather conditions, ocean currents, typical and storm condition wave heights and frequency, as well as sea floor composition and topography. Because of the complexity and importance of this subject, a full technical discussion of cage mooring considerations and conclusions thereof is included in a separate section of this study.

Fish Feeding Systems

Automatic fish feeding systems consist of (a) feed storage components, (b) feed conveying equipment, c) pump or blower and distribution apparatus, and (d) on-cage feed delivery components.

It is envisioned that an offshore mariculture operation will include platform-mounted bulk storage hoppers with capacity to store enough feed to supply grow-out cages for a planned number of days depending upon location, ease of access, etc. The hoppers will deliver feed through screw-type or gravity conveyors to an automatic distribution hopper, which forms part of the automatic feeding system. A rotary distributor mechanism will distribute feed to each separate cage pipe on a schedule programmed into a control computer. This will be through mostly horizontal conveyors to gravity drop lines or through blown-dry feed or pumped liquid feed.

Each cage would be supplied with feed through a flexible plastic pipe run from the platform floor (feed storage and distribution area) down into the water and out to a distribution or spreader nozzle mounted on each fish cage. The cage feed pipes will be clustered and run through protective steel pipe casing from the platform floor to beneath the water surface to a predetermined depth to protect the relatively flexible feed tubing from damage by waves and wind. The feed tubes will then be run from the end of the protective casing out to the cage structures with feed discharge spreader nozzles on each floating cage structure.

Feed will be distributed to each cage and discharged for feeding as commanded by a computer program. Feed will be discharged into the cages multiple times per day during daylight hours in quantities determined by the number and weight of fish in each cage being fed. The computer program should be routinely updated to allow for calculation of quantities and frequency of feeding. Quantities will be based upon the amount of feed the fish in each cage will take before allowing unused feed to pass through the cage (wasted).

Optimum feeding is attained when the fish consume all feed provided at all feedings, allowing no waste to pass through the net area, and growing at maximum rate.

Offshore Support Systems (Platform Operations & Maintenance)

An operations and maintenance (O&M) crew composed of a shift supervisor and support personnel will man the platform on a 24-hour per day basis. Duties of the crew will include controlling and monitoring fish feedings, inspecting cage and net installations, checking mooring systems, unloading and storing feed, performing routine maintenance of equipment and fish stock, offloading and transferring fingerlings to grow-out cages, and harvesting.

An Operations Center located on the platform would probably be equipped with a personal computer (PC) system, remote video monitors for viewing all above and below surface mariculture systems, all recording and monitoring instrumentation for observing and collecting data on water temperature, quality, current, etc., and telephone/radio equipment for communication with onshore operations.

Farm operating equipment should include a heavy duty diesel-powered crane for lifting and changing nets, for loading bulk feed containers, for lifting boats and personnel, and for lifting and transferring fish during harvesting or fingerling stocking as necessary. Electrical power generating capacity should be provided on the platform, complete with fuel storage tank(s), if necessary, and all electrical distribution wiring and switchgear necessary for the operation of automatic feed storage and distribution equipment, other operations center equipment, and platform security and operations lighting.

Crews will be provided with adequate living quarters that will include sleeping, cooking, food storage and recreational facilities. The installation will also be provided with quarters for visitors and temporary work crews.

Onshore Operations

It is envisioned that onshore operations will include either a fish hatchery or, as a minimum, a fingerling holding and transfer facility in addition to mariculture company administration, sales, product distribution, and logistics operations.

If the mariculture operating company also decided to raise its own fingerlings, hatchery operations would have to be accessible to transport and tender boats or ships which will transport fingerlings from the hatchery to offshore operations. The same boats will supply fish feed, platform supplies, equipment and fuel, as well as transportation for crew shifts. The hatchery will be complete with spawning tanks or pools, larvae rearing areas, and fingerling grow-out pools or ponds, as well as equipment for the production of all food such as phytoplankton, zooplankton and organisms O&M deem necessary for the successful production of fingerlings of the different species being cultured offshore.

Product Transportation Systems

The farm should own or lease a purpose-built transport/tender boat which will be used to transport fingerlings from the hatchery to the offshore installation(s). The transport hold or tank needs to have the capacity to re-circulate outside water for the purpose of acclimating fingerlings to the temperature, salinity and turbidity conditions of water in the location of the grow-out cages. The transport/tender boat should also be equipped with a crane and storage space for cage nets, ice, and other supplies necessary for the operation of the offshore station. The tender will also be used to transport shifts of O&M crews to and from the platform. The transport/tender boat could also be used to transport harvested fish to shore as necessary.

Equipment Assessment

Mariculture Cage Systems

Two general types of cage systems are used in open ocean mariculture today: the floating type and the submersible type. Each type is manufactured commercially in a wide variety of specific configurations and materials of construction.

Typical surface cage systems consist of a floating structure which supports underwater fish containment and predator net systems and which is kept in position on the open sea by a mooring and anchoring system. Overhead bird predator nets, personnel access platforms and walkways, and feeding accessories and/or control, monitoring or navigational aid equipment may also be supported by the flotation structure.

Submersible cage systems consist of a net system support structure which, upon command, can be fully or partially submerged to a given controlled depth beneath the surface by means of various types of ballasting and floatation control systems. The structure is directly connected to a seabed mooring and anchoring system, similar to surface system mooring. Many submersible-type cage systems may also be used as fully enclosed surface systems only.

Surface Cage Systems

Rectangular and Modular Pens: This sub-group of cage- or pen-type is manufactured in several configurations by a number of manufacturers. Some of the types and manufacturers of this type cage are: The floating spar-type as manufactured by Ocean Spar Technologies, LLC, known as the Sea Cage System; Wavemaster Steel Pens, manufactured by Wavemaster Canada, Ltd. of British Columbia; articulated flexible hose-type Tempest Fish Cages and High Seas Fish Cages manufactured by Dunlop Aquaculture and Bridgestone Corporation, respectively. These cage systems are all viable and are widely used for near-shore installations around the world. Generally speaking, rectangular/modular systems are used in smaller installations, with cage sizes up to approximately 25 m, and are generally arranged in even numbers of modules as a system of multiple pens joined by common accessways and flotation structures.

Floating Spar Buoy Systems: The main structural component of this type system is the spar buoy, a metal tube reinforced by ring stiffener members spaced along its length which floats in a vertical position. Spar buoys support the net enclosures at corners with a system of tensioned shackle rigging connected to the top and bottom of the buoy. The tensioned connections to the buoys keep the net enclosures from becoming inoperably distorted by wave and ocean current action. The buoys are moored to the sea floor by a system of anchors and lines attached to middle ring stiffeners. Net enclosures may be arranged as rectangles (four buoys), pentagons (five buoys), hexagons (six buoys), etc. The square configurations are manufactured in sizes up to 24 meters on a side; the system may be configured with up to 10 sides (10 buoys) to obtain cage surface areas of up to approximately 3000 m^2.

Modular Rigid Steel Pen Systems: These systems are composed of integral galvanized steel members connected by articulated bushings to form rectangular modules up to 30 m on a side, supported by polystyrene-filled flotation tanks. The cage system is moored by standard anchoring systems. Net enclosures are supported by the structural members, and are weighted to form relatively stiff net panels underwater. Structural members serve as accessways and walkway platforms. These systems appear to function well in calm, protected inshore waters, but would probably not be well suited to rough weather in unprotected offshore waters. Although the modules are provided with some flexibility through articulated connections between main structural components, the relatively rigid structural system is probably not compatible with high frequency, short period ocean wave action as encountered in the open waters of the Gulf of Mexico.

Circular Plastic Tubing Systems: A single or double ring of heavy-walled, semi-rigid plastic tubes filled with polystyrene-type foam forms the flotation support structure of these systems. The tubing material is usually high-density polyethylene (HDPE) because of its rugged strength, wearing characteristics and ease of fusion for welding. Twenty to 50 centimeter (cm)-diameter pipe lengths of HDPE are welded or fused into continuous rings, and are held in shape by systems of metal or HDPE clamps, retaining rings and stanchions spaced evenly around the circumference of the structure. Handrails, walkways, net systems and mooring lines are connected to the structure by metal clamps or hook and ring fittings that are incorporated into the stanchions. These systems are produced by a number of manufacturers in Europe, America and Australia, such as Polar Cirkel (Helkgeland Plast AS) of Norway, Wavemaster of Ireland and Canada, Global Contract Services of Australia, and others. These cage systems are manufactured in large sizes, up to 70m total diameter.

Particular advantages of HDPE tubing structures are a relatively low cost, simplicity of fabrication, and – because of the low weight of the structure material – ease of transport and installation.

The tubing used for the larger diameter cages is usually of heavy wall thickness, between 35 and 50 mm, and is therefore rugged and wear resistant. Welding (heat fusion) of pipe lengths together to form a continuous ring is easily accomplished on-site, and joints are reported to be reliable and strong. Since the pipe is filled with polystyrene foam, flotation is positive even when the pipe itself is damaged by collision or by some other event. Manufacturers and many users claim that the larger diameter (30m and above) cage structures are quite flexible, and therefore are well suited for installation in offshore areas where rough seas are common.

Fish containment nets are supported from stanchions along the inside diameter of the rings, and are maintained in a vertical position in the water by weights suspended from a bottom circumference metal ring or from stiffeners run vertically along the net sides.

Petroleum Product Transfer Hose Sections – Articulated Flexible Cage Systems: Several rubber specialty companies, notably Dunlop of Britain and Bridgestone of Japan, manufacture aquaculture cage systems utilizing rubber hose technology perfected for use in the petroleum industry. Heavy duty reinforced rubber hoses, in combination with industrial-type corrosion-resistant steel couplings and reinforcement fittings, were developed by the above-mentioned companies for the purpose of transferring petroleum products from large sea-going tanker ships to underwater pipelines and dockside offloading manifolds. Because of the quantities and nature of the petroleum products handled, the hoses operate under high pressures and temperatures at sea, often in bad weather. Such duty requires extremely durable, flexible and strong construction. Having proven durability, seaworthiness, and flexibility, the hoses have been adapted for use as structural members on open ocean, floating mariculture cages. These type cages have been utilized for open sea operations for a number of years in Europe, Japan and Austral-Asia, and generally have received high marks from aquaculture users for durability, reliability and efficiency.

This type cage system is built from sections of rubber oil-product hose with sealed, airtight coupling flanges connected to both ends. The end coupling flanges are constructed in various angle configurations for connecting different shaped cages, for example, 45° couplings are used to connect four sides of hose sections in a rectangle, 30° couplings connect six sides of hose sections to form a hexagon, and so on. This system is configured in rectangular, hexagonal, octagonal and circular shapes. Sections of hose and additional coupling may be added to increase the size of the net systems as required, in some configurations.

Circular cages are manufactured in various sizes ranging from 18m to 40m inside diameter, for enclosed surface cage areas from 255 to 1260 m^2. Hexagonal and octagonal cages are built in size ranges from 16m to 20m on a side, for enclosed surface areas of 670 to 1000 m^2 and 1,240 to 1,930 m^2 respectively. Square cages of this type range from 12 m to 20 m on a side. Fish containment nets for all of these systems can be installed for depths up to 25 m, in proportion to the surface configuration.

Submersible Cage Systems

There are basically two types of submersible cage systems: "active" and "passive." The active-type system is based upon a variable buoyancy flotation structure. An example of such a system is the Ocean Spar Technologies, L.L.C. "Sea-Station," which incorporates a ballast valve in the central spar structure to vary its buoyancy.

The passive system depends on mechanical action acting upon a neutral or slightly positive buoyancy structure to raise or lower it in the water. This system requires mechanically adding weight (or downward force) to the system to submerge it and the mechanical release of the weight or force on the system to return it to the surface.

Variable Buoyancy Systems: There are several ballasted systems available commercially which employ variable structure buoyancy methods for submersion.

One is the Ocean Spar "Sea Station" system, mentioned above. Another is a Russian system, sold by SADCO-SHELF, Ltd. of St. Petersburg, which operates on a principle similar to the submarine. Marvel Investment Corporation of Tel Aviv, Israel manufactures a system which employs a variable buoyancy buoy to act upon a slightly positive buoyancy cage. In this case, when air is expelled from the mooring buoy, its buoyancy becomes negative and the buoy sinks toward the sea bottom, pulling the slightly positive buoyancy cage system under water through a system of lines and pulleys; when air is pumped into the buoy, forcing water out of it, it becomes strongly buoyant, allowing the cage system to rise. The cage structure's degree of buoyancy is controlled by a calculated quantity of weights attached to it; quick-acting couplings may be actuated, as a fail-safe measure, to release the weights in an emergency to have the cage float to the surface quickly.

Another ballasted system worthy of mention, although it is not a true submersible one, is the "Floating Fish Farm" system manufactured in Spain by Marina System Iberica, S.L. This system consists of a steel platform structure floating on variable buoyancy structural columns which raise or lower the platform in relation to the surface of the water, raising it up to six meters above sea level as required, mainly to keep the platform structure above wave height during storms. Seawater is pumped into or let out of the flotation columns, lowering or raising the structure in relation to sea level. A core grouping of cages are incorporated into the structure itself, but the system may be expanded by adding separate and independently moored cages around the platform. The independent cages may be supplied with feed from the platform, and maintenance or inspection carried out by the floating platform crew as well.

Most variable ballast submersible cage systems operate on similar principles of ballast control. Although some such systems do function satisfactorily, mechanical valves, pumps, pulleys and other moving parts are complications which can contribute to the risk of malfunction and potential operational problems in the unforgiving environment of the open ocean.

Passive or Neutral Buoyancy Systems: There are several commercially-available cage systems which may be submerged by mechanical means, either to grow out fish at depth or to escape violent sea states brought about by storms. In most cases, the cage systems are designed to have neutral or slightly positive buoyancy, which allows the system to be pulled easily to a desired depth by mechanical means, and then returned to the surface.

One such system is the "Trident" cage system manufactured by Coastal Services, Inc., which is built of tubular aluminum members connected in a "geodesic" structural pattern with patented bolted connectors to form a geodesic-type spherical enclosure. The system is modular. Because of its relatively light construction, the system in easy to rotate while in the water, which permits the cage netting attached to the inside of the structure to be exposed to sunlight, therefore eliminating some net bio-fouling and permitting inspection of the net for maintenance without divers. Since the cage is totally enclosed (spherical), it may be submerged by adding weight to it or by mechanically pulling it beneath the surface.

Some cage systems now being used in the Mediterranean, specifically in Italian waters, incorporate net enclosures only, without solid structural support, for the culture of sea bass and sea bream. Because of the net material's relatively light weight, the "free floating" net supported by floats or buoys, can be submerged and raised with a minimum of force. The system seems vulnerable to predators, but in areas where predators are scarce, it could be viable and certainly inexpensive.

Containment Nets

Fish containment netting is available in a wide variety of types, material, sizes and meshes. Flexible netting is available in natural as well as synthetic fiber, but synthetic fibers such as nylon polyesters are the most widely used in today's mariculture systems. Nets made of this material are available with knotted and unknotted mesh, in a variety of colors, mesh sizes and cord thickness. Size mesh and cord weight will largely be determined by the size and type of fish being contained, and by whether the cage will be moved (towed) or used for product transfer and harvesting purposes. Stiff, extruded plastic netting is also available commercially, generally manufactured of high or medium density polyethylene. This type netting is available in rolls and may be cut to size to form stiff panels or circular pens. Because of the thickness and inflexibility of this type netting, cages made up of it may become difficult to handle in rough weather or high sea-current situations.

All types of containment netting can be treated with anti-fouling compounds to reduce marine growth bio fouling at sea.

Whatever type or size netting is used, the system employed for attaching and detaching the nets from the structure must be simple and quick so that routine repairs, cleaning and net changing can be accomplished without major effort. The system should also incorporate zipper-closure-type access openings for removal of mortalities, diver inspections, and harvesting or fish transfer procedures.

Mariculture Feeder Systems

General

Commercial fish feeding systems for aquaculture are designed to distribute either dry or liquid feed to fish pens or tanks. This study will address the delivery of pelletized dry feed to floating or submersible cages in the open Northern Gulf of Mexico.

Feed can be delivered to the pens or cages by farm personnel, using methods as uncomplicated as manually throwing the feed from an open bucket directly onto the surface of the water from cage-side, or as complex as automatic delivery from large storage hoppers through a system of pipes or conveyors. Since the quantity of fish to be raised by the mariculture systems described herein is measured in tons, it is envisioned that the feed delivery systems employed will be fully automated, controlled by computer programs to obtain optimum consumption and fish grow-out rates at the lowest possible feed conversion ratio (FCR), designed to deliver large quantities of feed reliably and efficiently.

Dry feed delivery systems consist of the following elements: storage bins or hoppers, conveying ducts to transport measured quantities of feed from the hoppers to a distributor, conveying systems to transport the feed from the distributor to each individual cage, and spreader nozzles on the cage to "spray" pellets onto the water. A mechanism at the cage-end of a conveying duct spreads the feed over the surface of the water in a manner designed to optimize access to the feed by the fish in the cage. The quantity of feed delivered to each cage is controlled by a computer, which is programmed to deliver optimum feed amounts per cage per feeding, based upon the number and size of the fish in the cage, the amount of feed consumed during each feeding, etc. Ideally, the program will deliver only the amount of pellets per feeding which can be consumed totally by the caged fish per cycle, each cycle repeated the number of times per day necessary to achieve optimum fish growth rates. The feeding program will be dependent upon information feedback from detection systems in the cages, comparison of actual growth rates to calculated rates, and operational experience with the species being raised.

Auger or Disk Conveyor Delivery Systems: In this type system, feed is delivered to a tubular (pipe) conveying duct from a storage hopper, through a rotating impeller which evenly controls the quantity of feed pellets fed into the duct. The feed is pushed or pulled through the duct system by a continuously rotating screw auger or by a series of cable connected disks. The operational speed of either system must be controlled to avoid crushing the pellets. Filters for collecting any fines generated by crushed feed are incorporated to avoid clogging downstream distribution elements. The feed is carried to individual drop units over each cage for delivery. The drop units may be sized on a volumetric or gravimetric basis to deliver a specific volume or weight of feed to each cage during each feeding cycle. The volumes or weights delivered by each drop unit may be set in accordance with a feed scheduling computer program.

This type system is very effective and efficient for delivery of feed to accessible and rigidly stationary cages or pens, such as tanks or pools in an onshore aquaculture operation. One positive advantage of these systems is the low electrical power consumption required to deliver relative large amounts of feed over a considerable distance and the ease of distribution to any number of cages.

The obvious disadvantage of using such a system in an open ocean installation is that the conveyor ducts must transport the feed from hoppers located on a high platform, down to and below the water surface, then up again to the cages for delivery in a corrosive atmosphere and in a constantly moving environment due to waves, wind and ocean currents.

Air-Based (Blower) Feed Systems: In these systems, dry pelletized feed is fed evenly through a rotating impeller or dosing valve from a storage hopper through a pneumatic conveying tube to a blower unit, and into a rotating distributor unit. The rotating distributor selectively distributes feed to individual pneumatic pipes, one for each cage. The air blower system pushes the dry feed through pipes to each cage, where it is delivered through a "spreader"-type nozzle to the surface of the water over the cage enclosure. Some systems are capable of distributing large amounts of feed to up to 64 cages per blower system. The blower and distributor are capable of being controlled by remote computer to supply each cage with a specified amount of pelletized feed any number of times per day in accordance with a program.

Several specialized aquaculture equipment manufacturers produce this type system. This type system has been operated successfully for many years in almost every kind of open sea environment, domestically as well as overseas.

<u>System Configuration</u>

Main components of air based systems are as follows:

<u>Air Blower</u>: Generally a centrifugal fan-type blower, electrically driven by motors ranging between 7.5 kw to 20 kw, depending upon feed volumes and distance to cages. The blower units are equipped with pressure controls and monitors, and often include an air cooling system to cool the air before it reaches the storage hoppers. The cooler air reduces damage to the feed pellets and reduces feed dust and fish oil transmission into the system. The blower unit is mounted on a frame upstream of the storage hoppers.

<u>Feed Hoppers and Dosing Valves</u>: Generally, a mariculture farm will use multiple separate hoppers, or silos, the number depending upon how many types of different feeds need to be distributed to different sizes or different species of fish. The size of the hoppers may vary but a common size is four to six tons, which measures approximately 8 x 8 feet wide by 8 to 10 feet high. Each hopper is equipped with a doser valve flange bolted onto the bottom. This valve contains a metal impeller, mounted horizontally, which is a rotor that turns slowly to drop feed evenly and accurately into the pneumatic stream in the supply conveyor. The doser valve is designed to prevent damaging or breaking up the feed as it transfers from the hopper into the conveying system and accelerates on its way toward the distributor unit.

<u>Distributor Unit</u>: The conveyor pipe from the storage hoppers enters the distributor unit in its center. Inside the unit is a curved pipe that rotates, in either direction or in a complete circle, between 24 to 32 cage feeding pipe outlets. For larger farms, two distributors are mounted in a side-by-side configuration to service up to 64 cages per system. Bi-directional and 360 degree rotation allows the rotating pipe to switch to the next position between cages by the shortest route. HDPE feeder pipes to each cage are connected to feeder nipples, and then are bundled and passed through a long radius, heavy-duty strain relief bracket before dropping vertically into the water.

Cage Feeder Pipe and Spreader Nozzles: Black high-density polyethylene (HDPE) is used exclusively as feeder pipe to the individual cages. HDPE is not water absorbent, and does not react with saltwater, sunlight, or the oils in fish feed. It is also relatively flexible and non-kinking, and is very durable and abrasion resistant. In an oil production platform scenario, an important consideration will be to secure these feeder pipes on the platform and down past the waterline to protect against damage in rough weather and from constant wave action. It is envisioned that this protection will be afforded through the use of large diameter steel well casing pipe, which will serve as a conduit from the platform floor to a safe depth below the waterline. At the cage-end of the feeder pipes specially designed spreader nozzles are installed to enable an even spreading pattern in order to minimize feed pellet breakage.

Controls: Control cabinets and a computer are mounted in a control room on the platform. The computer (PC) is used as a communication terminal for the feed delivery system, and will control and monitor blower motors, valves, and sensors in the cages and feed system. The PC may be controlled remotely through a controller card and directional antenna, if so desired. A battery pack system and inverter/charger is connected to the control system for provision of stable power whenever the generator system is running or down.

Worldwide Offshore Mariculture

Offshore mariculture was first investigated in Japan during the early 1970s. Consideration of offshore aquaculture at that time was due to Japan's diminishing catch of wild fish species, steady increase in demand for fresh finfish, improving aquaculture techniques and extremely limited access to inshore coastal resources used by traditional fishing and aquaculture industries. The Japanese company, Bridgestone, which manufactures large diameter flexible hoses for use in the dredging and mining industries, was the first offshore cage designer and fabricator to commence research on farming finfish species in exposed waters. It was seen as a positive diversification strategy for the company when increasing concerns with industrial and urban pollution were emerging within the Japanese aquaculture industry.

Research and manufacture for limited usage continued through the late 1970s but it was not until the early 1980s that the commercial demand for such cages led to full commercialization and manufacture, and increased commercial use in Japan, Russia and Norway.

By the late 1980s salmon production in Norway and Ireland had moved commercially into exposed regions leading to a new generation of farming systems being designed and manufactured. This was the second generation of semi-exposed finfish farms with automated feeding systems, rough weather cages, service vessels and operational techniques for efficient finfish management and harvesting.

In the early 1990s, the growth rate of new farms and farming areas for finfish slowed in Norway with efficiency of farm operations and economic returns becoming the main focus of the industry. At the same time, Japanese and Norwegian mariculture technology was being applied on a worldwide basis to new species such as southern bluefin tuna in Australia, sea bream and bass species in Greece and Italy, salmon in Chile, red drum and yellowtail in China, snapper and tuna species in Japan, and salmon and bass species in the North American region. Many of the countries had limited sheltered coastal resources so the offshore farming technology developed by Japan and Norway further expanded internationally.

By 1995 this worldwide expansion of offshore finfish aquaculture had produced a range of proven systems designed and commercially in use in exposed and formerly thought to be hostile farming locations. The technology has led to the successful commercial expansion of offshore farming operations for salmon farming in Ireland, Shetland Islands, Faeroe Islands, Canada and Australia; tuna farming operations in Australia, the Mediterranean and Japan; sea bream and bass farming in Italy and Greece, and yellowtail and snapper operations in Japan.

To summarize, the development of commercial offshore finfish farming is due to:

- Environmental concerns, limited availability and user conflicts in inshore areas
- Large useable offshore areas in the outer coastal zone
- Lower disease risks offshore
- Development of proven technology which is now available
- Increasing worldwide demand for fish
- Stagnant or decreasing supply from traditional fisheries

In addition, commercial operations offshore in the last 10 years have shown:

- Possibilities of lower production costs per kilo of fish
- Better environmental, biological and growth conditions for fish
- Potential for larger, more flexible farming sites
- Potential for economies of scale through larger production volumes

Trends

Current investment trends in the last five years within finfish farming and offshore finfish farming industries have seen the development of fully vertically integrated corporate structures in many countries, especially Italy, Greece, Spain, Norway, Chile, Australia and New Zealand. This breed of new companies has been formed either through merger of larger marine farming resources or through accumulative acquisition of smaller, less efficient operations within the industry. The new companies have annual production capacities in excess of 2,000 tons and as high as 50,000 tons and are expanded capital investment structures involving both listed companies and large, privately operated ventures.

A further recent trend has been the investment by large fishing companies into aquaculture and offshore finfish farming through redeployment of previously under-utilized fishing vessels from within their fleet structures. This is especially apparent in Australia and is being promoted in the U.S. and Canadian industries through financial incentives and government support programs.

Offshore finfish farming requires a high level of initial capital investment in comparison to inshore operations; cages are larger, mooring systems heavier and operational support vessels for farm management more substantial. This limits smaller sized operators from individual entry but does create significant opportunities for subcontracting to large offshore operators. Smaller operators do not exist in the offshore environment except in Japan, where the collective co-operative fishing skills of a whole Prefecture have been combined into a single project with Prefecture financial backing.

Vertical integration begins at hatchery level with production of fingerlings or fry, includes raising of juvenile fish, subsequent grow-out activities, processing and final direct marketing of the company's finfish product. Marketing directly to large-sized end-product users is seen as essential to maximize farm returns while ensuring long-term supply contracts for increasing volumes of production. In many instances, the inclusion of a large distribution/retail partner in the enterprise is seen as essential to ensure market focus and contract-based production activity.

The above trends are expected to continue in the future due to the physical environment within which offshore finfish culture must operate and the level of capital investment required to achieve economies of scale in operations.

Countries, Companies and Offshore Operations

Japan

Japan's finfish aquaculture industry is spread from single working farmers as part of a larger fishing/aquaculture co-operative, to medium-sized companies farming at inshore sites, to recent "mega" sized company involvement in offshore finfish production, processing and marketing.

The development of flexible rubber cages has led the offshore industry since the 1970s with major interest in the farming of red sea bream and yellowtail species and, recently, trevally and tuna species. Recent pollution has pushed cage farming of finfish into more exposed areas and the requirement for an intermediate cost cage to handle four to five meter seas has been identified. Japan is adopting Norwegian and Australian technology in these areas due to cost of units and proven overseas success.

Recently, Japanese interest has been in the establishment of large offshore platform structures from which to base farming operations in open exposed conditions, including seasonal typhoons. Three newer large-scale platform finfish operations have been established since 1988. Two of these remain in full commercial operation. The other one was sunk due to a dispute between fishermen over traditional fishing ground access.

The platforms were constructed on a floating base which was then floated into position and jacked up to 60 feet clear of the sea surface. All feeding equipment, cage monitoring, dead fish removal and biomass estimation equipment was supplied from Norway for both projects, which are growing salmon and yellowtail species. The programs for platform development were promoted by the Japanese Ministry of Agriculture, Forestry and Fisheries and, so far, have proven operationally successful in a variety of seasonal weather patterns since 1992. One platform is financially backed by a large fishing co-operative in partnership with the local Prefecture administration. The second platform is commercially backed by Mitsubishi Industries, a major steel manufacturer, working in co-operation with local fishermen.

Both platforms have produced fish for five years. The Northern Hokkaido platform has been through two typhoons with 10-meter seas without any recorded losses of equipment or fish. Both platforms have remote control capability for onshore management and monitoring of operations via VHF and short-wave video link.

Japan produced 833,000 metric tons of fish and shellfish; the two major fish species being yellowtail (165,000 tons) and sea bream (80,000 tons) in 1996.

Australia

In Australia the offshore industry group is comprised of two separate groups. The salmon farming group located in Tasmania and the southern bluefin tuna farming group in South Australia.

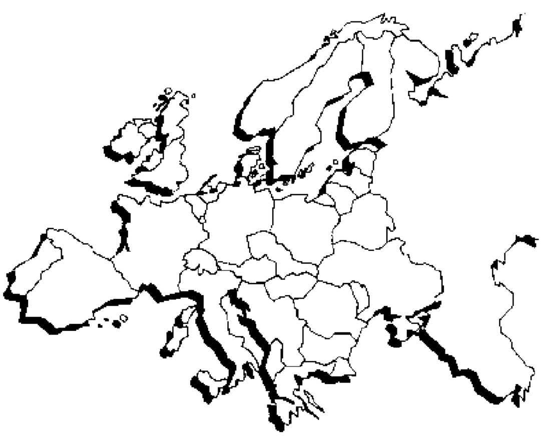
The Tasmanian Salmon Industry is dominated by three publicly listed companies; Nortass, Tassal and Aquatas, which are fully integrated enterprises created through purchase of smaller operators. They all manage their own hatchery facilities, grow-out, processing and marketing operations. Nortass has recently established a fully offshore farm area on the Southern East Coast using two 50-meter octagonal Bridgestone cages, with three units further proposed. Tassal and Aquatas are both expanding to offshore sites with large-sized polyethylene cages of 40-meter and 50-meter-diameter in 1997/1998. Combined production levels of the three companies were approximately 5000 metric tons in 1997.

The southern bluefin tuna farming operations in South Australia include 12 commercial farming operations, 17 farms, 80 large cages plus 8 research cages, 22 companies and approximately five hundred people directly involved in farm management – capture, feeding, harvesting and processing. All farms extensively utilize the latest generation of polyethylene single-collar and double-collar cages designed and manufactured in Australia. This industry purse seines southern bluefin tuna which are then transferred to 50-meter-diameter towing cages and towed up to 500 kilometers back to farm sites ranging from one mile to eight miles offshore from land. During the tow, cages are exposed to extremely harsh conditions from full southerly exposure being at times up to 150 miles offshore. Individual tows can take up to one month to complete at an average cage speed of one knot.

In 1990, Bridgestone cages were used almost exclusively in a joint research effort between the South Australian Tuna Industry and Japanese research teams. Now single-ring, new generation polyethylene cages are being introduced for both towing units and offshore farming cages. The industry has grown from 50 fish in 1990 to a 2500-ton industry valued at close to $100 million dollars in just seven years. All companies are privately owned but operate with some Japanese investment funding and Japanese marketing co-ordination.

This technology is now being exported worldwide to Croatia, Italy, Greece, Spain, Malta, Libya, Southern Africa, China, Philippines, Indonesia, Canada and the U.S. The cost of cages and the increased returns from controlled marketing of wild captured fish to Asian and European markets are the driving forces for this development. Hatchery and juvenile rearing programs are currently being researched.

Polyethylene cages are now also being utilized for yellowfin capture fisheries and the aquaculture of snapper species in both Western Australia and Queensland, on the east coast of Australia.



Northern Europe and Great Britain

The Norwegian salmon industry is progressing further toward offshore development based on requirements for expansion, disease risk reduction, water quality parameters and availability of farming space. Traditionally polyethylene has been used extensively for cage manufacture centered on two adjacent rings and a platform structure for working around the cages. Steel frame cages supported by large buoyancy units are also used in very sheltered waters.

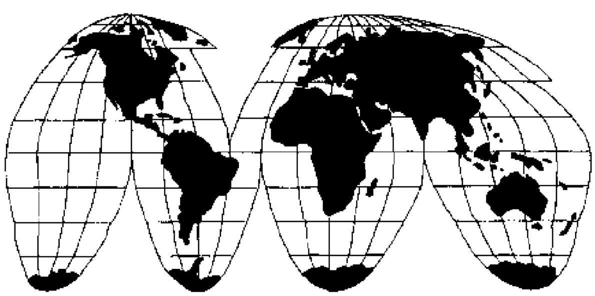
The Norwegian salmon industry is dominated by the larger companies who own, operate and process their own fish and/or supplement processing volumes with contract grown fish from smaller growers. The majority of the larger sized companies are publicly listed with production volumes for a number of them exceeding 20,000 tons and for one company, exceeding 50,000 tons.

Due to EU and Norwegian Industry imposed production restrictions, industry focus has been directed to improving farm technology, automation and efficiency, thereby reducing production costs. Feed development and improving feed conversion ratios is also a continuing dynamic for the industry. Much of this inshore-based farm management technology is now being applied to offshore facilities and is successfully achieving operational economies both in Norway and on an international basis.

Ireland has what is regarded as one of the most successful offshore salmon industries in the world with approximately 30 percent of production claimed to come from exposed North Sea sites. Flexible rubber cages have now been used in this region for eight years and are produced locally in association with an Irish engineering company. A combination of square 20-meter cages and larger 40-meter octagonal units have been produced for the salmon industry. These have been successful in maintaining fish in all weather conditions with up to 10-meter seas. Five of the main companies use these units in exposed locations and have been in operation for up to eight years producing salmon. The companies are privately owned or partial co-operatives between traditional smaller growers.

The Scottish salmon industry has also adopted the same cage types with similar results at the exposed locations. In both Ireland and Scotland it has been observed that in extreme weather conditions fish will stop feeding for up to three weeks without noticeable loss in condition or growth rates when compared to inshore fish one month after the event.

Shetland Islands and Faeroe Islands both have exposed offshore salmon industries based on flexible rubber cage technology. Almost all farming operations in these two regions are exposed through a minimum of 180 degrees to North Sea weather conditions.



Mediterranean

Until very recently the central focus of Mediterranean finfish farming production in Greece, Italy, Spain, Yugoslavia and other minor producers was directed toward inshore sea bream and sea bass culture. The first three countries, as well as more recently Malta and Croatia, have recently commenced building offshore farms at moderately exposed and fully exposed offshore sites with a variety of cage systems.

Surface cages initially were secured from Norwegian suppliers but performance in exposed conditions was found to have limitations. Submersible cages supplied by the Russian company SADCO have also been trialed very successfully in Italy, though cost and size limitations have appeared to restrict further sales in this region. Bridgestone cages and, more recently, Australian-made single-collar polyethylene cages have wide acceptance. The Australian cages are especially popular in the large sizes for use within the northern bluefin tuna industry, which the Australians are actively assisting to develop in Spain, Greece, Italy and Croatia.

Spanish constructors, MSI, have also built fully self-contained platform structures for four clients in exposed coastal areas. These cages feature a fixed steel structure, which can be raised or lowered several meters depending on sea conditions and stock densities in cages. The system has advantages in that it can be used for feeding to other cages attached to the perimeter of the structure and has loading capacity for all farm operations, feed storage, grading work and – due to the external frame work for each cage – loss of cage volume in high current flow or medium wave action is greatly reduced.

The trend to much larger sized production units for both tuna culture and sea bream farming operations has resulted in increased interest in both polyethylene cages and flexible rubber cages by all the major operators in open waters in this region. Yellowtail (amberjack), grouper, mahi mahi and local black sea bream are seen as future species for an expanding Mediterranean industry.

The trend in industry development is for large integrated companies to commence offshore operation establishment. Prior to this, family operations of limited size or medium-sized co-operatives of fishermen predominantly drove inshore farming. Amalgamations between large-scale companies have seen the large vertically integrated producers extend their market reach from the Mediterranean throughout major markets in middle Europe such as France and Germany.

Asia

Recent interest in offshore aquaculture from international funding agencies such as the World Bank and Asian Development Bank has resulted in projects being established in Philippines, Indonesia, Malaysia and China. Three cage systems have so far been used; polyethylene single collar cages, flexible rubber cages from Bridgestone and Dunlop, and the submersible system from Ocean Spar Technologies of the USA.

Extensive inshore pollution problems and limited near shore deep water in many parts of this region coupled with typhoon, hurricane and monsoon weather conditions throughout the equatorial sector have placed expansionary growth for finfish farming in the offshore regions where depths enable structural force reduction, improved fish growth and risk reduction to development funding agencies.

Inshore and inland aquaculture has historically been the basis of finfish aquaculture in these regions with current investment following proven international trends from the above advanced countries.

North America

Canada and the United States have been slow to adopt offshore technology due to the late development of finfish farming and more restrictive permitting processes in most inshore coastal regions. Recent development in offshore technology has induced a total reassessment, at State and Federal level, of the potential and impact of these industries. In 1996, 1997 and 1998 successful conferences on offshore aquaculture in Maine, Hawaii and Texas have attracted international participation and high levels of American and Canadian involvement.

Salmon farming in the Bay of Fundy has been successful despite extreme ice conditions, strong currents and, at times, gale force wind conditions. Ocean Spar Technologies has successfully developed both submersible and floating cages for the salmon industry in this region.

Recent successful trials growing northern bluefin tuna off the coast of Maine using Australian polyethylene technology cages has initiated a number of applications for offshore fish farms for the species around Newfoundland and Nova Scotia. Wild caught fish were penned 10 miles offshore and fed for an eight month period without apparent difficulty or equipment or biological problems. Growth rates were good. Permitting procedures may restrict further development of this offshore industry in Maine and Connecticut.

There have also been some attempts to establish offshore operations in the Gulf of Mexico. These are detailed in Chapter 4 of this study.

2

Assessment of Candidate Marine Finfish

Summary of Species Assessment

Fifteen species of finfish were reviewed for suitability and biological feasibility for offshore mariculture in the Gulf of Mexico. Two of the species, red drum and striped bass, are already established in commercial culture. They are both suitable for cage culture and biologically feasible for offshore culture in the Gulf of Mexico. Red drum has already been reared in offshore cages on an experimental level (Miget 1995). Red drum and striped bass can serve as good "models" for development of production methods for finfish culture in the offshore environment. Several other very promising "high" value species are reviewed that might be quickly brought into production with the appropriate public and private investments in research. Development of commercial scale nursery and grow-out methods should be the first priority for the under-developed species. Grow-out technology will need to be developed that is specifically suited to the offshore environment. Strongly tied to successful grow-out will be the refinement of feeds specifically suited for high value marine species. Many of the species reviewed appear to have requirements for higher quality feeds than those currently used to rear other species. Disease problems will undoubtedly be an issue for all of these species and will need to be addressed as they are encountered. Disease detection and treatment methods that will be effective in the offshore environment will pose a special challenge for culture operations. In reviewing successful culture practices for high value species abroad, it is clear that many foreign culture operations preferentially use naturally produced seed and exploit low value finfish species as feed for culturing high value species. The cultural acceptance of these practices overseas may prove to be a major competitive advantage over efforts to develop high values species for mariculture in the U.S. Currently the use of bycatch in the U.S. is discouraged by management agencies. However, this policy may need to be re-evaluated if mariculture in the U.S. is to be competitive in global aquaculture markets. Strong collaborations between public and private enterprise along with nationally supported regional mariculture centers have also been an important part of the successful development of mariculture in other countries. Many of the high value species reviewed in this assessment could be grown out by existing fish culture operations if reliable cost effective sources of fingerlings were available. The high costs and risks associated with the research, development and production of seed for high value species is currently a major impediment to expansion of existing culture operations and entry of new commercial ventures. The Gulf of Mexico has numerous marine finfish with strong potential for mariculture. A regional mariculture center could foster development of new species through research, technology transfer and production of seed for grow-out trials by private enterprise.

Introduction

Global aquaculture production of finfish in 1995 was approximately 12.5 million mt. Currently, both world and U.S. production of finfish is dominated by freshwater species (FAO 1995), chiefly catfish and trout in the U.S. Furthermore, global mariculture is currently dominated by shellfish, rather than finfish production. Given the vastness of the ocean and its tremendous productivity, these patterns seem likely to change in the future. Unlike aquaculture production, world fisheries landings have always been dominated by marine fish and shellfish (New 1997). In the future, freshwater systems are likely to have limited potential to expand production compared to marine systems because of limitations of land, available clean fresh water and competition for these resources with other forms of agriculture. As the costs associated with land-based systems increase and land-locked aquaculture production peaks, pressure will increase to promote the development of marine species for culture. This, coupled with the recent changes in the more conservative management of fisheries in the U.S. mandated by the Magnuson-Stevens Act, results in a push for aquaculture enterprises to develop coastal and offshore culture systems to meet projected increased demands for seafood (New 1997). Many coastal bays and estuaries are already faced with serious ecological problems from pollution and eutrophication (Caddy 1993), indicating that the future of mariculture may be in the offshore environment.

Offshore culture systems offer some unique problems and some advantages. Winter temperatures can limit production of land-based systems and can cause devastating winter mortality, even in southern climates (Lutz et al 1997). Within the Gulf of Mexico, offshore environments offer warmer winter temperatures for grow-out and cooler summer temperatures than shallow water systems and buffer abrupt temperature changes better than shallow systems. Another distinct advantage is the inherently better water quality and stable salinity regimes typical of offshore environments.

The following review is focused on marine finfish species believed to have potential for mariculture in the coastal and offshore environment of the northern Gulf of Mexico. Issues such as genetic diversity of hatchery produced fish, escapement of captive stocks and introductions of exotics have significant implications for management of wild fish stocks and threaten to complicate permitting for aquaculture in open water environments. Therefore, we have limited this assessment to species indigenous to the Gulf of Mexico and Caribbean region. These species have been selected because they are regarded as suitable or believed to have strong potential for development as mariculture candidates in the Gulf region. Each was also specifically evaluated with regard to their potential for offshore cage culture. In order to avoid an exhaustive list of species, the evaluation is focused on species that have had some level of development for culture. The review outlines their strengths and weaknesses as culture species, along with an evaluation of some of the fundamental research needed to make them biologically viable for culture. Fisheries economic issues are complex and prices fluctuate with market demand and availability from natural fisheries as well as price and availability of alternatives in the marketplace. Those issues are considered elsewhere in this report. However, the evaluation is also heavily weighted toward species that could be categorized as "high" value. Only a few of the species that have been evaluated are now in commercial culture in the Gulf region. With the exception of redfish and hybrid striped bass, each of the other species will require various levels of additional research before they will be viable for mass culture in offshore cages.

The following species were evaluated:

Amberjack, Greater, *Seriola dumerili*
Flounder, Southern, *Paralichthys lethostigma*
Mahimahi, *Coryphaena hippurus*
Grouper, Gag, *Mycteroperca microlepis*
Drum, Red, *Sciaenops ocellatus*
Snapper, Gray, *Lutjanus griseus*
Snapper, Mutton, *Lutjanus analis*
Tuna, Ocean Ranching
Cobia, *Rachycentron canadum*
Grouper, Nassau, *Epinephelus striatus*
Grouper, Red, *Epinephelus morio*
Pompano, *Trachinotus carolinus*
Snapper, Red, *Lutjanus campechanus*
Snapper, Yellowtail, *Ocyurus chrysurus*
Striped Bass, *Morone saxatilis* and SB hybrids

How was this task completed?

Literature reviews were conducted in ASFA (Aquatic Sciences and Fisheries Abstracts), literature searches in databases held by FAO, NMFS, CSC, Sea Grant Sites, ICES and USDA. Literature and citations were compiled and reviewed for relevance. The Internet was also searched for aquaculture web sites and general web searches were conducted to locate recent and relevant information from institutional world wide web pages. Finally we relied to a lesser degree on interviews with culturists working in the areas and with the species of interest.

Each species was evaluated with regard to the following categories and associated criteria:

Biological Profile and Rationale for Inclusion

Why target the species for mariculture?

What are some of the important ecological requirements and tolerances, spawning seasons and location, growth rates in the wild and status of natural stocks?

Status of Nursery and Grow-out Methods

Nursery requirements - Are spawning methods established and suitable for production? Are broodstock readily available?

Larval rearing - What are the food size, salinity and temperature requirements?

Grow-out requirements - What are the temperature and salinity ranges and optima?

Is cannibalism an issue for a given species?

Nutritional and Feed Issues

What type and quality of feed is needed for a particular culture species? (quality and type = dry or moist pellet, protein, lipid content).

Suitability for Cage Culture

What is the track record for this or a related species in cage culture?

Are there any specific constraints related to offshore cage culture?

Disease Issues

Are there any known diseases or conditions specific to this species likely to be a serious threat to commercial culture?

Potential Limitations for Culture

What are the known or likely constraints for this species?

What constraints might be predicted based upon best available knowledge?

Special Considerations

Is Polyculture an option?

Are hybrids possible and potentially advantageous?

Are there issues or conflicts related to natural fisheries?

A Note on the Bibliography and Citations

A bibliography is organized at the end of this document with compilations of both cited and uncited literature listed by species. For general fisheries and aquaculture references, they are either listed in a separate section titled "General Fisheries and Aquaculture" or where they are specific to a species, within their section.

A Note on Abbreviations

p. o. = personal observation
p. c. = personal communication

Amberjack, Greater, *Seriola dumerili*

Brief Biological Profile and Rationale for Inclusion

Members of the amberjack family are a group of widely distributed migratory species of significant commercial and recreational value as a fishery (Manooch and Potts 1997).Their strength and fighting ability is legendary among sport fishermen. Currently amberjacks are considered overfished in the Gulf of Mexico (NMFS 1997), possibly making the prospects for their future culture more economically feasible. Recreational limits have been reduced to one fish per day with a 28 inch size limit in the Gulf.

Commercial culture of amberjack has never been attempted in the U.S., but the Japanese and Chinese have researched culture of greater amberjack and the Koreans and Japanese have invested a significant effort into a closely related species, the yellowtail, *Seriola quinqueradiata* (Aoki 1995). Yellowtail culture has been one of the most successful marine species cultured over the past decade. Unfortunately, pressure on natural stocks from taking of fingerlings for seed and other problems have limited production in recent years (Aoki 1995; Furuya 1995). In Europe efforts are also underway to culture greater amberjack, *Seriola dumerili* and in Ecuador a related species, *Seriola mazatlana* is being researched (Bennetti et al 1994, 1995).

Amberjack are schooling fish that are often associated with structures such as oil rigs or wrecks. Greater amberjack grow rapidly and can reach a maximum size of around 68 kg and 1.5 meters in length in the wild (Manooch and Potts 1997). Because of their rapid growth rates, good palatability, and prolific spawning capability, greater amberjack and some closely related carangids have been recognized for their potential in commercial culture.

Status of Nursery and Grow-out Methods

Very little work on nursery and grow-out techniques for amberjacks has been reported for the United States. Therefore the review of nursery and grow-out will focus on some of the research done on *Seriola dumerili* overseas and work on closely related species, such as yellowtail. Nursery and grow-out of yellowtail in Japan was recently reviewed (Aoki 1995).

Reproductive potential of amberjack is tremendous. Amberjack are serial spawners and have extensive spawning seasons in the Gulf of Mexico (Ditty et al 1988). Greater amberjack have been spawned in captivity by injection with salmon pituitary and genital hormone (Tachikara et al 1993). No reported spawning by temperature-photoperiod manipulations suggests that amberjacks may difficult to spawn by those methods. After injection the greater amberjack produced large broods of eggs. Amberjack eggs are relatively large (1.05-1.20 mm) and the larvae began feeding on rotifers at a size of 3.9 mm after 4 days at 25 °C (Tachihara et al 1993). In European growth experiments, larvae reached first feeding and a size of 5 mm after 6 days at 19°C (Lazzari 1991). In nature, greater amberjack can reach a length of 36 cm in a year (Manooch and Potts 1997) suggesting they would grow quickly in culture.

Cannibalism in intensive grow-out may be the biggest problem in the nursery phase (Sakakura and Tsukamoto 1996). Like many species of fast growing open water marine finfish adapted for culture, cannibalism is likely to be a problem in the juvenile phase. Studies with yellowtail, showed an onset of cannibalism shortly after metamorphosis to the juvenile stage (~10 mm TL) which coincided with formation of schools.

Nutritional and Feed Issues

Successful grow-out trials with *Seriola dumerili* show that feed acceptance or development of appropriate feeds should not be a serious impediment to developing grow-out technology for greater amberjack. However, feeds specific to amberjack apparently will need to be developed by the U.S. feed industry. Amberjack apparently do not readily accept dry feeds and considerable research has been done to develop and test moist and semi-moist pellets and refine feeds for both yellowtail and amberjack in Japan and elsewhere (Di Bella et al 1991; Sekiya et al 1991; Shimeno et al 1992, 1993a,b,c; Watanabe et al 1992; Viyakarn et al 1992). Work with yellowtail has shown a need for HUFA's consistent with other marine fish and fish larvae (Di Bella et al 1991). Limited nutritional work has been done specifically with greater amberjack, although the extensive nutritional development for both grow-out and spawning that has been done for yellowtail should be applicable in large part to the greater amberjack (Di Bella et al 1991).

Suitability for Cage Culture

Given their requirements for high salinity and relatively warm temperatures, amberjack appear to be best suited to coastal cage and perhaps pond culture where high salinity water and warmer winter temperatures would be available. Based upon successes in cage culture of the yellowtail in Japan (Aoki 1995), in Korea (Kim and Myoung 1995) and trials with greater amberjack in China (Liao et al 1995) and Europe (Di Bella et al 1991), it seems likely that greater amberjack will be readily adaptable to cage culture in the GOM.

Disease Issues

Significant problems with disease have developed in cage culture of yellowtail in Japan and significant mortalities have been reported (Aoki 1995). Much of this is reportedly due to very high stocking densities and stresses related to intensive culture in semi-enclosed basins.

Potential Limitations for Culture

Although spawning technology has been developed for yellowtail, grow-out of yellowtail in Japan and greater amberjack in Europe have been largely supported by collections of wild fingerlings (Nakada and Murai 1991). Given the current trend in wild amberjack fisheries in the GOM and a different cultural view of exploiting wild seed for grow-out in the U.S., spawning and larval culture techniques will need to be developed before any efforts at commercial grow-out can be attempted.

Special Considerations

Amberjack are very palatable, especially smaller fish. Because of the size restrictions placed upon capture fisheries by managers trying to protect spawning stocks, it may be possible to develop a market for smaller fish than can be taken in the commercial fishery with mariculture. Since amberjack grow quickly to a marketable size but don't reach sexual maturity to a size much larger than ideal market size (46-51 cm. or 18-20 in.), amberjack from cultured stock would potentially open up a unique market in the U.S. Another significant factor for amberjack is their reputation for accumulating ciquatoxin in tropical reef environments. Although this is not a problem in the northern GOM, cultured fish could be certified, potentially increasing their value in the marketplace.

Successful larval culture is an important component of any mariculture operation. Amberjack early life stages have some attributes which may enhance their grow-out potential. Their eggs are relatively large (1.05-1.20 mm) (Tachihara et al 1993) compared to some other subtropical fishes (i.e. Lutjanids) and for that reason may be somewhat easier to grow in the nursery phase. Cannibalism during intensive grow-out is likely to be the biggest problem in the nursery phase (Sakakura and Tsukamoto 1996).

Research Needed to Reach Biological Feasibility

Virtually every phase of research and development needs more work for amberjack to reach biological feasibility. However, the research taking place in Europe and in Asia, with the same or similar species, should allow rapid development of amberjack culture in the U.S., if the appropriate infrastructure and avenues of technology transfer are developed.

Cobia, *Rachycentron canadum*

Brief Biological Profile and Rationale for Inclusion

Cobia (Ling, Lemonfish) is a widely distributed migratory species of significant commercial and recreational value as a fishery. Commercial landings of cobia in the Gulf and Atlantic region for 1991-1996 totaled 1,046 mt with an average ex-vessel value of $3.54 per kg (NMFS 1998). Commercial scale culture of cobia has never been attempted, but some preliminary studies on growth rates and spawning suggest it has excellent potential for mariculture (Hassler and Rainville 1975; Caylor et al 1994). Given their salinity and temperature requirements cobia appear to be best suited to coastal cage and perhaps brackish pond culture. Cobia grow rapidly and can reach a maximum size of around 60 kg. (Vaught-Shaffer and Nakamura 1989). Because of their rapid growth rates, excellent palatability, and prolific spawning capacity they offer excellent potential for commercial culture. These characteristics of cobia have apparently been recognized in Taiwan as well, where they are reportedly under development as a mariculture species (Liao et al 1995).

In nature males can reach a length of 31 cm in a year and females grow somewhat faster reaching 36 cm after a single growing season (Richards 1977). Cobia males can mature as early as age 2 and females at age 2-3 (Richards 1967). Cobia fecundity is high with a 50 pound female carrying 3-4 million eggs (Richards 1967). Cobia are serial spawners that spawn in summer months, however the precise details and location of peak spawning in the Gulf of Mexico and elsewhere are currently unknown. Juveniles recruit to the coastal areas and are often captured in nets and by hook and line in late summer and early fall (E. Chesney, p. o.).

Status of Nursery and Grow-out Methods

Locally from late April to November, mature cobia concentrate along the Louisiana coast seaward of the barrier islands and around offshore structures such as oil platforms, providing excellent opportunity for brood stock collection (E. Chesney, p. o.). Cobia have been reared from field collected eggs to juveniles to assess their potential for mariculture (Hassler and Rainville 1975). Based on those initial results cobia were judged to have excellent potential for culture, but no work was done on spawning in captivity until recently. They have exceptional growth rates as larvae, growing more than a mm per day for the first thirty days of life (Hassler and Rainville 1975). As juveniles they can reach a length of 46 cm TL (18 in) in a year and maturity at 2 years and approximately 94 cm TL.

Cobia were recently spawned in captivity by U.S. scientists using hormone injections (Caylor et al 1994). Initial attempts lacked males to fertilize the eggs but subsequent attempts proved successful in generating viable eggs and larvae (J. Franks, personal comm.). Cobia have a relatively large egg (1.25 mm) and larva for a subtropical marine fish larva (3 mm at hatch). By first feeding they are 4-5 mm TL, thus they are capable of eating rotifers and then *Artemia* soon after first feeding and grow rapidly to metamorphosis (Hassler and Rainville 1975). Our own observations of field collected specimens of juveniles show that they could reach a marketable size (16-18 inches) within a single growing season if properly managed, including feeds of appropriate quality and palatability. Currently a 94 cm TL (37 inches) size limit and a two fish per day creel limit for recreational fishermen is in effect for cobia caught in U.S. waters. Both commercial and recreational fishing for cobia are now limited because of past over-exploitation, making the prospect for developing markets for a cultured product favorable.

Nutritional and Feed Issues

In the wild, cobia eat large quantities of crustacea (primarily crabs) and fish (Franks et al 1996; Meyer and Franks 1996). This suggests that they will probably require a high quality diet to maximize growth. Cobia juveniles will accept a feed, but in experimental trials they were difficult to convert to a dry generic pellet (Chesney, p. o.). Research on both the quality of feeds and on feeding stimulants are likely to improve results for feed acceptance, growth and food conversion rates.

Suitability for Cage Culture

When held in tanks cobia often lay on the bottom to rest (E. Chesney, p. o.). They grow to a size suitable for stocking in cages and are strong swimmers at an early age. Presumably the combination of good swimming ability and the ability to rest on the bottom of the cages would allow them to grow more efficiently than species that are constantly on the move when confined to a cage. Hassler and Rainville (1975) noted that even healthy larvae began to rest on the bottom when not feeding. They should be highly suited to cage culture in coastal and offshore environments since they can tolerate a range of temperature and salinity from moderate to high as larvae and juveniles (Hassler and Rainville 1975). However, specifically how reduced salinity might affect their growth rates has not been quantitatively assessed and may limit brackish water culture.

Disease Issues

Since cobia have not been cultured extensively at high stocking densities, little is known about potential diseases that might afflict them in culture, hence problems with diseases would have to be solved after initial attempts at mass culture.

Potential Limitations for Culture

Although cobia offer excellent potential for mass culture, research is needed on spawning and grow-out before mass culture can even be attempted. No commercially viable culture industry has been established to date and only a limited amount of work has been done on feeding in the larval phase and nothing has been found in the literature on feeding juveniles pelleted foods. Virtually nothing is known about nutritional requirements or feed acceptance of cobia. Based on limited work to date in the lab with juveniles it seems likely that cobia juveniles may be difficult to convert from live foods to feeds, although they can be successfully converted (E. Chesney, p. o.). Broodstock are only readily available from May to October in the northern GOM, although some over-wintering fish occur offshore. Cobia can probably be conditioned to spawn with photoperiod-temperature manipulations but nothing has been published to date. Some anecdotal reports suggests it will be more difficult than for some species and may require hormone injections or implants. There is a strong potential for severely limited growth in winter because the majority of cobia are believed to migrate south in late fall. Almost nothing is known about their disease resistance.

Special Considerations

Cobia are very palatable, especially at smaller sizes. They also grow quickly to a marketable size and will not reach sexual maturity during grow-out to a market size. Because female cobia reach maturity at age 2 and at a size of approximately 94 cm TL a size limit of 94 cm (37 inches) and a creel limit of 2 fish per day for recreational fishermen has been placed on cobia in U.S. waters. Smaller plate size cobia (45-50 cm or 18-20 inches) from cultured stocks would potentially open up a unique market for cobia in the U.S.

Successful larval culture is an important component of any mariculture operation. Cobia have several attributes which make them especially suited to grow-out. Their eggs (1.25 mm) and larvae are relatively large compared to other subtropical fishes and for that reason potentially easier to grow in the nursery phase than many other subtropical fishes. Some potential for cannibalism in cultures exist at all life stages, although if grow-out is carefully regulated that can be minimized.

Research needed to Reach Biological Feasibility

Virtually all phases of development need additional research for cobia. However some of the major hurdles such as spawning and larval rearing have already been proven as feasible. With refinements to those areas and a serious effort to resolve nutrition and feed issues, cobia could quickly reach the status of biological feasibility.

Flounder, Southern, *Paralichthys lethostigma*

Brief Biological Profile and Rationale for Inclusion

Because of their delicate flavor and white flesh, flatfishes have always been prized as food fishes. Southern flounder are highly valued as a food fish and command a high market price. They are also a popular recreational species throughout the south. There is growing interest in the culture of flounders in the U.S. and by Gulf coast culturists currently targeting other species. Flounders appear to have good potential as a coastal pond and cage culture species in the northern GOM if spawning and grow-out technology can be fully developed. In 1994, the average price paid to commercial fishermen in Louisiana was $2.88/kg live weight (Adkins et al. 1996) which is over 1.5 times the price currently received by channel catfish producers. Global markets can undoubtedly bring even higher prices. Given more restrictive management initiatives now underway and declining harvest of natural stocks of southern and summer flounder, prices are likely to increase in the future.

In addition to a reasonably high market value, southern flounder tolerate a wide range of temperatures and salinity (Burke et al. 1991; Prentice 1989; Daniels et al 1996), and have exhibited growth rates of up to 1.5 kg per year in freshwater (Laswell et al. 1977). These characteristics make southern flounder an excellent candidate for mariculture in waters ranging from low salinity up to full strength sea water. At the 1998 world aquaculture meeting, research papers on pond production and spawning were presented, indicating a growing interest in the culture of this species.

Status of Nursery and Grow-out Methods

While southern flounder were first spawned in captivity many years ago (Arnold et al 1977), research has only recently established hatchery procedures for spawning (Berlinsky et al. 1996) and larval production (Daniels et al. 1996) on an experimental level (Jenkins et al 1997). Production of juvenile and market-size fish has not been extensively investigated. Several research efforts to develop local knowledge and refine spawning methods for southern flounder are currently underway in Texas, Florida, South Carolina and North Carolina.

In the wild, summer flounder migrate offshore in the fall to spawn during late fall through winter (Reagan and Wingo 1985). Adults aggregate near barrier islands in late summer prior to their migration and can be captured for broodstock in shallow areas along the beaches with a seine. Researchers (Arnold et al 1977; Henderson-Arzapolo et al 1988) were able to tank spawn flounder without hormone injections, but this method has not proven to be reliable for summer flounder. Other researcher have had success using hormone injections (Lasswell et al 1978). Recent attempts have been most successful using hormone treatment, especially hormone implants along with photoperiod manipulation to extend the spawning period (Berlinsky et al 1996).

Larval grow-out trials with southern flounder have also been conducted (Daniels et al 1996). Stocking density, salinity and light intensity were evaluated. Good growth and metamorphosis to juveniles were observed at 20 and 30 ppt, but not at 0 and 10 ppt (Daniels et al 1996). Overall survival rates in these initial experiments were low (<10%) and improved culture methods will undoubtedly improve upon these results in the future.

Nutritional and Feed Issues

Experimental grow-out trials in ponds have been attempted for southern flounder using salmon feeds (Jenkins et al 1997). Results were equivocal. Fish grew quickly at first, but growth slowed later in the experiment possibly due to increased summer temperatures (Jenkins et al 1997). Clearly significant work on optimizing feeds and feeding regimes needs to be done with southern flounder. As with other species, concurrent development with closely related species (*P. dentatus*) and species already well developed for commercial culture (*P. olivaceus*) should serve as good models.

Suitability for Cage Culture

Successful commercial production utilizing cage culture with a related species of flounder (*Paralichthys olivaceus*) has been established in Japan and elsewhere (Matsuoka 1995; Seo-Min 1995). Many species of flatfish, when not actively swimming, are most comfortable lying on the bottom covered with sediment for camouflage. Offshore cages suspended in the water column may prove to be less suitable for flounder culture than cages in contact with bottom sediments, however suspended cages are currently in use and have been successful.

Disease Issues

Flounder suffer from many of the same diseases that afflict other fishes (see Hawke, disease section). Albinism and ambicoloration are common problems in cultured flatfish that can affect their market value, but not necessarily the fishes health (Gartner 1986; Iwata and Kikuchi 1998). Although the exact causes for these phenomena are unknown they are believed to be related to diet and to rearing conditions (Denson and Smith 1997), since there is a very high incidence of these conditions in culture flatfish. Ambicoloration was reduced in Japanese flounder by giving them a granular substance with which to bury themselves (Iwata and Kikuchi 1998).

Potential Limitations for Culture

Southern flounder are not currently in commercial production. There are currently several research efforts in the southern U.S. devoted to developing and refining spawning and grow-out techniques for southern flounder. Most finfish are produced by stocking juveniles into grow-out facilities to allow production of market-size fish. For example channel catfish and red drum are cultured by stocking juveniles of 5-7 cm fingerlings into grow-out systems which many growers purchase from a production facility (Lutz et al 1997). Spawning procedures may turn out to be too complicated for flounder for many growers to tackle, especially those already involved with grow-out of other species. Currently there are no commercial production facilities for southern flounder in the GOM. Thus for southern flounder culture to be widely successful in the GOM, a hatchery production facility may need to be established.

Special Considerations

Polyculture has been evaluated for flatfish in net cages (Holm and Thoreson 1986). Flounder, *Platichthys flesus*, were cultured in conjunction with salmon to utilize uneaten feed that reached the bottom and went uneaten by the salmon (Holm and Thoreson 1986). Flounder apparently had no problem consuming feed that reached the bottom, thus reducing organic loading and improving efficiency of the system.

Research Needed to Reach Biological Feasibility

Southern flounder are close to biological feasibility for grow-out, but substantial refinement and research still needs to be done. Much of the research and development (spawning, feeds, nutrition) taking place elsewhere with closely related species should be applicable to southern flounder (see Stickney 1997). Given the advances that have been made with related species in Asia and in northeast U.S., and the current efforts being devoted to this species throughout the south, a commercial venture seems likely in the foreseeable future.

Groupers — Gag Grouper, *Mycteroperca microlepis*, Red Grouper, *Epinephelus morio*, Nassau Grouper, *Epinephelus striatus*

Brief Biological Profile and Rationale for Inclusion

Grouper are sought by both recreational and commercial fishermen because of their exceptional palatability and high market value. Declines in catches in the Gulf and elsewhere and a desire for better management have resulted in size restrictions in U.S. waters to protect spawning stocks and aid recovery of natural populations. Commercial landings of all groupers, principally Black, Marbled, Nassau, Red, Snowy, Warsaw, Yellowedge and Yellowfin Grouper in the Gulf and Atlantic region for 1991-1996 totaled 23,301 mt with an average ex-vessel value of $4.33 per kg (NMFS 1998). There are several species of grouper with commercial value and potential for mariculture development in the Gulf and Caribbean region. Because only limited research and development has taken place with just a few species of groupers in the U.S., they will be considered as a group. As far as we know, there are no commercial operations successfully culturing any grouper in the U.S. and only a small amount of grouper being produced worldwide, mostly in Asia.

Progress on spawning and/or grow-out has been made with several species of grouper that reside in the Gulf and Caribbean region. The red grouper, *Epinephelus morio*, the Nassau grouper, *Epinephelus striatus* and the Gag, *Mycteroperca microlepsis,* will be considered here. Red grouper are found exclusively in the Atlantic Ocean from the coast of Massachusetts southward to Brazil. It is most abundant along the western Florida shelf and off the north coast of the Yucatan Peninsula, Mexico (Richardson and Gold 1997). Nassau grouper are restricted to more tropical reef environments and are not known to occur in the northern Gulf (Heemstra and Randall 1993). Gag are very common throughout the northern Gulf and occur relatively close to shore in water depths of 40-100 m (Heemstra and Randall 1993). Juvenile Gag often occur inshore, showing they are likely to be somewhat more tolerant to reduced salinity than their adult counterparts and perhaps other groupers (Weaver 1996).

Status of Nursery and Grow-out Methods

Groupers are protogynous hermaphoditic fishes, developing first as males then females as they grow (Heemstra and Randall 1993). Sex reversal is possible with hormone treatments and has been stimulated in red grouper with methyltestosterone implants (Neidig et al 1996). Numerous species of grouper from around the globe have been spawned in captivity and reared through the juvenile stage (Tucker 1994), although commercial grow-out in some countries still relies heavily on natural seed production because of unreliable methods and limited seed production success (Pillay 1990; Chen and Liao 1991; Ruangpanit and Yashiro 1995).

The Red, Nassau and Gag grouper have all been spawned in captivity by hormone injection (Head et al 1996; Watanabe et al 1995, 1996) and naturally by photoperiod-temperature cycles (Tucker 1994; Tucker et al 1996). The only limitation with groupers is that they tend to produce large, relatively synchronous spawns, especially when spawned with hormones (Tucker 1994). The eggs and subsequent larvae of the Red, Nassau and Gag are relatively small (820-975 µm) and require small foods such as rotifers at first feeding (Tucker 1994; Watanabe et al 1995, 1996a). Nassau grouper eggs hatch in 20-26 h at 26-30°C and first feeding begins in about 3.5 days at 26°C (Watanabe et al 1995).

Commercial scale grow-out or grow-out trials through market size have not been reported for any of the species of grouper considered here. Commercial grow-out with other species in Asia suggests that with appropriate feeding and stocking densities groupers can reach a marketable size of 600-800 g in 8 months at 25-32 °C (Ruangpanit and Yashiro 1995).

Nutritional and Feed Issues

Grow-out methods and research done in other countries with related species as well as studies done with the species reviewed here should allow rapid development of suitable feeds and grow-out procedures to support commercial production (Chen and Liao 1991; Ruangpanit and Yashiro 1995; Boonyaratpalin 1997). Research has shown that groupers need high protein and high energy level diets for proper growth (Chen and Liao 1991; Ellis et al 1996, 1997). Research on feed utilization and grow-out of Nassau and Red grouper (Ellis et al 1996, 1997) suggest that reasonable growth and food conversion rates are possible although more research is needed.

Growth and food conversion rates can be low for groupers and survival can be affected if feeds are not adequate (Chen and Liao 1991; Chen and Tsai 1994; Ellis et al 1996; Shiau and Lan 1996). For example, growth performance was significantly better with Nassau grouper juveniles fed a research diet high in protein (>55%) and lipids (Ellis et al 1996). Food conversion was also better on the higher protein diets (Ellis et al 1996), although growth rates were relatively slow (1-3% $\cdot$ d^{-1}) on all the diets tested.

Suitability for Cage Culture

Grouper have a long history of being cultured in cages and appear to be very adaptable to confinement in cages (Teng et al 1978; Toledo et al 1993). Some grouper may be especially sensitive to low dissolved oxygen (Brule' et al 1996), which could be a consideration for cage culture in the northern Gulf of Mexico.

Disease Issues

Very little specific information is available on diseases in culture of grouper. See Hawke's general discussion on diseases in culture.

Potential Limitations for Culture

Since the northern Gulf is outside their natural range, Nassau grouper may not tolerate the winter temperatures and perhaps reduced salinity common in the northern Gulf of Mexico. However considerable progress has been made with development of this species and it shows good promise for culture in appropriate environments within the Gulf region. It also may be possible to culture them in closed indoor systems (Brule' et al 1996). Perhaps the best candidate for the northern Gulf is the Gag grouper. Progress to date shows that they are a viable candidate from the perspective of seed production and they are a relatively fast growing grouper in the wild. However, they still require considerable research and development before a commercial venture is feasible.

Spawning behavior of groupers is another potential limitation. The synchronous spawning habits and difficulty in producing eggs over a protracted time frame currently limits out of season seed production. Additional research may overcome this problem in the future. As with many marine fishes, cannibalism in juvenile grouper can be a problem if fish are not properly graded and fed (Chen and Liao 1991).

Special Considerations

Hybrid grouper have never been produced with any species indigenous to the Gulf, however grouper hybrids have been produced with two Asia Pacific species and the larvae have been successfully reared to juveniles (Tseng and Poon 1983). Given the diversity of groupers in the Gulf numerous possibilities for hybrids exist, especially if sperm of selected species could be cryopreserved.

Research Needed to Reach Biological Feasibility

Some species of grouper are in commercial production around the world. Many of the early efforts and much of the progress in actual commercial production has taken place in China, Korea, Japan, Taiwan, Thailand, and Vietnam (Li 1995; Liao et al 1995; Ruangpanit and Yashiro 1995; Wong 1995). Nevertheless considerable progress has been made with species that are indigenous to the Gulf and Caribbean region. Improvements upon the established technology coupled with some additional interest and investment in development of grouper culture should allow commercial production of groupers in the Gulf in the foreseeable future. The areas of research and development that need the most attention are development of reliable methods for adequate seed production and advancements in feeds and grow-out strategies to promote rapid growth rates.

Mahimahi, Common Dolphin, Dorado, *Coryphaena hippurus*

Brief Biological Profile and Rationale for Inclusion

The common dolphin or mahimahi is an open ocean species found in tropical and subtropical seas throughout the world (Palko et al 1982). They are a popular gamefish because of their aggressive nature and fighting ability and valued as commercial catch because of their excellence as a foodfish and high value. Seasonally they appear in the northern Gulf of Mexico. Commercial landings of dolphin in the Gulf and Atlantic region for 1991-1996 totaled 4,715 mt with an average ex-vessel value of $3.19 per kg (NMFS 1998). The dolphin or mahimahi has long been recognized as a strong candidate for mariculture because of its rapid growth rate, high market value and palatability (Avault 1996). Mahimahi has recently been thoroughly reviewed with regard to development for aquaculture including the status of nursery and grow-out techniques and its potential as a culture species (Kraul 1991; Szyper 1991; Ostrowski 1995). Attempts at commercial scale culture are reportedly underway in the U.S. and Australia (Szyper 1991; Kraul 1993) although we are unable to report the current status of those efforts. Besides its tremendous potential for culture, grow-out technology has undoubtedly benefited from interests by the state of Hawaii in stock enhancement, where it is a premier sport fish (Szyper 1991).

Status of Nursery and Grow-out Methods

Several aspects of mahimahi biology make them seductive candidates for culture. Among the most appealing are the early maturity of female dolphin in captivity, their tremendous fecundity and their readiness to spawn in captivity (Kraul 1990; Szyper 1991; Ostrowski 1995). Mahimahi females can mature in captivity at 50 cm and 5-6 months of age (Kraul 1991; Szyper 1991; Ostrowski 1995). Mahimahi are serial spawners and early spawns can produce as many 15,000 eggs with subsequent spawns growing in size as females mature (Szyper 1991; Ostrowski 1995). Spawning stock requires special donut shaped holding facilities to reduce or avoid damage during bursts of activity such as chase (Szyper 1991).

Mahimahi eggs are pelagic and relatively large (1.4-1.6 mm diameter) and hatching occurs in 40 h at 26°C (Szyper 1991; Ostrowski 1995). Larvae are relatively large for a tropical marine fish larva (4.2 mmSL) and begin to feed 2-3 days after hatch. First feeding success is maximized when rotifers or a zooplankter of equivalent size are offered, however methods developed at the Oceanic Institute suggest that commercial rearing can produce adequate survival more economically by only offering *Artemia* (Ostrowski 1995). As with many marine fishes, mahimahi larvae don't grow or survive as well on *Artemia* as on natural plankton (copepods) because they lack the appropriate highly unsaturated fatty acids that are essential to marine species and commonly available in marine plankton (Watanabe 1983). This can apparently be overcome for mahimahi by enriching *Artemia* with HUFA's (Kraul 1990; Ostrowski and Divakaran 1990; Ostrowski 1995).

For grow-out, another appealing aspect of mahimahi culture is their rapid growth rates in both the larval and juvenile stage (Kraul 1991; Szyper 1991; Ostrowski 1995). Mahimahi larvae can grow 30-50% per day or more (Szyper 1991). Mortalities during grow-out can be a problem. Survival can be enhanced by tank designs that minimize chances for collision with hard walls, which can result in very high mortality rates in larger fish (Ostrowski 1995).

Nutritional and Feed Issues

Conversion from live feeds to pelleted foods have been accomplished and details of the weaning process are outlined in Ostrowski 1995. Food conversion efficiencies of dolphin are reportedly high although they apparently require specialized feeds with very high protein and lipid content (Ostrowski 1995). Attention to the quality of feed is reportedly critical to any commercial ventures (Ostrowski 1995). Research at the Oceanic Institute has shown that juvenile mahimahi require feeds high in protein and moderate in lipids and carbohydrate (Ostrowski and Duerr 1994). Feeds containing 55-60% protein, 10-14% lipids and <12% carbohydrates are recommended for juveniles.

Suitability for Cage Culture

Culture system design is a critical element of successful mahimahi grow-out. Even with the best available designs a significant level of mortality in mahimahi culture is associated with containment in tanks. Some of this mortality might be relieved if stocking into cages proved to be a less restrictive environment for juvenile mahimahi. We are unaware of any attempts to stock mahimahi into cages, but since they are an open ocean pelagic capable of quickly reaching high speeds, cages might prove to be a better venue for mahimahi culture if their other requirements can be met.

Disease Issues

Agonistic behavior during the weaning phase can cause stress and lead to a high incidence of red tail disease, a problem associated with nipping (Ostrowski 1995). Once skin damage is prevalent, ambient infectious diseases can spread quickly if not treated. Presumably mahimahi are vulnerable to other disease problems as well (see Hawke section for general discussion of diseases).
Potential Limitations for Culture

It is generally believed that although some limitations still exist for mahimahi culture, there are no insurmountable problems to limit commercial culture. In the ocean, common dolphin are generally restricted in their distribution by the 20°C isotherm (Palko et al 1982), suggesting they require water temperatures warmer than occur in the northern Gulf during winter. This may be a problem if grow-out cannot be completed in a single summer growing season. Salinity may also be a problem for mahimahi or for a hybrid (if one were produced), since the pompano dolphin are strictly found in open ocean environments (Palko et al 1982). Mahimahi larvae and juveniles may require salinity greater than 28 (Szyper 1991; Ostrowski 1995). Overall, improving survival throughout the grow-out process seems to be the single most important obstacle to overcome (Ostrowski 1995).

Special Considerations

A hybrid between common and pompano dolphin is a possibility for grow-out (Hagood and Rothwell 1979). Since a hybrid would be sterile, a dolphin hybrid might reduce problems with slower growth in females when they reach maturity and might also reduce fears by managers of escapement of cultured fish into the wild.

Research Needed to Reach Biological Feasibility

Mahimahi culture is biologically feasible at this time. Feed quality and culture system design are the two most critical factors for mahimahi culture. Poor survival rates in the larval phase due to cannibalism, expensive high quality feed requirements for grow-out and sources of unknown mortality (Ostrowski 1995) are probably the major factors that could potentially limit the economic success of a commercial venture at this time. Continued research with mahimahi will undoubtedly improve on the current technology.

Pompano, *Trachinotus carolinus*

Brief Biological Profile and Rationale for Inclusion

The Florida pompano was identified as a strong candidate for mariculture in the Southeastern U.S. in 1965 because of its high market value and excellence as a foodfish (Finucane 1972; Gilbert 1986; Avault 1996). It has recently been thoroughly reviewed with regard to it status and potential as a culture species along with two related species, the permit, *Trachinotus falcatus* and the palometa, *Trachinotus goodei* (Watanabe 1995).

Pompano are relatively abundant in coastal waters throughout the Gulf of Mexico (Gilbert 1986). A modest commercial fishery exists for pompano in the Gulf of Mexico and along the east coast of Florida (Watanabe 1995). Harvests peaked at about a million pounds in the Atlantic and Gulf region and have declined to about 376,000 lbs. in 1996. Commercial landings of pompano in the Gulf and Atlantic region for 1991-1996 totaled 1,675 mt with an average ex-vessel value of $6.69 per kg (NMFS 1998). For a species of such keen interest as a foodfish, the natural history is poorly understood. Pompano have a protracted spawning season ranging from April through October in the Gulf (Gilbert 1986). Data on age and growth in the field are lacking and age at maturity and fecundity data are limited.

In the late 1960's through the 1980's a considerable research effort was directed at developing pompano culture methods, although these early ventures met with limited commercial success (Finucane 1972; McMaster 1988). A commercially viable operation was temporarily in place but went out of business for reasons apparently unrelated to the biology (see McMaster 1988) suggesting that early efforts at pompano culture were not totally in vain. Many of the early problems identified in the literature, such as poor food conversion, appear to be solvable and a renewed interest in the culture of pompano and related species has emerged in the 90s. In Asia a closely related species, the permit, *Trachinotus blochii*, is being cultured in coastal sea farms (Chou et al 1995). Although this species is a relatively new introduction to the area, their modest success suggests that Florida pompano could be successfully cultured in the U.S. using similar methods.

Status of Nursery and Grow-out Methods

Initially, fingerling production was a limiting factor for pompano (McMaster 1988; Avault 1996). Subsequently, pompano were spawned in captivity by both photo-period temperature manipulation and by hormone injection, including a commercial scale effort (Hoff et al 1972, 1978a,b;

McMaster 1988). Unfortunately many of the early successes with breeding methods were by private enterprise and details remain unpublished. Nevertheless, successful breeding of closely related species (Chou et al 1995) and apparent success breeding pompano in Venezuela (Watanabe 1995) suggest they can be consistently spawned in captivity with appropriate methods.

Pompano are a hardy animal that can tolerate a wide range of temperature and salinity, are resistant to handling, crowding, and disease, and will readily eat a variety of foods in confinement including pelleted foods (Jory et al 1985). Broodstock are readily available seasonally throughout the northern GOM, spawning along the coast with juveniles recruiting to the beaches throughout the summer (Bellinger and Avault 1970; Gilbert 1986).

Nutrition and Feed Issues

Poor food conversion and growth rates have been reported for pompano larger than 200g (McMaster 1985). However, subsequent research has shown that high energy feeds can greatly improve food conversion, growth rates and survival (Williams et al 1985). Furthermore the grow-out technologies available for intensive culture 10-15 years ago were limited compared to current methods and may have contributed to poor performance in the larger fish. It is likely the reported problem is solvable with better feeds and more efficient rearing systems. In Asia a related species, the permit, is fed minced trash and occasionally commercial pellets with reasonably high food conversion rates (Chou et al 1995). In recent feed trials with the palometa, *Trachinotus goodei*, juveniles were grown in tanks and fed 3 diets formulated for salmonids and a fourth diet formulated for a warm-water marine finfish containing 60% protein (Cole et al 1997). Good growth rates and food conversion efficiency were observed on all the feeds. Pompano appear to be an especially good candidate for recirculating systems as well as coastal cage culture or some combination of both (Watanabe 1995).

Suitability for Cage Culture

Pompano have been tested for cage and pond culture and in polyculture systems (Swingle 1972; Rossberg and Strawn 1980a,b; Avault 1996). Pompano and related carangids have also been cultured in cages in Venezuela and China (Cairoli and Conroy 1987; Hongke 1994). Pompano have apparently not been extensively tested in cages placed in an open water environment (offshore), although they over-winter in that environment in the northern Gulf. One of the principal barriers to previous attempts at pompano culture in the U.S. is their sensitivity to temperature (Avault 1996). Pompano stop feeding at low temperatures and winter mortality can occur (10°C) and growth rates can be limited by their active nature and a need for high energy feeds (Allen and Avault 1970; Williams et al 1985; McMaster 1988; Avault 1996). Low temperature sensitivity might be detrimental to pompano held in cage systems placed in shallow coastal environments, especially in the Northern Gulf.

Disease Issues

Very little is known or has been reported about specific diseases affecting pompano in captivity. Outbreaks of vibriosis and other diseases were reported for cage culture grow-out trials in Venezuela (Cairoli and Conroy 1987; Gomez-Gaspar 1987). See also disease section for general evaluation of diseases (Hawke).

Potential Limitations for Culture in the GOM

In spite of several research efforts devoted to reaching commercial status, it is fair to say that considerable work still needs to be done on spawning and grow-out of pompano. Growth may be severely limited in winter and thermal mortality could be a problem if they are caged too far inshore. If problems of temperature and spawning can be overcome, prospect for pompano culture are likely to be high in the future, especially given the renewed interest in the culture of pompano and closely related species around the world (Trebaol. 1991; Hongke 1994; Watanabe 1995).

Red Drum, *Sciaenops ocellatus*

Brief Biological Profile and Rationale for Inclusion

Red drum, also commonly known as redfish or spot-tail bass, have been a focus for culture in the Southeastern U.S. and Caribbean for many years. In the United States it is one of the most well developed marine species currently in commercial culture. Because of its recognized potential for commercial culture, operations have developed in Taiwan and elsewhere around the world. Development of culture techniques have taken place for two principal reasons. Initially red drum culture was pursued by state agencies. Declines in natural stocks of red drum in some southern states lead to an interest in spawning adults and rearing the larvae for stock enhancement programs. As demands on natural fisheries increased and supplies of wild fish decreased, interest in red drum culture increased and it was soon recognized as a viable candidate for mariculture (Arnold 1988). Red drum stocks have rebounded, but conservation organizations have endeavored to preserve them for recreational interests, making the prospects for their culture commercially viable.

Red drum are estuarine dependent species which spawn near tidal passes and inlets along the Gulf coast in the fall (September-November) (Matlock 1987). Adults and juveniles tolerate a wide range of temperatures and salinity making them especially well suited to culture in cages and ponds (Neill 1987). Red drum are long lived and grow reasonably fast as juveniles, making it possible to produce a market size fish in less than 2 years and possibly in a single growing season if properly managed (Lutz et al 1997).

Status of Nursery and Grow-out Methods

Nursery and grow-out techniques are well developed for red drum (Holt et al 1987; Arnold 1988) and have recently been reviewed (Henderson-Arzapalo 1995). Red drum can be spawned in captivity by both photoperiod-temperature manipulation (Arnold 1988) and by hormone injection (Thomas and Boyd 1988). Because they are a serial spawners, multiple batches of eggs can be generated and with careful manipulation of temperature, spawners can be maintained in spawning condition for extended periods (Arnold 1988).

Red drum spawn at night shortly after dark. Eggs are pelagic and relatively small (0.9-1.0 mm) as are the larvae (~2.4 mm SL at first feeding). They hatch in about 24h at 25°C and larvae begin to feed about 2 days post hatch. Red drum larvae require small prey at first feeding. Typically rotifers are offered and eventually *Artemia*, although it is possible to begin weaning larvae on to a

#1 crumble after only a few days of growth. As with other marine fish larvae, growth and survival rates can be enhanced by enriching zooplankton with HUFA's (Craig et al 1994).

The most significant issue to deal with in grow-out of red drum appears to be cannibalism in the late larval stages of development (Soletchnik et al 1988). Cannibalism occurs frequently during the period when larvae are weaned from zooplankton onto dry diets and is facilitated by variable growth rates among larvae within a culture unit. Cannibalism can dramatically reduce survival through the larval stage. Impacts can be reduced and largely eliminated by maintaining feeds during the critical phases and by grading larvae by size as they develop into juveniles.

Nutritional and Feed Issues

Because red drum are currently being commercially cultured, numerous feed studies have been conducted and red drum nutrition has been reviewed (Robinson 1988; Henderson-Arzapalo 1995). Feeds which are suitable for red drum grow-out are commercially available from a number of different feed manufacturers and refinements to practical diets for red drum continue to be developed (Davis et al 1995; Craig and Gatlin 1997). Robinson et al (1990, 1991) estimated that a red drum diet for grow-out should contain 35-45% protein, 3.5-4.0 kilocalories of energy/g diet and 5-6% fat. Since red drum cannot fully utilize plant proteins, Ellis and Reigh (1992) found the best compromise between cost and efficiency for feed formulation was a 1:1 soy protein:fish protein diet.

Reported food conversion ratios for red drum are highly variable, reflecting different diets, culture environments and culture protocols. For the northern Gulf of Mexico, it is reasonable to assume that it is possible to produce a 1 kg red drum in about 14 months, depending upon temperature, culture conditions and food quality (Henderson-Arzapalo 1995).

Suitability for Cage Culture

Temperature limitation for over-wintering of juveniles in ponds and cages is undoubtedly the major impediment to the widespread development of redfish culture (Henderson-Arzapalo 1995; Lutz et al 1997). Redfish appear to be highly suited to offshore cage culture in the north-central GOM for several reasons. Wild juvenile redfish normally prefer lower salinity, although they are more tolerant to cold stress when acclimated to higher salinity. Depending on the degree of acclimation to reduced temperature and salinity, they can tolerate temperatures down to about 3-5 °C before stress and then mortality occurs (Ward et al 1993). Feeding ceases between 7 and 9 °C. Offshore cage culture may avoid many of the problems encountered by inshore and land-based systems, because of the warmer winter temperature found offshore. Thirty to forty miles offshore winter water temperatures remain above 12-15 °C, thus avoiding any chance of thermal stress.

Previous attempts have been made to culture red drum in offshore cages with mixed success (Miget et al 1996). Many of the problems that this initial attempt reported were related to the engineering required to operate in the harsh offshore environment, although poor food conversions by the red drum in offshore cage was reported as a problem (Miget et al 1996). It is difficult to know whether the principal problem was related to biological performance of the fish or the delivery system for the feeds, although the latter seems more likely. Better delivery systems, refinements in the buoyancy of the food pellets in high salinity environments and a better understanding of the behavior of the fish in cages will probably greatly improve feeding success and food conversion. Another offshore cage culture effort growing redfish is currently underway off Texas. Progress made by this effort may portend the chances for success in future offshore enterprises.

Disease Issues

Because red drum are native to the Gulf of Mexico and have been commercially cultured for several years the disease problems typically encountered with redfish culture are well established (Johnson 1987). See section on diseases (Hawke).

Potential Limitations for Culture

There are no major problems related to the biology to prevent the development of cage culture of red drum in the northern Gulf of Mexico. Environmental requirement may affect growth rates somewhat in the offshore environment when fish are small since they typically inhabit estuarine environments, but those losses may be made up as the fish grow and by longer growing seasons in the offshore environment. Offshore culture will also offer more flexibility in harvest schedules (Lutz et al 1997).

Special Considerations

Because red drum are an important recreational species in the Southeastern U.S. and the subject of significant conservation efforts in several southern states and are also commercially cultured, considerable potential exists for the illegal harvest and sale of wild caught red drum. In order to distinguish between wild and farm raised red drum law enforcement officials utilize fatty acid profiles in muscle as a forensic tool (Villarreal et al 1994). If a major culture operation for red drum were to be established it would be advisable to gather baseline information on fatty acid profiles of the cultured fish to avoid potential conflicts with enforcement efforts.

Research Needed to Reach Biological Feasibility

Although refinement can always be made to culture procedures and techniques no further research is needed to reach biological feasibility for commercial culture of red drum.

Red Snapper, *Lutjanus campechanus*

Brief Biological Profile and Rationale for Inclusion

The commercial and recreational fishery for red snapper, *Lutjanus campechanus*, in the Gulf of Mexico and SE Atlantic is a valuable resource. Trends in commercial and recreational catches of red snapper indicate they were declining in the Gulf of Mexico from the early 1970's (Goodyear and Phares 1990). Total commercial and recreational landings declined from 14-15 million pounds in the early 1980's to 5-6 million pounds in 1987-1988. Red snapper CPUE as bycatch in the shrimp fishery also declined significantly, indicating a real decline in red snapper populations. Fishery independent statistics, such as the NMFS fall groundfish survey, indicated similar trends with CPUE of juvenile fish declining 3-5 fold since 1972. Although it is often difficult to identify specific cause and effect mechanisms for population declines, it appears that (1) overfishing by directed fisheries and (2) bycatch of juveniles in trawl fisheries are significant contributing factors. Both creel and size limits (currently 5 fish per day and a 16 in. TL size limit in federal waters) have been instituted for the recreational fishery and a catch quota has been instituted for the commercial fishery. Worldwide there is a strong interest in the culture of Lutjanids because of their excellence as a foodfish and suitability for confinement in tanks and cages.

Status of Nursery and Grow-out Methods

Red snapper are serial spawners whose spawning season extends from May through October in the northern Gulf of Mexico. Batch fecundity is reasonably high with a 22 in. female capable of producing 255,000 eggs in a single spawn (Chesney and San Fillippo 1994). Both males and females mature at 2-3 years of age and a size of 31-41 cm TL(12-16 in.).

Attempts to spawn and rear red snapper have been underway for some time in the U.S. (Arnold et al 1978; Minton et al 1983). In spite of early success in spawning red snapper, rearing the larvae of red snapper, *Lutjanus campechanus*, has proven more difficult than for many other species, including other lutjanids. Successful spawning and larval culture of other snappers such as the mangrove red snapper, *Lutjanus argentimaculatus*, in Asia (Chou et al 1995; Emata et al 1995; Liao et al 1995), the St. John's snapper, *Lutjanus johni* (Lim et al 1985) the lane snapper, *Lutjanus synagris* (Clarke et al 1992) and most recently the mutton snapper *Lutjanus analis* (Watanabe et al 1998), suggest that red snapper culture is highly feasible. Nevertheless, a significant effort has been made to culture red snapper through the larval phase with extremely limited success. A recent effort in Alabama was able to produce a few hundred red snapper juveniles, but no mass culture effort has succeeded thus far.

Red snapper larvae are relatively small at hatch (2.3 mm TL) but no smaller than other snappers, suggesting the problem in rearing red snapper may not be related to their small size or larval food. In the field, summer spawned young-of-year snapper juveniles reach a size of 50-90 mm by August and September (Holt and Arnold 1982) and by age 2 they are 267-378 mm TL (Nelson and Manooch 1982). Only a small fraction of two year old fish reach sexual maturity (Chesney and SanFilippo 1994).

Nutritional and Feed Issues

Because of difficulties with rearing the larvae, no extensive research has been done specifically on nutritional requirements of juvenile snapper or feed development. Juvenile red snapper can be readily adapted to commercial feeds in captivity with little or no mortality related to the weaning process (E. Chesney, p. o.). Experience with other snapper suggests they will require high quality feeds. In recent experimental spawning and grow-out studies with mutton snapper *Lutjanus analis*, juveniles were reared to an average size of 140 g in 168 days with a high survival (98%) and good food conversion (FCR=1.2) on a high protein pelleted feed (56% protein) (Watanabe et al 1998). Similar results should be possible with red snapper.

Suitability for Cage Culture

Cannibalism should not be a major problem in the culture of red snapper. Red snapper are tolerant to a wide range of temperatures and appear to prefer a moderate range of salinity from medium (25 ppt) to full strength seawater. This will make them a good candidate for offshore cage culture but they may not do as well in cages located in low salinity environments (<25), although this needs to be tested. As reef fishes snappers are extremely structure oriented, associating with natural and artificial reefs, hard bottoms and structures such as oil platforms. Their strong schooling behavior and affinity for structure should make them highly suited for offshore cage culture.

Disease Issues

Very little is known about specific diseases affecting red snapper in captivity. See disease section for general evaluation of diseases (Hawke).

Potential Limitations for Culture

Considerable work needs to be done on spawning and grow-out of red snapper. No commercially viable mariculture industry has been established to date, because of the inability to grow-out larvae. These problems should be solvable with additional research effort. Broodstock are available year-round in the northern GOM and they have been conditioned to spawn with photoperiod-temperature manipulations (Arnold et al 1978), although hormone-induced methods may prove more reliable, so the potential to produce fingerlings will be strong once the larval rearing problems can be solved. Since they have not been mass cultured before, there are a number of unanswered questions about their growth, food conversion and disease resistance in culture that will need to be answered. When red snapper larvae have been successfully reared through the juvenile phase, agonistic or territorial behavior has been observed which can reduce growth of subordinate individuals or cause mortality (E. Chesney, p.o.). There is some potential for conflicts with commercial fisheries and fisheries regulations because of strict management regulations and harvest quotas now in place. However that might also prove to be an advantage for the development of red snapper culture since red snapper are a target for bycatch reduction and the fishery is currently in a recovery phase. There are also efforts underway to attempt stock enhancement of red snapper in the Gulf that would bolster initiatives to develop mass culture.

Special Considerations

Red snapper are relatively slow growers in the wild and may require more than 1 growing season to produce a marketable size fish depending on market demands for size and their potential to grow faster in culture than in nature.

Research Needed to Reach Biological Feasibility

Red snapper are a highly valued species with good potential for aquaculture. However, until the problems with larval grow-out can be overcome and grow-out trials conducted, biological feasibility will not be reached in the foreseeable future.

Other Snappers —
Mangrove Snapper, *Lutjanus griseus*, Mutton Snapper, *Lutjanus analis*, Yellowtail Snapper, *Ocyurus chrysurus*

The gray or mangrove snapper, *Lutjanus griseus* is a close relative of the red snapper that resides in reasonably large numbers in the northern Gulf of Mexico. Wild fish have the reputation of not taking dead baits as readily as the red snapper and consequently, are not captured as frequently as red snapper in directed hook and line fisheries. Mangrove snapper have several characteristics which make them a species worthy of consideration for culture. In terms of their biology they are very similar to red snapper. They are serial spawners and spawn throughout the summer offshore. Their larvae have been reared in the laboratory using standard methods (Richards and Saksena 1980) although no mass culture or grow-out research has been reported. They appear to be more tolerant to reduced salinity than red snapper, because both the adults and their juveniles reside in areas lower in salinity than their red snapper counterparts.

They, along with other Lutjanids residing in the Gulf, offer good prospects for developing hybrid snappers (Domier and Clark 1992). A hybrid would be likely to be more tolerant to reduced salinity, thus opening up the prospect of culturing them in coastal ponds. Currently, we do not know of any effort to develop mangrove snapper for mariculture, although its potential for culture has been recognized in the literature.

Other relatively new candidates for mariculture within the GOM are the mutton snapper, *Lutjanus analis*, and the yellowtail snapper, *Ocyurus chrysurus*. In recently reported research, mutton snapper were successfully spawned in captivity with hormones and their larvae reared in significant numbers (>36,900) through the larval phase using standard techniques for rearing fish larvae (Watanabe et al 1998). Mutton snapper larvae are small and required a small food item (ss-type rotifers) at first feeding and then *Artemia*. Grow-out trials were also conducted with a portion of the juveniles (1,390). The mutton snapper juveniles were reared to an average size of 140 g in 168 days. Survival rate was high (98%) and food conversion was excellent (FCR=1.2) on a high protein pelleted feed (56% protein) (Watanabe et al 1998). Although limited research has been done with mutton snapper, prospects for this species appear to be good based upon their biological performance and adaptability to culture. The only potential limitation for culture of mutton snapper within the Gulf of Mexico may be the tropical nature of this species which could potentially limit its culture to warmer environments within the Gulf. More information on their temperature and salinity tolerances is needed to determine their environmental requirements.

The yellowtail snapper, *Ocyurus chrysurus*, is another tropical snapper which is indigenous to the Gulf of Mexico and has been targeted for mariculture. They have been spawned in captivity and their larvae reared (Soletchnik et al 1989; Riley et al 1995). Yellowtail are apparently easily spawned in captivity by either photoperiod-temperature manipulation or by hormone injection (Soletchnik et al 1989). Larval rearing has met with mixed success. Eggs are 0.96 mm in diameter (Riley et al 1995). First feeding larvae are 3.36 mm SL at 3 days post hatch (Riley et al 1995). In nature, yellowtail snapper grow at rates similar to other lutjanids suggesting they are a good candidate for culture (Mason and Manooch 1985). There are no literature reports of mass propagation through the juvenile phase, although some grow-out trials with juveniles have been conducted in cages where various diets were tested (Venchaurd 1988). Yellowtail snapper growth in cages was optimal on a diet containing 44% animal protein (fish meal) with a P/E ratio of 22 mg protein per kJ (Venchaurd 1988). Yellowtail snapper can be hybridized with lutjanids opening up the possibility of producing a variety of hybrid crosses for mariculture (Domeier and Clarke 1992; Loftus 1992). As with the mutton snapper the tropical nature of yellowtail snapper may limit locations for its culture within the Gulf, however hybrids with any of the many gulf snappers may prove to be a key to successful snapper culture in the future.

Striped Bass and SB Hybrids, *Morone saxatilis*

Brief Biological Profile and Rationale for Inclusion

Striped bass and striped bass hybrids have been a focus for culture in the U.S. and elsewhere for many years and culture methods have been reported and thoroughly reviewed (Stevens 1966; Bayless 1972; Bonn et al 1976; McCraren 1984; Rees and Harrell 1990). In the U.S., striped bass is one of the most well developed marine species currently in commercial culture as evidenced by the voluminous published literature on their culture (see bibliography). Because of its recognized potential for commercial culture, research and commercial ventures have developed throughout the world.

Development of culture techniques for striped bass and striped bass hybrids has taken place for two principal reasons. Initially striped bass culture was pursued by state agencies, first because they were recognized long ago as an excellent gamefish for stocking into reservoirs and elsewhere (Stevens 1966). More recently, striped bass research was stimulated by the declines in natural stocks of striped bass in the mid-Atlantic and Gulf states and California which lead to an interest in spawning adults and rearing the larvae for stock enhancement programs. As demands on natural fisheries increased and supplies of wild fish decreased, interest in striped bass culture heightened and it was eventually promoted as a viable candidate for commercial culture, especially as a hybrid.

Striped bass are anadromous, typically spawning just upstream of the freshwater-saltwater reaches of rivers along the Atlantic and Gulf coast in the spring. Adults and juveniles tolerate a wide range of temperatures and salinity making them especially well suited to culture in cages and ponds (Hodson 1991). Striped bass are long lived and grow reasonably fast, making it possible to produce a market size fish in less than 2 years.

Status of Nursery and Grow-out Methods

Striped bass are the only anadromous species and only batch spawner to be included in this feasibility assessment. These attributes have probably slowed progress in developing year round spawning of striped bass in captivity. Nonetheless, out of season spawning in captivity has been successfully accomplished and other aspects of their biology make them especially well suited to culture. There are numerous commercial producers of fingerlings and grow-out operations, as well as state and federal fingerling production programs, in the U.S. Spawning has been typically accomplished by capturing wild broodstock in reservoirs or on the spawning grounds of rivers and then injecting them with hormones. Domesticated strains are also available (Curry-Woods et al

1992; Hodson and Sullivan 1993; Harrell and Woods 1995). Striper males typically mature at an age of 2 years and females typically by age 3 (Setzler et al 1980; Olsen and Rulifson 1992). The best broodstock are believed to be larger, older females which produce larger, higher quality eggs (Zastrow et al 1989). At one time striped bass were typically strip-spawned (Stevens 1966; Bayless 1972; Bonn et al 1976), but as experience has increased more hatcheries have allowed fish to spawn in holding tanks. More recently, researchers have successfully used photoperiod-temperature manipulations and hormone implants to modify maturation rates of striped bass and produce spawns out of season (Blythe et al 1994; Tate and Helfrich 1995; Mylonas et al 1996). Striper sperm has been successfully cryopreserved, potentially facilitating production of hybrids (Kerby et al 1985).

Hybrids were first successfully produced for management purposes (Bayless 1972). Although many *Morone* hybrids combinations are possible, they are typically produced by crossing a striped bass female with a white bass male (*M. saxatilis* x *M. Chrysops*) (Hodson 1991). Eggs of SB hybrids hatch in 40-48 h at 16-20°C (Hodson 1991). The eggs and larvae (5.5 mm SL at first feeding) of stripers and their hybrids are relatively large (Zastrow et al 1989), especially compared to many of the other species evaluated in this assessment. First-feeding typically begins around 5 days after hatch at 19°C and larvae can be fed *Artemia* immediately. It is also possible to completely skip live foods and begin feeding larvae artificial feeds (Wawronowicz and Lewis 1979), although this may result in reduced survival. Striped bass and SB hybrid larvae can grow 15-20% per day at 19°C (Houde and Lubbers 1986; Chesney 1989) and metamorphose at 10-12 mm SL.

Striper larvae can be cannibalistic although this can be reduced or avoided with proper feeding procedures and grading (Ludwig and Tackett 1991). Poor swimbladder inflation is a common problem with striped bass larvae which can lead to reduced growth and poor survival in the larval phase (Bailey and Doroshov 1995). Minimizing stress during the early larval phase and good culture practices can minimize this problem.

Nutritional and Feed Issues

Dietary requirements have been extensively tested in experimental feeding trials and commercial feeds specifically developed for striped bass and their hybrids and are available from several commercial feed producers (Zeigler et al 1984; Keembiyehetty et al 1992, 1993; Nematipour et al 1992; Brown et al 1993; Gatlin et al 1994). Procedures for weaning striped bass larvae onto dry diets are well established (Hodson 1991). Hybrids are typically weaned onto dry pellets at a length of 25 mm and fed a #1 crumble of the appropriate diet (Hodson 1991). Numerous studies have evaluated the growth performance and the fillet quality of cultured products relative to nutrition of striped bass and their hybrids (Fowler et al 1994; Gallagher 1994, 1995; Griffin et al 1994).

Suitability for Cage Culture

Striped bass and their hybrids have been cultured in almost every venue possible. Most culture work to date has been done in ponds, tanks, raceways, and cages (Hodson 1991; Hogans 1994). The natural habitat for juvenile striped bass are the freshwater brackish areas of estuaries. Temperature and salinity regimes offshore might affect their growth rates and susceptibility to diseases, although given their proven performance in coastal cage culture in Louisiana this is unlikely to be a major problem. Many of the problems typically associated with brackish and freshwater pond production might also be avoided in the offshore environment.

Disease Issues

Diseases afflicting striped bass in nature and in culture have been thoroughly studied and reviewed (Mitchell 1984; Wechsler et al 1986; Baya et al 1992, 1996; Harms et al 1996; Hrubec et al 1996). A major problem for the success of SB hybrids in coastal Louisiana has been a temperature specific disease commonly called Pasteurillosis (see Hawke, diseases). Culturing stripers at higher salinity may reduce this problem and other salinity associated problems such as *Saprolegnia* (a fungal infection) which have been reported for freshwater culture systems.

Potential Limitations for Culture

In the case of striped bass and its hybrids, it is not a matter of whether it is possible to culture them or not in the Gulf, but whether it is the appropriate species for the chosen culture environment and method. Commercial operations along the Gulf coast have been trying to culture striped bass hybrids in cages for several years, with mixed success. The original appeal of striper hybrids was their good growth performance and better resistance to cold temperatures than red drum. An unpredictable problem in the culture of SB hybrids in coastal Louisiana has been a temperature specific disease, Pasteurillosis (see Hawke, diseases). It is possible that the impact of this disease might be reduced or avoided in the offshore environment since it has not been a serious problem in other parts of the country. Within Louisiana, Pasteurillosis has been primarily encountered by hybrid striped bass culture operations located in coastal brackish water ponds. Since the disease can lay dormant in sediments for months, it is possible that close contact with sediments may exacerbate contracting the disease in shallow pond culture.

Special Considerations

Striped bass hybrids are believed to be superior for culture because they exhibit heterosis or hybrid vigor resulting in faster growth rates, greater disease resistance and higher survival than either parent species (Hodson 1991). Striped bass and their hybrids need to be tested in an offshore cage environment to see how their performance is affected by salinity, currents and unforeseen problems associated with the offshore environment.

Research Needed to Reach Biological Feasibility

None.

Ocean Ranching of Tuna

Rationale for Inclusion

Tunas, especially bluefin, *(Thunnus thynnus)* bring premium prices if they are of the appropriate size and quality to be sold in Asian markets for sashimi (Nicoll 1992; O'Sullivan 1993; Anon-a. 1996). Ocean ranching has become increasingly commonplace throughout the world as an alternative method to commercial fishing for reliably producing high quality fresh tuna. Because of the extreme difficulty of spawning and rearing tunas in captivity, ocean ranching has emerged as an intermediate form of culture. Ocean ranching consists of capturing wild stocks of tuna at sea and confining them in sea cages. Cages are slowly towed to coastal areas where the tuna are fed and fattened on a diet of inexpensive fish and in some cases pelleted feeds. This practice has become more common wherever tuna of the appropriate size, species and value can be captured, such as in the Pacific, northwest Atlantic, the Mediterranean and Australian waters.

Reported FCRs have been very high for captive tunas, in the range of 25-35:1 for fish fed chopped fish and crude pelleted foods, however better results on a recently developed moist pellet (8:1 wet weight to wet weight basis) were reported at Aquaculture 98. Given their large size, high metabolic rates and active swimming behavior it seems unlikely that good FCRs will ever be achieved for tuna. This makes feed costs for ocean ranching operations very high.

Research Needed to Reach Biological Feasibility

Ocean ranching of tunas is not a new concept, although production of fish via this method has grown significantly in the last several years and is projected to grow even further (Jeffriess 1993). Successful ocean ranching of tuna is not a matter of biological feasibility since the practice has primarily evolved among fishermen turned fish farmers and has been practiced since the late 1970s. The primary considerations are economic feasibility and cultural acceptance among resource users competing for tuna resources in the Gulf of Mexico. Yellowfin tuna are abundant in the Gulf during the entire year while bluefin are seasonal migrants that leave the Gulf after spawning in April through June (Magnuson et al 1994). Yellowfin tuna are more abundant in catches in the GOM, but of lesser value than bluefin. In 1995, exvessel value of bluefin was $23.19 per kg for bluefin compared to $4.63 per kg for yellowfin (NMFS 1998). The second most valuable tuna in the region has been the bigeye at $9.23 per kg (NMFS 1998). Catches of all three species have declined somewhat in recent years with yellowfin catches at 3,097 mt, bluefin at 918 mt and bigeye at 425 mt in 1996 in the Gulf and South Atlantic region (NMFS 1998). Pilot holding and culture trials with bluefin tuna have been attempted by the New England aquarium off Virginia (Plante 1996). However, given the current status of bluefin stocks in the western Atlantic, permitting for bluefin ranching and capture of bluefins is likely to be a serious impediment to extensive ocean ranching in the Gulf or elsewhere in U.S. waters in the foreseeable future (Magnuson et al 1994). Also recent economic downturns in Asian markets have changed the demand for premium grade tuna and could affect their marketability. An economic analysis, based on operations in other countries, could determine the economic feasibility of ranching tunas in the Gulf of Mexico. Significant amounts of finfish bycatch are produced by directed fisheries for shrimp in the northern Gulf (Adkins et al 1993). If properly handled, this could serve as a potentially inexpensive source of high quality protein to support ocean ranching of tunas in the future.

Chapter 3

Assessment of Platform Availability

General Locations and Numbers

There are numerous oil and gas production platforms on the Outer Continental Shelf (OCS) in the Northern Gulf of Mexico (GOM) located off the coasts of Texas, Louisiana, Mississippi and Alabama. These platforms produce oil and gas primarily, and to a much lesser extent, sulfur. Exhibit 3-1 depicts the preponderance of production platforms in the northern Gulf and also shows the 100- and 200-foot depth contour lines. The reader should recall that a finfish mariculture operation was deemed by the project team to be most feasible if located within the 100- to 200-foot contours (see Chapter 1 for explanation).

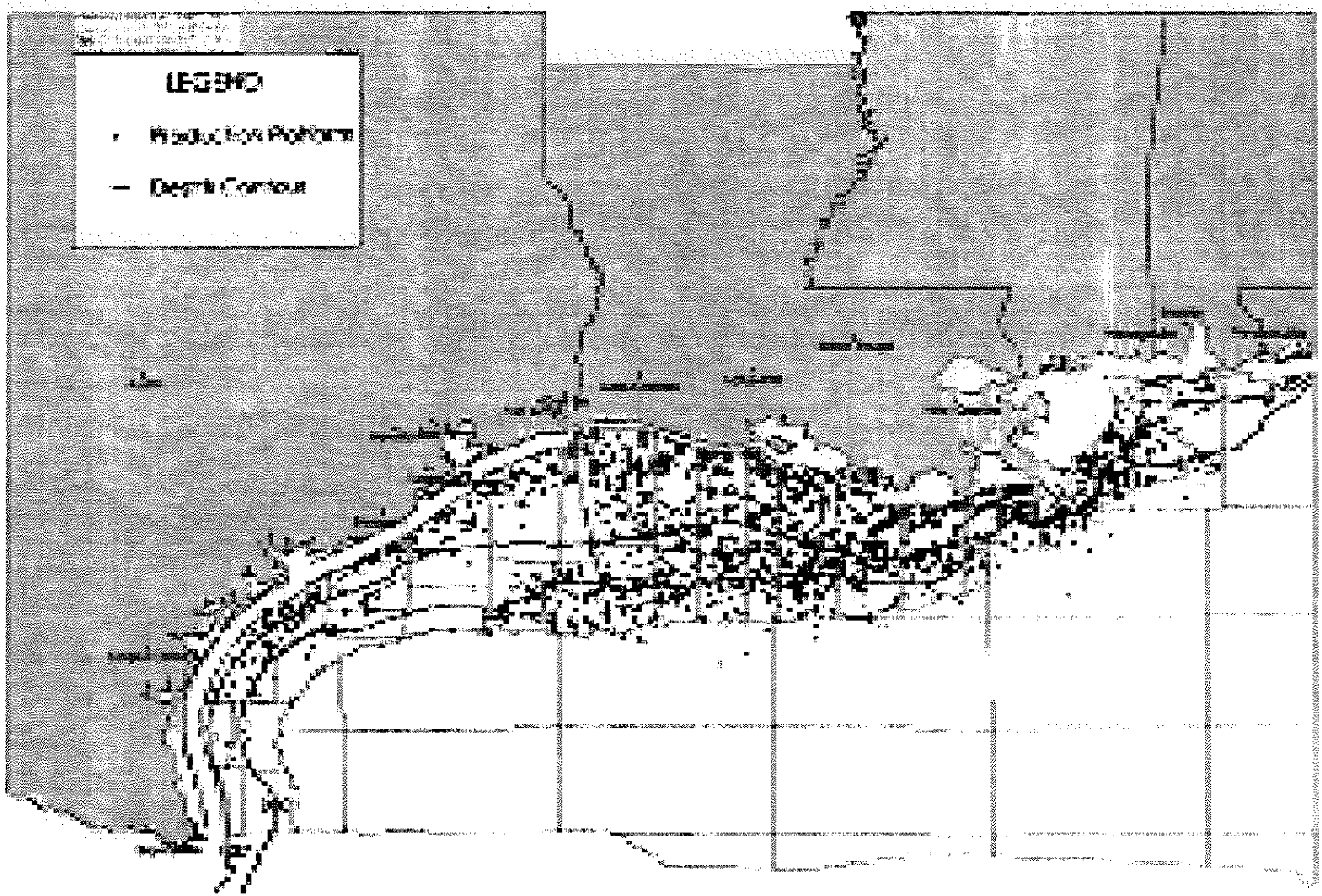
According to records maintained by the Minerals Management Service (MMS) there are approximately 4000 platforms in the GOM at present.

The conventional types of platforms and configurations vary widely and they are generally found in water depths ranging from 10 to over 1000 feet. These conventional types of platforms range from single well caissons (steel pipes used to protect wells) to multi-pile jackets. A distribution chart of the platform types is shown in Exhibit 3-2. The largest concentration of the candidate platforms is found along the Louisiana continental shelf between the South Pass and West Cameron blocks with approximately 800 major structures in that area.

A caisson platform does not provide adequate deck space to allow storage of feed and necessary equipment, crew quarters, office space, etc., for a commercial scale mariculture operation. It has been calculated that a minimum of 500 square meters (approximately 5000 square feet) of deck space is required for the base case installation described in Chapter 1. This requirement necessarily means that a larger structure is required, most probably either a multi-deck four-pile jacket or larger single deck platform.

The MMS maintains a database of all platforms in the GOM. Data maintained include year of installation, type of platform, location (lease number, area and block number), owner, etc. By scanning and querying this database it is possible to estimate the number of platforms suitable for mariculture in the GOM. Exhibits 3-3 and 3-4 show the distribution of platforms in the GOM by depth and age. The project team estimates that there are approximately 900 platforms existing in the GOM which are larger platforms (four-pile or larger) and within the 100- to 200-foot depth contours. The ideal platform for mariculture use is one which has finished its service in oil and gas or sulphur production and would therefore be abandoned or "reefed" if another beneficial use were not found.

Exhibit 3-1. *Location and Oil and Gas Platforms in the Gulf of Mexico.*



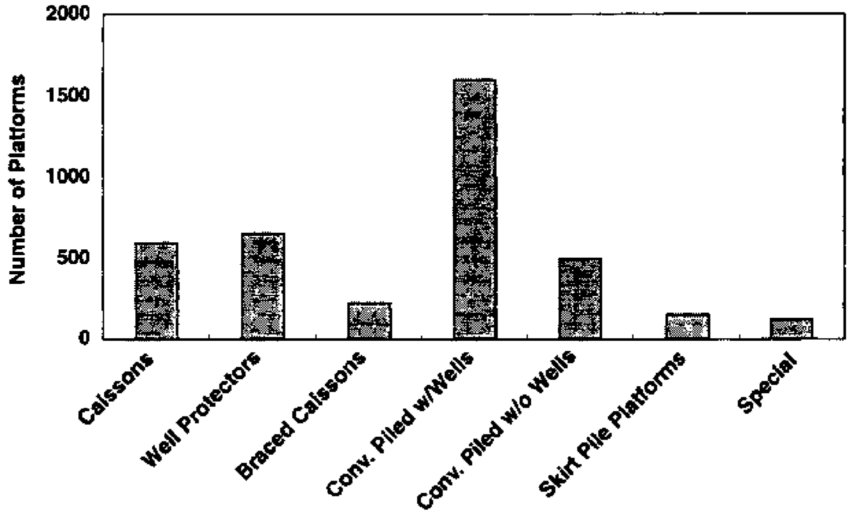


Exhibit 3-2 Distribution of existing platforms in the Gulf of Mexico. Source: MMS (1994, 1995).

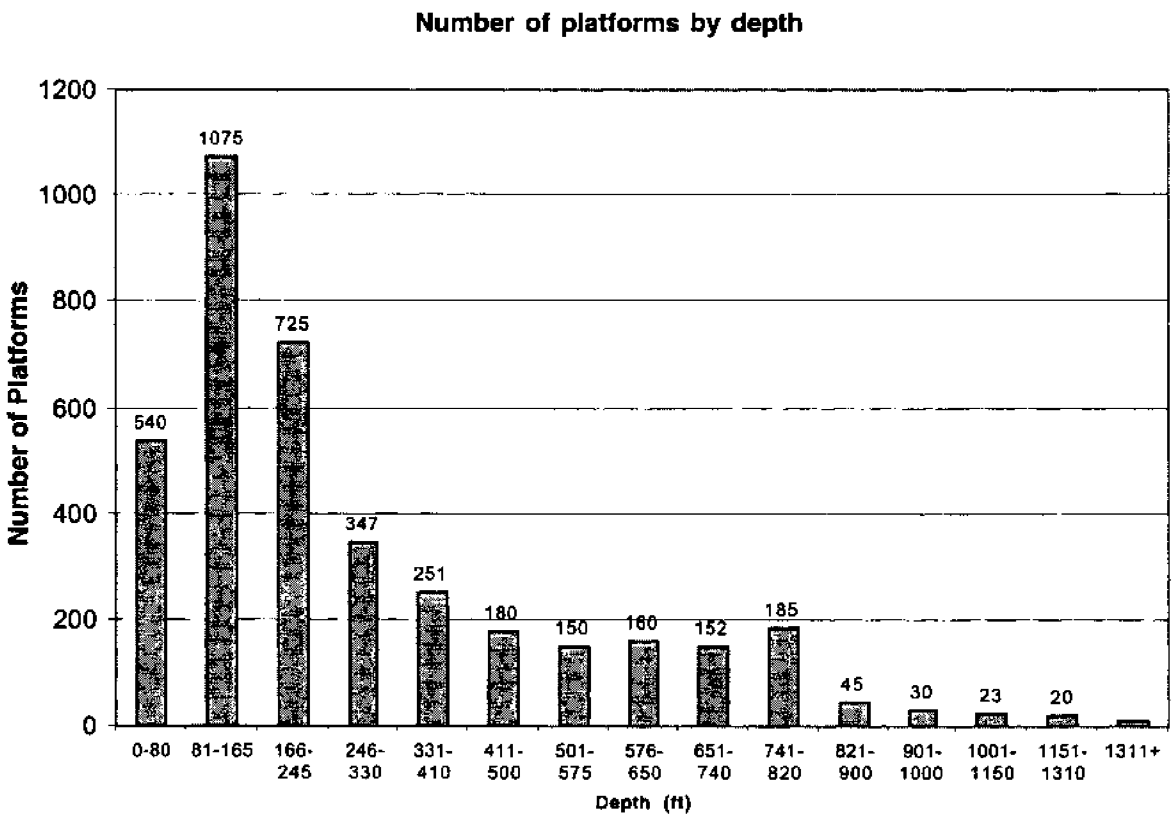


Exhibit 3-3. Platforms by depth.

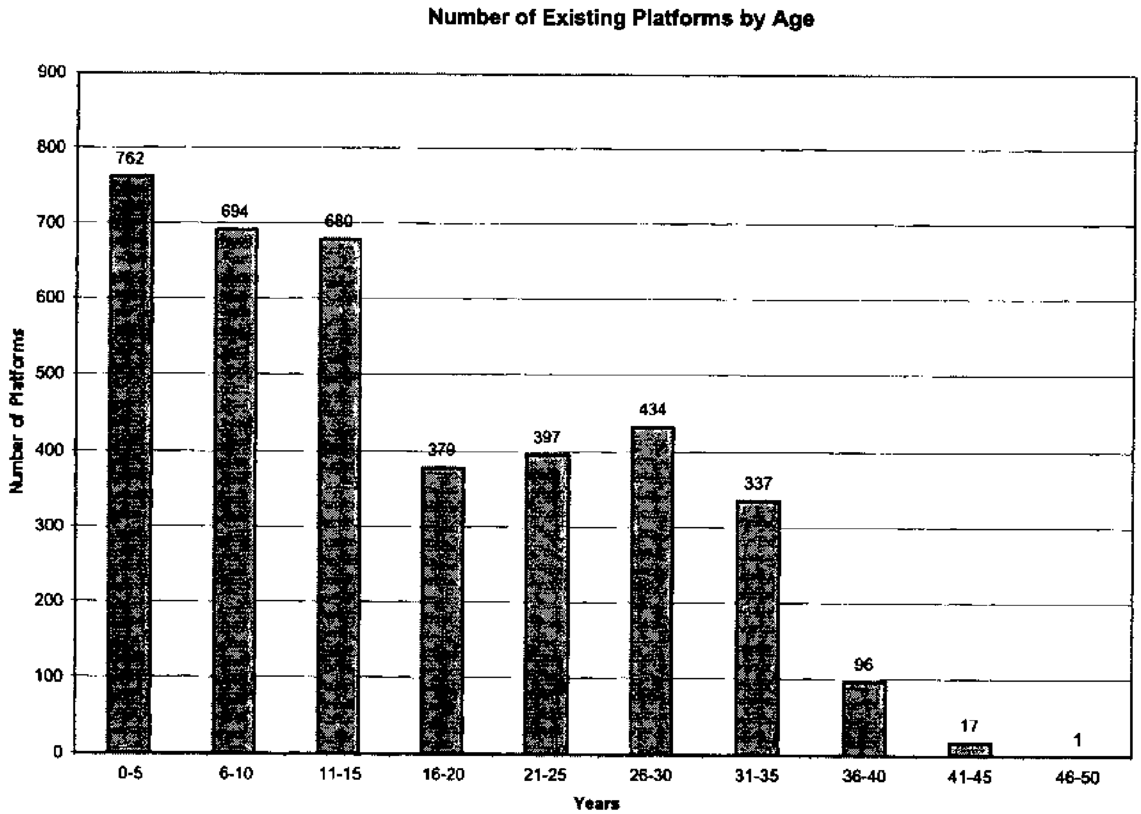


Exhibit 3-4 Platforms by age.

Platforms Scheduled for Abandonment (Decommissioning)

In the years between 1988 and 1996, MMS records report that 1,035 platforms were removed from the GOM OCS for an average of 115 per year. The majority of the removals were shallow water structures; however, about 20% of the platforms removed were major platforms from production sites with greater than 100-foot water depths. The life expectancy is estimated to be 25 to 30 years for a major platform in waters greater than 100 feet deep (NRC 1996). MMS reports that there are 885 platforms 26 years or older on the GOM OCS (MMS 1997). The first oil and gas production platforms in water depths greater than 100 feet were established in 1955 (MMS 1996).

Once the decision is made to cease production at a given location, oil and gas operators must notify the MMS of their intent to plug the wells and cease production. MMS regulations at 30 CFR 250.112 mandate the oil and gas lessee/operator remove the production equipment and return the site to pre-production conditions. The lessee/operator must provide the MMS a surety bond to insure the removal of the platforms (see discussion in Chapter 4 following). NRC (1996) estimates that the cost to remove a typical four-pile platform from 100-foot depth begins at $620,000 and increases to $810,000 for an eight-pile platform – the prices do not include transportation time, well plugging, and site clearance verification costs. When these other items are added, the total cost to remove a structure in these depths will probably range between $1 and $2 million. These costs can be reduced somewhat if the platform is situated in a designated "rigs-to-reefs" area wherein the platform can be cut off below the mudline and toppled in-place after well plugging and removal of production equipment.

The MMS publishes a quarterly "Platform Removal Report" available to the public that lists all the platforms scheduled for removal along the OCS. The information contains the name of operator of the platform, the depth, location, method of removal, and name of the structure.

Areas of the Gulf of Mexico Suited for Mariculture

Water depths of 100 feet and greater generally provide safer conditions for open ocean mariculture operations along the Texas-Louisiana continental shelf. First, commercial scale open ocean net-pens may reach up to 50 meters in diameter and 20 meters in depth. Generally, a measure of clearance is desired below the net to allow fallout from uneaten feed and fecal materials to be swept away by ocean currents. Accumulation of such materials can promote disease among the culture organisms and water quality problems for net-pens (refer to environmental impact section). Second, zones of hypoxia cover portions of the Gulf floor during mid summer and early autumn along the inner continental shelf from the Mississippi delta to the upper Texas coast (Rabalais, 1994).

This hypoxic layer is less persistent in areas on the Louisiana continental shelf outside of the 100-foot contour. If hypoxic conditions do appear along the mid-shelf it is usually confined to the lower one-third of the water column. Estuarine influences can quickly change the water quality around the net-pens. Fresh water intrusion can be prevalent during spring and early summer months. Platforms close to the estuaries such as the Mississippi and the Atchafalaya may experience a temporal surface layer of turbid fresh water.

Concentrations of Platforms Scheduled for Abandonment

Platforms are generally removed once the cost to maintain operations exceed the revenues generated from production. Fields play out and not all wells are successful and sometimes platforms cease operations after a couple years of production. On the other hand, successful drilling can generate up to 30 years of profitable production. Older successful fields along the outer continental shelf can be found in South Timbalier (ST), Ship Shoal (SS), and Eugene Island (EI) off Louisiana. In 1993 MMS reported that there were 42 major platforms in waters greater than 100-foot depths in the ST region that were 25 years or older. As of October 1997, 24 of these platforms had been removed.

Logistic Considerations

Choosing a mariculture site should involve careful analysis of logistic considerations. Transportation of culture organisms, equipment, and feed will contribute a significant percent of operational expenses. Moving west of the Mississippi, the Texas-Louisiana continental shelf broadens and the gradient to the continental slope is much shallower. The travel distance required to reach adequate mariculture depths of 100 feet south of Fourchon, Louisiana is 13 miles and near the Texas-Louisiana border, south of Port Arthur, Texas the distance from shore to 100 feet of water is 70 miles. Along the Texas coast south of Freeport, the 100-foot contour does move in closer to shore and there are a significant number of platforms in that area (Exhibit 3-1). Although there are numerous production platforms on the continental shelf as stated earlier, the presence of suitable ports along the coasts of Texas and Louisiana are somewhat limited. Inshore base operations will require a facility with vessel access to transport fingerlings and supplies to the offshore farm and harvested products back onshore. Reduction of travel time between the offshore farm and base camp will reduce the risk of damage to the culture organisms. There will also be more opportunity to take "quick trips" to the farm site during suitable weather windows. All future offshore mariculture ventures will have their own individual characteristics, but easy access between the base facilities and farms should be considered in selecting a farm location.

Concerns of Platform Owners

A major concern of oil and gas companies is the successful transfer of liability from the oil and gas lessee. The mariculture company must demonstrate the capability to underwrite the long-term liability for the ultimate disposal of the platform. Should the operation fail and the mariculture company default on the decommissioning obligation, absent posting of sufficient security, liability for decommissioning the platform will probably fall back upon the previous owner (the oil and gas lessee). In addition, the mariculture operators must be responsible for personal injury and property damage which might occur during mariculture operations, maintenance of navigational aids, platform repairs and maintenance of the structural integrity of the structure, and proper platform decommissioning at the end of the project (which may include platform removal, necessitating proper site clearance). These liability concerns will be addressed in more detail in Chapter 4.

Chapter 4

Regulatory Environment

Permitability Assessment of Commercial Project

Summary

Currently, no federal legal structure exists to promote mariculture (i.e., no federal laws, agency, or programs specifically addressing mariculture), although affected federal and state agencies have created procedures which will enable a mariculture project to commence. The Department of Commerce has recently published a draft Aquaculture Policy (March 17, 1998) which, if adopted, could significantly promote the development of an offshore mariculture industry in the U.S. under existing statutes and regulations.

Two regulatory problems remain however for any project that pursues regulatory approvals. First, there is limited availability of property rights to protect the investment in the mariculture operator's project. Concerns arise regarding security of ownership of fish in cages and regarding the nature of the governmental authorization received by the mariculture operator. Second, in order to secure approval to possess species with minimum size or quota restrictions, an "exempted fishing permit" must be secured from the National Marine Fisheries Service. These permits are effective for a maximum of one year, but may be renewed upon re-application. Although this approach could at least enable the commencement of such projects, federal law should be implemented to exempt mariculture operations from these regulations in the future. All of these issues will be discussed in this chapter.

Projects Proposed for Gulf of Mexico to Date

A listing of the proposed mariculture operations in the Gulf of Mexico known to date are the following:

SeaFish Mariculture, L.L.C.: Received final approval for mariculture project from the Corps of Engineers, Galveston District on July 3, 1997.

SeaPride Industries: Received final approval from Corps of Engineers, Mobile District, for project in Mobile Bay, Alabama (November 3, 1993), but after approval National Marine Fisheries Service expressed objection that insufficient opportunity for comment had been provided. That permit expired November 3, 1996.

Watermark Corporation: Submitted an application to the Corps of Engineers, New Orleans District, in August of 1994, to establish a platform supported fishery in Grand Isle Blocks 75 and 76. The application was returned to the applicant January 12, 1995.

Marine Artificial Habitats, Inc.: Submitted an application to the Corps of Engineers, New Orleans District, in 1994, to establish a privately managed artificial reef and processing plant in South Timbalier 176. The application was denied, then withdrawn by the applicant.

Oxy-Texas A&M: This small-scale research project was conducted off the Texas coast, involving an Occidental Petroleum platform.

Permits Which Are or May Be Required for a Commercial Project

Corps of Engineers Permit

Permit Application: A permit from the applicable district of the U.S. Army Corps of Engineers (COE) is the primary certificate of approval necessary for establishing a structure for a mariculture project. Applications for these permits are open for review and comment through public notice and notices sent directly to state and federal agencies, as well as concerned private interests (at the discretion of the applicable COE district engineer). It can be expected that these other agencies will participate in the permit process through COE solicitation of evaluation and comment. In state territorial waters, state authorization precedes federal approval. The application form used to apply for a permit is Engineer Form 4345, "Application for a Department of the Army Permit." Copies of application materials can be obtained from the applicable Corps district office.

The application must include a series of drawings depicting the structure as it stands, one drawing of the structure's location and orientation within the permitted area including latitude and longitude and Louisiana Lambert coordinate readings (for structures off Louisiana's coast) for the four corners of the permitted area and fishing reef, and a plot of the location of the permitted units within the block, including all pipelines, structures and contour lines before and after placement of the structure.

In addition to the application and drawings, the COE will require the mariculture operator to provide an operational plan. A guide for preparation of this plan is provided by the New Orleans District Corps of Engineers letter of December 12, 1994, to the Watermark Corporation. Consideration should be given to (1) choosing a platform in a designated "rigs-to-reefs" (artificial reef) site, or (2) having the area around a chosen platform designated as a rigs-to-reefs area, or (3) moving a chosen platform to an area already designated by either Louisiana or Texas as an artificial reef site, as this might help in the permitting process. As an aside, in the Louisiana and Texas rigs-to-reefs donation programs, state agencies handle the COE application as well as the "nav aids" application (to the Coast Guard) below.

Agency Offices and Contacts: *U.S. Army Corps of Engineers:* New Orleans District: P.O. Box 60267, Foot of Prytania Street, New Orleans, Louisiana 70160-0267. Attn: LMNOD-S. Permits:

504-862-2255. Contacts: Barton Rogers (862-2663) and Mike Farabee (862-2292). Galveston District: P.O. Box 1229, Galveston, Texas 77553-1229. Permits: 409-766-3941. Mobile District: P.O. Box 2288, Mobile, Alabama 36628-0001, Attn: SAMOP-s. 334-690-3261 Contact: John McFadyen. Jacksonville District: P.O. Box 4970, Jacksonville, Florida 322302-0019, Attn: SAJRD. 904-791-1659.

Enabling Acts and Implementing Regulations: Section 10 of the Rivers and Harbors Act of 1899 (33 U.S.C. 401-687) prohibits the unauthorized construction in or over, obstruction or alteration of any navigable water of the United States. The legislative authority to prevent inappropriate obstruction to navigation was extended to installations and devices located on the seabed to the seaward limit of the Outer Continental Shelf (OCS) by Section 4(e) of the Outer Continental Shelf Lands Act (OCSLA), as amended (43 U.S.C. 1333 [f]). Although the Corps of Engineers is the agency granted authority over "artificial islands, installations, and other devices" on the OCS, pursuant to 43 USC 1333 (e), the COE cedes its authority over OCS oil and gas drilling and production installations to the MMS under the COE's nationwide permit system, 33 CFR Part 330, Appendix A, Sec.B.8).

Structures placed within the territorial seas of a state must also comply with Section 404 of the Federal Water Pollution Control Act (Clean Water Act) of 1972 (PL 92-500; 33 U.S.C. 1251 et seq). Regulations promulgated under Section 404 (33 U.S.C. 1344) require that a Corps permit be obtained before dredge or fill material is discharged into any of the navigable waters of the United States and stipulate state certification of discharge projects. The term "discharge of fill material" is defined at 33 CFR 323.2(1).

The COE is required to conduct a "public interest review" pursuant to 33 CFR 320.4(a)(1), which involves a balancing of all the reasonably expected benefits and detriments to the public interest, including environmental, economic, aesthetic, navigation, property rights, and international interests. The COE is responsible for publishing the public notice for artificial reef and mariculture projects and for providing final approval of such projects.

NMFS Exempted Fishing Permit

Permit Application: An "exempted fishing permit" (EFP) must be obtained from the National Marine Fisheries Service (NMFS) in order to avoid violating federal OCS fishing regulations. Depending upon the species being cultured, the operator may violate regulations by possessing fish that are less than minimum size, out of season, beyond regulated trip limits or fish that are altogether banned from possession in federal waters (such as redfish).
Cobia, snappers, groupers and amberjack have federally enforceable bag and size limits and tuna have minimum size limits in the Gulf of Mexico.

Agency Offices and Contacts: NMFS is under the National Oceanographic and Atmospheric Administration (NOAA) in the Department of Commerce. The Regional Director of the NMFS is Dr. Andrew J. Kemmerer at Southeast Region (9721 Executive Center Drive N., St. Petersburg, Florida 33702). He sits on the Gulf of Mexico Fishery Management Council (GMFMC), Lincoln Center, Suite 331, 5401 W. Kennedy Boulevard, Tampa, Florida 33609-2486, 813-228-2815.

Enabling Acts and Implementing Regulations: The Magnuson Fishery Conservation and Management Act of 1976 (MFCMA) (16 U.S.C. 1801-1882) also known as the FCMA, or the Magnuson Act, established a fisheries conservation zone for the United States and its possessions and delineates an area from the States' seaward boundary out 200 nautical miles. The Act created eight Regional Fishery Management Councils (FMC's) and mandated a continuing planning program for marine fisheries management by the Councils. The Act, as amended, requires that a Fishery Management Plan (FMP) based upon the best available scientific and economic data be prepared for each commercial species (or related group of species) of fish that are in need of conservation and management within each respective region.

Applicable regulations are found at 50 CFR Parts 600 et seq., "Fishery Conservation and Management, National Oceanic Atmospheric Administration, Department of Commerce." Separate parts address shrimp, red drum (redfish), coastal migratory pelagic and reef fisheries of the Gulf of Mexico. The Magnuson Act, and the regulations adopted pursuant to it, also establish the regional fishery management councils.

Additionally, the regulations expressly recognize that certain actions taken by NOAA pursuant to the Magnuson Act will trigger the requirement that NOAA prepare a draft Environmental Impact Statement (EIS), or environmental assessment (EA). The purpose of conducting the EA is to confirm a "finding of no significant impact" in order for a proposal to proceed in accordance with the National Environmental Policy Act of 1970 (NEPA), 42 USC 4321 et seq. NMFS prepared an environmental assessment for issuance of the exempted fishing permit for the SeaFish Mariculture project off the Texas coast.

The authority of NMFS to regulate the placement and/or operation of mariculture facilities (referred to therein as "aquaculture facilities located in the U.S. exclusive economic zone [EEZ]") was addressed in a February 7, 1993, memorandum to James W. Brennan, then NOAA's Acting General Counsel, from Jay S. Johnson, Deputy General Counsel, and Margaret F. Hayes, Assistant General Counsel for Fisheries. This memorandum was prompted by the question of whether NOAA had authority to regulate the mariculture proposal of American Norwegian Fish Farm, Inc. The memorandum concludes:

> Aquaculture facilities are subject to the Magnuson Fishery Conservation and Management Act because they engage in the "harvest" of fish from the EEZ. Barges and other vessels used to support such facilities are "fishing vessels" within the meaning of the Magnuson Act. U.S. vessels that support such facilities and that measure five net tons or larger must obtain Coast Guard documentation, including a "fishery endorsement." U. S. vessels are subject to additional regulations at the discretion of a Regional Fishery Management Council, subject to the approval of the Secretary of Commerce.
>
> The rationale for this position follows:
>
> *The Magnuson Act:* NOAA's principal regulatory authority is the Magnuson Fishery Conservation and Management Act, 16 U.S.C. 1801 et seq. The Act contains an exceptionally broad definition of the term "fishing" [16 U.S.C. 1802 (10)]

encompassing not only the catching of fish and "any other activity" expected to result in, or "other operations at sea in support of," the "catching, taking, or harvesting of fish." Use of the term "harvesting" is particularly significant since it adds an additional concept beyond "catching" or "taking" – harvesting connotes the gathering of a crop – which brings within the purview of the Act any aquaculture facility located in the EEZ.

The fact that Congress generally considers aquaculture to be equivalent to fishing is reinforced by the definition of "fisheries" in the Vessel Documentation Act [46 U.S.C. 1201 (a) (1)], which includes the terms "planting, cultivating, catching, taking, or harvesting fish . . . in the exclusive economic zone."

Additionally, regarding vessels:

46 U.S.C. 12108 (b) states that only a vessel holding a fisheries endorsement may be "employed in" the fisheries. Only such vessels may plant, cultivate, or harvest fish within the EEZ. Further, the Magnuson Act prohibits foreign fishing except by permit, 16 U.S.C. 1821 (a), defines foreign fishing as that done by a vessel "other than a vessel of the United States," 16 U.S.C. 1802 (12), and defines "vessel of the United States" so as to require Coast Guard documentation of vessels measuring five net tons or larger, 16 U.S.C. 1802 (31). In combination, these definitions require all large U.S. commercial fishing vessels to obtain U.S. documentation and a fisheries endorsement to avoid the application of the much more stringent provisions of the Magnuson Act that govern foreign fishing vessels.

NMFS regulations establish minimum size limits for certain species of finfish, require a vessel permit to fish for such species within the EEZ, and make it unlawful for anyone to possess any less-than-minimum-size specimens of the regulated species.

Additionally, to date, nine FMP's have been implemented by the GMFMC, including FMP's for reef fish in 1984 and for red drum in 1987. SeaFish Mariculture required authorization to harvest, possess, and sell red drum, greater amberjack and red snapper taken from the federal waters of the Gulf of Mexico. In addition, authorization was sought to possess or sell greater amberjack or red snapper below the minimum size limit, and to harvest or possess red snapper in excess of established trip limits and/or during a closed season. Some of these activities are prohibited by these FMP's. [See 50 CFR 622.4 (a) (v) and (ix); 622.32 (b) (2) (iii); 622.37 (d); 622.42 (a); 622.43 (a) (1); and 622.45 (b)].

In order to accommodate SeaFish Mariculture's plans, NMFS required of SeaFish Mariculture that it obtain an exempted fishing permit. This EFP is issued pursuant to 50 CFR 600.745, which provides that a NMFS Regional Director may authorize, for limited testing, public display, data collection, exploratory, health and safety, environmental cleanup, and/or hazard removal purposes, the target or incidental harvest of species managed under an FMP or fishery regulations that would otherwise be prohibited.

The regulation lists potential grounds for denial of an EFP, and also provides that, if granted, the EFP may contain terms and conditions consistent with the purpose of the exempted fishing.

Pursuant to this regulation, NMFS made a preliminary determination in that SeaFish Mariculture's application contained all of the required information and that it constituted an activity appropriate for further consideration. NMFS then published a notice of receipt of an application for an exempted fishing permit and a request for public comments (62 FR 37034, July 10, 1997).

Before issuing the EFP to SeaFish Mariculture, NMFS conducted an environmental assessment (including in the title of the EA that the EFP was for "A Feasibility Study of Net Cage Culture of Finfish Associated with Offshore Oil and Gas Platforms in the Northern Gulf of Mexico"). The EA was completed in September of 1997.

EPA NPDES Permit

Permit Application: At the same time as submittal of these above permits, application should be made to the Environmental Protection Agency for a permit for discharges to the waters of the Gulf pursuant to the National Pollutant Discharge Elimination System (NPDES). Until recently, marine aquaculture activities in the U.S. have been limited to state waters and therefore, all discharge permits and monitoring plans have been handled at the state level (Rieser 1996). In 1997, Seafish Mariculture initiated a feasibility pilot study of net-pen culture on an offshore oil and gas structure in federal waters. Since the Seafish Mariculture project intends to raise federally regulated species, it is necessary that the National Marine Fisheries Services (NMFS) issues an Exempted Fishing Permit (EFP) to allow for the harvest of regulated species in federal waters. During the 30 day public comment period for the federal (EFP), the U.S. Environmental Protection Agency (EPA) noted that the mariculture operations must apply for a discharge permit under the U.S.EPA NPDES discharge permit system.

Agency Offices and Contacts: *Environmental Protection Agency (EPA):* (For Texas and Louisiana) Region 6, 1445 Ross Avenue, Dallas, Texas 75203, Attention: Myron Knudson. 214-665-6444. (For Mississippi, Alabama and Florida) Region 4 ______________________

Enabling Acts and Implementing Regulations: The EPA, pursuant to Section 402 of the Clean Water Act (33 USC 1342), has established the National Pollutant Discharge Elimination System (NPDES) for the permitting of discharge of pollutants into U.S. navigable waters. An NPDES general permit exists for OCS oil and gas activities. Presumably, because no general permit exists yet for mariculture activities, the EPA will have to issue a special permit for such discharges. However, there is a specific reference to aquaculture activities in 33 USC 1328, and authority exists for the establishment of a general permit for such activities in 40 CFR 122.25.

Platform Abandonment Liability Bonding/Escrow Account with the MMS

Permit Application: The Minerals Management Service should be consulted early in any planned OCS mariculture activity. The MMS will require some type of security to assure proper decommissioning (or "plugging and abandonment") of the platform and associated wells , and site clearance upon the conclusion of the mariculture operation. The MMS will require, as a condition of approval of ownership transfer, that a security bond be posted or some type of escrow account be established to cover the cost of decommissioning and site clearance in the event of default of the mariculture enterprise. The agency requires this of its oil and gas operators in the Gulf of Mexico (see 30 CFR 256.58-62, especially the revisions issued May 22, 1997, at 62 FR 27948). Although the basic rule is that before a lessee installs a platform to begin producing a lease it must post at least a $500,000.00 individual lease bond, the MMS regularly exercises its authority to require "supplemental bonding" over and above that level to ensure proper abandonment and lease site clearance.

Although there is no mechanism in place for the MMS to enforce its regulations on a mariculture enterprise, an illustration of what the MMS would require of OCS oil and gas operators is provided by the lessee's and operator's bond form, a copy of which can be obtained from the MMS.

Agency Offices and Contacts: _Minerals Management Service (MMS), U.S. Department of the Interior:_ Gulf of Mexico OCS Region, 1202 Elmwood Park Boulevard, New Orleans, Louisiana 70123-2394, 504-736-2894 for platform removal approval (Arvind Shah), 504-736-2803 for platform abandonment liability security approval (Carrol Williams).

Enabling Acts and Implementing Regulations: Authority is pursuant to the Outer Continental Shelf Lands Act (OCSLA) of 1953, as amended in 1978 (43 U.S.C. 1331 et seq.) OCSLA established Federal jurisdiction over submerged lands on the OCS seaward of State boundaries (for Gulf coast states, 3 statutory miles from the coastline, except for Florida and Texas, which are 3 marine leagues [approximately 9 miles] from the coastline). Under the OCSLA, the Secretary of the Interior is responsible for the administration of hydrocarbon and mineral exploration and development of the OCS. Title 30 of the Code of Federal Regulations contains the implementing regulations for the agency pursuant to OCSLA.

Plugging and Abandonment Requirements: Oil and gas exploration and production operations on the OCS are conducted pursuant to oil and gas leases (and sulphur exploration and production operations on the OCS are conducted pursuant to sulphur leases) issued by the MMS. Leases in the water depths appropriate for mariculture are granted for primary terms of five years – it is highly unlikely a platform ready for decommissioning will be located on a lease within its primary term. According to 30 CFR 250.13, as to a lease beyond its primary term, no time lapse in production, drilling, or well-reworking operations of greater than 180 days shall continue the lease in effect unless production or other operations on the lease have been suspended in accordance with MMS approval. (Reasons for granting a suspension of production or other operations are provided in 30 CFR 250.10.) The MMS, in Section 22 of its standard lease, Form MMS-2005 (March 1986), provides that all structures shall be removed from a lease within one year after lease termination. Thus, as to leases beyond their primary term, all structures thereon must be removed within a year and a half from the date of cessation of production.

Per 30 CFR 250.112, all structures shall be removed down to a depth of 15 feet below the sea floor (i.e., 15 feet below the "mudline"). Per 30 CFR 250. 114, the lessee shall verify site clearance. Pursuant to this regulation, the MMS issued Notice to Lessees (NTL) 92-02 reiterating the requirement that all well and platform "locations" be cleared of all obstructions. The "location" is defined as a circle consisting of a radius of various lengths, based on the type of structure. For platforms, it is a 1,320-foot radius circle centered on the platform's geometric center (for single well caissons and well protectors, a 600-foot radius circle). For such structures located in water depths of greater than 300 feet, all that is required for site clearance verification is a sonar search of the location. For such structures located in water depths of less than 300 feet, 100% of the limits of the location must be trawled in two directions. This requirement potentially raises substantially the costs of removal operations. All objects caught in the trawl net must be brought to the surface for disposal. The states of Louisiana and Texas have adopted similar regulations for platforms in state waters.

The anticipated expense of site clearance may be reduced by donating the platform to either Louisiana's or Texas' "rigs-to-reefs" program (addressed in detail at the end of this section). The donor also donates one-half of anticipated savings to the appropriate state for maintenance of the site. Savings are realized from avoided expenses of hauling the platform to shore and disposing of the platform for scrap. Additional savings are realized where a platform qualifies for a donation in place. In such case, the site clearance expenses may be avoided.

Paragraph 5 of Article 5 of the 1958 Continental Shelf Convention, a treaty to which the United States is a party, states that any installations on the Continental shelf which are abandoned or disused must be entirely removed. The rationale behind removal is to allow for other uses of the OCS, such as shrimp trawling and commercial and recreational fishing. Additionally, left in place platforms might pose a hazard to navigation. All structures on expired leases have to date been either toppled in place (their location having been designated a rigs-to-reef site), toppled and towed to a rigs-to-reef site, salvaged for reuse at another location, toppled and towed to shore for salvaging and disposal, or(in one case) donated in place to a rigs-to-reef program.

Liability for Plugging and Abandonment Obligations: Formerly the MMS had stated the position that if it had unconditionally approved an assignment of a lease, the agency was required to look to the assignee solely for the all obligations under the lease, including platform abandonment. (This position was stated in letters dated June 6, 1988, from the MMS to Amoco Production Company, and November 6, 1989, from the Associate Director for Offshore Minerals Management to the Regional Director, Gulf of Mexico Region).

The MMS repudiated that position as "erroneous" and "mistaken" in the final rule on surety bond coverage issued August 27, 1993, at 58 FR 45255 (see, especially, p. 45257). The MMS later reiterated this position in NTL (Notice to Lessees) 93-2N, "Liability of Assignors, Assignees, and Co-lessees for Plugging of Wells and Removal of Property on Termination of an Outer Continental Shelf Oil and Gas Lease," issued October 6, 1993.

Revised MMS regulations took effect August 20, 1997, clarifying that an assignor of an OCS lease remains responsible for compliance with the lease abandonment obligations associated with structures set while the assignor was lessee. Additionally, the regulations clarify that co-lessees and operating rights owners are jointly and severally liable for compliance with the obligations imposed by MMS leases and regulations. The revised regulations, 30 CFR §§ 250.8, 250.110 and 256.62, were issued on May 22, 1997 (62 FR 27948).

State Agencies to be Consulted

Although these agencies will not issue a permit, they should be consulted at the time of the above discussions. They will have much input regarding the Corps of Engineers' permitting process.

For Louisiana: Louisiana Department of Wildlife and Fisheries, P.O. Box 98000, Baton Rouge, Louisiana 70898-9000. Artificial Reef Coordinator: Rick Kasprzak. 504-765-2375. For Texas: Texas Parks and Wildlife Department, 4200 Smith School Road, Austin, Texas 78744. Director, Coastal Fisheries Policy: Hal R. Osburn. 512-389-4862. Additional State agency for Louisiana: Coastal Management Division, Louisiana Department of Natural Resources, P.O. Box 44487, Baton Rouge, Louisiana 70804-4487. Administrator: Terry W. Howey. 504-342-7591.

The Coastal Zone Management Act (CZMA) (16 U.S.C. 1451 et seq.) was enacted by Congress in 1972 to improve the nation's management of coastal resources. Specific concerns were the loss of living marine resources and wildlife habitat, decreasing open space for public use, and shoreline erosion. Congress also recognized the need to resolve conflicts between various uses that were competing for coastal lands and waters (USDOC, NOAA, 1988a).

The basic goal of the CZMA is to encourage and assist coastal states to voluntarily develop comprehensive management programs. The CZMA established a State-Federal partnership in which the States take the lead in managing their coastal resources, while the Federal Government provides financial and technical assistance and agrees to act in a manner "consistent to the maximum extent practicable" with the federally-approved State management programs. The CZMA is administered by the Office of Ocean and Coastal Resource Management (OCRM), within NOAA's National Ocean Service.

The Coastal Zone Reauthorization Amendments of 1990 amended the Federal consistency provisions to address the Supreme Court's 1984 decision in Secretary of the Interior v. California. This clarified that all Federal agency activities, whether in or outside of the coastal zone, are subject to the consistency requirements of Section 307(c)(1) of the CZMA if such activity "affects" natural resources, land uses, or water uses in the coastal zone. 16 U.S.C. 1456(c)(1). In accordance with this provision, the Coastal Management Division exercises consultative authority, along with the Louisiana Department of Wildlife and Fisheries, over mariculture projects proposed for state and federal Gulf of Mexico waters off of the Louisiana coast. Similarly, the State of Texas exercises consultative authority over mariculture projects proposed for state and federal waters off the coast of Texas.

U.S. Coast Guard Nav Aids Permit

Permit Application: After the required COE permit is obtained, application must be made to the U.S. Coast Guard to establish private aids to navigation. The Coast Guard exercises regulatory authority over artificial structures in OCS waters to ensure that obstructions in U.S. waters are properly marked for the protection of maritime navigation. Offshore oil and gas platforms are classified as obstructions to navigation and must be marked in accordance with current U.S. Coast Guard Eighth District (for offshore Louisiana) "Guidelines for marking submerged artificial structures in the Gulf of Mexico." The following criteria are general guidelines; specific decisions regarding each reef site are made on a case-by-case basis. Application for a permit is accomplished by completing and submitting a "Private Aid to Navigation Application Form CG-2554" to the proper U.S. Coast Guard District Office.

Agency Offices and Contacts: For offshore Texas, Louisiana, Mississippi, Alabama and Florida (west of Appalachicola): U.S. Coast Guard Eighth District, 501 Magazine Street, New

Orleans, Louisiana 70130-3396, Attention: Aids to Navigation. 504-589-6234. For offshore Florida east of Appalachicola: U.S. Coast Guard Seventh District, Federal Building, 51 SW 1st Avenue, Miami, Florida 33130, Attention: Aids to Navigation. 305-350-5654.

Enabling Acts and Implementing Regulations: Authority is granted the Coast Guard under 43 U.S.C. 1333 (e), 14 U.S.C. 81-87, and 33 CFR, Parts 64-66). Under 43 U.S.C. 1333(e), the Secretary of Transportation has the authority to "promulgate and enforce such reasonable regulations" with respect to aids to navigation. Further, under 14 U.S.C. 81, the Coast Guard is given authority to establish and maintain a system aiding navigation for commerce and the armed forces. Under 14 U.S.C. 83-85, penalties are prescribed for establishing unauthorized aids to maritime navigation, for interference with aids to navigation, and for failure to comply with rules and regulations set forth in 33 CFR Parts 64 and 66. Under 43 U.S.C. 86, the owner of an obstruction is held liable to the United States for the cost of such marking "until such time as the obstruction is removed or its abandonment legally established or until such earlier time as the Secretary may determine."

Regulatory authority is delegated to the Coast Guard district commander (within the confines of his respective district) under 33 CFR 66.01-3. At the recommendation of the COE district engineer, the district commander will decide, on a case-by-case basis, if marking is required (33 CFR 64.30) and the type, number, and description of the required markings (Sec. 64.20-1).

Platform Removal Application and Site Clearance Report

If it is decided that, as part of the mariculture project, a platform will be removed from one site to be moved to another, a platform removal application will have to be filed with the MMS. After the platform has been removed, site clearance will have to be conducted and a site clearance report will have to be filed. Also, even in the event that a platform acquired for a mariculture project remains in place, at the end of the useful life of the platform, the platform will have to be removed. The applicable regulations have been summarized above.

Other Environmental Issues

Solid Waste: The Corps, before it issues a permit, the Coast Guard, and the EPA will demand proof that proper disposal of wastes is going to be accomplished, whether that waste is disposed of onshore or in OCS waters. Disposal of any solid waste or garbage anywhere in the marine environment is prohibited under the regulations of the MMS (30 CFR 250), the EPA (40 CFR 435) and The Coast Guard (33 CFR 151).

The Marine Plastic Pollution Act of 1987 directed the Coast Guard to implement Annex V of MARPOL 73/78 (the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978). The regulations adopted pursuant to this Act, codified in 33 CFR Part 151, regulate the disposal of solid wastes in OCS and state territorial waters, and require waste disposal plans and placement of placards summarizing solid waste disposal rules.

Oil Spills: The Coast Guard is also responsible for enforcement of Section 311 of the Clean Water Act, 33 U.S.C. 1321, as amended by the Oil Pollution Act of 1990, which governs oil spills. As with the above paragraph regarding solid waste disposal, no permit from the Coast Guard is required. However, in the event of a spill which creates a sheen, the Coast Guard will be the interested agency.

Air Emissions: The Clean Air Act Amendments of 1990 affirmed the authority of the MMS over air emissions from OCS oil and gas facilities off of Louisiana and Texas. However, EPA's Region 6 would, presumably, have authority over the air emissions from a mariculture operation. If the operation is placed within 100 km of the Breton Wilderness Area this could be problematic as the BWA is a Class I PSD Area (receiving EPA's highest level of protection under its "prevention of significant deterioration" of air quality program).

Other Potential Permits

Permit for Laying of Electrical Cables: Pursuant to 33 CFR Part 330, although the laying of electrical cables offshore is covered by a Nationwide Permit, if the mariculture operation included the laying of electrical cables, drawings must be submitted to the COE and approval secured before commencement of cable laying operations.

Major Potential Problem Areas and Recommendations for Fostering a Commercial Mariculture Industry in the Gulf of Mexico

The National Research Council (NRC) established a committee in 1992 under its Marine Board to assess the technology and opportunities for mariculture on U.S. territorial seas. This committee concluded that many of the problems that presently constrain mariculture could be resolved if "a reasonable and predictable regulatory framework" was developed. That such a framework does not yet exist even after Congress and the Executive Branch have twice (in 1980, with the "National Aquaculture Act" and 1985, with the "National Aquaculture Improvement Act") collaborated to pass sweeping legislation regarding aquaculture may not bode well for such an effort.

Additionally, Congress failed in 1995 and 1996 (in the 104th Congress) to pass Senate Bill S.1192, "The Marine Aquaculture Act of 1995", proposed on behalf of NOAA by Senators Kerry, Pell and Inouye. No attempt was made in 1997 (in the 105th Congress) to renew the effort. In a paper which provides an excellent overview of mariculture issues and critique of that bill, the author proposes, in lieu of a federally managed system, one in which oversight is delegated to the states (Rieser 1996). The author does not refer to the experiences of Texas and Louisiana regarding such a delegation of authority under a program with a related agenda, the National Fishing Enhancement Act of 1984, cited earlier. However, because the experiences of the affected state and federal agencies under the "rigs-to-reefs" program are relevant to this discussion, at the end of this section is a summary of federal and Louisiana law implementing this program.

It is not here recommended, however, that there be a renewal of an effort to provide an overall federal framework, nor is it recommended that there be a federal delegation to the states. There has been an offshore oil and gas industry for over fifty years in the Gulf of Mexico, and this has necessitated the cooperation of the same agencies involved in mariculture projects in the Northern Gulf of Mexico. Additionally, over the past ten years, the rigs-to-reefs program has brought the same federal and state agencies together in cooperation. Thus, as was stated at the beginning of this section, affected agencies are performing their respective functions regarding potential mariculture applications. Thus, concerns regarding enforcement of redundant regulations, poorly defined agency jurisdictions, and poorly defined standards that fail to reduce conflicts among competing users of federal waters, cited in the National Research Council's 1978 report (NRC 1978) are not problems which prompt a need for changes in federal law in order to foster a mariculture industry using oil and gas platforms in the Northern Gulf of Mexico.

However, there are several other potential problems that at least require clarification regarding federal law, and may require changes in federal law. Among these are inappropriate restrictions designed to protect wild fish stocks and limited availability of property rights or other interests that can secure a mariculture operator's investment (NRC 1978 and Rieser 1996). Additional concerns, unique to the use of oil and gas platforms in the Gulf of Mexico exist, as well. All of these concerns are addressed below:

Fisheries Management Issues

Standard 5 in NOAA's rules to the Regional Fisheries Management Councils regarding their Fisheries Management Plans (FMP's), found at 50 CFR Subpart B, Appendix A, provides:

> NOAA believes that an FMP should not restrict the use of productive and cost-effective techniques of harvesting, processing or marketing, unless such restriction is necessary to achieve the conservation or social objectives of the FMP.

The GMFMC has also issued the following "Mariculture Policy and Guidelines":

- The Council recommends that native species receive priority as candidate culture species. Exotics should be listed only after thorough investigation has demonstrated no detrimental impacts on native species. The Council opposes use of non-native species in mariculture systems unless demonstrated it has no detrimental impacts on native species.

- The Council recommends that mariculture activities are environmentally responsible and ensure that operations do not alter existing habitat with respect to habitat in that: existing shoreline, bottom and open-water habitats should be protected from physical alterations or degradation.

- The Council recommends that the ingress and egress of native wild organisms in natural and public waters should not be impeded by physical or water quality barriers; and navigation in natural and public waters should not be impeded.

- In regard to research and monitoring, the Council recommends that the mariculture industry demonstrate, in part, its stewardship of Gulf waters by: actively educating its member institutions about necessary regulation and permits; actively participating in cooperative research and monitoring to improve the understanding of mariculture's relationship to coastal and marine ecosystems; and participation in cooperative research to enhance knowledge of cultured species.

- The Council recommends that mariculture operations should be located, designed and operated to reduce, prevent, or eliminate adverse impact to estuaries and marine habitats and native fishery stocks. These impacts that cannot be fully mitigated in-kind. Conditions should be maintained to sustain healthy, diverse, native biological communities without the production of nuisance, toxic or oxygen demanding conditions. Standard operating procedures should contain methods to prevent escapement, accidental transport or release of cultured organisms.

- In regard to Water Quality, the Council recommends that mariculture facilities should be operated in such a manner that the impacts to the local environment by utilizing water conservation practices and discharging effluent that protect existing designated use of receiving water. Mariculture facilities are responsible for developing, implementing, and monitoring best management practices to conserve water and improve effluent water quality.

- The mariculture activities should have procedures established that: prevent the importation or spread of pathogens or parasites; minimize impacts of disease outbreaks if they occur; and eliminate disease problems wherever possible.

NOAA and the GMFMC, acting in accordance with these policies, approved the EFP application of SeaFish Mariculture. It is expected that other technically sound proposals will be approved. While such policy endorsements are welcome, for mariculture to exist in the OCS there must be a legal provision that specifies private ownership of fish within the cage or netpen. Without such a provision, there is little incentive for private industry to invest under such financially risky circumstances (Kacergis, 1996). Also, the restrictions on species, circumvented in the short term by EFP's, must be addressed in order to foster the long-term future of the industry.

Security of Ownership of Fish in the Cages: Again, the Magnuson Act does not address mariculture or aquaculture in its text. It does state, however, "the United States claims . . . sovereign rights and exclusive management authority over all fish, and all Continental Shelf fishery resources, within the exclusive economic zone." Thus, as to fish in a mariculture cage, management authority rests with the federal government. Arguably, too, even though such fish may have been raised onshore and, if onshore, would be deemed to be owned by the mariculture operator, offshore they are owned by the federal government (Kacergis 1996). Appropriate language appears to exist with respect to mariculture projects in Canadian waters as the Canadian Aquaculture Act states in section 16 (5):

> All aquacultural produce of the species and strains specified in the aquaculture license, while constrained within the boundaries of the aquaculture site, are the exclusive personal property of the licensee until sold, transferred, or otherwise disposed of by the licensee.

Security of Tenure: A concern related to security of ownership of the fish in the cages is security of the interest the mariculture operator receives from the government (Rieser, 1996). Currently there are no provisions for the granting of a license or permit to conduct a mariculture enterprise, nor are there, alternatively, provisions for the granting of a lease to operate in a specified area of federal waters. Also lacking are criminal sanctions and a civil right of action against individuals who violate the mariculture operator's rights as lessee of the seabed and water column or as licensee (Rieser 1996).

The Marine Aquaculture Act of 1995, cited previously, proposed to set up a system in which the Secretary of Commerce would issue permits authorizing the ownership, construction, or operation of a mariculture facility. The facility could be privately owned, but the area of the ocean where operations were conducted would remain in public ownership. The permit would be for ten years and be renewable, as well as revocable, for causes listed. Upon revocation, surrender, or expiration of the permit, the facility would have to be properly disposed of or removed as directed by the Secretary.

An example of the alternative approach to granting a license or a permit, that of granting a lease, is the mechanism used in the Outer Continental Shelf Lands Act, cited above. Such a lease conveys the right to private companies to explore for and develop oil and gas or sulphur resources found under a defined area of the seabed. The State of Maine also uses the lease for aquaculture in state waters (Rieser, 1996).

While there are advantages and disadvantages to each approach, the most important shared disadvantage is that, again, to implement a system to provide for administration of permits, licenses or leases would require a major piece of federal legislation. While in the future such a need may arise, it does not exist now, when there are no commercial scale operating mariculture facilities in the Gulf of Mexico.

Restricted Species: NMFS can use the EFP as a mechanism for circumventing its species-specific restrictions, however, the EFP is limited in the purposes for which it may be issued. NMFS issued SeaFish Mariculture an EFP for research purposes, and, presumably, a few more EFP's may be issued for this purpose. However, at some future point in time feasibility of mariculture projects will have been established, and NMFS will probably no longer be able to issue EFP's for such purpose.

Having established that the Magnuson Act covers mariculture, it must next be determined what is the best mechanism for exempting mariculture from species-specific restrictions. One option is to amend the Magnuson Act itself. A second option is for NMFS to exercise its authority, under the Magnuson Act as it exists now, to exempt mariculture. A final option is for the GMFMC to amend FMP's for affected species in order to allow mariculture.

An additional problem exists, however, in the event that it is determined that the GMFMC has such authority. It must be determined whether this authority is, itself, sufficient enough to foster a mariculture industry, given the diversity of interests involved. For this reason, amendment to the Magnuson Act, or authorization from NMFS, would be preferable. It is recommended here that, as in the case of regulation of the proposal of American Norwegian Fish Farm, Inc., a memorandum opinion be requested on this subject from NOAA's Office of the General Counsel. In the event that it is determined NMFS lacks the requisite authority to provide the necessary exemptions for mariculture, then the option of changing federal law may be pursued. However, it should be argued that the intent of the Magnuson Act is to avoid the "tragedy of the commons," which can, and has, resulted in overfishing. Such concern does not apply to fish raised from hatchlings onshore, then moved offshore for growing.

Structures Issues

Platform Abandonment Liability: If an oil and gas platform is to be acquired from an OCS (federal waters) lease operator, that operator and its partners (if any) must be satisfied that the platform will be properly disposed of and the site (assuming the platform is not moved) will be properly cleared of obstructions at the end of the project's life.

However, as discussed above, both the MMS, the agency in charge of regulating OCS oil and gas development, and the Corps of Engineers, the agency in charge of permitting structures for placement in U.S. navigable waters, will need such assurances, too.

The level of concern on the part of the MMS here can hardly be overstated. The agency fully recognizes the dearth of support for the offshore oil and gas industry outside of Louisiana and Texas. Also, there is currently no legislative mechanism in place to allow the MMS to take over a platform and conduct abandonment in the event of default of a bankrupt operator.

Authorization to Leave the Structure on the OCS After MMS Removal Deadline: Another potential problem area is whether the MMS has the legal authority to grant a mariculture enterprise the right to use an oil and gas platform on the OCS for a purpose other than oil and gas operations after the regulatory deadline for removal of the structure. OCSLA's provisions regarding the authority of the Secretary of the Interior, 43 USC 1334, specifically address the granting of oil and gas leases, the oversight of oil and gas operations, and the granting of pipeline rights-of-way.

The MMS has a mechanism for allowing a party to operate a platform on a former lease site after the lease has expired, the "right of use and easement," provided for under 30 CFR 250.7. However, this regulation is issued pursuant to 43 USC 1334 (a), which provides:

> "The regulations prescribed by the Secretary under this subsection shall include, but not be limited to, provisions . . . (6) for drilling or easements necessary for exploration, development, and production . . ." It is not clear that, under OCSLA, the MMS has the authority to grant a right of use and easement for purposes other than oil and gas exploration and production. The regulation itself limits issuance of rights of use and easement to installations "used for conducting exploration, development, and production activities or other operations on or off the lease which are related to such activities."

However, it is not clear that there needs to be a grant of authority to the MMS to allow a structure to remain on the site after expiration of the MMS's regulatory deadline for removal. Again, as stated above, the Corps of Engineers is the lead agency for granting approvals for the installation of devices located on the seabed of the OCS. Although the Corps' authorization of SeaFish Mariculture's project in the Brazos area was limited to the nets which were to be hung from a producing oil and gas platform (thus, the platform itself was authorized by MMS regulation), the Corps granted approval for a structure similar in size to an oil and gas platform to be placed in the OCS waters off of Alabama (in the permit application of SeaPride).

Additionally, the Corps grants permits to the states of Louisiana and Texas for placement of artificial reefs in OCS waters (see the discussion regarding the "rigs-to-reefs" program below). Initially, such artificial reefs were entirely submerged. Recently, however, an "in-place" donation of a platform (the "Grand Isle" complex at Grand Isle Block 16) was authorized by the Corps (permit application was filed by the state of Louisiana on behalf of the operator, Freeport-McMoRan Resource Partners).

An Aside—The "Rigs-to-Reefs" or Artificial Reef Program

The National Fishing Enhancement Act of 1984, Title II of Public Law 98-623, also known as the Artificial Reef Act, established broad artificial reef development standards and a national policy to encourage the development of artificial reefs that will enhance fishery resources and commercial and recreational fishing. The Secretary of Commerce developed a National Artificial Reef Plan that identifies design, construction, siting and maintenance criteria for artificial reefs and that provides a synopsis of existing information and future research needs. The Secretary of the Army (through the Corps of Engineers) issues permits to responsible applicants for reef development projects in accordance with the National Plan, as well as regional, state, and local criteria and plans (administered in waters off Louisiana and Texas by the above agencies). The law also limits the liability of reef developers complying with permit requirements and amends the Reefs for Marine Life Conservation Law to include the availability of all surplus Federal ships for consideration as reef development materials.

Although the Act mentions no specific materials other than ships for use in reef development projects, the Secretary of the Interior cooperated with the Secretary of Commerce in developing the National Plan, which identifies oil and gas structures as acceptable materials of opportunity for artificial reef development. The MMS adopted a "Rigs-to-Reef" policy in 1985 (Reggio,1987) in response to this Act and to broaden interest in the use of oil and gas platforms as artificial reefs. The first step in providing authority for a Louisiana program was to enact enabling legislation. The Louisiana Fishing Enhancement Act (Act 100-1986), signed into law on June 25, 1986, provides for the following:

1. Establishment and administration of the Louisiana Artificial Reef Development Program.

2. Creation of the Louisiana Artificial Reef Council, consisting of the:

    - Secretary, Louisiana Department of Wildlife and Fisheries (Chairman)
    - Dean, Center for Wetland Resources, Louisiana State University
    - Director, Louisiana Geological Survey

3. The roles of the Louisiana Department of Wildlife and Fisheries, the Center for Wetland Resources, the Louisiana Geological Survey, the Louisiana Sea Grant College Program, and the Louisiana Artificial Reef Initiative.

4. Establishment of the Artificial Reef Development Fund to provide monies for program development, operation, and research.

5. Development of the Louisiana Artificial Reef Development Plan and its legislative approval.

6. Establishment of the state of Louisiana as the permittee for artificial reefs developed under the plan and appointment of the Louisiana Department of Wildlife and Fisheries as agent for the state.

7. Relief of the state, donors, and other participants in the program from liability, provided the terms and conditions of the federal artificial reef permits are met.

The Louisiana Artificial Reef Plan contains the rationale and procedures for the implementation and maintenance of the state artificial reef program. The plan is intended to serve as a flexible working document that will be periodically updated through the Council on the basis of the results of operation. However, neither the Plan nor the Act specifically addresses mariculture projects.

Act of Donation. Pursuant to the National Fishing Enhancement Act of 1984 (the Artificial Reef Act) and the Louisiana Fishing Enhancement Act of 1986 (Louisiana Artificial Reef Act) for Louisiana, and the Artificial Reef Act of 1989 for Texas, a donor of an oil and gas platform to a rigs-to-reefs program can secure a release from potential future liability. The donor accomplishes this by signing an Act of Donation with the appropriate state, paying one-half of its savings (versus hauling to shore for salvage) to the state, then depositing the structure in the proper site.

Chapter 5

Economic Analyses

Introduction

The economic feasibility of establishing an offshore finfish mariculture venture is dependent upon a number of factors including:

Costs

- Start-up, Capital, Operation and Maintenance
- Financing, Engineering, Regulatory
- Base Facilities (support services)
- Offshore Facilities
- Acquisition of Fingerlings (private hatchery or commercial source)
- Personnel
- Platform and Platform Maintenance
- Feed (food conversion ratios)
- Extent of mortalities and when they occur in grow-out cycle
- Insurance

Revenues

- Species Raised (numbers, size, fillet yields)
- Market Value
- Ability to Deliver on Market Timing
- Quality of Product
- Sale to First Wholesaler or Company Processing

Obviously, all of the above cost and revenue figures are highly dependent upon the specific offshore operation proposed. The feasibility study team has attempted to provide estimates of costs where appropriate. Costs are presented for the "base case" scenario as described earlier. Some information is also provided on the revenue side including information on market demand for finfish, fillet yields for different candidate species and finally an analysis of the costs associated with setting up an offshore processing operation. More detailed revenue side numbers would have to be calculated by individual operators with specific knowledge of their proposed operation (species, numbers, etc.).

Following are sections on cost projections, forecast market demand for finfish, analyses of food conversion ratios, fillet yields for various candidate species and an assessment of the costs involved in setting up an offshore fish processing operation.

Cost Projections—Capital, Operations & Maintenance

The start-up, capital, and operation and maintenance costs associated with an offshore finfish mariculture operation are obviously dependent upon the size and complexity of proposed operations. The costs presented in this report were derived based upon the assumption that the "base case" mariculture operation would be implemented. This "base case" is a commercial-scale operation using platforms in water depths between 100 and 200 feet. It also assumes that a new base camp installation will be built and operated as well as a hatchery operation capable of supplying the necessary number of fingerlings to the farming operation offshore. Should a developing finfish mariculture operation elect to purchase fingerlings from either existing or future hatcheries, then considerable monies could be saved in the start-up and capital costs. Regardless of source of fingerling supply, an internal hatchery or purchase of fingerlings from commercial hatcheries, this could very easily be the most significant factor which limits the initial size and scale-up of an offshore mariculture industry.

The start-up, capital and operation and maintenance costs presented in this chapter were derived based upon the following assumptions:

1. Offshore Platform – This platform will be in 100 to 200 feet of water and will, in all likelihood, be an aging platform with significant costs necessary for refurbishing the platform to make it suitable for use as the base of an offshore farming operation. A crane to lift loads up to 15 tons onto the platform deck will be necessary. The platform will also require the installation of small crews' quarters and office space. Significant container storage of pelletized feed will be necessary on the platform. Feed distribution to the individual nets surrounding the platform will be computerized and via a pneumatic system.

2. Cages and Nets – The cages will be floating-type and will be of a size suitable for grow-out of up to 500,000 fish to harvest size (approximately 1 kilogram). The cages will be held in place by a tension buoy system with the tension buoys moored to the bottom. Bird and predator nets will be installed on each cage. A more complete description of these installations can be found in Chapter 1.

3. Base Camp – The base camp will contain office space and, depending upon location, quarters for the staff necessary to run the onshore operations. It will be located on navigable water so that a large vessel (70-120 feet) can tie to the docking facilities and be loaded and unloaded. There will be several vehicles required at the base camp, including at least one vehicle with tankage capable of transporting fingerlings short haul distances.

4. Hatchery – The hatchery will include a relatively large climate-controlled building for holding the finfish broodstock and the larvae prior to being moved into grow-out ponds

at the hatchery. Larvae feed production systems will be installed in this climate-controlled building. Intermediate grow-out tanks will be placed within a roofed enclosure. A water distribution system with temperature control will service these intermediate grow-out tanks. The fingerlings will be raised to a 3- to 6-inch size in aerated earthen ponds. A water flow-through system will be installed on these ponds with capacity for treatment of flow-through water prior to discharge.

The estimate for the start-up and capital costs associated with this mariculture operation is presented in Table 5-1. The total estimated start-up and capital cost for this type of installation is $7.5 million. This price includes two cages in-place for the first year of operation. Additional capital monies will have to be spent in subsequent years to allow for expansion.

Table 5-1
Start-up and Capital Costs

Item	Unit Cost ($1000)	Cost ($1000)
Start-up Costs		
Land (Base Camp) – 2 acres	40/acre	80
Land (Hatchery) – 30 acres	25/acre	750
Permitting		100
Platform Abandonment Escrow		500
Engineering and Legal Fees		300
Other Consultants		100
Financing Costs	2%	200
Capital Costs		
Base Camp		
Buildings (Trailers)		100
Maintenance Shop		150
Loading Dock with Crane		500
Fuel Storage and Loadout Facilities		100
Trucks/Service Vehicles		100
Fish Transport Vehicle		100
Camp Equipment		100
Hatchery		
Buildings		360
Juvenile Feed Production		50
Tanks		80
Ponds (14 @ 50' x 100'), aerated		280
Water Treatment and Distribution		200
Laboratory		100
Offshore Farm		
Cages and Moorings (2)	185/net	370
Power Generation and Tankage		100
Feed Storage and Distribution		175
Vessels (100'+, small outboard)		1,035
Crane		200
Buildings		80
Platform Refurbishment		500
		Subtotal = 6,760
		Contingencies (10%) = 676
		Total Estimated Start-up and Capital Costs = $7.5 million

Note: Costs above reflect purchase of land and vessel, both major expense items.
Initial costs could be reduced by leasing/renting the land/vessel.

The operation and maintenance costs associated with such an operation, including personnel, other operating costs, as well as maintaining equipment and the offshore platform itself is also estimated. It is envisioned that the crews for the offshore firm will work on a weekly shift basis similar to offshore oil and gas production facilities. Each three-person crew will work seven consecutive 12-hour days and then be replaced by another crew for the next seven-day period. The onshore base camp and hatchery staff will work normal 8-hour shifts except for night watchmen and maintenance staff on call.

Other operation and maintenance costs include maintenance on the platform, i.e., routine painting, welding, maintenance of protective anode systems, etc. The anticipated operation and maintenance costs associated with the base case mariculture operation are shown in Table 5-2. These annual costs will be in the $2.2 million range for this scale of operation.

Table 5-2
Annual Operating Costs

Item	Costs ($1000)
Personnel	
Manager	110
Supervisor	70
Farm Crew (3)	150
Vessel Crew (4)	220
Base Camp and Hatchery Staff (9)	430
Operating Costs	
Farm Insurance (4% of revenue)	
Other Insurance	75
Fuel	100
Equipment Maintenance	250
Platform Maintenance	200
Operations	300
Other	75
Subtotal =	1,980
Contingencies (10%) =	198
Total Estimated Operating and Maintenance Costs = $2.2 million	

Note: Personnel costs are shown as burdened in table.

FOOD CONVERSION RATIOS

It has been reported that feed costs can be as high as 30% of total operational expenses for an aquaculture operation (NCR 1992). The majority of the feed costs occur after the cultured species reach the juvenile stage on to the point of harvest. Efficient food conversion of feed into fish flesh is measured frequently to control this important expense. Food conversion ratios (FCR) is a method commonly used to measure the amount of feed that results in fish growth. This section focuses on the factors that influence food conversion ratios and compares results of various FCR studies for warm water finfish deemed to be potentially suitable for offshore mariculture in the Gulf of Mexico.

Food conversion ratios can be calculated by comparing weight of feed to growth of fish. FCR is the weight of feed offered divided by the weight gain of the fish. For example, a 1.0 kg fish fed 1 kg of feed and grows to 1.5 kg, the FCR is 2 (1 kg feed/0.5 kg weight gain=2). The lower the number of the FCR the more efficient the cultured species is in converting a particular feed to flesh. FCR is influenced by food type and distribution, physical, chemical, and biological factors, and the type, size and general condition of the cultured species, and percent mortality experienced in grow-out phases.

Feed Characteristics and Food Conversion Ratios

One of the goals of aquaculture is to produce a crop as rapidly as possible. Thus it is necessary to accelerate growth through dietary manipulation to optimize the FCR. Research is required to determine the nutritional requirements of any aquaculture species and a supply of adequate feed should be available in sufficient quantities to optimize the FCR. There are several types of potential feed which can be used: trash fish; minced fish; and pelletized feeds, either moist, semi-extruded or dry. Using fresh and frozen fish as feed would have FCRs in the range of 7 to 8, moist feeds in the range of 5 to 6, semi-extruded in the range of 4 to 5, and dry in the range of 1 to 2.5. Prepared moist feed can consist of minced fish, crustaceans, or various agriculture products. The FCRs for the moist feeds are higher due to water content.

Dry prepared diets can reach conversion ratios of 1 for some species. The feeds consist of various amounts of protein, carbohydrates, and lipids and are often supplemented with vitamins, fatty acids, and minerals. The size and shape of feed can affect the conversion rate. Food conversions improve when a suitable form of feed correlates with the age and size of culture organism and is easily digestible. The food portion should also be stable in water and remain intact while fish are feeding. If the food item falls apart before fish consume the pellet, the dissipation of food will obviously reduce the food conversion efficiency.

FCRs are affected by time of feeding, quantities of feed, presentation of feed, spatial distribution of feed, and number of feedings a day. Sedentary fish can grow rapidly at low feeding rates, whereas a highly active fish may require higher rates of feeding (Wedemeyer 1996). In order to optimize food conversion ratios, fish should be fed to satiation two to five times daily. Daily rations of feed offered to penned finfish should be determined independently for each species and can range from 1% to 25% of the cultured organism's body weight. FCRs become lower as the efficiency of feed utilization increases. Individual farm operators should experiment with various feeding strategies in order to minimize the FCR for that species.

Open ocean aquaculture operations can be subjected to fast currents where the feed may be swept away by the current before the culture organisms have an opportunity to consume the feed. An efficient feed distribution system should disperse food items to allow: (1) an even distribution to all organisms and (2) as close as possible to 100% consumption of the feed distributed. Food distribution efficiency should be frequently monitored to achieve low FCRs. Other mariculture operators around the world have successfully minimized food wastage by employing the video/sonar systems described in Chapter 1.

Bio-energetics of Food Conversion Ratios

Metabolism is the result of all the chemical and energy transformations that occur within a living organism. Metabolism includes the storage of energy (anabolism) as fat, protein, and carbohydrate, and the transformation of these storage products into free energy (catabolism). The amount of energy expended for maintenance is typically about twice that devoted to growth, and can be affected by the species of fish, its age, the environmental conditions, dietary composition, reproductive state, and other factors (Lovell 1989). Since metabolic rate of most fishes is highly temperature-dependent, food conversion ratios can be expected to vary both seasonally and diurnally as fluctuations occur in water temperature of their environment (Wedemeyer 1989). Smaller animals generally have higher weight-specific metabolic rates than larger ones, although total metabolic costs of smaller/younger fish are less thus the weight-specific growth rates of smaller fish is greater than that of older individuals. As the total metabolic costs to support existing biomass climbs, individual growth rates and thus food conversion efficiencies generally decline. These principals are important building blocks for the efficient production of cultured fish.

Food Conversion Rates for Candidate Species

The project team has compiled available data on FCRs for the candidate species (Table 5-3). Considerable caution should be observed when reviewing these food conversion data because of the array of different standards used in reporting FCRs. These FCRs we report were largely composed of investigations and controlled studies by governments or educational or nonprofit technological institutions rather than from commercial operations. A few FCR rates from private commercial ventures are presented in this report and are marked with an asterisk. The FCRs from commercial operations are from Asia and tend to be rather high because the culture organisms were fed trash fish and the FCRs are not based on a dry weight. The FCRs are reported on a dry weight basis whenever the results are available in dry weight, however, if the word "wet" is next to the FCR, it signifies that the FCR is on a wet weight basis. Also, for a given species FCRs are always better for juvenile fish than adults under ideal conditions, so under the section called "duration of study" when the time period begins with the word day – "day 30-60" – this indicates the age of the fish in days. Otherwise, the length of the study period is provided and the age of the fish was not available. Young fish tend to have lower FCRs between one and two, and adult fish tend to have higher FCRs between one and one-half and three. Whenever possible, FCRs of closely related species are presented to evaluate potential growth ratios for candidate species that lack FCR studies and reports. For example, Taiwanese red snapper (*Lutjanus argentimaculatus*) is provided as a surrogate species for evaluation of Gulf of Mexico red snapper (*Lutjanus campechanus*).

Absent in food conversion ratio literature from the United States are data on the greater amberjack (*Seriola dumerili*), cobia (*Rachycentron canadum*), southern flounder (*Paralichthys lethostigma*) and the snapper (*Lutjanidae*) family. These species have not been raised successfully for commercial application in U.S. coastal waters, although there is significant aquaculture production of greater amberjack in Japan (FAO 1990) and encouraging results of snapper (*Lutjanus argentimaculatus*) in Australia (Chaitanawisuti 1994). Some preliminary studies of captive cobia (Caylor 1994) are currently underway in the Gulf of Mexico and cobia are being successfully raised in Taiwan (Liao 1995). The FCRs presented are the result of a conglomerate of studies that

Table 5-3
FOOD CONVERSION RATIOS FOR CANDIDATE SPECIES

Author & Year of Pub.	Species of Fish	FCR wet/dry wt.	Temp. C	Dry, semi-moist, or moist	Duration of study	tanks, nets, or cages	Feed content or description of experiment
Liao 1995*	Pompano	1.6,2	17-28 C	dry pellet	duration of growout	ponds	emphasize various size pellets
Colura 1989	Red drum	1.5,4.8	>9C	dry		ponds	trout/catfish feed
Boren 1995	Red drum	1,8,3.3	27C	dry	day 30-86	tanks	theronine
Craig 1997	Red drum	1.13,1.42		dry	day 30-72	tanks	lecithin&choline
Reigh 1992	Red drum	1.94					
Jirsa 1997	Red drum	1.24,2.62	25-28C	moistt & dry	70 days	tanks	4 diets grain & meat
Sandifer 1993	Red drum	2.15,2.60	8.0-31.8C	dry	547 days	ponds	trout pellets
Trimble 1979	Red drum	1.1					
Miget 1995*	Red drum	3.8	15-30C	dry	day 60-365	offshore nets	
Ellis 1996	Grouper	0.94,5.90	28-32C	dry	56 days	tanks	4 experimental diets of energy to protein ratio
Chen 1994	Grouper	.94,1.38	27C	moist	50 days	tanks	semi-purified diets of various protein levels
Shier 1996	Grouper	1.1,1.6	28	dry	56 days	tanks	experimental diets of various protein levels
Kayano 1993	Grouper	1.28,.91	22-28 C	dry	day 90-130	net-pens	feeding frequency of 51% protein diet
Liao 1995*	Grouper	0.8 dry, 3.6 wet	20-30 C	fresh fish	duration of growout	ponds	
Li 1995*	Grouper	7.64 wet	15-30C	fresh fish	duration of growout	net-pens	trash fish is most commonly used
Chou 1995*	Mangrove snapper	4.0-5.0 wet	17-32C	fresh fish	duration of growout	net-pens	trash fish is most commonly used
Liao 1995*	Snapper	2.2,2.5	17-28 C	moist pellet	duration of growout	ponds	chopped trash fish is fed to snapper in nursery
Liao 1995*	Snapper	7,9 wet	17-28 C	trash fish	duration of growout	ponds	chopped trash fish is fed to snapper in nursery

Table 5-3

FOOD CONVERSION RATIOS FOR CANDIDATE SPECIES

Author & Year of Pub.	Species of Fish	FCR wet/dry wt.	Temp. C	Dry, semi-moist, or moist	Duration of study	tanks, nets, or cages	Feed content or description of experiment
Ostrowski 1992	Mahimahi	1.1, 1.2	25-28C	moist &dry	day 60-164	tanks	herring/fishsoybean
Ostrowski 1992	Mahimahi	0.6,0.9	25-27C	semi moist	day 42-56	tanks	fishmeal
Benetti 1994	Mahimahi	1.6	25-27C	semi moist	1yr.,9.5 mn.	tanks	squid/fish
Oceanic Institute 1993	Mahimahi	1.5	25-28C	dry	day 45-180	tanks	60% protein
Kraul 1993	Mahimahi	1.6					
Hagood 1981	Mahimahi	3.3 wet					
Szyper 1990	Mahimahi	1.8,3.3	26C	semi-moist	juvenile	tanks	squid/menhaden
Garcia 1993	Amberjack		13-26C	moist	day 40-150	tanks	frozfish/(m)pellet
Cavalier 1989	Amberjack	3			110 days	tanks	
Greco 1993	Amberjack	4,5-wet	14-22C	moist	300 days	tanks	fish&chicken liver
Nakada 1987	Yellowtail	8,3.4	11-26C	moist pellet	2 yrs.	net-pens	frozenfish/moist pellet
Shimeno 1993	Yellowtail	1.4,2.18	not translated	dry & moist	90 days		4 diets grain & meat
Shimeno 1992	Yellowtail	1.2,1.3	24.2-29.0 C	extruded pellet	60 days		soybean
Shimeno 1993	Yellowtail	2.0,2.15	18.4-29.0 C	dry	120 days	cages	soybean
Aoki 1995*	Yellowtail	1.0,2.5	17-19C	Pellet and fresh fish	18 mn.	net-pens	formulated diets
Viyakarn 1992	Yellowtail	2.18,3.13	20.6 -26.1 C	soft-dry pellet	70 days	cages	soybean
Viyakarn 1992	Yellowtail	1.0,1.3	24.2-25.1 C	soft-dry pellet	35 days	tanks	soybean
Watanabe 1995	Pompano	2.7, 5.91	17-34 C	dry, moist, fresh	duration of growout	cages	soybean,trash fish, and prepared meals
Williams 1985	Pompano	1.86, 2.04	28C	dry	48 days	tanks	soybean diets
Tatum 1972	Pompano	3.47	15-28C	moist	113 days	cages	menhaden/soy oil and trout chow
Finucane 1972	Pompano	1.0,2.0	15-28c	dry	1yr.,9.5 mn.	cages/ponds	trout chow
Swingle 1972	Pompano	5.4	>15	dry	90 days	cages	trout chow

might not represent the conditions of a commercial operation very well. Because so many variables can affect FCRs of cultured finfish, any attempt at commercial culture should establish conversion ratios under their culture conditions.

Revenue Potential

As stated previously, the project team did not attempt to fully analyze the revenue side of a prospective mariculture operation as that would be so highly dependent upon the types and numbers of fish raised, size at harvest, market conditions at harvest, etc. We did assess several factors which will be useful to potential operators in deriving their own revenue projections including an assessment of the potential U.S. market for finfish products and an analysis of fillet yields for some of the candidate species.

Projected Demand

A detailed analyses of the possible future U.S. consumption of finfish was performed and is attached in its entirety in Appendix B. This analysis went into a number of different issues including past history of finfish landings, past history of prices paid for some of the candidate species, competing recreational harvest of certain species, assessment of the present level of fish processing capacity in the Gulf of Mexico area, and an analysis of consumption and projected U.S. consumption scenarios. The reader is advised to study the full report presented in Appendix B.

The analysis presents a forecast of U.S. consumption based upon two scenarios: (1) a worst case scenario whereby future consumption estimates are tied to a relatively low level of per capita consumption with increases due to expected population growth alone, and (2) a best case scenario whereby future consumption estimates are based upon a higher growth rate reflective of increased consumption due to increased availability of finfish products reflective of the middle 1980s when consumption was increasing at an annualized rate of 4.4 percent. Using these two scenarios, one can predict an increase in seafood consumption in the U.S. over the next 10 years of 340 million pounds edible weight (one billion pounds live weight) and 2,774 million pounds edible weight (8 billion pounds live weight) for the worst and best case respectively. Based on these numbers, there is obviously a real and large potential market for farm raised products in the U.S. alone.

Fillet Yields

Another factor which will influence the revenue side of a mariculture operation is the percent of edible meat obtained from a cultured species. Since it is the fillet portion of the fish that is often the only part of a fish eaten by the U.S. consumer, fillet yields inform the fish buyers of the percent of the fish that is edible. Defining the percent of fillet yields indicates the value of the whole fish. To determine the cost of a fillet, the price of a whole fish can be divided by the percent fillet yield. For example, a drawn fish may cost $2 a pound and have a fillet yield of 42%. This conversion can be calculated by dividing the whole cost of the fish by the percent yield of the fish ($2.00/.42=$4.76). The real cost to the purchaser is at $4.76 a pound for the edible portion of the fish. Also, if a percent yield is known (for example, 42%) the mariculturist can grow the fish to produce a certain size fillet. To produce two 8 oz. dinner fillets, the fish must be grown to (16 oz/.42=2.38 lbs). The length of required grow-out period can be determined if the producer knows the growth rates of the various fish species. In order to obtain this significant value of whole and drawn fish, a survey was conducted of several U.S. seafood processors to determine the percent yield of boneless, skinless fillets of the potential marine finfish species for culture in the Gulf of Mexico. The results are presented later in this section.

Processing the Fillets

Most of the table fish commercially harvested in the Gulf of Mexico such as snapper, grouper, and amberjack, are distributed to processors fresh and drawn (whole with entrails removed). Fish processors can deliver whole fish to restaurants, grocery chains, seafood retailers or they can sell fish in the fillet form. Whole fish reassure seafood buyers of freshness allowing for examining the condition of gills, eye color, and firmness of the fish. Once the fish is filleted, the handling of this portion of the fish is exposed to decomposing producing bacteria and oxidative rancidity that can rapidly deteriorate the condition of the meat and reduce the shelf life of the fresh product with proper cooling. A fresh whole and drawn fish will have a shelf life of two weeks and a fillet will have a shelf life of three to seven days depending on how long after the harvest the fillet was cut from the whole or drawn form.

Forms of Products

Several factors affect the percent of fillet yields for finfish. The size, shape, and bone composition changes from fish to fish and alters the resulting fillet. There are several methods to fillet a fish. In its simplest form, a fillet can refer to the portion of fish cut away, down the backbone, from both sides of a fish. A whole fillet can contain rib bones, pin bones, nape (the fatty flesh around the entrails), a bony tail, and can be with or without the skin intact. Boneless, skinless fillets are the most expensive form of a fish and are often most desired by retail consumers and restaurants.

Fresh and frozen fish are bought and sold in six general forms between seafood processors, brokers, wholesalers, retailers, restaurants, and consumers in the U.S. seafood market (different processing schemes can occur in global markets and should be investigated by farmers/processors attempting to serve those markets). The first and least expensive is the whole fish that has not been cut and with everything intact. This form is not as common as others, however, whole fish experience trade as a frozen product, industrial fish, or a low cost ground fish. Secondly, is the drawn or gutted form in which the entrails are removed. It is a common practice to gut a fish to remove the bacteria producing contamination found in the viscera. The third form removes the head, gills, and guts and a fish processed in this manner is referred to as headed and gutted (H&G) in the seafood industry.

Large finfish such as swordfish and tuna are headed and gutted at sea by fishermen and are often traded widely until processed by retailers and restaurants where they are cut into steaks by the chef or butcher. Just as often processors will "loin" a tuna or a swordfish which involves cutting the top section of a large fish away free from backbone, bloodline, and rib bones. Tuna and swordfish loins are cut into steaks and sold to the consumer. Fish are also traded as roast. This form cuts across the fish from behind the rib bones and includes all the meat through the tail. Roasts are then cut into steaks that contain the large back bones. Finally, fillets are distributed by all sectors of the market and come in many forms. Depending upon species, fillets are often the most desired by consumers at retail outlets and restaurants.

Survey of Fillet Yields

A survey was conducted to estimate the percent yield of fillets for several candidate species suitable for mariculture applications in the Gulf of Mexico. Contributions were made by New Orleans Fish House, David Junkart, P&L Seafood, LA Seafood, Bon Secour Fisheries, Seafood Handbook[1], Beaver Street Fisheries, and
Louisiana Seafood Exchange.

Discussion of Fillet Survey

Fillet yields showed some variation with all species of fish with survey contributors remarking that fillet yields are influenced by several factors. The first significant variation is the skill of the fish cutter. Survey participants remarked that a proficient fish cutter can produce a three to seven percent increase in yields over an unskilled fish cutter. Some survey respondents remarked that warm and cold seasons can affect fillet yields significantly. Fish fatten up over winter and colder temperatures reduce catabolic rates. Feeding habits during the warm and cold seasons can affect the percent of fillet on a fish by two percent. The size of the organism at harvest can affect the fillet yield. Participants remarked that small fish compared to large fish usually result in lower prices and in lower fillet yields of two to three percent.

Most of the fillet yields were produced from wild caught fish with the exception of tilapia and red drum. Tilapia were all pond raised, however, the red drum were both wild caught and pond raised. Some survey participants remarked that aquaculture-raised red drum can have a two to three percent higher fillet yield than the wild caught red drum for the same size fish. It is not exactly known why the yields are higher, but there was speculation that the increase may be the result of high feeding rates and containment within a pond or cage. The fish discussed in the survey were pond raised fish contained in environments where the culture organisms were not swimming against a current. Mariculture fish raised in pens in open ocean settings with a pronounced current may exhibit the fillet yields of wild caught fish. Table 5-4 presents the results of the survey on fillet yields.

Table 5-4
Survey Responses
Percent Yield of Fillets of Candidate Species

Species of Fish	1	2	3	4	5	6	7	Average
Red Snapper	35	35-40	40	38	40	~	33	37.28
Grouper	35	35-38	47	38	42-48	40-42	33	39.80
Red Drum	36-38*	33	33	34	40	~	30	34.85
Mahimahi	50	65	52	52	40	40-45	49-43	48.44
Flounder	45	60	40-45	38	30	28-30	40-42	39.80
Greater Amberjack	43	45	45	38	65	~	38	45.67
Cobia	44	40	55	50	50-55	~	40	47.33
Pompano	60	~	~	55	30	~	40	43.33
Tilapia	~	~	~	~	30-35	~	~	32.50

~ no response; * figure distinguishes a pond raised product.
Note: Participants were asked what they thought the fillet percent yield is for a boneless and skinless fillet taken from a whole drawn fish.

Feasibility Analyses of Offshore Finfish Processing

In addition to performing a feasibility analysis on an offshore mariculture farming operation in the Gulf of Mexico, a cursory separate review of the feasibility of establishing a finfish processing plant offshore is presented herein. This was a designated scope item in the Cooperative Agreement with the National Marine Fisheries Service.

It became obvious early in the analysis of offshore processing that such a venture necessarily had to be located on its own offshore platform. The space requirements for a large farming operation would take up most of the usable deck space on even a large platform therefore it would not be feasible to try to set up a processing operation on the same platform as the farming operation. It might be possible to have co-use of some of the larger platforms, particularly the sulfur mining platforms.

An appraisal of independent offshore finfish processing was therefore conducted. This potential venture was assessed as an independent operation and not necessarily tied to joint farming and processing operations through a single corporate entity. There would obviously be some economies if the same company undertook both operations, i.e., crew transportation, joint use of vessels, base camps, etc. It should also be stated that there appears to be adequate existing capacity in onshore seafood processing facilities to handle the expected production from offshore farms, at least in the near future (see Ken Roberts report in Appendix B).

Implementing offshore processing would have some inherent advantages in that only the edible portions of the finfish product would be transported onshore rather than the whole fish. If the end market was frozen product it could also be frozen quicker, leading to a longer shelf life. It might also be possible to utilize some of the non-edible portion of the fish (head, bones and entrails) for producing either a food to supplement the pelletized feed used in the farming operation or in preparation of fish meal. The advantages and disadvantages of an offshore fish processing operation were not studied in detail in this project. It is obvious that extensive amounts of investigation, including a detailed environmental impact analysis, would be required prior to implementing such an operation.

Due to the high cost of sustaining a labor force offshore, the processing plant conceptualized for this appraisal consisted of an automatic processing train as opposed to labor intensive, hand processing systems. There is adequate technology to implement such an operation whereby facilities can process many thousands of tons per annum with relatively low labor requirements. In order to automatically fillet the fish, the fish must first be sent through a head machine, then a gut machine, and then through a fillet machine. Conveyor belts would channel the fish from machine to machine. One processing train shown schematically in Exhibit 5-1 can handle the expected production from a single offshore base case installation (4500 metric tons per annum). In the cost analyses presented later, there are two sets of equipment provided in case of breakdown, thereby supplying redundant capacity. A blast freezer is included to allow the option of quick freezing product offshore. Miscellaneous processing equipment includes tables, knives, supplies, etc. Operationally, it is anticipated that a supervisor and a crew of 14 persons could handle the processing train shown in Exhibit 5-1. As was the case for the farming operation, it is anticipated that the processing plant will be manned by two, 14 person crews (not counting the supervisor) which will work 12-hours

PROCESSING FACILITY

Capacity: 30 MT of fish a day
7290 MT of fish a year

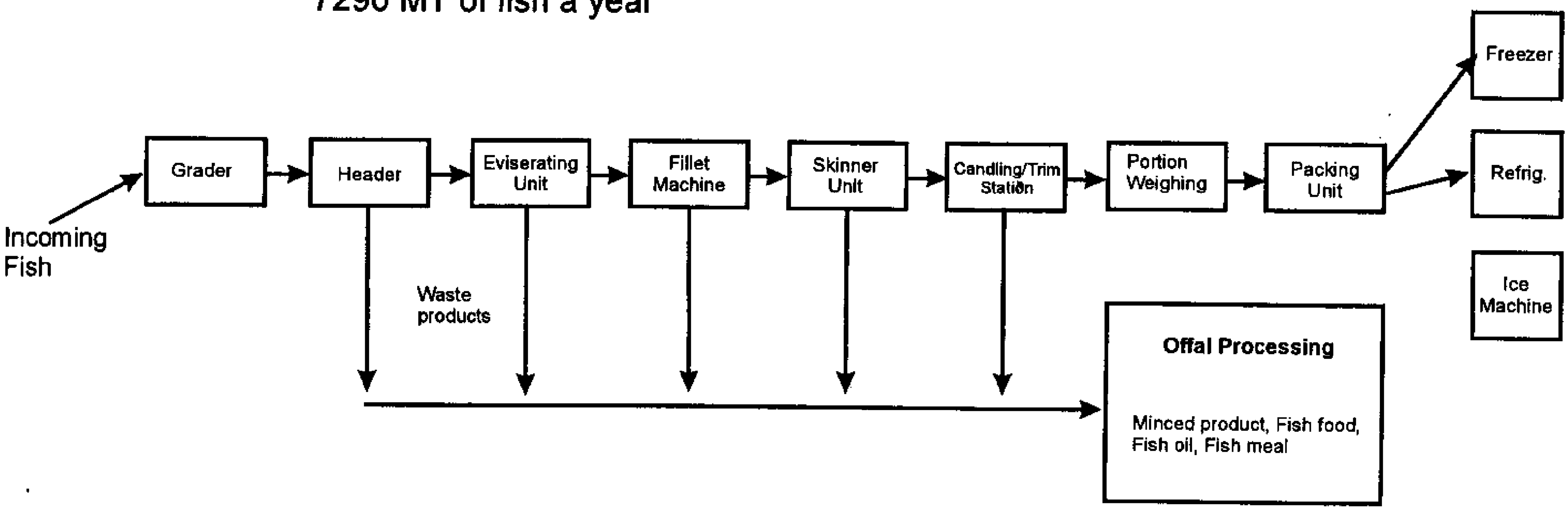


Exhibit 5-1 Fish Processing and Offal Recovery Systems

per day for seven consecutive days. The crew will be replaced by another, similar crew to work the next one week period. Crews will reside in a quarters building located on the platform.

Optimally, a single processing train during a 12-hour shift can process approximately 80,000 pounds per day. This is based on the rate limiting equipment item which is the fillet machine. Ice production should be at least on a 1:1 ratio with two units capable of producing 80,000 pounds per day. (Depends on whether freezing product or distributing fresh.)

Forecast start-up, capital, and annual operation and personnel cost are shown in Tables 5-5 and 5-6. As can be seen, it is anticipated that an offshore processing plant will require an initial capital investment of approximately $6 million with annual costs anticipated to be in the $3.2 million range.

To assess the economic feasibility of implementing such a venture, an examination was made of different processing plant throughput rates. Intuitively, there should be a minimum throughput rate below which the operation does not make financial sense. It is common for onshore processing facilities in the Gulf to calculate the cost of fillets by first estimating the real value of the whole fish. Then the processors will add a processing cost and a sales margin. A summary spreadsheet was generated analyzing the attractiveness of such an investment. Assumptions made in the analysis included:

- Term of loan = 5 years
- Interest rates = 15%
- Cost data from Tables 5-5 and 5-6
- No sharing of infrastructure with farming operation
- Real value of whole fish = (whole fish ∏ fillet yield)
- Processing cost = 30?/lb
- Sales margin = 20%

The financial analysis indicated that under these assumptions an offshore processing operation would need a throughput of approximately 5000 metric tons per annum in order to reach a break even point for the project.

It should also be mentioned here that an offshore processing operation does not necessarily have to rely only on processing farm raised product. It is obvious that should a processing operation be implemented offshore, that it could be set up to receive captured fish from commercial fishermen. The processing facility would presumably pay the commercial fisherman for his catch on a per pound basis with prices dictated by species, quality, size, etc. In this fashion, the processing facility could readily supplement the throughput expected from a farm-only operation. This potential practice of purchasing fish offshore from commercial fishermen could be of great benefit to the commercial fishing industry. If the commercial fishing industry had a market for its catch situated offshore, there would be obvious cost savings to the commercial fisherman with respect to reduced usage of ice, fuel, etc., and also allow the commercial fishing vessel to stay offshore for longer periods of time.

In summary, the potential for establishing an offshore processing entity is realistic, however, it would probably not be implemented early in an offshore farming operations life. It would probably require a throughput of at least 5000 metric tons per annum which would not necessarily have to be all from the farming operation but could be supplemented by purchase of catch from the commercial fishing industry.

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[1] The Seafood Handbook *Everything You Need to Know About Seafood*, published by Seafood Business 1996 Portland ME, Phone: 207-842-5606.

Table 5-5
PROCESSING PLANT COSTS
START-UP COSTS

Item	Qty	Unit cost	Total Cost
Engineering	1	$ 200,000	$ 200,000
Permitting	1	$ 80,000	$ 80,000
Legal fees	1	$ 75,000	$ 75,000
Financing	1	$ 200,000	$ 200,000
Sub-Total			**$ 555,000**

On-shore and Platform Related Costs

Item	Qty	Unit Cost	Total Cost
Abandonment Escrow	1	$ 500,000	$ 500,000
Platform Refurbishment	1	$ 400,000	$ 400,000
Crane	1	$ 200,000	$ 200,000
Power Generation	1	$ 100,000	$ 100,000
Base Ops Facility	1	$ 60,000	$ 60,000
Base Crane	1	$ 100,000	$ 100,000
Office Operations	1	$ 80,000	$ 80,000
Truck and service vehicle (Base)	2	$ 50,000	$ 100,000
Sub-Total			**$ 1,540,000**

	life expectancy 10 yrs on equipment		
Processing Equipment	**Qty**	**Unit cost**	**Total Cost**
Header	2	$ 35,000	$ 70,000
Fillet machine	2	$ 150,000	$ 300,000
Candling-Trimming unit	2	$ 20,000	$ 40,000
Scaling/skinner unit	2	$ 45,000	$ 90,000
Ice machine	2	$ 40,000	$ 80,000
Freezer	2	$ 40,000	$ 80,000
Refrig unit	3	$ 50,000	$ 150,000
Conveyor system	14	$ 10,000	$ 140,000
Processing building	1	$ 720,000	$ 720,000
Offal processor/fishmeal plant	1	$ 200,000	$ 200,000
Crew Qtrs.	2	$ 40,000	$ 80,000
Electrical service	1	$ 50,000	$ 50,000
Switchgear	1	$ 15,000	$ 15,000
Packing unit	2	$ 25,000	$ 50,000
Misc. processing equip.	1	$ 50,000	$ 50,000
Install expense 40% of equip. cost	1	$ 800,000	$ 800,000
Sub-Total			**$ 2,915,000**
Miscellaneous 10%			$ 290,000
Start-up cost (above)			$ 555,000
Platform and Onshore cost			$ 1,540,000
Sub-total			$ 5,200,000
Contingencies 15%			$ 780,000
TOTAL CAPITAL COSTS			**$ 5,980,000**

Table 5-6
ANNUAL COST ESTIMATES
OFFSHORE FISH PROCESSING FACILITY

OPERATIONAL AND MAINTENANCE COSTS Item	Annual Expense
Liability Insurance	75,000
Insurance	75,000
Vessel support	500,000
Tech. and Safety training	20,000
Platform maintenance	200,000
Catering Services	120,000
Fuel (Power Generation)	75,000
Fuel expense-Onshore	40,000
Sales support	300,000
Office operations	50,000
Equipment maintenance	150,000
Operations and Maintenance Costs	**1,605,000**

*Packing materials are not included in operational cost or sales revenues.

PERSONNEL COST Job Description	Qty.	Unit Cost	Yearly Expense
Management	1	112,000	112,000
Supervisor	2	72,000	144,000
Staff (offshore)	28	34,000	952,000
Base OPS staff	4	34,000	136,000
Personnel Cost			**1,344,000**
Operational cost (above)			**1,605,000**
Sub-total			**2,949,000**
Contingencies @ 10%			**295,000**
TOTAL OPERATIONAL COST			**3,244,000**

Chapter 6

Environmental Impact Analyses

Introduction

Aquaculture activities through the years have developed a reputation for causing moderate to severe impact to the environment. Historical practices have been mostly inland or coastal activities and there have been many instances internationally but also in the U.S. where an aquaculture site has caused water quality or biological problems in its area of impact. The list of potential negative impacts to the natural environment of an offshore open Gulf or ocean mariculture site should include:

- Water quality concerns,
- Potential spread of disease to native fish populations,
- Potential impact to the gene pool of native fish populations if captive fish were to escape the net pens, and
- Impact to protected marine species by interference with migratory routes or entanglement in nets.

Each of these issues will be addressed in the following Natural Environment section. Socioeconomic or impacts to the human environment will be discussed in the Socioeconomic section.

Natural Environment

Water Quality Issues

The raising of marine finfish offshore has the potential to impact the quality of the surrounding water column due to discharges from the net pens or the platform (farm center) itself. Potential water quality impacts due to existence of one or multiple net pens depends upon a number of factors including the size of a given mariculture operation, its location in the Gulf of Mexico (currents, depths, existing water quality), and the type of feed used and method of feeding. Obviously a larger operation closer to shore in areas with existing water quality concerns would be expected to have the potential to further exacerbate those problems. The project team performed an extensive water quality impact analysis on discharges from the net pens of the defined "base case" mariculture operation. This operation was assumed to be in 100 to 200 feet of water depth and have current velocities representative of those water depths in the northern Gulf of Mexico. This entire analysis can be reviewed in Appendix E. A summary is presented here.

Research from major mariculture producing nations have noted in several studies the potential of intensive aquaculture to cause detrimental effects to regional coastal areas, enclosed bays, and estuaries (Rosenthal 1989, Hirata et al 1994, Gowen and Bradbury 1987, Gillibrand and Turrel 1997, EPA 1991, Aure and Stigebrandt 1990). Environmental concerns have initiated efforts around the globe to move aquaculture activities offshore of the sensitive coastal zones to open ocean areas in search of improved water quality conditions and to reduce potential harmful impacts of fish farming (Grove et al 1994, Burgrove et al 1994, Thompson 1996). The presence of currents and sufficient depths to distribute and dilute mariculture wastes are significant factors as to whether mariculture discharges will prove harmful to the surrounding environment (Penchage 1991, Gowen et al 1989). Current velocities of 20 to 30 cm/sec are common near the surface (Jochens and Nowlin 1995, Phillips and James 1988) along the Texas-Louisiana shelf although there can be episodic periods of calm and extreme sea states. At these current velocities, the volume of water passing through an offshore net-pen can replace the water within the net 200-1500 times a day. Miget 1994 reported that relative to inshore aquaculture, offshore culture on oil and gas platforms reduces the "potential for pollution of the receiving water via effluent". The high water exchange rates should assist in dispersal of wastes from the aquaculture site operations providing a good medium to fish culture.

Source Description

The detailed water quality impact analysis evaluated impact potential from two sources: food not eaten by fish and thus escaping the net pens, and metabolic wastes from the cultured fish. The analysis used a figure of five percent of the feed distributed to fish escaping the nets. At a 5% feed loss and a 95% consumption, fecal materials contribute the majority of carbon and nitrogen loadings to the water column (bio-deposits represent 80% by weight of the particulate carbon and soluble nitrogen discharges). The two primary wastes of concern from mariculture activities are organics and nutrients. Phosphorus is present in uneaten food and particulate fecal materials, however, phosphorus discharges are more of a concern for fresh water aquaculture (EPA 1991). The principal nutrient of concern for mariculture discharges are nitrogenous compounds since nitrogen is a limiting factor to life in the marine waters of the Gulf and has been reported to cause nuisance plankton blooms (Rabalais et al 1996).

Food and fecal waste discharges contain both conventional and unconventional pollutants. Based on federal NPDES regulations (40 CFR 401. 16), the unconventional pollutants include turbidity, disease control medications (see Appendix A), nutrients (principally nitrogen compounds), and settleable solids. Conventional pollutants include biochemical oxygen demand (BOD), total suspended solids (TSS), and pH. Metabolic activity also results in oxygen consumption and consequent production of carbon dioxide waste. All food consumed by fish is eventually utilized for metabolic processes, synthesized into new tissue growth, or excreted as waste. Fecal wastes include dissolved NH_3 and NH_4 and particulate carbon and organic nitrogen (proteins). Marine fish excrete 60% to 90% of their waste nitrogen as soluble ammonia through the gills (Lovell 1989). An indigestible organic residue of 20% usually remains to be excreted as feces (Penczack et al 1982). Sources of carbon and nitrogen discharges are also released from the proteins, fats, and carbohydrates in the fish food not eaten by the cultured organisms. (See Figure 1).

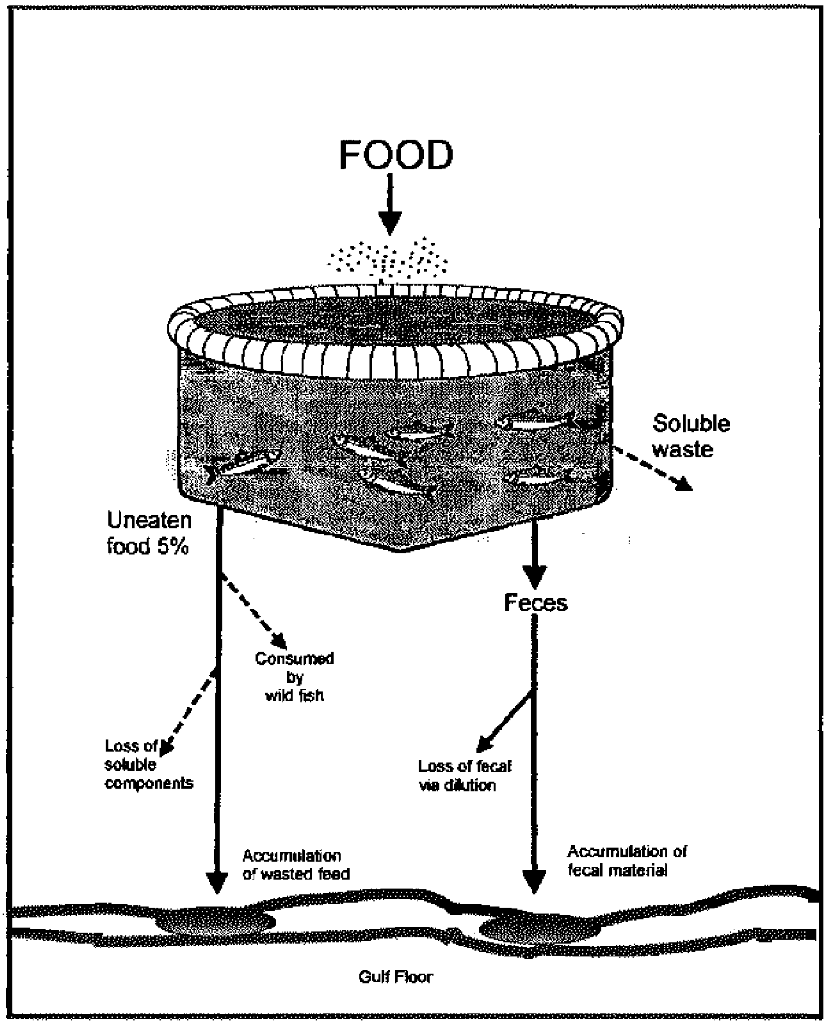


FIGURE 1 DISTRIBUTION OF WASTE FROM A NET-PEN FACILITY

Impact to the Environment

The decomposition of feed and organic wastes, fish respiration, and nitrification of metabolic wastes can lower dissolved oxygen levels in the water column in and down current of the net-pens. Dissolved oxygen and organic enrichment are interrelated in that organic enrichment fuels bacterial decomposition and can result in oxygen depletion (EPA 1991). This depletion occurs primarily by microbes in the water and sediment consuming oxygen as they decompose organic matter. The decay of solid wastes may also result in alterations in the benthic community due to burial and chemical changes effected within the sediments. Nutrient enhancements from mariculture discharges have the potential to encourage nuisance plankton blooms by providing micro-environments and transport opportunities (Dortch 1998). Sedimentation and decomposition of solid waste discharges involve the release of potentially toxic de-cay byproducts like methane and disas-sociated hydrogen sulfide (Aure 1990). Decomposition of settled solid waste may result in the consumption of dissolved oxygen contributing to hypoxic conditions common-ly found along the seafloor of the Texas-Louisiana shelf. Nutrients are also released during the decay of solid wastes, which may contribute to phytoplankton productivity.

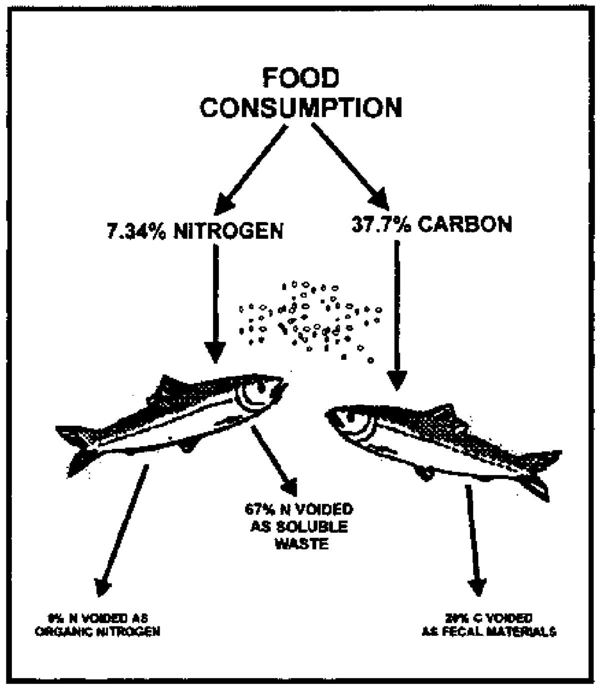


FIGURE 2 AMOUNT OF CARBON AND NITROGEN DISCHARGE FROM THE CONSUMPTION OF FEED

The detailed water quality impact analyses (see Appendix E) indicated that the presence of 20 to 30cm/sec currents along the Texas-Louisiana 100-200 ft isobath should minimize the potential harmful conditions that may be caused by mariculture nutrient and organic effluents. In the areas subjected to these currents, the dilution of ammonium plumes should prevent the accumulation of soluble nitrogenous waste in the water column and minimize the risk of nuisance plankton blooms. The open Gulf environment should maintain safe levels of dissolved oxygen in and around the mariculture site. The dispersal rate of wastes and aerial extent of sedimentation will determine whether benthic communities in the vicinity will be impacted by net-pens. The sea-states and exchange of water should prevent harmful accumulation of feed wastes and feces in the areas beneath the net-pens. A more extensive review of the significance of feed and fecal effluents can be found in Appendix E. The marine chemical and biological processes affected by mariculture discharges are discussed in that analyses which used a base case scenario to estimate the impact of nitrogen and carbon loadings for a commercial scale operation.

The other potential issues concerning water quality are discharges from the farm center or platform itself. These really fall under two categories – routine discharges of sanitary waters and potential spills of materials such as fuels, paints, anti-fouling compounds, etc. A typical farm center crew stationed on the platform will probably not be composed of numerous persons. A well run and mostly computer operated and mechanized operation would probably not have more than three to five farm staff on the platform with the possible exception of stocking/harvest times. Flows from sanitary facilities for this small crew would not be significant and might even be stored on the platform for occasional transport back to shore. Should an operation want to treat and discharge these waters, they would have to abide by the USEPA NPDES rules and regulations. These regulations are specifically intended to minimize water quality impacts to adjacent waters. Spills of fuels, chemicals, paints, etc., from the platform could also have an impact on water quality. Preliminary estimates of power requirements for the "base case" operation yielded a peak requirement of approximately 50 kw. Even for diesel powered generators this should not require diesel storage in excess of 300 gallons and adequate containment practices will significantly reduce release potential due to storage and loading fuels. This type of power requirement also lends itself to alternative energy sources including wind and solar.

In summary, the small amounts of fuels or chemicals stored or used on the platform, when adequately contained, should not be a serious water quality concern.

Potential Impacts on Native Fish Stocks

The potential for introduced species or escaped cultured species to impact native wild stocks of aquatic organisms has become a major problem and concern around the world (Cataudella and Crosetti 1993; Bartley 1995; Burnham-Cutis 1995; Hilsdorf 1995). The principal problems that have developed are (1) displacement of indigenous species by the introduction or escapement of non-indigenous species into the wild (Keenan and Salini 1990; Dochoda and Billington 1991; Evan and Willox 1991;Ogutu-Ohwayo and Hecky 1991); (2) the threat of altered natural gene pools from the introduction or escapement of hatchery produced fishes with limited genetic diversity into the wild (Busack and Currens 1995; Benzie and Williams 1996; Mitrofanov and Lesnikova 1996); and (3) the transfer of diseases from cultured fish to native species. If aquaculture is to grow to meet future demands for seafood and play a more active role in rebuilding overfished stocks (Brown 1997), these issues will need to be addressed in hatchery and growout operations.

In a mariculture operation, the simple solution to avoid introduction of non-indigenous species is to only culture indigenous species, unless no possibility of escapement exists (such as with recirculating system technology). Net cages and floating net pens are potentially vulnerable to storm damage, predator damage and subsequent escapement of fish. Variation in size of fingerlings might also result in some escapement when stocking cages with small fish.

There are several ways to address these problems in a finfish growout operation. Indigenous species can be collected from the local environment and used for broodstock. Escapement at stocking can be avoided by carefully grading fish before stocking. The simplest way to maintain genetic diversity would be to collect wild fingerlings and culture them as is done in some other parts of the world, but this practice would probably not be politically or socially acceptable in the U.S. The most feasible way to maintain genetic diversity of hatchery produced fingerlings is to develop protocols which diversify broodstock and produce genetically diverse batches of fingerlings. This can be accomplished by rotating male and female broodstock from duplicate brood tanks and by providing multiple males to spawn with each female. This approach is being adopted by many public and private hatcheries in the US and elsewhere. Broodstock rotation is most feasible if the fish are serial spawners which can be spawned repeatedly by photo-thermal manipulation. In cases where ripe broodstock are collected and spawned by hormone implant or hormone injection, fertilization of eggs by multiple males and spawning of multiple females may be the best option. Cryopreservation of sperm from multiple males can play an important role in maintaining genetic diversity of fingerlings in cases where broodstock are difficult to collect or in limited supply (Piironen 1993; Rana 1995). Although cryopreservation technology is a promising tool, methods will need considerable refinement and more broad scale development before they can be widely applied in mariculture (Rana 1995).

Producing hybrids is another option to consider that will minimize potential impacts of escapement on wild stocks. Hybrids can be produced for closely related species with similar spawning seasons or by cryopreservation of gametes for producing crosses between congeners with dissimilar spawning seasons. The many hybrids of striped bass that have been produced and stocked in reservoirs and lakes throughout the U.S. and also cultured in cages and ponds are a good example of this approach. Hybrids can eliminate the threat of escaped hatchery produced fingerlings breeding with native stocks and minimize impacts of escapement.

Protocols for the conservation of genetic diversity of various species of fish and shellfish produced by hatcheries have been developed and adopted (Doyle et al 1991; Hadley 1992; Mace and Harvey 1994; Bartley et al 1995; Hedgecock 1995). The degree of broodstock rotation depends on the genetic diversity of the natural populations of a given species. For example, Florida has adopted a procedure for rotation of broodstock used to produce fingerlings for stock enhancement (Roberts et al 1994). A similar approach can be used in hatchery programs to support offshore mariculture. Genetic diversity of hatchery fingerlings and native stocks can be monitored with standard genetic methods (Wolfus et al 1997).

Disease-free fish are almost impossible to produce in a hatchery and impossible to maintain in an open environment. Furthermore, challenges to healthy, unstressed fish can be an important step in developing immunity to pathogens. Introduction of diseases from hatchery produced fish to wild fish can be avoided by subsampling a representative number of fingerlings from hatchery stocks and then certify their health through an aquatic veterinary clinic prior to stocking in cages. Naturally occurring diseases, toxic alga blooms, stress from low oxygen, cold stress, nipping or degraded feeds can all potentially cause mortality of fish reared in cages. If significant unexplained mortality occurs in any of the net cages after stocking, specimens should immediately be collected and the cause of death determined by a fish pathologist.

Protected Species

Potential Impacts to Marine Mammals and Endangered and Threatened Species

The purpose of this section is to review possible impacts of Gulf of Mexico mariculture activities on marine mammals and endangered/threatened species. The following text is a brief description of classified species and the activities that may create a potential impact to these animals. Analogies can be drawn from many of the day to day activities of offshore oil and gas production as they will be similar to offshore activities. Additionally, mariculture will involve net-pens and discharges of uneaten food and fecal material which could impact protected species. This section will review the common impacts of mineral production and mariculture and discuss how net-pens and fish waste may influence marine mammals and protected species. The text will not cover impacts as the result of oil and gas production, i.e., produced fluids, oil spills, etc. This information is available in a series of Environmental Impact Statements provided by the Minerals Management Service for the sale of mineral leases of OCS lands.

Potential impacts to protected species from mariculture operation in the open Gulf can be attributed to the following:

- Vessel traffic and noise.
- Use of explosives for platform removal (although mechanical removal methods are common along the 100- to 200-foot isobath).
- Accidental discarded trash and debris from service vessels and farm structures.
- Nuisance or toxic plankton growth due to increased nutrient loading.
- Reduction of dissolve oxygen within close proximity of net-pens.
- Entanglement in net-pens utilized in mariculture operations.

Marine Mammals in the Gulf of Mexico

Thirty-three species of cetaceans have been identified in the Gulf of Mexico (Table 1). The majority of these species are typically found in deeper waters (the continental shelf edge and beyond), with the exception of the bottlenose dolphin and Atlantic spotted dolphin, which commonly inhabit nearshore and shelf waters (MMS EIS 1993). By an order of magnitude, the bottlenose dolphin is the most common marine mammal in this area. Information on the distribution, abundance, movements, and behavior of the other species is limited. Six endangered cetacean species have been reported in the Gulf of Mexico. They include the sperm, blue, sei, fin, right, and humpback whales. All are uncommon, and only the sperm, fin, and sei whales have been seen in the Central and Western Gulf of Mexico in recent years. Observations suggested that the sperm and fin whales have a resident population in the Gulf and that other species are occasional migrants or vagrants (Tucker & Associates, Inc., 1990). Current information on the distribution, abundance, and movements of great whales in the Gulf is sketchy or nonexistent.

The blue whale *(Balaenoptera musculus)* is the largest and rarest of the great whales. Historical records suggest that it infrequently passed through the Gulf of Mexico. There have been only two recorded sightings: one off Louisiana in 1924 and another off Texas in 1940. The latter identification is questionable (Schmidly, 1981). The fin whale *(Balaenoptera physalus)*, the second largest of the baleen whales, feeds on krill and small schooling fish. Schmidly (1981) reported five strandings and four sightings in the northern Gulf, and the NMFS made several sightings off the Mississippi delta in 1989. Humpback whales *(Megaptera novaengliae)* are a coastal species and feed primarily on krill and fish. Humpbacks have been sighted in the Central Gulf in 1952 and 1957. They have also been found in the Eastern Gulf near the mouth of Tampa Bay in 1962 and

1983, and near Seahorse Key, Florida, in 1983 (Schmidly, 1981). There are no records suggesting that the humpback whale was ever more than an infrequent transient in the Gulf.

Right whales are the most endangered cetacean in the Western Hemisphere. Their population in the northwestern Atlantic Ocean is estimated at 250-350 individuals. The right whale has rarely been sighted in the Gulf of Mexico, the most recent observations occurring offshore of Brazoria County, Texas, in 1972 (Lowery, 1974). Sei whales *(Balaenopters borealis)* have been reported from the Gulf in 1956, 1973, and 1989. They usually travel in groups of two to five individuals. Their population is unknown and they feed on copepods, krill, and small schooling fish. The sperm whale *(Physeter catodon),* the most abundant great whale in the Gulf of Mexico, has been sighted during all seasons by Fritts et al. (1983) and the DOC (USDOC, NMFS, 1988). Watkins (1977) noted that it inhabits offshore waters deeper than 1,000 m (3,281 ft). In the northern Gulf, it is most frequently sighted along the continental shelf break (Tucker & Associates, Inc., 1990).

Potential Impact to Marine Mammals

Operational wastes can potentially impact cetaceans via displacement or removal of food sources or via the degradation of water quality. As was seen in the water quality analyses, most operational discharges will be rapidly diluted and dispersed when released in offshore areas and are not considered to be lethal or detrimental to cetaceans. Indirect effects to cetacean food supply are not expected to occur due also to rapid dispersion of organic wastes.

Entanglement of marine mammals in fishing gear is a relatively common occurrence in the regional fisheries (MMS EIS 1993). The potential exists for marine mammals to become entangled in the net-pens at a mariculture operation. To mitigate this potential, the outer most predator nets should be weighted to keep the webbing taut to prevent the entanglement of marine mammals and other species. Miget 1997 reported in a pilot study of offshore mariculture there were no observed entanglement of cetaceans or sea turtles in net-pens nor any intrusion of sharks during the course of that particular project.

The passage of support vessels in proximity to cetaceans can elicit a startle response with subsequent avoidance or evasive behavior. This effect is sub-lethal, though it could temporarily disrupt ongoing feeding, mating, resting, or migratory behavior, or cause the dispersion of a social group. This behavioral response could be a result of noise and/or visual disturbance. The response of cetaceans to such noise is somewhat species specific and appears to be, in part, a function of sound intensity, distance, the fact that the noise source is in motion (compared to a static and non-changing source), season (primarily mating season), and individual variability in whale behavior (MMS EIS 1993). Evidence suggests that certain whales have reduced their utilization of certain areas heavily used by vessel traffic, though continued presence of various whale species in such areas indicates a considerable degree of tolerance to vessel noise and disturbance (Richardson et al, 1991). Groups of dolphins and porpoises are often attracted to vessels making way in order to bow ride or, in the case of fishing vessels, take advantage of discarded by-catch.

Support vessels involved in operations could presumably collide with and physically impact cetaceans, especially larger species and those that remain at the surface for extended periods of time (MMS EIS 1993). Many of the larger species of cetaceans are deep-diving odontocetes, which commonly spend extended periods of time at the surface in order to restore oxygen levels within their tissues. The normal distribution of these mammals appears to be beyond the continental shelf edge, well into the bounds of the continental slope. Cetaceans that inhabit the continental shelf and near-shore waters, most commonly bottlenose and spotted dolphins, are agile swimmers that often approach vessels making way, even when in the confines of narrow navigation passes and waterways, and seem well able to avoid such vessels when deemed necessary. The probability of OCS service-vessel collisions is therefore greater within areas of the Gulf that are off the shelf edge.

Removal of offshore platforms by means of explosive charges can directly impact cetaceans. The effects of underwater detonation of explosive charges is dependent upon the amount of explosive used, distance from the charge, and body mass. Hemorrhaging in and around the lungs is the primary source of injury to submerged mammals, as well as injuries from the effects of explosive impact upon gas bubbles within the intestines (Goertner, 1982). The effects of explosives could also damage the ears of submerged cetaceans, and thus affect intraspecie communication, feeding, and navigation. Although death and permanent injuries have been speculated, none have been documented. In order to minimize the likelihood of removals occurring when cetaceans may be nearby, MMS has issued a series of guidelines (NTL 92-02) for explosive platform removal to offshore operators. These guidelines specify platform removal only during daylight hours, staggered detonation of charges, placement of charges 5m below the seafloor, and extensive pre- and post-detonation surveys of surrounding waters.

Pollution of the marine environment with non-biodegradable plastic debris discarded from offshore sources (structures, and vessels) and coastal sources (litter and solid waste disposal) has become an issue of increasing concern, especially with regard to entanglement of and ingestion by marine mammals. Typically, marine mammals become entangled in various types of debris (mostly lines of various types) and inactive or active fishing gear. Plastic debris has also been reported in the gut contents of several stranded marine mammals. In some cases, ingestion of such material is believed to be the cause of death (Barros and Odell, 1990: Sadove and Morreale, 1990; Tarplev, 1990). It is believed that the animals either mistake the plastic material, which is in suspension in the water column, as a food item, or in the case of larger baleen whales, it is ingested along with prey species (Sadove and Morreale, 1990). The MMS prohibits the disposal of equipment, containers, and other materials into coastal and offshore waters by oil and gas lessees (30 CFR 250.40). Presumably, a mariculture operation would be under the same kind of prohibition. Prohibition of the discharge and disposal of vessel and offshore structure-generated garbage and solid waste items into both offshore and coastal waters was established January 1, 1989, via the enactment of MARPOL, Annex V, Public Law 100-220 (101 Statute 1458), which is enforced by the U.S. Coast Guard.

Conclusion

The impact of the proposed action on marine mammals is expected to result in primarily sublethal effects (behavioral effects and nonfatal exposure to or intake of aquaculture discharges or discarded debris) that are both chronic and sporadic. These impacts could cause acute or chronic physiological stress, alter normal behavioral patterns, and result in some degree of avoidance, either temporary or permanent, of the impacted area(s).

Table [illegible]
CETACEANS

Sub-order	Family	Species	Common Name	Endangered	Abundance
Mysticeti	Balaenidae	*Eubalaena glacialis*	right whales	yes	rare
	Balaenopteridae	*Balaenoptera musculus*	blue whale	yes	rare
		Balaenoptera borealis	sei whale	yes	rare
		Balaenoptera physalus	fin whale	yes	rare
		Balaenoptera edeni	Bryde's whale	no	rare
		Balaeanoptera acutorostrata	Minke whale	no	rare
		Megaptera novaeangliae	humpback whale	yes	rare
Odontoceti	Physeteridae	*Physeter macrocephalus*	great sperm whale	yes	common
		Kogia breviceps	pygmy sperm whale	no	common
		Kogia simus	dwarf sperm whale	no	uncommon
	Ziphiidae	*Mesoplodon densirostris*	Blainville's beaked whale	no	rare
		Mesoplodon europaeus	Antillian beaked whale	no	uncommon
		Mesoplodon bidens	North Sea beaked whale	no	rare
		Ziphius cavirostris	goosebeaked whale	no	uncommon
	Delphinidae	*Orcinus orca*	killer whale		
		Feresa attenuate	pygmy killer whale		
		Pseudorca crassidens	false killer whale		
		Globicephala macrorhynchus	short-finned pilot whale		
		Steno bredanensis	rough toothed dolphin		
		Delphinus delphis	saddleback dophin		
		Peponocephala electra	melon-headed whale		
		Grampus griseus	grampus		
		ursiops truncarus	Atlantic bottlenose dolphin		
		Stenella frontalis	Atlantic spotted dolphin		
		Stenella attenuate	pantropical spotted dolphin		
		Stenella clymene	short-snouted spinner dolphin		
		Stenella longirostiis	long-snouted spinner dolphin		
		Stenella coeruleoalba	striped dolphin		
Pinnipedia	Otariidae	*Zalophus californianus*	California sea lion	introduced	rare
Sirenia	Trichechidae	*Trichechus manatus*	West Indian manatee	endangered	common

Marine Turtles

The green turtle *(Chelonia mydas)* population in the Gulf once supported a commercial harvest in Texas and Florida, but the population has not completely recovered since the collapse of the fishery around the turn of the century. Reports of nesting in the northern Gulf are isolated and infrequent. The closest nesting aggregations are on the Florida east coast and the Yucatan Peninsula. Green turtles prefer depths of less than 20 m (66 ft), where seagrasses and algae are plentiful (NRC, 1990). Leatherbacks *(Dermochelys coriacea),* the most oceanic of the marine turtles, occasionally enter shallow water in more northern areas. Their nesting is concentrated on coarse-grain beaches in the tropical latitudes (Ogren et al, 1989), but there are rare occurrences on the Panhandle and Flagier County coasts in Florida. They feed primarily on jellyfish but also consume crustaceans, fish, and some algae.

The hawksbill *(Eretmochelys imbricate)* is the least commonly reported marine turtle in the Gulf. Texas is the only Gulf State where stranded turtles are regularly reported (Ogren et al, 1989), and these tend to be either hatchlings or yearlings. Northerly currents may carry them from Mexico, or their nesting range may be expanding northward into Texas. They are more frequent in the tropical Atlantic, Gulf of Mexico, and Caribbean. Hawksbills prefer reefs and water less than 15 m deep where marine invertebrates are abundant.

The Kemp's ridley sea turtle *(Lepidochelys kenipi)* is the most imperiled of the world's marine turtles. The population of nesting females has dwindled from an estimated 47,000 in 1947 to 600 today (NRC, 1990). An estimated 800 nests are laid annually (NRC, 1990), primarily on a 17-km (10.5-mi) stretch of beach in Rancho Nuevo, Vera Cruz, Mexico (Thompson, 1988). Nesting in the United States occurs infrequently on Padre and Mustang Islands in south Texas from May to August (Thompson, 1988). Natural nesting is supplemented by a NMFS hatching and rearing program on Padre Island National Seashore. Female Kemp's ridleys appear to inhabit nearshore areas, and congregations of Kemp's have been recorded off the mouth of the Mississippi River (Byles, 1989).

The loggerhead sea turtle *(Caretta caretta)* occurs worldwide in depths ranging from estuaries to the continental shelf. It has been reported throughout the Atlantic from Newfoundland to Argentina (NRC, 1990). Nesting also occurs worldwide.

In the Central Gulf, loggerhead nesting has been reported on Gulf Shores and Dauphin Island, Alabama; Ship Island, Mississippi; and the Chandeleur Islands, Louisiana. Nesting in Texas occurs primarily on North and South Padre Islands, although occurrences are recorded throughout coastal Texas. Hildebrand (1982) noted that banks offshore the central Louisiana coast and near the Mississippi Delta are also important marine turtle feeding areas.

Impacts to Marine Turtles

This section discusses the effect of the proposed action on the loggerhead, Kemp's ridley, hawksbill, green, and leatherback marine turtles of the Gulf of Mexico. Major impact-producing factors that may occur as a result of the proposed action are reviewed in detail in Decline of the Sea Turtles: Causes and Prevention (NRC. 1990) The major impact-producing factors related to the proposed action that may affect Gulf marine turtles include: operational discharges, entanglement in net-pen webbing, vessel traffic, explosive platform removals, OCS related trash and debris, and water quality degradation.

Mariculture operation wastes could potentially impact marine turtles by displacement of food sources through the degradation of water quality. Our analyses do indicate however that operational discharges should rapidly dilute and disperse when released in offshore areas. Indirect effects to food supply are not expected to occur due also to rapid dispersion of organic waste.

Structure removal and water quality degradation may adversely affect marine turtle habitat through destruction of live-bottom communities used by marine turtles. Noise from service-vessel traffic may elicit a startle reaction from marine turtles and produce a temporary, sublethal stress (NRC, 1990). Service vessels could collide with and harm marine turtles while they are at the sea surface, but this appears to be less than 4 percent of their total time (Bytes, 1989; Lohoefener et al., 1990). Vessel-related injuries were noted in 9 percent of stranded marine turtles examined in the Gulf of Mexico during 1988, but this figure includes turtles that may have been struck by boats post mortem (USDOC, NMFS, 1989).

Explosive platform removals can cause capillary damage, disorientation, and loss of motor control in marine turtles (Duronslet et al., 1986). Although marine turtles far from the site may suffer disorientation, those near detonation sites could sustain fatal injuries. Deaths have been suspected but not documented in previous explosive platform removals.

Entanglement of marine turtles in fishing gear is a relatively common occurrence in the regional fisheries. The potential exists for marine mammals to snare up in net-pens. The NMFS protected species group was contacted regarding this possibility. They indicated that the predator nets be weighted to keep the webbing taut and use of a mesh size of four inches or less. This should reduce the entanglement of marine mammals and endangered species. Miget 1993 reported in a pilot study of offshore mariculture there were no observed entanglement of sea turtles during the course of the project.

Marine turtles can become entangled in monofilament fishing line, netting, 6-pack yokes, etc., which may cause injury or death. Marine turtles, particularly leatherbacks, are known to be attracted to floating plastic debris because it resembles their preferred food, the jellyfish. Ingestion of plastic and styrofoam materials could result in drowning, lacerations, digestive disorders or blockage, and reduced mobility resulting in starvation (MMS EIS 1993). The MMS prohibits the disposal of equipment, containers, and other materials into offshore waters by structure lessees (30 CFR 250.40). In addition, MARPOL, Annex V, Public Law 100-220 (101 Statute 1458), prohibits the disposal of any plastics at sea or in coastal waters.

Conclusion

Eventual explosive structure removal, if practiced, entanglement in mariculture net-pens, and vessel traffic resulting from mariculture operations could have an impact on marine turtles. Mariculture discharges could temporarily disturb some turtles and their habitats. The impact of future mariculture operations on marine turtles is expected to result in primarily sublethal effects (behavioral effects and nonfatal exposure to or intake of aquaculture discharges or discarded debris) that could be both chronic and sporadic.

Coastal and Marine Birds: Endangered and Threatened Species

Of the endangered coastal and marine birds found in the Northern Gulf of Mexico, the brown pelican is likely to willingly venture out to an oil and gas structure along the 100 to 200 isobath. Brown pelicans inhabit the coast, rarely venturing into freshwater or flying more than 32 km (20 mi) offshore (MMS EIS 1993). Brown pelicans have been removed from the Federal endangered species list in Alabama and Florida but remain listed as endangered in Mississippi, Louisiana, and Texas. Their decline is primarily the result of hatching failure caused by ingestion of fish containing pesticides (MMS EIS 1993). Nesting occurs in colonies on coastal islands. Pelicans are known to get caught in fishing line and may ingest plastic debris mistaking it for potential food.

Interaction with plastic materials is therefore very serious, and can lead to permanent injuries and death. It is expected that coastal and marine birds will seldom become entangled in or ingest OCS-related trash and debris as a result of MMS prohibitions on the disposal of equipment, containers, and other materials into offshore waters by lessees (30 CFR 250.40). In addition, MARPOL, Annex V, Public Law 100-220 (101 Statute 1458), which prohibits the disposal of any plastics at sea or in coastal waters, went into effect January 1, 1989. For the purpose of this analysis, OCS oil- and gas-related plastic debris will seldom interact with coastal and marine birds, and therefore, the effect will be negligible. The MMS prohibits the disposal of equipment, containers, and other materials into offshore waters by structure lessees (30 CFR 250.40). In addition, MARPOL, Annex V, Public Law 100-220 (101 Statute 1458), prohibits the disposal of any plastics at sea or in coastal waters.

Conclusion

Brown pelicans and coastal and marine birds are commonly entangled and snared in discarded trash and debris. In addition, many species will readily ingest small plastic debris, either intentionally or incidentally. The brown pelican may encounter periodic disturbance from proposed activities. It is expected that the majority of effects from mariculture on coastal and marine birds are sublethal (nonfatal exposure to or intake of OCS-related discarded debris).

It is possible that brown pelicans could be ensnared in the bird netting placed atop of floating net pens. Operators should attempt to disengage these birds if it occurs. The problem will be reduced the farther offshore an operation is.

Socioeconomic Environment

Since there are no commercial-scale mariculture operations in the Gulf of Mexico at present, any development of commercial-scale operations in a coastal community would obviously have some impact to the socioeconomic make-up of the community and region. The prediction of these impacts, both positive and negative, is obviously difficult without knowledge of where the facilities would locate along the Gulf of Mexico. Employment estimates for the "base case" operation include persons necessary for the offshore farm, base camp installation supporting the farm, staff for a hatchery – if that is in the plan of development – and possibly vessel crews to transport fingerlings and feed containers offshore, farm crew change-out, and product back onshore. Conservative estimates of employment for a start-up commercial-scale mariculture operation is 20 to 25 persons. Estimates of total annual salary for this staffing level is approximately $1,000,000. The impact to the local community closest to the onshore and offshore mariculture operations should not be too great for this size operation unless located in a very small town. Three quarters of this estimated staff is land-based therefore if they elected to live in the community, the multiplier effect (2.0) of indirect to direct labor could mean an increase in employment levels of 45 persons. It is doubtful whether even those numbers of direct and indirect employees plus spouses and children would cause a serious adverse affect on available infrastructure (roads, water, sewerage, drainage, hospitals, schools, etc.) on all but the smallest community. Obviously, as the industry expands and more operations are initiated the ripple effect could be significant and would have to be periodically evaluated.

Chapter

7

Management of Disease in Mariculture

Introduction

The feasibility of intensive production of marine fish in sea cages and other types of mariculture systems has been confirmed for a number of species on a worldwide basis and the potential for success exists for a number of others. Following an extensive literature review, and also drawing from my own experience, I have come to the conclusion that this form of aquaculture will probably experience the growing pains encountered in others and that is; as the technology increases to the point where fish growth rates and densities are maximized to reach production goals, disease will inevitably become a limiting factor in the production scheme. In some instances the diseases may be facultative in nature (caused by opportunistic bacteria or parasites) which only become significant when the cultured fish population becomes stressed due to poor water quality, overcrowding, injury resulting from handling, or inadequate nutrition. In other situations, high fish density and ease of transmission may allow obligate pathogens (bacteria or viruses) that are highly infectious and host specific to cause explosive mortality and high losses before they can be brought under control.

The control of parasitic diseases with chemical treatments is most economical in closed recirculating systems, tanks and small ponds. In order to treat cages or net pens, a plastic envelope would have to be fitted around the cage and aeration provided for a short-term (1-2 hour) treatment. Treatment with antibiotic feeds is usually an effective means of managing bacterial diseases; however, resistant strains of bacteria may be selected if antibiotics are used too often or in an improper fashion. In the case of food fish species that have only been cultured on an experimental basis, there may not be any drugs or chemicals cleared by the USFDA for treatment of disease. Permission from the USFDA to use a particular drug may be obtained in the form of an Investigational New Animal Drug Permit (INAD) which involves an agreement on the part of the producer to use the drug in accordance with FDA guidelines and to collect and report data on efficacy and residue etc. Ideally, a university researcher is involved in designing the protocols and helping with the presentation of data.

Vaccination is another management tool available but many fish vaccines are still in the developmental stage. If a particular fish species is known to be at risk from a disease year after year, vaccination may be the best route of management. This is true for the salmon industry, which was hampered by vibriosis until successful killed vaccines were developed for application to fingerlings by immersion before they are taken offshore to sea cages for grow-out.

If preventative measures are not effective, the ability to recognize a problem in its early stages by the producer and the utilization of available technical support such as that offered by the Aquatic Animal Diagnostic Laboratory at the LSU School of Veterinary Medicine may mean the difference between losing large numbers of fish or just losing a few.

In this report I will try to describe the various parasites and diseases that are known to affect the survival of the primary and secondary candidate species that have been proposed and suggest the best ways to manage these problems in a commercial aquaculture setting. In the second section I will list each candidate species and the diseases that are problematical for each. Any unusual host specificity or sensitivities to certain treatments will be discussed.

Parasitic Agents

Amyloodinium ocellatum

Epizootiology

The marine dinoflagellate protozoan parasite *Amyloodinium ocellatum* is, in my opinion, the most serious parasitic disease known from cultured marine fish. It affects all life stages from very small fingerlings to adults. This parasite has a complex life cycle which is completed more efficiently in aquaria, tanks and closed recirculating systems (Noga, 1996). This feature makes the parasite most devastating in the infection of brood fish held in closed spawning systems on temperature photoperiod regimes. Fry and fingerlings cultured in closed recirculating and semi-closed tank systems and ponds receiving low water replacement rates are also at risk. This parasite is not very host specific and is capable of infecting and causing disease in a variety of hosts (Lawler, 1977).

Life Cycle

The life cycle begins with a free-swimming dinoflagellate stage (dinospore) which attaches to the gills and skin of a fish host. The attached parasite (trophont) enlarges, becomes rounded, and sends rhizoid processes into the host cell and feeds on the epithelial tissue causing localized tissue damage to the epithelium at the site of infection. It has been speculated that a toxin may be released locally that has an overall effect on the pathology of the disease since numbers of trophonts present often seem inadequate to cause death of the fish. The parasite matures further, enlarges (50-350 μm), retracts its rhizoids (tomont stage) and drops off the host where it undergoes multiple divisions on the bottom of the tank (palmella stage). These give rise to approximately 50-250 infective motile dinospores. It has been my experience that red drum cultured in cages and net pens that have become infected with *Amyloodinium* or were stocked already infected, did not succumb to the disease and the parasite eventually disappeared. This indicates that even moderate water exchange, as occurs with tidal action, is adequate to disrupt the efficiency of the life cycle.

Environmental Requirements

The optimum temperature for development is 23 to 27∞C (73-81∞F). Infestations do not occur at less than 17∞C (63∞F). Disease has occurred in salinities ranging from 3 to 45 ppt but some isolates vary as to their salinity tolerance. Red Sea isolates do not reproduce below 12 ppt whereas Gulf of Mexico isolates cause disease efficiently at 3 ppt.

Treatment

Treatment of Amyloodiniasis is extremely difficult because of the complex life cycle. Certain stages are resistant to chemical treatment (trophont and tomont) and others (dinoflagellate) are very sensitive. Therefore it should be remembered when treating this parasite that you are only controlling one stage and multiple or continuous treatment will be required to eradicate it.

Formalin – 100-200 mg/l for 1-3 hours detaches the trophonts from the fish but they remain viable. This treatment may be of some benefit if large-scale water exchange is done following application and dislodging of the parasite. Dinospores seem to be somewhat resistant to formalin treatment.

Chelated Copper Sulfate – (Cutrine, Copper Safe®) is effective at levels between 0.15-0.2 mg/l free copper ion but these levels must be maintained almost continuously for one month to achieve eradication. Copper levels must be assessed daily with a copper test kit (e.g., LaMotte Chemical Co., Hach Chemical Co., Aquarium Systems).

Chloroquine Diphosphate – Chloroquine diphosphate at 10 mg/l kills dinospores immediately but has no effect on tomont division. Chloroquine may also be added to the feed at 10mg/kg/day for systemic control of the parasite.

Lowering the temperature – is usually not feasible and only suspends the development of the parasite.

Lowering the salinity – *Amyloodinium* can tolerate low salinities and usually fresh water is required to eradicate it. Red drum can tolerate fresh water extended periods and this may actually be one of the better treatments if it can be done without stressing the fish. Fresh water baths dislodges most but not all of the trophonts (Lawler 1977).

UV Irradiation – Dinospores are killed with UV irradiation however the rate of water exchange in a closed recirculating system may determine if this is an effective treatment or not. If the rate of exchange is not high enough the life cycle can be successfully completed in the tank.

Filtration – Dinospores may be removed from the water in a closed recirculating system by filtration through diatomaceous earth or saran screen however the pore size must be 10 mm or less since the dinospores range in size from 8-13.5 mm in length to 10-12.5 mm in width. A combination of UV irradiation and filtration may keep the parasite infestation rate at a low level and prevent mortality in closed systems.

Management

Management of amyloodiniasis is best accomplished by prevention of introduction of the parasite into the production cycle. Brood fish captured from the Gulf of Mexico, should be quarantined in a separate closed recirculating system where they can receive prophylactic treatments prior to stocking into the temperature photoperiod controlled spawning system. The suggested prophylactic treatments are as follows:

Formalin (static bath) – 100-200 ppm for 1 hour followed by flushing of the tank and replenishing with fresh synthetic seawater.

Chloroquine phosphate – 10 mg/kg/day in a gelatin capsule added to squid or other food item for one month.

Chelated copper sulfate – 0.15-0.2 mg/l free copper ion maintained continuously by checking with a copper test kit and adding additional copper as necessary for one month. At the conclusion of this one-month quarantine the brood fish can be added to the spawning system. Fry and fingerlings produced from these parasite-free brood stock should remain parasite-free as long as they are cultured in closed synthetic seawater systems or in ponds that are filled with saline ground water. Under no circumstances should natural unsterilized brackish water from bays, marshes or the Gulf of Mexico be used to culture the fry or fingerlings. This should maintain their parasite-free state until they are moved offshore where water exchange rates should be high enough to prevent the parasite from becoming a problem. Should fry or fingerlings become infected in the hatchery tanks or nursery ponds one of the above-mentioned treatments could be used to treat the infestation.

Cryptocaryon irritans

Epizootiology

This ciliated protozoan parasite is considered the marine counterpart to "Ich" and shows very little host specificity infecting 27 different species of fish in the New York Aquarium (Nigrelli and Ruggieri, 1966). Typical signs of infestation are white spots approximately 0.5 mm on the skin and gills. Although it is more obvious on the skin the majority of the pathology takes place on the gills. This parasite is difficult to treat having a complex life cycle almost identical to "Ich" in freshwater and similar to *Amyloodinium*. *Cryptocaryon* is an obligate parasite requiring a fish host to survive and therefore must be introduced into a new system by an infected fish or water from a source containing infected fish. Like other protozoan parasites with a complex life cycle, they are more prevalent in closed systems and prolonged treatment is required for eradication.

Life Cycle

The cycle begins with attachment of a small (20-50 mm) free-swimming stage (theront) to the skin or gill epithelium. This stage penetrates the epithelium and encysts within a nodule and forms the feeding stage (trophozooite or trophont). After feeding and enlarging (50-450 mm) the troph breaks through the epithelium, falls off the host and forms an encapsulated dividing stage (tomont). After several divisions, tomites break through the nodule wall to produce infective free-swimming theronts. The life cycle progresses fairly quickly and treatment must be administered as soon as the infection is diagnosed. Thus far, infections with this parasite have only been seen in red drum cultured in tanks and closed systems and it has not been reported from cage culture operations in Louisiana. It has, however, been reported as a problem in young grouper cultured in sea cages in Southeast Asia (Leong, T.S., 1990), in cultured sea bass and grouper in Thailand (Tookwinas, 1990), and in Japanese flounder (Kaige and Miyazaki, 1985). It is primarily a disease of ornamental marine aquarium fish and is a serious problem in large public aquaria (Joe Choromanski, Audubon Institute, personal communication).

Environmental Requirements

Cryptocaryon is pathogenic at 20∞ to 30∞C (68∞ to 86∞F) with optimum reproduction at the high end of the range. The life cycle can be completed in as few as 6 days however 11 to 15 days is most typical. Up to 200 theronts may be produced from one tomont. Lowering the temperature below 19∞C stops reproduction. The salinity tolerance is not as great as *Amyloodinium* and the parasite can be treated by lowering the salinity to 10 ppt. At 25∞C theronts remain infective for only 24 hours however tomonts have been observed to survive and release theronts as long as 72 days after leaving the fish.

Treatment

Treatment of this parasite should be done promptly following diagnosis because it reproduces quickly.

Formalin – 100-200 mg/l for 1-3 hours. Not known to be completely effective since encysted forms are not susceptible.

Chelated Copper Sulfate - Same as for *Amyloodinium*

Lowered salinity – lowering the salinity to 10 ppt or less is effective on euryhaline species such a red drum.

Chloroquine diphosphate – same as for *Amyloodinium*

Management

Since *Cryptocaryon* is an obligate parasite, avoidance or prevention of introduction via new fish by quarantine is the only logical approach in closed recirculating systems. Basically all the points made concerning *Amyloodinium* are true for this parasite. Caution: Fish that have survived outbreaks may have acquired immunity and can be carriers of low levels of the parasite. They can then infect new immunologically naive additions to the system which can later become diseased. Some of the reports in the literature indicate this parasite can attack fingerlings after transfer to sea cages and I find this troubling. Whether or not this will become a problem for red drum is yet to be determined.

Other protozoan ectoparasites: *Chilodonella, Brooklynella, Uronema, Cryptobia, Paramoeba* and *Epistylis*

Epizootiology

Organisms in this class are true parasites which reside on the surface of the host (skin and or gills) and cause localized damage at the site of attachment. They may or may not be obligate parasites and host specificity varies with the individual parasite. They are differentiated from the first two parasites discussed in that they reproduce by binary fission and do not have a complex life cycle and replicate without leaving the host. Therefore, treatment of this class of parasite is much easier than *Amyloodinium* or *Cryptocaryon* with only a single application of a chemical being required. The trichodinid ciliates usually cause mild disease with the harmful effects resulting from blockage of the respiratory epithelium when the ciliates reach high numbers. The others in this group cause more localized gill and skin pathology and there is evidence that the protozoa feed directly on the gill epithelium. Secondary bacterial infection is common with most of these parasites. The flagellate *Cryptobia branchialis* is a weak pathogen and like its freshwater counterpart *Ichthyobodo* is an indicator of poor water conditions or stress. These parasites can occur at a wide range of temperatures and salinities. *Epistylis* is the cause of "red sore disease" and typically causes shallow ulcerations at the base of the stalk which are invariably infected by secondary bacterial organisms. Gill amoeba have not been reported from any of the candidate species but have been seen as pathogens of trout after transfer from fresh water to sea cages.

Treatment

Formalin – 15 ppm indefinitely or 100-200 ppm for 1-3 hours. Should eradicate the parasites with a single treatment. Fish should be examined periodically for recurrence.

Chelated Copper Sulfate – add to achieve an initial dosage of 0.2 ppm copper ion. A single treatment should suffice to eradicate all of the above parasites.

Lowered salinity – certain parasites such as *Brooklynella, Uronema* and *Paramoeba* are strictly marine and lowering the salinity to 10 ppt or less should effect control.

Management

Fry and fingerlings should be monitored and treated with chemical treatments as needed in the hatchery and nursery ponds. Is imperative that fish be free of all parasites of this type prior to moving offshore. If fish densities are kept at a reasonable level, stress is kept at a minimum and good nutrition is supplied, the chances of having to treat these types of parasites in grow out cages should be low.

Ectocommensal protozoa: *Apiosoma* (formerly *Glossatella*), *Ambiphrya* (formerly *Scyphidia*), *Riboscyphidia.*, *Trichodina*, *Trichodinella*, and *Dipartiella*

Epizootiology

These organisms are not true parasites but are believed to be ectocommensal, using the gill or skin as a place for attachment and to gain access to food and deriving little if any nutrition directly from the fish. Attachment takes place by a holdfast present on the base of the organism and results in little or no damage to the epithelium of the host. Increasing loads of these organisms on the gills are indicators of stress or poor nutrition in the host. Heavy loads of ectocommensals impede water flow and gas exchange at the surface of the gill lamellae resulting in fish behaving as if they were suffering from an oxygen depletion when levels of oxygen are still adequate in the water. These organisms have a simple life cycle reproducing by binary fission and show little host specificity. They seem to increase in number in the cooler months of the year and decline in the mid summer.

Treatment

Treatment of these organisms should always be accompanied by improving the environment.

Formalin – 100-200 mg/l for 1-3 hours. The parasites in this class are usually easily controlled and a single application is adequate. Some species of ectocommensals develop resistance to formalin and should be treated with copper sulfate.

Chelated Copper Sulfate – A single dose of 0.15-0.2 ppm is usually effective in eradicating ectocommensals.

Lowered salinity – Lowering the salinity rapidly should control most marine ectocommensals. Those that are encountered in brackish water environments may be able to tolerate more of a salinity change.

Management

Management of this group is the same as the protozoan ectoparasites #3.

Microsporidian protozoa: *Glugea, Pleistophora* and *Nosema*

Epizootiology

A number of debilitating parasitic diseases of marine fish are the result of microsporidian invasion and proliferation. These are often diseases seen in wild caught fish and tend to affect survival of the young more than the older fish. They are also responsible for a number of serious disease in cultured fish (Noga, 1996). Microsporidians, unlike the myxosporidia, are intracellular parasites which cause hypertrophy of host cells to form grossly visible cysts or tumor-like areas "xenomas." The host tissues and organs most seriously affected are the skin, muscles, digestive tract, and nerves. In some cases the infections can be debilitating to the host without causing mortality. The intestine may become occluded, and the ovaries or testes degenerate in advanced infections. Tumor-like masses in the muscle tissue of fish can affect marketability of fillets.

Life Cycle

Microsporidians are not seen as commonly as myxosporidians and are usually very host-specific, however, some such as *Pleistophora hyphessobryconis* and *Glugea stephani* can infect a broad range of fish species. All microsporidians are intracellular parasites with a direct life cycle. A thick-walled spore is formed which contains the sporoplasm. When a host ingests the spore, the sporoplasm is discharged through the channel of a tubular polar filament that is stored coiled within the spore. The sporoplasm then migrates to the target organ and starts a proliferative phase (merogony), producing a large number of cells (meronts) by binary or multiple fission. In the final stages, meronts give rise to sporonts which undergo sporogony producing mature spores. Mature spores may be released from the host by the rupture of a cyst near the body surface or after death of the host. How infection spreads within a host is unknown.

Treatment

Aside from disinfection and quarantine there are no proven treatments for microsporidian infections.

Myxosporidian protozoans: *Kudoa, Henneguya* and *Myxobolus*

Epizootiology

Diseases caused by members of the phylum *Myxozoa* are common in marine fish (Lom, 1984). They are usually very host specific infecting only one species or a closely related group. Many wild caught fish harbor myxosporidians but epizootics in tank or aquarium reared fish have not been reported. This is probably the result of an intermediate host being absent in the tank environment.

The myxozoa localizing in the somatic muscles of marine fish are considered some of the most destructive parasites and can be of great economic impact. These histozoic forms are associated with a condition in which the muscle tissue contains necrotic foci associated with cysts containing numerous spores characterized by rapid postmortem deterioration. I have diagnosed *Kudoa* sp. causing this condition in cage-reared hybrid striped bass in Louisiana but it occurred in one year only and mortality was light (Hawke, LAADL Case records, 1991). Infection with histozoic myxosporidians possibly would lower the value of the fillet even if mortality was light. Myxosporidians may infect other tissues as well including the pyloric caecae, intestine, heart, liver, gall bladder, urinary bladder, brain, spinal cord and gills.

Life Cycle

The parasites in this group are obligate parasites of tissues i.e. histozoic forms that reside in intercellular spaces of certain target organs. The characteristics of the Myxozoa include the

development of a multicellular spore, presence of polar capsules in their spores and endogenous cell cleavage in both the trophozoite and sporogony stages. There is evidence that at least some of the myxosporidians have an indirect life cycle that involves a vertebrate (fish) and an invertebrate (annelid) with each life cycle having its own sexual and asexual stages. The early stages of the life cycle in fish usually incite little host reaction but plasmodia accompanied by mature spores cause considerable inflammation. In many cases, tissue damage is greatest after death of the host when enzymes released by the parasites cause muscle liquefaction.
The occurrence of myxosporidians in pelagic hosts also suggests a method of transmission from fish to fish by spore release or the existence of a planktonic intermediate host.

Treatment

There have historically been no treatments for myxosporidians other than controlling intermediate hosts such as snails. New drugs for the treatment of these infections such as fumagillin may be cleared in the near future.

Monogenetic trematodes - *Gyrodactylus, Neobenedenia, Benedenia, Ancyrocephalus, Axine, Heteraxine, Microcotyle, Bicotylophora*

Epizootiology

Monogeneans are ectoparasitic worms that are blood, tissue, and mucus feeders. The trematodes are divided into two major groups and four subgroups: the gyrodactylids, the dactylogyrids and the capsalids which are in the Monopisthocotylea and possess an attachment organ (haptor) consisting of hooks, clamps, and suckers that may cause extensive damage to the gills and skin of hosts and the Polyopithocotylea which possess a haptor made up of a battery of small muscular adhesive suckers. Additionally, monogeneans have a direct life cycle which allows for rapid proliferation directly on the host or when fish are closely confined in tanks and aquaria. Most show host specificity however this may break down in aquaculture situations. Environmental stress, as a result of poor sanitation, poor nutrition, and deteriorating water quality may cause fish to become more heavily infested with these parasites. Adult fish can usually tolerate low levels of infestation with no ill effects. Reproduction rate is under temperature control with the fish being at greatest risk in the spring. Monogeneans that have hooks and anchors that pierce the skin can also transmit pathogenic bacteria and other agents (Cusack and Cone, 1986).

Reproduction

Two major modes of reproduction exist within the monogenetic trematodes which affects management strategy. Oviparous monogeneans lay eggs that usually settle to the bottom to develop. After hatching, the free swimming infective stage (oncomiracidium) seeks out and attaches to a new host and crawls to its final attachment site. Viviporous monogeneans give birth to living young at the site of attachment to the host.

Treatment

Formalin – 100-200 mg/l for 1- 3 hours will control but may not eradicate all the trematodes that are embedded in and protected by mucus. Repeated treatments may be required.

Organophosphate bath – For marine capsalid monogeneans add 2-5 mg trichlorfon per liter for 1 hour or .25 mg/l indefinitely.

Freshwater bath – only practical on euryhaline species.

Praziquantel – for marine monogeneans 20 mg/l for 1.5 hours, 10 mg/l for 3 hours or as a prolonged immersion at 2 mg/l.

Digenetic trematodes (grubs)

Adult digenetic trematodes are common in the digestive tracts of marine fish with over 1300 species being described and marine fish also harbor the larvae (metacercareae) of trematodes the definitive hosts of which are shore inhabiting birds or mammals. These parasites have little impact on the survival of fish in mariculture so they will not be discussed further.

Cestodes (tapeworms)

As in the case of the trematodes cestodes commonly infest the digestive tract and have little impact on the cultured fish. On the other hand, some larval forms encyst in the muscle tissue of fish as part of the intermediate stage of the life cycle and may cause the fillet to be unsightly. The parasite of this type known from the Gulf of Mexico is the spaghetti worm *Poicilancistrium caryophyllum* which is commonly seen in spotted seatrout.

Nematodes

Nematodes are also seen in wild fish from the Gulf of Mexico, but do not pose a serious threat to cultured fish. The best known worm of this type is *Anisakis* which can cause gastric problems in humans if fish infested with this parasite are eaten raw.

Copepods: sealice *Caligus*, fish lice *Argulus*, *Ergasilus*

Of the known parasitic copepods 90% are marine and can cause severe damage to the host. These parasites are becoming increasingly important in cultured fish populations.

Life Cycle

The life cycle of parasitic copepods typically comprises 1-5 free-living nauplius stages , 1-5 free-living or parasitic copepodid stages, 1 pre-adult and adult. Three major types are found on cultured fish: ergasiliform, caligiform, and lernaeiform. The sea lice are in the caligiform type and are most important in marine aquaculture. Once established in a cultured population, parasite numbers slowly increase over time, eventually causing an epidemic. Cultured fish are infected by wild fish which carry low numbers of the parasites.

Treatments

Organophosphate bath – see above

Formalin bath – see above

Freshwater bath – see above

Isopods

Parasitic isopods are common crustacean parasites of wild tropical marine fish. They are rare in cultured fish although some problems occur in sea-caged salmonids in Australia. The large parasites are visible on the skin or in the gill chamber of the host and because of their large size can cause considerable damage by biting and sucking fluids from the host. There are no published treatments for the control of isopods.

Turbellarians

Turbellarians are a phylum of free living worms related to the trematodes. Only a couple of parasitic turbellarians are known and these are the tang turbellarian *Paravortex* and one from cultured carangids tentatively identified as *Ichthyophaga* sp. The latter produces a proliferative epithelial response and could be considered a potential problem in mariculture. Treatments include freshwater baths, formalin baths, organophosphates and praziquantel.

Bacterial Diseases

Photobacteriosis (Synonymous with, Pasteurellosis, Pseudotuberculosis) – *Photobacterium damsela* subsp. *piscicida* – previous name *Pasteurella piscicida*

Epizootiology

Photobacterium damsela subsp. *piscicida* is a gram negative, marine bacterium that causes a generalized septicemia in a variety of fish hosts. It is recognized as one of the most serious diseases of cultured marine fish in Japan causing heavy economic losses yearly since the 1970s. Since 1990 it has been recognized as one of the most significant diseases of cultured marine fish in the Mediterranean. It is a slow growing somewhat fastidious organism that is best isolated on media such as blood agar or BHI with 2% salt. The disease progresses rapidly and clinical signs are not always obvious. The name "pseudotuberculosis" is given in reference to granulomatous white lesions seen in the spleen of diseased Japanese yellowtail. Hybrid striped bass and striped bass are highly susceptible to infection by this bacterium and fail to show any clinical signs except for splenomegaly. The bacterium is thought of as an obligate pathogen, surviving for only a few days in water but remaining viable for a number of months in bottom muds. Transmission of photobacteriosis is believed to be primarily via the water route since experimental challenges with as few as 1000 cells per ml cause 50% mortality in hybrid striped bass (Hawke, 1996).

Environmental Requirements

Photobacteriosis has a narrow temperature window in which disease can occur. Most outbreaks occur between 20 and 26∞∞C, although in the laboratory growth occurs between 15 and 30∞∞C. The bacterium is halophilic, having a salt requirement of 0.5% in growth media. The salinity range in which mortalities have been recorded is 5-30 ppt. The organism appears to be endemic to the Northern Gulf of Mexico region with mortalites occurring yearly since 1990 in hybrid striped bass cultured in Louisiana (Hawke, 1997 LAADL).

Treatments

Treatment of photobacteriosis is difficult due to the rapid onset of infection and disease. Diseased fish lose their appetite making therapy with oral antibiotics fruitless. Antibiotic therapy via medicated feeds has been successful when administered early in the infection prior to fish going off feed. Treatment is complicated by the development of resistant strains of the bacterium following exposure to the antibiotics Romet and Terramycin. This is a common problem in Japan and has been documented in Louisiana outbreaks when antibiotic feeds were used. The resistance was shown to be the result of a plasmid carrying genes for resistance to Romet and Terramycin (Hawke, 1996). Amoxicillin and Ampicillin have also shown promise but recurrent infections have been a problem with all antibiotics tried. Currently there are no antibiotics cleared by the USFDA for the treatment of bacterial disease in the candidate species listed and treatment must be applied under the requirements of an Investigational New Animal Drug (INAD) protocol obtained through the USFDA. For the aforementioned reasons, vaccination is believed to be the best management tool for photobacteriosis in the future. Current research at the LSU School of Veterinary Medicine has resulted in development of both killed and live attenuated vaccines for this disease. These vaccines are in the early developmental phases and are not ready for commercial use.

Amoxicillin – 80 mg/kg/day for 10 days in feed by INAD

Oxytetracycline – 80 mg/kg/day for 10 days in the feed by INAD or Catfish feed

Romet – 50 mg/kg/day for 5 days in feed by INAD or Catfish feed

Vibriosis (synonymous with Bacterial Hemorrhagic Septicemia) – *Vibrio anguillarum, V. damsela, V. vulnificus, V. harveyi* and various other species

Epizootiology

Vibriosis is caused by one of several members of gram negative bacteria in the genus Vibrio and is one of the most important diseases affecting marine fish. The range of host susceptibility is very large with probably all marine species being susceptible to one or more species. The vibrios are facultative pathogens that live and multiply in the environment and different environmental strains and fish pathogenic strains may exist. The highest prevalence of environmental strains is in the highly enriched near-shore seawater and brackish waters of bays and marshes. Except for a few cold water salmonid pathogens, vibriosis is a disease caused by opportunistic pathogens when fish are under environmental stress.

Vibrio anguillarum is the most common of the fish pathogenic vibrios causing disease in salmonids and other cold water species when they become stressed due to high water temperatures in the summer and it can be a pathogen of warm water fish in the winter. *V. anguillarum* has been isolated from diseased hybrid striped bass cultured in cages in the winter months in South Louisiana (Hawke, 1991 LAADL case records). This bacterium causes a septicemia much like *Photobacterium* which is accompanied by acute mortality if the fish are under stress and chronic mortality if conditions are good.

Other vibrios such as *V. vulnificus* and *V. damsela* have only recently been recognized as fish pathogens and cause a variety of clinical signs in infected fish. These organisms primarily cause external infections such as skin ulceration and fin rot and generally do not cause heavy mortality. *Vibrio damsela* is now synonymous with *Photobacterium damsela. V. harveyi* has been isolated from snook following transport and from wild jack crevalle.

Environmental Requirements

The vibrios as a group are halophilic organisms, requiring salt in the medium for growth. Only *V. cholerae* and *V. mimicus* do not have a salt requirement even though they have a high salt tolerance and are often isolated from coastal waters. Vibriosis occurs over a wide temperature range but as stated earlier *V. anguillarum* occurs most frequently in the winter on the Gulf Coast and *V. vulnificus* and *V. damsela* occur more frequently in the summer when temperatures are highest.

Treatment

Vibriosis is a classical example of a stress related disease. Treatments are much more effective and losses much lower if stress is kept at a minimum. Medicated feeds containing Romet or Terramycin are effective in reducing mortalities. For rates see previous section. Amoxicillin is not effective.

Enteric bacterial disease – *Edwardsiella tarda, Citrobacter freundii*

Epizootiology

Enteric disease caused by the gram negative bacteria *E. tarda* and *C. freundii* are rare diseases in cultured marine fish. *E. tarda* is primarily a disease of eels and sea bream in Japan causing heavy losses in the summer months and *C. freundii* has occasionally caused disease in marine fish in public display aquariums. Edwardsiellosis in marine fish is characterized by hemorrhagic ulcers on the body surface. Dying fish display erratic swimming behavior and may exhibit malodorous abscesses with hemorrhagic ulcers on the body surface and head and exophtalmia.

Treatment

Treatment is the same as for other gram negatives with oxytetracycline and Romet being most effective. Vaccination is not thought to be feasible since as many as 148 different serotypes have been identified.

Streptococcosis/Enterococcosis – *Enterococcus seriolicida, Enterococcus faecalis, Streptococcus iniae, Streptococcus difficile* and Group B *Streptococcus* sp.

Epizootiology

Since 1974, streptococcosis has been recognized as one of the most serious diseases in marine aquaculture in Japan causing millions of dollars in losses yearly. The disease once known as streptococcosis is now recognized as a complex of diseases caused by an assortment of gram positive *Enterococci* and *Streptococci* that are only now being placed in the proper taxonomic categories. *E. seriolicida* is the most important organism economically, causing heavy losses in cultured yellowtail. *E. seriolicida* causes a form of hemorrhagic septicemia that begins with bacterial proliferation in the intestinal tract. The development of the disease is related to toxins produced by the bacterium including hemolysins, leukocidins and proteases. A common clinical sign of this disease is erratic swimming behavior and exophthalmia resulting from infection of the brain, optic nerve and eye. These signs are common to all streptococcal infections in all species.

Disease in mariculture of hybrid striped bass in Louisiana waters caused by a Group B type Ib *Streptococcus* sp. occurred yearly between 1989 and 1993. This bacterium has also been implicated in fish kills in brackish water areas in Alabama, Florida, Maryland and Louisiana (Plumb et al. 1974, Baya et al. 1990, and Hawke 1997 LAADL case records), causing mortality in a variety of marine species. This organism causes disease in *Fundulus grandis* (cocahoe minnows) which are cultured in brackish water ponds and recirculating systems. A question exists as to whether this bacterium is the same as *S. difficile* which has been described as a pathogen of tilapia reared in brackish water ponds in Israel or if it is a biotype of *S. agalactiae*. In any case this organism presents a threat to a number of species that may be cultured in gulf waters.

Streptococcus iniae is best known as a disease of tilapia reared in freshwater recirculating systems but has been shown to be an important pathogen in Japanese mariculture causing disease in yellowtail.

Environmental Requirements

Streptococci grow and cause disease in a wide range of salinities and a wide range of temperatures however disease is most pronounced in the warmer months. Most streptococci grow well at 37∞C and some such as the enterococci grow at 45∞C.

Treatments

Best results in treatment of this disease have been obtained with erythromycin, amoxicillin, ampicillin, oxytetracycline and spiromycin in medicated feed. Thus far an effective vaccine has not been developed.

Mycobacteriosis/Nocardiosis – *Mycobacterium marinum*, *Nocardia asteroides, N. kampachii*

Epizootiology

Both mycobacteriosis and nocardiosis are chronic, slowly progressing diseases which cause low level mortality and are caused by gram positive, acid-fast, rod-shaped bacteria. Mycobacteriosis "fish tuberculosis" is primarily a disease of captive marine fish raised in tanks or aquaria. Hybrid striped bass are particularly susceptible to mycobacteriosis but few cases have been reported from pond cultured or cage cultured fish in Louisiana. Mycobacteriosis is characterized by granulomas in the liver, kidney and greatly enlarged spleen of susceptible hosts. Affected fish lose their appetite and begin a process of wasting and weight loss until they die.

Nocardiosis, on the other hand, is an important disease in Japanese mariculture causing disease in cultured yellowtail. Most cases of this disease occur in the late summer and early fall with the bacterium having an optimum temperature range of 25-28∞C. The disease is characterized by abcess-like lesions in the skin and tubercles in the spleen.

Treatment

Little information is available on the treatment of acid-fast bacterial infections in fish. In most cases the length of time required for effective treatment is so long that the cost is prohibitive.

Anaerobic bacterial infection – *Eubacterium tarantellus*

Epizootiology

Anaerobic bacteria are not generally known as pathogens of marine fish but recent literature contains accounts of epizootics and mortalities in cultured fish due to the bacterium *Eubacterium tarantellus*. The disease, which usually presents as a meningitis, causes disoriented behavior in infected fish followed by emaciation and mortalities. Natural fish kills have been reported from the Texas Gulf Coast (Henley and Lewis 1976) as well as Biscayne Bay, Florida (Udey et al. 1977) and also occasional disease has been documented in cultured red drum fingerlings (Hawke LAADL case records).

Treatment

Treatment of *Eubacterium* infections is accomplished with oxytetracycline medicated feed.

Myxobacteria – *Flexibacter maritimus* and related organisms

Epizootiology

Flexibacter columnaris is one of the most important pathogens of fish cultured in fresh water. *F. maritimus* causes a disease which is the marine counterpart to columnaris disease. Saltwater myxobacteriosis occurs typically in fry or fingerlings and infections appear to be secondary to mechanical damage to the skin or fins. Environmental stress also seems to exacerbate disease problems due to this pathogen. The disease is best known from salmonids reared in sea cages but can occur in many other species being cultured under stressful conditions.

Treatment

Treatment of saltwater myxobacteriosis is best accomplished by the removal of stress. Chemical treatment with potassium permanganate at 2 ppm over the demand or hydrogen peroxide at 150 ppm may be effective. Feeds medicated with Romet or Terramycin may also be effective.

Rickettsial Diseases

A new disease of salmonids reared in marine sea cages off the coast of Chile is *Piscirickettsia salmonis*. Thus far there is no reason to suspect this disease will affect any of our candidate species so it will not be discussed further.

Viral Diseases

Viral diseases have received increased attention in recent years due to the emergence of new viral diseases in freshwater aquaculture, mariculture and crustacean aquaculture. Viruses are best known in marine fish as agents of neoplastic, hyperplastic and hypertrophic diseases however some are known to cause mortality particularly in fry or fingerlings. Most of the viruses of marine/euryhaline species that have been isolated or visualized have a restricted geographic range. A few are widespread in their occurrence and will be discussed individually. These include lymphocystis, viral erythrocytic necrosis (VEN), infectious pancreatic necrosis (IPN), infectious hematopoietic necrosis (IHN), viral hemorrhagic septicemia (VHS) and viral nevous necrosis (VNN). It should be pointed out that to isolate and propagate a virus, so that River's postulates may be satisfied, one is required to have a suitable cell line capable of supporting viral replication. For many marine species, particular some of the candidate species listed in the feasibility study, these cell lines do not exist. Treatment of viral diseases of fish is not feasible and avoidance is the only method of control. Since young fish are most susceptible to mortality from viral disease, sanitation in the hatchery and avoidance is most important.

Lymphocystis

Lymphocystis is probably the best known viral disease of marine fish. It has a broad host range infecting 33 families of fish and over 83 species. Lymphocystis manifests as grey to white nodules on the body and fins of fish caused by the hypertrophy of fibroblasts and osteoblasts. The connective tissue cells grow to a large size and become surrounded by a capsule. Lymphocystis may occur occasionally at epizootic levels in wild populations of fish and has also been documented from intensively cultured fish. The principal transmission of lymphocyctis is by waterborne virus. This virus has a broad host range being described from 30 families of fish. The disease is rarely fatal but greatly disfigures affected individuals. On the basis of several characteristics the causative agent has been described as an iridovirus.

Viral Erythrocytic Necrosis (VEN)

Viral erythrocytic necrosis is known principally from marine teleosts and the primary pathological condition is infection of the red blood cells by an iridovirus. Intensity of infection is variable with from 1 to > 90% of red blood cells affected. The result of severe infection is anemia and susceptibility to stress and secondary infection. Massive mortalities have not been reported for this disease however. The virus has a fairly broad range with 17 families of fish known to be susceptible.

Infectious Pancreatic Necrosis (IPN)

Infectious pancreatic necrosis was the first virus disease described from fish and has been isolated over the years from a variety of marine and euryhaline species. The virus, described as a birnavirus, has been proposed as the cause of "spinning disease" in Atlantic menhaden and has caused mortalities in southern flounder and three other species from the east coast of the U.S. The relationship of IPN virus with disease in fish is not always clear as the virus is sometimes isolated from asymptomatic and atypical hosts such as the striped bass.

Infectious Hematopoietic Necrosis (IHN) and Viral Hemorrhagic Septicemia (VHS)

IHN and VHS are primarily viral diseases of salmonids and will not be discussed further.

Viral Nervous Necrosis (VNN)

VNN is a newly described viral disease in Japanese mariculture, also known as viral encephalopathy and retinopathy, which affects larval and juvenile sea bass, turbot, parrotfish, redspotted grouper, and striped jack. This viral infection usually results in massive mortality in affected stocks of fish. The agent of VNN in striped jack has been identified as a nodavirus. The clinical signs of infection include: whirling or corkscrew swimming, swimbladder hyperinflation. The earliest mortalities occur 9 days post hatch and vertical transmission has been confirmed in striped jack.

Control of VNN is difficult because of the vertical transmission. Screening broodfish by PCR techniques should insure specific pathogen free (SPF) brood stock. Reduced stress on spawning populations may also alleviate the occurrence of disease.

Susceptibility of Candidate Species

In the following section in table form, I will list the candidate species and those diseases which I feel are a threat to their survival. The codes for the tables are as follows:

"blank"	organism not expected to occur
+	organism has the potential to occur at low levels but little or no adverse affect is expected
++	organism has the potential to occur at moderate levels but is unlikely to cause adverse affects or mortality
+++	organism has the potential to occur at moderate levels and cause some adverse affects and mortality
++++	organism has the potential to occur at heavy levels or high incidence and cause significant mortality

The red drum is an excellent species to begin evaluation of offshore aquaculture. Much is known about its reproduction, larval culture, nutrition and growth rates. From a disease standpoint it is one of the most hardiest fish. Of course new problems may surface with this new form of aquaculture but that is true for any of the species being tried.

Diseases which will be most troublesome will occur in the fingerling production phase and these include *Amyloodinium ocellatum, Cryptocaryon irritans, Vibrio vulnificus and Vibrio* sp.

I will reiterate that disease control begins with good conditions in the hatchery and fingerling culture in ponds receiving saline ground water free of infectious diseases and parasites. If fish can be brought through this early fry/fingerling stage of culture in good condition chances of disease occurrence in grow-out will be greatly reduced. Disease is a fact of life in all forms of aquaculture and the goal is to minimize problems.

Diseases are reported from snapper in general since very few references could be found for *Lutjanus campechanus.*

Diseases of yellowtail *Seriola quinqueradiata* are used as examples of problems that might be encountered in amberjack since they are in the same genus.

Extensive work has been done on the treatment of diseases in cultured yellowtail that can be applied to cultured amberjack.

Cobia and Dolphin – At this time references to diseases of mahimahi or cobia are being searched for. As additional information on parasites and diseases of these hosts is obtained it will be forwarded as a supplement to this report.

MANAGEMENT OF DISEASE IN MARICULTURE
BY JOHN P. HAWKE, PH.D.

Table 1. Red Drum

Parasitic Agents

Disease or Parasitic Agent	Hatchery Phase	Fingerling Pond Phase	Grow-out Phase
Amyloodinium	+	++++	+
Cryptocaryon	+	++++	++
Trichodinids	+	++++	+++
Ambiphrya	+	++++	+++
Henneguya ocellata		+	++
Parvicapsula renalis		+	++
Epieimeria ocellata		+	++
Goussia floridana		+	++
Cryptosporidium		+	++
Gyrodactylus		+++	++++
Caligus		++	+++
Argulus		++	+++
Isopods			++

Table 1. Red Drum

Bacterial Agents

Disease or Bacterial Agent	Hatchery Phase	Fingerling Pond Phase	Grow-out Phase
Vibrio vulnificus	++	++++	+++
Vibrio anguillarum	++	++++	+++
Vibrio damsela	++	++++	+++
Aeromonas spp.	++	++++	+++
Streptococcus sp.	++	++++	+++
Eubacterium	+	++++	+++
Flexibacter sp.	+	++	++

Table 1. Red Drum

Viral Agents

Disease or Viral Agent	Hatchery Phase	Fingerling Pond Phase	Grow-out Phase
Lymphocystis		++	+++

Table 2. Hybrid Striped Bass

Parasitic Agents

Disease or Parasitic Agent	Hatchery Phase	Fingerling Pond Phase	Grow-out Phase
Amyloodinium	+	+ + + +	+
Cryptocaryon	+	+ + + +	+ +
Trichodinids	+	+ + + +	+ + +
Ambiphrya	+	+ + + +	+ + +
Epistylis	+	+ + + +	+ +
Apiosoma	+	+ + + +	+ + +
Riboscyphidia	+	+ + + +	+ + +
Kudoa spp.		+ +	+ + +
Gyrodactylus		+ + +	+ + + +
Dactylogyrus		+ +	+ + +
Isopods			+ +

Table 2. Hybrid Striped Bass

Bacterial Agents

Disease or Bacterial Agent	Hatchery Phase	Fingerling Pond Phase	Grow-out Phase
Photobacterium	+	+ + + +	+ + + +
Vibrio anguillarum	+	+ + + +	+ + + +
Vibrio vulnificus	+	+ + + +	+ + +
Streptococcus sp.	+	+ + + +	+ + + +
Aeromonas spp.	+ + +	+ + +	+ + +
Mycobacterium sp.		+ +	+ + + +
Flexibacter sp.	+ + +	+ + +	+ + +

Table 2. Hybrid Striped Bass

Viral Agents

Disease or Viral Agent	Hatchery Phase	Fingerling Pond Phase	Grow-out Phase
Infectious Pancreatic Necrosis	+ + +	+ + +	+ + +
Lymphocystis		+ +	+ + +

Table 3. Pompano

Parasitic Agents

Disease or Parasitic Agent	Hatchery Phase	Fingerling Pond Phase	Grow-out Phase
Amyloodinium	+	++++	+
Cryptocaryon	+	++++	++
Trichodinids	+	++++	+++
Ambiphrya	+	++++	+++
Gyrodactylus		+++	++++
Neobenedenia		+++	++++
Bicotylophora		+++	+++
Cryptobia	+	+++	+++

Table 3. Pompano

Bacterial Agents

Disease or Bacterial Agent	Hatchery Phase	Fingerling Pond Phase	Grow-out Phase
Aeromonas spp.	+++	++++	+
Vibrio anguillarum	+++	++++	++++
Vibrio vulnificus	++	+++	++++

Table 4. Grouper

Parasites

Disease or Parasitic Agent	Hatchery Phase	Fingerling Pond Phase	Grow-out Phase
Cryptocaryon	+	++++	+++
Amyloodinium	+	++++	++
Sphaerospora		+	+++
Pseudorhabdosynochus		+	+++
Prosorhynochus		+	+++
Benedenia		+	+++

Table 4. Grouper
Bacteria

Disease or Bacterial Agent	Hatchery Phase	Fingerling Pond Phase	Grow-out Phase
Vibrio alginolyticus	++++	++++	+++
V. harveyi	++++	++++	+++
V. parahaemolyticus	++++	++++	+++
V. vulnificus	++++	++++	+++

Table 4. Grouper
Viruses

Disease or Viral Agent	Hatchery Phase	Fingerling Pond Phase	Grow-out Phase
Nodavirus (VNN)	++++	+++	
Picorna-like virus	++++	+++	
Reovirus	++++	+++	

Table 5. Snapper

Diseases are reported from snapper in general since very few references could be found for *Lutjanus campechanus*.

Parasites

Disease or Parasitic Agent	Hatchery Phase	Fingerling Pond Phase	Grow-out Phase
Amyloodinium	+	++++	+
Cryptocaryon	+	++++	+
Haliotrema		++	++++

Table 5. Snapper

Bacteria

Disease or Bacterial Agent	Hatchery Phase	Fingerling Pond Phase	Grow-out Phase
Vibrio spp.	+ + + +	+ + + +	+ + +
Streptococcus sp. Group B	+	+ + +	+ + + +
Flexibacter sp.	+ + +	+ + + +	+ +

Table 6. Amberjack (Yellowtail)

Diseases of yellowtail *Seriola quinqueradiata* are used as examples of problems that might be encountered in amberjack since they are in the same genus.

Parasites

Disease or Parasitic Agent	Hatchery Phase	Fingerling Pond Phase	Grow-out Phase
Amyloodinium	+	+ + + +	+ +
Cryptocaryon	+	+ + + +	+ +
Kudoa sp.		+ +	+ + + +
Benedenia		+ +	+ + + +
Heteraxine		+ +	+ + + +
Caligus		+ +	+ + + +

Table 5. Snapper

Bacteria

Disease or Bacterial Agent	Hatchery Phase	Fingerling Pond Phase	Grow-out Phase
Enterococcus	+ +	+ + + +	+ + + +
Photobacterium	+ +	+ + + +	+ + + +
Vibrio anguillarum	+ +	+ + + +	+ + + +
Nocardia kampachii	+	+ + +	+ + + +
Edwardsiella tarda	+ +	+ + + +	+ + + +
Streptococcus iniae	+ +	+ + + +	+ + + +
Mycobacterium sp.		+ +	+ + + +
Flexibacter sp.	+ + +	+ + + +	+ + +

Chapter 8

Market Analysis

Supply of Fishery Products

Consumers of seafood in the United States have needs met by domestic capture fisheries, domestic aquaculture, imports from capture fisheries and imports of aquaculture origin. Therefore, estimating total supply in a timely manner is difficult. There are also many sources of data and a diversity of species. Consumption estimates, kept on an edible weight basis, are not readily compared to supply, reported on a live weight basis. In addition, the significant contribution of imported products to supply complicates comparisons. The imported data are reported by U.S. Customs on a product weight basis. Live weight, product weight and edible weight data appearing in government documents related to supply and utilization must be acknowledged in usage. Otherwise comparisons will be misleading. Conversion data to live weight or other choice was pursued when information facilitated accuracy.

The focus of the net pen mariculture project for the northern Gulf of Mexico is finfish. Supply data are identified for edible finfish species by source (Table 1). The live weight edible finfish supply from domestic and import sources increased from approximately 7 billion pounds to 10.7 billion pounds between 1985 and 1996. (The product weights of edible finfish imports are shown in Table 2). Imported finfish exhibited a no-growth to minor decrease trend during the period. The frequently reported poor performance of domestic fisheries is not evident from the approximate tripling of domestic finfish production. This annualized growth of 10.1 percent had its origin in the pollock and salmon fisheries of the north Pacific. A negative trend in finfish imports pulled the net growth rate in total supply (10.1%) down to 4 percent annually.

Characteristics of the U.S. market that attract imports so dominate typically supply descriptions that exports are overlooked. Exports are reported in product weights. Several assumptions are necessary to estimate the live weight equivalent. In 1996, fresh and frozen finfish exports were estimated by the author to be 3,927 million pounds. Various species of salmon, sole, pollock, cod and mackerel comprise the majority of finfish exports. With the exception of mackerel and some tuna, essentially all finfish exports have origins other than the Gulf of Mexico. The availability of finfish to meet 1996 consumer demand excluded the 3,927 million pounds of domestic supply that was exported. Allowing for effects of all forms of finfish exports, the U.S. finfish utilization was 6,800 million pounds in 1996.

An additional source of finfish supply comes from the nation's aquaculture producers. From 1985 to 1995 the nation's finfish growers increased production of edible finfish from approximately

250 million pounds to 542 million pounds. Catfish comprise 84 percent of production. Rainbow trout and salmon accounted for most of the remainder. Only small quantities of warm water species were produced. Tilapia, hybrid striped bass and red drum production combined for approximately 30 million pounds. The red drum component would be about 3 million pounds. Red drum are grown in Texas and Louisiana.

There is interest in the use of offshore Gulf waters as a location for oyster culture. U.S. domestic oyster supply decreased from 1985 to 1995 (Table 3). Domestic sources were the East Coast, Gulf of Mexico and Pacific Northwest states. Domestic production fell from early in the time period to a low in 1990 to be followed by a stable recovery. During the period, East Coast states declined as points of supply and the Pacific Northwest producers gained market share following significant aquaculture successes. Pacific Northwest states produce an oyster species different from the eastern oyster best known to East Coast and Gulf of Mexico states. Though dissimilar, these two oyster species do substitute one for the other in certain markets for limited periods. Import supplies fell in dramatic fashion to the point where they have a 25 percent market share from a 50 percent share in 1985. Most of the decrease was in the supply of canned oysters from Asia. Domestic supply will remain the origin of half-shell and shucked oyster products in the U.S. Offshore culture will have to use cost effective technology to be competitive in competition with existing oyster culturists in Connecticut, Louisiana and the Chesapeake Bay states.

Summary

This study has characterized domestic edible finfish supply by origin with conversions to live weight. Supplies increased in the 1985-95 period. As Table 1 illustrates the increase came from domestic supplies. Increases, however, were from northern Pacific Ocean fisheries. The only significant supply increases of warm water species were of aquaculture origin. Catfish production accounted for 94 percent of warm water supply with tilapia comprising most of the rest. Red drum at approximately three million pounds was confined to Texas and Louisiana sources.

Table 1. U.S. Supply of Edible Commercial Capture Finfish, 1985-1996

	Domestic	Import	Total
	million pounds meat weight		
1985	2273	4718	6991
1986	2240	4847	7087
1987	2769	5150	7919
1988	3306	4480	7786
1989	4897	4838	9735
1990	5747	4373	10120
1991	5564	4622	10186
1992	6182	4115	10297
1993	6770	4026	10796
1994	6612	4107	10719
1995	6414	4278	10809
1996	6205	4494	10699

Source: Fisheries of the United States, U.S. Department of Commerce

Table 2. Edible Finfish Imports, Fresh and Frozen, in Product Weight and Value, 1985-1996

	Product Weight (million lbs)	Value (million $)
1985	1655	1512
1986	1806	1847
1987	1970	2372
1988	1743	2104
1989	1914	2235
1990	1628	2109
1991	1675	2234
1992	1523	2048
1993	1582	2086
1994	1609	2169
1995	1711	2370
1996	1809	2459

Source: Fisheries of the United States, U.S. Department of Commerce

Table 3. U.S. Oyster Supply, 1985-1996

	Domestic	Import	Total
	million pounds meat weight		
1985	44.2	45.9	90.1
1986	48.8	50.0	98.8
1987	39.8	52.1	91.9
1988	31.9	46.4	78.3
1989	29.3	37.7	67.0
1990	29.2	27.6	56.8
1991	31.9	30.5	62.4
1992	36.2	26.5	62.7
1993	33.6	28.2	61.8
1994	38.1	24.7	62.8
1995	40.4	24.2	64.6
1996	38.0	21.7	59.7

Source: Fisheries of the United States, U.S. Department of Commerce

Candidate Species

Commercial Landings

Candidate species were selected to provide some specifics to the general opportunity for mariculture at offshore structures in the Gulf of Mexico. Red drum is the candidate fish. The red drum are well known to Gulf Coast consumers. In the peak period of seafood consumption, red drum were marketed in quantities far larger than the other candidate species. In addition, red drum are known as highly desirable recreationally caught fish – this for both angling and consumption purposes. Only Mississippi, among Gulf States, allows a commercial harvest. Red drum have been under a total harvest ban in federal waters of the Gulf for all harvesters. Red drum landings peaked at 14.5 million pounds in 1986 (Table 4). Atlantic and Gulf regions will continue to produce less than 200,000 pounds annually.

The other candidate species – Florida pompano, dolphin and cobia – are well known to consumers. People in the Gulf States have been exposed to these species as anglers and in restaurant offerings. However, the quantity reaching consumers from commercial sources has been highly constrained. Dolphin landings increased in response to buyer interest to a level of 1.6 million pounds in 1996 (Table 4). It is the only of the four species over the landings level of one million pounds since 1990. It has been a no-growth fishery during the period. Cobia landing exhibited slight growth for the period but never exceeded half a million pounds. Collectively, the four species represent 2.5 million or less pounds of commercial landings annually.

Of the Candidate Species

Red drum is the only species being grown in the Gulf States. One Louisiana and two Texas producers use varied systems. The Louisiana grower uses net pens in an inshore brackish water bay. The Texas growers use either recirculating tank or pond grow-out approaches. An infrastructure inclusive of hatcheries, feeds and marketing system makes red drum the most appropriate species with which to begin. There is no aquaculture production of pompano, dolphin and cobia.

Prices

Prices received by harvesters are referred to as ex-vessel prices. Ex-vessels prices for the candidate species are quite different. Pompano at well over $3.00 per pound are the most valuable. Cobia and dolphin prices are in the $1.60 to $.80 per pound range. Dolphin landings are four times larger than cobia landings. Red drum landings at the peak (1896) resulted in ex-vessel prices of $.65 per pound. The small quantities produced in recent years bring about $1.00 per pound. Farm grown red drum bring substantially higher prices. The farm-harvested prices have been in the $2.25 to $2.75 per pound range. Aquaculture producers receive higher prices due to production of red drum linked more closely to market needs in terms of fish size and timing. Initially, offshore culture of red drum will depend on securing these two advantages, while maintaining consistent flavor and appearance. Offshore mariculture managers must develop a strategy to achieve these advantages. It can not be assumed that fish prices will increase to cover any level of red drum production costs. The lack of significant growth in shore based red drum culture businesses supports this conclusion.

Table 4. Commercial Landings of Candidate Species for Gulf of Mexico Offshore Mariculture, 1985-1996

	Red Drum		Florida Pompano		Dolphin		Cobia	
	mils/lbs	$ mils	mils/lbs	$ mils	mils/lbs	$ mils	mils/lbs	$ mils
1985	6.6	4.1	0.7	2.3	0.4	0.4	0.1	0.1
1986	14.5	9.5	0.7	2.2	0.6	1	0.2	0.2
1987	5.2	5.7	0.8	2.5	0.6	1	0.2	0.3
1988	0.5	0.5	0.8	2.2	1	1	0.2	0.3
1989	0.4	0.4	0.8	3	2	2	0.3	0.4
1990	0.1	0.1	1	3	2	2	0.2	0.3
1991	0.1	0.1	0.7	2	2.4	3	0.3	0.4
1992	0.2	0.2	0.6	2	1.1	1.3	0.3	1
1993	0.3	0.3	0.6	2	1.2	2	0.4	1
1994	0.2	0.1	0.7	2	1.4	2.4	0.4	1
1995	0.2	0.2	0.5	2.3	3	4	0.4	1
1996	0.1	0.2	0.3	1.7	2	3	0.4	1

Source: Calculated from National Marine Fisheries Service data

Ancillary Supply: Recreational Harvest

The harvest of recreational fishermen is significant. Anglers nationwide in 1995 kept 158 million marine fish. The live weight equivalent was approximately 230 million ponds. Gulf of Mexico anglers accounted for 73 million pounds of the total. This live weight can be converted to edible weight on a one-third basis. The equivalent 24 million pounds, though not sold in commercial channels, is relevant to a complete description of candidate species availability.

The catch of the candidate species entering the food supply is this manner is shown in Tables 4 and 5. Red drum (Table 5) nearly doubled for the 10-year period. This is in spite of a zero harvest constraint from federal waters in the Gulf of Mexico. Dolphin poundage in the Gulf was at peak levels in 1995 (Table 5). The estimates indicate an upward trend in supply of dolphin to please the palates of anglers. Comparable weights for two other candidate species, Florida pompano and cobia, were not available from the marine recreational fisheries statistics survey. Nonetheless, the 73 million pounds (live weight) of angler caught fish in the Gulf of Mexico indicates the prominent role for red drum and dolphin in actual consumption.

The catch of these species indicate angler preferences for at least two factors. First, the fish have fighting abilities enjoyed by anglers. Second, these species are also sought for edibility reasons. Each factor suggests that millions of Gulf anglers have knowledge of the candidate species. This knowledge is favorable and therefore an additional basis on which to build markets.

Table 5. Recreation Landings of Red Drum and Dolphin, Gulf of Mexico, 1985-1996

	Red Drum	Dolphin
	weight (million lbs)	
1985	6.5	1.3
1986	5.2	3
1987	4.6	2.7
1988	2.9	1.2
1989	5.7	2.9
1990	4.1	4.9
1991	5.4	5.4
1992	7.8	3.9
1993	8.7	3.5
1994	7.5	2.7
1995	11.9	6.8
1996	11.7	4.6

Source: Marine Recreational Fisheries Statistics Survey, U.S. Department of Commerce

Seafood Prices

Prices received by seafood producers are referred to as ex-vessel prices. Ex-vessel prices of wild-caught red drum, dolphin, cobia and pompano are reported as annual averages. The average size of fish associated with the government's reported price is not known. Therefore, first seller prices are of limited use to culturists since the size of fish and time of quote are important price determinants. As previously noted the small remaining wild red drum sell for a price over $1.00 per pound. Farm-raised red drum in 1997 were bringing approximately $2.50 per pound. The difference is due to demand for a fish size most useful to retail and restaurant markets. A more reliable, consistent supply from a given seller also results in the premium price. These factors must not be lost when culture system managers anticipate sales.

Ex-vessel prices for the candidate species are shown in Table 6. There are no published data on farm raised red drum. Previous comments on the wide divergence between wild and farmed red drum may indicate the wild ex-vessel prices are of limited use in projecting producer prices for cultured species. For example, farmed catfish in 1997 were selling for $.70 per pound when wild catfish brought fishermen $.45. Tilapia producers in Louisiana were receiving $1.80 per pound for live fish at the production site. Wild tilapia from Florida bring $.33 per pound to fishermen. This wide divergence in wild and cultured prices may indicate essentially different products.

Trends in finfish prices at ex-vessel are kept by the National Marine Fisheries Service. The indexes are based on 1982 as the base year. Selected indexes are shown in Table 7. All edible finfish is the composite index most representative of the diverse candidate species. Between 1987 and

1996, the index showed wide fluctuation. The range was 96(1996) to 161(1988). There was no clear change that represented a trend for finfish. There was an upward trend, for edible shellfish. Applying an annual inflation rate of four percent in the economy since 1982, the various indexes would have to be 173 in 1996. Thus, oyster prices thereby exceeded the inflation rate. Edible finfish and shellfish prices were below inflation neutral rates.

Table 6. Ex-vessel Prices for Candidate Gulf of Mexico Offshore Mariculture Species, 1985-1996

	Red Drum		Florida Pompano		Dolphin		Cobia	
	$/lb	Index	$/lb	Index	$/lb	Index	$/lb	Index
1985	0.63	100	3.19	132	1.06	134	0.81	156
1986	0.66	105	2.93	121	1.01	128	0.86	165
1987	1.9	173	2.98	123	1.2	152	0.98	189
1988	0.99	157	2.83	117	1.22	154	1.1	212
1989	0.9	143	3.04	126	1.09	138	1.17	225
1990	0.61	97	2.8	116	1.05	133	1.29	248
1991	0.67	106	2.75	114	1.15	146	1.36	262
1992	0.91	144	3.0	124	1.24	157	1.5	289
1993	0.95	151	3.11	129	1.42	180	1.56	300
1994	0.83	132	3.1	128	1.71	216	1.61	310
1995	0.93	148	3.26	135	1.57	199	1.73	333
1996	1.05	167	3.07	127	1.62	205	1.81	348

Source: Calculated from National Marine Fisheries Service data

Table 7. Indexes of U.S. Ex-vessel Prices, 1987-1996

	Total Edible Finfish	Oysters (1982 = 100)	Total Edible Finfish
1987	125	165	109
1988	161	175	113
1989	110	198	108
1990	120	228	111
1991	106	219	110
1992	106	225	115
1993	97	183	110
1994	122	175	138
1995	130	179	135
1996	96	214	124

Source: Fisheries of the United States, U.S. Department of Commerce
NA: not available

Table 8. Producer Price (PPI) and Consumer Price (CPI) Indexes for Finfish, 1987-1996

	PPI			CPI
	Unprocessed Finfish	Fresh Pkg. Finfish	Frozen Pkg. Finfish	Fresh & Frozen Finfish
	(1982 = 100)			(1982-84 = 100)
1987	145.2	173.5	122.2	143.6
1988	172.7	173.6	128.3	149.2
1989	135.3	175.1	127.9	155.2
1990	142.2	182.7	135.9	161.4
1991	136.2	178.5	148.8	163.8
1992	155.8	180.8	148.0	168.7
1993	169.8	184.7	143.6	174.5
1994	175.4	198.1	144.1	183.6
1995	172.8	210.5	146.5	194.1
1996	186.5	206.6	145.9	196

Source: U.S. Bureau of Labor Statistics

The U.S. Bureau of Labor Statistics provides the only indication of price trends past the primary production point. The Producer Price Index (PPI) reflects the prices wholesalers receive. Consumer prices paid are reported in the Consumer Price Index (CPI). Each are highly aggregated as to species and product form. The PPI is available for unprocessed finfish, fresh fish and frozen fish. The CPI combines fish and shellfish in fresh or frozen form in a single index. The change over time in these aggregated, yet relevant, indexes is presented in Table 8. Wholesale prices indexed to 1982 showed year to year variation for all three market forms. This is the norm for products with fluctuating domestic and import supplies for the many species comprising the indexes. The indexes do not distinguish domestic from imported product. However, with the exception of tropical species imported through Miami, air freighted salmon from many countries and Canadian trucking of finfish to the northeast, most imports would be in frozen form. The unprocessed fish index increased approximately 29 percent for the period. At 187 in 1996 this index out-performed an assumed inflation rate of four percent over the period 1982-96. Anything over an index of 174 represents an outpacing of the inflation rate in the general economy. Fresh packaged fish similarly outpaced the assumed inflation rate. These products began in 1987 at 174 and increased to 207 (1982=100). By 1996 the index increased to 207 or approximately 19 percent above the inflation rate. Frozen packaged fish exhibited the lowest increase of the PPI indexes. At 146 in 1996 the frozen packaged fish index was the lowest of the three wholesale indexes. Frozen packaged fish evidently is at a competitive disadvantage with respect to unprocessed and fish package fish. The frozen packaged fish index failed to increase at the pace of general inflation.

An available index of retail price trends was found, fresh and frozen fish. With 1982-84 as the base, the CPI increased to 144 and 196 in 1987 and 1996, respectively. The increase was uninterrupted. Fresh and frozen fish at retail exceeded the general inflation increase in the economy. This retail index had increases higher than unprocessed finfish and lower than fresh packaged fish.

Processing Perspective

Other than pricing and demand information, post harvest information is needed to evaluate mariculture investments. Wholesale and retail price indexes for edible finfish were reviewed as the best available information to add perspective past the harvest level. The finfish indexes are an aggregation of numerous species. However, this is the primary historical guide as to what candidate species may command over time. There also are competitive challenges from processors if mariculture investors choose to maintain fish ownership beyond harvest. Becoming a processor puts management in the position of perhaps achieving profits at that level either in addition to production profit or to offset production losses. This is the reason for venturing into establishing a processing facility.

Sufficient capacity among Gulf of Mexico processors is available to handle a mariculture venture s finfish production within the range contemplated. A 1994 report on the finfish processing industry is the basis of this conclusion (Roberts, Keithly and Kearney 1994). Annual reports of wholesaling and processing activities submitted by firms to NMFS served as the database. The study period was 1973 to 1990. The number of finfish processors increased from 41 to 96 in this period. Most of the growth in number of firms (31) occurred after 1985. A large increase in the number of firms was associated with a decrease in processed product weight. Excess capacity was clearly present in the finfish processing industry as late as 1990. New firm entry brought more than enough capacity to the industry to offset the effect of higher Gulf finfish landings. In general, finfish processor plant size was largest in the Alabama/Mississippi region and smallest in Louisiana. The substantial increase in Gulf firms led not only to a smaller average sized firm, but also to a more specialized firm. For example, 70 of the 96 firms processing at the end of the data period had 95 percent of their sales from finfish products. Finfish product weights per firm in the Gulf averaged 141,301 pounds worth $439,358. Louisiana firms averaged 103,376 pounds worth $267,720. The combination of excess capacity and highly specialized firms is conducive for agreements being struck between mariculturists and existing processors.

The growth in numbers of processors may indicate there are minimal barriers to entry. The average finfish processing plant in 1990 employed eight people. Employees averaged 13,000 pounds of product weight (43,000 lbs. live weight) annually. Gulf finfish processors use minimal technology and low capital outlay to produce the products. The procedures are as basic as washing, grading icing and boxing and at the top end of the line, filleting. Breading, ready to eat tray pack entrees and other high value added products are seldom produced in Louisiana. A mariculture business able to produce quantities above the industry average from a reliable harvest that can be optimally scheduled will have no barrier to entry to processing its own harvest

A more recent study of Gulf processors was confined to reeffish primarily (snappers and groupers). Twenty-nine of the 46 processors were interviewed. There was a wide range of firms comprising the industry. The industry was operating at 64 percent capacity. This reaffirms a conclusion from the previous study of the entire finfish industry. Plants operated 294 days annually but 71 percent of these involved eight or fewer hours per day. Again, the conclusion from the previous study regarding mariculturists finding sufficient processing opportunities with existing processors holds. Reeffish processors had an average raw product cost of $4.32 per pound and another $1.04 per pound of other costs. Thus, 80 percent of total processing costs are related to the purchase of fish.

The Gulf finfish processors sold 38 percent of their total reeffish volume in unprocessed form. The remainder was processed basically as one product, fillets. Snapper had an unprocessed rate of 31 percent with groupers at 25 percent. The implication is that other reeffish are more highly processed. Insight to profitability in the industry was provided by Keithly (1997) given this mix of processed and unprocessed product Snapper products averaged $.46 profit per pound with a wide range among firm sizes. Small firms, medium and large processors of snappers averaged profits of $.09, 41.06 and $.41 per pound, respectively. The variability in the industry is also evident when reviewing the situation with another species, groupers. Estimated profits averaged $.84 per pound. Small, medium and large firms averaged $.86, 4.70 and $1.19 per pound, respectively.

Reeffish processors achieved profits by utilizing only a small share of the total harvest. A mariculturist through negotiation should be able to access excess capacity of existing finfish processors. If not, profitability prospects from vertical integration into processing is possible even at the small scale of processing.

The conclusions regarding finfish processing in the Gulf of Mexico states from these two studies completed in the 1990's are:

- The number of firms has increased over-time but appears to have stabilized. The increased indicated no barrier to entry.
- Firms were widely ranging as to size.
- Specifically for reeffish; only 15 percent of the snapper and approximately 33 percent of the grouper were utilized in processing.
- Excess capacity was evident from the high proportion of days operating less than eight hours.
- Excess capacity was evident because 38 percent of reeffish received was re-marketed as unprocessed.
- Seventy percent of firms were almost exclusively committed to finfish (95 + percent of sales from finfish).
- Technology and capital outlay are at low levels because the finfish products receive minimal processing prior to marketing.
- Eighty percent of total processed reeffish product cost was due to fish purchases.
- Average reeffish product profitability ranged from $4.46 to $.84 per pound.

Consumption

Seafood consumption estimates are made annually by the National Marine Fisheries Service. The estimates are made on the basis of edible weight consumed. Scores of species comprise consumer purchases. Heavy shelled molluscs, varied types of shellfish and finfish of distinctly different shapes make generalization a necessity. There are only limited species specific consumption estimates available. Shrimp, salmon, sardines and tuna consumption are reported separately. The candidate species are insignificant compared to these groups and overall seafood supply. Thus, there are no government consumption estimates for the candidate species. For this reason focus must be on aggregated consumption data. Historical estimates and forecasts estimates are available by which to guide in the most general of ways those interested in seafood related investments.

Total consumption trends varied in the past twenty years Table 9. When seafood consumption reached the record level of 16.2 pounds in 1987, optimism for future gains was evident. A print and video media wave of reports touted the health attributes of seafood. Rooted in positive views about healthy seafood and less than favorable reviews of red meats, optimism was logical. Those making forecasts formed a consensus that predicted and promoted a 20 pound per capita consumption level by the year 2000. Shortages from the domestic wild harvest were to be filled by imports and farmed products. If correct, the climate was favorable for aquaculture investment and rising prices. However, using present consumption of 14.7 pounds per capital annually, the 20-pound per capita level will not be reached by 2000 unless a 33 percent increase occurs between now and 2000.

The growth opportunity for seafood products more logically will be related to U.S. and world population and income growth as opposed to health conscious consumers. The National Fish and Seafood Promotional Council reported on a series of food focus groups. The 1991 report was prepared when consumption had fall to approximately 15 pounds after the 1987 peak. Extensive publication of the health benefits of seafood helped position seafood more prominently. Consumption by infrequent seafood consumers was found to be more closely tied to taste and enjoyment of eating seafood. For heavy users of seafood, health also was secondary to taste. Each group related that foods must first be enjoyed based on their culinary merits.

Population growth in the U.S. is approximately one percent annually. When compared to the annualized edible finfish supply growth rate of approximately .8 percent, there is little opportunity for per capita growth. There remains a substantial market for additional seafood via population growth alone. Also the aging of the population into the post 40-year old baby boomers is significant. For the next 15 to 20 years this group will be in what the National Fisheries Institute terms the fish stage of life. By 2000, approximately 30 percent of the population will be 50+. This group will be near peak earning potential. Seafood is a good source of protein and omega fatty acids. However, when compared to terrestrial meats, the relatively high prices make seafood more sensitive to personal income growth. ID Magazine forecasts that 80 percent of U.S. seafood consumption will occur away from home (AFH). In addition, at home (AH) consumption will show rapid growth via purchases of ready to eat products at supermarkets. Seafood purchased in convenient forms can only be supported by growth in real disposable income.

Table 9. U.S. Annual Per Capital Consumption of Commercial Fish and Shellfish, 1976-1996

	Per Capita Consumption (lbs edible weight)			
	Fresh & Frozen (2)	Canned (3)	Cured (4)	Total
1976	8.2	4.2	0.5	12.9
1977	7.7	4.6	0.4	12.7
1978	8.1	5	0.3	13.4
1979	7.8	4.8	0.4	13
1980	7.9	4.3	0.3	12.5
1981	7.8	4.6	0.3	12.7
1982	7.9	4.3	0.3	12.5
1983	8.4	4.7	0.3	13.4
1984	9.0	4.9	0.3	14.2
1985	9.8	5	0.3	15.1
1986	9.8	5.4	0.3	15.5
1987	10.7	5.2	0.3	16.2
1988	10.0	4.9	0.3	15.2
1989	10.2	5.1	0.3	15.6
1990	9.6	5.1	0.3	15.0
1991	9.7	4.9	0.3	14.9
1992	9.9	4.6	0.3	14.8
1993	10.2	4.5	0.3	15.0
1994	10.4	4.5	0.3	15.2
1995	10.0	4.7	0.3	15.0
1996	10.0	4.5	0.3	14.8

Source: Fisheries of the United States, U.S. Department of Commerce

In 1995, the National Restaurant Association surveyed 350 restaurants in a Catch of the Day study. Restaurant managers indicated it was necessary to change seafood offerings almost daily due to availability and price fluctuations. When farmed fish were available consistently, half of the respondent s stated a preference for these products. Their views indicated wild fish held an advantage in taste. Generally it appears that the quality of each must be acceptable but availability is more important. Aquaculturists should strive to provide consistent supply of an essentially standardized product (fish size).

Per capita consumption estimates for the candidate species are not available from government sources. The above information was presented to provide perspective on the national trends with which the candidate species may be associated. Actually, generalization is possible because of the lack of exports for the species. It is more risky to generalize about imports. As stated previously, the national import/export publication of the National Marine Fisheries Service does not disaggregate candidate species as to supply. It is probable that only insignificant quantities of Florida pompano, red drum and cobia are imported. Detailed data from U.S. Customs Service or National Marine Service may be costly to obtain. Imports of dolphin may be larger and more significant in relation to domestic supply. Dolphin is marketed as mahi mahi. Several Latin American countries provide fresh, gutted dolphin to the U.S. via Miami. A special request to identify the quantity of this import may be useful in the future.

For the near-term the pertinent consumption estimate is that of red drum. Limited imports from Mexico and Ecuador will continue to not be relevant. Farm-raised supply from only three growers and significant capital constraints to interested aquaculture startups suggests rapid, large supply increases have a low probability. Reopening of the capture commercial fishery in the Gulf may be more likely. This is the only prospect of large supply increases in red drum. However, the prospect is low that a commercial fishery would be established prior to 2000. It may be so tightly controlled at that time as to include a quota that suppresses prices temporarily until the quota is met. This phenomena occurs in the federally controlled red snapper harvest. Harvest of red drum in the federal waters of the Gulf would involve red drum much larger than the fish size produced from culture. Smaller fish have attracted higher prices.

The catch quota of red drum from federal waters, when allowed, will reflect a cautious approach. Commercial interests will get only a share of this highly sought recreational species.

Consumption Projection Scenarios

The diversity of species comprising seafood available to consumers is problematical in any estimation attempt. This includes the foundation of all projections, i.e., annual per capita consumption. All the species, various sources and yield differences result in tenuous estimates. Overtime, the National Marine Fisheries Service has essentially developed a procedure that reflects disappearances from the market. That is, there is no polling or surveying of consumers to annually yield consumption estimates. Essentially the following projections of edible weigh of seafood to be consumed are based on previous trends alone. There has been no attempt to forecast real disposable income, a key component of demand for seafood. No allowance could be made for known charges in population age, ethnicity and aggregate supply. Over the next 10 years, it is known that the proportion of the population over 50 will increase. Hispanic and Asian segments of the population will be higher proportionally than historically. Aggregate supply to the U.S. will remain dominated by imports. The role of China as a consumer will be different over the projection period than the base period used for the projection. For example, China has been viewed as a major seafood supplier. Their role as an importer has been overlooked. An indication of the potential is the import trade with the U.S. In 1990, China imported $1 million of seafood products from the U.S. In 1996, the estimate is approximately $100 million.

The aging of the population may be beneficial but there are several influences of unknown impact. The newly fifty+ people may be more health conscious. However, an ability to act on the health image of seafood depends on disposable income growth. A concern on the negative side is the potential impact on income earners of social programs needed to support an aging population. This aging arises from both a higher proportion of 50+ years old and longer life expectancies. A review of scientific literature yielded no projections of U.S. seafood consumption in the 21st century.

Articles on preferences for seafood (Edwards 1992) and Kinnucan 1993) deal with the past without reference to the future. Location of the consumer and ethnicity were demonstrated to determine preference for seafood. Preference was found to be influenced by availability. A species frequently available results in exposure to the consumer and a higher likelihood of purchase. Wholesalers and distributors of seafood hold the availability and reliability aspect of supply as critical to success.

Consumption predictions with this background were organized on a best case, worst case basis. The worst case basis was based on the lowest level of per capita consumption experienced over the most recent 5-year period, 1992-1996. A best case scenario was based on identifying the longest period of historical sustained increases in per capita consumption.

> **Worst case:** The 1992-96 period low per capita consumption was 14.8 pounds. This occurred in 1992 and 1996. The three other years consumption included two at 15.0 and one at 15.2. Thus, this 5-year period had minimal change and represents a stable base from which to project. The 14.8 will also serve as the worst because a level below that was not experienced after 1984. After 1984 per capita consumption ranged from a low 14.9 to the record high of 16.2.
>
> **Best case:** The best case scenario was chosen on a different basis, growth rate of per capita consumption. From 1982 to 1987, consumption growth was uninterrupted increasing from 12.5 to 16.2 pounds per capita. The annualized growth rate for the period is 4.42 percent. This growth rate was extended on the base of 14.8 pounds per capita, the 1996 level.

The **worst case** results in an increase of 341 million pounds, edible weight, in total consumption (Table 11). This is the population growth rate influence on a recent year low level of consumption. On a live weight basis this would equate to approximately 1 billion pounds. In 1996, imported fish and shellfish comprised 57 percent of U.S. consumption. If this were to remain the share, then domestic supply would have to increase 430 million pounds for the period.

The **best case** scenario results in an increase of 2,774 million pounds, edible weight, in total consumption. Population increase at the low per capita level of 14.8 pounds would account for 341 million pounds. The remainder, 2,433 million pounds, reflects the per capital growth rate of 4.42 percent. If the domestic supply proportion does not change, capture fisheries and aquaculture must produce an increase of approximately one billion pounds in live weight. This would be unlikely. Growth in foreign consumption via population increases and rising disposable income will occur. This will lessen the prospect that imports can completely erode this opportunity facing U.S. aquaculturists.

The long-term potential yield (LTPY) predictions of the National Marine Fisheries Service provide insight to the **worst** and **best** case results. In the NMFS report Our Living Oceans (1996) the LTPY of fishery resources utilized by the U.S. was compared to the recent average yield (RAY). Of the 275 fish and shellfish stock groups addressed 30 percent were estimated to be below LTPY. The other levels were 27 percent near LTPY, 9 percent above and 34 percent unknown. Of the 275, there are 158 stock groups with known status under the control of NMFS. A high percentage of this group, 46 percent, is harvested at levels below LTPY. If it is assumed that stocks below LTPY are stocks in poor condition, then 46 percent of known stock status groups are at unhealthy abundance levels. There will have to be landmark management successes for these stocks to contribute significantly in meeting future consumer demand for seafood.

Conclusion

If the domestic share (43%) of the total U.S. fish and shellfish supply remains constant in the near future, the **worst** and **best** case forecasts portend opportunity. From 430 million to 1.2 billion pounds of additional supply would have to arise from domestic sources. The imported product may supply some of the shortfall.

Table 10. Elements of U.S. Seafood Consumption, 1987-1996

	U.S. Population (mils)	Per Capita Consumption (lbs)	Total Consumption (mil lbs)
1987	241	16.2	3904
1988	243	15.2	3694
1989	245	15.6	3822
1990	248	15	3720
1991	251	14.9	3740
1992	254	14.8	3759
1993	256	15	3840
1994	259	15.2	3937
1995	261	15	3915
1996	265	14.8	3922

Source: Fisheries of the United States, U.S. Department of Commerce

Table 11. Projections of U.S. Seafood Consumption, 1997-2007

	U.S. Population (mils)	Consumption Worse Case (mil lbs)	Consumption Best Case (mil lbs)
1997	268	3966	4140
1998	270	3996	4355
1999	272	4026	4580
2000	275	4070	4834
2001	277	4100	5360
2002	279	4129	5345
2003	281	4159	5620
2004	284	4203	5930
2005	286	4233	6235
2006	288	4262	6555
2007	291	4307	6914

Source: Calculated for this study

Chapter 9

Cage Candidates, Hydrodynamic Modeling, Sensors and Control Systems

Introduction

The plan to convert inactive oil platforms in the Northern Gulf of Mexico to mariculture centers is an appealing one. An offshore oil rig establishes a fixed base of operations for environmental sensors, system control, and communication. It can be used to anchor a number of fish cages, store food, and serve as a feed distribution center. Beyond that, the platform can be used as a winch base, which can move each cage in the water column under direction of an intelligent control system. To help select an appropriate platform, historical records of the environment and ocean currents are available from the oil rig operator's files, as well as physical property measurements of the site's ocean floor, which were required for the platform foundation design. This information will assist in the cage mooring design and deployment. Most likely, the modification cost of an existing platform would be significantly lower than outlays for new platform construction.

The drawbacks to converting the oil platforms include the significant modification cost of an installation not initially designed for aquaculture support, a potentially high annual maintenance budget, and significant decommissioning expenses. There is also the possibility for serious site contamination from the drilling platform usage, which could be toxic to fish. Additionally, the site location may not be optimal for aquaculture either due to distance from a port, water depth, sea floor properties, or physical properties such as insufficient natural water circulation or improper temperature. However, the large number of inactive platforms should allow selection of the most suitable structures and sites as aquaculture centers. By far the largest challenge to using the platforms for mari-culture, with suitable fish species, is the shortage of fully engineered and fully proven net cage systems for unprotected offshore deployment. The system requires cages that can endure the waves and currents present at the site without failure and without endangering the contained fish. Significant progress has been made in new cage designs and improvements, and in understanding the complex mechanics of cage systems and their response to waves and currents. But most cage systems require some shore protection which acts as a shield from the open ocean storm waves associated with hurricanes, typhoons, or similar extreme high wind and wave weather events. This report summarizes: (1) some appropriate fish farm experiences; (2) fish cages; (3) mooring/anchoring considerations; (4) modeling cage/moorings; (5) an on-board control approach with (6) integrated sensors for system monitoring.

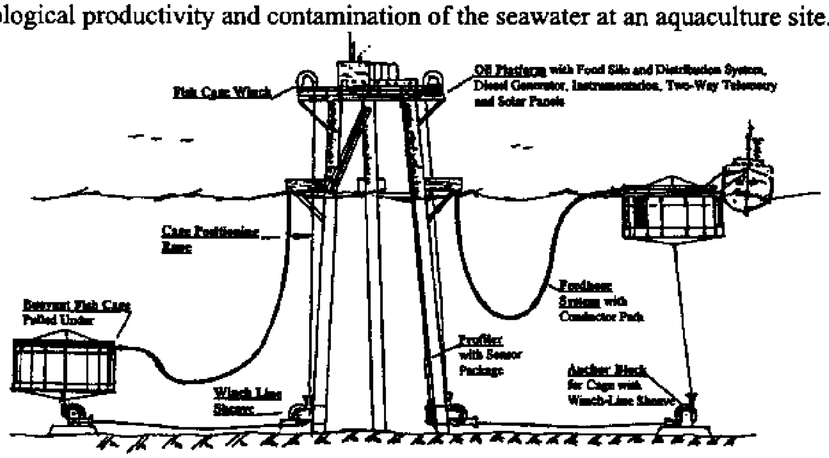
Multi-Discipline Approach: WHOI's Project Support

The advancement of aquaculture into offshore locations requires the application of supporting biological, related science, engineering, and operational know-how in order to understand and overcome significant scientific and engineering difficulties and challenges. Biological efforts will aid in the selection of suitable species which can survive and which can be successfully raised in captivity. Expertise in the biology of suitable fish species for the Northern Gulf of Mexico is best available from local fishermen, the National Marine Fisheries Service, and universities[1]. The ecosystem analysis of the waters of interest, (including the ecological impact of offshore petroleum-producing platforms, investigations of water bio-productivity, sediment and nutrition transport and accumulation, water temperature, weather and current monitoring), are well studied and understood (for example: Twilley et al., 1996; Rabalais, et al.,(1994).

The Woods Hole Oceanographic Institution (WHOI) contributes to this feasibility study with its specialized knowledge on intelligent oceanographic sensor and control systems, advanced numerical hydrostatic and hydrodynamic modeling of buoy, long-line and aquaculture cage moorings, expertise in rope technology, and offshore mooring and anchoring experience. Together with the structural offshore engineering capability of Waldemar Nelson International, sufficient engineering depth and expertise is available to tackle the challenging opportunity to develop viable and durable technical solutions required to raise fish in captivity in the unprotected waters surrounding oil platforms.

To assist in the design and system evaluation, we considered utilizing the oil platform as a base of operations. We also considered what it would do in automated system control to reduce manpower cost on the platforms and take advantage of "intelligent" control systems and two-way telemetry for information control from a single shore station. Also, we considered a winch system that would pull cages under water to reduce wave forces on the cage and to allow movement of th cage (and fish) within the water column (Figure C-1). At the current state of cage development, submersible cages do not have the best record of success, but have potential as will be discussed.

[1] The specialized biologist for a particular shellfish or finfish species is most likely to be found at a local university. Biology expertise is also required to supply the veterinary support for the cultivated fish, as well as aid in the analysis of the biological productivity and contamination of the seawater at an aquaculture site.



Prior Regional Experiments

A significant earlier attempt (1990-1994) to convert oil platforms in the Gulf of Mexico to aquaculture sites was, at best, a mixed success (Miget, 1995). In Phase I of this program, two 15-ft diameter, 20-ft high cylindrical net pens were suspended from two bays of an eight-pile oil platform, located in 97-ft water depth. After the experience at 10 and 20-ft depth proved to have too strong a wave interaction with the cage, the pens were lowered into a position where the net cage top was 47 ft below the sea surface. The cages' horizontal movement was restricted by "anchoring" each cage with a large diameter polyester rope and clump weight. One half of the 10,000 red drum fish deployed died in the first weeks of a grow-out experiment due to hypoxic stress during transfer. The remaining 5,000 fish, having grown two to three times their deployment weight, were harvested a year later. The food conversion and growth rate was considered poor due to clogging of the food supply hose and to excessive feeding in the wintertime. Both problems can easily be corrected

In Phase II, a small Ocean Spar net pen system[2] was anchored at a new site in 270 ft of water and stocked with 10,000 red drum fingerlings in April 1992. A severe storm damaged the pen a month later, allowing most of the fish to escape. The project was canceled after this mishap. The net pen system was re-deployed adjacent to a different platform closer to shore, and again stocked with 10,000 red drum fingerlings. One of the four 10,000 pound anchors shifted many times in winter storms. After each shift, the anchor had to be repositioned to maintain the net pen shape. A total collapse of the system in March 1993, apparently caused by the failure of a small hardware piece[1], killed all enclosed fish, forcing the termination of the experiment. An alternative net pen system with an octagonal flotation collar was constructed which was lowered through ballast changes in the supporting HDPE[2] pipe structure. Frequent dragging of the outside positioning anchors de-coupled the flexible feed delivery hose between platform and cage. The feed pipe system failed in service. The system was removed, and a new octagonal cage of the same size was built with aluminum tubing and deployed. A severe storm ripped the containment net from the tubing a month later and moved the two outer anchors. Again, the test was terminated. None of the systems survived as well as the Phase I system

Cages were attached to the outside of the platform legs 20 ft below the surface. Coated wire mesh replaced the nylon netting to discourage predators. In December 1993, the new pen configuration was installed and filled with 6,000 hybrid striped bass. Three months later, the wire mesh became detached from the framing in a number of positions, allowing the fish to escape. The test was repeated with 4,000 hybrid striped bass after replacing the wire mesh with one-inch square nylon netting. The nylon net tore away from several frame attachment points a month later, again leading to a loss of all stocked fish. The project was severely reduced in scope in the summer of 1994. The last reported installation was that of a small pen (6 ft. x 10 ft.), in which fiberglass containment panels replaced the containment netting. This program has now ceased to exist after the sponsoring oil company stopped its support.[3]

[1] Manufactured by Ocean Spar Technologies, Bainbridge Island, WA. The net cage measured 30 ft x 30 ft x 20 ft.

[1] G. Loverich, Ocean Spar Technologies, personal information July 22, 1998.

[2] HDPE = High Density Polyethylene.

[3] Tel. information of Russ Miget, Texas A&M University, November 23, 1998.

Project Assessment: The only cage systems which stood up to the tests were those in Phase I. The cages were upright "cylinders" with octagonal, perforated, top and bottom steel plates, operating 47 ft below the sea surface in order to escape severe surface wave interaction. The Phase I containment netting consisting of nylon, reinforced with heavy polyester fabric strips sewn onto the rims, provided both compliance and extra strength for the attachment hardware. This configuration was able to endure the one-year grow-out experiment. Rigid net panels from wire mesh, used in Phase III, proved to have insufficient compliance to adapt to the deformation of the tubular support piping structure. Its replacement, nylon netting without extra reinforcing polyester fabric at its rims, failed in service. It was determined that support piping had to be metallic, as plastic piping proved to be too flexible and fractured (Phase II). The Ocean Spar platform, while showing significant endurance in a semi-shielded location at Whiskey Creek (Loverich and Swanson, 1993), did not survive in the totally unprotected offshore locations in the Gulf of Mexico. Some of the failures were caused by anchor movements, which can be avoided by proper anchor selection and anchoring methods. However, the entire system may need further research and understanding of the role of the spar buoys at each end, including details of the lee-side net configuration in heavy currents and the effects of heavy sea state interaction with the system[1].

[1] Spar buoys are driven by the wave pressure acting on the bottom of the spar. With the natural attenuation of waves with depth, the spar buoy motion is generally much less than that of a wave-following surface buoy. However, spar buoys can be strongly affected by wave motions whose frequency approaches the spar's resonance frequency. The resonance frequency decreases with increasing spar length, i.e. increased mass and damping. The goal is to develop a spar buoy that will resonate at a slower frequency than that of the lowest ocean swell at the site, which i bout 1/ 20th Hertz range. The Ocean Net Spar buoy has a resonance period of 6.2 seconds. In order to reach 20 seconds, the spar would have to be 30 to 60 ft long. If the spar buoy would go into resonance, than a very damaging interaction with the connected net cage could occur, resulting in jerking, tearing, and dynamic loading of the containment net. However, G. Loverich from Ocean Spar observed that their spar buoy's main resonating mode is a rolling motion around the spar's base, not a heave resonance. This may be attributed to the installed damper plates below the spar buoys, which tend to convert the spar buoy behavior to a wave follower.

Which Cage Systems Should Be Proposed for the Northern Gulf?

Classification of Cage Systems

Loverich and Gace (1997) of Ocean Spar Technology divide cage systems into four main groups, called Class 1 through 4, which are illustrated in Figures C-2 through C-5. Most available cage systems can be categorized as the systems below, but nearly all of them are of a hybrid nature, forming compromises between the different classes.

Class 1: Gravity Cages (Figure C-1) hold their shape and internal cage volume only through distributed buoyancy and weight. A weighted net bag suspended entirely from a moored floating support structure is defined as the Gravity Cage. See Figure C-2 and C-3 as examples.

Class 2: Anchor Tensioned Cages maintain their shape due to anchor-line tension. The *Ocean Spar Sea Cage* (Figure C-4), is the main candidate in this category. The anchor line tensions are transferred to four corner spar buoys. The corner spar buoys transfer the anchor line loads to the four vertical edges of the net pen through mooring lines.

Class 3: Semi-Rigid Cages: Ocean Spar's *Sea Station*, (Figure C-5), is the prime candidate in this group. Metallic internal framing and a central support column provide the shape for the net system. The framing, connected to the central column with tensioned ropes, responds with sufficient compliance to allow some deflection of the cage under external forcing.

Class 4: Rigid Structure Cages: A rigid metallic structure provides support for the net cage (Figure C-6). Netting connected between adjacent legs of an oil rig, as used in Phase I of the Gulf of Mexico experiments (Miget, 1995), would fall under this category. A different rigid structure cage is the *Trident* cage, (Figure C-7). It is constructed as a buoyant geodesic sphere, with containment and predator netting filling the spaces between its frame elements.

An attempt is currently being made to extract pertinent information from the available literature, from questioning designers and operators, and from the engineering assessment at WHOI, to determine which cage systems are the best option and which would be most likely to survive in fully exposed, open-ocean locations.

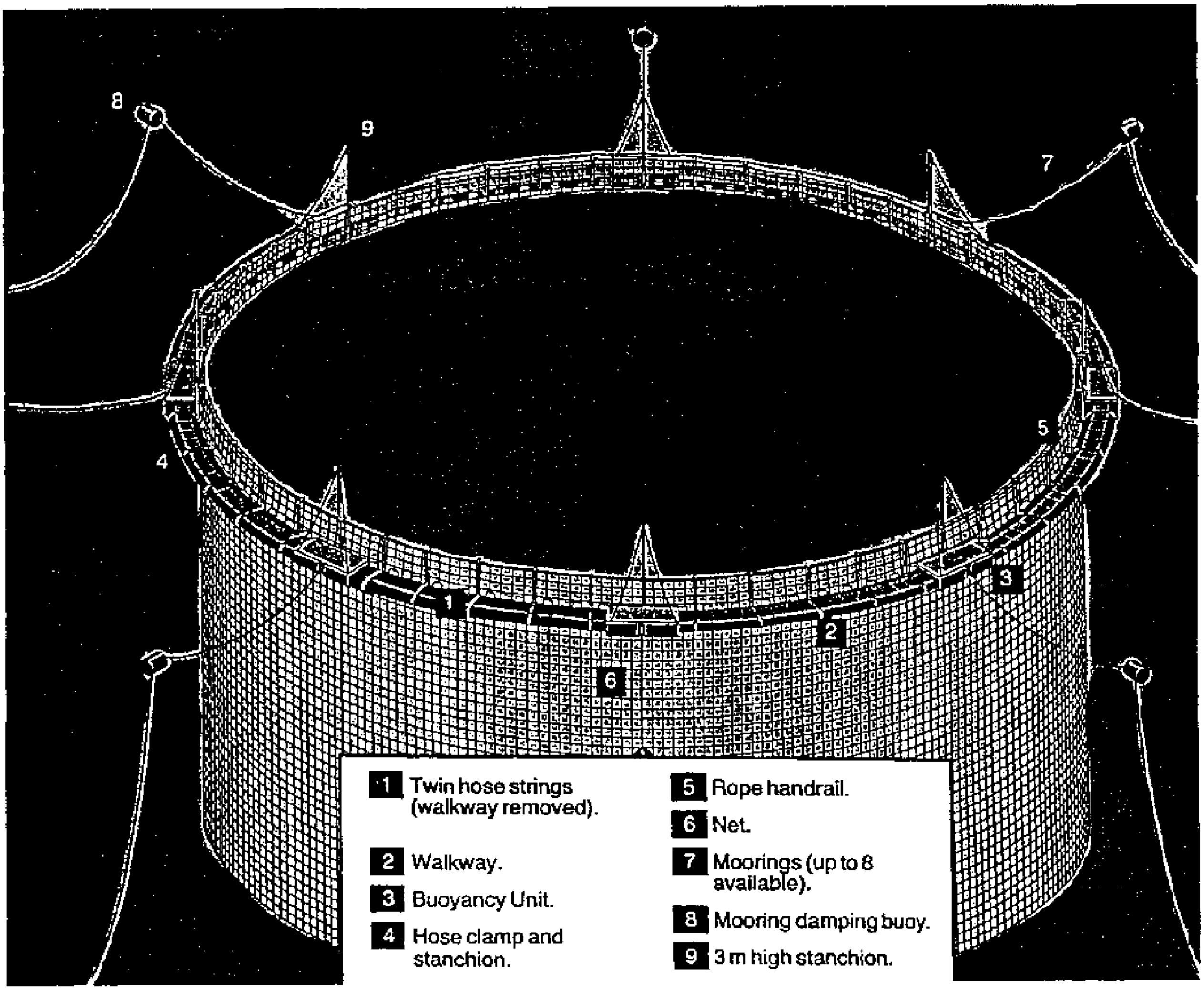


Figure 2 : " Gravity Cage," Example 1: Tempest Fish Cage, Great Britian/ Ireland

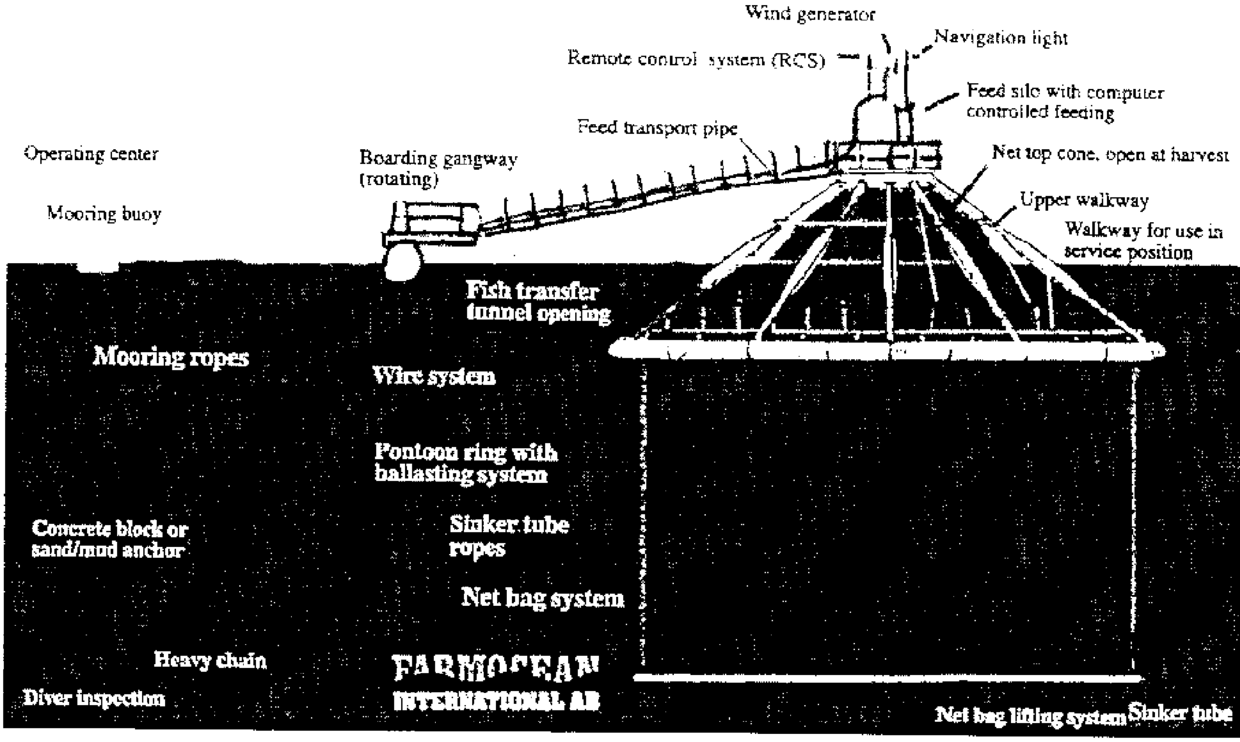


Figure 3: Gravity Cage, Example 2: FARMOCEAN Offshore system, Sweden

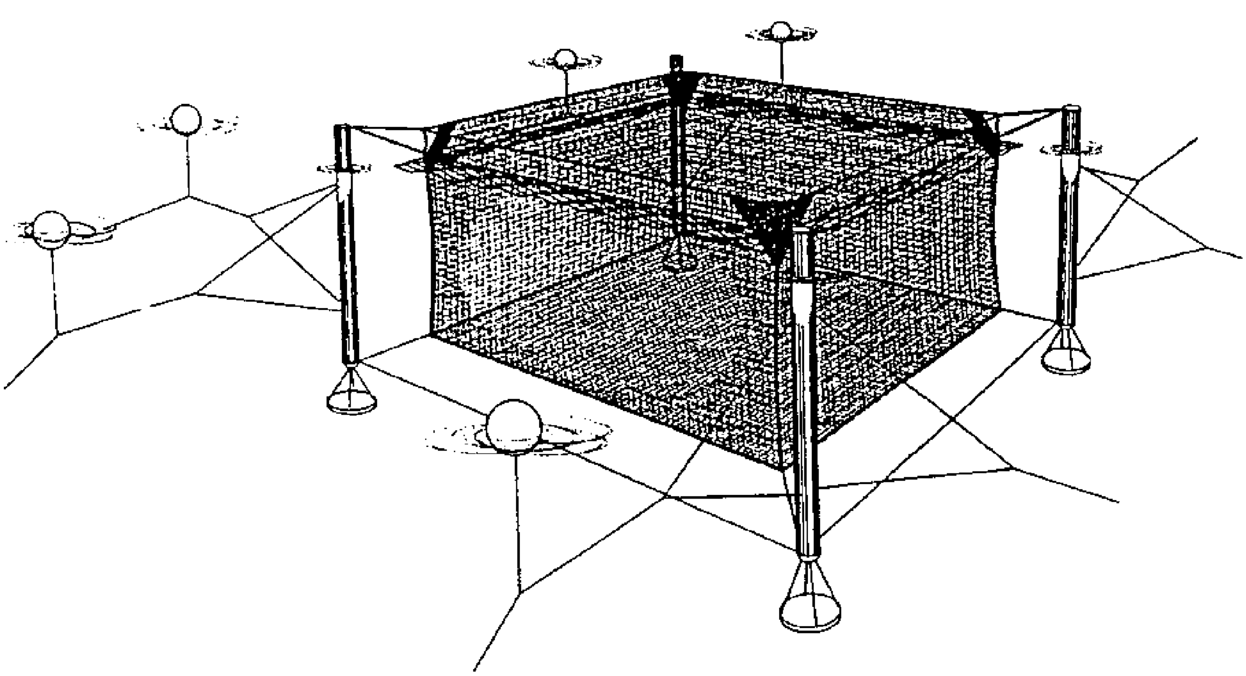


Figure 4: Anchor Tension Cage: Ocean Spar Sea Cage, USA

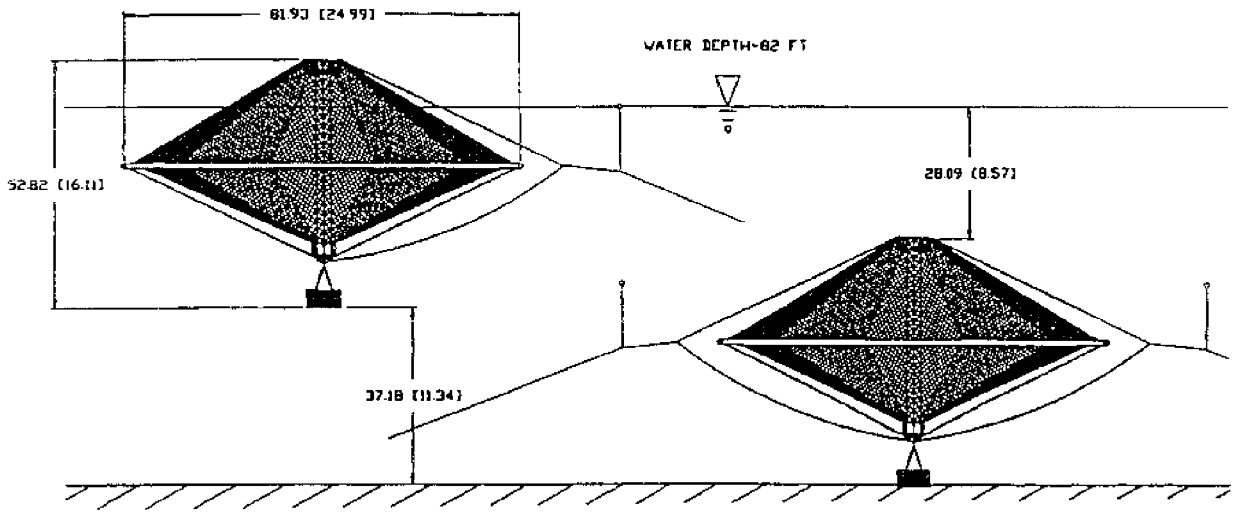


Figure 5: Sea Station, Ocean Spar Technology, USA

Figure 6: Rigid Net Cage Used in the Gulf of mexico

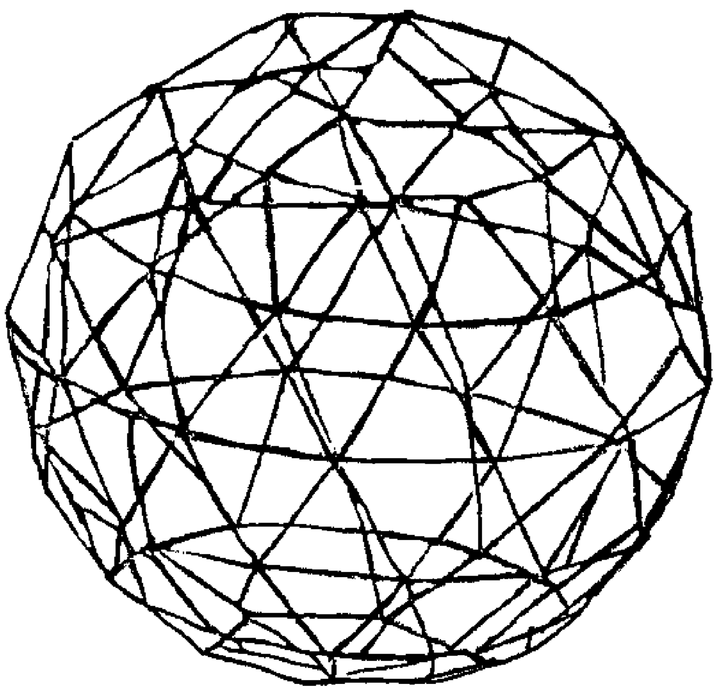


Figure 7: Example of a Rigid Cage, Trident Cage, Canada

Class 1: Gravity Cages

Introduction

The total net cage system area exposed to a current determines the drag force. The net cage configuration's buoyancy and weight distribution as well as the mooring lines' geometry and properties affect the dynamic response to wave forcing. The behavior of the moored net cage system depends on the frequency and amplitude of the sea state. In a sea state with low wave height and low frequency swells, the flotation collar of a cage responds as a wave follower. At higher sea state with highly energized rapid ocean waves, the surface flotation is unable to continuously follow the sea surface contour, and it will be washed over by some of the waves. Hydrodynamic modeling and wave tank model testing has to be performed to provide the needed cage behavior information detail. Practical at sea experience adds to the understanding of the complex response of the cage system to its ocean environment. Site inspections will identify wear components and help in establishing good maintenance practices. Similar modeling and test procedures can be developed for all cage types.

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[1] Aarsnes, J.V.; H. Rudi, G. Loland: *Current Forces on Cage, Net Deflection;* (1990). Engineering for offshore fish farming. Thomas Telford, London 1990, pp. 137-152. The report shows that in some cage designs with freely hanging nets and bottom weights, more than 80 percent of the volume contained by the net gets lost when exposed to two-knot currents.

Examples of At Sea Behavior

Two anchor and gravity tensioned cage systems, selling under the trade names "Tempest" and "Bridgestone High Seas" have been used with good results. Gunnaran (1996) reports 2 p years of operation with hardly any repairs in completely exposed locations off the West Coast of Ireland and the Faroe Islands. The cages consist of two concentric hexagonal, octagonal, or circular assemblies of extremely rugged reinforced rubber hose, which form the surface flotation collar from which the net cage is suspended (Figure C-2). The hoses are of the same, almost non-destroyable construction as developed for offshore oil docking hose. They are employed to load super-tankers from open ocean single point buoy moorings, which are connected to oil wellheads on the sea floor. Individual offshore loading hoses have a service life of eight years or more. The net side walls are typically 40 to 50 ft high and are connected to the bottom net enclosure with vertical support ropes. The bottom of the net wall is ballasted with chain weights. between the net wall and surface float. The shock net cushions any impact from loading experienced in heavy sea state due to the out-of-sinc vertical motion of the bottom weights relative to the surface flotation. Knotless nylon nets, with additional reinforcement panels between the side walls and net floor, are used to construct the entire cage. A larger mesh predator net made from polyolefin material surrounds the net enclosure [1]. However, stretchy nylon netting is able to absorb significant mechanical energy differences and shock loading between different portions of the net enclosure. The nets, made from large nylon twines, are heavy compared to the Spectra nets used by Ocean Spar systems. Spectra[2], due to its much lower elongation under tension, responds to sea-state loading like a stiffer spring, leading to shock loading conditions.

Another example of anchor and gravity cages are Tension Leg Cages produced in Italy, originally developed by MARINTEC in Norway. These cages have only a small flotation collar at the sea surface and are anchored with vertical mooring lines. The cage system is designed to pull under in high currents, preserving most of the net volume due to a lower reinforcing ring and distributed flotation buoys. This design works well in low currents off Sicily. The deployment depth is less than 50 meters to limit current effects. The cages have survived up to eight meter surface waves and produce sea bass and sea bream (Lisac, 1996). Other examples of gravity cages are the Farmocean offshore cages from Sweden (Henriksson, 1996) and the SADCO cages from Russia (Bugrov, 1996). These cages operate in waters with some shore protection.

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[1] Net detail information provided by Seamus Gillespie, Manager, Coastal Cages, Ltd., Ballymoon, Kilkar, Ireland.

[2] Spectra is the trade name of the Allied Signal corporation for its high-performance fiber from Ultra-High-Molecular-Weight Polyethylene (UHMWPE). The same chemical composition fiber is also available from DSM High Performance Fibers in Holland under the trade name Dynema. The strength of these low stretching lightweight fibers is 2.5 times higher than nylon. Nylon fiber stretches 15 to 20 percent at break, UHMWPE fibers only 3 to 4 percent.

Class 2: Anchor Tensioned Cages

These cages are represented by the Ocean Spar Net Pen shown in Figure C-4. This is a well thought out concept. The cage is held in position at the sea surface by attachments to four spar-type corner buoys, which are moored and tensioned by large gravity anchors. The spar buoys are equipped with bottom damping plates and respond to sea-state forcing with little roll and heave motions, until they come into their resonant frequency condition. The net pens stay positioned near the sea surface, experiencing very little rocking from most sea states. The net cage stays taut due to the anchor rope tension and thereby survives with little response to the sea-state forcing at the ocean's surface due to lack of cage-attached flotation. However, the failures experienced during the prior Gulf of Mexico experiment (Miget, 1995) indicate that the system behavior in high sea states is not yet completely understood. Therefore, the use of the Ocean Spar system is not recommended at this time.

Class 3: Semi-Rigid Cages

A distinct design of cage systems has been developed which can be classified as semi-rigid. Such a type is the Sea Station from Ocean Spar Technology (Figure C-5).

A semi-rigid cage system is designed with a basic frame around which the containment nets are placed. The framing provides the structural backbone of the net system. The *Sea Station*'s frame (Ocean Spar Technology) has a large tubular ring at the equator of the structure which is suspended from a center column and held in position by rope stays.

Our assessment of the semi-rigid cage system is that it provides good, workable stations for semi-protected and protected waters, but it is not designed to withstand the full onslaught of open-ocean storm waves at the sea surface unless submerged. A semi-rigid structure with modifications to allow easy winching to submerged locations would be a strong candidate for the planned Gulf of Mexico project. This requires development of controlled winching of the cages. A significant drawback of the semi-rigid cage design is its difficult access for maintenance, exercised now by large zippers, through which divers leave to enter the containment net structure.

Class 4: Rigid Cages

These cages consist of rigid self-supporting structures "assembled from jointed beams, columns, and trusses capable of withstanding compression, tension and bending loads" (Loverich and Gage, 1998). Cages used in the earlier GOM experiment, see Figure C-6, are one example of rigid cages. This cage was successfully deployed submerged 47 ft below the sea surface and lowered into position from an oil platform along a heavy polyester rope. The cage was built with perforated steel top and bottom plates. Its design has to be reviewed in detail, since only one type of reinforced netting survived the deployment without tearing out. The cage failed when deployed 20 ft below the sea surface. Other rigid cage candidates are steel-framed net pens used to grow salmon in protected locations. An alternative design is the *Trident Cage*, see Figure C-7, which is built like a geodesic sphere (Willinsky, 1994, 1996). It is constructed from foam filled aluminum tubing sections forming triangular segments of the spherical cage structure. The resulting cage is positively buoyant and has to be pulled under water by its mooring. Nets are sewn together to fit as taut netting inside the structure, using bolt ropes. The structure can operate both submerged and at the surface. However, long-term, open-ocean operation at the surface in storms is not recommended by the manufacturer.

The rigid net cages are good candidates for a fish farm from an oil rig, if they can be kept out of the major surface wave energy zone. However, only a few rigid cages can be installed under an oil platform due to the limited number of available bays in most structures. For economic reasons, additional cage systems are required which must be accommodated in waters outside the space occupied by the platform. The spacing density depends on water quality requirements, which may hinder close proximity between adjacent cages. In order to utilize the advantage of cage control by oil rig mounted winch systems, reliability and survivability issues of the sea floor mounted and anchored cage rope sheaves have to be solved. Such development will require some time, and the use of other platform connected fixed cages is not practical for the first demonstration project.

The Recommended Cage System Selection and Future Considerations

At the present stage of fish cage development and experience, the choice of suitable cage systems for open ocean mariculture is rather limited. Primarily because of proven records of survivability in unprotected ocean locations, the Anchor and Gravity Tensioned Cage candidates are considered the best configurations for the planned project. Either the *Bridgestone High Seas* or Dunlop's *Tempest* cages (Figure C-2) should be procured. These cages are supported by surface flotation from reinforced rubber hose segments arranged as octagons at the sea surface. They are to be equipped with proven net configurations, including an upper shock net and a net covering the cage opening to prevent predation by birds. Details such as the safe anchoring, mooring configuration, and mooring line optimization will need to be worked and modeled for each site.

In addition, a small number of Rigid Cages could be arranged in the bays between the oil platform legs. They must be deployed at sufficient depth below the sea surface (57 ft worked in 1990 with a 20 to 30-ft net). Net details would duplicate the surviving construction of the 1990 experiment (Phase 1) in the Gulf of Mexico. Only a few rigid cages can be installed under an oil platform due to space constraints and water quality requirements.

Both the sufficiently submerged Rigid Cage System and the selected Anchor and Gravity Tensioned Cage System candidates have the best survival guarantee for open ocean deployment based on past experience. For the future, the development of the winching technology to allow submergence of cages on command, reducing severe sea state impact, would greatly improve the longevity of surface deployed cage systems and their payload in bad weather (see Figure C-1). Many detail tasks have to be solved to develop such systems and to later automate them to eliminate the need for personnel stationed on a platform.

Mooring and Anchoring of Offshore Cage Systems

Mooring Component Selection

Mooring line candidates have significant influence on the elastic and configuration characteristics of a mooring system. A wide choice of candidates is available with greatly different mechanical properties. These include (1) chain, (2) wire ropes, and (3) fiber ropes as discussed below.

<u>Chain</u> is the heaviest of all mooring elements and, in most applications, combines a poor utilization of the metallic strength with the best endurance against abrasion. With almost zero elastic elongation, chain is a poor shock absorber. However, a chain mooring can provide compliance when operating in a catenary configuration, or when chain links are raised from the sea floor by a surface buoy's heave motion in waves or current. Chain is most useful as the bottom section of a mooring, forming the linkage to the anchor, where its ability to take abrasion is required. Chain terminations are the easiest of all, with one or more shackles through any chain link forming the connecting link.

<u>Wire ropes</u> are heavy, resistant against cuts and most abrasions, but elongate up to _ percent under working load. Wire rope constructions differ in flexibility, elongation, torsional, and rotational response to applied tensions. All wire rope constructions are threatened by kinking and hockling in service, particularly when the load on a tensioned rope is suddenly released. Nearly all wire ropes develop significant torque when loaded, or rotation when allowed to spin. Sudden unloading releases the stored torsional energy suddenly, which can lead to kinks that make a wire rope useless. Due to their small elongation under load, the ropes are poor shock absorbers. Wire ropes are inherently stiff, and guiding ropes over undersized sheaves can permanently bend the rope due to yielding of the rope wires. Commonly used galvanized wires reduce corrosion in seawater substantially. Wire ropes would be the most suitable choice for winched cage systems. Adding exterior plastic jacketing and electrical conductors are available design options. Wire rope termination technology, either through eye splices or swage fittings, is well established. Swivels may have to be used to remove rope rotation under load changes. Special attention has to be given to prevent kink formation in service, for instance by preventing anchor spinning while deploying a mooring. Only wire rope constructions with high levels of torque balance are useful for moorings at sea.

Fiber Ropes are lightweight and are mostly threatened by cuts, fish bite, and external abrasion. They can be made from low-stretch, high-performance fibers or from weaker polyester, nylon, or polypropylene fibers. The rope construction technique used has a noticeable effect on a rope's behavior. The rope construction amplifies the fiber elongation through the **twisting and braiding** processes. The increase in elongation is coupled with a reduction in fiber strength efficiency and rope stiffness. Braided ropes inherently do not kink or hockle under changing load levels. Typical elastic elongation of well used ropes loaded to 30 percent of their new breaking strength is anywhere between one and 10 percent. Nylon is in the eight to 10 percent stretch range, polyester and polypropylene stretch under four percent, and high performance ropes around one percent. The higher elongating ropes provide a significant shock absorbing capability which is important in the control of the sea-state motions of cages. Fiber rope terminations are usually made through construction-specific eye splice techniques.

The cage moorings must be designed utilizing the best possible combination of mooring components. Numerical modeling of the cage moorings will allow optimization of the mooring component selection for best survival and operational performance in a given configuration and conditions at a particular site. Attention to detail will be applied to the connecting hardware to ensure longevity of the mooring. The WHOI mooring experience will assist in the screening and selection process to optimize a mooring link's performance and longevity. WHOI mooring engineers and technicians will screen a mooring link and system candidate to assess its ability to be deployable, serviceable, and retrievable. They will also make sure that proper detail and selection of the mooring hardware is taken into account.

Anchors

The proper selection of the most suitable anchoring method for sea cages is of prime importance to the survival of the cage system since the tensions due to currents on a large cage system in typical currents can be many tons. The sea floor geophysical conditions and the interaction of surface waves with the sea floor will dictate the anchor selection at a particular site. Special anchors and anchoring techniques have been developed to cope with the loads of the oil industry in the sea floor mud in the Northern Gulf of Mexico. These are suction pile anchors and vertically loaded drag anchors. Vertically loaded drag anchors (VLAs), specifically designed for offshore oil platform moorings, are produced by Vryhof in Holland, and Bruce VLA Ltd. in Great Britain. The Stevpris Mk5 anchor from Vryhof allows adjustment of the angle between anchor fluke and shaft for sand/hard clay, medium hard sand, and very soft clay and mud. In soft mud, the ultimate holding capacity of 30 times the anchor weight is being achieved. Embedment tensions are up to 40% of the ultimate anchor holding capacity, requiring support vessels with high pull capacity. Both Vryhof and Bruce VLA Ltd. have conducted extensive test programs to support the most demanding anchoring requirements of the oil industry with detailed holding power data for their different anchor models. Suction or special embedment technology is used in muddy sea floors to get the anchors below the mudline and into harder soils. Helical screw-in anchors, made by Straight Moorings in Canada, which have superior holding power in hard soils, are not suitable for soft mud. Deadweight anchors can be either steel or concrete. Concrete anchors are rather bulky, losing about 40% of their weight when immersed. The advanced anchor options will be addressed once sea floor conditions of a planned oil platform site is known. For more information on these anchors, see Huang and Lee, 1998.

Numerical Modeling of Aquaculture Systems

A key component of future work will involve simulations with *WHOI Cable* [1]. This is a numerical cable dynamics program that was developed for simulating the motions of two and three-dimensional cable systems. The program is built around a mathematical model that includes the effects of geometric nonlinearities, material nonlinearities, material bending stiffness, and material torsion. By including geometric nonlinearities and bending stiffness, WHOI Cable can accurately model systems in which cable segments go slack.

Important Features of Mathematical Formulation

The effect of bending stiffness (EI) can be illustrated by considering the static governing equations for an extensible cable in two dimensions. Neglecting drag terms, a force balance in the tangential and normal directions on an infinitesimal element yields:

$$\frac{\partial T(\varepsilon)}{\partial s} - w_o \cos(\phi) = 0$$

$$T(\varepsilon)\frac{\partial \phi}{\partial s} + w_o \sin(\phi) = 0$$

T(e) is the tension in the cable as a function of strain *e*, *f* is the angle of inclination from the vertical, and w_o is the weight per length of the cable. With this formulation, the equations are singular if the tension in the cable becomes zero. Incorporating the effects of bending stiffness, specifically a shear force, allows us to avoid this singularity. The second equation above for the forces in the normal direction becomes:

$$\frac{\partial S_n}{\partial s} + T(\varepsilon)\frac{\partial \phi}{\partial s} + w_o \sin(\phi) = 0$$

[1] For complete details and additional references, see article by Gobat & Grosenbaugh (1998), "WHOI Cable: Time Domain Numerical Modeling of Moored and Towed Oceanographic Systems," in the Proceedings of Oceans '98, Nice, France.

S_n, the shear force, is governed by the additional equation:

$$EI\frac{\partial^2\phi}{\partial s^2}+S_n(1+\varepsilon)^3=0$$

where E is the Young's Modules of a cable, and I its moment of inertia. The way in which material nonlinearities are incorporated into WHOI Cable can be illustrated by the following analysis. For tension as a function of strain, we can write:

$$\frac{\partial T(\varepsilon)}{\partial s}=\frac{dT}{d\varepsilon}\frac{\partial \varepsilon}{\partial s}$$

Substituting into the equation for the tangential forces we get:

$$T'(\varepsilon)\frac{\partial \varepsilon}{\partial s}-w_o\cos(\phi)=0$$

Thus, if we know the constitutive relationship for a material, T(e), its first derivative, T'(e), and the material never deforms plastically (T'(e) > 0 for all e), the nonlinear stress-strain behavior of a material can be fully modeled.

Previous derivations of the three-dimensional cable equations have used coordinate transformations based on Euler angles. When using this transformation for cable equations, there is a singularity in the angular spatial derivatives associated with a specific rotation angle. The traditional method of avoiding this singularity was to choose the rotation sequence such that the singular rotation was unlikely to be encountered. For long time simulations of moorings with large motions and cables that can go slack, however, such a choice may be impossible. WHOI Cable uses a coordinate transformation based on Euler parameters to avoid this singularity. Rather than a sequence of three successive rotations using Euler angles, transformations based on Euler parameters make use of Leonard Euler's principal rotation theorem to represent an arbitrary change in orientation by a single rotation about a single vector. This is a four degree of freedom transformation (three vector components and an angle) compared to the three degree of freedom Euler angles transformation.

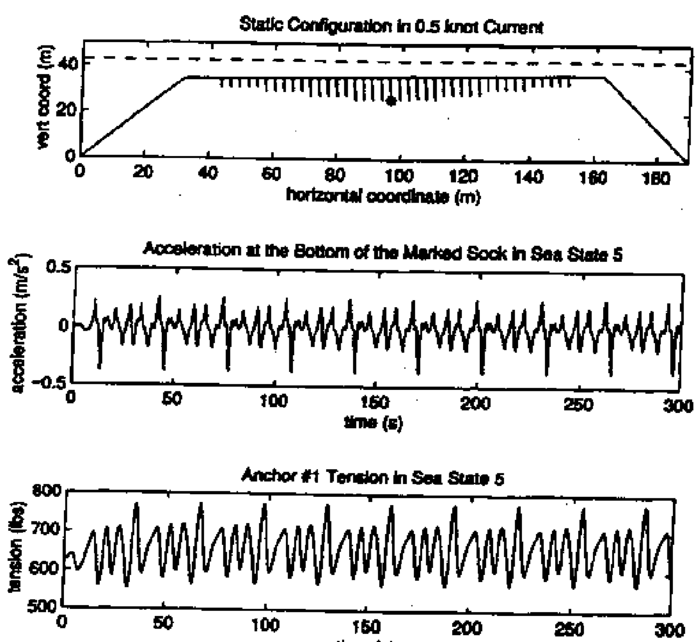
The model for the interaction of cable segments with the sea floor is based on a linear elastic foundation. For nodes with vertical coordinates below the bottom, an additional normal force linearly proportional to the distance below the bottom is applied. For static problems, this force is not allowed to exceed the weight of the cable. This restriction is not imposed in the dynamic problem where impact forces can occur. A velocity proportional damping force is also applied in dynamic problems. Tangential static friction forces are based on the net normal force and a simple friction coefficient.

Numerical Algorithm

The mathematical problem in each case is posed as a system of coupled, nonlinear partial differential equations. The program solves this system numerically by discretizing the continuous (exact) forms of the governing equations using finite differences centered on the half-grid points (which makes the approximation second order accurate). This discrete system of nonlinear equations is solved by an iterative, implicit relaxation technique. For the static solution, the initial guess for the iteration procedure is based on a catenary solution for a uniform cable with equivalent weight, stiffness, and length properties. For the dynamic solution, the initial guess at each time step is the solution from the previous time step. At each iteration the equations are solved using a sparse Gaussian elimination algorithm for which the computational effort scales linearly with the number of nodes.

Simulations of Aquaculture Structures

As part of a Sea Grant demonstration project, WHOI and industry partners are developing a mussel long-line installation for deployment offshore Massachusetts. Because WHOI's experience with such structures is limited, *WHOI Cable* modeling is an integral part of the design phase of this installation. The top panel of Figure C-8 shows the two-dimensional response of one of the proposed configurations in 0.5 knots of left-to-right current. In this configuration, several different sock lengths would be deployed along the line to better understand the effects of sock length and mussel depth on growth rates. WHOI Cable static modeling was used to calculate the required distribution of buoyancy along the line to balance the varying weights of these lines in a variety of two-and three-dimensional current conditions. The second and third panels present results from dynamic modeling of this same configuration in a simulated sea state of 5 meters (3.5 m significant wave height and 24 ft winds). The sock acceleration shown in the second panel can be an important factor in the retention of the mussels on the sock. The third panel shows the total tension at the left anchor; anchor tension results are critical in the selection of an anchor for a given bottom condition.



Given the current state of development of WHOI Cable, additional types of aquaculture structures could be modeled. Large floating rings, moored via a series of anchoring lines, of the type used to support some net cages can presently be described within WHOI Cable's mathematical framework. With this kind of model, net forces are treated as point loads acting at the point of attachment to the primary structure. With ongoing improvements, work could include a more complete generalization of structure geometry to allow for the modeling of the net system and cages themselves.

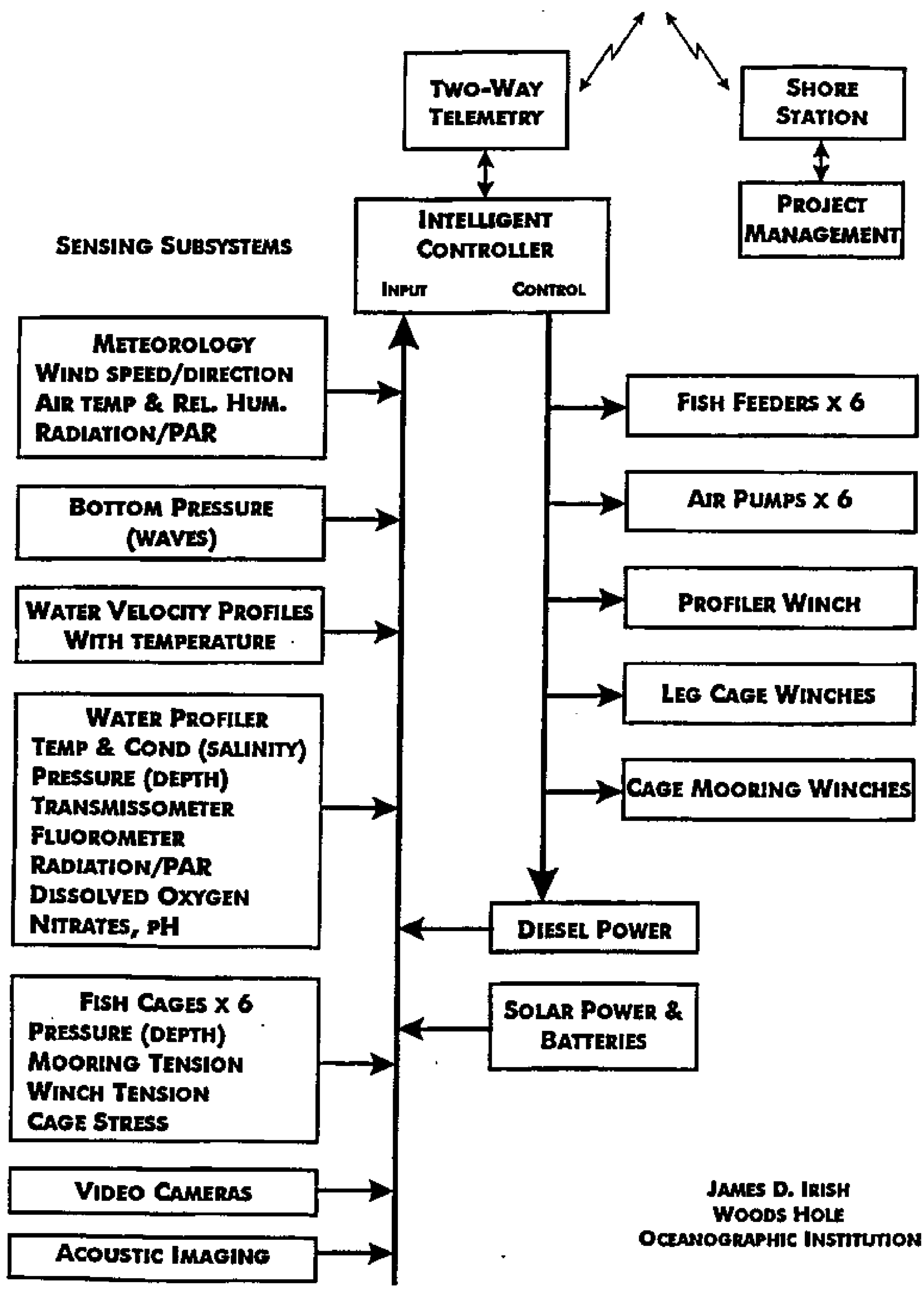
For designed planning of a mariculture system, WHOI cable can make significant contributions to the system requirements in its current state, and will improve its predictive power in the future. Modeling should be a central part of any moored fish cage program.

Intelligent Sensing and Control Systems

Computer System

With modern, low-powered controllers, an intelligent computer system would be an important part of the sensing and control system of the mariculture project. This automated control system has the potential to reduce the manpower required for a platform operation. A goal would be to have no one on the platforms, with a shore-based management and response team to support the operation. The response team could respond to problems on a particular platform identified by the sensing system and relayed by the telemetry to the management team. It is this control of the fish cages within the water column which might prove an advantage over fixed systems, allow the avoidance of fish loss and justify the added complexity of winches and moveable cages. A block diagram of a data system with inputs and controls is shown in Figure C-9. This diagram relates to the conceptual sketch in Figure C-1. The basic computer and sensing system could be powered from solar charged batteries most of the time, as the power requirement is minimal. These power systems have proven reliable in land and buoy based systems and should provide reliable power on the platforms. When an action is required which needs more power, the system then has the ability to turn on a generator to supply thehigher power required for winches, feeding systems, etc. The control system would collect data from a number of enviromental sensors at standard times, and make intelligent decisions based on these observations. As an example, the system would profile the water column for water temperature, and then, based on these observations, move the fish cages up or down in the water column to the optimum temperature for fish growth.

A computer-based control station with two-way telemetry with sensor interface and control capability would cost in the $15 to $ 10K range. This includes onboard data backup should the telemetry link provide inadequate. A solar power system with panels, batteries and regulators would be $2 to $3K.


Two-Way Telemetry
Shore Station
Project Management
Intelligent Controller
Input
Control
Sensing Subsystems
Meteorology
Wind speed/direction
Air temp & Rel. Hum.
Radiation/PAR
Bottom Pressure
(waves)
Water Velocity Profiles
With temperature
Water Profiler
Temp & Cond (salinity)
Pressure (depth)
Transmissometer
Fluorometer
Radiation/PAR
Dissolved Oxygen
Nitrates, pH
Fish Cages x 6
Pressure (depth)
Mooring Tension
Winch Tension
Cage Stress
Video Cameras
Acoustic Imaging
Fish Feeders x 6
Air Pumps x 6
Profiler Winch
Leg Cage Winches
Cage Mooring Winches
Diesel Power
Solar Power &
Batteries
James D. Irish
Woods Hole
Oceanographic Institution

Control of Fish Cages

By utilizing the oil platform as a center anchor for a number of fish cages spaced around the tower, the central platform has the ability to control a number of fish cages (Figure C-1). If these were not floating on the surface, but totally submerged, then winches on the platform could raise and lower one end of the cage with a winch system along the legs of the platform. The ends of the fish cages away from the platform would have to be anchored, and could also be raised through a series of winches and cables to flotation on the outboard end of the fish cage. Once the cages are constructed regulating new developments and/or improved design so that they can be controlled, the intelligent system could then take over and control the position and monitor the status of the fish cages. By monitoring light, temperature and currents, the system could make a decision and move the cages to a depth with environmental conditions for optimal fish growth. In response to environmental forcing such as a storm or hurricane, the system could move the cages to the bottom to minimize damage to the cages and injury to the fish. Based on environmental conditions, the intelligent control system could also alter the time and amount of external food to supplement that naturally occurring and adjust for seasonal and environmental fixed changes in food requirements

Two-Way Telemetry

The data system would also rely on two-way cellular phone or satellite telemetry to return data from the platform to shore and to allow the shore-based management team to monitor, control and alter several subsystems from the shore. Data (see discussions below) would be routinely collected on the platform along with water, fish and cage status and relayed to shore on a regular basis (e.g. first thing in the morning and later in the afternoon). The management could also request additional data between normal transmissions and alter the sampling or control it in real-time from shore to have a "hands on" system while still on shore. Besides sending the normally sampled data on a regular basis, the system would also have the ability to send alerts as soon as it detects some abnormal condition. High waves (significant wave height exceeding some pre-selected limit resulting from modeling of the system) or oxygen levels which fall below the normal statistics for the region and season would trigger immediate calls to shore. Those on shore would be alerted and receive data from the sensing systems to assist in making management decisions.

Video Imaging

The data system relies on inputs from a variety of sensors on the platform, in the water and on the fish cages themselves. Remote video imaging from the platform would allow the system to be an observer, without a man in residence. Both above and underwater video cameras and acoustic imaging will be used. The images could be compressed, stored on the platform and telemetered to shore for analysis. Depending on the visibility of the water, underwater cameras could image critical components of the fish cages, the fish behavior and mortality. They will also monitor the degree of biofouling of the cages. Above water cameras will monitor the condition of the tower, keep an eye out for poachers and provide an endangered species alert; that is if a whale were to become entangled in the system. Simple pattern recognition algorithms could detect differences between images and alert the management team on shore.

Acoustic Imaging

Acoustic imaging has better potential for underwater imaging when optical visibility is not optimum. Multi-frequency acoustics can penetrate opaque waters with fine sediment or biological growth. It also allows the fish size and number to be determined to help observe fish growth rates and health. Acoustic imaging could also locate the fish within the cage and indicate potential problems and mortality by observing the original strength as a function of frequency since swim bladders change with fish size and responds at standard acoustic system frequencies.

Cage Monitors

To monitor the cages in addition to the optical cameras, tension would be monitored in the cage-mooring members. This would alert of significant biofouling, which can significantly increase mooring tensions beyond the modeled tension for the cages in the observed current field. This would also give an indication of outside influence on the cages, e.g. poachers or entangled whales. Certain critical structural members in the cage would also be monitored with strain gauges to assure that applied forces did not exceed predicted levels based on system modeling and design. Finally, cameras would monitor the cage location in the water column to assure that the cages are where and at what depth they are supposed to be.

Meteorology Sensors

A suite of sensors would be fixed to the tower to give nearly continuous readings of environmental variables in support of operations. This includes the meteorology forcing at the tower. Wind speed and direction would be measured and used to predict waves and direct force predictions. Air temperature and relative humidity would be used with sea surface conditions to predict local heating of the water. Photosynthetically Active Radiation (PAR) would provide information on the radiation-driving primary productivity (photosynthesis) and an estimate of the radiation causing local heating of the water. If more complete information on the radiation fluxes is desired, short-wave and long-wave radiation sensors can easily be provided but are probably not required.

Pressure/Wave Sensor

A pressure sensor on one leg of the tower will monitor sea-surface elevation, and when averaged to low-frequency, will provide information on tides and weather-forced sea surface changes. The density of the water column will be measured by a profiling package, and this can be used with the vertical equation of motion to estimate sea surface elevation from pressure. When burst sampled rapidly, the pressure sensor will provide information on the local wave spectra and the significant wave height. This can be used with shallow water wave theory to predict the wave forcing on the cages as a function of depth and to alert the management team if the waves are approaching some predetermined critical condition. With the predictions of increasing winds, the model of local wave growth and conditions can be fine-tuned to give greater warning to the potential of large wave damage.

Profiling Sensor Package

The water column quality will be measured at desirable points in time by a profiling system. Oceanographers use shipboard observations made by profiling systems. This approach has the advantage of requiring only one sensor suite to obtain information at all depths. This approach risks missing high frequency internal wave activity which may be important at some sites because of the large vertical excursions and horizontal current shear associated with such activity. However, for normal monitoring of water conditions due to local heating and cooling, advective changes in water properties, this profiling approach should be entirely adequate and cost effective. A sensor suite would be stored in a protective "house" out of the water to reduce biofouling, especially on the optical sensors, and to remove it from wave forces except when profiling. The system would be pulled up and down one leg of the tower by a winch assembly under control by the data system. The observations would be recorded and processed by the data system for storage and relay to shore. The controller would decide when to profile and would have a regular schedule such as six profiles a day to monitor the slow local and advective changes in water quality. If conditions deviate from expected or standard and approach some critical value, the profiler would run more often to obtain data and to provide necessary information to enable corrective action to be taken, preventing damage to the cages and/or loss of fish.

Physical Sensors

Sensors on the profiler would include the standard physical and bio-optical varieties. Temperature, conductivity (for estimation of salinity) and pressure (depth in the water column) would be standard observations along with water velocities. The temperature would show the profile of heat and indicate the optimum depth for the fish cages, indicating any excessive temperatures or temperature changes to be avoided. A temperature sensor with the pressure sensor on the tower could fill the time history of temperature fluctuations at one depth between profiles. Salinity profiles would alert to any fresh water runoff or advective changes which may be detrimental to the fish. The current profiles could be made with a point-acoustic current sensor on the profiling fish or by a more expensive Acoustic Doppler Current Profiler (ADCP) attached to the bottom of one leg of the tower and profiling the water column. Both configurations have advantages and disadvantages and both would work. The currents would allow an estimate of the forces on the cages, and be compared with the measured tension/forces to an estimated degree of fouling and alert for potential problems resulting in cage damage and fish loss.

Bio-Optical Sensors

The bio-optical sensors would include a PAR, the 4 ; sensor measuring light from all angles driving primary productivity. The profile of PAR would allow estimation of the attenuation coefficient and the amount of suspended particles in the water. A transmissometer, or optical back-scattering sensor, would also be used to estimate the particles and visibility in the water. The optical attenuation is largely due to the finer particulates in the water column, and would give a warning of low light penetration. Since monitoring primary productivity is important to indirectly determine the nutrient levels and chlorophyll in the water column, a chlorophyll-a fluorometer could be added. An oxygen sensor would monitor the profiles of dissolved oxygen and alert for anoxic conditions. However, dissolved oxygen sensors are among the least robust sensors available today, and may not have the reliability required for the desired task. Other measurements of nutrients (nitrate, nitrite, ammonia and phosphate or pH) are normally made in the laboratory with an autoanalizer or laboratory instrumentation. Some in-situ systems are now being constructed, but they again are not routine measurements that can be made remotely. To get around these sensor limitations, the profiler could collect water samples for later laboratory analysis on shore. The system is flexible and could easily be expanded to utilize any new sensing system as it becomes available. The Sea Bird Electronic Model 911 system is an example of a shipboard system which has been successfully adapted to unattended profiling in coastal environments (ref. LEO-15). A system such as prepared here would cost in the $75K range, and directly interface to the control computer with little difficulties.

Summary: Intelligent Sensing and Control System

The intelligent data system with two-way telemetry, shown in a block diagram as Figure C-7, can relay information from the video and acoustic imagery, environmental and cage sensors to the shore-based management team to connect them with several platforms and their operation at one time. The management team can communicate with the platform and command more information and images, or command the platform to perform one of its standard set of operations under control of the data system. Also the data system can monitor environmental, fish, and cage conditions and take responsive actions without a manned presence at the platform, or without a command having to be made from shore. Having the remote system able to react to environmental conditions will improve fish growth and reduce the possibility of cage damage. Combined with the alert of problems on the platform or in the fish cages, these factors will improve the probability of an economically viable operation.

Chapter

10

Oceanographic/Water Quality Data

Executive Summary

This report summarizes the physical, chemical and biological parameters that are important in selection of appropriate locations for moored mariculture facilities in the north-central and northwestern Gulf of Mexico. The conditions summarized are applicable to conditions that might affect the integrity of the structure and the health of the penned fish. Also, the potential influence of the penned fish on the ambient environment is outlined.

Winds, waves and currents are the physical parameters most important in determining the structural integrity of the moored structures. Winds are typically < 20 m/s. Winter storms create moderately high winds 28 to 37 km/h, with extremes up to 89 km/h. Tropical storms and hurricanes represent the worst case scenario with winds of 18 to over 44 m/s. Tropical storms generate waves up to 2-3 m. The record wave height up to the period of Hurricane Andrew in 1992 was 7.3 m in summer. Hurricane Andrew generated a wave peak of 9.1 m in close proximity to the eye of the storm off Terrebonne Bay.

The currents of the study area are not typically affected by oceanic currents, but anticyclonic gyres which spin off the Loop Current can travel westward along the outer shelf and impinge on the study area. Strong currents of 50 cm/s are associated with eddies near the Flower Garden Banks. Shelf currents are less strong (20-30 cm/s). Currents are usually to the west, but a clockwise eddy is a fairly permanent feature of the Mississippi River delta bight region. During the passage of Hurricane Andrew in 1992, one mooring (LATEX-A) near the eye of the storm recorded three peak currents at 134 cm/s, 92 cm/s, and 50 cm/s. Another mooring (NECOP) on the other eye of the hurricane recorded a 175 cm/s north component and a 115 cm/s east component in the bottom waters during passage of the storm.

Surface water temperatures are more variable on the inner shelf (12-15 to 29°C), while the outer shelf temperatures are more moderate (18-19 to 21-25°C). Bottom waters are more homeothermal with values of 20 to 24°C in 50 to 100 m water depth. A strong thermal stratification occurs in summer. Salinities approach 15 to 18 ppt near shore and closer to the river discharge. Bottom water salinities approach the 35 ppt range most of the time.

The suspended sediment load of the Mississippi and Atchafalaya Rivers is seen in turbidity plumes near the deltas. There is also reduced light transmittance near the bottom when nepheloid layers are present. Turbidity in the surface waters is often due to biological particles, particularly algal blooms that respond to riverine nutrient flux.

The plume of the Mississippi River is an extremely productive environment with high primary productivity values of 290-320 $gC/m^2/y$. Flux of particulate organic carbon (POC) is high in waters less than 100 m, and averages 50% in a 20-m water column. POC flux values averages 500-600 $gC/m^2/d$ in 15 m depth at Station C6B off of Terrebonne Bay. According to the models of flux versus primary production, there will be less flux of particulate organic carbon with distance offshore and in deeper water; however, there is still a large proportion of the primary production that is fluxed in a water column < 100 m (usually about 50%). Export of surface water carbon is highest in the spring, lowest in the summer, and intermediate in the fall. The flux of materials added by mariculture operations could contribute to the carbon flux that fuels oxygen depletion in the spring and summer. The physical structure (stratification intensity) of a 50-m water column, however, would not likely support sustained low oxygen levels in the lower water column. The flux of organic matter could alter the benthic community structure, but surface deposit feeding polychaetes and smaller opportunistic polychaetes are already part of the community in this area.

Hypoxia (bottom water oxygen levels less than 2 mg/l) typically occur in 5 to 30 m water depth across much of the inner Louisiana shelf from May through September. Hypoxia does not occur commonly in 50 m water depths. Oxygen minimum zones in the upper water column do occur but are not frequent for stations within the 30 to 60-m water depth. The mid-water oxygen minimum zones are usually confined to a 5-m extent of the vertical structure, but may be as much as 10-m thick. Most are associated with organic particle fallout from the river plume and a stratified water column.

Harmful algal blooms are a matter for concern in offshore mariculture operations, both those that might affect the health of the caged fish and those causing indirect effects similar to mariculture operations contributing to harmful algal blooms as seen elsewhere in the world. Several blooms of toxin-producing harmful algae that can cause fish kills occur in the northwestern Gulf of Mexico. Some of the harmful algal blooms produce toxins that affect human health; these are of concern if shellfish are cultured.

Introduction

In preparation of deployment of moored mariculture facilities in the north-central and northwestern Gulf of Mexico, fundamental information is required on general oceanographic conditions that might affect the integrity of the pen structures and the health of the fish. Additionally, the influence of the mariculture activities need to be assessed with regard to impacts on the surrounding environment.

This report outlines the general oceanographic conditions of the north-central and northwestern Gulf of Mexico, with an emphasis on the Louisiana continental shelf from the birdfoot delta of the Mississippi River to the upper Texas coast. Information was obtained from the primary literature, agency reports, and data sets archived under the supervision of Dr. Nancy N. Rabalais, Louisiana Universities Marine Consortium (LUMCON). Data sets maintained by Dr. Rabalais include results from several programs which focused on the distribution of hypoxia and related hydrographic parameters, and general physical oceanographic and biological features of the Louisiana-Texas shelf.

Data from cruises which sampled the continental shelf from the Mississippi River delta to the upper Texas coast (some to the middle Texas coast) exist for the period 1985-1997, primarily in the summer, but also a few from the spring and fall. Similar data for a more limited geographic area but with greater temporal coverage exist for a transect off Terrebonne Bay (Transect C) on a bimonthly or monthly basis for 1985-1986, 1990-1997. The data set for the hypoxia studies of Dr. Nancy Rabalais (LUMCON) and Drs. R. Eugene Turner and William J. Wiseman, Jr. (Louisiana State University, LSU) contains approximately 41,000 records representing 60-80 stations with multiple sample dates (= 2,200 station/date combinations). Additional stations (approximately 100/cruise) were obtained in a Louisiana-Texas (LATEX-B) Physical Oceanography program sponsored by the Minerals Management Service (MMS). These data are maintained in a master data file at LUMCON in dBase and Access software and can be statistically analyzed and queried with the help of standard software packages. All data sets are available through NOAA's National Oceanographic Data Center (NODC). Figures and Tables (unless referenced to a publication, report, or individual) come from the master database (hypoxia studies and LATEX-B).

General Oceanography

Large scale water circulation in the Gulf of Mexico is influenced by the Loop Current and associated eddies, the semipermanent gyre in the western Gulf, winds, freshwater input and the density structure of the water column. Water enters the Gulf of Mexico through the Yucatan Strait and forms the Loop Current. Part of the current bends to the right, flows through the Straits of Florida and joins the Florida current. Some of the water flows farther north into the Gulf and then veers to the right to form a clockwise gyre which is bounded by two or more smaller counterclockwise gyres off West Florida. The remaining water turns left after traversing most of the width of the Gulf and contributes to a complex series of anticyclonic warm eddies that travel west across the Gulf in a process of decay that typically lasts 4 to 10 months. The Loop Current has an annual cycle of growth and decay, but the variability in patterns from year to year is significant.

The 80-km protrusion of the Mississippi delta into the Gulf alters and affects the currents, tides and wave fields in the local coastal waters. The shallow sound and shelf east of the delta, the severe bathymetric curvature of the delta itself, and the long-regular coast and shelf extending to the west create large-scale topographic controls in the flow field. The Mississippi River is also the major source of river discharge. The discharge (averaging 13,528 m^3/s) flows mostly to the shelf edge of the prodelta and westward. The long-term average peak discharge in April is 30,000 m^3/s, and the long-term low discharge in September to October is 10,000 m^3/s. The area between the Mississippi River and Cape San Blas also receives substantial river runoff (3837 m^3/s) with most contributed from Mobile Bay (2068 m^3/s) and Mississippi sound (943 m^3/s). The Atchafalaya River carries one-third of the flow of the Mississippi River along with that of the Red River. The influence of the combined flows of the Mississippi and Atchafalaya rivers is especially prominent in the reduced salinity of inner shelf waters as far west as Galveston. Occasionally, during the late spring this influence may extend farther offshore and down the Texas coast.

Tides

Gulf of Mexico tides are of reduced amplitude compared to those of the eastern U.S. and range from 0.3 to 1.5 m, with the magnitude being the lowest on the south Texas coast. The Gulf tides are predominantly diurnal but major variations create mixed or semidiurnal tides along certain shores. Tidal currents are typically much slower in the Gulf of Mexico (generally $\leq$ 14 cm/s) than the open continental shelf of the Atlantic Ocean, especially the more northerly areas where tidal ranges are generally < 8 cm/s. Around inlets, keys, or barrier islands, however, they may frequently reach a velocity of 150 cm/s.

Winds/Waves

The Azores-Bermuda atmospheric high pressure cell dominates wind circulation over the Gulf, particularly during the spring and summer months. During the relatively constant summer conditions, winds are predominantly southeasterly but are more southerly in the northern Gulf. In October there is a generally easterly flow throughout the Gulf. Winter winds usually blow from easterly directions with fewer southerlies but more northerlies. Winds in the summer season fall mostly between 2 to 5 km/h, but the winter winds dominate over a wider range of 2 to 12 km/h.

For the LATEX-B cruises, wind velocities were recorded in transit during cruises in April 1992, October 1992, April 1993, July 1993, July 1994 for shelfwide cruises and April 1994 for the Mississippi River delta bight. These typical spring, summer and fall wind velocities are presented in Figures N1-N7. Both April cruises show the passage of a cold front mid-cruise, with strong winds from the east and southeast prior to frontal passage and strong winds from the north during frontal passage (Figures N1 and N2). Both July cruises show a persistent southerly wind (Figures N3 and N4). The October cruise was affected by strong easterly and southeasterly winds with a short northerly/northeasterly period in mid-cruise (Figure N5). The April 1994 cruise in the bight region shows southeasterly winds in Phase 1, and northeasterly and easterly winds in Phase 3 following the passage of a front (Figures N6 and N7).

Wave heights during both summer and winter are predominantly in the 0 to 3 m range but there is a shift in dominance towards larger wave heights during the winter season. Most waves are in the 0.5 to 1.8 m range. Summer conditions are 0-0.6 m with lower wave climates off the North Central area and off the south Texas shelf in the Northwestern area. Winter storm systems frequently cause moderately high winds (28 to 37 km/h) and waves that mask local tides. These conditions are occasionally harsh (> 89 km/h), yet the most extreme conditions are associated with tropical storms. Winter waves are mostly 1.2 to 1.8 m.

The Wave Information Study (WIS) was authorized in 1976 by the U.S. Army Corps of Engineers. Computer simulations models were used to generate and propagate ocean surface waves given a time history of wind velocities on a numerical grid (Hubertz, 1988). Wave model results compared satisfactorily with available measurements, thus showing that the approach was feasible. Waves were hindcast for the period 1956-1975. Beginning in 1976 wind data were saved for stations in the Gulf of Mexico identified in Figure N8 (from the WIS web site, http://www.bigfoot.wes.army.mil/a0078.html). In the data base are summaries for each location that provide mean wave height by month and maximum wave height by month along (example of Station A2055

off the Mississippi River delta in Table TN1) along with 20-year summary statistics (Table TN2 for Stations A2055 through A2064) (Mississippi River to Atchafalaya River).
The largest and most destructive storms affecting the Gulf of Mexico and adjacent coastal zones are tropical cyclones which have their origin (during mid-season of June through October) over the warm, tropical waters of the central Atlantic Ocean, Caribbean Sea or southeastern Gulf of Mexico. The frequency of storms per unit area per 100 years for those with wind speeds of 18 m/s are illustrated in Figure N9. More severe class storms generate winds of 33 m/s and 52 m/s, and the frequency distributions are similar. The historical maximum for waves in the northwestern Gulf was 7.3 m in summer, until Hurricane Andrew.

When Hurricane Andrew, a relatively small but intense Category 4 hurricane, moved across the southeastern Louisiana shelf in August 1992, there were 4 bottom-mounted wave gauges deployed in the northwestern Gulf of Mexico (Jochens and Nowlin, 1995) (Figure N10). The easternmost gauge at LATEX mooring 16 was located within 30 km of the eye of the storm. As Hurricane Andrew entered the eastern Gulf of Mexico, long period waves, i.e., waves of period 10 sec or greater were propagated. Such waves periods are rare in the Gulf of Mexico for all but the most extreme weather events. Long period waves are of particular interest because larger orbital velocity added to mean flow can resuspend sediments at much greater depths than under normal conditions. Arriving several hours before the storm's eye, the long period waves first reached mooring 16. Although considerable distances from the storm center, the wave gauges at the more western locations also recorded longer period waves. The significant wave heights at each LATEX mooring during the 48-hr period centered on the time of highest waves at mooring 16 are shown in Figure N11. The most striking feature is the peak height of 9.09 m at mooring at approximately the time the eye was closest to this location. The maximum waves heights observed at moorings 20, 23, and 1 occurred when long period waves represented a large percentage of spectral energy. The waves traversed broad shelf regions before arriving at moorings 23 and 20. Wave heights were lower at these locations than at mooring 1 even though the distances traveled were shorter.

Currents

The area from the Mississippi River delta east to Cape San Blas (North Central area) is seldom under the direct influence of the Loop Current, but warm eddies often break off from it and move northward particularly in May or June. The northwestern shelf is not influenced directly by major ocean currents, except for the passage of anticyclonic gyres which spin off the Loop Current and travel westward along the outer shelf. Circulation on the Louisiana-Texas shelf is more affected by wind forcing, tides and river discharges. A net westward (Louisiana) and southwesterly (Texas) flow along the shelf characterizes the predominant conditions from fall to early spring. In summer, the flow is to the west and southwest from Louisiana to about 95YW where it converges with an opposing flow to the north and northeast. A clockwise eddy is frequently found just west of the Mississippi River delta. This eddy advects part of the river's plume back toward shore where it may be entrained in the coastal current. An easterly flowing countercurrent and energetic cross-shelf currents characterize the shelf break. A counterclockwise gyre has been observed off South Texas during the winter that migrates along the shelf edge to the north during spring and summer. The gyre may cause transient summer upwelling of cooler water on the Texas shelf during summer.

Current Speeds

Large (> 200 km diameter), strong (swirl speeds greater than 50 cm/s) eddies, both anticyclonic and cyclonic, are frequently observed near the outer continental shelf or deep part of the continental slope in the northwestern Gulf of Mexico (Kelly and Brooks, 1988). An example in Figure N12 shows a period of persistently eastward flow at the Flower Gardens during May 1980, when wind forcing was weak and variable. Inner shelf circulation is less strong, except during passage of hurricanes.

The Dept. of Energy, Strategic Petroleum Reserve studies off Freeport, Texas and Cameron, Louisiana provided documentation of average conditions at 20-m and 10-m water depth, respectively (Figure N13). Figure N14 shows the alongshore component of wind stress, the alongshore component of near-surface waters, the cross-shelf component of near-surface currents, and the cross-shelf component of near-bottom currents for Bryan Mound off Freeport in 20-m depth. Alongshore surface currents are mostly in the range of 25-50 cm/s, but reach 75 cm/s on occasion. Cross-shelf surface currents are mostly in the less than 25 cm/s range. Bottom currents are generally less than 15 cm/s. The long-term annual progression of alongshore components of wind stress and currents for Bryan Mound and West Hackberry are shown in Figure N15. Both the stress and current means are less off Cameron than off Freeport, in large part because of the change in the orientation of the coastline in relation to the mean direction of the winds and because of both the weaker response of current to alongshore wind in shallower waters and an increase in bottom friction.

For the LATEX-B cruises, ADCP underway current velocities were recorded in transit during cruises in April 1992, October 1992, April 1993, July 1993, April 1994 and July 1994. These typical spring, summer and fall wind velocities are presented in Figures N16-N28. Figures N16-N18 depict downcoast flows in April 1992 during a low spring Mississippi River discharge. Figures N19-N21 show downcoast flows in April 1993 during typical high Mississippi River discharge. Figure N22 depicts downcoast flows during seasonally low flow of the Mississippi River in October 1992. Figure N23 shows an upcoast regime during low flow in July 1994. A similar upcoast regime is seen in Figures N24 during record flooding of the Mississippi River in July 1993. The same pattern of upcoast flow was seen in July 1992 during a NECOP shelfwide cruise (Figures N25-N26, Rabalais, Turner and Wiseman). Figures N27-N28 depict current reversals in the Mississippi River delta bight before and following the passage of a front in April 1994.

The LATEX-A program had several current meter moorings placed across the Louisiana-Texas shelf during a 1992-1994 (Figure N29). Table TN3 lists the maximum current speed and direction during deployments in year 2 of the study. Moorings 14-25 are those most relevant to the northwestern Gulf area at 10, 20 and 50 m depth. Moorings 1 and 2 are off the south Texas coast. Maximum speeds were in the upper part of the water column, near-surface and approx. 10 m. Speeds reached 36 to 83 cm/s. There appears to be no temporal pattern to the frequency of the highest current speeds.

Hurricane Conditions

Two instrument moorings were in place on the southeastern Louisiana coast during the passage of Hurricane Andrew in August 1992. Both recorded current speeds and direction as the eye of the hurricane passed close by. The LATEX mooring 14 (50-m contour) recorded currents at 11 m below the surface as the eye of the storm passed to the northeast. Water speeds began increasing shortly after 1200z on the 25th with water flowing to the southwest pushed in the general direction of the hurricane winds. Current speeds of 134 cm/s were reached shortly after the eye of the storm passed. After the eye passed, the currents moved to the north, then the east, then the west. The rotary cycle with a period of about 24 hours was also seen in the magnitude of the current, which exhibited a series of damped peaks separated by about 1 d. The second peak in velocity of about 92 cm/s occurred about 24 hours after the passage of the eye, and a third peak in velocity close to 50 cm/s occurred about 48 hours after the passage of the storm (Figure N30, Fortnightly, LA-TEX Newsletter, Vol. 1, Iss. 16, Dec. 7, 1992). The NECOP mooring at South Timbalier Block 53 was located to the northeast of LATEX mooring 14 in 21-m depth (Rabalais, Turner and Wiseman, unpublished data). The near-surface current meter in 8-m depth was destroyed, but the meter in 19-m water depth continued to record during passage of the storm. Figures N31-N32 show the north and east component of the bottom currents. The north component exceeded 175 cm/s and the east component exceeded 115 cm/s during passage of the eye of the hurricane. In both instances there was instantaneous mixing of the water column with reduced water temperatures (Figure N33) and increased salinities (Figure N34) and dissolved oxygen. Given the magnitude and strength of Hurricane Andrew, it can be presumed that these current speed values represent some of the worst case conditions to be expected in the study area.

Salinity/Temperature

Reduced surface water salinities are evident to many kilometers from riverine sources, with the greatest influence being exerted by the Mississippi and Atchafalaya River plumes. Examples of surface water salinities within the Louisiana and upper Texas coasts are shown in Figures N35-N36. The lowest salinities, of course, are present during peak flows of the Mississippi and Atchafalaya Rivers. For the period May 1964, lower salinities (e.g., 15-25 ppt) covered large areas of the inner to mid shelf but otherwise the salinities were mainly in the 28 to 32 ppt range. The period of the M/V Gus III cruises, however, was during a period of lower Mississippi River discharge.

Thermal plumes from riverine sources do not extend as far as the salinity influence. Surface water temperatures for late fall and early winter are shown in Figures N37-N39. These values are basically 24°C for late November, and 16°C for mid- to late-December in the nearshore waters off Louisiana and warmer off south Texas.

Bottom water temperatures for winter to summer conditions for the areas under consideration are shown in Table TN4.

Although surface waters undergo seasonal temperature fluctuations (typically 20 to 28YC) and may have reduced salinity as a result of river discharges, bottom waters over the outer half of the shelf exceed 34 ppt and are very homeothermal – 20 to 24YC from 50 to 100 m and 15 to 17YC at the shelf break.

Table TN4. Average water temperatures for portions of the Gulf of Mexico.

	Inner Shelf	Outer Shelf	Shelf Break
North-Central	~12-15YC to 29YC	~18-19YC to 21-25YC	~19 to 22YC
Northwestern	15-16YC to 17-28YC	18-19YC to 21-25YC	19-20YC to 22YC
South Texas	14-15YC to 28YC with latitudinal differences	15-17YC to 25YC with latitudinal	19-22YC differences

Cross-shelf Features

Representative cross-shelf contours of temperature, salinity, sigma-t and dissolved oxygen are presented in Figures N40-N43 for typical areas off Freeport, Texas and Cameron, Louisiana. The first set is for winter conditions off Freeport, which shows reduced surface water temperatures (14°C) in the nearshore but more moderate surface to bottom water temperatures (16-17°C) at 25 km offshore in 20-m depth. Salinities are reduced in the nearshore coastal current (29 ppt), but are more uniform offshore (35-37 ppt). Dissolved oxygen is high (approx. 8 mg/l) throughout the water column. Summer conditions show warm surface layers (29-30°C) with thermal stratification below 15 m. Surface salinities are reduced somewhat nearshore (11, 15 or 18 ppt), with strong haloclines near 5 m. There is also a gradient in dissolved oxygen from well-oxygenated surface waters (8-10 mg/l) to depleted oxygen at depth (3 mg/l down to below 1 mg/l). The reduction in oxygen with depth is more likely to occur closer to the effluents of the Mississippi and Atchafalaya Rivers than to the west of Galveston. Low oxygen is non-existent south of Matagorda along with south Texas coast.

Surface water salinities are normally negatively correlated with river discharge; however, LATEX information shows a reduced salinity in mid summer and higher salinities in winter. Surface water temperatures peak in June-September at values near 30°C. Surface water nitrogen is composed primarily of nitrate which peaks with peak river discharge in the spring. Ammonia follows the same pattern and contributes significantly to the dissolved inorganic nitrogen pool in the spring. Silicate and phosphate are variable through the year. Surface chlorophyll *a* biomass peaks in April and May following peak Mississippi River discharge and delivery of nutrients to the continental shelf. Surface waters are well-oxygenated, often supersaturated in February through June.

Bottom waters (at 20 m) are more uniform with salinities between 30 and 35 ppt. Bottom waters gradually warm through the year and reach their warmest (average of 27°C) in September. The lowest temperature are in January at approximately 16°C. Bottom water nitrate peaks in late spring, but are fairly high through the year. Bottom water ammonia is also fairly high through the year. Bottom water nitrite peaks in July and August. All the dissolved inorganic nitrogen species are fluxed from the sediments during alternating nitrification/denitrification processes which are variably affected by dissolved oxygen concentrations. Similarly, the higher levels of bottom water silicate and phosphate are during the summer in low oxygen conditions. Bottom water chlorophyll *a* biomass peaks in the spring, similar to the surface levels. Phaeopigments (the degradation products of chlorophyll *a*) peak in summer during periods of low dissolved oxygen. Dissolved oxygen in bottom water follows a seasonal cycle of highs in winter with a gradual decline in spring to the lowest values in June through August. Bottom waters are well below saturation levels for most of the year.

Because conditions are not necessarily indicative of conditions expected within the upper water column at a station in 50-m water depth near within the Mississippi River delta bight (anticipated location of moored mariculture grow-out facilities), we determined the descriptive statistics for stations in our data base that were located in water depths greater than 30 m and less than 60 m. The results of those analyses are presented in Table TN5 and represent data from 220 station/date combinations for the NECOP studies and 72 station/date combinations for the LATEX studies. The mean, minimum, maximum and standard error for the variables of surface and bottom water (combined) temperature, salinity, % transmission, chlorophyll *a*, total pigments, and bottom water dissolved oxygen for July 1993 and 1994 are shown in Table N5.

Table TN5. Summary mean values for average hydrographic conditions for stations in water depths of > 30 m but < 60 m.

	NECOP, *n* = 220			LATEX, *n* = 72		
	min	**max**	**mean**	**min**	**max**	**mean**
Oxygen (mg/l)	0.0	16.5	4.8	0.5	12.8	6.2
Salinity (ppt)	13.2	37.1	33.3	8.3	36.5	33.0
Temperature (°C)	17.9	32.3	25.2	18.1	30.1	22.5
% transmission	3.0	97.2	81.1	9.1	97.3	88.2
Chlorophyll *a* (mg/l)	0.0	153.7	3.6	0.1	39.5	3.0
Total pigments (mg/l)	0.0	209.7	5.0	0.2	42.0	3.7

Geology/Sediments

The sediment regime of the North Central Gulf is characterized by a pronounced east-west and depth-related transition. The Mississippi River delta system forms a continental margin province that dominates the north central portion of the Gulf of Mexico. Most of the sediment of the Mississippi River is delivered directly to the shelf edge or is transported to the west due to the distribution of the major distributaries and the Coriolis force acting on the plume. Sediments on the eastern margin of the delta change from mud to a sand sheet of predominantly quartz off Alabama and northwest Florida. The sediments to the west are finer with a low carbonate content (< 25%) and have Mississippi-type heavy mineral and clay mineral suites. Sediments with higher carbonate content (> 75%) and finer particles are found at the shelf edge along the margins of De Soto Canyon. Bathymetric relief features from the Mississippi delta to Cape San Blas are relict spur-like ridges and pinnacles that are common on the outer shelf, at the shelf break and around the margins of De Soto Canyon. Structures resulting from salt dome intrusion are located in the area immediately south of Mobile Bay. Farther offshore from the Florida panhandle in 21 to 27 m are large (10 m high) sand waves. Bathymetric contours also suggest the presence of several incompletely filled channels and associated deltas mostly at a depth of 6m between Cape San Blas and Mobile Bay.

The stage of sedimentary evolution for the Northwestern area grades from allochthonous at the Mississippi River delta to a climax grade on the south Texas continental shelf. The result is a complex of sediment regimes with a decrease in the silt/clay content in the nearshore regions to the west and south where the percentage sand increases. In general, the sediment sand content decreases across the shelf. There are exceptions to this, associated mostly with topographic features and the allochthonous sedimentary regime near the Mississippi River delta. A high percentage of silt and clay is found in the area nearshore south-southwest of Timbalier and Barataria Bays. There is an area of increased sand content off Terrebonne Bay on Ship Shoal, which emerges 4 to 6 m above the surrounding silty floor, and nearshore off Vermilion and Atchafalaya Bays. The sediments of the southeastern Louisiana shelf are poorly to very poorly sorted. Off southwestern Louisiana, the sediment regime of the inner shelf (10 m) is soft mud, with the sand content never exceeding 48% and frequently less than 20%. With few exceptions, the substrate is silty clay or sandy mud.

Off Texas, the drowned Pleistocene deltaic plain of the Brazos-Colorado River and the Pleistocene Beaumont formation contribute compacted silts and clays to an area otherwise characterized by sands and muddy sands. Within the 11-m contour, the sediments are primarily firmly packed silts and clays that may be covered by a thin veneer of very fine silt, depending on preceding weather conditions. At 17 to 20 m, the sediments are mostly very fine sand with occasional patches of clay or silt. A coarser shell hash forms a subordinate fraction. The sediments of the south Texas shelf include a wide range of textures from muddy sands to silty clays with a decrease in abundance of sand-sized sediments seaward. Silt is the predominant mud constituent of sediments in this area with clay restricted mostly to areas off Port Aransas and Matagorda Island.

The continental shelf from the Mississippi River delta to the Rio Grande is gently sloping and wide, over 200 km off of the Texas-Louisiana border. There are many more physiographic irregularities in the central part of the shelf than to the east and southwest. Topographic features include many channels, most of which are associated with longitudinal ridges, and largely filled extensions of large rivers across the shelf. The topography of the northwestern Gulf north of Matagorda Bay is marked along the 17-, 60- and 85-m isobath by numerous protuberances caused by salt or shale diapirs. The shelf-edge carbonate banks and reefs of the northwestern Gulf are located in complex diapiric structures. Where conditions are appropriate, these structures favor the growth of tropical reef communities dominated by corals and coralline algae.

Turbidity/Light Conditions/Nepheloid Layer

General water column turbidity results from both riverine-delivered suspended sediments, sediments suspended from the seabed, and from biological particles (i.e., zooplankton fecal pellets, phytoplankton detritus, aggregates). Water clarity can be measured with a Secchi disk depth. The average value for LATEX cruises for spring, summer and fall are listed in Table TN6 (corresponding to stations in Figure N44). Lower values indicate more turbid waters shelfwide in April 1992 and 1994 (high river flow) and October 1992 (resuspension of sediments following frontal passage). The highest values (clearest water) were in mid-summer of 1993 and 1994 (even with 1993 being a record flood year) and in April 1993 (also high flow of the Mississippi River).

Suspended sediments and phytoplankton pigments are the main contributors to the extinction coefficient (k) in coastal systems, although dissolved materials, such as humics, may be significant inhibitors to light transmittance at some wavelengths. Two figures (Figures N45 and N46, Turner and Rabalais, in press) illustrate the spatial and temporal scales of variability in the light regime on the Louisiana shelf. Figure N45 shows changes in extinction coefficient (k) and primary production rates along a transect south of Grand Isle in April 1992. The Louisiana Coastal current is on the right side, moving westward. The extinction coefficient (k) ranges from less than 0.2 to greater than 1.5 on this transect. There was a mid-shelf area of slightly higher turbidity, likely related to a nepheloid layer (see below). Phytoplankton production rates (relative scale) are highest at the shoreward end of the transect and at the surface. Figure N46 illustrates the percent surface irradiance with depth along the 20-m isobath from south of Terrebonne Bay to the south Texas coastline in October 1992. At no place is light impinging on the bottom. In fact, light did not penetrate below 10 m anywhere along the transect on this cruise.

As a result of the broad, shallow shelf and abundance of fine sediments, nepheloid layers of resuspended sediments are common in the water column of the northwestern Gulf shelf. Typically these are located in a bottom mixed layer above the bottom, but mid-depth nepheloid layers may also exist in association with density discontinuities. These probably represent turbid, near-bottom water masses which have been transported offshore and have overriden clearer, denser water.

Biological Processes

Nutrient Levels

Average conditions for nutrients are shown in the Station C6* monthly figures in the Appendix. Average conditions for the shelfwide LATEX cruises are listed in Table TN6. The longitudinal distribution of dissolved inorganic nitrogen, nitrate, ammonia, silicate and phosphate are show in Figures N47 and N48. The influence of freshwater inputs at the Mississippi River and the Atchafalaya River are obvious for the nitrate and the silicate.

Productivity

Nutrients delivered by the rivers support high primary production (Sklar and Turner, 1981; Lohrenz et al., 1990, 1994), of which approximately 50% fluxes to bottom waters and the sea bed (Lohrenz et al., 1994; Qureshi, 1995). The high particulate organic carbon flux fuels hypoxia in the bottom waters below the seasonal pycnocline (Qureshi, 1995; Justic et al., 1996). The distribution of phytoplankton biomass as chlorophyll *a* follows a similar pattern as the distribution of nutrients along a longitudinal gradient away from the deltas of the Mississippi and Atchafalaya Rivers (Figure N49).

High biological productivity in the immediate (320 g $C/m^2/yr$) and extended plume (290 g $C/m^2/yr$) of the Mississippi River (Lohrenz et al., 1990, 1994 1997; Sklar and Turner, 1981; respectively) is mediated by high nutrient inputs and regeneration, temperature and favorable light conditions. Small-scale and short-term variability in productivity are the consequence of various factors, such as nutrient concentrations, temperature and salinity (Lohrenz et al., 1990, 1994) (Figure N50, Lohrenz et al., 1997). Maximum values of biomass (Turner and Rabalais, unpubl. data) and primary production (Lohrenz et al., 1990) are typically observed at intermediate salinities and coincide with non-conservative decreases in nutrients along the salinity gradient (i.e., biological uptake). Patterns of nutrient depletion provide evidence that riverine inputs of dissolved inorganic nitrogen and its pattern of regeneration ultimately limit the extent of river-enhanced areal productivity and biomass. The nutrient most relevant to the amount of phytoplankton production in the broad region fueling hypoxia is nitrogen. Primary production in shelf waters influenced by the Mississippi River plume was significantly correlated with the nitrate plus nitrite concentrations and fluxes of the river discharge (Figure N51, Lohrenz et al., 1997).

Particulate organic carbon flux to the lower water column is high in the plume over the inner shelf (approximately 500 to 600 mg C/m^2/d in 15 m water depth; Qureshi 1995; see also Redalje et al., 1994). The fraction of production exported from the surface waters is highly variable, ranging from 10 to 200% of the integrated primary productivity, but averaging about 50%, with statistically higher percentages in spring. A large proportion of the particulate organic carbon flux reaches the bottom incorporated in zooplankton fecal pellets (55%; Qureshi, 1995), but also as individual cells or in cell aggregates. In a particle trap study at station C6B, the fluxes of fecal pellet carbon, organic carbon and nitrogen, and phytoplankton carbon varied similarly between seasons, with the highest sedimentation in spring and the lowest in summer (Qureshi, 1995). The fluxes of all components were greater in 1991 than in 1992. Seasonal variations in fecal pellet number and carbon fluxes were positively correlated with indicators of high surface water productivity in 1991, but not in 1992. A higher spring freshet of the Mississippi River in 1991 compared to 1992 corresponded to higher fluxes of total particulates, total carbon and fecal pellet carbon in 1991. The carbon fluxed via fecal pellets in spring 1991 was sufficient to deplete the bottom water oxygen reserve in spring, thus creating hypoxic conditions that then prevailed through the stratified summer period. Fecal pellet carbon flux into the bottom trap was low in spring of 1992, and the oxygen depletion rate for this flux was close to the calculated oxygen depletion rate.

Hypoxia

Oxygen-depleted bottom waters are seasonally dominant features of the Louisiana-Texas continental shelf adjacent to the deltas of the Mississippi and Atchafalaya Rivers (Rabalais et al. 1991, 1996, 1997). The areal extent of bottom-water hypoxia ($\leq$ 2 mg/l) in mid-summer may cover up to 18,000 km^2. Prior to the 1993 Mississippi River summer flood, the average areal extent of bottom water hypoxia in mid-summer averaged 8,000 to 9,000 km^2. Data from biweekly to monthly sampling off Terrebonne Bay on the southeastern Louisiana shelf and continuous time series data from a station in 20-m water depth within the core of the hypoxic area document hypoxic bottom waters as early as February and as late as October, with widespread, persistent and severe hypoxia/anoxia from mid-May through mid-September. Spatial and temporal variability in the distribution of hypoxia exists and is, at least partially, related to the amplitude and phasing of the Mississippi and Atchafalaya River discharges and, consequently, to nutrient fluxes to coastal waters and subsequent flux of carbon from surface waters to the lower water column and seabed. Physical features of the system, e.g., large-scale circulation patterns, strong and persistent density stratification, and destratification caused by wind-mixing events from local winds, tropical storm activity and cold fronts, also control the dynamics of hypoxia.

The influence of the riverine discharge and flux of nutrients is obvious in the diagram of frequency of occurrence of bottom water hypoxia in mid-summer from 1985-1997 (Figure N52).

This figure is a composite of the individual annual shelfwide surveys to determine the extent and severity of hypoxia (Figures N53-N61).

The occurrence of back-to-back cruises in July 1993 and July 1994 during the maximal extent of hypoxia verified that hypoxic water masses persist over half a month to a month (mid- to late July) (Rabalais 1997). Thus, hypoxia, at least in mid-summer, is not an ephemeral event but severely reduced oxygen occurs over large areas of the Louisiana-Texas coast for extended periods. During maximal extent of mid-summer hypoxia, the severity, areal extent and distance up into the water column differs on the southeastern Louisiana coast versus the southwestern coast. Much of the lower half of the water column is hypoxic on the southeastern coast compared to a few meters above the seabed on the southwestern coast. Reasons for the differences include: less freshwater flux and subsequent differences in physical structure and biological processes (e.g., less freshwater content on the southwestern coast and less stratification); less nutrient flux, surface net production, and carbon flux on the southwestern coast; and better light conditions which allow for photosynthetic generation of oxygen in the lower water column.

The shelfwide hypoxia monitoring cruises in mid-summer provide information over a large area, but for a limited time scale. Data from monthly cruises along a transect off Terrebonne Bay (Transect C) illustrate the variability from nearshore to 30 m water depth through the months of the year (Figures N62 and N63). The distribution through time of the <2 O_2 mg/l and < 1 O_2 mg/l along a transect on Transect C off is shown in the figure. Hypoxia is variably present and smaller in size in the spring. Beginning in May, it becomes persistent, widespread, voluminous, and severe.

Hypoxia is mostly a bottom-water or lower water column phenomenon. However, it does extend well up into the water column and can affect up to 80% of the total volume of the water column (Figures N64). Upper-water column or mid-water column oxygen minimum layers also occur, primarily where subsurface chlorophyll maxima peak. These conditions are most likely to occur within the plume of the Mississippi River where flux of organic material is high and stratification exists. We searched our hypoxia monitoring cruise data set for stations in which low dissolved oxygen occurred well up in the water column at stations in greater than 25 m water depth (likely conditions of the proposed mariculture moorings). Of the 41,000 records, there were 9,145 values (1,002 stations) ≤ 4 mg/l, 7,164 values (380 stations) ≤ 3 mg/l, and 5,249 values (173 stations) ≤ 2 mg/l (frequency distributions in Figures N65-N67). Of these, a limited number of stations were in water depths greater than 25 m (all but 25 stations for 4 mg/l, 14 for 3 mg/l, and 6 for 2 mg/l). Inclusion of the LATEX data set would potentially increase the number of stations exhibiting a subsurface oxygen minimum zone, but the likelihood is low, because the LATEX stations are in a shallower part of the continental shelf and mostly removed from the influence of the Mississippi River. Examples of the oxygen minimum zone in the upper water column of stations in > 30 m water depth are given in Figures N68 and N69. Note that the zone occurs in the 10-20 m water depth range and usually extends for a few meters depth, but can extend for as much as 10 m. On occasion low dissolved oxygen values are variably located through the water column.

Harmful Algal Blooms

A review of toxic and noxious phytoplankton was completed by Q. Dortch (LUMCON) for the Status and Trends of Eutrophication, Pathogen Contamination, and Toxic Substances in the

Barataria-Terrebonne Estuarine System (Rabalais et al. 1995) and updated for the Proceedings of a meeting (Dortch et al., submitted). Parts of those reports are excerpted here. Blooms of toxic and noxious phytoplankton, or "red tides" as they were once called, are natural phenomenon that may be exacerbated by human activities including nutrient pollution, aquaculture and shipping. Such blooms can have various impacts, including human illness and death, mortality of other organisms at higher trophic levels, including commercially important species, and loss of recreational and aesthetic value because of water discoloration and unpleasant odors. There are published accounts of "red tides" within the study area. Further, increasing coastal eutrophication, which is the situation for the coastal plumes of the Mississippi and Atchafalaya Rivers, may lead to increases in toxic and noxious algal blooms. The potential impacts of toxic and noxious algal species that have been observed in recent studies of Q. Dortch or in historical samples from within NECOP and LATEX study areas are listed in Table TBN7 (data of Q. Dortch, LUMCON). These may be divided into those with known impacts to human health and those with impacts on higher tropic levels including shellfish and fish. The impacts to human health are usually through the consumption of primarily shellfish contaminated with toxins produced by certain algae. If the mariculture facility limits its operations to fish, the likelihood of human health impacts are minimal. If shellfish are cultured, then several phytoplankton have the potential for affecting humans.

Three toxins generated by phytoplankton found in offshore waters that can affect human health have been documented in the study area: domoic acid (causes Amnesiac Shellfish Poisoning, *Pseudo-nitzschia* spp.), okadaic acid (causes diarrhetic shellfish poisoning, *Prorocentrum* and *Dinophysis* spp.), and brevetoxins (cause neurotoxic shellfish poisoning, *Gymnodinium breve*) (Dortch, pers. comm., see Table TBN8). There have been no known human health impacts, but *Gymnodinium breve* is the organism responsible for oyster bed closures east of the Mississippi River delta during winter 1996-97. This was the first closure of oyster beds in Louisiana due to *Gymnodinium breve. Gymnodinium breve* is known to kill fish, and blooms are often first noticed due to massive fish kills. It is usually more of a problem in high salinity, although after the closures in 1996-97, low salinity areas may be susceptible as well. Many species of *Prorocentrum* and *Dinophysis* produce okadaic acid which causes diarrhetic shellfish poisoning, DSP), but no species abundant in Louisiana waters does. However, okadaic acid, venerupin poisoning, and human health impacts (including death) are problems elsewhere (Chesapeake Bay and Japan) that sufficient caution should be taken with these organisms (i.e., knowing their presence and potential toxicity) (Dortch et al., submitted).

Gymnodinium sanguineum occurs at low levels in the offshore zone at all times, but blooms periodically (Q. Dortch, pers. comm.). Fish kills are often associated with the blooms. Since *Gymnodinium sanguineum* may be associated with low oxygen and also produce ichthyotoxins, the cause of the fish kill is often difficult to determine.

Alexandrium monilatus is a species unique to the Gulf of Mexico. It is related to the PSP causing dinoflagellates and produces a toxin which kills fish and shellfish. It forms massive blooms all along the coast, particularly in the fall and tolerates a wide range of salinity. During the fall of 1996, the blooms were particularly widespread (Q. Dortch, pers. comm.). Not much is known about the species and the relationship of nutrient stimulation, nor the nature of the toxins and how it may affect mariculture (Q. Dortch, pers. comm.). *Alexandrium ostenfeldii* has been tentatively identified and sent for confirmation, because of the possibility that it is toxic (Dortch et al., submitted).

Heterosigma akashiwo is a toxic species well known in Asia (Japan and China) and in the Pacific Northwest for causing problems in mariculture. Major blooms have occurred in Louisiana coastal waters since 1990 (when systematic sampling was begun by Q. Dortch of LUMCON) and is currently present in samples collected east of the Mississippi River (Q. Dortch, pers. comm.). This species forms a benthic resting stage, so that it can persist for long periods between blooms. The mechanism by which it kills fish is unknown, although several have been proposed including evidence of nutrient stimulation. Two related genera that cause similar problems (*Fibrocapsa* and *Chatonella*) have not been verified in Louisiana coastal waters but are likely inhabitants given the availability of suitable habitats (Q. Dortch, pers. comm.).

Water discoloration events have been documented for the region. The causative agents include *Alexandrium monilatum*, *Lingulodinium polyedra*, *Heterosigma* cf. *akashiwo*, *Noctiluca* sp., *Mesodinium rubrum* and *Scrippsiella* cf. *trochoidea*. Other events have occurred in nearby habitats, involving *Gymnodinium sangineum*, *Prorocentrum minimum* and *Oscillatoria erythraea*. Some of these blooms have extended for long distances along and across the shelf and have been associated with fish kills. In most instances the highest numbers were recorded usually in nearshore areas of the shelf. Very often fish kills may be associated with either the toxins produced by the algae or the resultant low dissolved oxygen from ungrazed toxic algae sinking to the bottom.

One of the reasons (among increased nutrients, growing global shipping, and growing awareness) given for the increase in both numbers of incidents of harmful algal blooms and the type of organisms which cause the problems (Shumway, 1990; Hallegraeff, 1993) is the increase in aquaculture and mariculture, which provides microenvironments, magnifies transport opportunities, and increased surveillance. In many areas of shellfish and aquaculture, harmful species have become problems where none were observed previously. Thus, there are some species that are currently present on the Louisiana shelf that are currently at very low levels, but that might be influenced by mariculture activities. For example, a species of *Chaetoceros* diatom with spines that blooms in some mariculture areas and kills fish by slicing up their gills is present in low numbers currently, but could increase if stimulated by additional nutrients (Q. Dortch, pers. comm.). Some level of algal monitoring will be prudent, since blooms can occur so readily in the area of interest under natural circumstances.

Benthic Communities

With the exception of localized hard-substrate habitats (limestone, carbonate reefs, oil platforms), the benthic communities of the northwestern Gulf of Mexico are typical soft-bottom communities composed of macroinfauna, primarily polychaetes, pericaridean crustaceans, bivalve molluscs, and sipunculans (reviewed by Rabalais et al., in press). The benthic community structure is variably influenced by bottom topography, the nature of bottom deposits (e.g., sediment grain size and organic content), sedimentation rates, sediment resuspension, temperature and salinity, depth related gradients of temperature, salinity, pressure and quantity of food, and in parts of the northern Gulf of Mexico extensive and persistent areas of low dissolved oxygen.

Where hypoxia is seasonally severe, there is a fairly linear decrease in benthic macroinfauna diversity, abundance and biomass as oxygen decreases from 0.5 mg/l towards anoxia (Rabalais et al. 1995). Macroinfauna from areas with persistent and severe hypoxia are characterized by limited taxa (none with direct development, e.g., amphipods), characteristic resistant fauna (e.g., a few polychaetes and sipunculans), a reduced species richness, severely reduced abundance (but never azoic), low biomass, and limited recovery following abatement of oxygen stress. Oxygen stress overwhelms sedimentary characteristics in structuring of benthic communities. By comparison, the benthic macroinfauna (e.g., WD32 block in 20 m water depth) is not as abundant or diverse (because of greater silt content in the sediment) but maintains a diverse and abundant fauna throughout the fauna since hypoxia is intermittent and not as severely low. While polychaetes were a large component of the benthic community at WD32, composition by other major taxonomic groups was greater than polychaetes in some spring and summer samples. The benthic community at WD32 was diverse, with a complement of pericaridean crustaceans, bivalves, gastropods and other taxa, not usually representative of the fine silty sediments.

The benthic community in a 50-m water column is not likely at risk from low oxygen events. Hypoxia extends on the NECOP Transect A rarely to 60-m water depth, but is most often limited to within the 30-m depth contour. Additional rain of organic material will affect the benthic community, with a shift in community composition, and potentially an increase in smaller, opportunistic organisms such as surface deposit feeding polychaetes. Such polychaetes, e.g., *Paraprionospio pinnata*, *Prionospio cristata*, *Magelona* spp., *Ampharete* sp. A, and *Owenia fusiformis*, are currently present in high abundance at the 20-m depth for WD32 block. The subsurface deposit feeding polychaete that is also considered an opportunist (high numbers in spring recruitment, *Mediomastus ambiseta*) may increase with increased organic content of the sediments, but is already a member of the benthic community.

Platform Communities

One effect of oil and gas development activities on the otherwise soft-bottom environment of the northwestern Gulf of Mexico is the addition of a hard substrate extending from the bottom sediments to above the water's surface (Galloway, 1981). These substrates serve as focal points for rich and diverse biofouling communities and a complex assemblage of platform-associated macrobiota. The diversity and biomass levels of the biofouling community that develops are controlled by the type of perennial shelled animal that dominates (e.g., barnacles, bivalves). The shelled organisms provide habitat diversity, space and food for other organisms. Fish which would normally be found scattered throughout a larger area are concentrated in the immediate vicinity of platforms, attracted to the food and/or shelter they provide. With the exception of a few plankton-particulate feeding pelagic species which apparently are platform residents, the pelagic predators (e.g, king mackerel, blue runner) and their prey (e.g., scaled sardine) essentially "drift" through the system. The attraction of large predatory gamefish to structures is well-known. The benthic reef fish community (usually dominated by red snapper) aggregate at the platforms, apparently only for purposes of cover since the majority of their diet is composed of organisms from the soft-bottom demersal fish and macrocrustacean community. In deeper, oligotrophic waters, coral communities develop on the platforms.

Water and Sediment Contaminants

A review of environmental contaminants in the northwestern Gulf of Mexico will necessarily focus on riverine-derived contaminants and those generated in the production of oil and gas. The large and relatively intense chemical signature of the Mississippi and Atchafalaya Rivers can be detected in the adjacent water column and bedded sediments (Means, 1994). These include dissolved, colloidal and particulate phases of such chemicals as low- and high-molecular-weight polynuclear aromatic hydrocarbons, herbicides, pesticides and PCBs. The gradient away from the river discharge is obvious (as is the gradient away from such estuaries as Calcasieu, Sabine and Galveston), and is much greater than the estuarine concentrations.

The intense development for oil and gas off Louisiana has resulted in remarkably few major oil spills, has not resulted in severe pollution of the Gulf, and has not had significant effects on endangered species – all concerns elsewhere (Rabalais, 1996). Rather, the environmental effects have been felt primarily in the onshore coastal zone with extensive channelization, onshore development, and until recently discharge of significant amounts of produced water. The major operational discharges in the offshore region are associated with oil and gas exploration, development and production in the form of drilling fluids, drill cuttings, and produced water. Because the acute toxicity of water-based drilling fluids is low and concentration of drilling muds and cuttings in the water column decline rapidly after discharge to dilution and sedimentation to the bottom, adverse impacts on water column organisms are expected to be very slight and of short duration. Longer-term impacts of such discharges are restricted to the benthos near the discharge point, where significant amounts of mud and cuttings solids settle and persist on the bottom in low-energy environments. The effects on the benthos have been limited to within a few hundred meters of the discharge. In the few cases where recovery has been monitored, residual effects are seen mainly in a different fauna attracted to an altered seabed.

Substantial volumes of produced water are discharged into the waters of the continental shelf of Louisiana and Texas. The environmental effects of produced water discharges are mediated by the constituents of hydrocarbons and metals and their concentration in the effluent, the volume of the discharge, the history of the discharge, and the characteristics of the receiving environment. Dilution of water-soluble contaminants is influenced primarily by the volume of the receiving waters, the current velocity, and the potential for resuspension of sediments. Dispersion of sediment-adsorbed contaminants is influenced by the bed shear stress, sedimentation rates, and the grain size distribution of surface sediments. Substantial contamination of fine-grained sediments with petroleum hydrocarbons (alkylated and nonalkylated polynuclear aromatic hydrocarbons) of produced water origin is usually evident near the discharge and up to 1 km away in interior waterways with minimal currents or likelihood of resuspension from winds and waves. Where tidal currents scour the bottom and/or winds and waves regular resuspend and transport sediments from an area, or as water depth increases, the sediment contamination is low and localized to the point of discharge (within a few hundred of meters). Impacts to the benthic community are localized to the point of sediment contamination, but these relationships may be confounded by changes in bottom sediment structure. Filter-feeding bivalves (e.g., oysters) are known to accumulate produced-water origin contaminants in their tissues (Rabalais et al., 1992). The fauna of an offshore production platform was examined for accumulation of radionuclides but the effects were minimal (Mulino and Rayle, 1992). Similar studies for accumulation of produced-water origin hydrocarbons in platform-resident and temporary fauna have been completed but not yet published (J. P. Ray, pers. comm.).

Chapter 11

Water Quality Analysis

Introduction

Research efforts from major mariculture producing nations have noted in several studies the potential of intensive aquaculture to cause detrimental effects to regional coastal areas, enclosed bays, and estuaries (Hirata et al. 1994; Gowen and Bradbury 1987; Gillibrand and Turrel 1997; EPA 1991; Aure and Stigebrandt 1990). Environmental concerns have initiated projects around the globe to move aquaculture activities offshore of the sensitive coastal zones to open ocean areas in search of improved water quality conditions and to reduce the harmful impacts of fish farming (Grove et al. 1994, Burgrove et al. 1994, Thompson 1996). The presence of currents and sufficient depths to distribute and dilute mariculture wastes are significant factors as to whether mariculture discharges will prove harmful to the surrounding environment (Panchang and Newell 1997, Gowen et al. 1989). Current velocities of 20 to 30 cm/sec are common near the surface (Jochens and Nowlin 1995, Phillips and James 1988) along the Texas-Louisiana shelf although there can be episodic periods of calm and extreme sea states. The currents passing through an offshore net-pen can replace the water within the cage 200 to 1500 times a day. Miget (1994) reported that relative to inshore aquaculture, offshore culture on oil and gas platforms "virtually eliminates the potential for pollution via effluent." The rapid water flow should disperse wastes from the mariculture site and provide good water quality conditions for the cultured fish.

Source Description

This water quality impact analysis is based on the nine net-pen base case scenario described earlier and is limited to the two major sources of aquaculture discharges: food which is not eaten by the fish and metabolic wastes. In well operated systems only about 5% of the feed distributed to the fish falls through the nets and goes uneaten. At a 5% feed loss factor and 95% consumption, fecal materials will contribute the majority of carbon and nitrogen containing effluent with bio-deposits representing 74% by wt. of the particulate carbon discharges and 92% by wt. of the soluble nitrogen discharges (see table 4). The two primary wastes of concern from mariculture activities are organics and nutrients. Phosphorus is present in uneaten food and particulate fecal materials, however, phosphorus discharges are more of a concern for fresh water aquaculture (EPA 1991). The principal nutrient of concern for mariculture discharges are nitrogenous compounds since nitrogen is a limiting factor to life in the marine waters of the Gulf and has been reported to cause nuisance plankton blooms (Rabalais et al. 1996).

Food and fecal waste discharges create conventional and unconventional pollutants. Based on federal NPDES regulations (40 CFR 401. 16), the unconventional pollutants include turbidity, disease control medications (see appendix A), nutrients (nitrogen compounds), and settleable solids. Conventional pollutants include biochemical oxygen demand (BOD), total suspended solids (TSS), and pH. Metabolic activity also results in oxygen consumption and consequent production of carbon dioxide. Fecal wastes include dissolved NH_3 and NH_4 and particulate carbon and organic nitrogen (proteins). Marine fish excrete 60%-90% of their waste nitrogen as soluble ammonia through the gills (Lovell 1989). An indigestible organic residue of 12%-20% usually remains to be excreted as feces (Penczack et al. 1982). Sources of carbon and nitrogen discharges are also released from the proteins, fats, and carbohydrates in the fish food not eaten by the culture organisms.

Dissolved Oxygen and Metabolic Waste

All food consumed by fish is eventually utilized for metabolic processes, synthesized into new tissue growth, or excreted as waste. Digested nutrients are absorbed into the blood by a combination of passive diffusion, active transport, and pinocytosis, and carried into the liver through the portal vein (Wedemeyer 1996). An indigestible residue of 12%-20% (see table 2) usually remains to be excreted as feces. Oxygen consumption increases by 50% or more and intestinal blood flow may double immediately after digestion begins (Wedemeyer 1996). The increased oxygen consumption and CO_2 release is associated both with digestion and the metabolism of amino acids and other nutrients. Salmonids, for example, expire about 1.4 g of CO_2 for every gram of O_2 consumed (Wedemeyer 1996) Respiration rates increase with water temperature and can have an influence on dissolved oxygen (DO) levels. Fish respiration, microbial decomposition of fish waste, and excess food have the potential of reducing dissolved oxygen levels near a mariculture site. The degree of dissolved oxygen reduction will depend on the water exchange rate at the site location, fish density, and feeding rate.

Nitrogen

The primary nutrient releases of concern from mariculture operations are nitrogenous compounds, since nitrogen can encourage nuisance phytoplankton growth in marine waters. The majority of nitrogen in fish waste is in the dissolved ammonium form, however, a small percent of nitrogen is complexed with organic carbon in waste food and feces and settles out of the nets. Nitrogen chemistry is complicated by the multiple oxidation states the element assumes in its compounds. Those of greatest importance to aquaculture activities, however, are the -3, +3, and +5 oxidation states: ammonia (NH_3), nitrite ion (NO_2^-), and nitrate ion (NO_3^-). Most of the nitrogenous compounds in fish waste are in the form of soluble inorganic NH_3 nitrogen (see Table 3). Marine fish excrete 60%-90% of their waste nitrogen as soluble ammonia and the majority of NH_3 waste is eliminated through the gills (Lovell 1989).

In aquatic systems excessive concentrations of nitrogen compounds can cause problems. The primary adverse effects are as follows: (1) Organic nitrogen compounds and ammonia are both oxidized in aquatic systems, with an accompanying loss of dissolved oxygen in the system; (2) In instances where nitrogen is limiting to growth in a particular aquatic ecosystem, discharge of nitrogen

species can be directly toxic to marine life. Lethal concentration (50%) value for 96h exposure to un-ionized ammonia to salmonids ranges from 0.83 to 4.60 mg/l (EPA 1991). When ammonia enters the water, the hydrogen ions present immediately react and convert the species into an equilibrium mixture of two forms: the relatively nontoxic ammonium ion (NH_4^+) and the unionized NH_3, which can be toxic. Reaction kinetics and the pH of natural marine waters (8.2 - 8.4) favors formation of the ammonium ion. At a temperature of 20°C, only 4.88 % of the un-ionized (toxic) form of ammonia will be present in seawater of a pH of 8.2 (Benefield et al. 1982).
Fish wastes contain small amounts of nitrogen incorporated into organic compounds, primarily unassimilated proteins. Bacterial action on such organic matter results in its degradation and the release of ammonia. The ammonia so produced may then be further oxidized to nitrite by bacteria such as *Nitrosomonas*, and the nitrite produced from this reaction can be oxidized to nitrate by other bacteria such as *Nitrobacter*. These biologically mediated reactions collectively referred to as *nitrification* and may be represented as follows:

$$2NH_3 + 3O_2 \rightarrow 2NO_2^- + 2H^+ + 2H_2O$$

$$2NO_2^- + O_2 \rightarrow 2NO_3^-$$

In areas subject to reasonably fast currents, the dilution of nitrogen occurs down current (Kiefer and Atkinson 1989) and oxidation of ammonia to nitrate prevents accumulation of soluble nitrogenous wastes in the water column.

Nitrogen Biochemical Oxygen Demand

Nitrogen is important in water quality assessments for reasons other than its role as a nutrient. For example, the oxidation of ammonia to nitrate during the nitrification process consumes oxygen and may represent a significant portion of the total BOD. Stoichiometrically 3.43 g of oxygen are consumed for each gram of ammonium-nitrogen oxidized to nitrite-nitrogen. During the second stage of nitrification, the nitrobacter bacteria oxidize nitrite to nitrate and 1.14 g of oxygen are consumed per gram of nitrite-nitrogen oxidized. If the two reactions are combined, the complete oxidation of ammonia can be represented by:

$$NH_4^+ + 2\,O_2 \rightarrow NO^{3-} + H_2O + 2H^+$$

$$(14\text{ g})\ (64\text{ g})$$

As seen, 64/14 or 4.57 g of oxygen are required for the complete oxidation of one gram of ammonia. In the reactions above, the organic-nitrogen form does not appear, since organic-nitrogen is hydrolyzed to ammonia, and does not consume oxygen in the process.

SolubleWaste

Soluble organic wastes have relatively high concentrations of oxygen demanding materials. Bacterial oxidation of the soluble organic matter discharged to receiving waters from aquaculture facilities results in the consumption of dissolved oxygen. Relatively low dissolved oxygen concentrations and obviously the complete absence of dissolved oxygen is lethal to a number of marine organisms, with the exception of obligate and facultative anaerobic bacteria. Within this region, mobile fish will avoid the discharge plume if conditions become stressful, however, immobile zooplankton and fish larvae near the discharge may experience altered respiratory or feeding ability due to stress, or clogging of gills and feeding apparatus (EPA 1991). In general, the Gulf offshore waters beyond the 30m contour are well oxygenated, which can provide a considerable buffer for the assimilation of soluble organic wastes.

Sedimentation

Settleable wastes from net-pens have the potential to adversely affect the benthos in the areas of aquaculture activities. The decay of these wastes may also result in alterations in the benthic community due to burial and chemical changes effected within the sediments. Sedimentation with anaerobic decomposition of waste discharges involves the release of potentially toxic decay byproducts like methane, and hydrogen sulfide (Aure 1990). Decomposition of these wastes can result in the consumption of dissolved oxygen contributing to hypoxic conditions sometimes found along the seafloor of the Texas-Louisiana shelf. Nutrients are also released during the decay of these materials which may enhance phytoplankton productivity and alter the phytoplankton community species composition.

The primary factors that determine the area over which uneaten food particles and fecal materials may be distributed are (1) the sinking rate of the waste, (2) the speed of the current, and (3) the settling distance, i.e. the distance of clearance between the bottom of the net and the seafloor (EPA 1991). Predominant currents determine the fate of much of these materials. Increased depths below the bottom of the pen allows for increased dispersion of waste materials. The size and configuration of the net/cage can also play a role in the diffusion of waste. The size, density, and sinking rate of feed and fecal material will affect the dispersion of uneaten food. Orientation of the multiple pens to the predominant current will also influence distribution rates of feed and fecal materials. The magnitude, areal extent, and rate of organic loading are the important factors which determine whether benthic communities in the vicinity of the mariculture operation will be impacted by these facilities.

Daily Mariculture Discharges - Base Case Scenario

Methods

This section presents a "snap shot" of waste discharges for a base case mariculture operation. Quantities and composition of uneaten food and fecal matter discharges are dependent upon a number of factors including: (1) amount of feed distributed per loading time; (2) percent of feed consumed; (3) percent of un-eaten food or fallout; (4) percent of proteins, fats, and carbohydrates in the feed; (5) percent of nitrogen and carbon composition of proteins, fats, and carbohydrates; and (6) percent of consumed nitrogen and carbon that is retained or excreted after food consumption. This exercise is performed to: (1) estimate quantities of carbon and nitrogen in waste streams, (2) assess the area of impact, (3) predict the dilution ratio or concentration of carbon and nitrogen discharges to the receiving water column, and (4) determine the rate of carbon sedimentation. The methods used to obtain these figures are discussed below accompanied with tables of multiple sources serving as references with data presented for averages. Calculations are presented using the supporting data and the formula are presented in tables and subjected to a range of environmental variables that might be encountered along the Texas-Louisiana continental shelf.

Assumptions

It is assumed that the base case operation produces 4500 MT of whole fish a year. There are nine circular nets 50m across by 20m deep. Each net produces 500 MT a year. The mariculture site is in 50m of water somewhere along the Texas-Louisiana shelf providing a clearance of 30m below the net-pen to the ocean floor. All the fish in a net, it must be assumed, are the same weight. Though the nine nets have fish all the same size in the pen, the weight of fish varies from pen to pen (age ranging from freshly stocked fish to adults ready to harvest). Fish will be fed 2% of their body weight a day. It is assumed that 5% of the feed will go uneaten and 95% will be consumed. Feed will be distributed evenly over a 24 hr. period and fecal materials are assumed to be generated and deposited evenly.

Current Velocity and Receiving Water Column Conditions

Culture organisms offshore can expect to be routinely subjected to near surface currents with maximum speeds ranging from 34 cm/sec to 84 cm/sec (Jochens and Nowlin 1995). Mid-depth currents below the net pens tend to be less, ranging between 10 cm/sec to 30 cm/sec (Phillips and James 1988) and bottom currents are generally under 15 cm/sec. Due to the nature of the currents, i.e. cyclonic, anti-cyclonic, loops, eddies, wind driven, and tidal, the net pens can expect water flow from all directions. Summer months can experience extremes, ranging from calm days to hurricanes and during the winter months there are often several extended periods of extreme sea states.

Weight of Uneaten Food Discharges

Daily amounts of feed distributed are usually determined by feeding the fish a percent of the total bio-mass within the net-pen. For instance, if there were 500,000 kg of fish in a net and the aquaculture program is feeding at 2% of the body weight of the fish, 10,000 kg of feed would be distributed into that net over the course of the day. The amount of feed not eaten by fish varies in each situation. Fallout of uneaten food has been reported as high as 15% (EPA 1991) and as low as 1.4% (Thorpe et al. 1990). Panchang and Newell (1997) reported that rates of food loss of 2.5% are commonly experienced in the mariculture industry in Maine. Large scale commercial operations will probably utilize a remote sensing device (video/sonar) to detect the presence of uneaten food and shut down food dispensing operations. These methods should reduce food loss to 1.5%, however, a 5% ratio of uneaten food to 95% consumption ratio is used for the assumptions for discharge estimates. These figures are used in the equations and tables below.

Equation (1)

Example of net-pen with full grown fish ready to harvest:

(wt. of fish in pen)(% of body wt. fed)(% fallout)=(wt. uneaten food)

(500,000 kg)(2%)(5%)= 500 kg

Composition of Feed

Feed compositions are usually reported as protein, fats or lipids, and carbohydrates by feed manufactures although further descriptions of various feeds can be found in publications through the ASFA network. An information search was performed to gather knowledge on the typical levels of protein, fats, and carbohydrates in fish food. The mean value from 15 sources was used to estimate percent levels of protein, fats, and carbohydrates (see Table 1). Averages were found to be: 45.5% protein, 13.11% fats, and 15.98% carbohydrates. The carbon and nitrogen fraction of fish food can be calculated by estimating the organic and nitrogen content of proteins, fats, and carbohydrates as shown in (Table 2). Fats contain 77.64% carbon, carbohydrates contain 40% carbon, and proteins contain 46% carbon and 16% nitrogen. Once these and the above estimates have been determined, the figures can be used to make predictions as to the weight of carbon and nitrogen discharges of un-eaten food to the water column (fallout).

Table 1
CHARACTERIZATION OF FISH FEED PRODUCTS COMMONLY UTILIZED IN AQUACULTURE

Feed Co./Publication	Species of fish	Feed Brand	Feed type	Feed size diameter (mm)	% protein	% fats/lipids	% Carbo-hydrates	% carbon	% nitrogen
BioProducts, Inc. EPA 1991	Salmon	Biodry 3000	Dry	4.0-12.0	44.50	15.00	14.70	38.00	7.12
Moore-Clark Co. EPA 1991	Salmon	Select Ext.	Dry	3.5-11.0	45.00	22.00	14.00	43.38	7.20
BioProducts, Inc. EPA 1991	Salmon	Biomoist F.3	Moist	4.0-18.0	39.00	13.50	11.80	33.14	6.24
Moore-Clark Co. EPA 1991	Salmon	Oregon Moist	Moist	2.4-9.5	35.00	11.00	13.00	29.84	5.60
Ziegler Bros. Ellis 1996	Grouper	Trout Grower	Dry	2.2-4	43.50	5.91	34.80	38.52	6.96
Rangen, Inc. Ellis 1996	Grouper	Salmon Grower	Dry	2.2-4	52.70	15.20	13.80	41.56	8.43
Dainichi Corp. Ellis 1996	Grouper	Carn. Fish Diet	Dry	2.2-4	55.60	7.79	20.70	39.90	8.90
Oceanic Institute Ellis 1996	Grouper	Mahi ex.diet	Dry	2.2-4	61.80	14.20	12.90	44.61	9.89
Corey Feed Mills www.1997	Salmon	Fundy choice	Dry	6.5-12	43.00	30.00	11.00	47.47	6.88
Recommend levels: Aquaculture 151(1997)	Grouper		Dry		43.00	14.00	8.00	33.85	6.88
Oceanic Institute 1993	Mahi-mahi	OI prepared diet	Dry	3.2-13.0	60.00	12.00	10.00	40.92	9.60
Williams 1985 Prog.Fi.Cult.1995	Pompano	Menhaden oil diet	Dry	1.6	42.00	12.00	7.00	31.44	6.72
Burris Mill & Feed	Hybrid Bass	Grower	Dry	2.3-11.0	42.00	7.00	19.00	32.35	6.72
Burris Mill & Feed	Reddrum	Grower	Dry	2.3-11.0	42.00	7.00	19.00	32.35	6.72
Burris Mill & Feed	Reddrum	Growers	Dry	2.3-11.0	40.00	10.00	30.00	38.16	6.40
AVERAGES					45.94	13.11	15.98	37.70	7.35

Note: Reported levels of protein, carbohydrates, and fats in fish food and the percent content of carbon and nitrogen

Table 2
PERCENT OF CARBON AND NITROGEN IN PROTEINS, FATS, AND CARBOHYDRATES IN FISH FOOD

Feed Components	% Carbon by Wt.	% Nitrogen by Wt.
Fats	77.64(a)	0
Carbohydrates	40(b)	0
Proteins	46(c)	16

a Assumes average fat molecules is $C_{57}H_{10}O_6$.

b Assumes carbohydrates are CH_2O.

c Assumes that protein consists of an equal molar contribution of 20 amino acids.

Equation (2)

Carbon

$$(\text{wt. of fallout})(\%\text{ of C in feed}) = (\text{wt. of C fallout})$$

$$(500\text{kg})(37.70\%) = 188.5\text{kg}$$

Nitrogen

$$(\text{wt. of fallout})(\%\text{ of N in feed}) = (\text{wt. of N fallout})$$

$$(500\text{kg})(7.35\%) = 36.8\text{kg}$$

Weight of Fecal Discharges

The majority of wastes released from net-pens are fecal materials. The amount and characteristics of fecal matter released from a net-pen depends on several factors, including the digestibility of the feed: how much of the feed is utilized for metabolic processes, and how much of the feed is synthesized into new tissue growth or excreted as waste. A literature search on the amounts of nitrogen and carbon retained and released from fish consumption of feed yielded the various percentages presented in Table 3. From these numbers an average value can be used in a formula to ascertain the amounts of nitrogen and carbon discharged in the form of dissolved nitrogen waste and organic fecal deposits. The earlier estimates are combined in the formula (Equation 3) to determine the amount of fecal carbon and waste nitrogen potentially discharged resulting from the consumption of food.

Table 3
PERCENT OF AMMONIA AND CARBON DISCHARGED FROM CONSUMPTION OF FEED

Source	% of Nitrogen in feed voided as soluble waste	% Carbon voided in fecal material
Lovell (1989)	50.0	
Andrade (1996)	65.0	
EPA (1991)	68.0	15.0
Gowen and Bradbury (1987)	86.0	30.0
Rosenthal (1996)	75.0	
Wedemeyer (1996)	55.0	10.0-20.0
Penzack et al. (1982)		20.0
Staples and Normura (1976)		21.0
Hendricks (1997)		12.0
Parsons and Seki (1971)		15.0
Average	**66.5**	**18.86**

Note: Estimation of the percent of nitrogen and carbon voided after consumption of feed.

Equation (3) For base case mariculture operation (per net)

Carbon

(wt. feed consumed)(% C in feed)(% C voided)= (wt. C discharged)

(9500kg)(37.7%)(18.83%)= 674.39 kg

Nitrogen

(wt. feed consumed)(% N in feed)(% N voided)= (wt N discharged)

(9500kg)(7.34%)(66.5%)= 463.70 kg

The calculations above are applied to the organic and nitrogen loadings from the base case mariculture projections (Table 4). The information represents the mariculture activities in full production and covers all nine pens with fish of various ages, receiving 2% of their body weight in food. The table includes both the soluble nitrogen and particulate carbon discharges from fallout of un-eaten food and fecal deposits. Total daily discharges for all nine nets presented in the base case scenario at the aquaculture site is 4,318 kg of particulate carbon and 2,391 kg of soluble nitrogen.

FEASIBILITY STUDY - OFFSHORE MARICULTURE

WATER QUALITY IMPACT ANALYSIS
BY STEVE KOLIAN

Table 4
NITROGEN AND CARBON LOADINGS FOR NINE NET PENS

Pen	Number of fish in net pen	Ave. wt. of fish in pen (kg)	Wt. of fish in pen (kg)	% of body wt. fed	Wt. of feed dist. (kg/day)	Wt. of food consumed @ 95% (kg/day)	Wt. of food uneaten @ 5% (kg/day)	Wt. of C from uneaten food (kg/day)	Wt. of N from uneaten food (kg/day)	Wt. of C from fecal (kg/day)	Wt. of N from fish wastes (kg/day)	Total carbon loading (kg/day)	Total nitrogen loading (kg/day)
1	500,000	0.06	30,000	2%	600	570.00	30.00	11.31	2.21	42.98	27.86	54.29	30.07
2	500,000	0.18	89,000	2%	1,780	1,691.00	89.00	33.55	6.54	127.50	82.65	161.05	89.19
3	500,000	0.30	147,500	2%	2,950	2,802.50	147.50	55.61	10.84	211.31	136.98	266.92	147.82
4	500,000	0.41	206,500	2%	4,130	3,923.50	206.50	77.85	15.18	295.83	191.77	373.68	206.95
5	500,000	0.53	265,000	2%	5,300	5,035.00	265.00	99.91	19.48	379.64	246.10	479.54	265.58
6	500,000	0.65	324,000	2%	6,480	6,156.00	324.00	122.15	23.81	464.16	300.89	586.31	324.70
7	500,000	0.77	382,500	2%	7,650	7,267.50	382.50	144.20	28.11	547.97	355.22	692.17	383.33
8	500,000	0.88	441,500	2%	8,830	8,388.50	441.50	166.45	32.45	632.49	410.01	798.94	442.46
9	500,000	1.00	500,000	2%	10,000	9,500.00	500.00	188.50	36.75	716.30	464.34	904.80	501.09
Total			2,386,000		47,720	45,334	2,386	900	175	3,418	2,216	4,318	2,391

Note: Estimated daily loadings of nutrients and organics of un-eaten feed and fecal waste at an aquaculture facility operating at full capacity

Diffusion of Waste

A literature search was performed to review the background concentrations of nitrogen and carbon normally present in natural waters (see Table 5) and compare the findings to projected discharges from aquaculture activities. Levels of nutrients and carbon have a wide range in the oceans (1 μg/l to 600 μg/l). Concentrations of nitrogen and carbon are lowest in the deep waters of the sea where the production of plankton is minimal. The areas with the highest concentrations are found near major tributaries. The mid-shelf region along the Texas-Louisiana continental shelf experiences relatively high inputs of nitrogen and organics year round.

Given the assumptions for daily nitrogen and carbon loadings estimated in Table 4, calculations can be performed to arrive at the ratio of waste to water by defining the water flow through the cages. The size of the net-pens in the base case will have a 50 m diameter and a 20 m depth. The plane through the center of the net will be 1,000 m^2 and the net-pens will be assumed to have a volume of 39,270 m^3. By comparing the volume of water passing through the net-pens to the weight of the waste, a measurement of loading rates to volume of water can be determined. Distributions of discharges are assumed to be dispersed evenly over a 24-hour period. Fish will be fed multiple times daily and fecal deposits are assumed to be random both day and night.

Table 7 demonstrates the waste to water ratios or the concentration of discharges for the nine net-pens using the assumptions discussed above. For the pen with the greatest daily discharges, diffusion rates range from 58 μg/l NH_3^- and 104 μg/l C for a 10 cm/sec current to 7.2 μg/l NH_3 and 13.09 μg/l C for an 80 cm/sec current. Dortch and Rabalais recorded levels of nitrogen between 1μg/l and 150 μg/l and carbon levels between 24 and 232 μg/l along the Louisiana continental shelf. A full description of the organics and nutrients frequently encountered in the subject area are discussed in detail in Appendix D. As seen by comparing background levels to projected discharges, the concentration of carbon and nitrogen from the net-pens at the aquaculture site are lower oe within the range of the levels commonly found along the mid-shelf regions influenced by the Mississippi and Atchafalaya Rivers.

Transport of Wastes

Several models are available to anticipate the area of impact of settleable materials from net-pens (Panchang and Newell 1997). The more complex models require data on site specific hydraulic and topographical information (Panchang and Newell 1997). Gowen et al. 1989 used a simple model that involves the tracking of the horizontal and vertical movements of the waste to determine where the waste settles (see Equation 4). The information requires three assumptions: (1) the sinking rates of the particles, (2) the speed of the current, and (3) the distance of fall i.e. the clearance between the bottom of net and the seafloor.

Equation (4) Dispersion/Sedimentation Model

$$D = \frac{d \times V}{v}$$

Where:

D= horizontal distance traveled by the particle
d= distance between bottom of net to the seafloor
V= current velocity
v= settling velocity of waste

In this analysis a settling distance of 30m from the bottom of the net to the ocean floor is assumed since the nets are 20m deep and the water column is 50m in depth. To gain some perspective of sinking rates for fecal matter and fish food, a literature search was conducted on the subject (see Table 6 below). The majority of the particulate carbon discharges, given a 95% food consumption ratio, consist of fecal materials. The settling calculations in Table 7 use a sinking rate of 5cm/sec to demonstrate the transport of waste. Numerous variables can be used in the model to give a general idea of the distribution of settleable solids. The area considered in this analysis is along the 30-60m isobath and frequently experiences maximum currents of 34 cm/sec to 84 cm/sec (Jochens and Nowlin 1995). Mid-depth and lower currents below the net pens tend to be less ranging between 10 cm/sec to 30 cm/sec (Phillips and James 1988). There can be episodic periods of calm and extreme sea states along the Texas Louisiana shelf. Current velocities applied to the model range from 10 cm/sec to 80 cm/sec.

Table 6
SINKING RATE OF FOOD AND FECAL PARTICLES

Source	**Description of particle**	**Estimated sinking rate of material m/sec**
EPA 1991	2.5 mm feed	0.02
Gowen et al. 1987	fecal material	0.04
Weston 1990	fecal material	0.04
Panchang and Newell 1997	fecal material	0.03
Panchang and Newell 1997	salmon feed	0.10
Stevens and Haaga 1994	Fish offal particles 5-25 cm	0.03
Stevens and Haaga 1994	Fish offal particles 5-25 cm	0.08

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Table 7
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Pen	Total carbon loading (kg/day)	Total nitrogen loading (kg/day)	Speed of current (m/sec.)	Vol. of flow-through nets (m^3/day)	Total C loading to water (μg/l) (conc.)	Total N loading to water (μg/l) (conc.)	Estimated sinking rate of material (m/sec)	Time to settle to ocean floor in (sec.)	Horizontal travel of feed/fecal particle (m)	Area of impact (m^2)	Area of impact ($miles^2$)	Amount of settling carbon (g/m^2/day)
1	54.3	30.1	0.1	8,640,000	6.28	3.48	0.05	600	60.0	11,304	0.004	4.80
2	161.1	89.2	0.1	8,640,000	18.64	10.32	0.05	600	60.0	11,304	0.004	14.25
3	266.9	147.8	0.1	8,640,000	30.89	17.11	0.05	600	60.0	11,304	0.004	23.61
4	373.7	206.9	0.1	8,640,000	43.25	23.95	0.05	600	60.0	11,304	0.004	33.06
5	479.5	265.6	0.1	8,640,000	55.50	30.74	0.05	600	60.0	11,304	0.004	42.42
6	586.3	324.7	0.1	8,640,000	67.86	37.58	0.05	600	60.0	11,304	0.004	51.87
7	692.2	383.3	0.1	8,640,000	80.11	44.37	0.05	600	60.0	11,304	0.004	61.23
8	798.9	442.5	0.1	8,640,000	92.47	51.21	0.05	600	60.0	11,304	0.004	70.68
9	904.8	501.1	0.1	8,640,000	104.72	58.00	0.05	600	60.0	11,304	0.004	80.04
1	54.3	30.1	0.2	17,280,000	3.14	1.74	0.05	600	120.0	45,216	0.017	1.20
2	161.1	89.2	0.2	17,280,000	9.32	5.16	0.05	600	120.0	45,216	0.017	3.56
3	266.9	147.8	0.2	17,280,000	15.45	8.55	0.05	600	120.0	45,216	0.017	5.90
4	373.7	206.9	0.2	17,280,000	21.63	11.98	0.05	600	120.0	45,216	0.017	8.26
5	479.5	265.6	0.2	17,280,000	27.75	15.37	0.05	600	120.0	45,216	0.017	10.61
6	586.3	324.7	0.2	17,280,000	33.93	18.79	0.05	600	120.0	45,216	0.017	12.97
7	692.2	383.3	0.2	17,280,000	40.06	22.18	0.05	600	120.0	45,216	0.017	15.31
8	798.9	442.5	0.2	17,280,000	46.23	25.61	0.05	600	120.0	45,216	0.017	17.67
9	904.8	501.1	0.2	17,280,000	52.36	29.00	0.05	600	120.0	45,216	0.017	20.01
1	54.3	30.1	0.3	25,920,000	2.09	1.16	0.05	600	180.0	101,736	0.039	0.53
2	161.1	89.2	0.3	25,920,000	6.21	3.44	0.05	600	180.0	101,736	0.039	1.58
3	266.9	147.8	0.3	25,920,000	10.30	5.70	0.05	600	180.0	101,736	0.039	2.62

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Pen	Total carbon loading (kg/day)	Total nitrogen loading (kg/day)	Speed of current (m/sec.)	Vol. of flow-through nets (m^3/day)	Total C loading to water (μg/l) (conc.)	Total N loading to water (μg/l) (conc.)	Estimated sinking rate of material (m/sec)	Time to settle to ocean floor in (sec.)	Horizontal travel of feed/fecal particle (m)	Area of impact (m^2)	Area of impact ($miles^2$)	Amount of settling carbon ($g/m^2/day$)
4	373.7	206.9	0.3	25,920,000	14.42	7.98	0.05	600	180.0	101,736	0.039	3.67
5	479.5	265.6	0.3	25,920,000	18.50	10.25	0.05	600	180.0	101,736	0.039	4.71
6	586.3	324.7	0.3	25,920,000	22.62	12.53	0.05	600	180.0	101,736	0.039	5.76
7	692.2	383.3	0.3	25,920,000	26.70	14.79	0.05	600	180.0	101,736	0.039	6.80
8	798.9	442.5	0.3	25,920,000	30.82	17.07	0.05	600	180.0	101,736	0.039	7.85
9	904.8	501.1	0.3	25,920,000	34.91	19.33	0.05	600	180.0	101,736	0.039	8.89
1	54.3	30.1	0.4	34,560,000	1.57	0.87	0.05	600	240.0	180,864	0.070	0.30
2	161.1	89.2	0.4	34,560,000	4.66	2.58	0.05	600	240.0	180,864	0.070	0.89
3	266.9	147.8	0.4	34,560,000	7.72	4.28	0.05	600	240.0	180,864	0.070	1.48
4	373.7	206.9	0.4	34,560,000	10.81	5.99	0.05	600	240.0	180,864	0.070	2.07
5	479.5	265.6	0.4	34,560,000	13.88	7.68	0.05	600	240.0	180,864	0.070	2.65
6	586.3	324.7	0.4	34,560,000	16.97	9.40	0.05	600	240.0	180,864	0.070	3.24
7	692.2	383.3	0.4	34,560,000	20.03	11.09	0.05	600	240.0	180,864	0.070	3.83
8	798.9	442.5	0.4	34,560,000	23.12	12.80	0.05	600	240.0	180,864	0.070	4.42
9	904.8	501.1	0.4	34,560,000	26.18	14.50	0.05	600	240.0	180,864	0.070	5.00
1	54.3	30.1	0.5	43,200,000	1.26	0.70	0.05	600	300.0	282,600	0.109	0.19
2	161.1	89.2	0.5	43,200,000	3.73	2.06	0.05	600	300.0	282,600	0.109	0.57
3	266.9	147.8	0.5	43,200,000	6.18	3.42	0.05	600	300.0	282,600	0.109	0.94
4	373.7	206.9	0.5	43,200,000	8.65	4.79	0.05	600	300.0	282,600	0.109	1.32
5	479.5	265.6	0.5	43,200,000	11.10	6.15	0.05	600	300.0	282,600	0.109	1.70
6	586.3	324.7	0.5	43,200,000	13.57	7.52	0.05	600	300.0	282,600	0.109	2.07

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Pen	Total carbon loading (kg/day)	Total nitrogen loading (kg/day)	Speed of current (m/sec.)	Vol. of flow-through nets (m^3/day)	Total C loading to water (μg/l) (conc.)	Total N loading to water (μg/l) (conc.)	Estimated sinking rate of material (m/sec)	Time to settle to ocean floor in (sec.)	Horizontal travel of feed/fecal particle (m)	Area of impact (m^2)	Area of impact ($miles^2$)	Amount of settling carbon (g/m^2/day)
7	692.2	383.3	0.5	43,200,000	16.02	8.87	0.05	600	300.0	282,600	0.109	2.45
8	798.9	442.5	0.5	43,200,000	18.49	10.24	0.05	600	300.0	282,600	0.109	2.83
9	904.8	501.1	0.5	43,200,000	20.94	11.60	0.05	600	300.0	282,600	0.109	3.20
1	54.3	30.1	0.6	51,840,000	1.05	0.58	0.05	600	360.0	406,944	0.157	0.13
2	161.1	89.2	0.6	51,840,000	3.11	1.72	0.05	600	360.0	406,944	0.157	0.40
3	266.9	147.8	0.6	51,840,000	5.15	2.85	0.05	600	360.0	406,944	0.157	0.66
4	373.7	206.9	0.6	51,840,000	7.21	3.99	0.05	600	360.0	406,944	0.157	0.92
5	479.5	265.6	0.6	51,840,000	9.25	5.12	0.05	600	360.0	406,944	0.157	1.18
6	586.3	324.7	0.6	51,840,000	11.31	6.26	0.05	600	360.0	406,944	0.157	1.44
7	692.2	383.3	0.6	51,840,000	13.35	7.39	0.05	600	360.0	406,944	0.157	1.70
8	798.9	442.5	0.6	51,840,000	15.41	8.54	0.05	600	360.0	406,944	0.157	1.96
9	904.8	501.1	0.6	51,840,000	17.45	9.67	0.05	600	360.0	406,944	0.157	2.22
1	54.3	30.1	0.7	60,480,000	0.90	0.50	0.05	600	420.0	553,896	0.214	0.10
2	161.1	89.2	0.7	60,480,000	2.66	1.47	0.05	600	420.0	553,896	0.214	0.29
3	266.9	147.8	0.7	60,480,000	4.41	2.44	0.05	600	420.0	553,896	0.214	0.48
4	373.7	206.9	0.7	60,480,000	6.18	3.42	0.05	600	420.0	553,896	0.214	0.67
5	479.5	265.6	0.7	60,480,000	7.93	4.39	0.05	600	420.0	553,896	0.214	0.87
6	586.3	324.7	0.7	60,480,000	9.69	5.37	0.05	600	420.0	553,896	0.214	1.06
7	692.2	383.3	0.7	60,480,000	11.44	6.34	0.05	600	420.0	553,896	0.214	1.25
8	798.9	442.5	0.7	60,480,000	13.21	7.32	0.05	600	420.0	553,896	0.214	1.44
9	904.8	501.1	0.7	60,480,000	14.96	8.29	0.05	600	420.0	553,896	0.214	1.63

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Pen	Total carbon loading (kg/day)	Total nitrogen loading (kg/day)	Speed of current (m/sec.)	Vol. of flow-through nets (m^3/day)	Total C loading to water (μg/l) (conc.)	Total N loading to water (μg/l) (conc.)	Estimated sinking rate of material (m/sec)	Time to settle to ocean floor in (sec.)	Horizontal travel of feed/fecal particle (m)	Area of impact (m^2)	Area of impact ($miles^2$)	Amount of settling carbon (g/m^2/day)
1	54.3	30.1	0.8	69,120,000	0.79	0.43	0.05	600	480.0	723,456	0.279	0.08
2	161.1	89.2	0.8	69,120,000	2.33	1.29	0.05	600	480.0	723,456	0.279	0.22
3	266.9	147.8	0.8	69,120,000	3.86	2.14	0.05	600	480.0	723,456	0.279	0.37
4	373.7	206.9	0.8	69,120,000	5.41	2.99	0.05	600	480.0	723,456	0.279	0.52
5	479.5	265.6	0.8	69,120,000	6.94	3.84	0.05	600	480.0	723,456	0.279	0.66
6	586.3	324.7	0.8	69,120,000	8.48	4.70	0.05	600	480.0	723,456	0.279	0.81
7	692.2	383.3	0.8	69,120,000	10.01	5.55	0.05	600	480.0	723,456	0.279	0.96
8	798.9	442.5	0.8	69,120,000	11.56	6.40	0.05	600	480.0	723,456	0.279	1.10
9	904.8	501.1	0.8	69,120,000	13.09	7.25	0.05	600	480.0	723,456	0.279	1.25
AVERAGE				38,880,000	18.86	10.45	0	600	270	288,252	0.11	8.10

Area of Impact

Currents along the Texas-Louisiana mid-shelf region come from all directions and the settleable solids will be assumed not to favor any direction over time: i.e. particles will fall out in a uniform circle around the net-pen. More specifically, since the particles will be transported in all directions, the area of impact is assumed to equal to $p\ r^2$ where r is the horizontal distance traveled by the particle for a given current condition. To estimate the area of impact for the net pens in the base case scenario, the above formula is applied to the model using variables of common oceanographic conditions found in the northern Gulf. The average area of impact for an average net-pen under normal conditions is estimated to be 288,252 m^2 or 0.11 mi^2. The average rate of organic sedimentation for one net pen is estimated to be 8.10g/m^2/day.

Although the concentrations of particulate carbon discharges are well within the background levels found along the Texas-Louisiana continental shelf, the results from the model indicate that the projected fallout discharges would be greater than the sedimentation rates commonly found in the area. Redalje (1994) reported sedimentation rates of 8.17g/m^2/day for areas subjected to the Mississippi River plume and rates of 1.89-3.02g/m^2/day for areas along the Louisiana continental shelf. An explanation for the greater sedimentation rates and lower concentrations of particulate carbon around net-pens is that the fish feed and fecal materials fallout of the system as a result of their greater density while the background particulate carbon remains suspended. The model predicts relatively high rates of particulate carbon sedimentation compared to background levels, however, the actual fate of waste materials are difficult to predict. Fish fecal pellets are easily broken apart in turbulent conditions (Gowen and Bradbury 1987) and the smaller particles would lose some density and not settle out as quickly as in controlled conditions. Also, most of the fish food that goes uneaten will probably be eaten by resident wild fish and crustaceans. At a fish farm operation at an offshore oil and gas platform in the Caspian Sea, Burgov (1996) noted the capacity of the local wild fish population to scavenge uneaten food and help keep the bethos around net-pens clean.

Yearly Discharge Loadings of Carbon

The yearly discharge estimates are based on the assumption that food will be distributed two out of three days over the year allowing for down time, cold weather, etc. By multiplying 240 days by the total daily carbon loadings for all 9 net-pens (4,318 kg), an estimate of total carbon discharges of 1,036 MT of particulate carbon will be released annually by the base case mariculture facility. Following the assumption above for food distribution and applying an average daily rate of sedimentation (8.10 g/m^2/day), the yearly rate of sedimentation for an average net-pen under normal conditions, is estimated to be 1.94 kg/m^2/yr. As mentioned earlier, these levels are greater than background sedimentation rates, however, compared to reported or modeled sedimentation rates of other fish farming operations, 8.10 g/m^2/day or 1.94 kg/m^2/yr is considerably lower than results found and projected elsewhere. The table below presents some estimates found in literature for sedimentation rates beneath net-pens.

Table 8
REPORTED SEDIMENTATION RATES BELOW FISH FARMING FACILITIES

Source	Daily Sedimentation Rates ($g/m^2/day$)	Yearly Sedimentation Rates ($kg/m^2/yr$)	Model or Sediment Trap
EPA 1991 (Clam Bay facility)	36.44		Sediment trap
EPA 1991 (Clam Bay facility)	9.90		Sediment trap
EPA 1991	36.44		Sediment trap
Weston 1990	32.00		Model
Tetra Tech 1991	31.87		Model
Andrade 1996		7.80	Model
Gowen and Bradbury 1987		10.00	Model

Environmental Impact

Potential Impacts to the Environment

The decomposition of feed and organic waste, fish respiration, and nitrification of metabolic waste can lower dissolved oxygen levels in the water column in and down current of the net-pens. Dissolved oxygen and organic enrichment are interrelated in that organic enrichment fuels bacterial decomposition and that can result in oxygen depletion (EPA 1991). This depletion occurs primarily by microbes in the water and sediment consuming oxygen as they decompose organic matter. The presence of excessive nutrients from mariculture discharges could have the potential to encourage nuisance plankton blooms by providing micro-environments and transport opportunities (Dortch et al. 1998). The decay of solid wastes may also result in alterations in the benthic community due to burial and chemical changes effected within the sediments.

Plankton blooms can result in fish kills in the northern Gulf of Mexico by creating anoxic conditions or releasing toxins. Approximately five species of plankton are found along the Louisiana coast that toxic to fish: *Alexandruium monilatum, Gymnodinium breve, Gymnodinium sanguineum, Heterosigma akashiwo, and Prorocentrum minimum* (Dortch et al. 1998). Decomposition of settled solid waste may result in the consumption of dissolved oxygen contributing to hypoxic conditions commonly found along the seafloor of the Texas-Louisiana shelf. Nutrients are also released during the decay of solid waste, which may contribute to phytoplankton productivity. Sedimentation and decomposition of solid waste discharges may contribute to anaerobic conditions in the sediment and involve the release of potentially toxic decay byproducts like methane and hydrogen sulfide (Aure and Stigebrandt 1990).

Conslusion

The fallout of feed and fecal materials could result in sedimentation rates greater than background levels commonly found along the Texas-Louisiana continental shelf. The presence of extreme sea states should periodically re-suspend and disperse these accumulated sediments. Local wild fish and crustaceans will probably scavenge the feed that falls through the net-pens and reduce the potential impact to the benthos around the culture area. The sedimentation rates calculated in the model presented herein are lower than those found at other intensive fish farming operations. The presence of 20 to 30 cm/sec currents along the Texas-Louisiana 100-200ft isobath should minimize the potential harmful conditions that may be caused by mariculture nutrient and organic effluents. In these areas subjected to rapid currents, the expeditious dilution of ammonium plumes should prevent the accumulation of soluble nitrogenous waste in the water column and minimize the risk of nuisance plankton blooms. The open ocean environment should maintain safe levels of dissolved oxygen in and around the mariculture site. The dispersal rate of wastes and aerial extent of sedimentation will determine whether benthic communities in the vicinity will be impacted by net-pens.

While the analyses presented herein leads to the conclusion that a well operated mariculture project in the open Gulf should not cause any serious water quality impacts, the real proof of this will come over time with the implementation and reporting of pre-project baseline and ongoing water/sediment quality data acquisition. Regulatory agencies should require such continuing monitoring of operations until such time as there is sufficient data to prove the conclusions presented in this analysis.

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CHAPTERS 1-6

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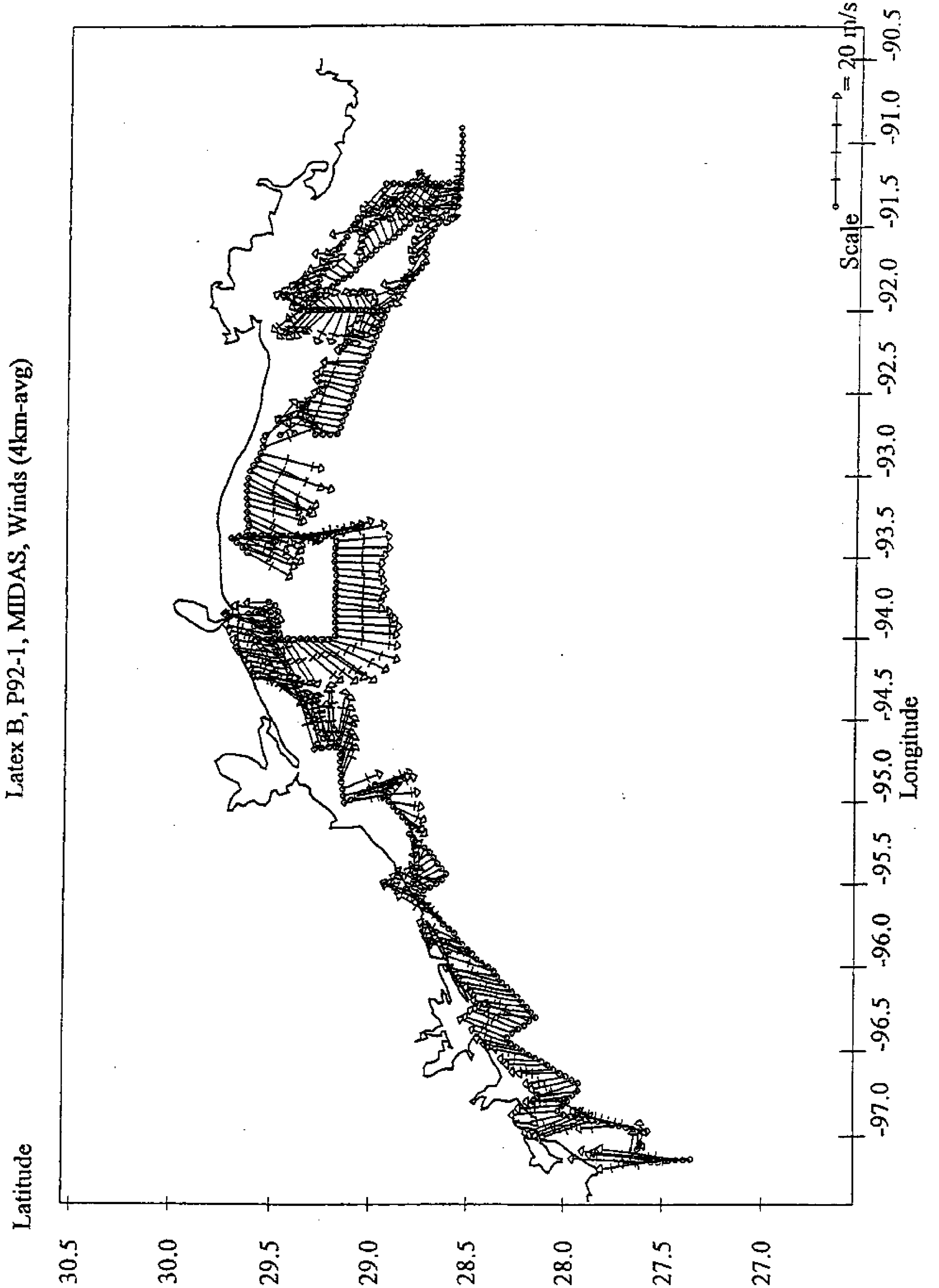
APPENDIX

LIST OF TABLES

LIST OF FIGURES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30.0
29.5
29.0
28.5
28.0
27.5
27.0
Longitude
-97.0
-96.5
-96.0
-95.5
-95.0
-94.5
-94.0
-93.5
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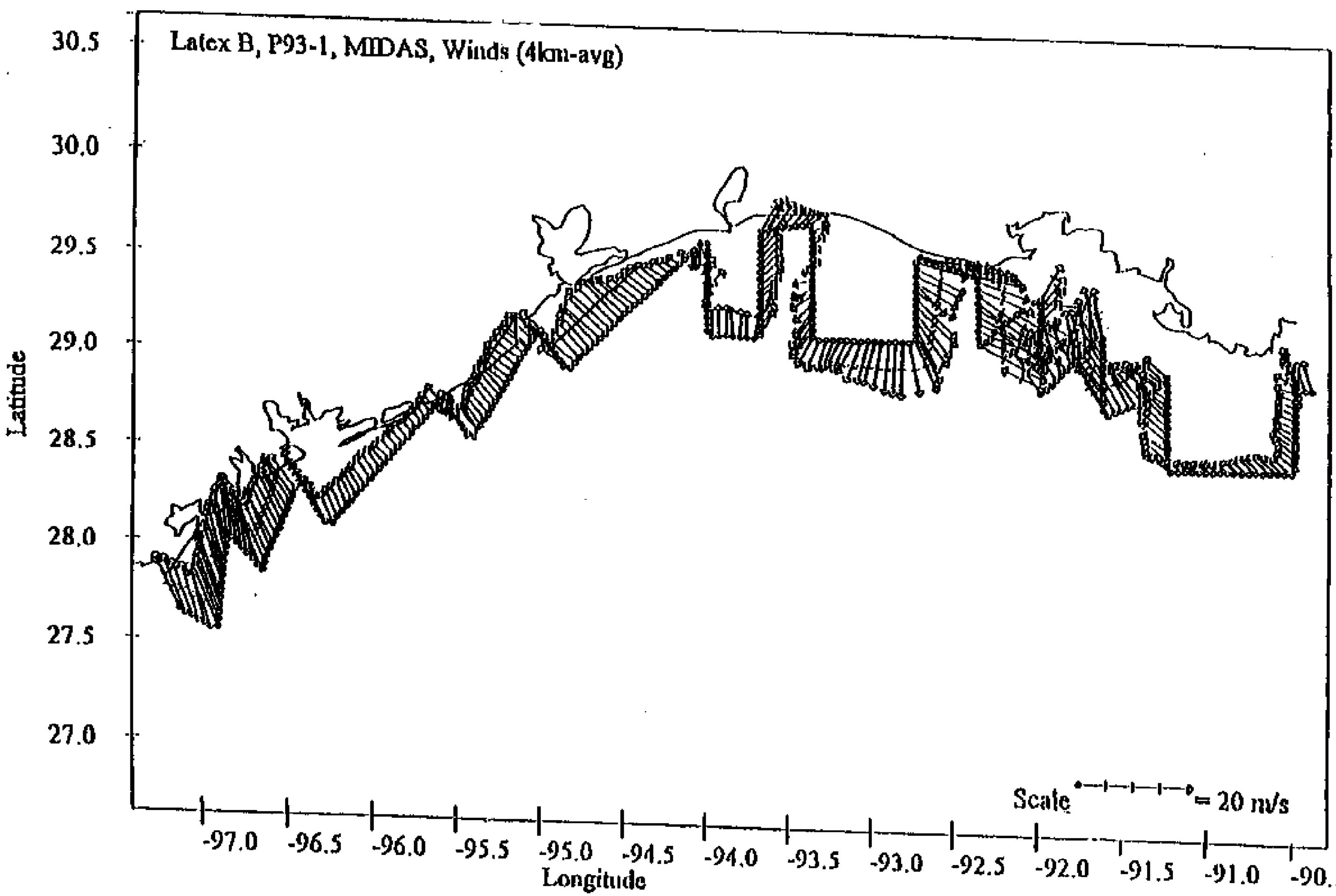
-92.5
-92.0
-91.5
-91.0
-90.5
Scale
= 20 m/s

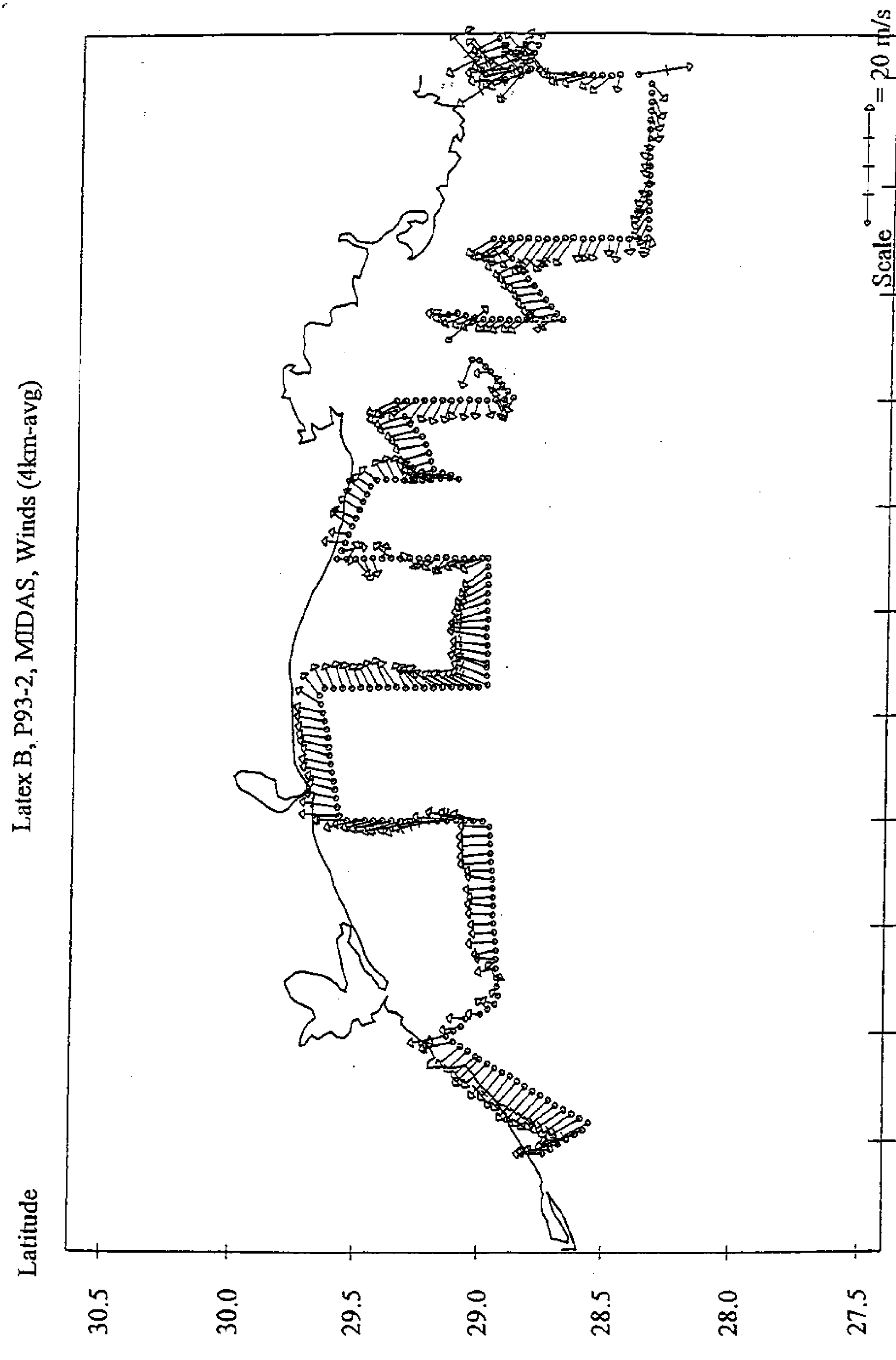
FIGURE N2 - April 93

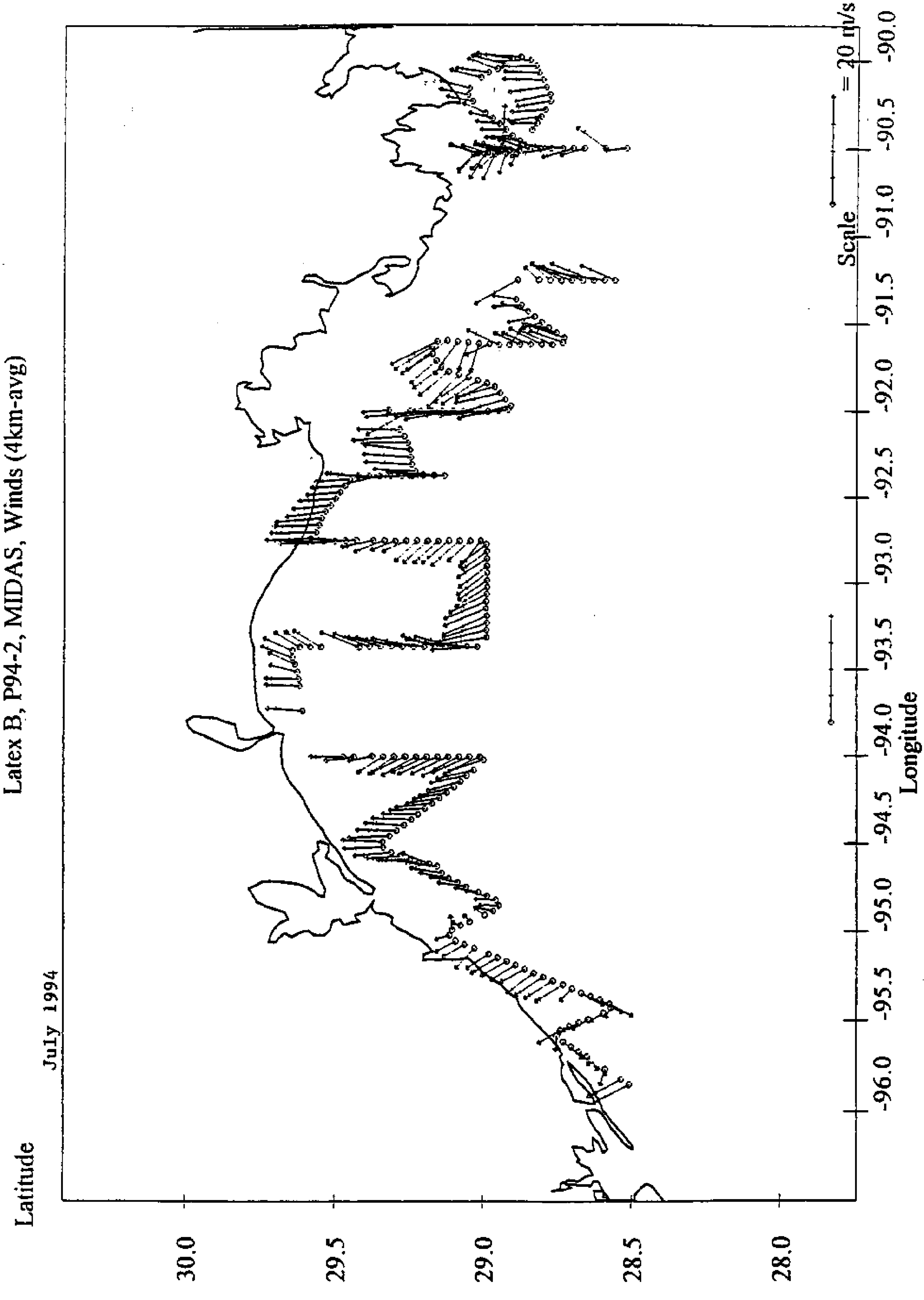


Shipboard "absolute winds, corrected for ship speed and heading, over the cruise survey. These data were collected by the Multiple Interface Data Acquisition System (MIDAS) aboard the R/V *Pelican*.

(from Murray and Donley, 1996)

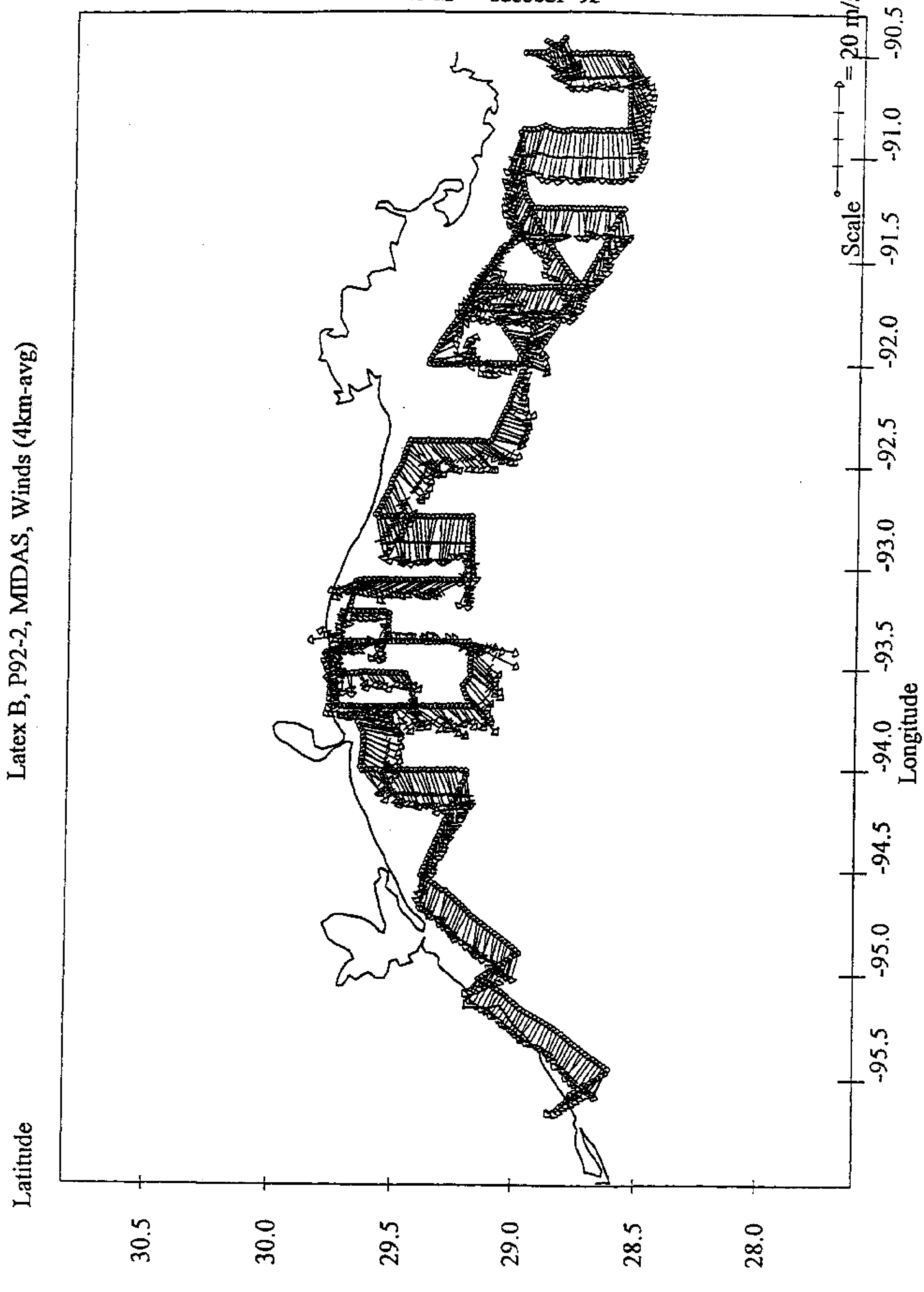
FIGURE N3 - July 93





(from Murray et al., unpubl. data)

FIGURE N5 - October 92



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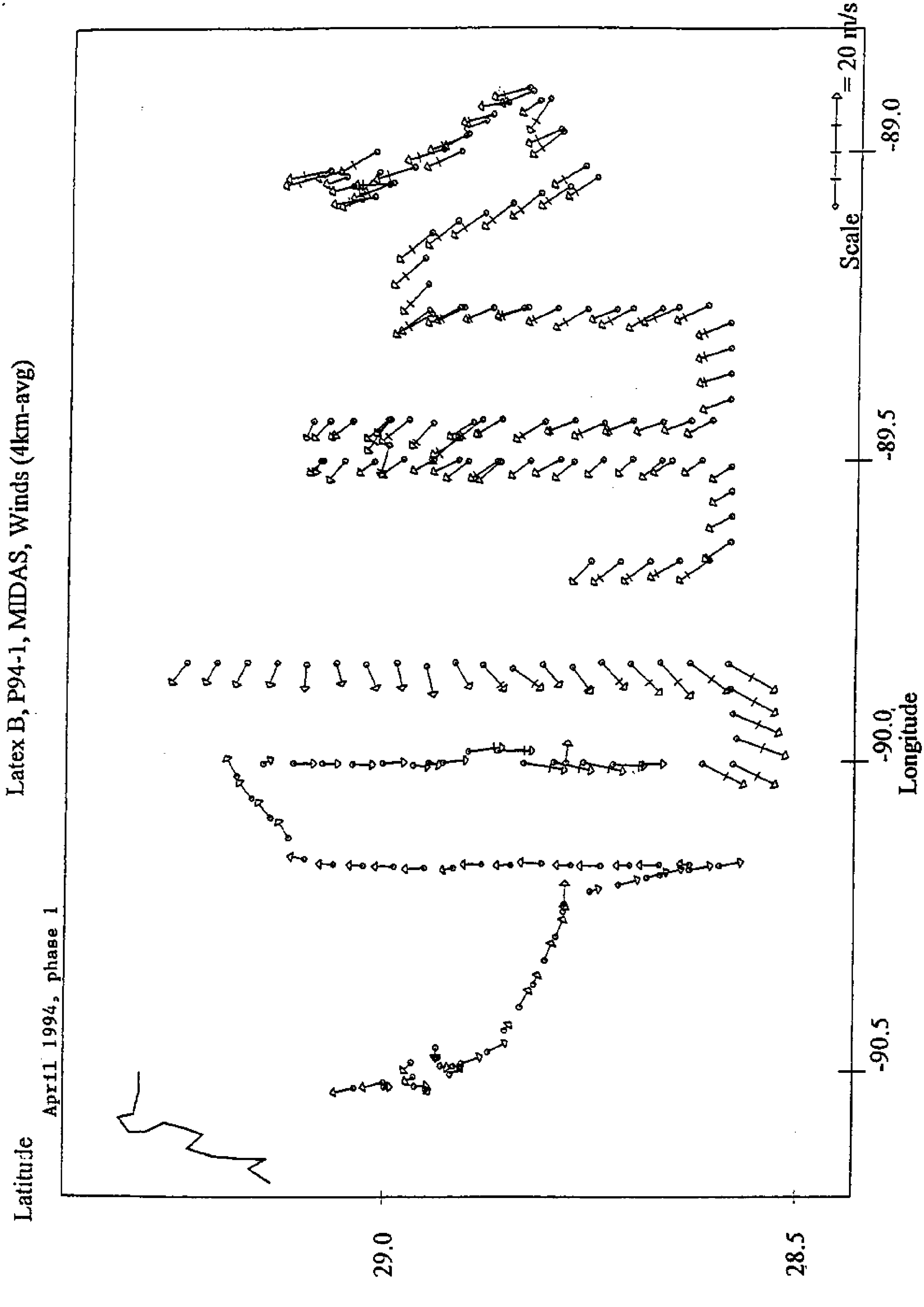

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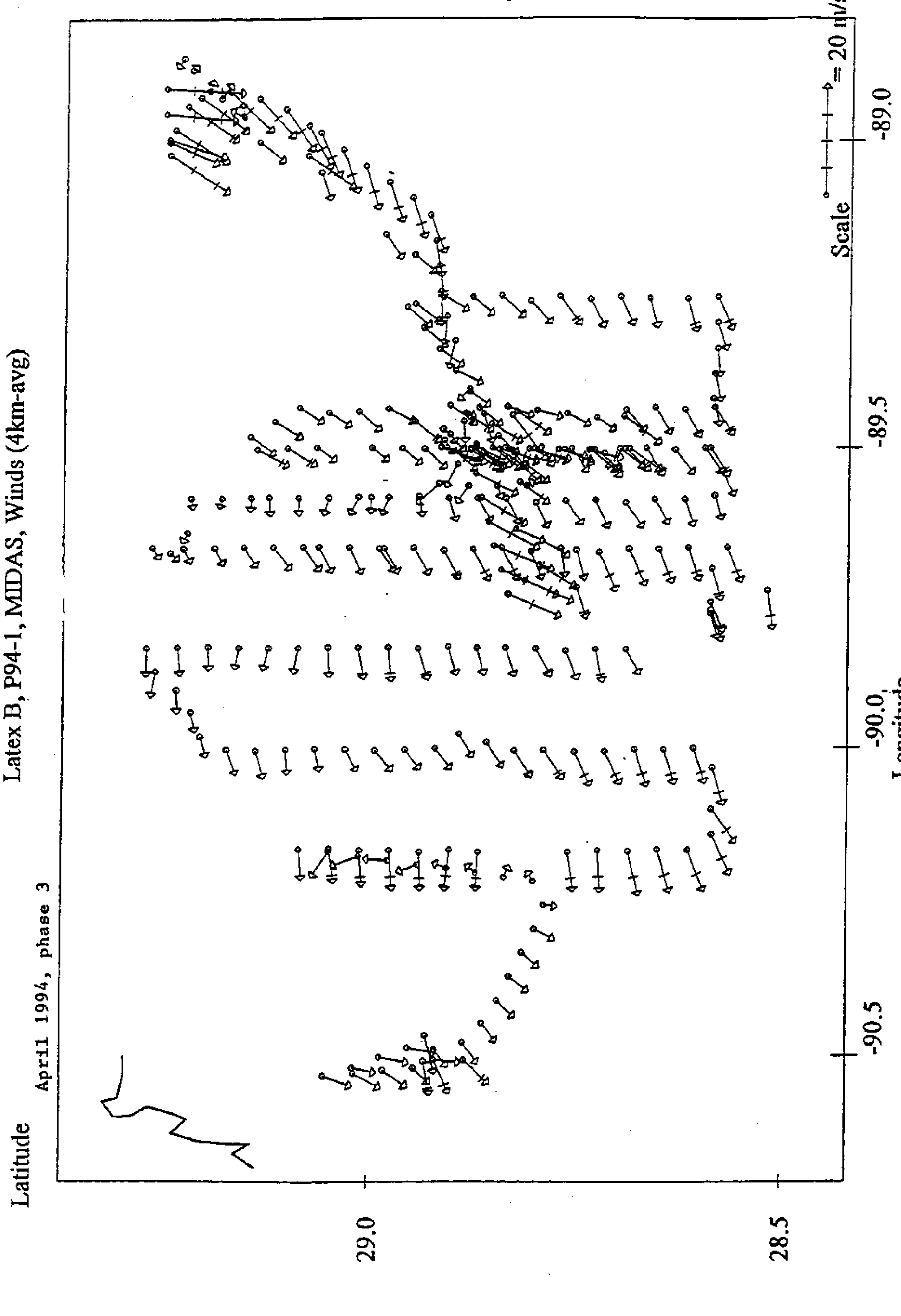

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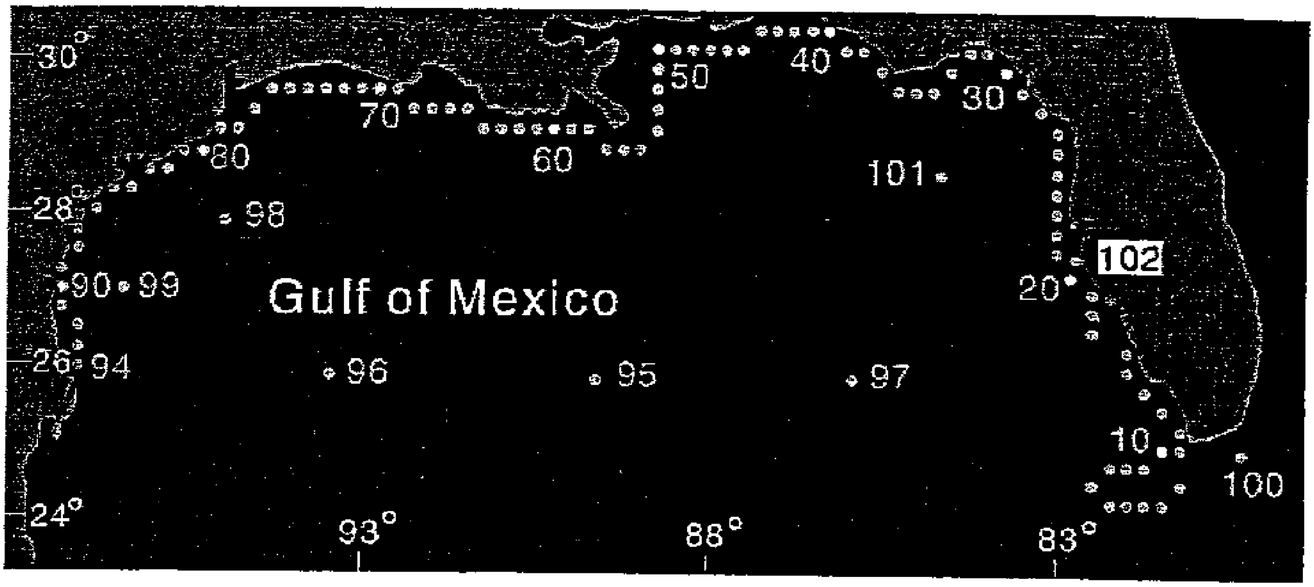
FIGURE N8



Location of stations where GOM data are saved

TABLE TN1

MEAN WAVE HEIGHT (IN METERS) BY MONTH AND YEAR

STATION: A2055 (28.75N/ 89.00W / 574.0M)

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	MEAN
1976	1.1	.8	1.2	.7	.9	.6	.3	.5	.5	1.1	1.0	1.2	.8
1977	1.3	1.3	1.6	1.1	.7	.4	.4	.9	.8	.8	1.1	1.2	1.0
1978	1.3	1.2	1.0	.9	.9	.7	.5	.6	.6	.8	.8	1.3	.9
1979	1.5	1.1	1.3	1.3	.8	.6	.9	.4	1.3	.9	1.1	1.0	1.0
1980	1.0	1.0	1.5	1.0	.8	.6	.5	.8	.6	.8	1.2	.9	.9
1981	.8	1.3	1.2	.9	.8	.7	.5	.5	.5	.8	.9	1.1	.8
1982	1.3	1.0	1.1	1.3	.7	.7	.3	.5	.8	1.0	1.1	1.7	1.0
1983	1.0	1.8	1.4	1.4	1.0	.7	.5	.6	.9	.8	1.3	1.5	1.1
1984	1.1	1.1	1.0	1.4	1.1	.6	.5	.5	1.0	.9	1.1	1.0	.9
1985	1.0	1.3	1.1	1.2	.6	.6	.4	.9	1.2	1.7	1.3	.9	1.0
1986	1.0	1.1	1.2	.7	.8	.5	.5	.5	.7	.9	1.1	1.2	.8
1987	1.1	1.1	1.4	.7	.6	.7	.5	.5	.5	.9	1.3	1.2	.9
1988	1.3	1.0	1.1	1.2	.8	.7	.6	.6	1.3	.8	1.4	.9	1.0
1989	1.0	1.1	1.1	.8	.8	.9	.7	.5	.8	.9	1.0	1.2	.9
1990	.9	1.4	1.1	.9	.9	.5	.5	.4	.5	.8	1.0	1.1	.8
1991	1.1	1.2	1.5	1.3	1.1	.6	.5	.4	.7	1.0	1.0	1.0	1.0
1992	1.0	1.0	.9	.9	.6	.6	.5	.9	.7	.9	1.3	.9	.8
1993	1.0	1.2	1.1	1.3	.9	.7	.4	.5	.6	.9	.9	1.1	.9
1994	1.6	1.2	1.2	1.0	.6	.8	.8	.7	.8	1.1	1.3	1.1	1.0
1995	1.4	1.2	1.5	1.3	1.0	.9	.8	.7	1.0	1.8	1.3	1.3	1.2
MEAN	1.1	1.2	1.2	1.1	.8	.7	.5	.6	.8	1.0	1.1	1.1	

LARGEST WAVE HEIGHT (IN METERS) BY MONTH AND YEAR

STATION: A2055 (28.75N/ 89.00W / 574.0M)

YEAR	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
1976	2.2	2.4	2.2	2.5	2.1	1.6	.7	2.6	1.8	3.1	2.7	2.6
1977	4.1	3.5	4.6	3.5	2.3	1.5	1.0	3.9	3.1	2.2	2.1	3.5
1978	4.3	3.2	2.9	1.7	2.7	1.6	1.1	2.7	1.1	2.3	1.8	3.0
1979	5.7	3.3	3.6	3.3	1.4	1.5	3.9	1.1	10.1	2.4	2.3	2.9
1980	2.2	2.2	3.2	3.5	2.3	1.4	1.1	4.5	1.5	2.3	3.1	2.2
1981	3.6	3.9	4.4	2.4	1.7	1.7	1.1	1.1	1.6	2.0	2.5	2.5
1982	3.6	1.9	3.3	2.8	1.9	1.7	.7	1.5	2.7	1.9	2.0	3.7
1983	4.5	5.7	4.8	4.2	2.3	1.2	1.5	1.7	2.3	1.5	3.2	3.2
1984	2.5	4.6	4.8	3.0	3.0	1.3	1.3	2.3	2.5	1.8	2.9	2.2
1985	2.6	3.6	4.1	3.0	1.4	2.0	1.2	6.7	3.5	9.4	9.6	2.0
1986	3.3	2.4	3.2	2.2	1.4	1.9	1.2	1.2	1.2	2.4	2.5	3.9
1987	2.9	2.9	4.0	2.1	1.4	1.6	1.3	1.2	1.4	2.2	3.1	2.9
1988	3.4	4.0	2.4	4.2	2.7	1.6	2.2	2.3	10.6	2.5	4.0	2.1
1989	3.7	2.3	2.6	2.0	1.4	2.4	3.8	3.6	2.4	2.6	4.8	4.5
1990	2.0	2.6	2.6	1.9	1.7	1.1	1.1	1.1	1.6	2.0	3.6	2.4
1991	2.2	2.8	3.1	3.3	3.5	2.0	.9	1.1	1.6	2.5	2.2	3.6
1992	3.9	2.6	2.1	2.1	1.3	1.6	1.9	12.9	2.1	3.4	2.6	2.7
1993	2.7	2.8	3.4	3.5	2.1	2.0	.7	1.0	1.8	3.2	2.0	3.5
1994	4.3	3.1	3.6	2.2	1.7	2.2	3.1	1.3	2.6	3.2	3.0	2.5
1995	3.5	3.2	3.3	3.9	2.2	3.4	2.9	2.2	3.3	8.5	4.5	3.7

TABLE TH2

1976 - 1995 STATISTICS

STATION: A2055 (28.75N/ 89.00W / 574.0M)

MEAN SPECTRAL WAVE HEIGHT	(METERS)	.9
MEAN PEAK WAVE PERIOD	(SECONDS)	4.9
MOST FREQUENT 22.5 DEGREE (CENTER) DIRECTION BAND . .	(DEGREES)	135.0
STANDARD DEVIATION OF WAVE Hmo.	(METERS)	.7
STANDARD DEVIATION OF WAVE TP	(SECONDS)	1.5
LARGEST WAVE Hmo.	(METERS)	12.9
WAVE TP ASSOCIATED WITH LARGEST WAVE Hmo.	(SECONDS)	14.0
PEAK DIRECTION ASSOCIATED WITH LARGEST WAVE HS.	(DEGREES)	133.0
DATE LARGEST Hmo OCCURRED 1992082522		

STATION: A2056 (28.75N/ 89.25W / 205.0M)

MEAN SPECTRAL WAVE HEIGHT	(METERS)	.9
MEAN PEAK WAVE PERIOD	(SECONDS)	4.9
MOST FREQUENT 22.5 DEGREE (CENTER) DIRECTION BAND . .	(DEGREES)	135.0
STANDARD DEVIATION OF WAVE Hmo.	(METERS)	.6
STANDARD DEVIATION OF WAVE TP	(SECONDS)	1.5
LARGEST WAVE Hmo.	(METERS)	13.0
WAVE TP ASSOCIATED WITH LARGEST WAVE Hmo.	(SECONDS)	14.0
PEAK DIRECTION ASSOCIATED WITH LARGEST WAVE HS.	(DEGREES)	133.0
DATE LARGEST Hmo OCCURRED 1992082522		

STATION: A2057 (28.75N/ 89.50W / 101.0M)

MEAN SPECTRAL WAVE HEIGHT	(METERS)	.9
MEAN PEAK WAVE PERIOD	(SECONDS)	4.9
MOST FREQUENT 22.5 DEGREE (CENTER) DIRECTION BAND . .	(DEGREES)	135.0
STANDARD DEVIATION OF WAVE Hmo.	(METERS)	.6
STANDARD DEVIATION OF WAVE TP	(SECONDS)	1.5
LARGEST WAVE Hmo.	(METERS)	13.2
WAVE TP ASSOCIATED WITH LARGEST WAVE Hmo.	(SECONDS)	14.0
PEAK DIRECTION ASSOCIATED WITH LARGEST WAVE HS.	(DEGREES)	130.0
DATE LARGEST Hmo OCCURRED 1992082522		

STATION: A2058 (29.00N/ 89.75W / 37.0M)

MEAN SPECTRAL WAVE HEIGHT	(METERS)	.8
MEAN PEAK WAVE PERIOD	(SECONDS)	4.6
MOST FREQUENT 22.5 DEGREE (CENTER) DIRECTION BAND . .	(DEGREES)	135.0
STANDARD DEVIATION OF WAVE Hmo.	(METERS)	.5
STANDARD DEVIATION OF WAVE TP	(SECONDS)	1.5
LARGEST WAVE Hmo.	(METERS)	10.1
WAVE TP ASSOCIATED WITH LARGEST WAVE Hmo.	(SECONDS)	14.0
PEAK DIRECTION ASSOCIATED WITH LARGEST WAVE HS.	(DEGREES)	173.0
DATE LARGEST Hmo OCCURRED 1992082604		

STATION: A2059 (29.00N/ 90.00W / 25.0M)

MEAN SPECTRAL WAVE HEIGHT	(METERS)	.8
MEAN PEAK WAVE PERIOD	(SECONDS)	4.7
MOST FREQUENT 22.5 DEGREE (CENTER) DIRECTION BAND . .	(DEGREES)	135.0
STANDARD DEVIATION OF WAVE Hmo.	(METERS)	.5
STANDARD DEVIATION OF WAVE TP	(SECONDS)	1.5
LARGEST WAVE Hmo.	(METERS)	10.6
WAVE TP ASSOCIATED WITH LARGEST WAVE Hmo.	(SECONDS)	14.0
PEAK DIRECTION ASSOCIATED WITH LARGEST WAVE HS.	(DEGREES)	151.0
DATE LARGEST Hmo OCCURRED 1992082602		

TABLE TN2 (cont.)

STATION: A2060 (29.00N/ 90.25W / 13.0M)

MEAN SPECTRAL WAVE HEIGHT	(METERS)	.8
MEAN PEAK WAVE PERIOD	(SECONDS)	4.7
MOST FREQUENT 22.5 DEGREE (CENTER) DIRECTION BAND . .	(DEGREES)	135.0
STANDARD DEVIATION OF WAVE Hmo.	(METERS)	.5
STANDARD DEVIATION OF WAVE TP	(SECONDS)	1.6
LARGEST WAVE Hmo.	(METERS)	8.2
WAVE TP ASSOCIATED WITH LARGEST WAVE Hmo.	(SECONDS)	13.0
PEAK DIRECTION ASSOCIATED WITH LARGEST WAVE HS.	(DEGREES)	144.0
DATE LARGEST Hmo OCCURRED 1992082603		

STATION: A2061 (29.00N/ 90.50W / 10.0M)

MEAN SPECTRAL WAVE HEIGHT	(METERS)	.8
MEAN PEAK WAVE PERIOD	(SECONDS)	4.7
MOST FREQUENT 22.5 DEGREE (CENTER) DIRECTION BAND . .	(DEGREES)	135.0
STANDARD DEVIATION OF WAVE Hmo.	(METERS)	.5
STANDARD DEVIATION OF WAVE TP	(SECONDS)	1.7
LARGEST WAVE Hmo.	(METERS)	6.3
WAVE TP ASSOCIATED WITH LARGEST WAVE Hmo.	(SECONDS)	13.0
PEAK DIRECTION ASSOCIATED WITH LARGEST WAVE HS.	(DEGREES)	169.0
DATE LARGEST Hmo OCCURRED 1992082609		

STATION: A2062 (29.00N/ 90.75W / 7.0M)

MEAN SPECTRAL WAVE HEIGHT	(METERS)	.8
MEAN PEAK WAVE PERIOD	(SECONDS)	4.8
MOST FREQUENT 22.5 DEGREE (CENTER) DIRECTION BAND . .	(DEGREES)	135.0
STANDARD DEVIATION OF WAVE Hmo.	(METERS)	.5
STANDARD DEVIATION OF WAVE TP	(SECONDS)	1.8
LARGEST WAVE Hmo.	(METERS)	4.4
WAVE TP ASSOCIATED WITH LARGEST WAVE Hmo.	(SECONDS)	14.0
PEAK DIRECTION ASSOCIATED WITH LARGEST WAVE HS.	(DEGREES)	148.0
DATE LARGEST Hmo OCCURRED 1995100422		

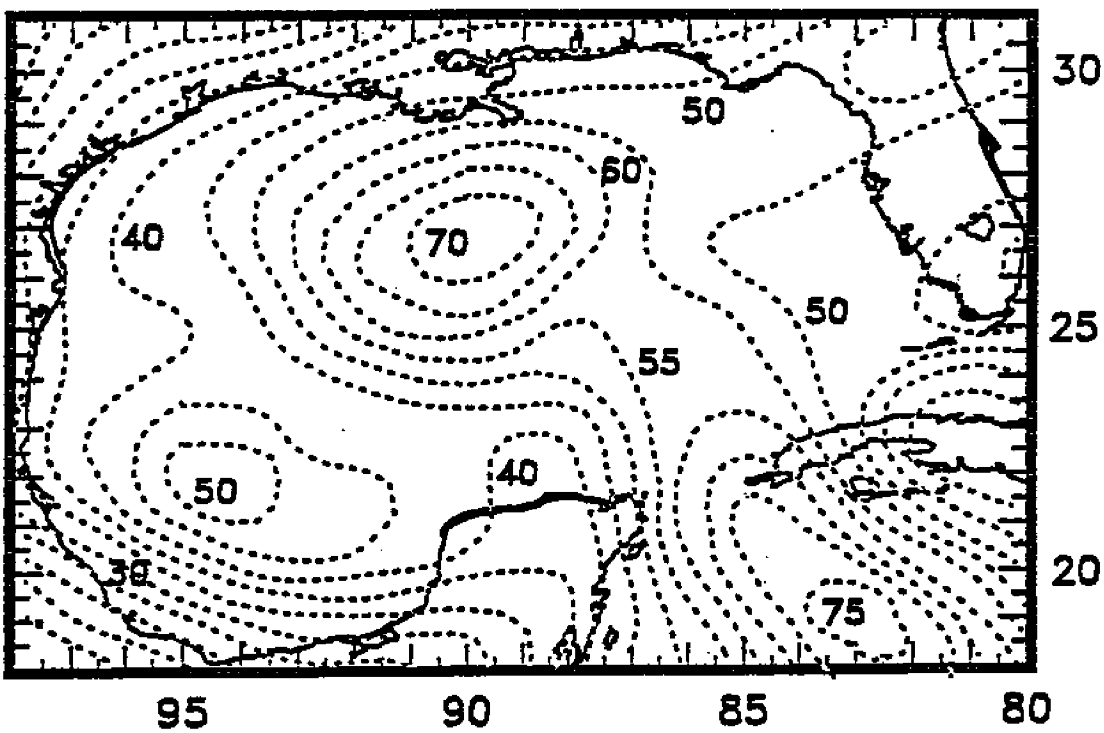
STATION: A2063 (29.00N/ 91.00W / 6.0M)

MEAN SPECTRAL WAVE HEIGHT	(METERS)	.8
MEAN PEAK WAVE PERIOD	(SECONDS)	4.9
MOST FREQUENT 22.5 DEGREE (CENTER) DIRECTION BAND . .	(DEGREES)	135.0
STANDARD DEVIATION OF WAVE Hmo.	(METERS)	.5
STANDARD DEVIATION OF WAVE TP	(SECONDS)	1.8
LARGEST WAVE Hmo.	(METERS)	3.8
WAVE TP ASSOCIATED WITH LARGEST WAVE Hmo.	(SECONDS)	14.0
PEAK DIRECTION ASSOCIATED WITH LARGEST WAVE HS.	(DEGREES)	148.0
DATE LARGEST Hmo OCCURRED 1995100500		

STATION: A2064 (29.00N/ 91.25W / 4.0M)

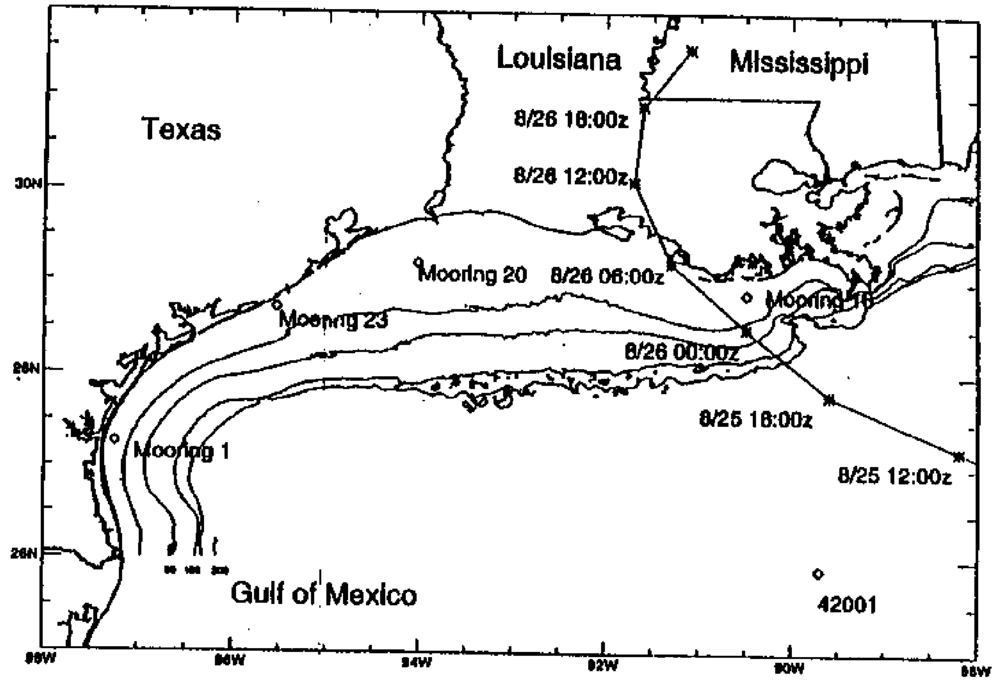
MEAN SPECTRAL WAVE HEIGHT	(METERS)	.7
MEAN PEAK WAVE PERIOD	(SECONDS)	4.9
MOST FREQUENT 22.5 DEGREE (CENTER) DIRECTION BAND . .	(DEGREES)	157.5
STANDARD DEVIATION OF WAVE Hmo.	(METERS)	.4
STANDARD DEVIATION OF WAVE TP	(SECONDS)	1.9
LARGEST WAVE Hmo.	(METERS)	2.5
WAVE TP ASSOCIATED WITH LARGEST WAVE Hmo.	(SECONDS)	9.0
PEAK DIRECTION ASSOCIATED WITH LARGEST WAVE HS.	(DEGREES)	220.0
DATE LARGEST Hmo OCCURRED 1995111112		

FIGURE N9



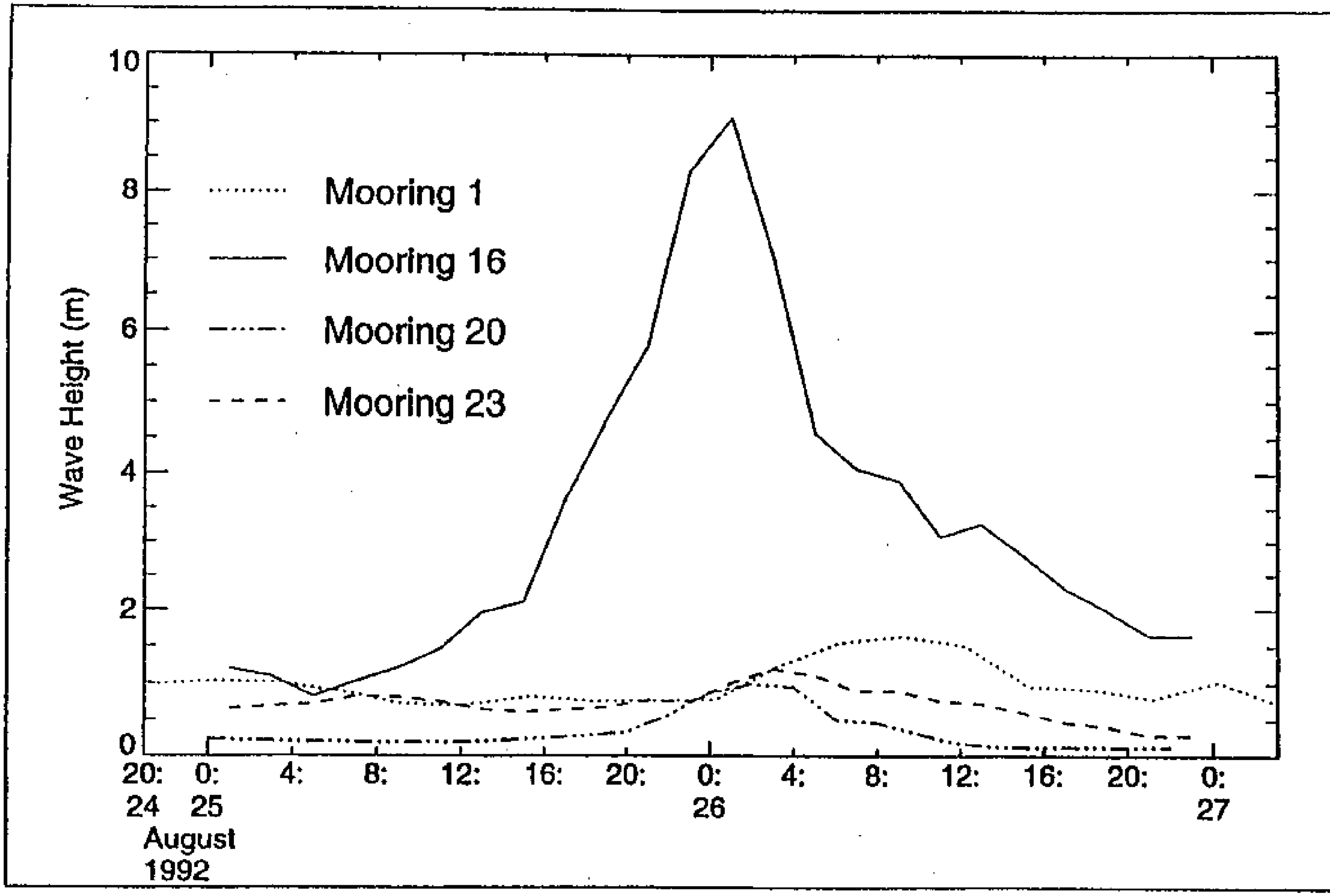
Frequency of tropical cyclones per 100 years with minimum wind speeds of 34 knots (18 m/s).

FIGURE N10



Map of the northwestern Gulf showing 50-, 100-, and 200-m isobaths, Hurricane Andrew storm track, and LATEX wave gauge and NDBC buoy locations.
(from Jochens and Nowlin, 1995)

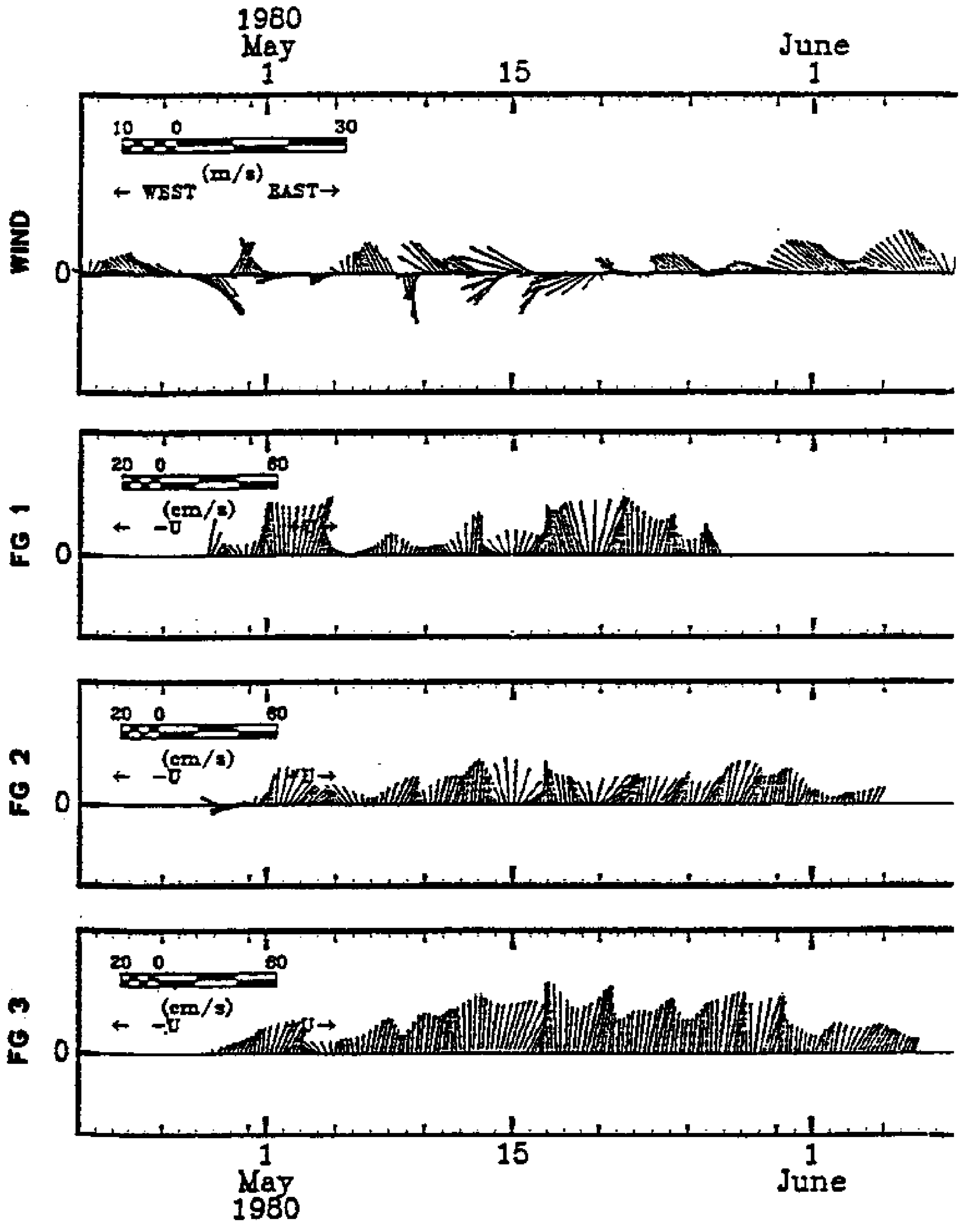
FIGURE N11



H_s measured at LATEX moorings 1, 16, 20, and 23 during Hurricane Andrew.

(from Jochens and Nowlin, 1995)

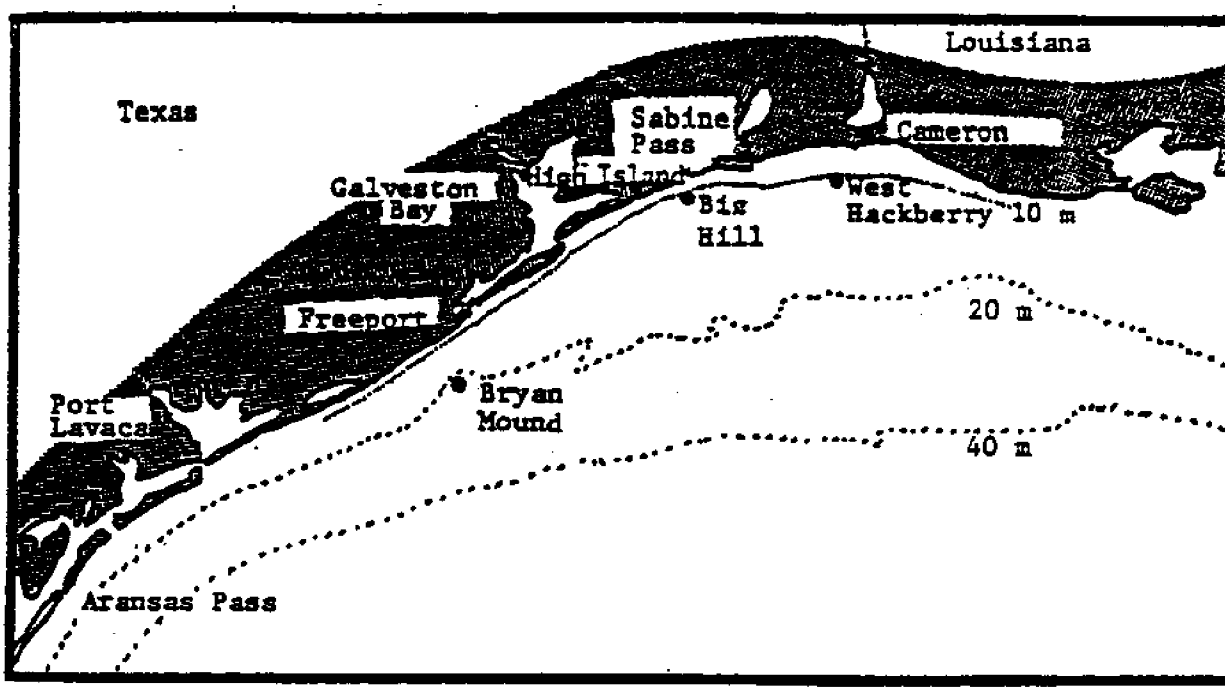
FIGURE N12



Comparative time-series plots of 40-hour low-passed stick vectors for wind from NDBC buoy 42008 (28° 47.07'N, 95° 18.71'W) and currents from Flower Garden sites 1, 2, and 3 (instrument depths, about 50 m; water depths about 100 m [Rezak et al. 1983]) for May 1980. Vertically up is toward the East for the current stick vectors and towards the North for the wind stick vectors.

(from Kelly and Brooks, 1988)

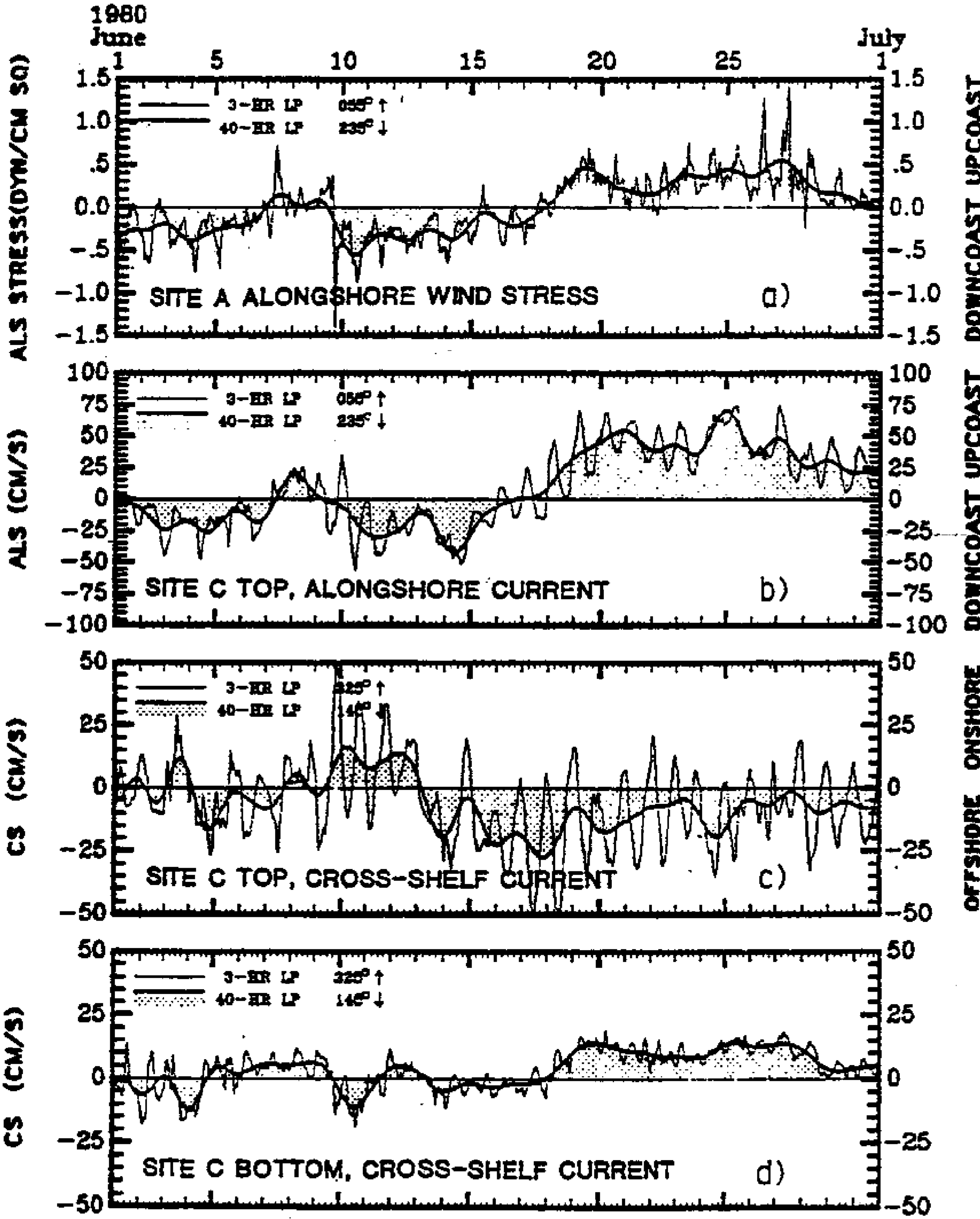
FIGURE N13



Locations of the Bryan Mound, Big Hill and West Hackberry offshore sites and coastal cities referenced in the text.

(from Kelly, 1988)

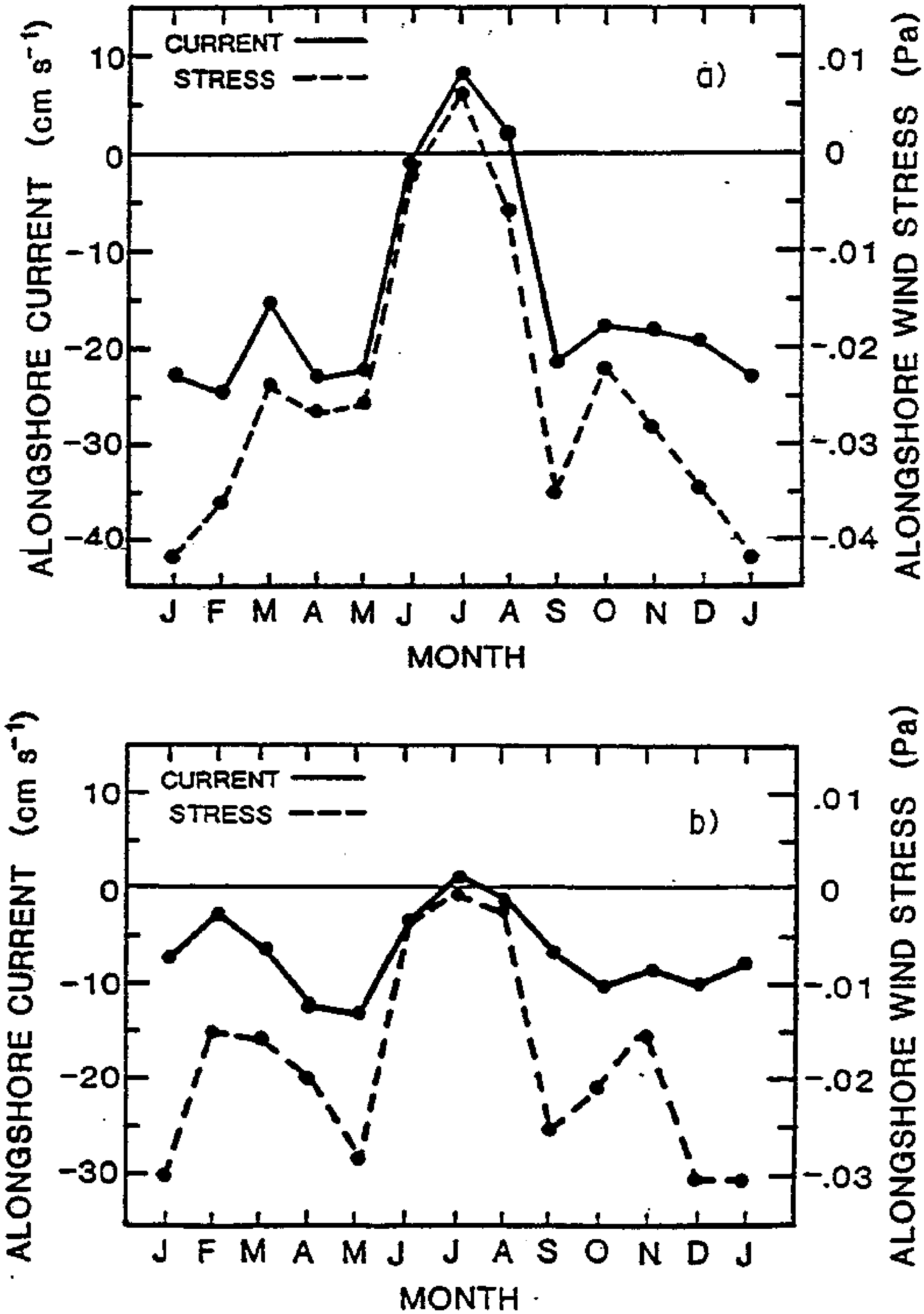
FIGURE N14



An example of the response of currents to the alongshore compo of wind stress from data collected during July 1980 at the B Mound site (Figure 20) where the water depth is approximately 2 a) alongshore (positive toward 55° true) component of wind str b) alongshore component of near-surface current (3.7 m below surface), c) cross-shelf (positive toward 325° true) componen near-surface current, d) cross-shelf component of near-bottom cu (1.8 m above the bottom). Light and heavy lines are 3-hour an hour low-passed, respectively.

(from Kelly, 1988)

FIGURE N15



Monthly mean alongshore component of wind stress together monthly mean alongshore component of surface current (3.7 m b sea surface): a) at the Bryan Mound site off Freeport, Texas, positive alongshore direction is 55° true; b) at the West Hackb site off Cameron, Louisiana, the positive alongshore directio 86° true (from Cochrane and Kelly 1986).

(from Kelly, 1988)

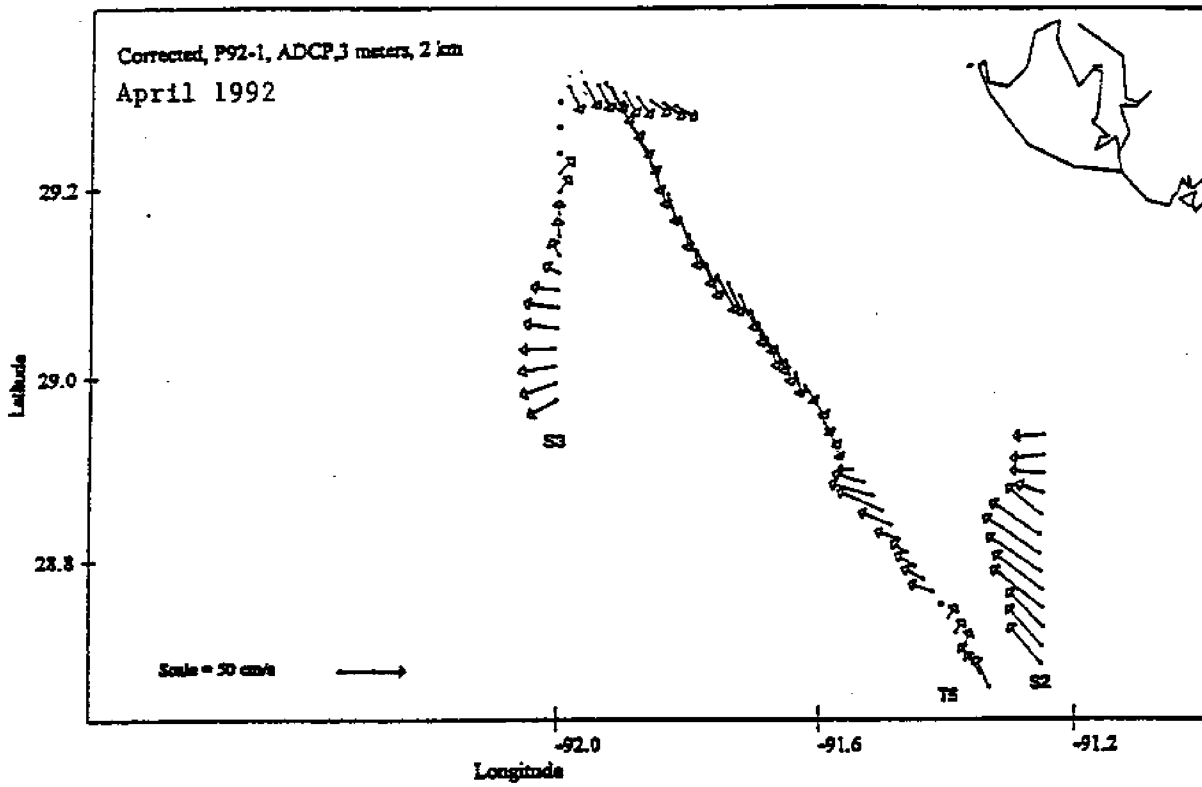
TABLE TN3

Maximum speeds and corresponding directions observed in 40-hr low-passed current record from each LATEX A mooring during the second field year.

Mooring	Latitude N	Longitude W	Depth (m)	S_{max} ($cm.s^{-1}$)	Dir_{max} (°T)	Date
1	27° 15.39'	97° 14.81'	19	86	196	20 June 1993
2	27° 17.09'	96° 58.81'	10	81	204	10 Nov. 1993
3	27° 17.35'	96° 44.18'	13	69	222	13 Mar. 1993
4	27° 07.76'	96° 21.63'	12	77	358	13 Feb. 1993
5	27° 27.82'	96° 04.12'	14	64	63	12 Aug. 1993
6	27° 42.59'	95° 39.85'	13	83	94	15 Feb. 1993
7	27° 50.12'	95° 04.19'	14	83	99	4 Aug. 1993
8	27° 49.47'	94° 10.77'	15	61	144	10 Mar. 1993
9	27° 48.92'	93° 31.91'	14	51	94	6 Jan. 1994
10	27° 56.07'	92° 44.70'	14	39	88	8 Mar. 1994
11	27° 50.64'	92° 00.45'	14	32	29	17 Jan. 1994
12	27° 55.76'	90° 29.64'	14	68	103	27 Oct. 1993
13	28° 03.48'	90° 29.18'	15	54	87	17 Aug. 1993
14	28° 23.74'	90° 29.65'	19	42	262	8 Jan. 1994
15	28° 36.49'	90° 29.53'	10	59	80	7 Aug. 1993
16	28° 51.96'	90° 29.50'	11	52	268	8 Oct. 1993
17	29° 11.82'	91° 57.89'	3	62	304	20 June 1993
18	28° 57.74'	91° 59.01'	10	69	271	8 Apr. 1993
19	28° 27.92'	92° 02.06'	3	52	309	11 Aug. 1993
20	29° 15.67'	94° 03.82'	3	73	12	13 Sept. 1993
21	28° 50.28'	94° 04.79'	14	46	264	19 June 1993
22	28° 21.39'	93° 57.34'	3	59	22	20 July 1993
23	28° 42.77'	95° 32.13'	10	72	246	19 June 1993
24	28° 32.21'	95° 23.61'	10	83	240	9 Nov. 1993
25	28° 19.33'	95° 21.57'	11	36	87	2 Apr. 1993
44	Removed					
45	Removed					
46	Removed					
47	Removed					
48	27° 58.98'	91° 16.99'	14	42	85	7 Jan. 1994
49	27° 23.13'	95° 53.96'	14	29	240	2 Mar. 1994

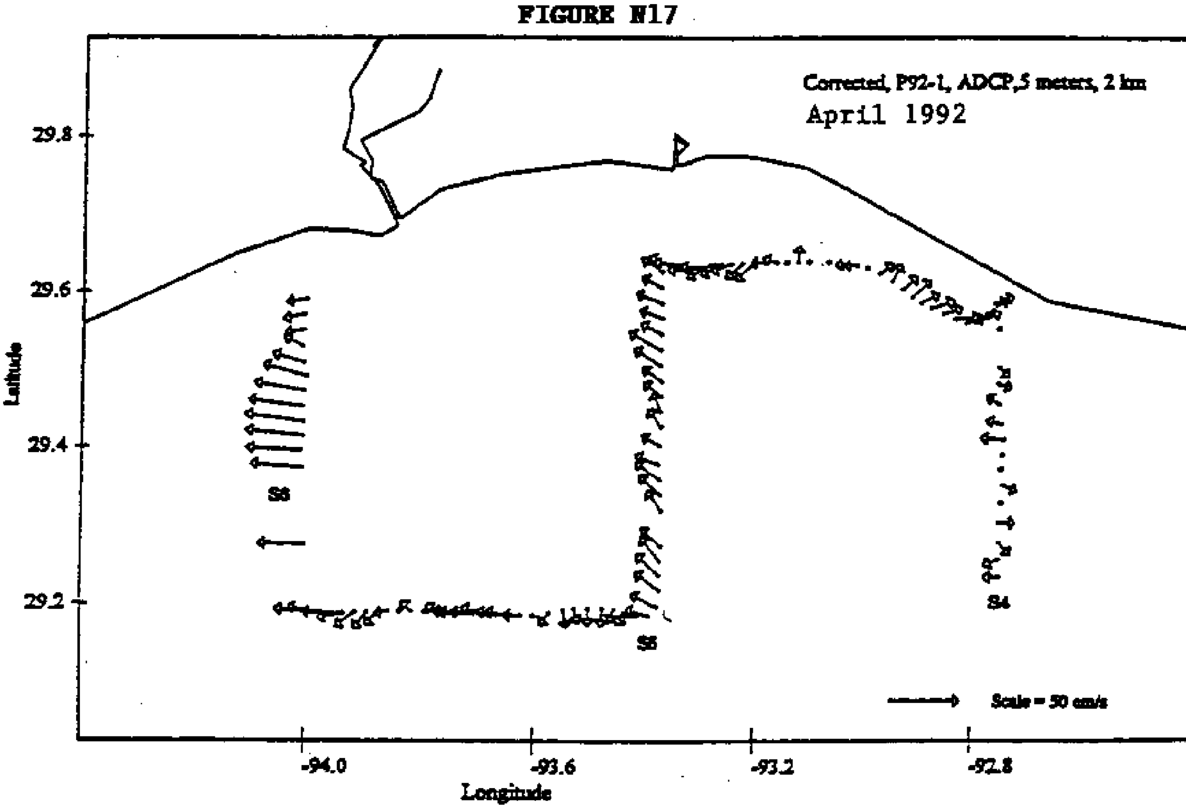
(from Jochens and Nowlin, 1995)

FIGURE N16



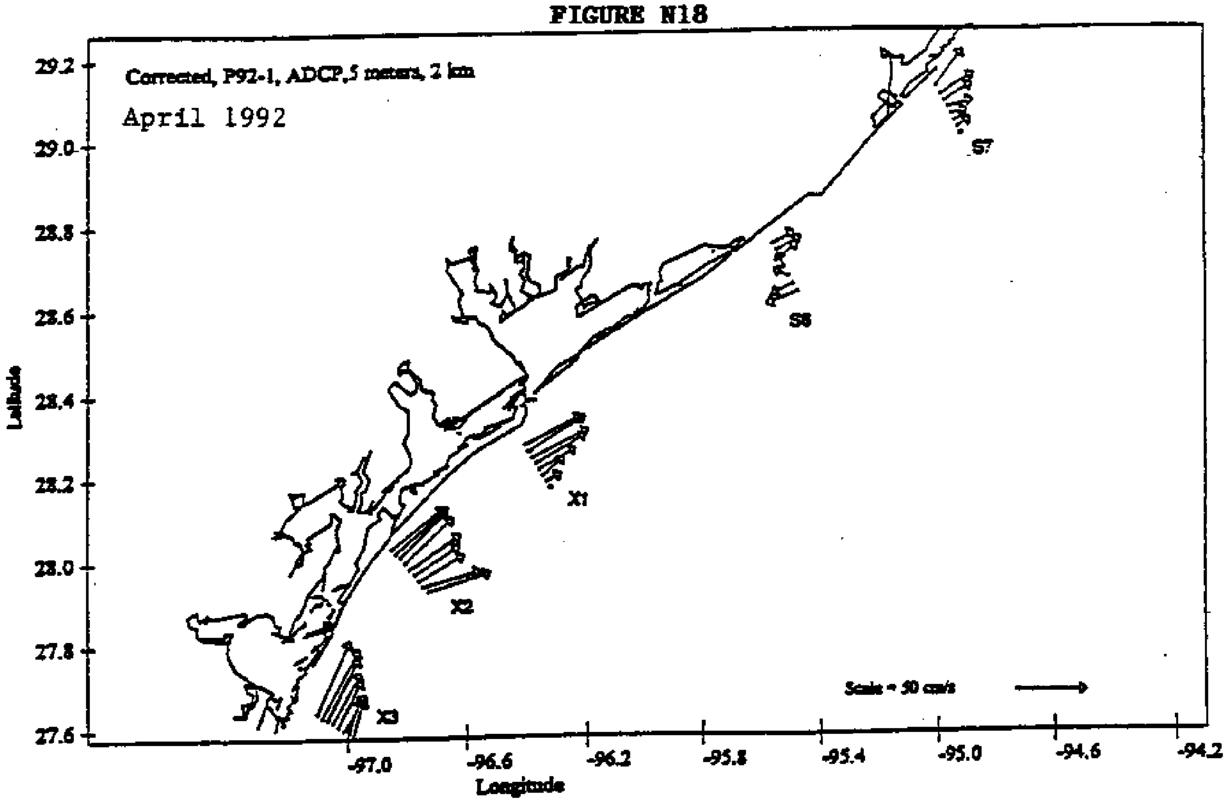
Near surface ADCP velocities at the 3 m level in the Atchafalaya source region.

FIGURE N17



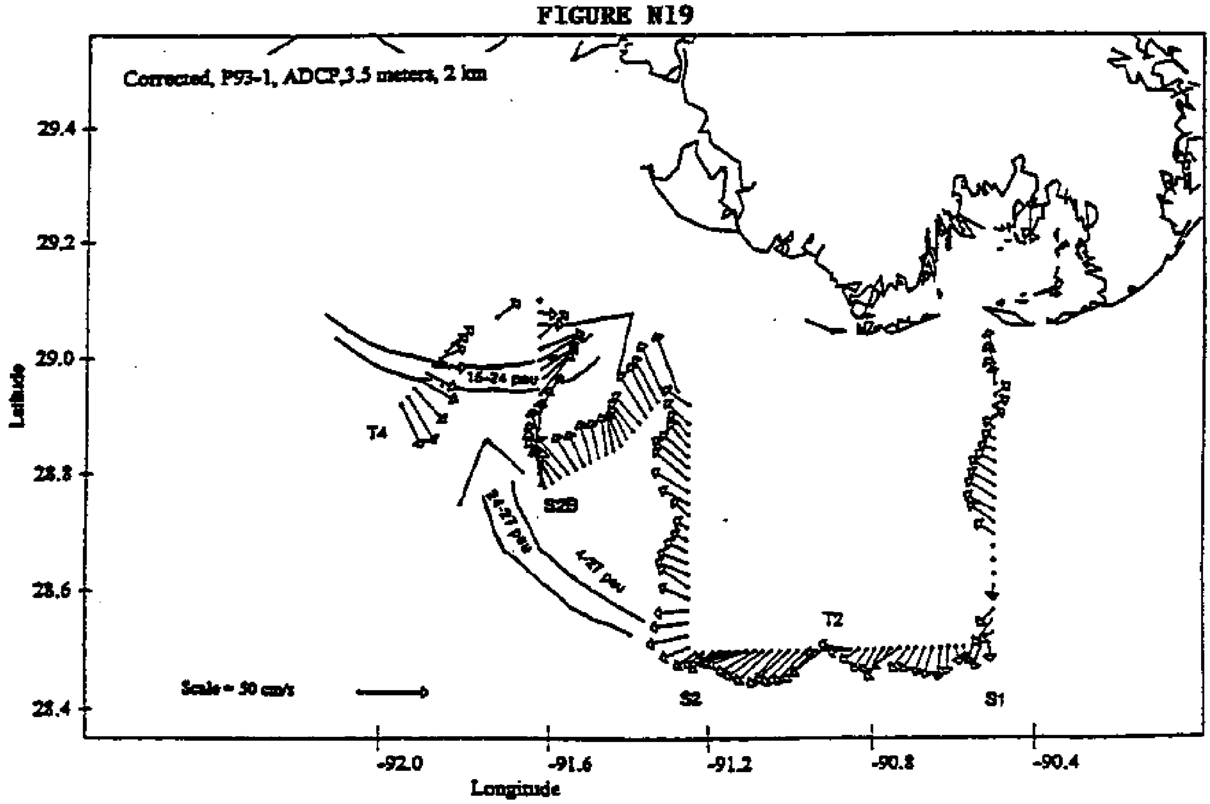
Velocity vectors from the ADCP at the 5 m level in the western Louisiana region. Open circles at ensemble points indicate velocities are less than the standard error of 4 cm/sec. (from Murray, submitted)

FIGURE N18



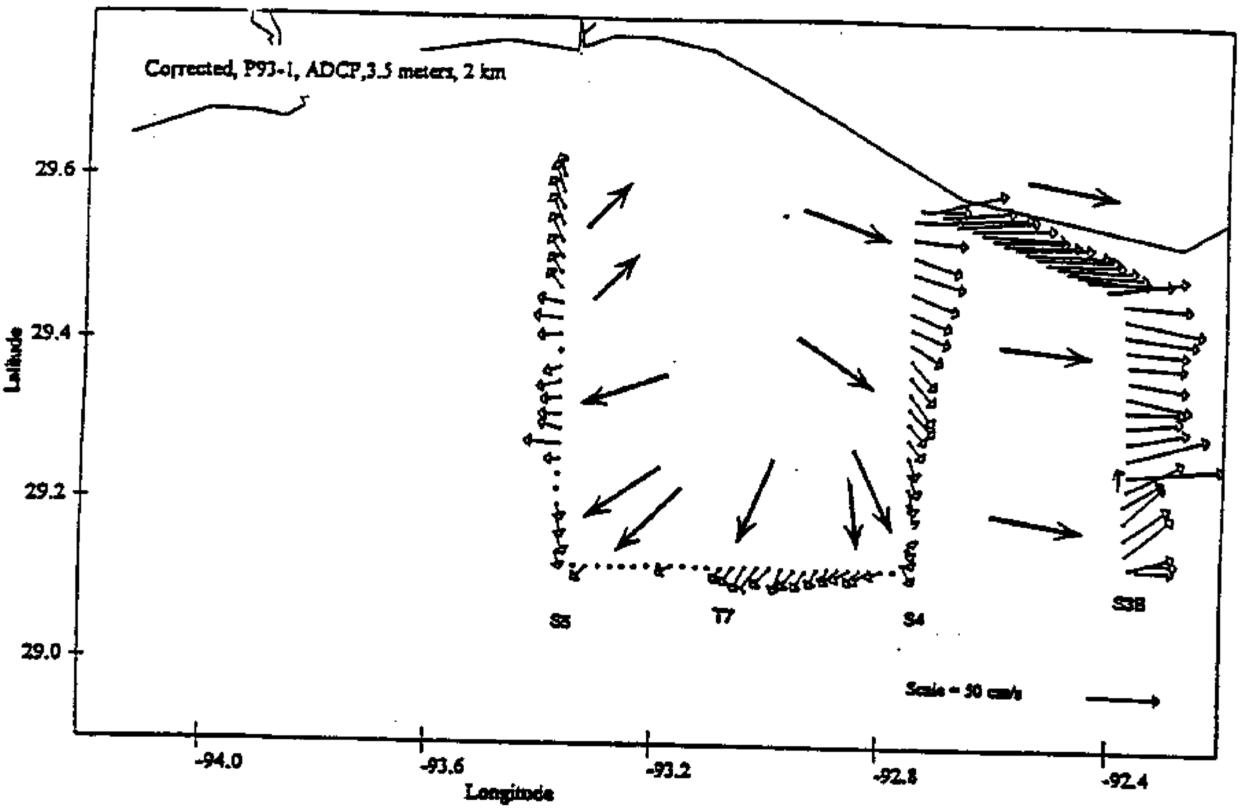
ADCP velocity vectors at the 5 m level in south-central Texas region of the coastal plume illustrating the episodic upcoast jet embedded in the downcoast coastal plume characteristic of this season. (from Murray, submitted)

FIGURE N19



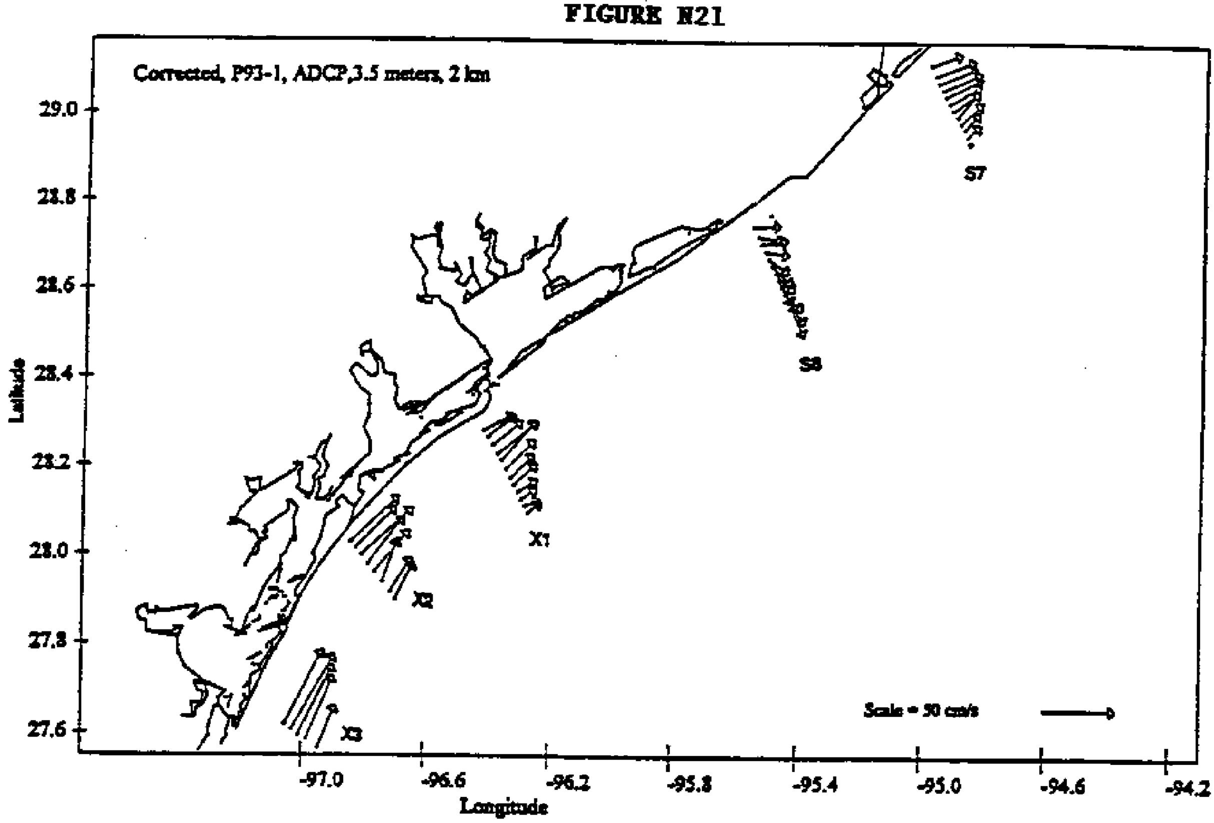
ADCP velocity vectors at the 3.5 m level in the source region east of the Atchafalaya outflow plume during the April 1993 observations.
(from Murray, submitted)

FIGURE N20

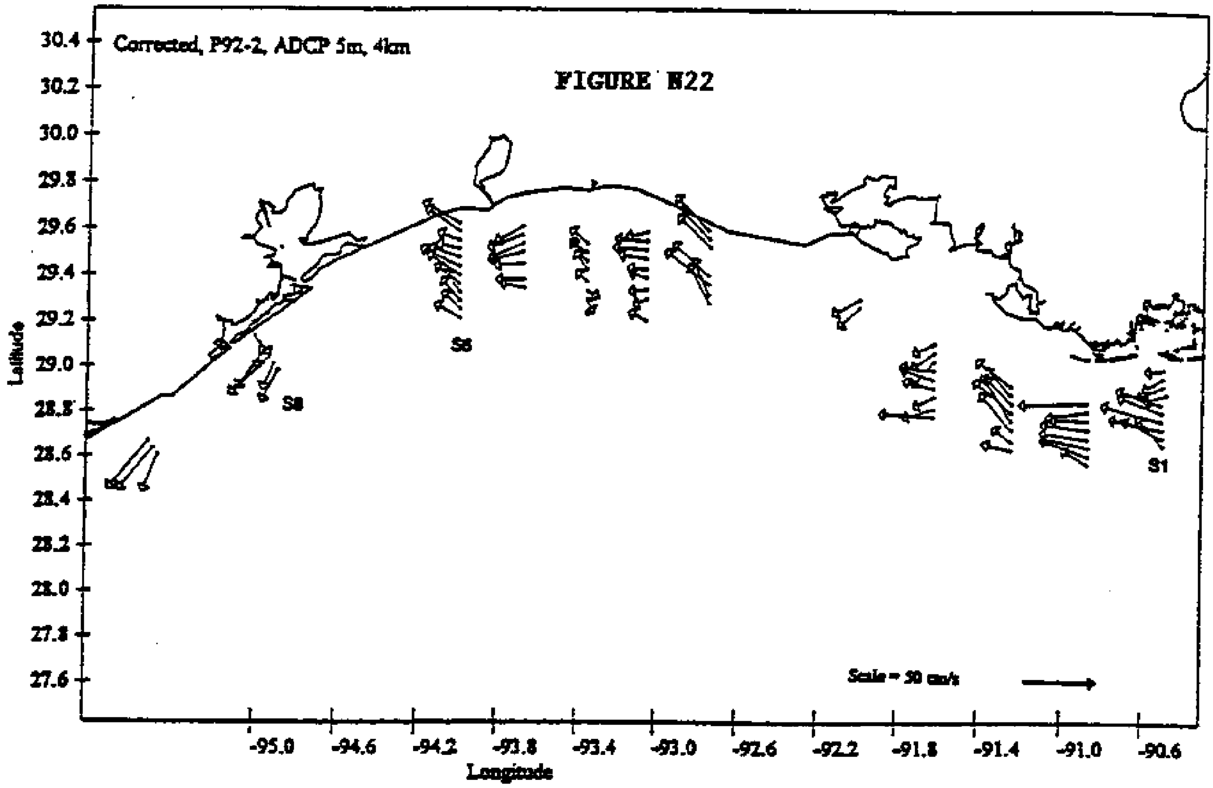


ADCP velocity vectors at the 3.5 m level in the region off western Louisiana during the April 1993 observations.

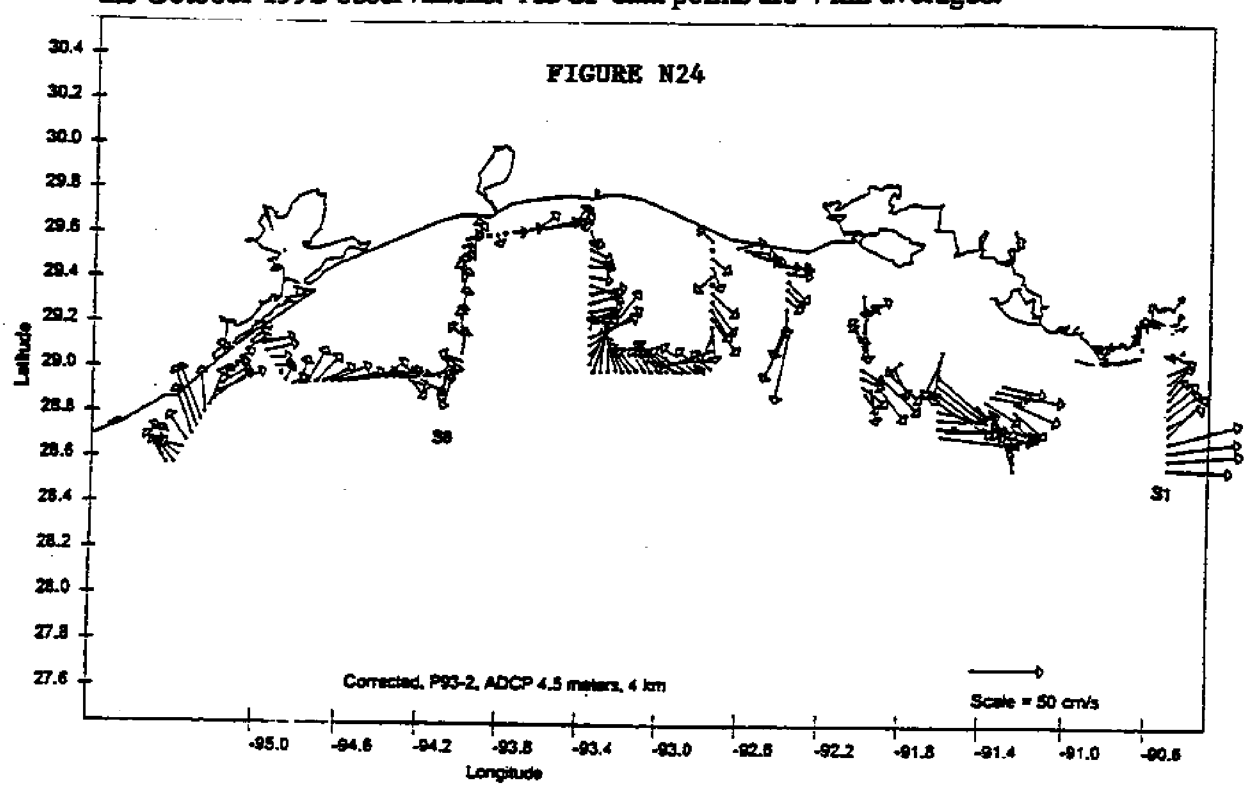
FIGURE N21



ADCP velocity vectors at the 3.5 m level in the region off south central Texas during the April 1993 observations.



ADCP velocity field at the 5 m level over the entire cruise observation domain during the October 1992 observations. ADCP data points are 4 km averages.



Velocity field at the 4.5 m level over the entire sampling domain during the July 1993 cruise observations.

(from Murray, submitted)

FIGURE N23 - July 94

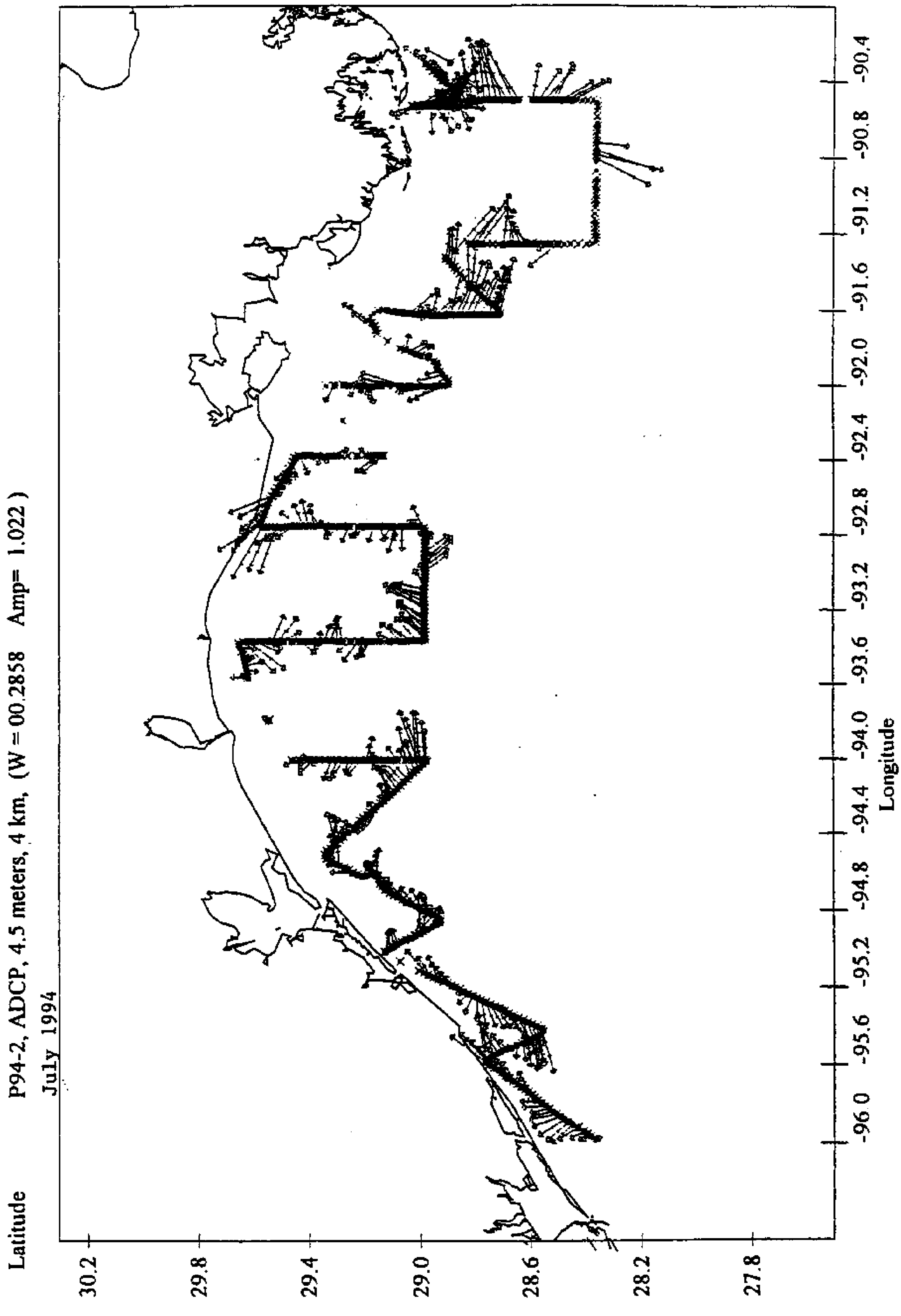
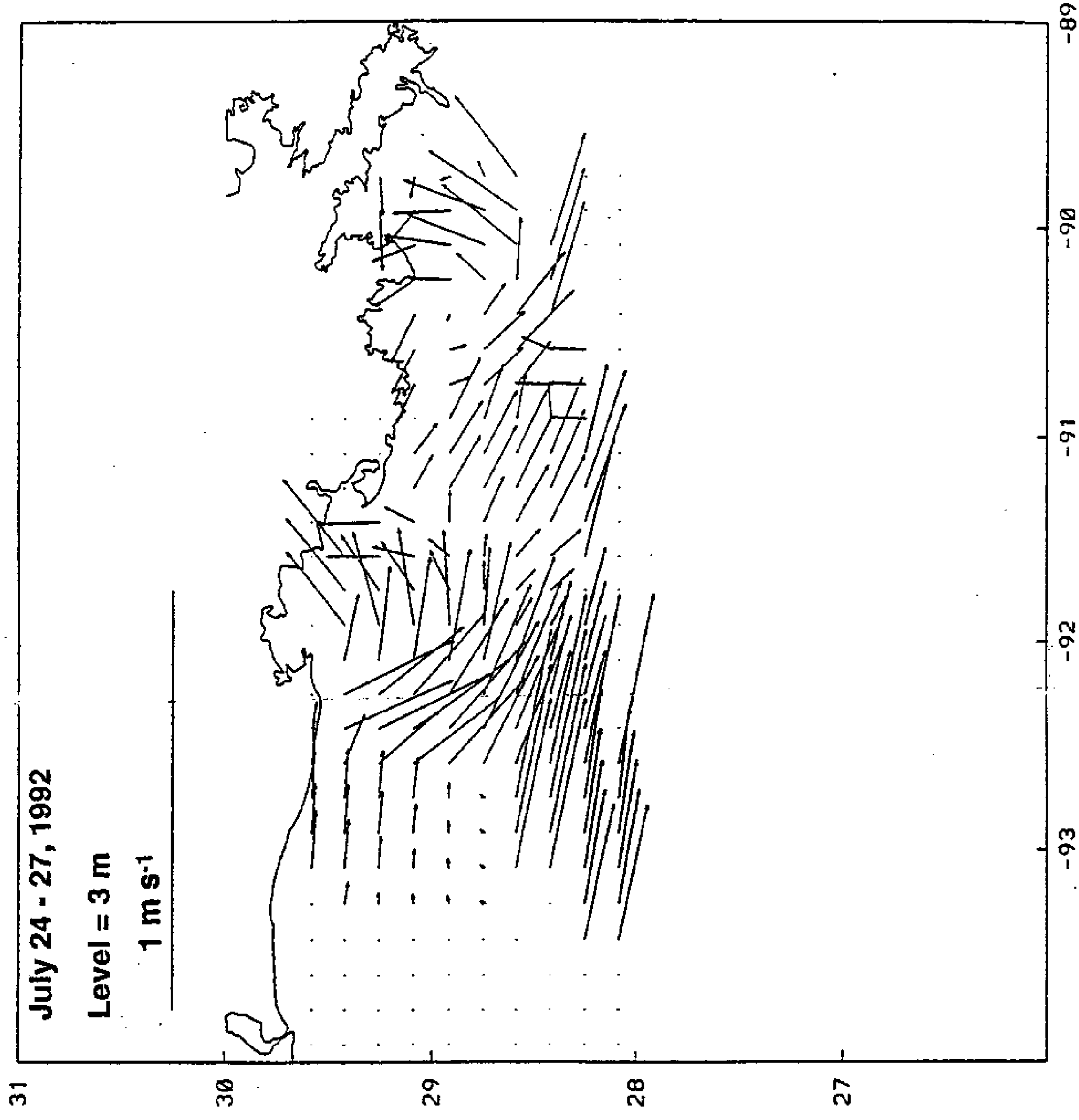


FIGURE N25 - July 92



(from Rabalais, Turner & Wiseman, unpubl. data)

FIGURE N26 - July 94

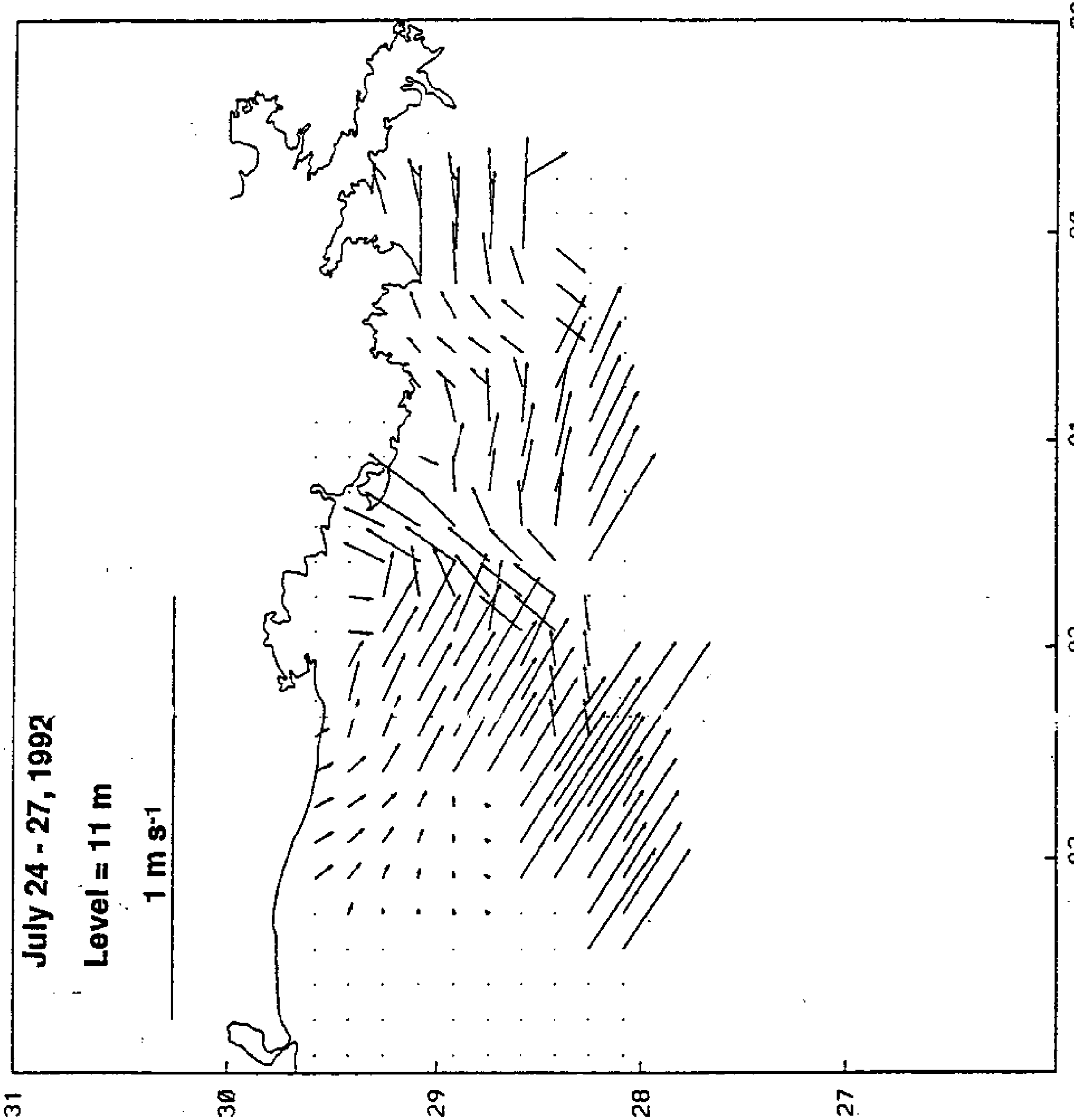
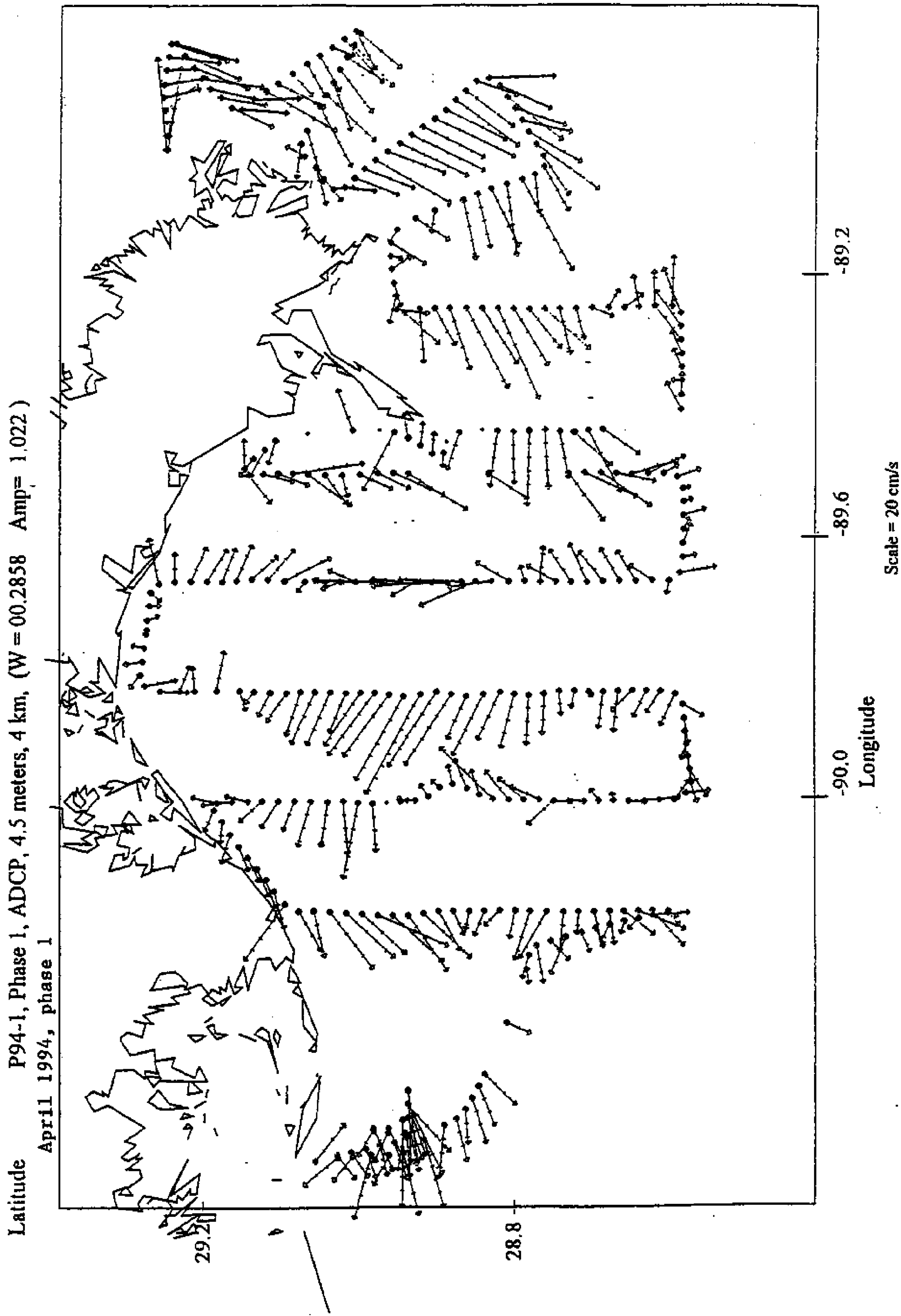
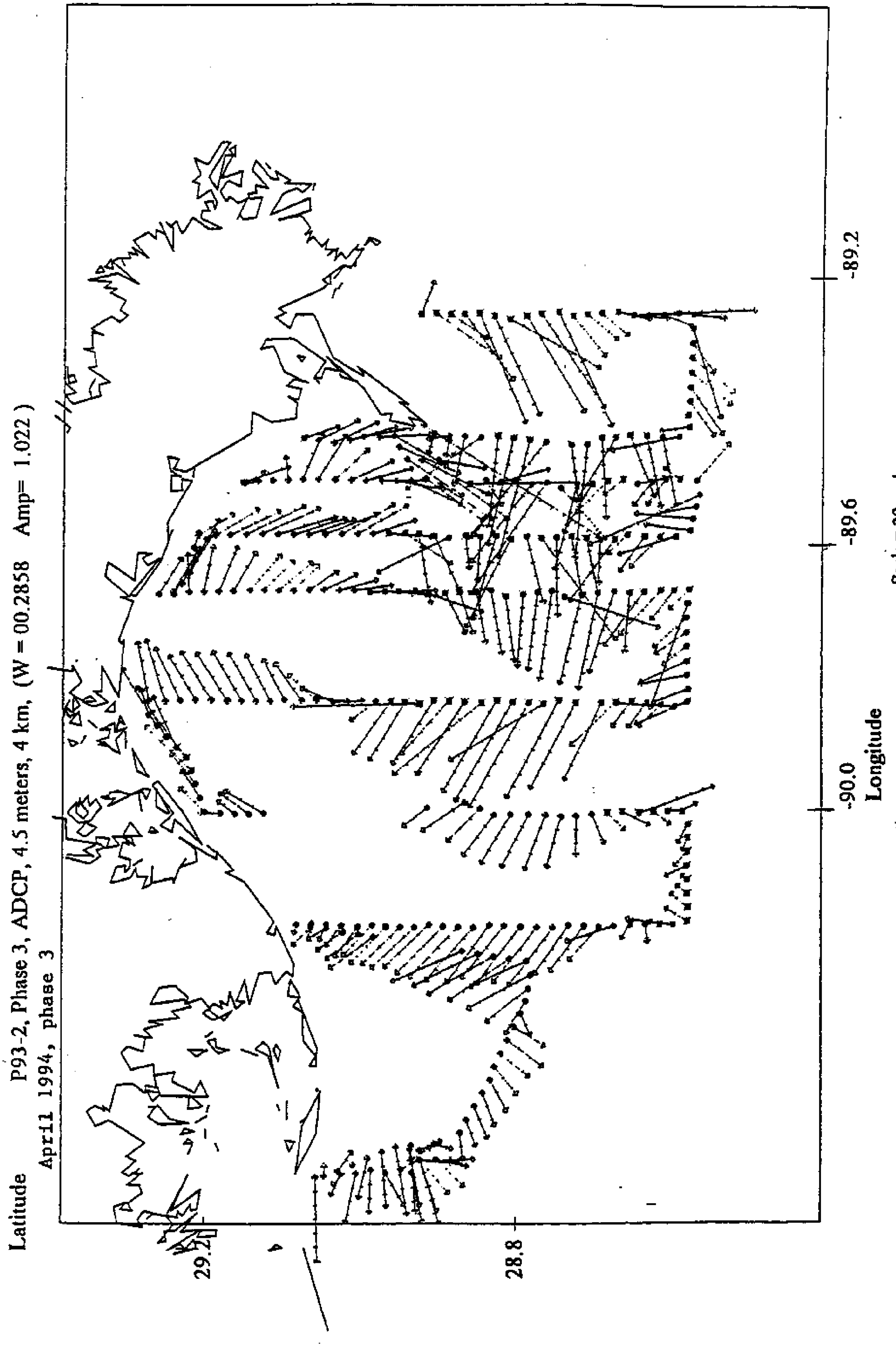


FIGURE N27



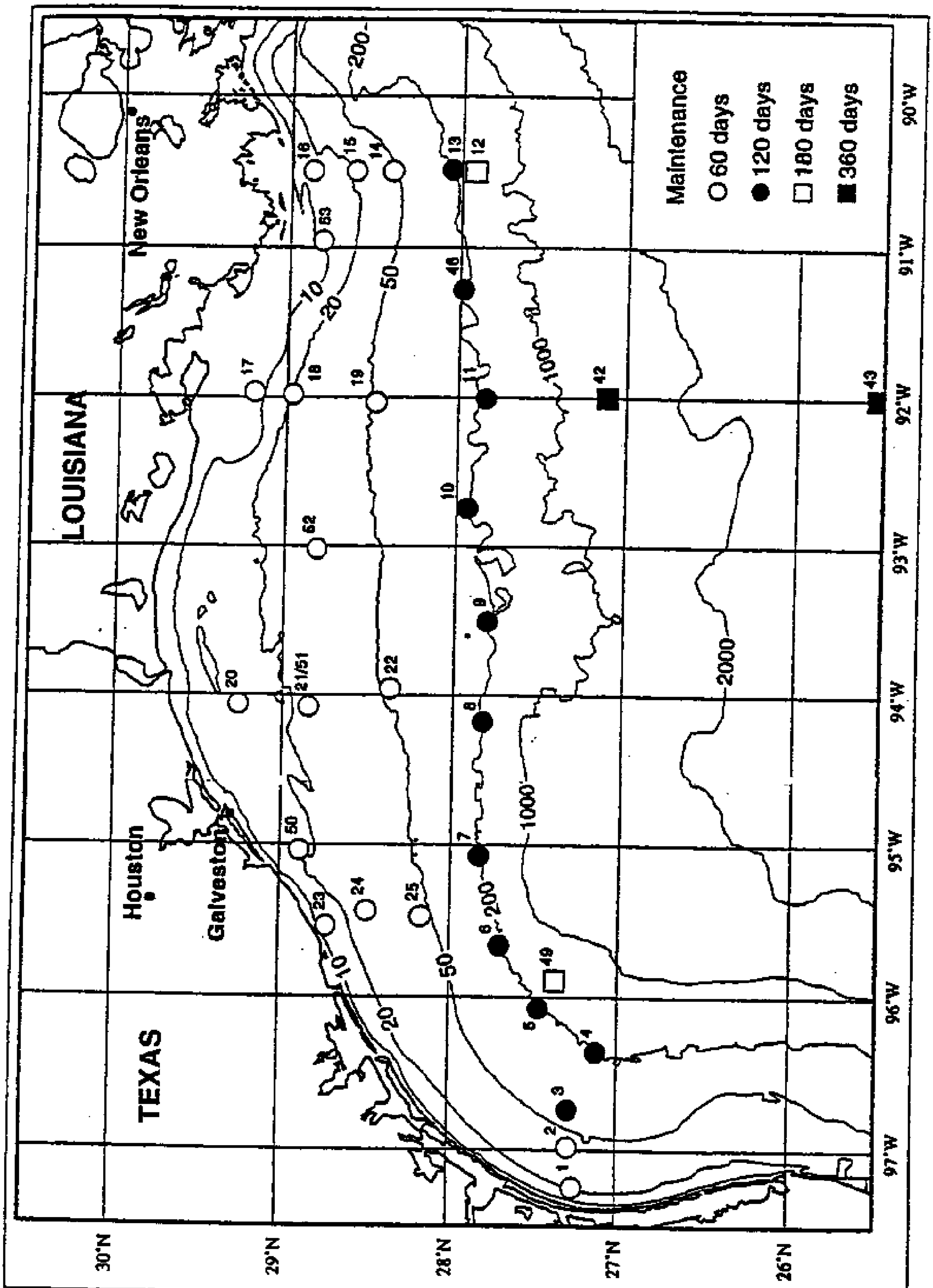
(from Rouse et al., unpubl. data)

FIGURE N28 - April 94



(from Rouse et al., unpubl. data)

FIGURE N29



Moored array locations.

(from Jochens and Nowlin, 1995)

LATEX MOORING RECORDS CURRENTS DURING THE PASSAGE OF HURRICANE ANDREW

Last August Hurricane Andrew passed over Florida causing widespread damage. This powerful storm then entered the Gulf of Mexico and curved to the north, passing through the LATEX study area. On August 25 between 2200Z and 2300Z the eye of the hurricane came within 10km of our mooring 14. The water at this mooring, located about 75 km south of Timbalier Island, is about 47 meters deep.

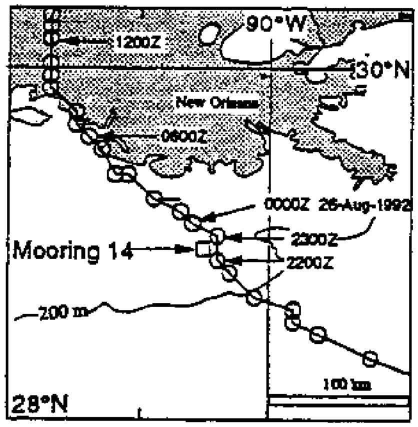
A Endeco SSM current meter attached to mooring 14 at 11 meters below the surface recorded the passage of Hurricane Andrew. Water speeds began increasing shortly after 1200z on the 25th with water flowing to the south west pushed in the general direction of the hurricane winds. Current speeds of 134 cm/sec were reached shortly after the eye of the storm passed.

After the eye had passed the currents moved toward the north at 0500Z on the 26th, toward the east at 1100Z on the 26th and moved to the west at 0230Z on the 27th.

This rotary cycle with a period of about 24 hrs. was also seen in the magnitude of the current, which exhibited a series of damped peaks separated by about 1 day. The second peak in velocity of about 92 cm/sec occurred about 24 hours after the passage of the eye and a third peak in velocity occurred about 48 hours of the passage of the storm.

As the eye approached the mooring the temperature decreased and the salinity increased most likely because of vertical mixing. The story is told in graphical form in the panels.

Track of Hurricane Andrew



Mooring 14 - Speed, Direction, Temperature, and Salinity

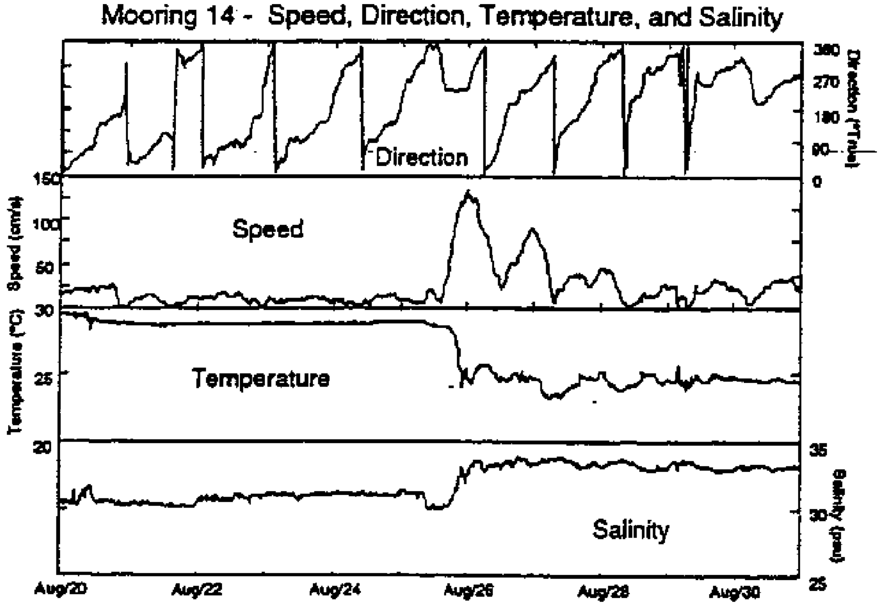
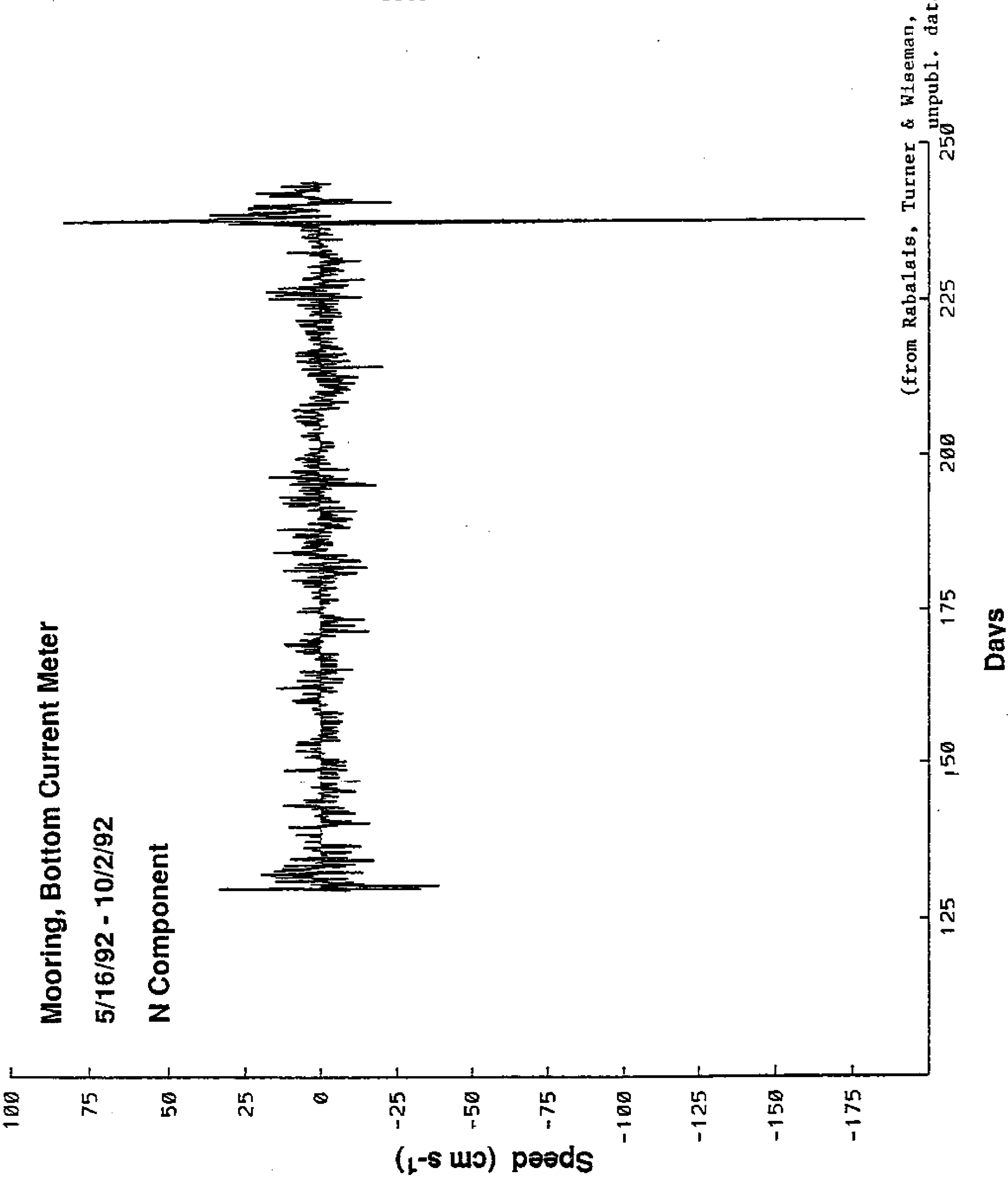


FIGURE N31



Mooring, Bottom Current Meter
5/16/92 - 10/2/92
N Component
Speed (cm s-1)
100
75
50
25
0
-25
-50
-75
-100
-125
-150
-175
Days
125
150
175
200
225
250
(from Rabalais, Turner & Wiseman, unpubl. data)

FIGURE N32 - Current Speed E Component

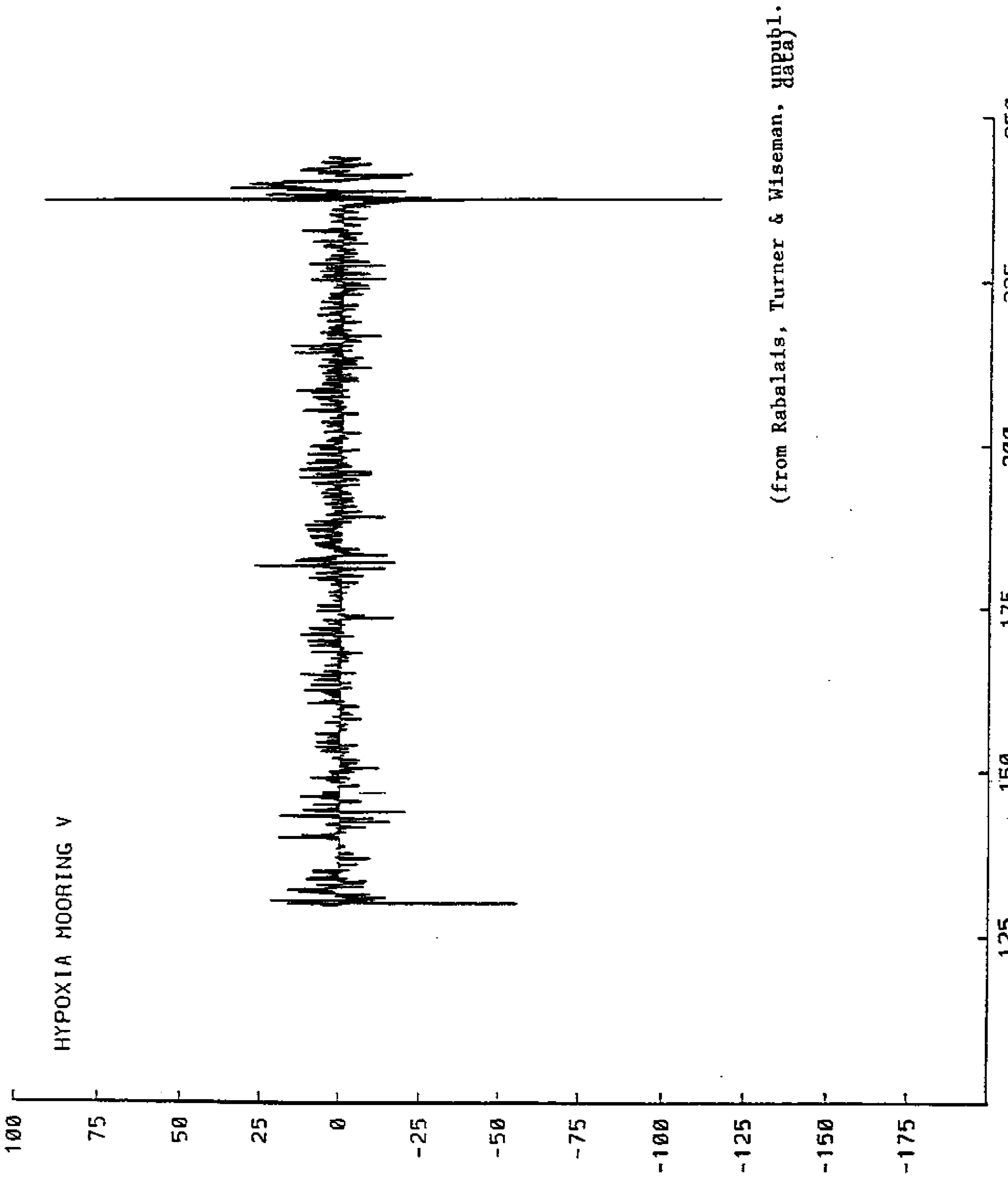
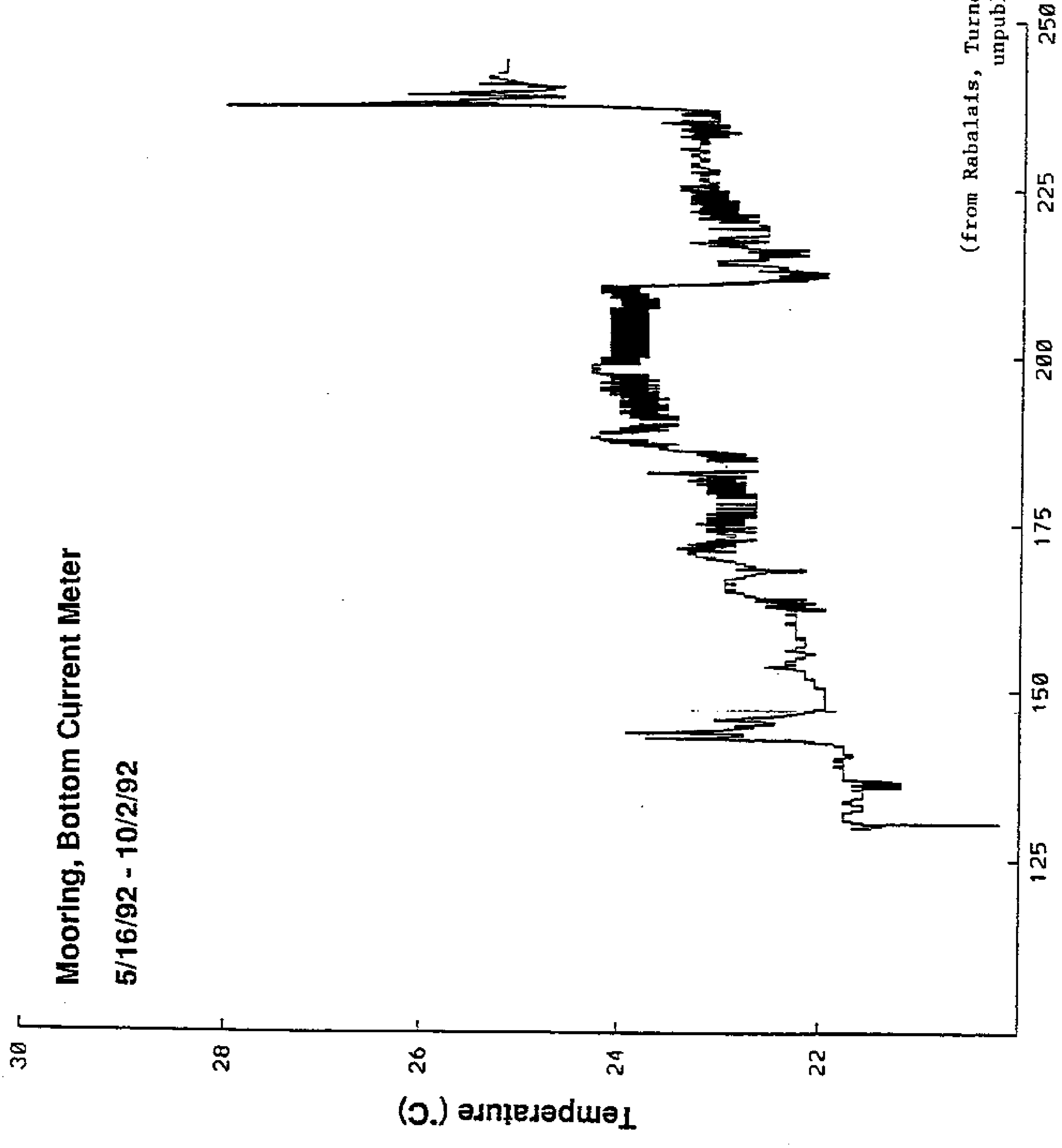
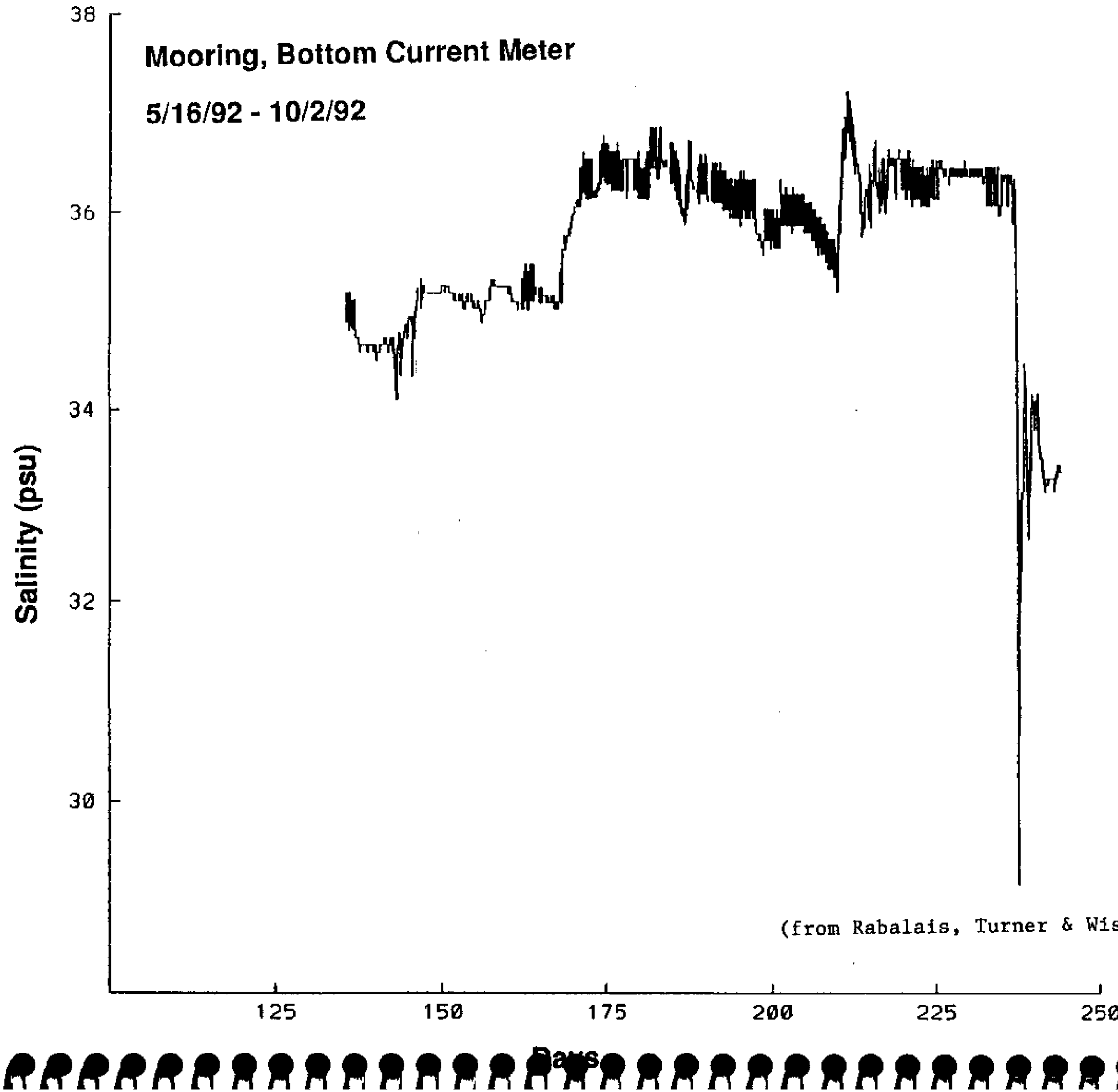


FIGURE N33



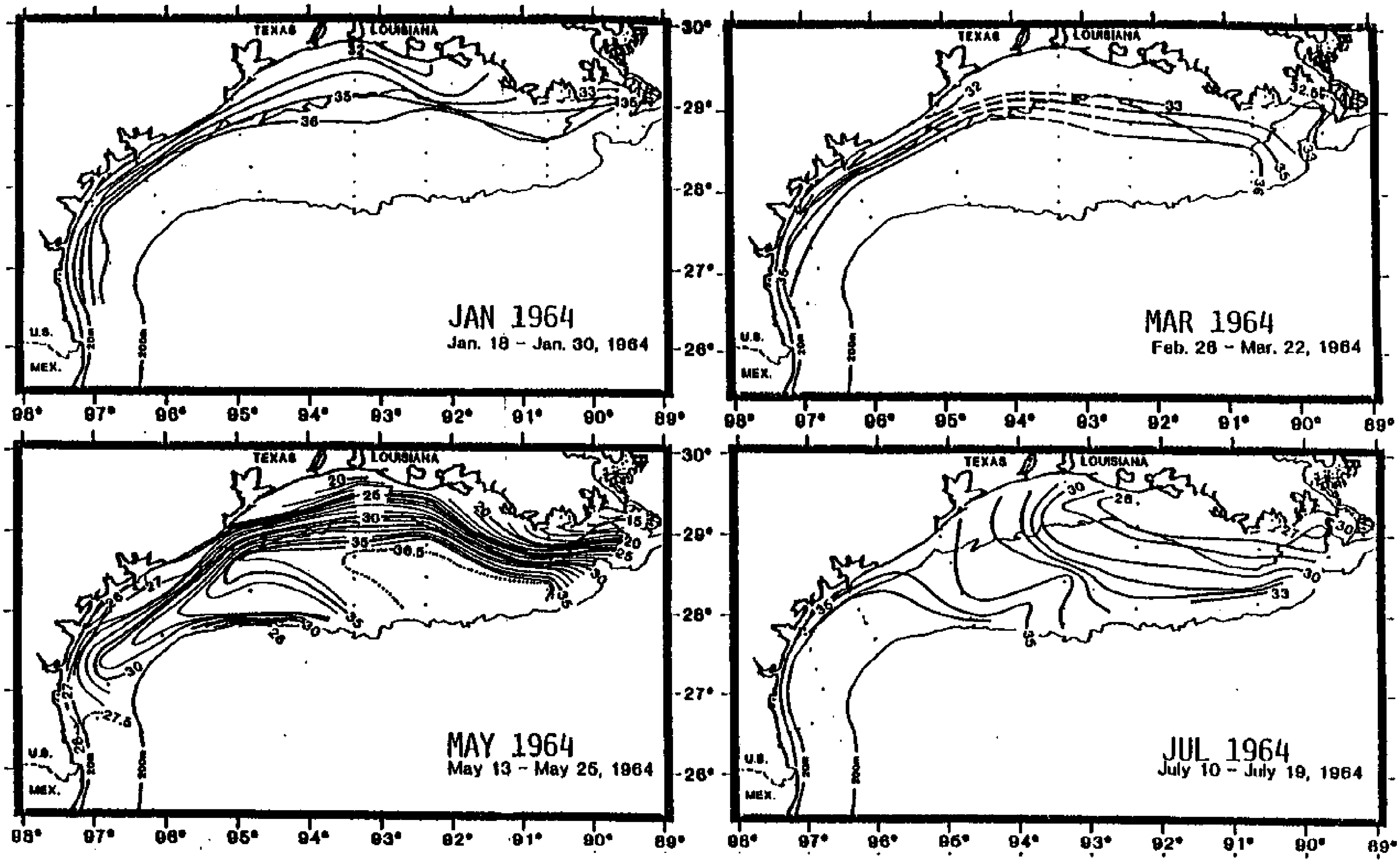
(from Rabalais, Turner & Wiseman, unpubl. data)

FIGURE N34



(from Rabalais, Turner & Wiseman, unpubl. data)

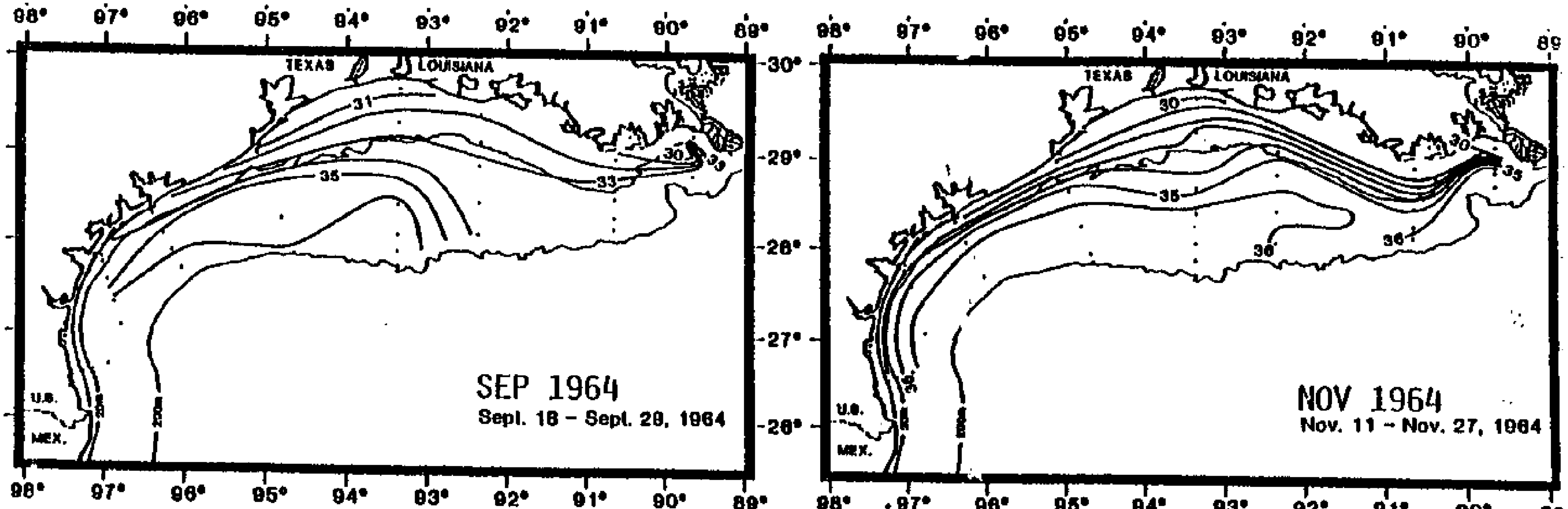
FIGURE N35



Sea-surface salinity (°/₀₀) for M/V Gus III cruises in January, March, May and July 1964 (from Kelly *et al*. 1980).

(from Kelly, 1988)

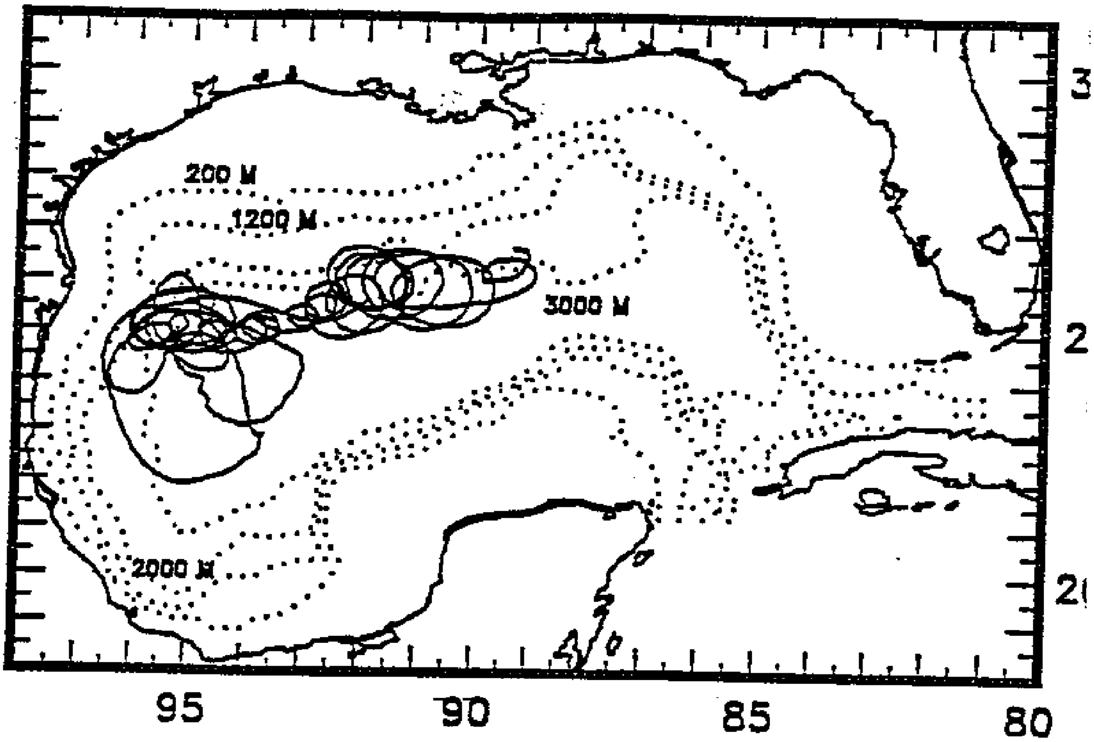
FIGURE N36



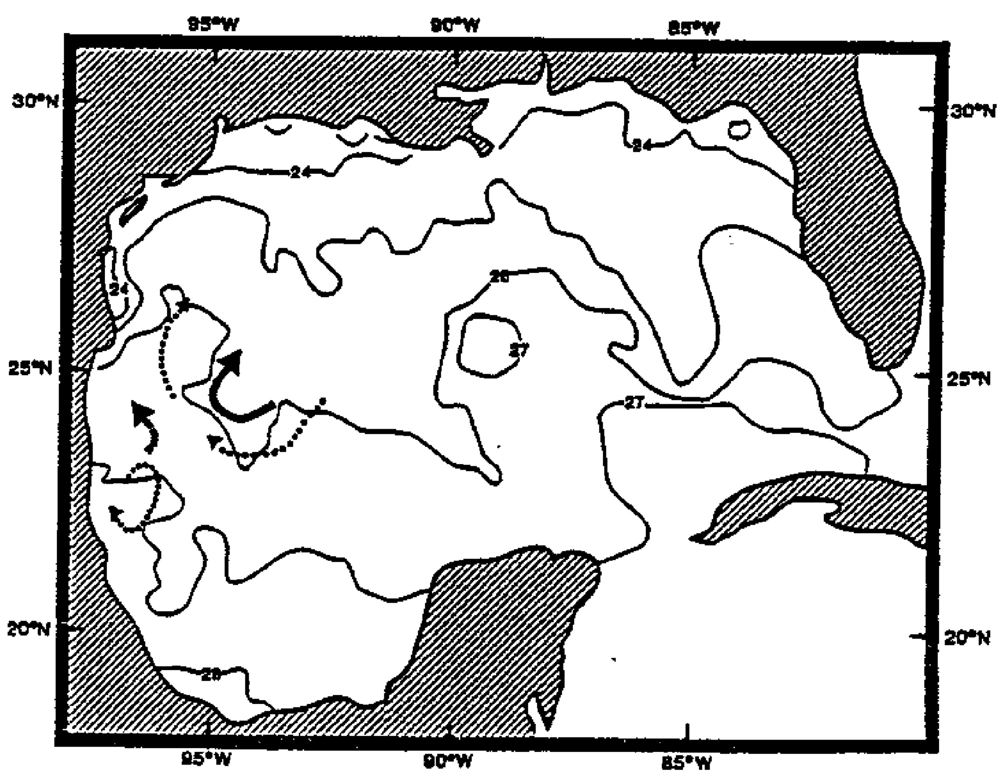
Sea-surface salinity for M/V Gus III cruises in September and November 1964.

(from Kelly, 1988)

FIGURE N37

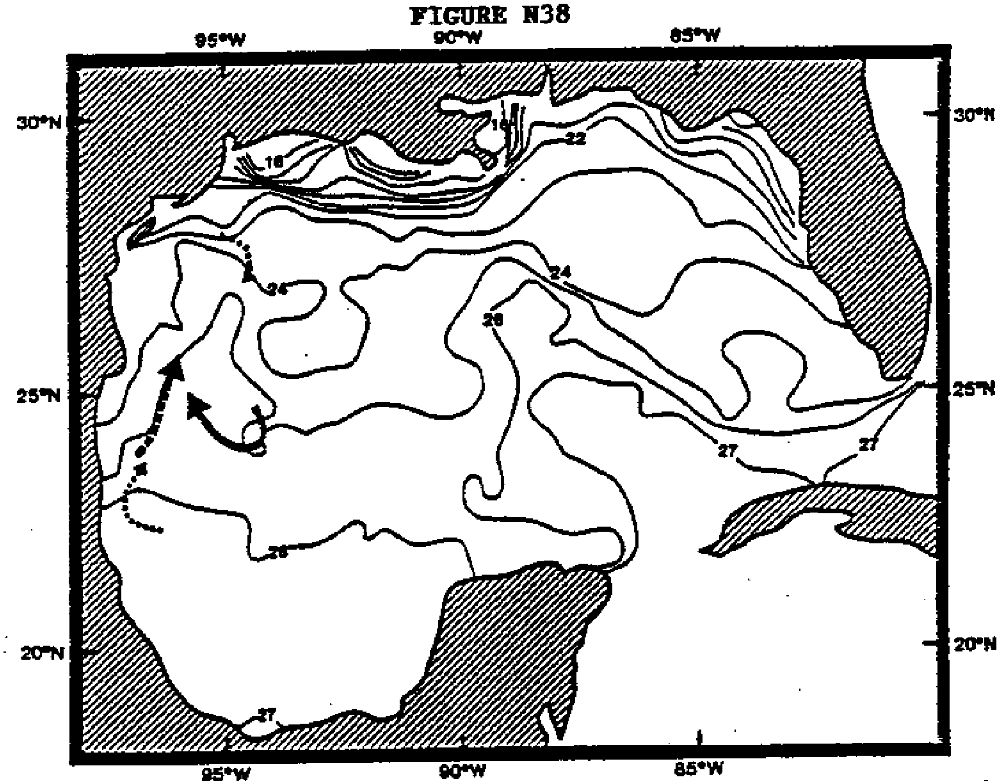


Trajectory for drifter 3378 in a Loop Current eddy. Depth co
are in meters.

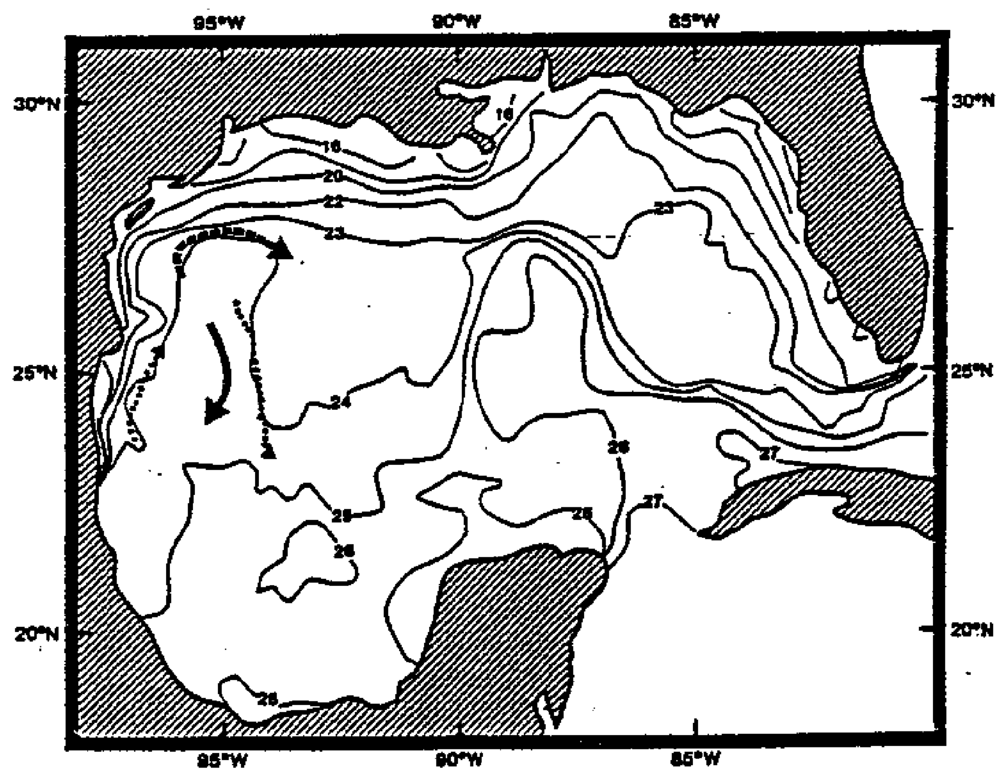


Sea surface temperature (°C) for the week of 26 November
Corresponding trajectories of drifters are shown by arrows.
(from Lewis, 1988)

FIGURE N38



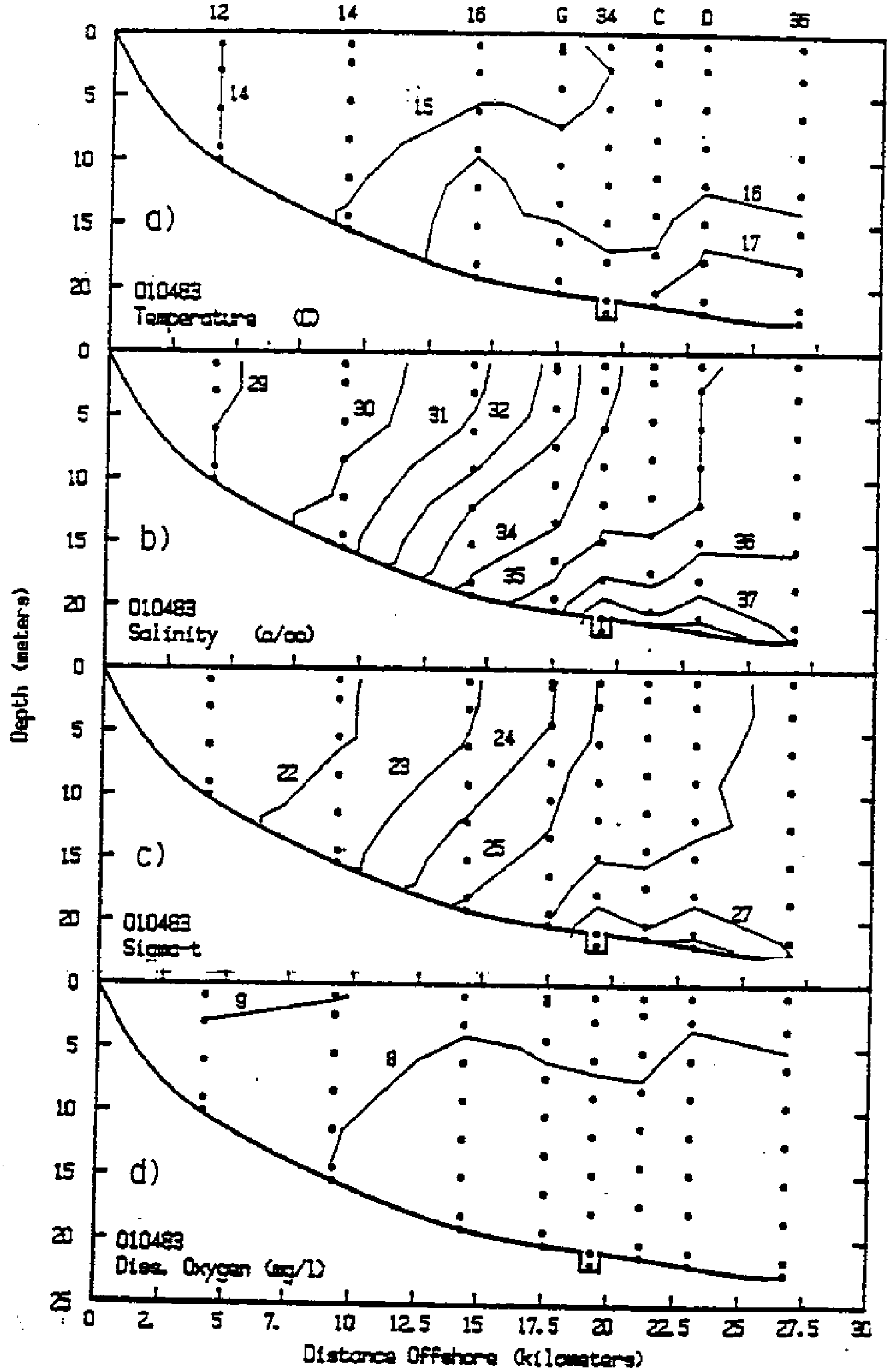
Sea surface temperature (°C) for the week of 17 December 1985. Corresponding trajectories of drifters are shown by arrows.



Sea surface temperature (°C) for the week of 28 December 1985. Corresponding trajectories of drifters are shown by arrows.
(from Lewis, 1988)

FIGURE N39

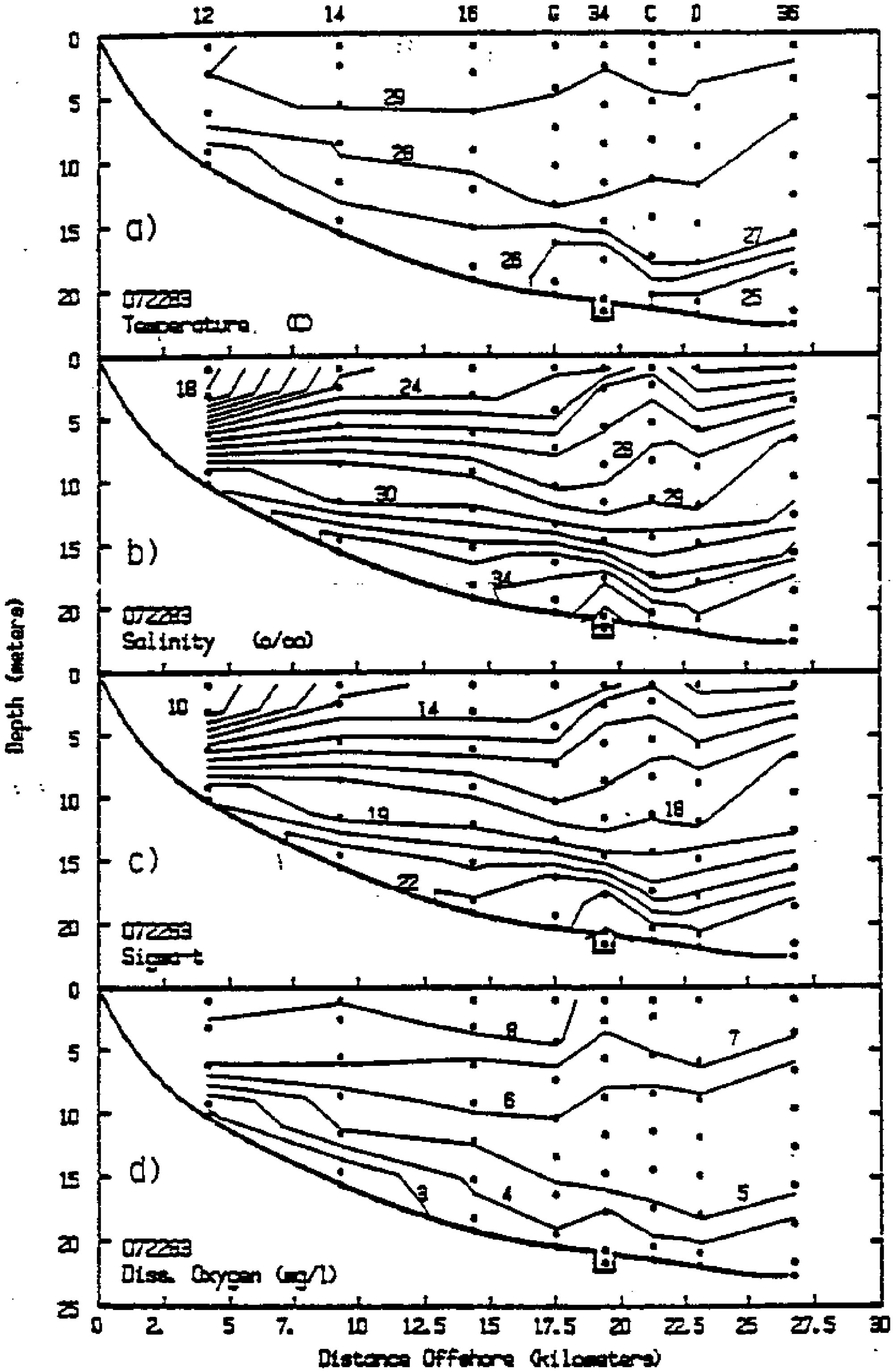
FIGURE N40



Hydrography for the cross-shelf transect offshore Freeport, Texas on January 4, 1983: a) temperature (°C), b) salinity (°/oo), c) sigma-t, dissolved oxygen (mg l^{-1}). (Note: the salinity values greater than about 36 °/oo near the bottom in the vicinity of station 34 were caused by the DOE/SPR brine disposal operations)(from Kelly et al. 1984b).

(from Kelly, 1988)

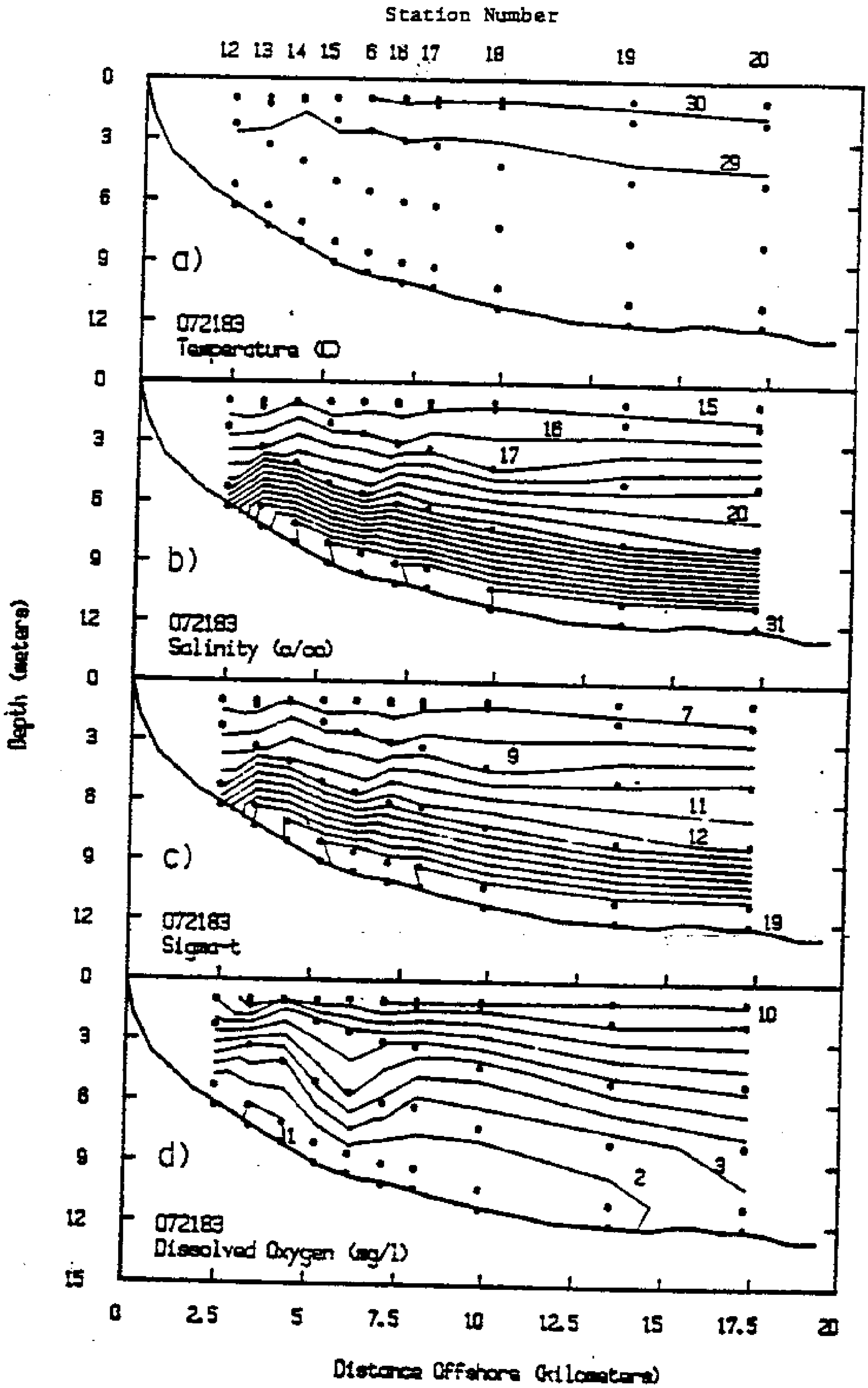
FIGURE N41



Hydrography for cross-shelf transect through the Bryan Mound site on July 22, 1983: a) temperature (°C), b) salinity (°/∞), c) sigma-t, dissolved oxygen (mg l^{-1}). (Note: the slightly higher salinity values near the bottom at station 34 were caused by the DOE/SPR brine disposal operations)(from Kelly <u>et</u> <u>al</u>. 1984b).

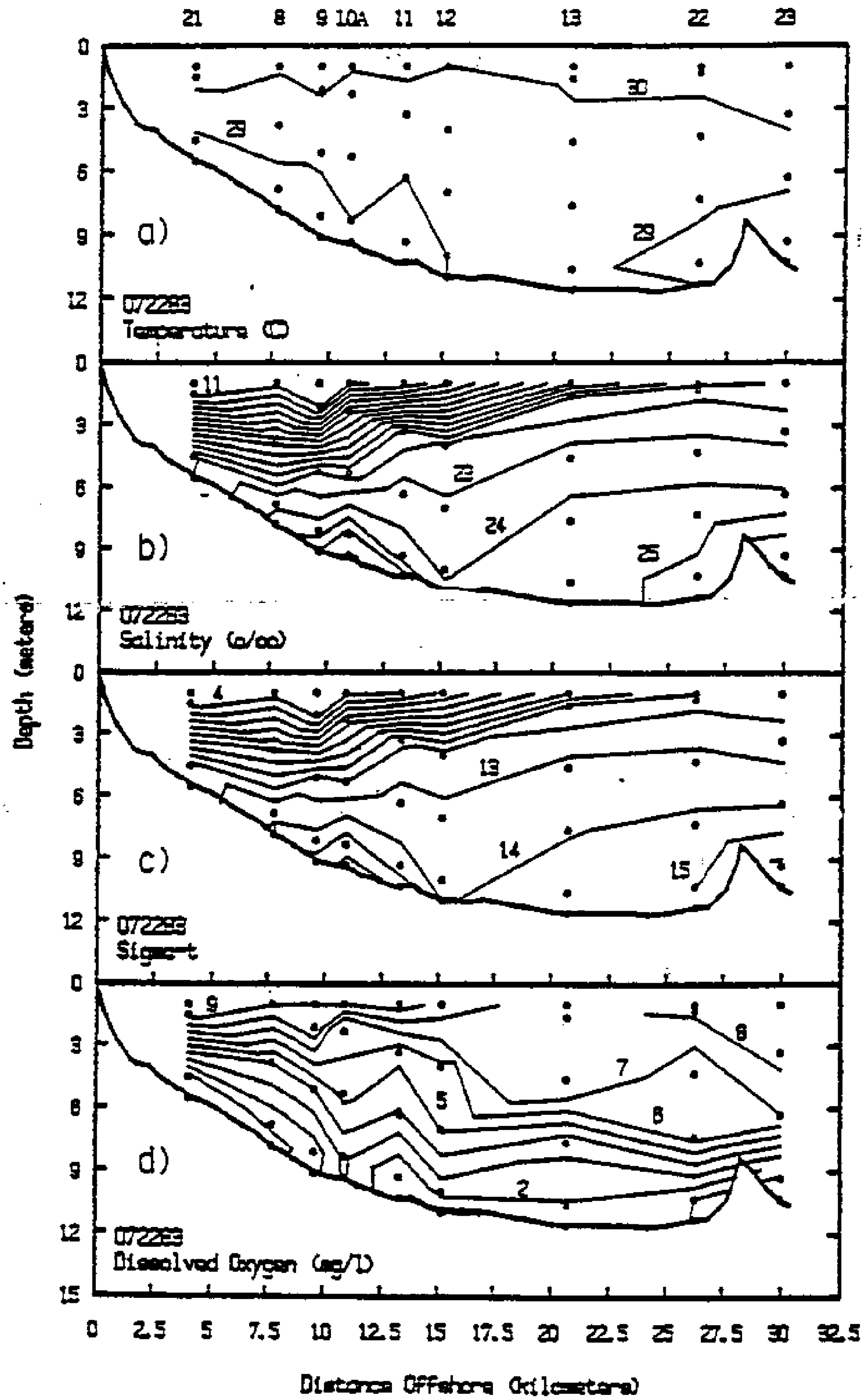
(from Kelly, 1988)

FIGURE N42



Hydrography for cross-shelf transect through the Big Hill site on July 21, 1983: a) temperature (°C), b) salinity (°/oo), c) sigma-t, dissolved oxygen (mg l^{-1})(from Kelly <u>et</u> <u>al</u>. 1984a).
(from Kelly, 1988)

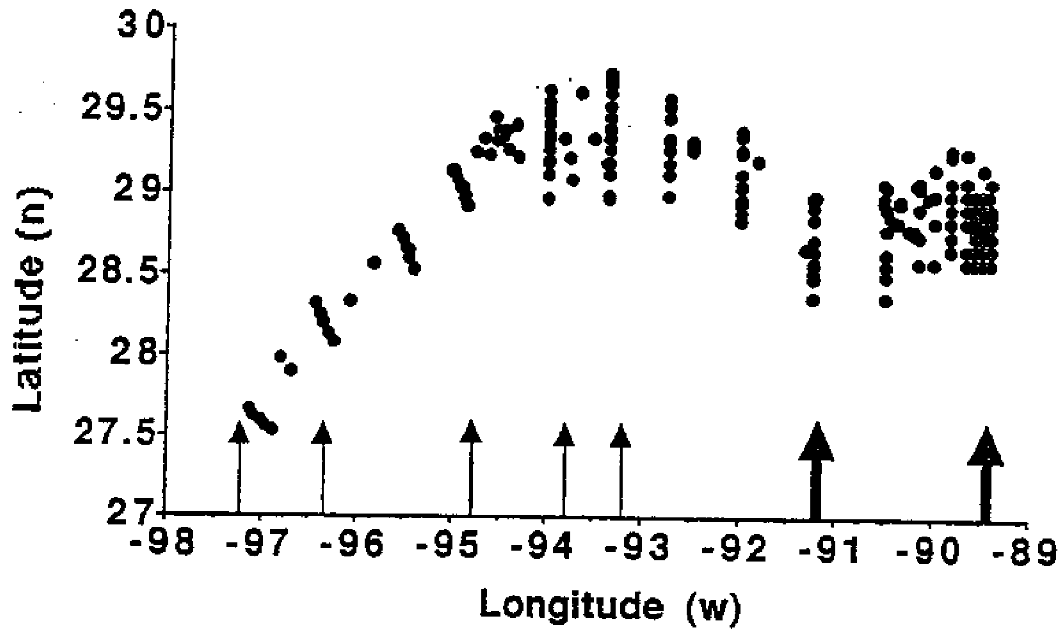
FIGURE N43



Hydrography for cross-shelf transect through the West Hackberry si on July 22, 1983: a) temperature (°C), b) salinity (°/oo), c) sigm t, dissolved oxygen (mg l^{-1}). (Note: the slightly higher salini values near the bottom at station A were caused by the DOE/SPR bri disposal operations)(from Kelly *et al*. 1984c).

(from Kelly, 1988)

FIGURE N44



LATEX stations sampled for nutrients and phytoplankton pigments. The arrows indicate the source and relative contribution of freshwater inputs.

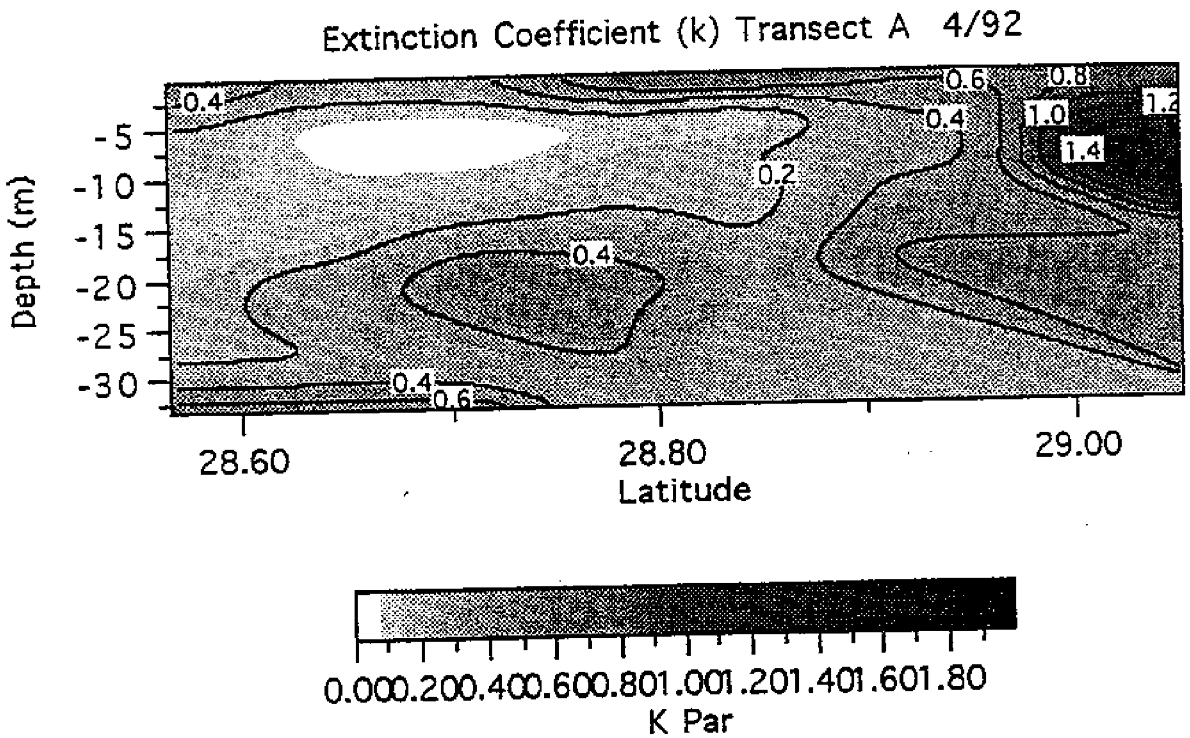
TABLE TN6

Average surface water values for chlorophyll *a*, salinity, Secchi depth, and selected nutrient parameters for six LATEX cruises (X ± se, *n*).

Cruise	Date	Chl *a* (μg/L)	Salinity (psu)	Secchi (m)	Nitrate (μg at/L)	DIN (μg at/L)	Silicate (μg at/L)	Si:N ratio	Phosphate (μg at/L)
P921	Apr 92*	9.09 ±1.62 *33*	27.67 ±0.79 *28*	1.69 ±0.44 *11*	6.18 ±1.14 *33*	8.68 ±1.28 *33*	3.08 ±0.40 *33*	0.33 ±0.06 *33*	0.33 ±0.07 *33*
P922	Oct 92	4.32 ±0.55 *42*	29.30 ±0.48 *42*	2.28 ±0.30 *24*	1.08 ±0.23 *42*	2.91 ±0.42 *42*	6.89 ±0.52 *42*	3.98 ±0.43 *42*	0.40 ±0.04 *42*
P931	Apr 93	5.65 ±0.85 *50*	27.27 ±0.70 *49*	5.12 ±0.92 *20*	2.54 ±1.09 *48*	3.88 ±1.22 *48*	10.04 ±2.15 *48*	3.69 ±0.50 *48*	0.20 ±0.02 *48*
P932	Jul 93	4.21 ±0.58 *66*	25.68 ±0.75 *66*	4.96 ±0.69 *17*	3.17 ±1.57 *66*	5.68 ±1.62 *66*	14.14 ±2.33 *66*	3.63 ±0.47 *66*	0.32 ±0.04 *66*
P941	Apr 94	7.98 ±1.29 *78*	18.13 ±1.21 *78*	2.92 ±0.78 *26*	32.08 ±2.83 *78*	36.38 ±2.97 *78*	30.38 ±2.36 *78*	1.05 ±0.13 *78*	0.71 ±0.06 *78*
P942	Jul 94	3.12 ±0.59 *61*	27.67 ±0.72 *61*	4.16 ±0.90 *20*	1.29 ±0.52 *39*	4.88 ±0.85 *38*	12.58 ±1.71 *54*	2.61 ±0.30 *37*	0.62 ±0.11 *52*

* station with high value of 209 μg/L Chl *a* omitted.

FIGURE N45


Extinction Coefficient (k) Transect A 4/92
Depth (m)
-5
-10
-15
-20
-25
-30
0.4
0.6
0.8
1.2
1.0
1.4
0.2
28.60
28.80
29.00
Latitude
0.000.200.400.600.801.001.201.401.601.80
K Par

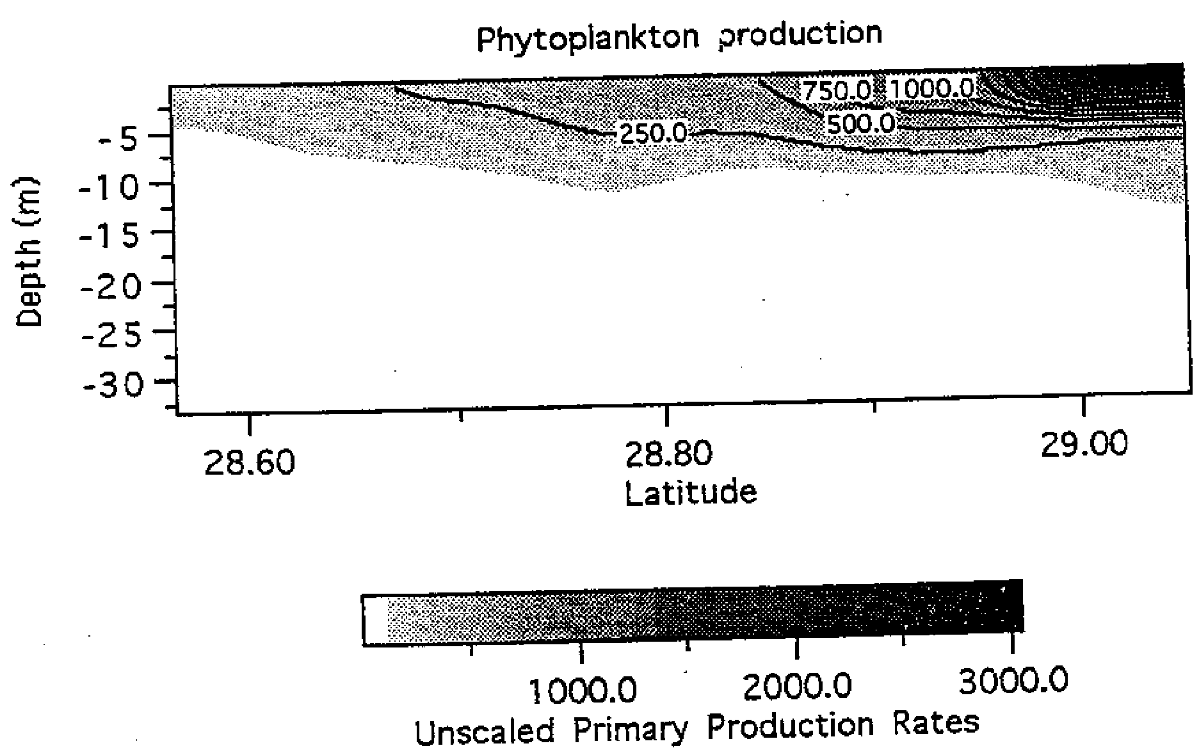
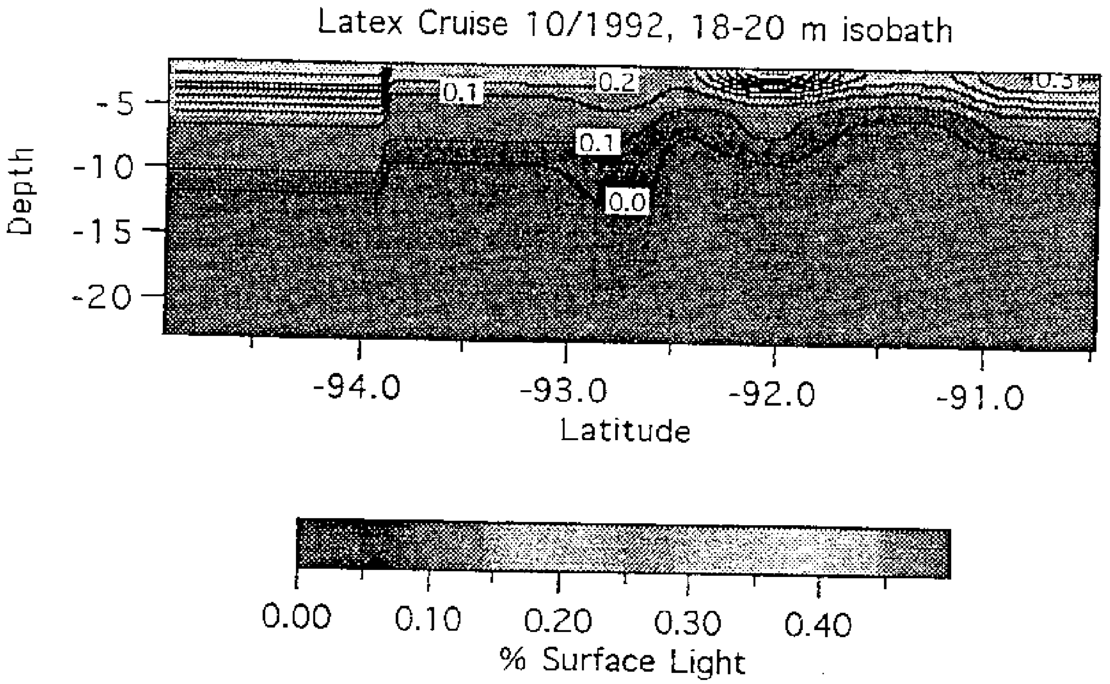
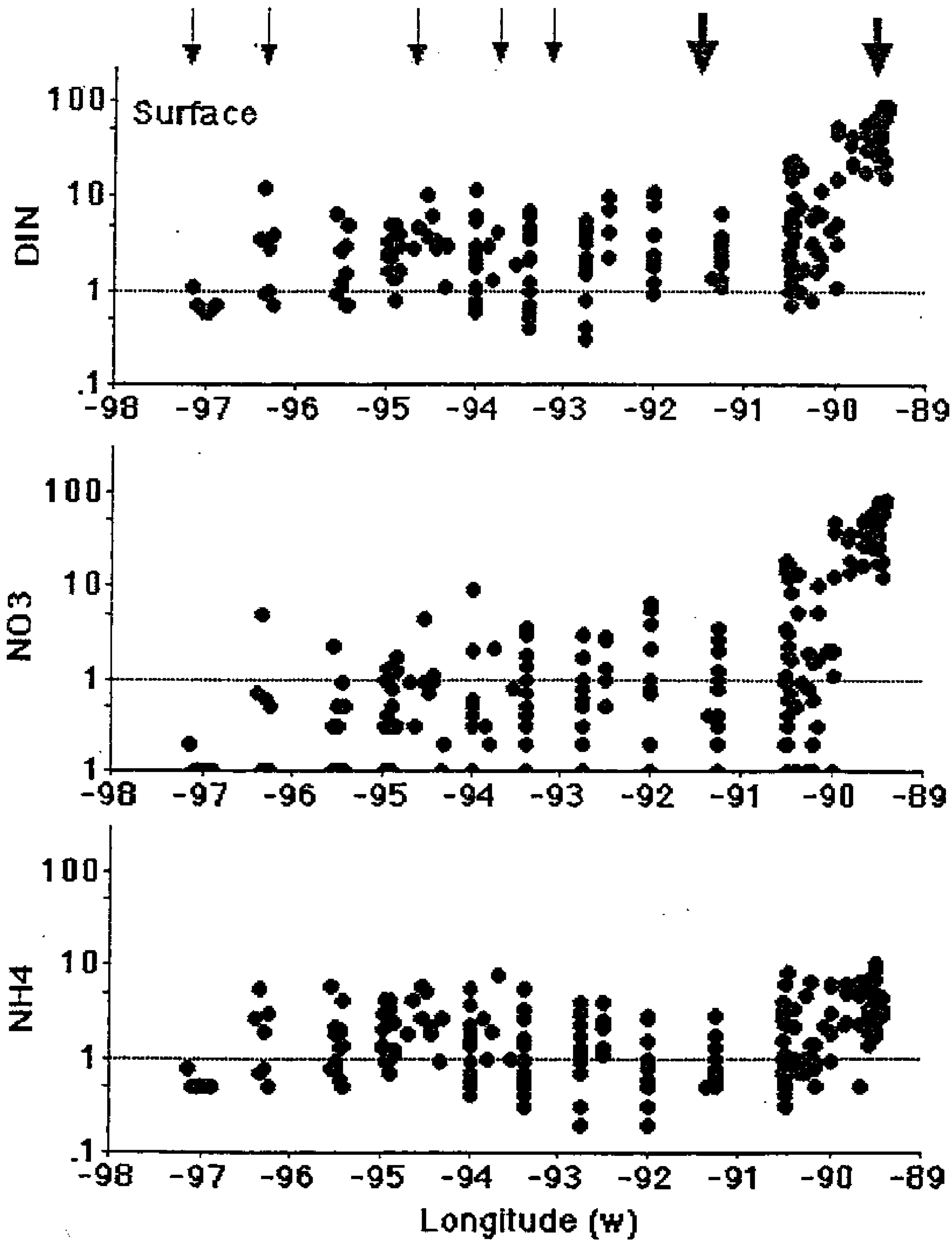

Phytoplankton production
Depth (m)
-5
-10
-15
-20
-25
-30
750.0
1000.0
500.0
250.0
28.60
28.80
29.00
Latitude
1000.0
2000.0
3000.0
Unscaled Primary Production Rates

FIGURE N46



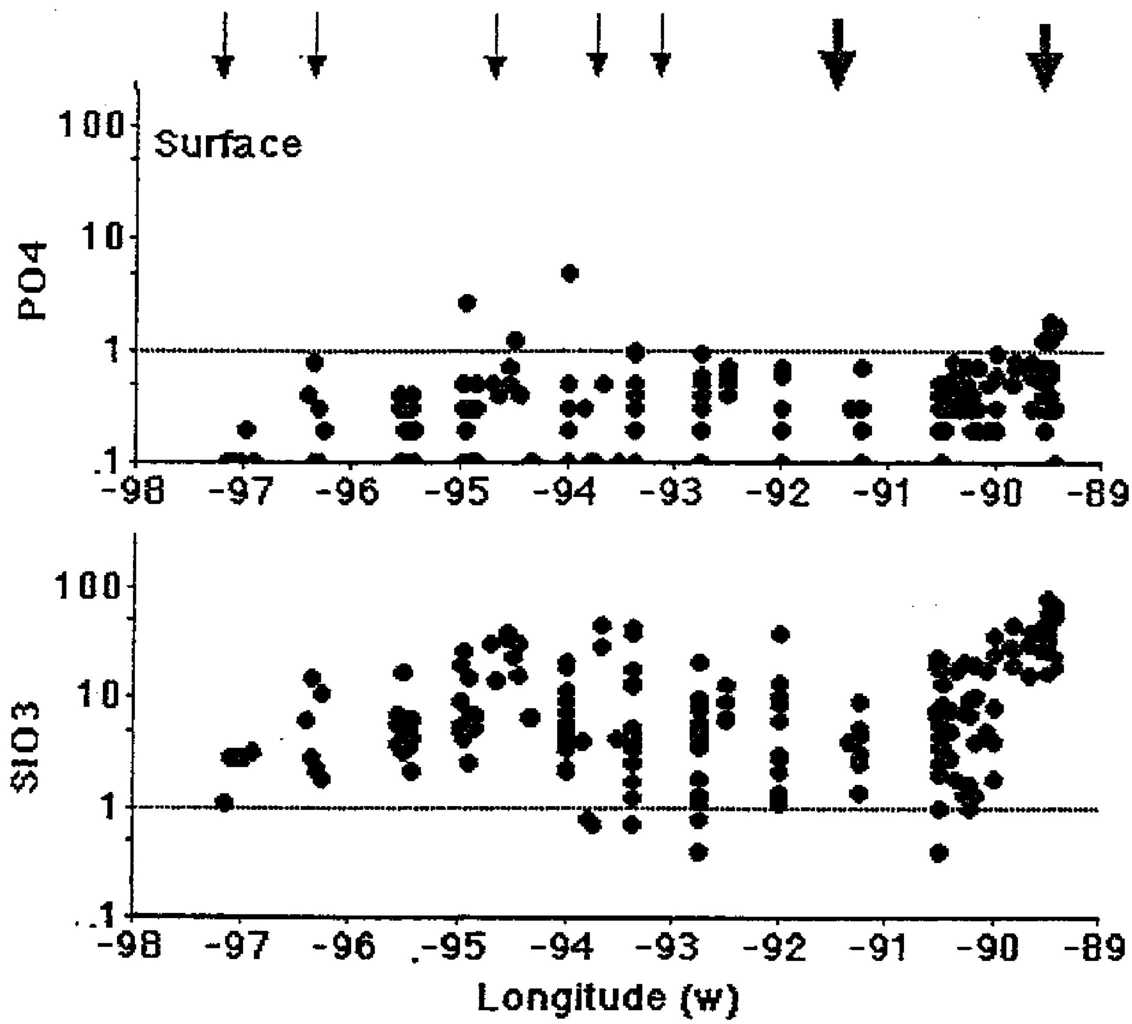
Latex Cruise 10/1992, 18-20 m isobath
0.1
0.2
0.3
0.1
0.0
Depth
-5
-10
-15
-20
-94.0
-93.0
-92.0
-91.0
Latitude
0.00
0.10
0.20
0.30
0.40
% Surface Light

FIGURE N47



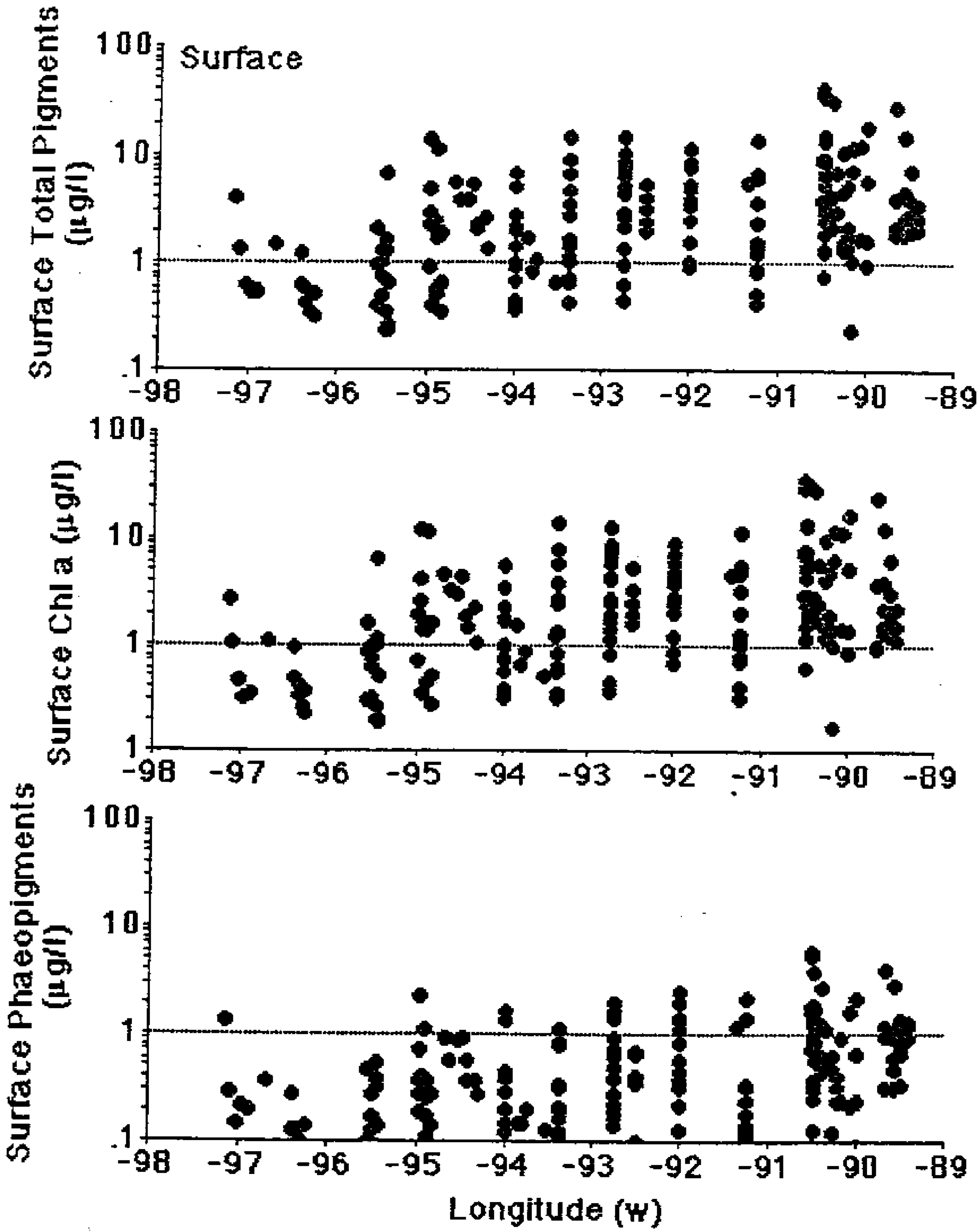
Concentration of dissolved nitrogen (DIN = $NO_3 + NO_2 + NH_4$; μg at l^{-1}) in surface waters at the LATEX sampling locations shown in Figure 1. Total depth at these stations is between 10 and 100 m. The arrows indicate the source and relative contribution of freshwater inputs.

FIGURE N48



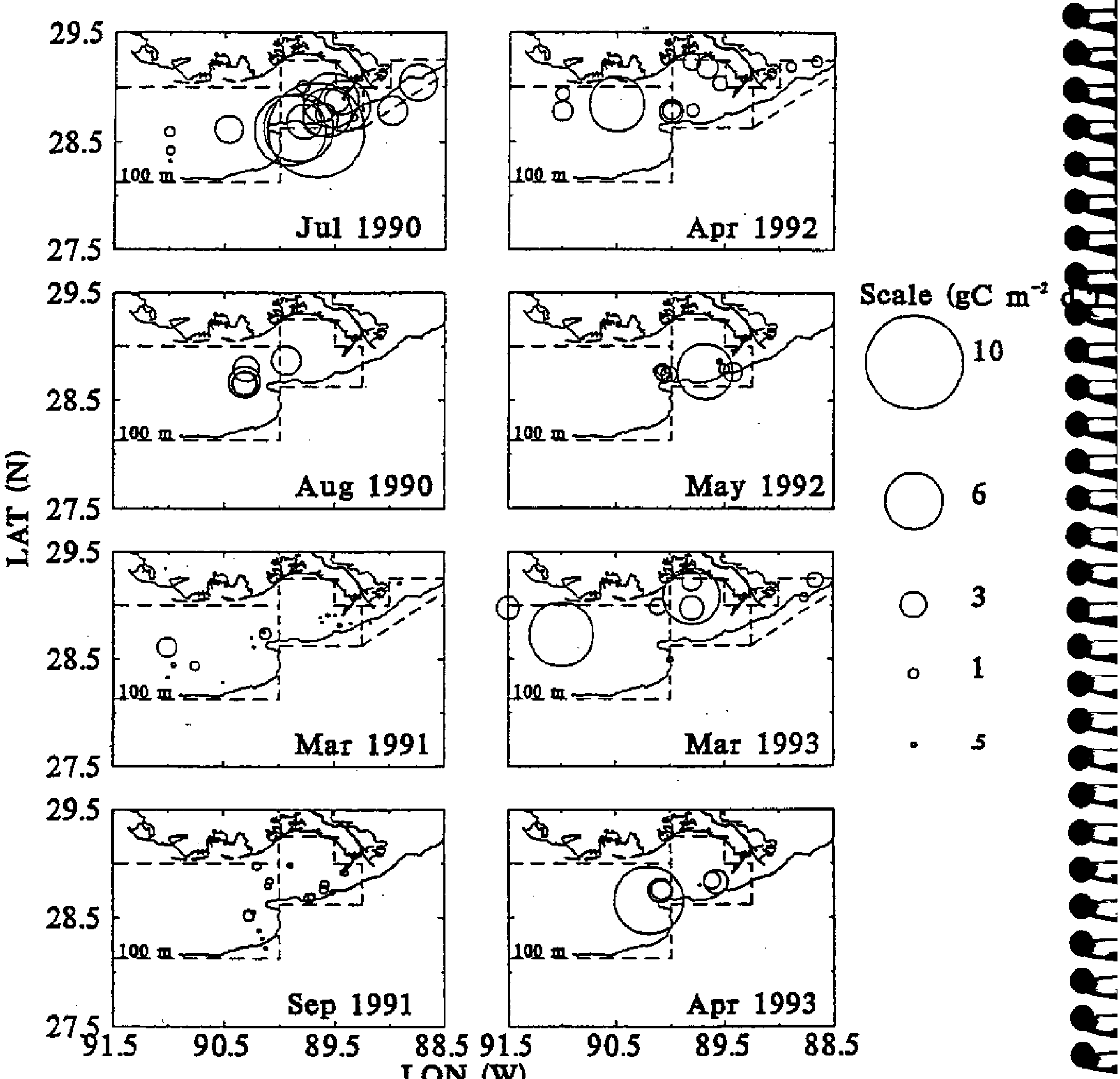
Concentration of dissolved phosphate and silicate (μg at l^{-1}) in surface waters at the LATEX sampling stations shown in Figure 1. Total depth at these stations is between 10 and 100 m. The arrows indicate the source and relative contribution of freshwater inputs.

FIGURE N49



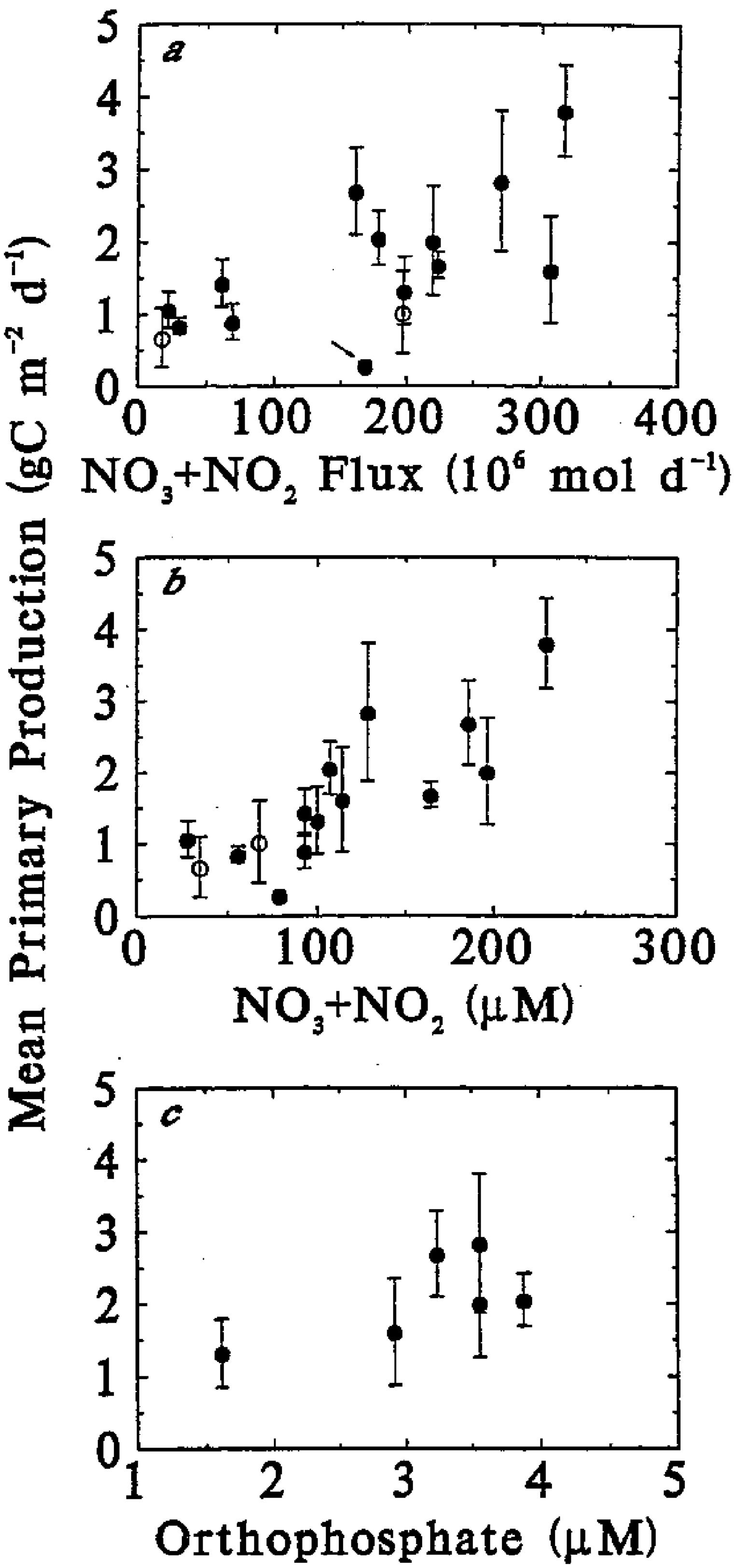
Relationship between the concentration of phytoplankton pigments (total, chlorophyll *a* and phaeopigments; $\mu g\ l^{-1}$) and longitude in surface waters at the LATEX sampling locations shown in Figure 1. Total depth at these stations is between 10 and 100 m.

FIGURE N50



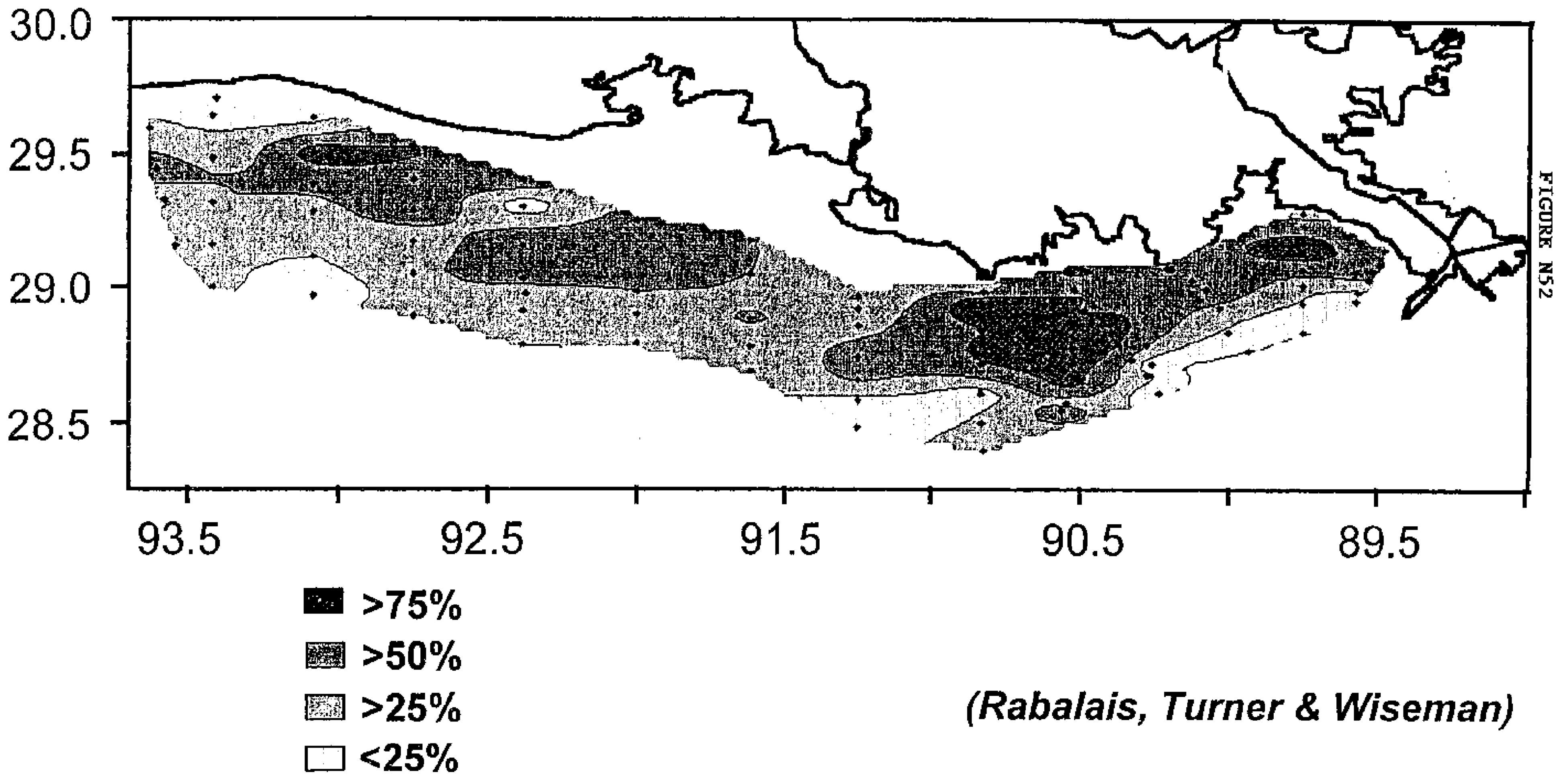
29.5
28.5
27.5
LAT (N)
100 m
Jul 1990
Apr 1992
Aug 1990
May 1992
Mar 1991
Mar 1993
Sep 1991
Apr 1993
91.5
90.5
89.5
88.5
LON (W)
Scale (gC m⁻² d⁻¹)
10
6
3
1
.5

FIGURE N51



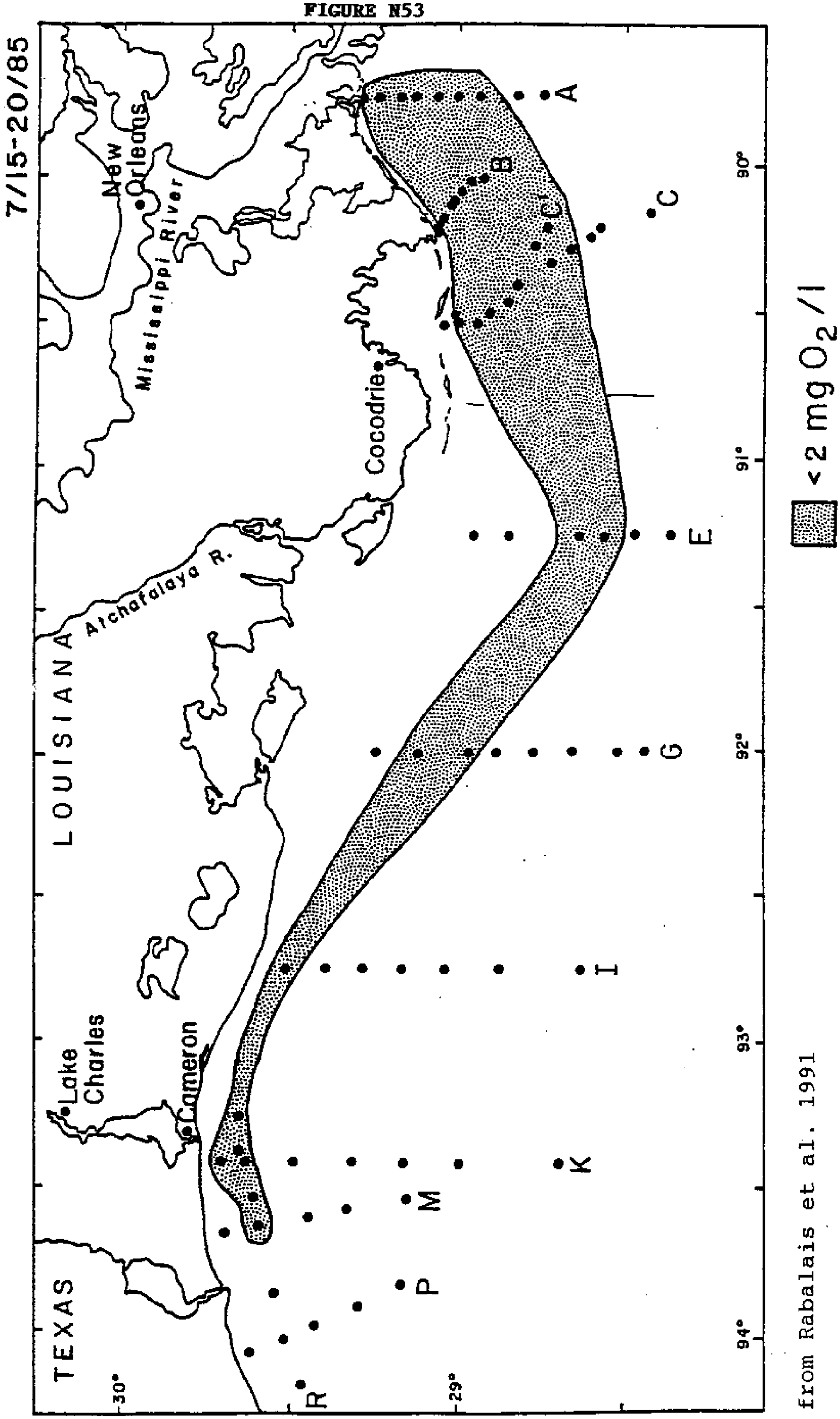
Mean Primary Production (gC m-2 d-1)
a
NO3+NO2 Flux (10^6 mol d-1)
b
NO3+NO2 (μM)
c
Orthophosphate (μM)

Mid-Summer Hypoxia Frequency of Occurrence 1985 - 1997



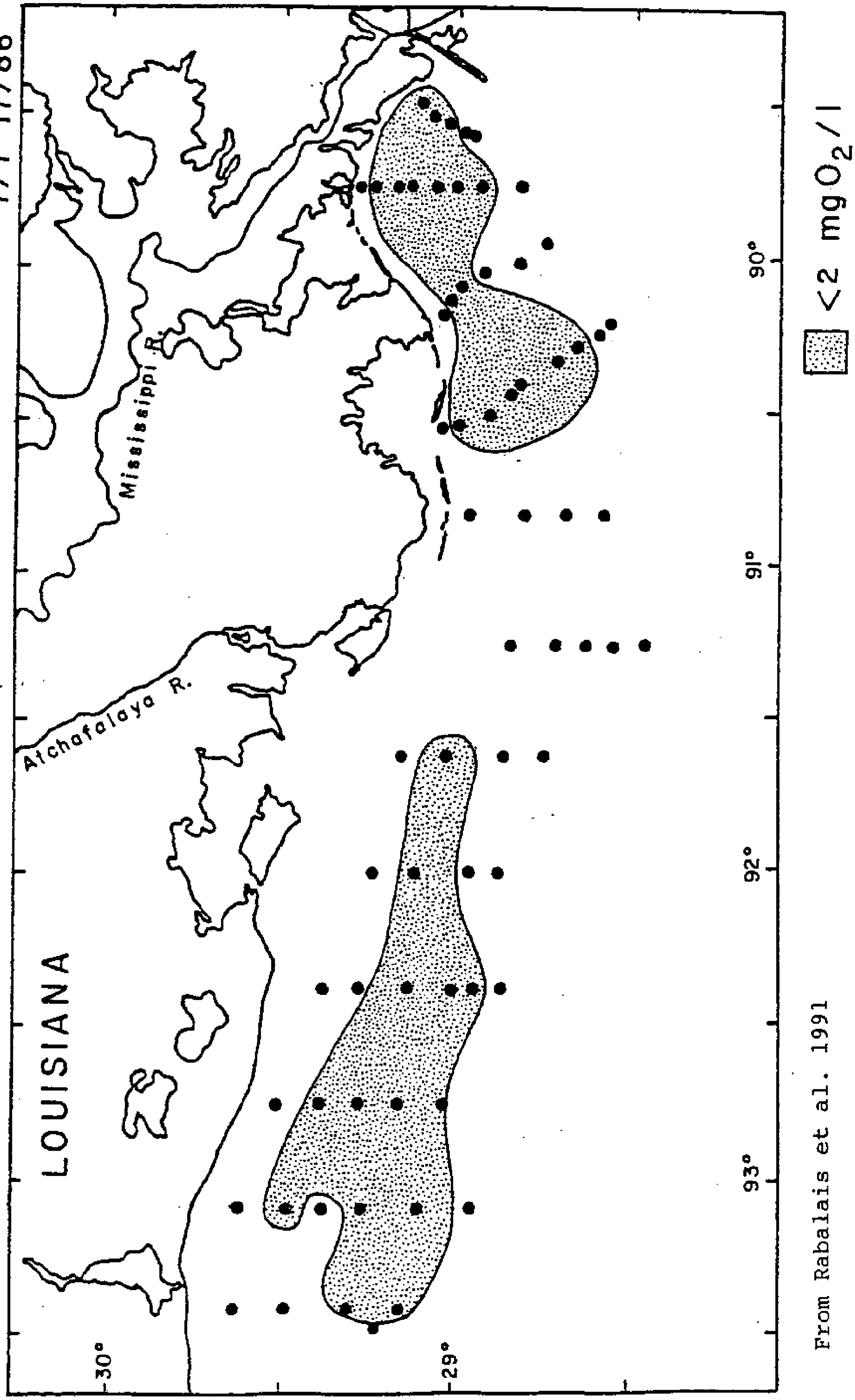
(Rabalais, Turner & Wiseman)

FIGURE N53



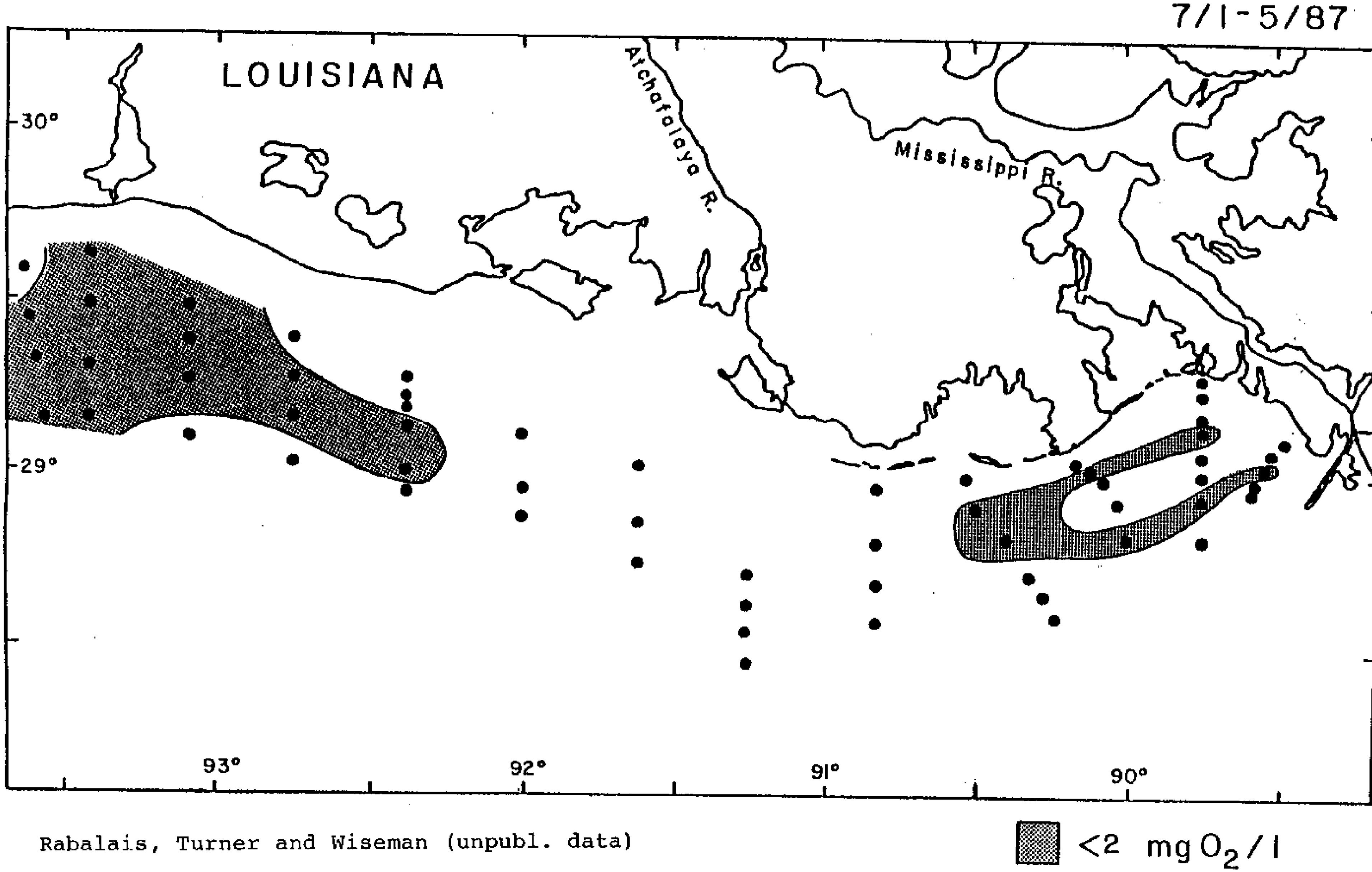
from Rabalais et al. 1991

FIGURE N54

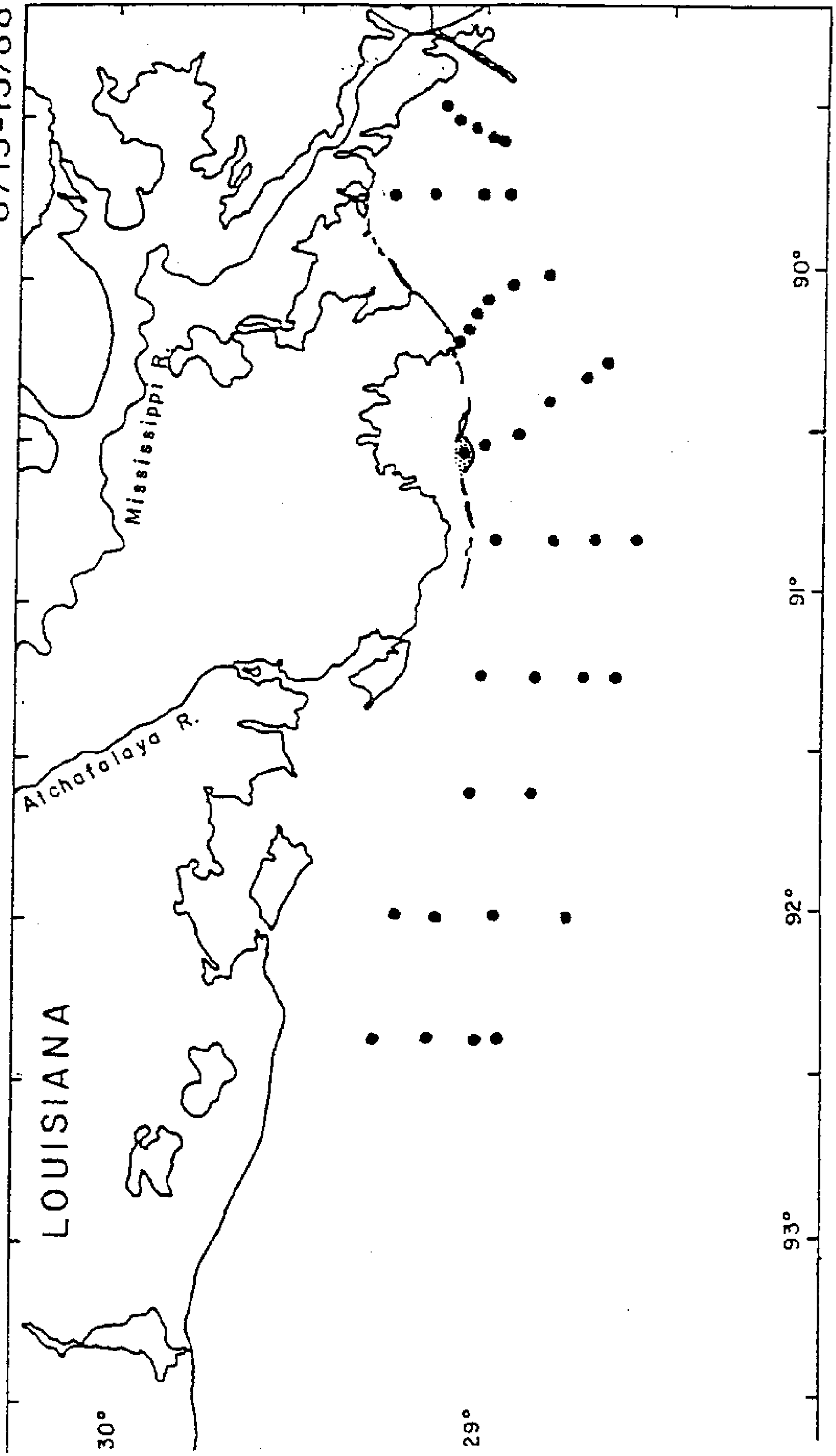


From Rabalais et al. 1991

FIGURE N55

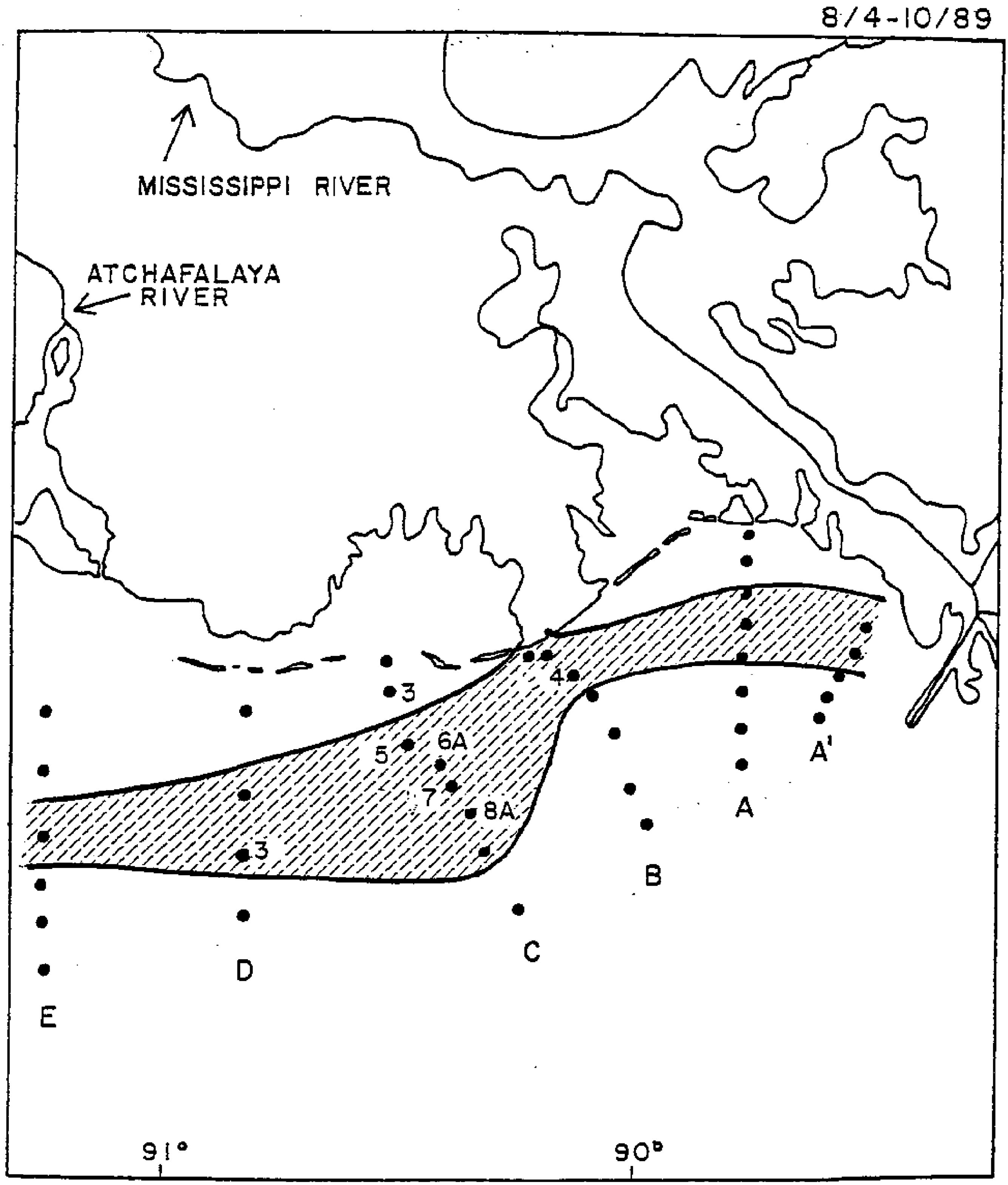


Rabalais, Turner and Wiseman (unpubl. data)



Rabalais, Turner and Wiseman (unpubl. data)

FIGURE N57

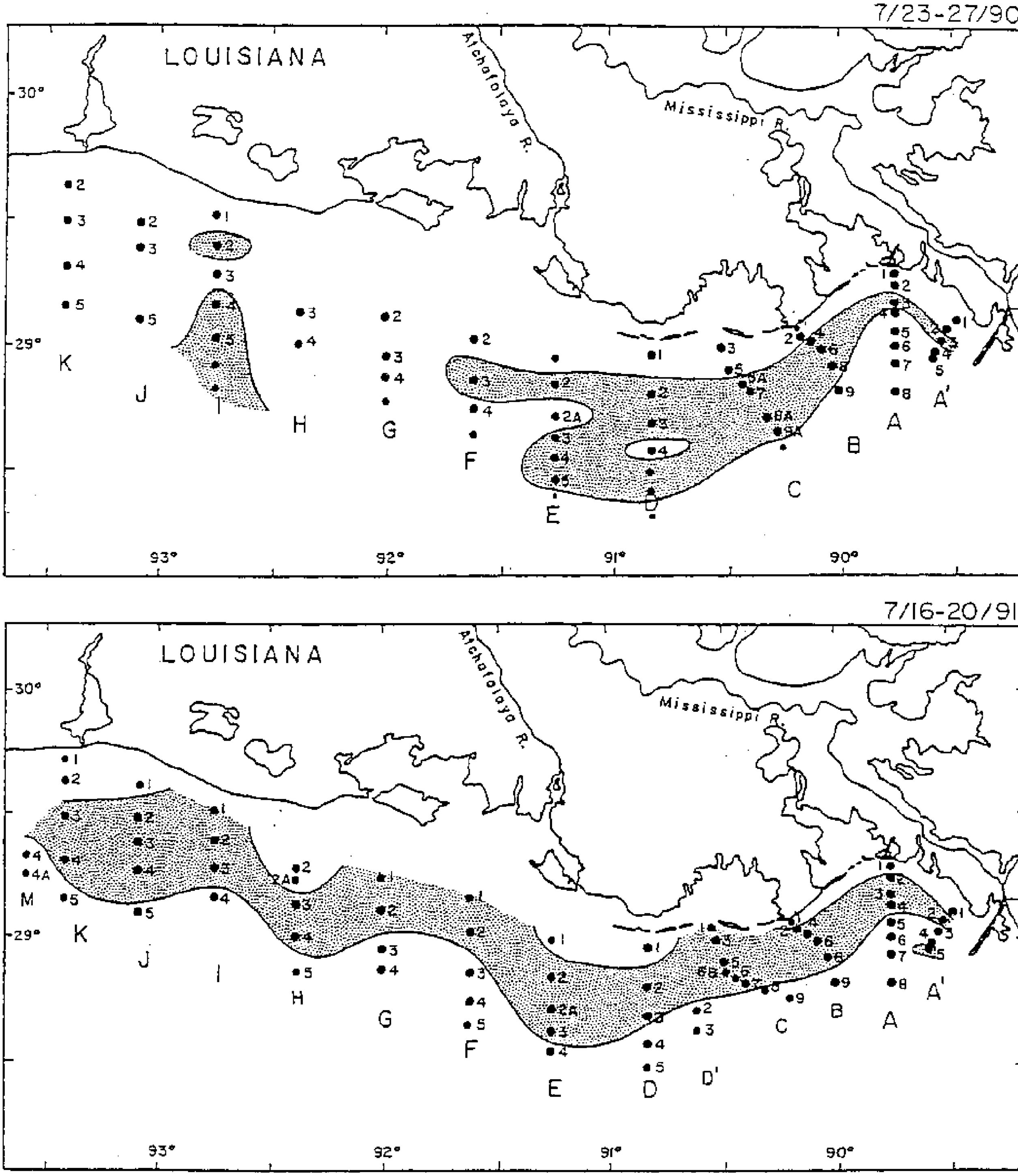


Rabalais, Turner and Wiseman (unpubl. data)

FIGURE N58

Hypoxia on the Louisiana Continental Shelf

1990 and 1991



Modified from Rabalais, N. N., R. E. Turner, and W. J. Wiseman, Jr. 1992. Distribution and characteristics of hypoxia on the Louisiana shelf in 1990 and 1991. In Proceedings of the NOAA Nutrient Enhanced Coastal Ocean Productivity Program Synthesis Workshop, Publ. No. TAMU-SG-92-109, Texas Sea Grant College Program, Texas A&M Univ., College Station.

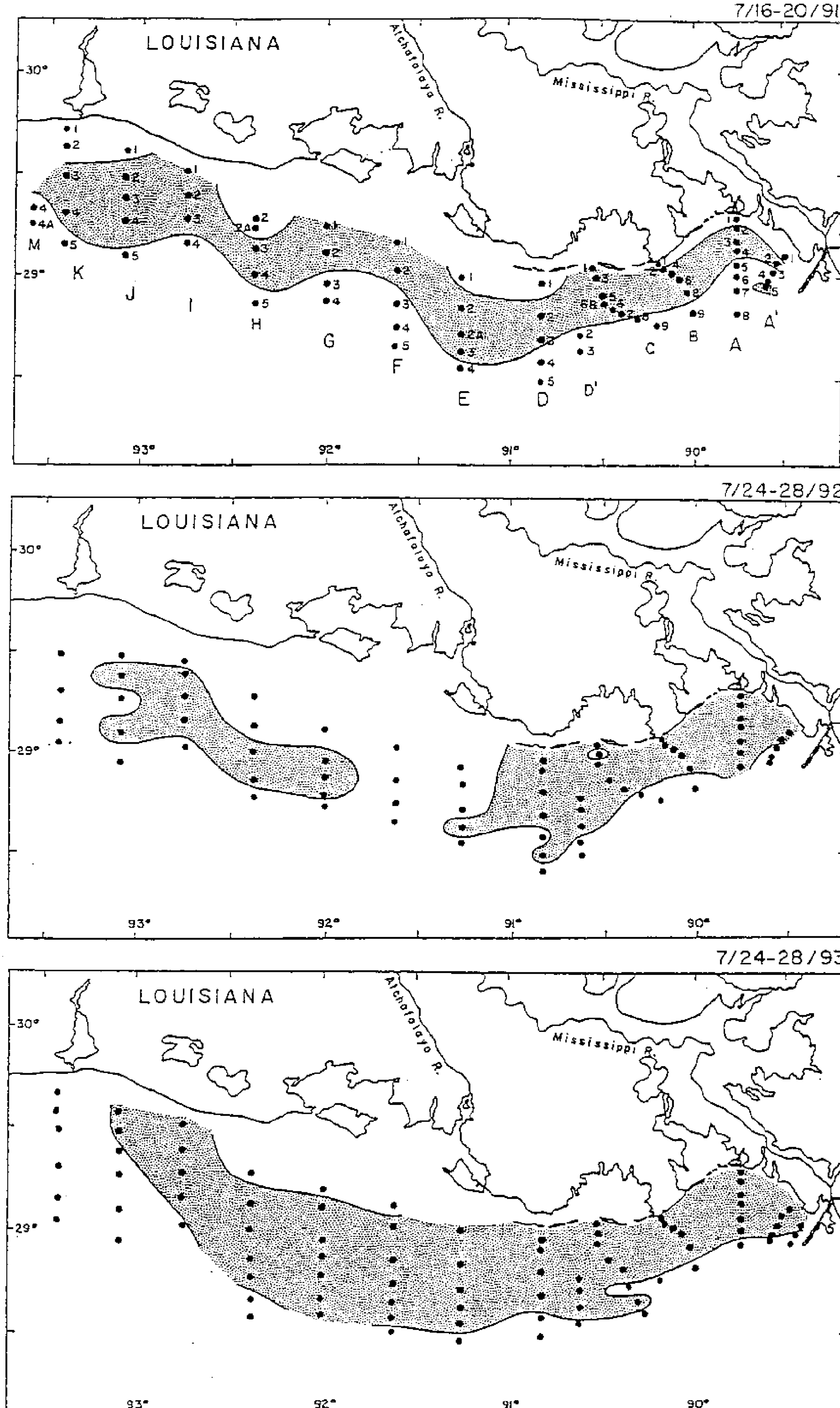
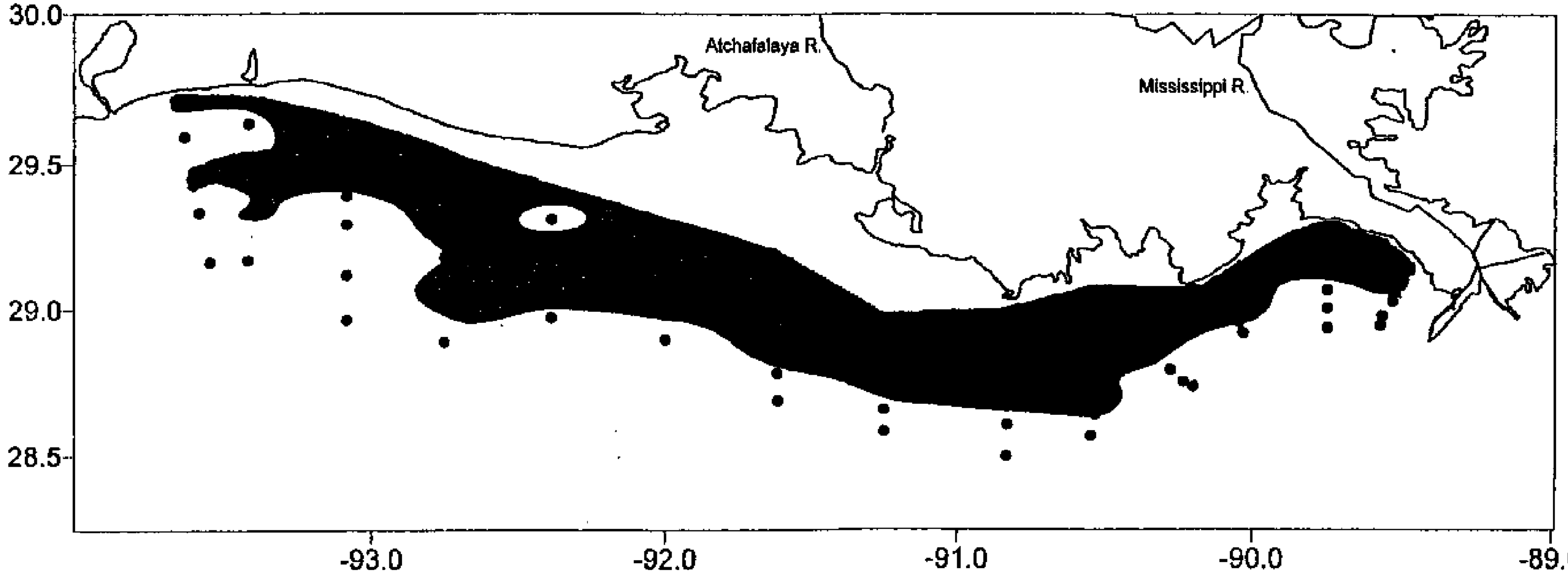

7/16-20/91
LOUISIANA
Atchafalaya R.
Mississippi R.
30°
29°
93°
92°
91°
90°
M
K
J
I
H
G
F
E
D
D'
C
B
A
A'
7/24-28/92
LOUISIANA
Atchafalaya R.
Mississippi R.
30°
29°
93°
92°
91°
90°
7/24-28/93
LOUISIANA
Atchafalaya R.
Mississippi R.
30°
29°
93°
92°
91°
90°

FIGURE N59

FIGURE N61

1997 Shelfwide Cruise
Hypoxic Area



(from Hypoxia Studies of Rabalais, Turner & Wiseman, Unpubl. data)

FIGURE N62

TRANSECT C

(from Hypoxia Studies of Rabalais, Turner & Wiseman, unpubl. data)

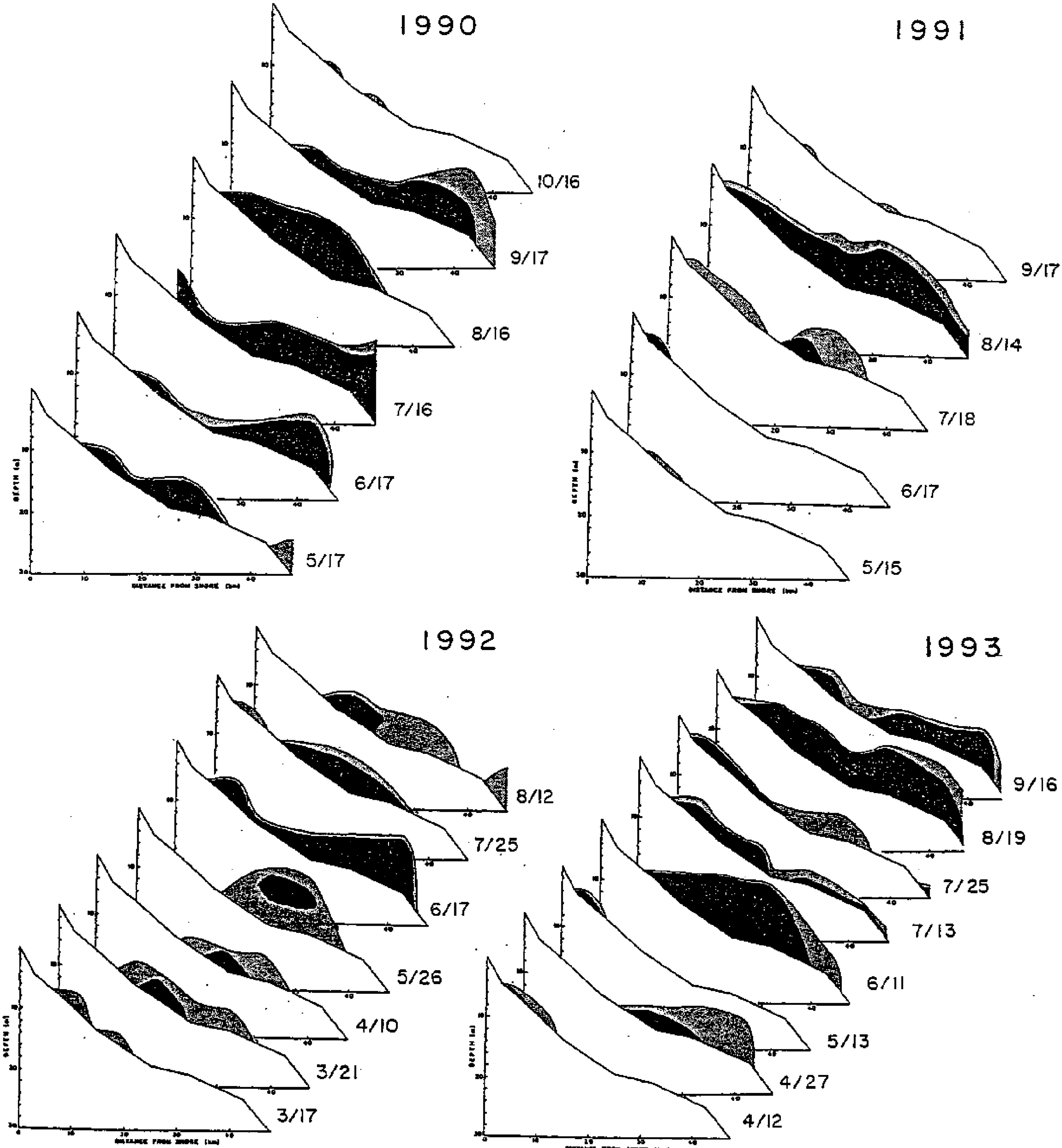
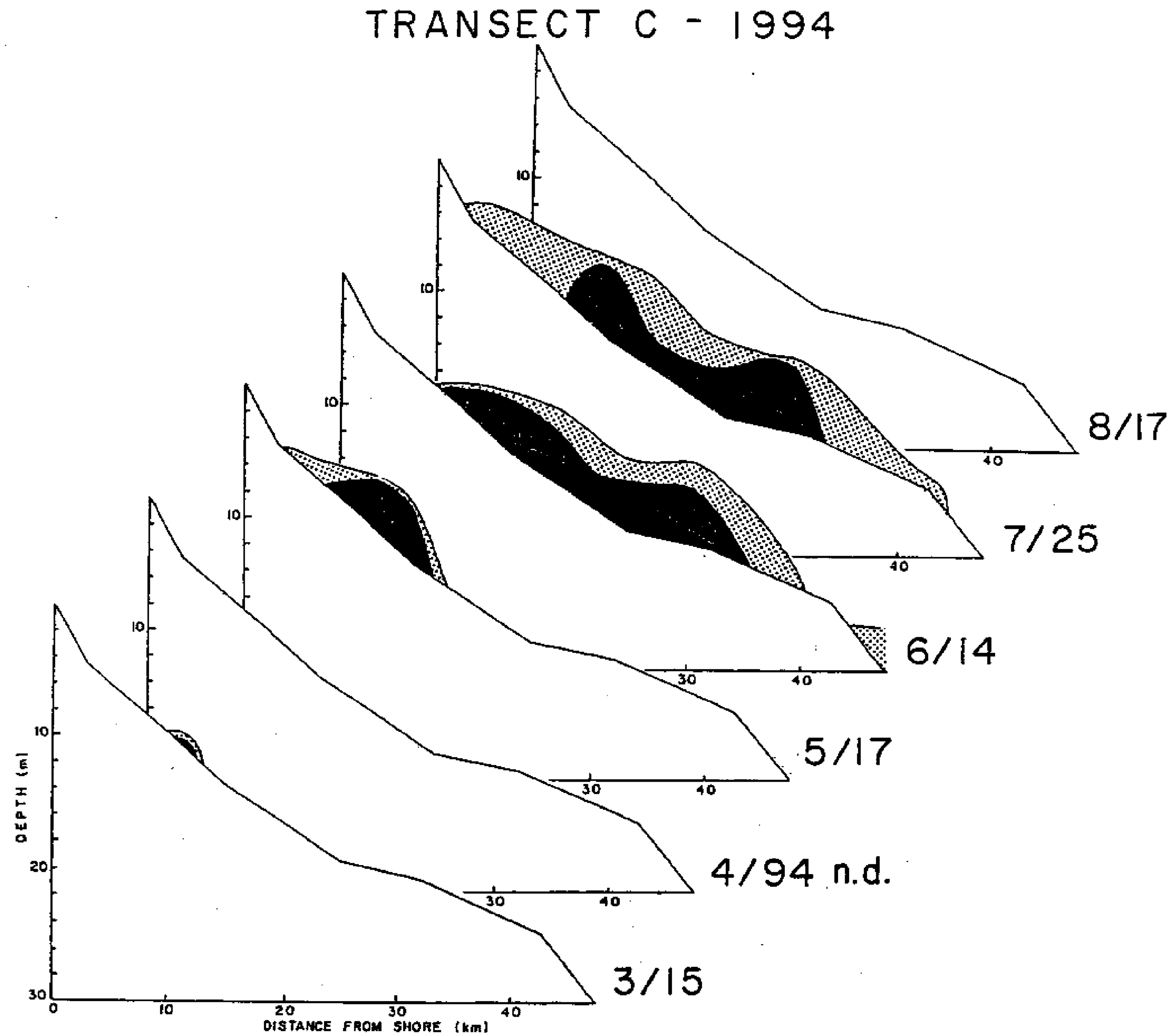


FIGURE N63



(from Hypoxia Studies of Rabalais, Turner & Wiseman, unpubl. data)

Hypoxia Encompasses a Large % of Water Column

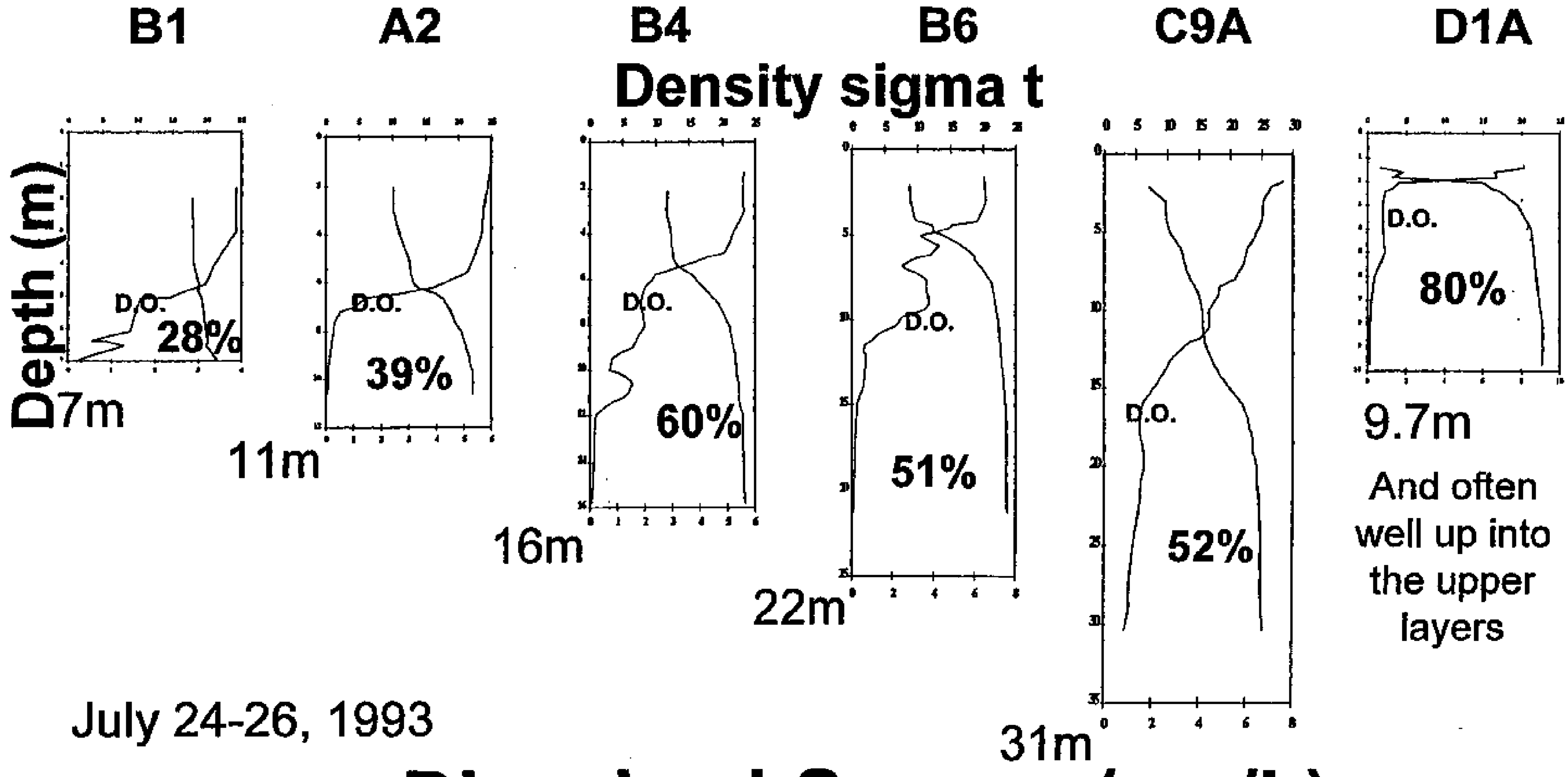


FIGURE N64

FIGURE N65

Dots on map represent stations where CTD oxygen values <=4 mg/L were found in the upper 15 m of the water column.

Scale is the percentage of the total water column with dissolved oxygen <=4 mg/L.

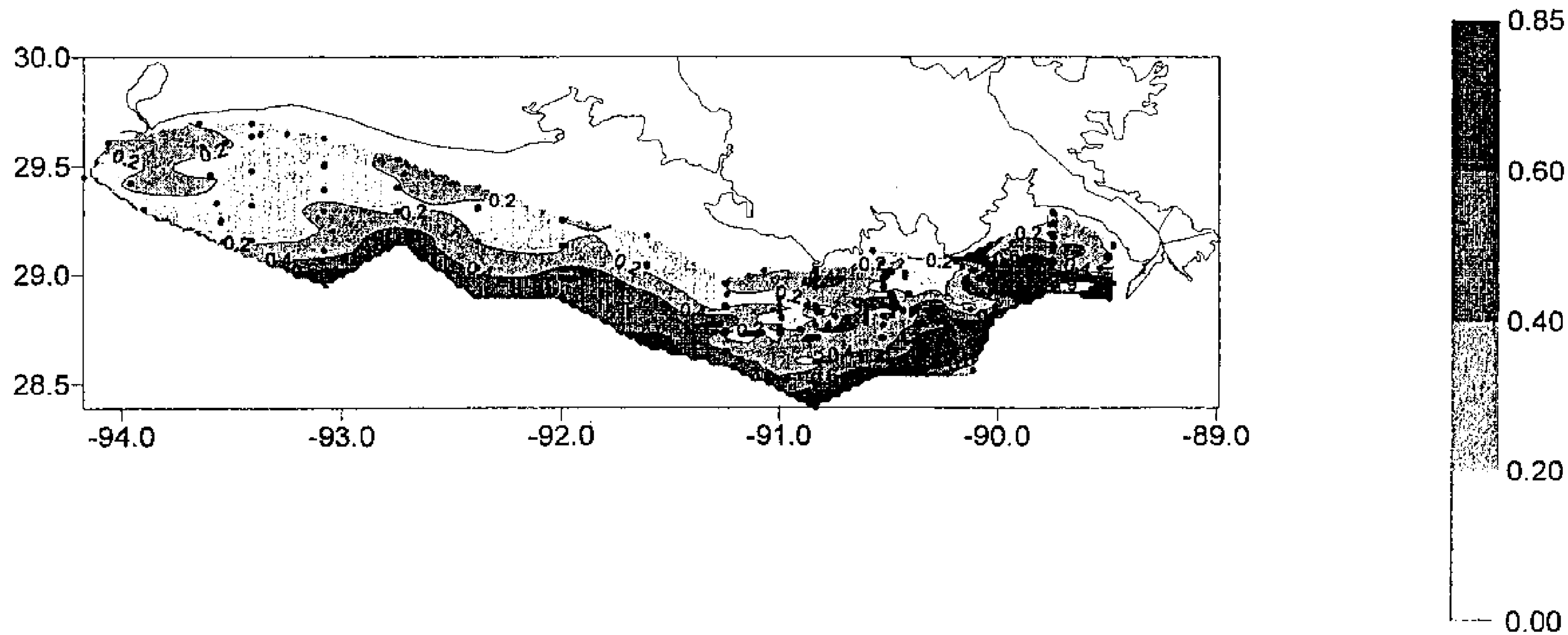


FIGURE N66

Dots on map represent stations where CTD oxygen values <=3 mg/L were found in the upper 15 m of the water column.

Scale is the percentage of total water column with dissolved oxygen <=3 mg/L.

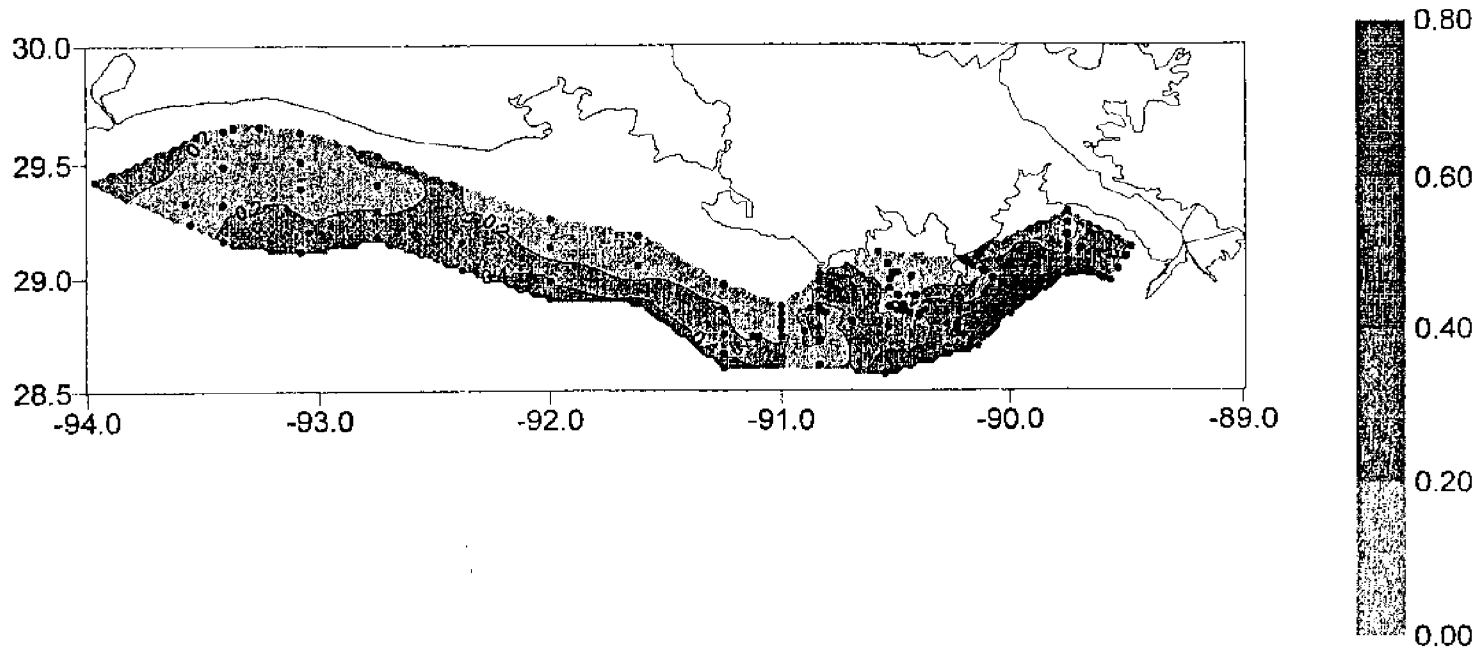


FIGURE N67

Dots on map represent stations where CTD oxygen values <=2 mg/L were found in the upper 15 m of the water column.

Scale is the percentage of the total water column with dissolved oxygen <=2 mg/L.

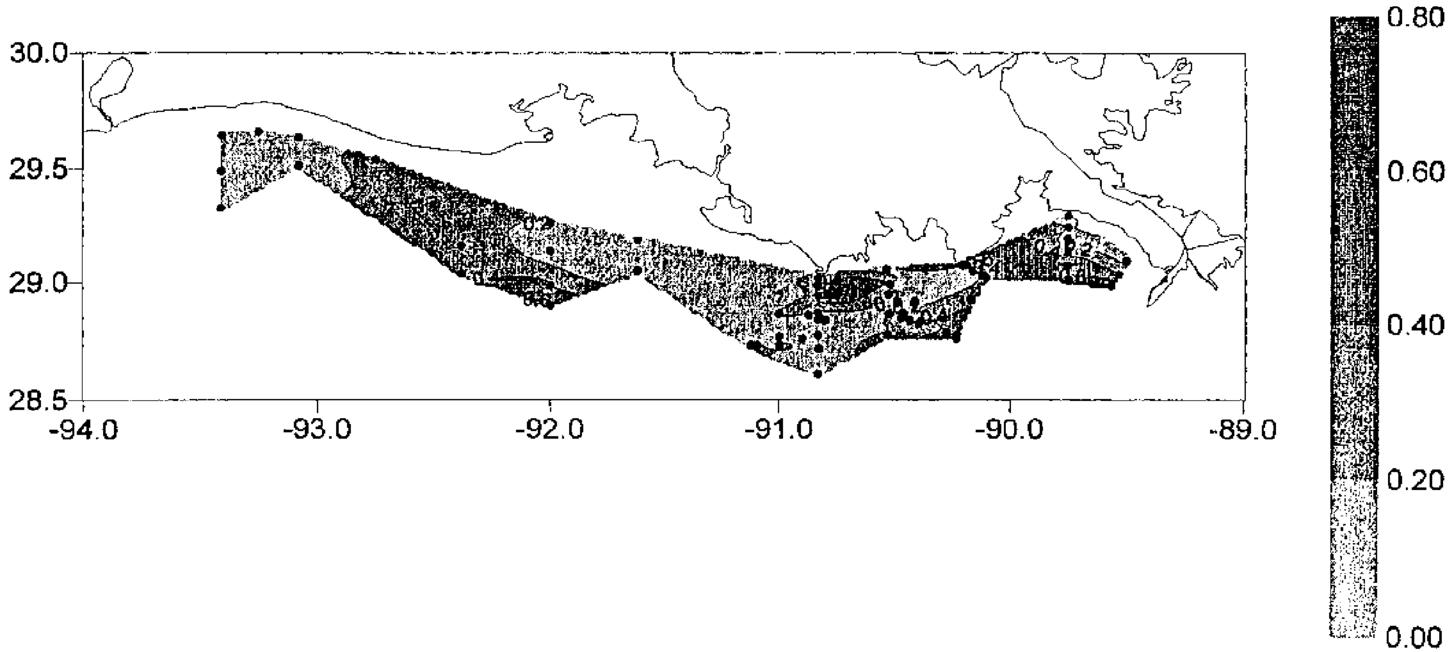


FIGURE N68

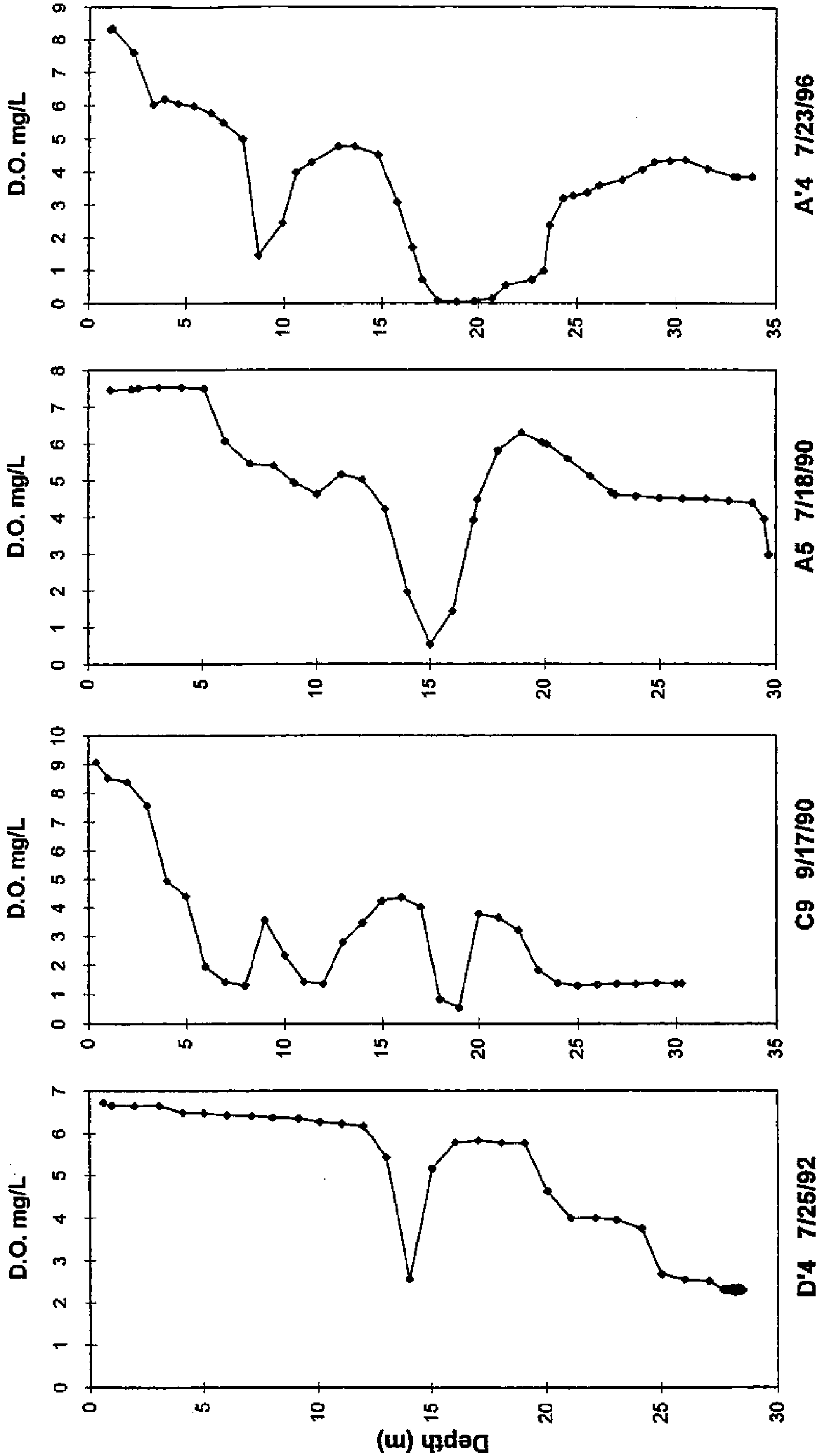


FIGURE N69

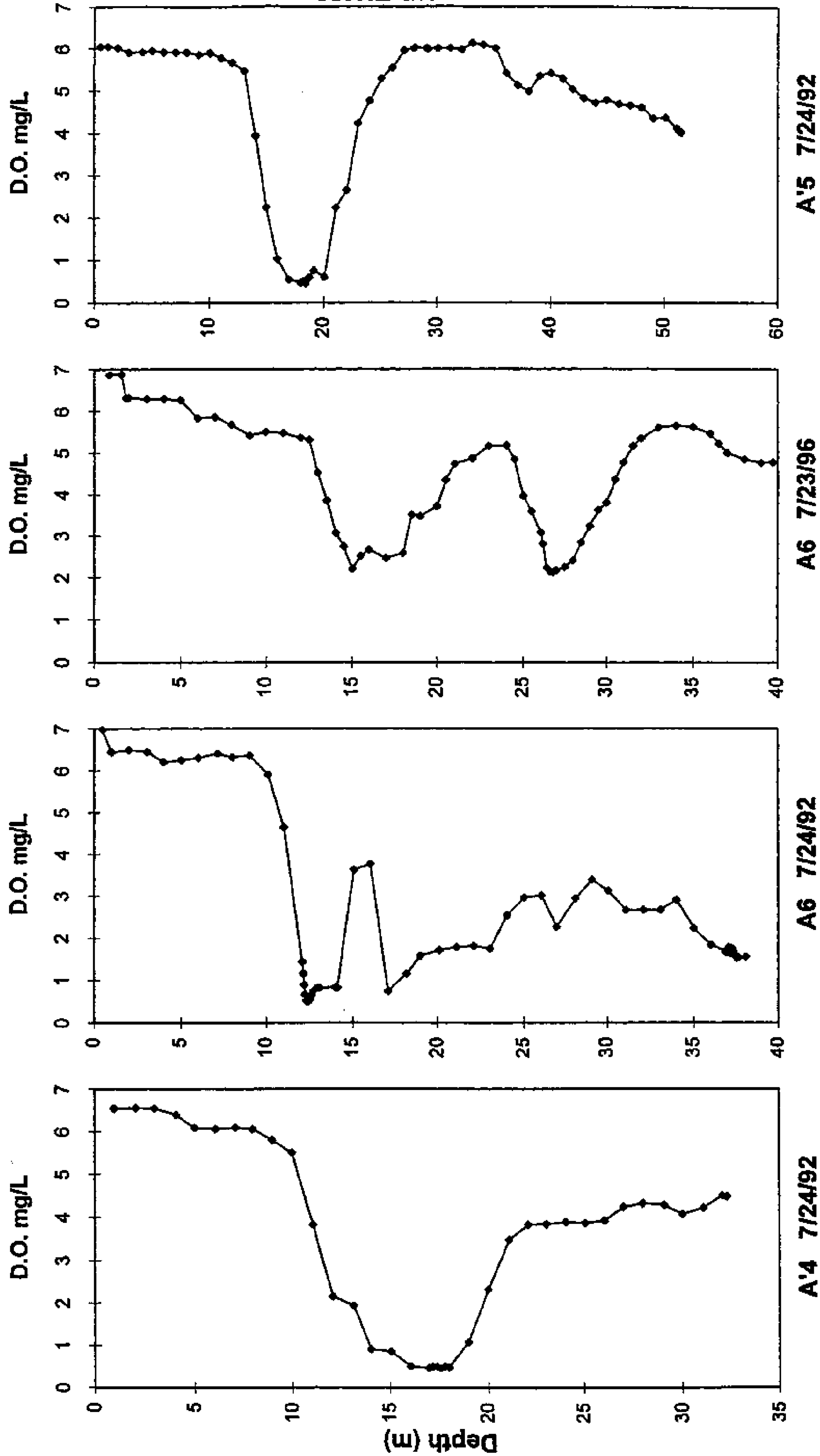


TABLE TN7

The possible impacts, temporal and spatial occurrence and bloom characteristics of HAB species in the Northern Gulf of Mexico. ? explained in text. PSP: Paralytic Shellfish Poisoning; DSP: Diarrhetic Shellfish Poisoning; ASP: Amnesic Shellfish Poisoning; Dino: dinoflagellate; Cyano: cyanobacteria; Raph: raphidophyte; Auto cil: autotrophic ciliate; Diat: diatom; F: freshwater; E: estuarine; c: Coastal; O: open ocean; F: fall; W: winter; Sp: spring; Su: summer; Y: Yes; N: No.

Species	Animal Mortality	Potential Human Illness/Mortality	Location	Season	Bloom Color	Bioluminescence
Alexandrium monilatum	X		E, C	F	Brown to Red	Y
Alexandrium ostenfeldii?		PSP?	E	W	Brown	Y
Anabena spp.	X	hepatotoxins neurotoxins?	F, E	Su	Green to Blue-Green	N
Ceratium tripos			C	Su	Brown	N?
Dinophysis caudata		DSP?	C	All	None	N
Gymnodinium breve	X	NSP	E?, C, O	Su,F	Red	N
Gymnodinium sanguineum	X		E, C	Su	Red to Brown	N
Heterocapsa spp.			E, C?	Sp	Brown	N
Heterosigma akashiwo	X		E, C	Sp?	Red	N
Lingulodinium polyedrum		PSP?	C	Su?	Brown	N
Mesodinium rubrum			E, C	All	Red	N
Microcystis sp.	X	hepatotoxins neurotoxins?	F, E	Su	Green to Blue-Green	N
Noctiluca sp.	X?		E, C	Sp	Red/Orange, Pink	Y
Procentrum micans		DSP?	E, C	All?	None	N
Prorocentrum compressum		DSP?	E, C	All?	None	N
Prorocentrum gracile		DSP?	E, C	All?	None	N
Prorocentrum mexicanum		DSP	?	?	?	N
Prorocentrum minimum		Venerupin poisoning? DSP?	E, C	All?	Red	N
Pseudo-nitzschia delicatissima		ASP	E, C?	All	Brown	N
Pseudo-nitzschia multiseries	X?	ASP	E?	All	Brown	N
Pseudo-nitzschia pseudodelicatissima		ASP	E, C?	All	Brown	N
Pseudo-nitzschia pungens		ASP?	C, O?	All	Brown	N
Scrippsiella spp.			E, C	Sp?	Brown	N
Trichodesmium spp.	X		C, O	Su?	Tufts & Puffs	N

Summary of outbreaks of toxic algae with human health impacts in the low salinity waters of the northern Gulf of Mexico.

- **Brevetoxins in Oysters (Neurotoxic Shellfish Poisoning, NSP)**
  - * *Gymnodinium breve* (Dortch et al. in press)
    - — Fall, 1996 in Louisiana, Mississippi, Alabama coastal waters
    - — Oyster beds closed for harvest for 1 to 5 months
    - — First confirmed bloom in low salinity waters
  - * Common HAB species in Gulf of Mexico (Tester and Steidinger 1997)
    - — Normally occurs at high salinities
    - — Causes fish kills and human respiratory problems as well as NSP
  - * Link to nutrient inputs unclear, but being re-evaluated

- **Cyanobacterial Hepatotoxins in Phytoplankton**
  - * *Anabena* spp. and *Microcystis* sp. (Dortch and Achee' in press)
    - — Summer, 1997, Lake Pontchartrain
    - — Probably resulted from increased nutrients due to diversion of Mississippi River water
    - — Advisory issued against recreational use
  - * Present in other fresh and very low salinity water bodies in Louisiana
    - — Lake Pontchartrain bloom July 1995
    - — Lake Salvadore bloom January 1995
    - — Lake Borgne July/August 1997
  - * Blooms of cyanobacteria and impacts increasing worldwide due to eutrophication (Pearl 1996)

- **Domoic Acid in Phytoplankton (Amnesic Shellfish Poisoning, ASP)**
  - * *Pseudo-nitzschia* spp.
    - — At least 4 toxin-producing species (Parsons et al. in press)
    - — High cellular domoic acid concentrations measured (Doucette et al. 1997)
  - * All coastal and shelf waters (Dortch et al. 1997; Parsons et al. in press)
    - — Most abundant in winter in estuary and in spring/fall on shelf
    - — On shelf peak in abundance corresponds to peak in river flow
  - * Link with nutrient inputs in Louisiana and elsewhere (Dortch et al. 1997)

- **Okadaic Acid in Oysters(Diarrhetic Shellfish Poisoning, DSP)**
  - * Measured at 2 locations in Northern Gulf of Mexico
    - — Mobile Bay, Fall, 1990 (Dickey et al. 1992)
    - — Terrebonne Bay, Jan.-Mar. 1995 (Dickey, pers. comm.)
  - * No species clearly linked to either occurrence
    - — *Dinophysis caudata* and *Prorocentrum* spp. frequently present but none shown definitively to produce okadaic acid
    - — *Prorocentrum mexicanum* known okadaic acid producer, rarely present
    - — Not possible to evaluate link to nutrients at present