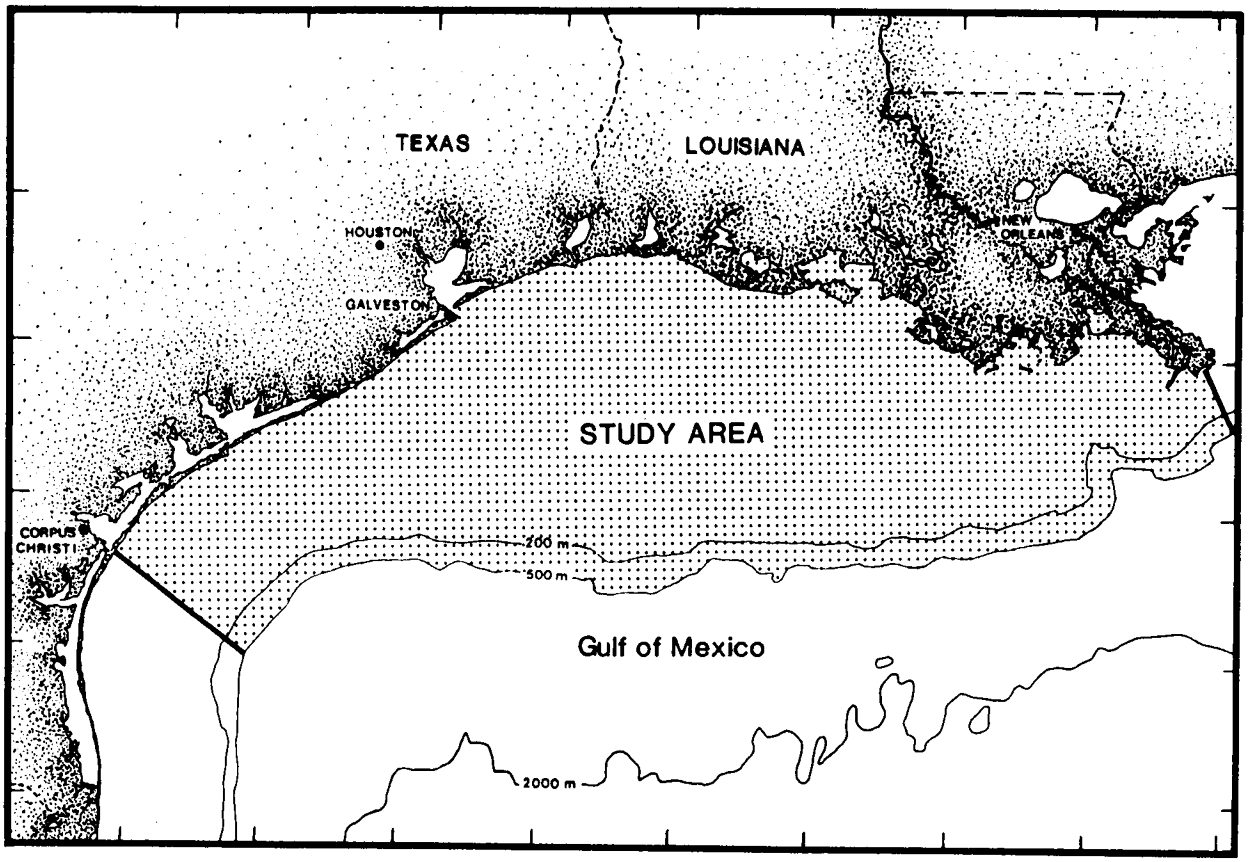
OCS Study
MMS 88-0067

Offshore Texas and Louisiana Marine Ecosystems Data Synthesis

Volume II: Synthesis Report



MMS
U.S. Department of the Interior
Minerals Management Service
Gulf of Mexico OCS Region

OCS Study
MMS 88-0067

Offshore Texas and Louisiana Marine Ecosystems Data Synthesis

Volume II: Synthesis Report

Editors

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- Bela M. James (Ph.D., Oceanography, Texas A&M University, 1972). Program Manager.

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- Suzanne R. Short -- Graphic Artist.
- Alexandra M. Mazzoni -- Word Processor Operator.
- Michelle H. Merz -- Word Processor Operator.
- Adrienne B. Holt -- Clerical.

LIST OF ABBREVIATIONS

API	--	American Petroleum Institute
BLM	--	Bureau of Land Management
COE	--	U.S. Army Corps of Engineers
DDT	--	Dichlorodiphenyltrichloroethane
DOE	--	U.S. Department of Energy
EIS	--	Environmental Impact Statement
EPA	--	U.S. Environmental Protection Agency
FCZ	--	Fishery Conservation Zone
FMP	--	Fishery Management Plan
GC	--	Gas chromatography
HMWH	--	High molecular weight hydrocarbon
LMWH	--	Low molecular weight hydrocarbon
MAFLA	--	Mississippi-Alabama-Florida
MMS	--	Minerals Management Service
MS	--	Mass spectrometry
NAS	--	National Academy of Sciences
NEDRES	--	National Environmental Data Referral Service
NMFS	--	National Marine Fisheries Service
NOAA	--	National Oceanic and Atmospheric Administration
NRC	--	National Research Council
NTIS	--	National Technical Information Service
OCS	--	Outer Continental Shelf
OEP	--	Odd-even preference
PAH	--	Polynuclear aromatic hydrocarbon
PCB	--	Polychlorinated biphenyl
SPR	--	Strategic Petroleum Reserve
SSMO	--	Sea Surface Meteorological Observation
STOCS	--	South Texas Outer Continental Shelf
TPWD	--	Texas Parks and Wildlife Department
TSM	--	Total suspended matter
UCM	--	Unresolved complex mixture
USDI	--	U.S. Department of the Interior
USFWS	--	U.S. Fish and Wildlife Service
USGS	--	U.S. Geological Survey
VLH	--	Volatile liquid hydrocarbon
VOC	--	Volatile organic compound

CHAPTER 1
INTRODUCTION

The continental shelf off Louisiana and Texas is the most highly developed region in the world for offshore oil and gas drilling and production. The area is also known for its abundant fisheries, extensive coastal wetlands and wildlife resources, and offshore hard-bank communities, including the northernmost coral reefs in the Gulf of Mexico (Flower Garden Banks). This abundance of living marine resources in a region of intense petroleum industry activity poses many questions and problems for sound environmental management and protection.

The Minerals Management Service (MMS), an agency of the U.S. Department of the Interior (USDI), is responsible for leasing Federal submerged lands and supervising oil and gas exploration, development, and production. Part of the agency's responsibility is to protect marine and coastal environments while promoting development of the nation's oil and gas resources. The USDI has sponsored numerous scientific studies of coastal and offshore marine environments off Louisiana and Texas through the Environmental Studies Program, which began in 1974 under the Bureau of Land Management (BLM) and was subsequently transferred to the newly created MMS in 1982. The MMS funded the present study to synthesize environmental and socioeconomic information from these prior USDI studies, as well as those sponsored by industry, the universities, and other government agencies. The goal was to assess current understanding of continental shelf ecosystems and processes, so that future study needs could be pinpointed.

The study area for the synthesis effort extends from Corpus Christi Bay, Texas to the Mississippi River Delta, and from the shallow sublittoral to 500 m depth (Figure 1.1). The study area includes parts of two Planning Areas (Central and Western) used for oil and gas leasing.

1.1 HISTORICAL BACKGROUND

1.1.1 Oil and Gas Industry

The first offshore well in the Gulf of Mexico was drilled off the Louisiana coast in 1937 to 1938 as an extension of exploration and production activities in the coastal wetlands of Louisiana (Gusey and Maturgo, 1973). This well, which was drilled about 2.5 km offshore and 15 km east of the mouth of Calcasieu Pass, resulted in the discovery of the Creole Field. However, significant development of offshore oil and gas deposits did not begin until 1947, when the Ship Shoal Block 32 Field was discovered about 20 km off the Louisiana coast (Bedinger, 1981). Offshore development began in earnest with the passage of the Submerged Lands Act in 1953 and the Outer Continental Shelf (OCS) Lands Act in 1954, which defined Federal jurisdiction over OCS oil and gas resources. Since the 1940's, over 25,000 wells have been drilled in the northern Gulf of Mexico, mostly off the Louisiana coast (American Petroleum Institute, 1982; Dodson and LeBlanc, 1988). OCS production off Louisiana and Texas since 1954 has totaled over 6 billion barrels of oil and

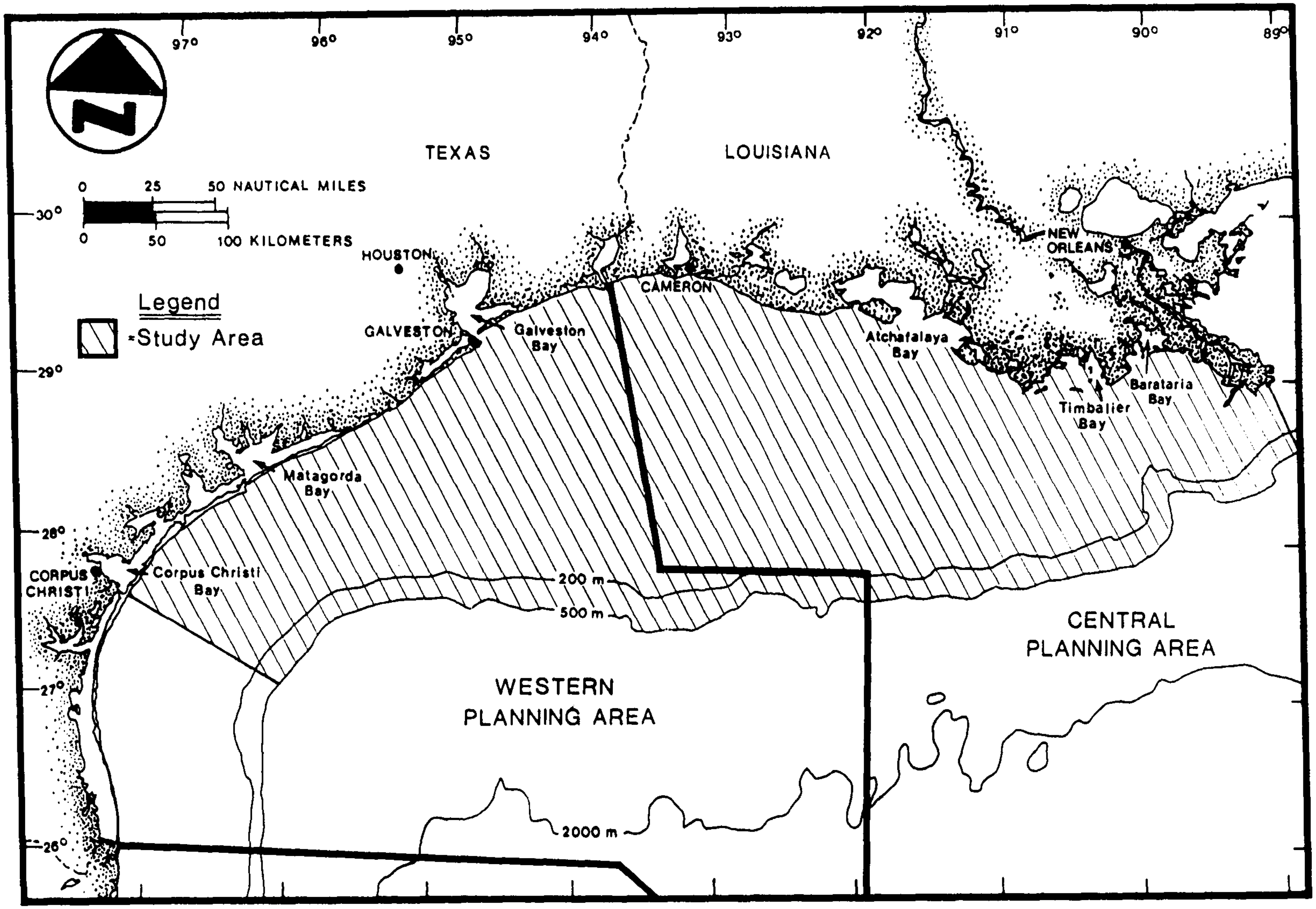

Figure 1.1. Study area for the synthesis effort.

70 billion cubic feet of natural gas (Risotto and Collins, 1986). In 1985, Louisiana contributed 87% of national OCS oil production and 90% of national OCS gas production.

As a result of technological advances and the continuing need to reduce U.S. dependency on foreign oil supplies, deeper waters of the Gulf of Mexico continental shelf and upper continental slope are now being explored. Water depths for exploratory drilling have increased dramatically in the last five years, with the deepest exploratory well to date in a depth of 2,330 m (Dodson and LeBlanc, 1988). In May 1988, Shell successfully installed a production platform southwest of the Mississippi Delta in 412 m of water. Although conventional fixed platforms are probably limited to depths of about 460 m, other methods such as floating production systems and tension-leg platforms will probably be capable of exploration and production at even greater depths (Dees, 1988).

Over the years, as the offshore oil and gas resources of Louisiana and Texas have been developed, an immense pipeline network has been installed to transport the oil and gas. As of December 1987, there were over 28,000 km of pipeline installed on the OCS in the Gulf of Mexico (USDI, MMS, 1988). About 90% of the pipeline mileage is in the Central Planning Area off the Louisiana coast, and about 10% is off Texas (Risotto and Collins, 1986).

1.1.2 Major Environmental Studies

Several major environmental studies have been conducted off the Louisiana and Texas coasts, including both descriptive (baseline) studies and monitoring programs (Figure 1.2). Major studies include the following:

- South Texas Outer Continental Shelf (STOCS) studies.
- Topographic Features Studies (Flower Garden Banks and other banks off Texas and Louisiana).
- Northern Gulf of Mexico Continental Slope Study.
- Offshore Ecology Investigation.
- Central Gulf Platform Study.
- Buccaneer Gas and Oil Field Study.
- Strategic Petroleum Reserve Program.

The first three were primarily descriptive studies, although both STOCS and the Topographic Features Studies included limited environmental monitoring of drilling operations. The other studies were designed to monitor oil and gas related operations, but also provided a considerable body of descriptive information. Because these studies are often cited in the individual subject chapters of this report, a brief summary of each is presented below. More detail on some aspects of the studies is presented in the individual chapters. Also, selected environmental monitoring programs are summarized in the Appendix.

Other pertinent field studies (not discussed below) include the Gulf Reef Fish Study (Continental Shelf Associates, Inc., 1982), the Louisiana Offshore Oil Port studies (Gosselink et al., 1976), and the

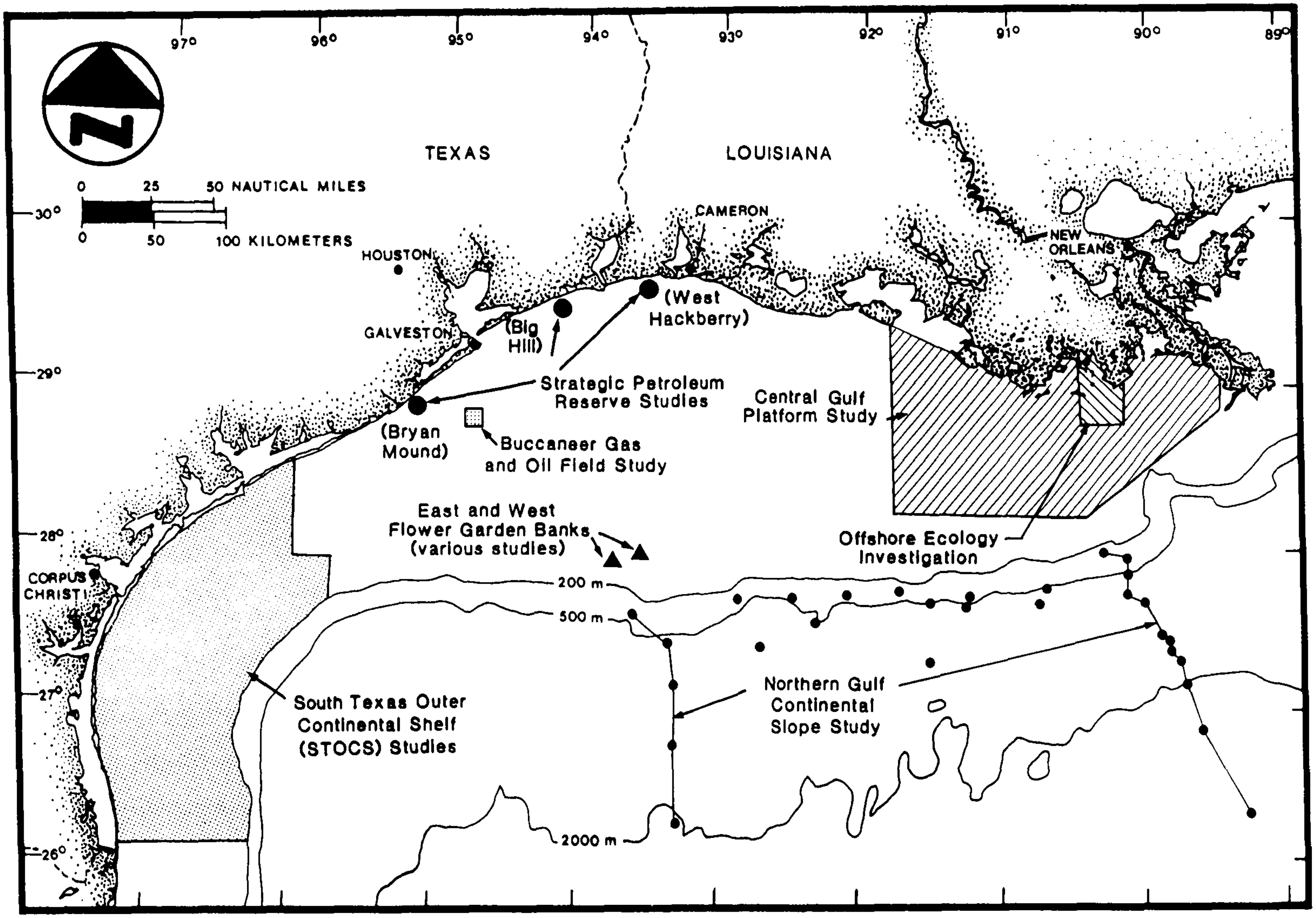

Figure 1.2. Locations of some major environmental studies on the Texas–Louisiana continental shelf and slope.

ongoing Submerged Lands of Texas series being conducted by the Texas Bureau of Economic Geology (McGowen and Morton, 1979; White et al., 1983, 1985, 1986, 1987). In addition to these reports from field studies, several synthesis documents are useful information sources, including the Northwestern Gulf Shelf Bio-Atlas (Darnell et al., 1983), An Ecosystem Analysis of Oil and Gas Development on the Texas-Louisiana Continental Shelf (Gallaway, 1981), and Reefs and Banks of the Northwestern Gulf of Mexico (Rezak et al., 1983, 1985).

South Texas Outer Continental Shelf (STOCS) Studies

These baseline studies were conducted from 1975 through 1977 on the continental shelf off southern Texas (Figure 1.2). There were three major groups of studies:

- Biology and chemistry--conducted by consortium consisting mainly of investigators from the University of Texas Marine Science Institute and Texas A&M University.
- Geology--conducted by the U.S. Geological Survey (USGS).
- Fisheries and ichthyoplankton--conducted by the National Marine Fisheries Service (NMFS).

The biology/chemistry study elements included hydrography; hydrocarbon analyses of water, sediment, zooplankton, nekton, and macroepifauna; trace metal analyses of sediments, zooplankton, nekton, and macroepifauna; plankton, neuston, and nekton sampling; grab sampling of sediments, macroinfauna, and meiofauna; and trawl sampling of demersal fish and macroepifauna (for taxonomy and histopathology). A rig monitoring study was also conducted in 1977 (see the Appendix). Study results were presented in annual reports and synthesized in a three-volume report (Benavides et al., 1980; Flint and Rabalais, 1980a,b). The results were also reported in a book edited by Flint and Rabalais (1981).

The other elements of the STOCS studies were reported separately. USGS studies of geologic structure, sediment texture and geochemistry, and suspended sediments were reported in Berryhill (1976, 1977a,b, 1978). The NMFS investigations of ichthyoplankton, historical zooplankton, and snapper/grouper fisheries, were reported in Angelovic (1975), Angelovic et al. (1977), Fable (1979), Park (1979), and Klima and Caillouet (1979).

Topographic Features Studies

A series of studies was funded by the BLM, beginning in 1974, to characterize topographic features (offshore reefs and banks) on the northern Gulf of Mexico continental shelf and slope. Surveys of the offshore banks began in 1961 when Texas A&M University researchers visited the Flower Garden Banks. This work eventually resulted in the production of a book on the biota of the Flower Garden Banks (Bright and Pequegnat, 1974). Beginning in 1974, the BLM sponsored reconnaissance and characterization studies of 35 banks all across the Texas-Louisiana shelf. Reports in the study series included A Biological and Geological Reconnaissance of Selected Topographical Features on the Texas Continental Shelf (Bright et al., 1976), South Texas Topographic Features Study (Bright and Rezak, 1978a), Northwestern Gulf of Mexico Topographic Features Study (Bright and Rezak, 1978b), Northern Gulf of Mexico Topographic Features Study (Rezak and Bright, 1981a), and Environmental Studies at the Flower Garden Banks and Selected Banks (McGrail et al., 1982a). This information on reefs and banks was synthesized in a report by Rezak et al. (1983), later published as a book (Rezak et al., 1985).

Offshore Ecology Investigation

This investigation, conducted by the Gulf Universities Research Consortium, was the first major study specifically directed toward determining the long-term effects of oil drilling and production on the marine environment. During 1972 to 1974, field studies were carried out in Timbalier Bay, Louisiana and the adjacent nearshore continental shelf, a heavily developed "oil patch" area (Figure 1.2). The Offshore Ecology Investigation included studies of hydrography, nutrient and pollutant chemistry, surface sediments, phytoplankton and zooplankton, benthic marine algae, foraminifera, macroinfauna, demersal fishes and macroinvertebrates, and platform biofouling communities. Results were initially reported in unpublished technical reports, then compiled in a book (Ward et al., 1979). The compilation volume included an overview of study design (Menzies et al., 1979) and an independent appraisal of study findings (Bender et al., 1979).

Central Gulf Platform Study

The Central Gulf Platform Study was conducted in 1978 to 1979 in the highly developed "oil patch" area just west of the Mississippi Delta (Figure 1.2). The study, directed by Southwest Research Institute under the sponsorship of the BLM, was intended to evaluate effects of oil and gas production platforms on the surrounding environment. The study included water column and sediment sampling around four "primary" and 16 "secondary" platforms, as well as a separate study of biofouling communities and platform-associated fishes. Study methods and results are presented in the final report edited by Bedinger (1981).

Buccaneer Gas and Oil Field Study

Another major investigation was the Buccaneer Gas and Oil Field Study (1975 to 1980), funded by the U.S. Environmental Protection Agency through interagency agreement with the National Oceanic and Atmospheric Administration (NOAA), and administered by the NMFS, Southeast Fisheries Center in Galveston, TX. The study site, a production field located 50 km south of Galveston (Figure 1.2), had been in operation for 15 years prior to 1975, providing an opportunity to examine long-term effects of oil and gas development and production activities. The study included current and hydrographic measurements; various analyses of water samples and suspended particulate matter; analyses of platform effluents for hydrocarbons, trace metals, and sulfur; analyses of sediment samples for grain size, mineralogy, total organic carbon, stable carbon isotopes, hydrocarbons, and trace metals; grab sampling of macroinfauna and meiofauna; trawl sampling of demersal fishes and macrocrustaceans; studies of biofouling communities and platform-associated fishes; bacteriological, histopathological, and toxicological analyses; observations of marine birds; and hydrodynamic and ecological modeling efforts.

The final year of the Buccaneer Gas and Oil Field Study produced six "milestone" or synthesis reports edited by Jackson and Wilkens (1980). A symposium was held in 1980, and the proceedings were published as a book edited by Middleditch (1981).

Strategic Petroleum Reserve Studies

As part of the Energy Policy and Conservation Act of 1975, the U.S. Department of Energy (DOE) implemented the Strategic Petroleum Reserve (SPR). This program is designed to store 1 billion barrels of oil in solution-mined salt cavities near existing petroleum distribution facilities along the Gulf coast. Large quantities of leachate and brine produced by this operation have been released into nearshore waters at each of the reserve storage sites. In order to assess the environmental effects of brine discharge, the DOE sponsored field studies between 1977 and 1985 at three coastal locations: West Hackberry (off Cameron, LA), Big Hill (off Texas east of Galveston Bay), and Bryan Mound (off Freeport, TX) (Figure 1.2). At the sites, pre-release studies were carried out to provide baseline data, and the environmental studies were continued through several years of brine discharge. Included were investigations of physical oceanography, water and sediment chemistry, and biology (phytoplankton, zooplankton, benthos, and nekton). Controls included data from the pre-release studies as well as from "test" stations located some distance from the brine release sites and which were likely unaffected by the brine. From a regional standpoint, these studies are of considerable interest because they provide an invaluable multi-year data base, and they document biological responses to summer bottom-water hypoxia in both areas.

Numerous reports have been produced from the SPR program. An environmental impact statement was prepared by the DOE (1981). A summary of chemical and biological baseline studies conducted by the NOAA under interagency agreement with DOE is contained in NOAA (1981). Annual reports from each site (e.g., Hann et al., 1985a,b,) contain a list of previous reports.

Northern Gulf of Mexico Continental Slope Study

This MMS-funded study, which began in 1983, was designed to supplement the meager existing information on continental slope ecosystems (summarized by Pequegnat, 1983). Field sampling, consisting of five sampling cruises, has been completed, but sample processing and data analysis are not complete at the time of this report (July 1988). Stations in depths ranging from 320 to 2,853 m were sampled along three transects perpendicular to the isobaths in the Western, Central, and Eastern Planning Areas; some additional stations were sampled along the isobaths (Figure 1.2). The study included water column sampling (temperature, conductivity, dissolved oxygen, nutrients, and particulate organic carbon); trawling and benthic photographic sampling of megafauna; and box core sampling of sediments (for grain size, carbon isotope, and hydrocarbon analyses), macroinfauna, and meiofauna. The most significant aspect of the study is the discovery of chemosynthetic communities around hydrocarbon seeps off Louisiana. The communities are similar to those recently found at the base of the Florida Escarpment and near hydrothermal vents in the eastern Pacific (Gallaway et al., 1988).

1.2 STUDY OBJECTIVES AND REPORT ORGANIZATION

The synthesis study had three main objectives:

- To identify, acquire, review, and annotate all pertinent environmental and socioeconomic literature (published and unpublished) for the study area.

- To synthesize information within major disciplines (geology, physical oceanography and meteorology, chemistry, biology, and socioeconomics) in order to describe the shelf environment and ecosystems.

- To identify major information gaps and recommend field studies to fill the gaps.

The study consisted of two tasks: (1) information collection and annotation, and (2) synthesis. In the first task, a literature search was conducted, and an annotated bibliography of 1,535 references was compiled. Topic areas for information collection were as follows:

- Marine geology.

- Physical oceanography and meteorology.

- Marine chemistry (including trace metals, hydrocarbons, and other contaminants).

- Marine biology (including plankton, nekton, benthos, fisheries, endangered species, and biologically sensitive areas).

- Socioeconomics (including commercial and recreational fisheries, the oil and gas industry, and other maritime industries).

- Oil and gas industry activities and effects, including consequences of major oil spills.

- Effects of other maritime industries and human activities.

In the second task, the available environmental and socioeconomic information was synthesized by scientists chosen for their expertise in the various subject areas. In this report, separate chapters are devoted to Geology, Physical Oceanography and Meteorology, Marine Chemistry, Marine Biology, and Socioeconomics. At the end of each chapter is a discussion of data gaps and information needs. The main subject chapters are followed by a chapter devoted to modeling the influences of oil and gas operations and other human activities on the ecosystems of the Texas-Louisiana continental shelf. A Conclusions chapter summarizes major findings and reviews data gaps and information needs.

CHAPTER 2
METHODS

2.1 INFORMATION COLLECTION AND ANNOTATION

One goal of the Minerals Management Service (MMS) Texas-Louisiana project was to produce a computerized, annotated bibliography of environmental and socioeconomic literature for the Texas-Louisiana continental shelf. The bibliography was compiled through a combination of computer searches, telephone contacts, library visits, and submissions from chapter authors. The final products consist of (1) a printed bibliography sorted by author and date; and (2) a set of data files, on IBM-compatible floppy disks, that have been indexed with the computer program FYI 3000 Plus[1] (FYI) to allow searching by author, date, topic and geographic keywords, or words in the title and source. The annotated bibliography consisting of 1,535 references [of which 947 (62%) have abstracts], is contained in Volume III of this report, and the disks will be submitted separately to the MMS as a project deliverable with the Final Report.

2.1.1 Information Sources

The sources of the 1,535 citations in the annotated bibliography were as follows:

- 496 from the MMS Tuscaloosa Trend bibliography.
- 404 from online data base searches.
- 301 from reprint collections of chapter authors.
- 217 from publication lists provided by various State and Federal agencies and organizations.
- 117 from the in-house library of Continental Shelf Associates, Inc.

Citations from the Tuscaloosa Trend bibliography and the online data bases were obtained first, on disk with accompanying printouts. The printouts were screened for pertinent citations, and the disk files were then edited with Word Perfect 4.2 to remove unwanted citations and to place those selected into a standard format. These references became the preliminary data base. All other references were added by typing them in Word Perfect, following the same standard format.

Many of the entries obtained from chapter authors, the in-house library of Continental Shelf Associates, Inc., and various agencies and organizations were duplicates of those already in the bibliography. Duplicates were located by indexing the data base by author after the Tuscaloosa Trend and online data base references had been entered. Once the initial data base was established, all subsequent entries were checked against the existing data base to avoid duplicates.

[1]FYI 3000 Plus is a trademark of FYI, Inc. of Austin, TX.

Tuscaloosa Trend Bibliography

A total of 496 citations were obtained from the previously compiled Tuscaloosa Trend Data Search and Synthesis (Barry A. Vittor & Associates, Inc., 1985). The study area for that program extended from the Alabama-Florida border to the Mississippi River Delta, and consequently many references were included from locations in or near the current study area. The entire data base of 1,106 citations was obtained on disk and as printouts from the MMS Gulf of Mexico OCS Regional Office. Each entry contained fields for author, date, title, source, abstract, and keywords. About 60% of the Tuscaloosa Trend citations included abstracts.

The Tuscaloosa Trend printouts were scanned for pertinent entries, which were saved into new text files using Word Perfect. The revised files were checked for spelling errors through the word processing program's dictionary, and duplicate entries were located and removed through the use of the indexing program described below.

Online Data Bases

The following data bases were searched through computer facilities at Harbor Branch Oceanographic Institution in Fort Pierce, Florida:

- OCEANIC ABSTRACTS
- SCISEARCH DATABASE (Science Citation Index)
- CONFERENCE PAPERS INDEX
- CA SEARCH (Chemical Abstracts)
- BIOSIS PREVIEWS (Biological Abstracts)
- AQUATIC SCIENCE AND FISHERIES ABSTRACTS
- METEOROLOGICAL/GEOASTROPHYSICAL ABSTRACTS
- DISSERTATION ABSTRACTS
- NTIS (National Technical Information Service)

The computer search results were obtained as both printouts and text files on IBM-formatted disks. The printouts were scanned for pertinent citations, which were then culled from the disk files using Word Perfect. The files were checked for spelling errors, and duplicate entries were removed. The data were edited into a common format, listing author, date, title, source publication, abstract (if available), and keywords.

The computer searches were very successful in pinpointing useful references. About 50 to 90% of the citations obtained from each data base were judged to be topically and geographically pertinent. The total number of references added from online data base searches (i.e., pertinent references not already added from the Tuscaloosa Trend bibliography) was 404. Most citations included abstracts and keywords. The keywords were retained initially for information purposes, though they were eventually replaced by a new set of keywords.

The National Environmental Data Referral Service (NEDRES) data base was also searched by contacting the NEDRES office in Washington, DC.

The NEDRES data base is a data locator that contains listings and descriptions of data sets from various environmental programs. Many of the entries also contain listings of publications from the studies. The NEDRES results were obtained as a printout only (no disk files), and nearly all of the publications listed were already obtained through other searches.

Publication Lists from Various Agencies and Organizations

Many additional references were obtained by contacting Federal and State agencies, universities, and research organizations in the Gulf of Mexico. A list of contacts is given in Table 2.1. In nearly all cases, the individual(s) contacted were able to supply us with a bibliography of publications or reports produced by their organization. Many of these also included abstracts. The total number of references added from these lists was 217.

Chapter Authors and In-House Library

All chapter authors were asked to submit lists of references, with abstracts if available, using the standard form shown in Figure 2.1. A total of 301 references were obtained in this manner (excluding those already in the data base from other sources). Also, the library reprint collections of Continental Shelf Associates, Inc. were searched manually for additional pertinent references. Another 117 references were added from this source--primarily unpublished technical reports, or "gray" literature. Included in the in-house literature was a second annotated bibliography, produced by TerEco Corporation (1979), covering the Texas continental shelf between Freeport and Sabine Pass.

2.1.2 Data Base Management and Computer Program

The bibliographic data base was compiled with a combination of computer programs on IBM-compatible computers: Word Perfect (a word processing program) for initial entry and text formatting, and FYI for indexing, searching, and sorting. FYI can operate on standard text files produced by the word processing program. This combination of programs has the advantage of easy keyboard entry, complete control of formatting, spelling check capability, and fast indexing of the resulting text files.

All citations for the annotated bibliography were formatted initially with Word Perfect, using a standard form that included blanks for the identification number (a five-digit number assigned sequentially as entries were added), author(s), date, title, source, abstract (if available), and keywords. These fields were chosen to match contract requirements for being able to search by author, date, geographic and topic keywords, words in the title, and words in the publication name. The text files in this original format were periodically indexed with FYI to keep track of the entries (avoid duplicates) and to help in refining the keyword assignments.

The text files containing the citations were kept on a 70-megabyte fixed drive that was backed up daily (all new or modified

Table 2.1. List of agencies and organizations contacted for literature or reference lists.

Agency/Organization	Contact(s)
FEDERAL AGENCIES	
Minerals Management Service Gulf of Mexico OCS Region New Orleans, LA	Public Information Section
National Marine Fisheries Service Galveston, TX	P. Sheridan
National Marine Fisheries Service Panama City, FL	R. Vaught
National Marine Fisheries Service Pascagoula, MS	S. Glynn
National Marine Fisheries Service Southeast Fisheries Center Miami, FL	L. Pulles
National Oceanic and Atmospheric Administration Atlantic Oceanographic and Meteorological Laboratories Miami, FL	G. Medina
National Oceanographic and Atmospheric Administration National Environmental Data Referral Service Washington, DC	M. Smith
National Oceanographic and Atmospheric Administration Marine Environmental Assessment Division Rockville, MD	K. Pechmann
U.S. Army Corps of Engineers New Orleans, LA	J. Hughes
U.S. Army Corps of Engineers Waterways Experiment Station Vicksburg, MS	Public Affairs Office
U.S. Department of Energy Strategic Petroleum Reserve Project	F. Kelly

Table 2.1. (Continued).

Agency/Organization	Contact(s)
U.S. Environmental Protection Agency Dallas, TX	Librarian
U.S. Fish and Wildlife Service National Wetlands Research Center Slidell, LA	Information Transfer Specialist
U.S. Geological Survey Baton Rouge, LA	P. Adams M. Eister W. McIntosh
U.S. National Park Service Padre Island National Seashore Padre Island, TX	M. Bjork
STATE AGENCIES	
Bureau of Economic Geology Austin, TX	T. Calnan
Louisiana Department of Natural Resources Coastal Management Division Baton Rouge, LA	P. Rooney
Louisiana Geological Survey Baton Rouge, LA	D. Lindstedt
Texas Parks and Wildlife Department Coastal Fisheries Branch Austin, TX	J. Telo
UNIVERSITIES/RESEARCH INSTITUTIONS	
Harbor Branch Oceanographic Institution Fort Pierce, FL	K. Metzger
Louisiana State University Sea Grant Program Baton Rouge, LA	Librarian
Louisiana Universities Marine Consortium Chauvin, LA	M. Sullivan

Table 2.1. (Continued).

Agency/Organization	Contact(s)
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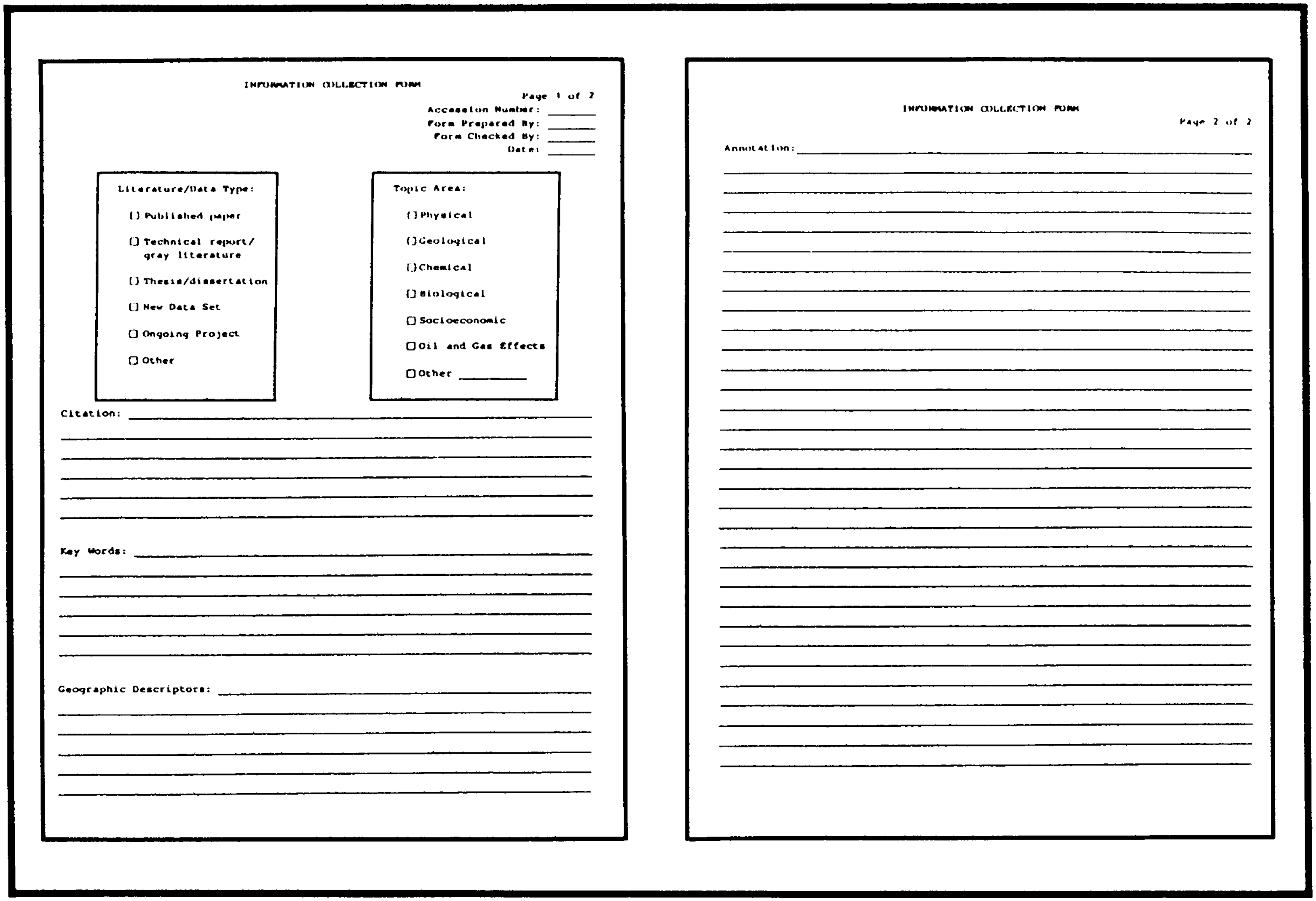
Texas A&M University Sea Grant Program College Station, TX	Marine Information Service



INFORMATION COLLECTION FORM

Page 1 of 2

Accession Number: ______
Form Prepared By: ______
Form Checked By: ______
Date: ______

Literature/Data Type:

- [] Published paper
- [] Technical report/ gray literature
- [] Thesis/dissertation
- [] New Data Set
- [] Ongoing Project
- [] Other

Topic Area:

- [] Physical
- [] Geological
- [] Chemical
- [] Biological
- [] Socioeconomic
- [] Oil and Gas Effects
- [] Other ______

Citation: ______

Key Words: ______

Geographic Descriptors: ______

INFORMATION COLLECTION FORM

Page 2 of 2

Annotation: ______

Figure 2.1. Information collection form.

files), weekly (all files), and monthly (all files, with off-site storage of the tape).

Once all of the entries had been added to the data base, we copied the original eight text files into a master text file, sorted the entries by author and date, assigned new identification numbers corresponding to the sorted list, and then formatted the text automatically through global "macros" created in Word Perfect. For the printed bibliography, this master file was then printed directly using Word Perfect (see Volume III for format). For the computer-accessible bibliography, we split the master file into four ≈350K text files (so that each could fit on a double-sided, double-density floppy disk), made some minor formatting changes (e.g., placing ID#: before each identification number to mark the beginning of each entry), then saved each file as a plain ASCII text file. These files were then indexed with FYI as described below.

The FYI program allows the user to define beginning and ending markers for entries, default keyword separators and logical operators, and keyword field markers. Only one field can be indexed in each "filing system;" however, a given data base can be indexed multiple times to set up multiple filing systems. In this case, the program was set up to index and search the data base in three different ways:

- Keywords--searching by topic and geographic keywords (any combination, with wildcards and logical operators).

- Author/Date--searching by individual authors and publication dates (any combination, with wildcards and logical operators).

- Citation--searching by full citation, which includes author names (without initials), words in the title, and words in the publication source (any combination, with wildcards and logical operators).

Once a search request is entered, the program immediately reports the number of citations matching the request. These citations can then be viewed on the screen ("browsing"), sent to the printer, or saved in a separate disk file. Because the bibliography has been sorted by author and date prior to indexing, all output to a printer or disk file will automatically be sorted in the same way.

2.1.3 Keyword Assignments

Keywords are critical to the usefulness of the computerized bibliography, because they are the most common means of searching for references. We started assigning keywords once a significant number of citations had been entered into the data base. The keyword assignment process went through several iterations, as new keywords were added and others discarded. To ensure that keywords were assigned consistently, we developed a standard vocabulary, which was applied by one person to the entire data base.

Two main types of keywords were used: geographic and subject. The manner in which each type of keyword was applied is described below. A complete list of keywords for the annotated bibliography is contained in the Appendix of Volume III.

Geographic Descriptors

The geographic descriptors consisted of place names and habitat descriptors. Place names included the following major terms:

Alabama
Florida
Louisiana
Mexico
Mississippi
Texas

The more general term "Gulf of Mexico" was applied if the exact location in relation to Gulf coastal states could not be identified. Also, if major parts of the study were outside the Gulf of Mexico, then terms such as "Atlantic Ocean" and "Pacific Ocean" were applied. For very general works applicable to the whole country, the term "United States" was applied.

If a study focused on an area of special interest, specific geographic terms were added to the keyword list for that entry. Examples include the Flower Garden Banks, the Mississippi River Delta, and most of the coastal bays of Louisiana and Texas.

Finally, at least one of the following major habitat descriptors was assigned to each entry (if it was possible to discern the habitat from the paper or abstract):

barrier island
beach
marsh
estuary
coastal waters
continental shelf
continental slope
deep sea

Topic Keywords

In addition to the geographic descriptors, major topic keywords were assigned to each entry. One or more of the following keywords was assigned to each citation:

Archaeology
Biology
Chemistry
Fisheries
Geology
Oil and Gas
Physical
Socioeconomics

Additional topic descriptors were added to each entry from the list in the Appendix of Volume III. Examples are "taxonomy" or "endangered species" under Biology, and "trace metal" or "pesticide" under Chemistry, etc.

Special topic descriptors were assigned to identify reports or papers from major oil and gas related studies in the area:

Buccaneer Field
Central Gulf Platform Study
Ixtoc
Offshore Ecology Investigation
STOCS
Strategic Petroleum Reserve

2.2 INFORMATION SYNTHESIS

2.2.1 Characterization of the Study Area

Chapter authors were responsible for summarizing and synthesizing the available information on their assigned topics. Each author was directed to include a discussion of data gaps and information needs at the end of the chapter.

The annotated bibliography was being compiled at the same time that the synthesis chapters were being written. Therefore, authors did not receive a complete printout of citations and abstracts for their topics. However, interim list of references in certain topic areas were printed on request for the authors. In general, the authors were already familiar with most of the pertinent references in their topic area(s).

2.2.2 Conceptual Modeling

Once the characterization chapters (Geology, Physical Oceanography and Meteorology, Marine Chemistry, Marine Biology, and Socioeconomics) were completed in draft form, the Program Manager sent copies to Dr. Darnell for use in the Conceptual Modeling chapter. This information was used to decide on the major ecosystems of the study area and the selected components for modeling.

CHAPTER 3
MARINE GEOLOGY

Richard Rezak

3.1 INTRODUCTION

The area under study extends seaward from the coastal region across the continental shelf to the continental slope, and from the western edge of Mississippi Sound to Corpus Christi, Texas. Figure 3.1 illustrates the bathymetry and physiographic features of the Gulf of Mexico. The major features of the study area are the Mississippi River Delta, the Texas-Louisiana shelf, and the complexly dissected Texas-Louisiana slope. In this report, we will examine the work that has been done in these regions, focusing on certain specific features within the regions to determine what further work, if any, needs to be undertaken.

3.1.1 Role of Geology in Ecosystems Studies

Studies have demonstrated that there is an intimate relationship between biological assemblages, geological factors, and hydrological conditions in any given area (Rezak, 1985; Rezak et al., 1985). The nature of the substrate is an important factor in controlling biotic distribution. For example, reef-building organisms require the presence of a hard substrate for their growth. Clear water, another requisite for reef growth, also may result from the presence of a hard substrate. However, not all areas of hard substrate are bathed in clear water. Some low-relief, hard bottoms may be immersed in turbid water (nepheloid layer) if they are surrounded by muddy, terrigenous sediments. The biota of such a hard bottom will consist predominantly of filter feeders, and the skeletal remains of these organisms will accumulate and gradually raise the hard substrate above the top of the nepheloid layer; at that point in time, reef-building organisms may begin to populate the substrate.

Tectonics, such as the salt diapirism so common on the Texas-Louisiana shelf, can speed up the process of raising the substrate above the nepheloid layer. The reef-building biota then begins to influence the geology and hydrology by contributing a variety of skeletal materials to the reef and its surrounding sediment apron, and by increasing current velocities as currents are steered around the bathymetric prominence. The increased current velocities perpetuate the clear water conditions as they winnow any fine sediment away from the reef as soon as it is produced, leaving only the coarser fraction as a lag deposit.

Studies of macroinfaunal and meiofaunal assemblages have demonstrated that sediment texture has a strong influence on their species composition (Parker, 1960; Harper, 1970).

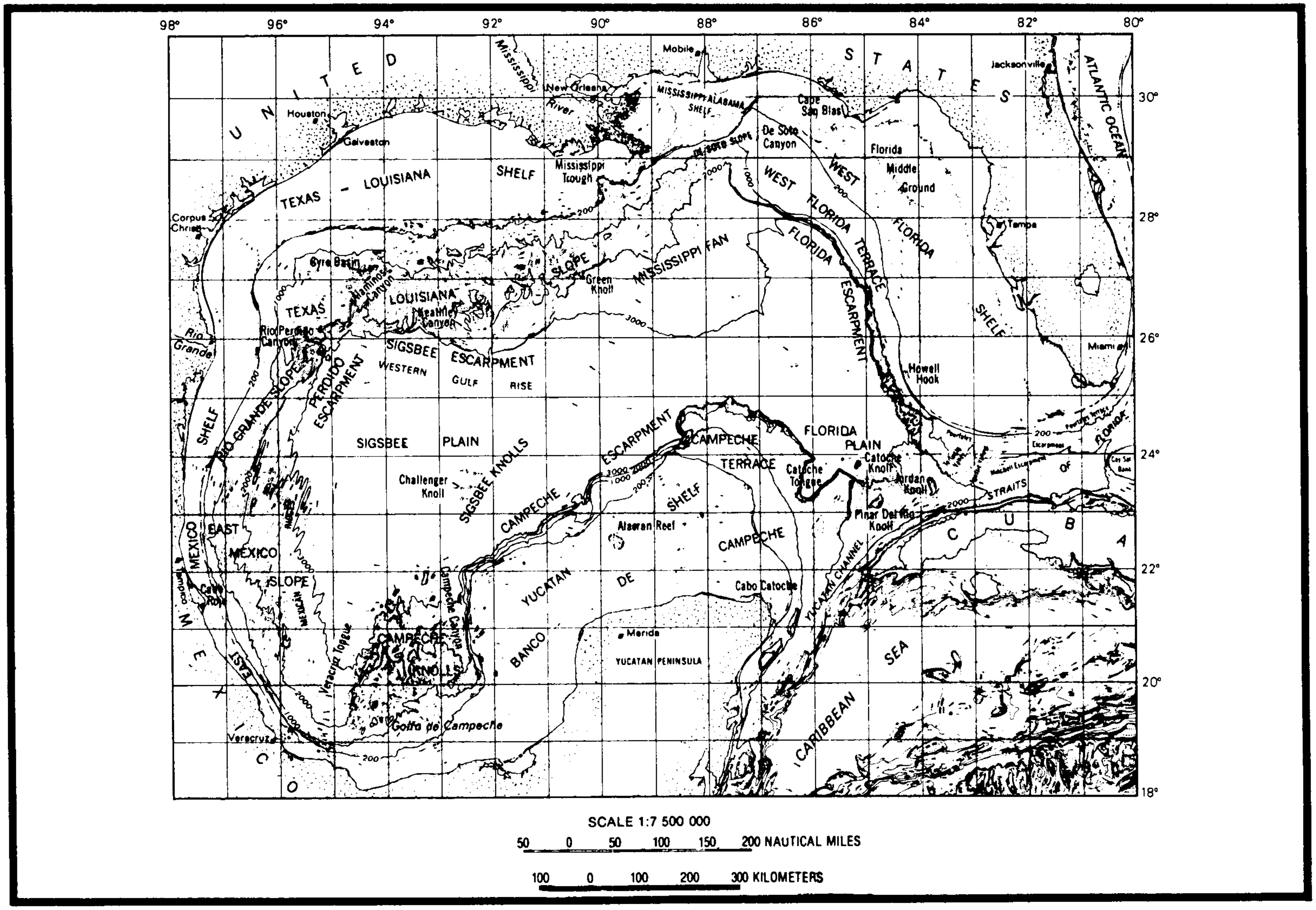


Figure 3.1. Bathymetry and major physiographic features of the Gulf of Mexico (From: Martin and Bouma, 1978).

3.1.2 Geologic History

Much has been written about the geologic history of the Gulf of Mexico, but it has been only in the past decade, through the use of multichannel seismic reflection surveys, ocean bottom seismograph refraction surveys, and the development of more sophisticated geophysical and plate tectonic models, that a clearer picture of the early history of the Gulf has emerged (Pilger, 1980; Buffler et al., 1980; Ibrahim et al., 1981).

The Gulf of Mexico is a small ocean basin (Menard, 1967) that is sometimes referred to as the American Mediterranean (Harding and Nowlin, 1966). It originated approximately 160 million years ago (Late Jurassic time) due to the rifting of the North American, African, and South American Plates (Humphris, 1978). The shallow, primordial Gulf has gradually evolved into its present configuration, being enlarged due to continued spreading, deepened due to subsidence, and slowly filled by sedimentation. Sedimentation and subsidence will continue as long as streams flow into the Gulf from the continent and lime-secreting organisms continue to thrive in areas of low stream outflow. Late Triassic and Early Jurassic time saw continental conditions in the area now occupied by the Gulf of Mexico (Salvador, 1980). As the North American Plate began to move away from the African and South American Plates, tensional grabens began to form in the area. These were filled with red beds and volcanics. With continued subsidence of the area, Pacific waters began to encroach by way of central Mexico during the latter part of the Middle Jurassic. Throughout the latter part of the Middle Jurassic and the early part of the Late Jurassic, the area was covered intermittently by shallow seawater that evaporated and produced the extensive salt deposits that we know as the Louann Salt. Connection with the Atlantic Ocean was finally established during the Late Jurassic (about 150 million years ago). Evaporite conditions ceased at that time, and shallow marine limestones began to be deposited. Deposition of shallow marine limestones continued into the Middle Cretaceous (about 100 million years ago) and culminated in an extensive shelf-edge reef complex composed mainly of rudistids, corals, algae, and foraminifera. The reef complex occurs in the subsurface of south Texas (Figure 3.2) and continues in the subsurface trending northeastward into southern Louisiana.

The most significant feature of post Mesozoic history of the Gulf has been the tremendous seaward growth of the Texas-Louisiana continental shelf. Early in Cenozoic time (about 60 million years ago), the Gulf began to receive the detritus from the Laramide Orogeny (formation of the modern Rocky Mountains) to the west and northwest. The major transporters of this sediment were the Mississippi and Rio Grande Rivers. The supply of sediment was so great that the rate of basin subsidence could not accommodate the great volume of material. As a result, the shelf edge prograded by as much as 400 km from the edge of the Cretaceous shelf to the present shelf break (Lehner, 1969; Woodbury et al., 1973). This great wedge of sediment, consisting mainly of terrigenous sandstones and shales, is approximately 15 km thick beneath the present coastline (Figure 3.2).

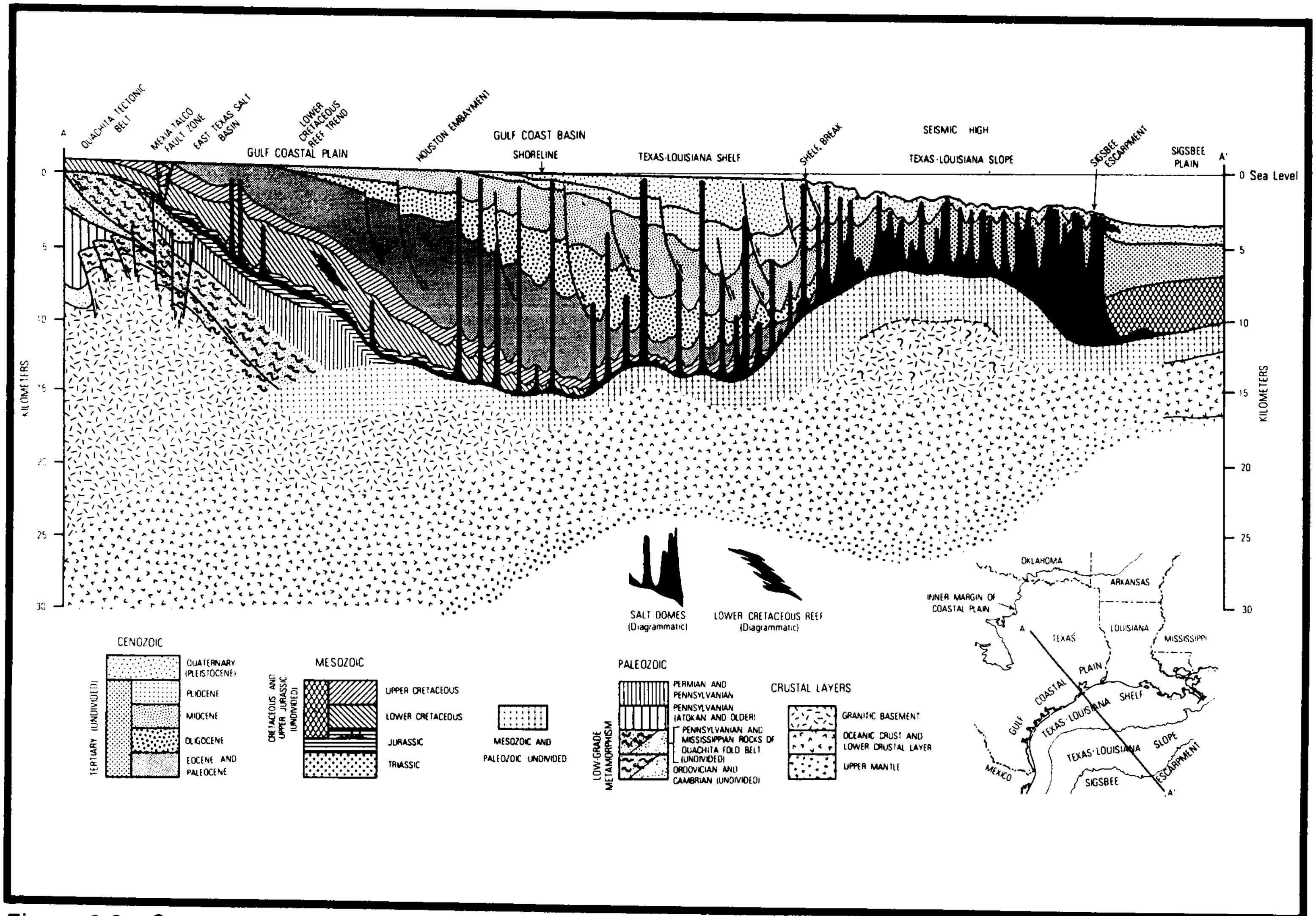


Figure 3.2. Structure section from Central Texas to the Sigsbee Plain (From: Martin, 1978).

3.2 COASTAL REGION

3.2.1 Physiography and Sediments

The coastal region of Texas and Louisiana can be divided into the following provinces:

- Mississippi River Delta.
- Chenier Plain.
- Barrier Islands.

Each province is discussed below with respect to physiography and sediments.

Mississippi River Delta Province

Physiography. The Mississippi River Delta has been described by Russell (1936), Russell and Russell (1939), Fisk et al. (1954), Kolb and Van Lopik (1958), Scruton (1960), Shepard (1960), Coleman (1976, 1982), Coleman and Wright (1971, 1973, 1974, 1975), and others. The Mississippi River drains an area of over 3,344,560 km^2. Annual sediment discharge is estimated to be about 2.4 x 10^{11} kg, and over the last 7,000 years, a deltaic plain was built having a total area of 28,568 km^2, nearly 85% of which is subaerial. The outflow of the Mississippi has migrated back and forth along this stretch of the Gulf Coast since early Tertiary time. During the Miocene, the outflow was close to Sabine Lake; since that time, the delta has migrated eastward to Mississippi Sound and then back toward the west and its current position. Figure 3.3 shows the locations of the various delta lobes and their sequence of development during the past 7,000 years. The area of Figure 3.4 is shown on Figure 3.3 as the Balize Lobe and illustrates the subdeltas of the modern birdfoot delta of the Mississippi River. Of the six subdeltas, only four have been dated. The earliest subdelta of the four is 150 years old.

After abandonment of a delta lobe, bay fill sedimentation stops, and subsidence and coastal retreat become the principal natural process. Coarse sediments become reworked by wave action, and barrier islands and bars may develop near the fringes of the once active delta lobe (Penland and Boyd, 1981). The St. Bernard, LaFourche, and Teche lobes (Figure 3.3) illustrate very well the results of this process. The Chandeleur Islands have resulted from the redistribution of St. Bernard Delta sands (Otvos, 1985). Redistribution of the sands in the LaFourche and Teche Deltas is responsible for the barrier islands at the mouths of Barataria and Timbalier Bays.

Sediments. The sediment discharge of the Mississippi River consists primarily of clay, silt, and fine sand, with clay amounting to about 70% of the total sediment load. The sediments of the subaerial part of the delta may be subdivided into (1) channel deposits (sands); (2) natural levee of overbank splays (sands and silts); (3) interdistributary bays (silts and clays); (4) marsh (peats); and (5) crevasse splays or bay fills (alternations of sands, silts, and organic clays with occasional peat layers). Beaches that may form at the seaward margins of interdistributary marshes consist of lag deposits of

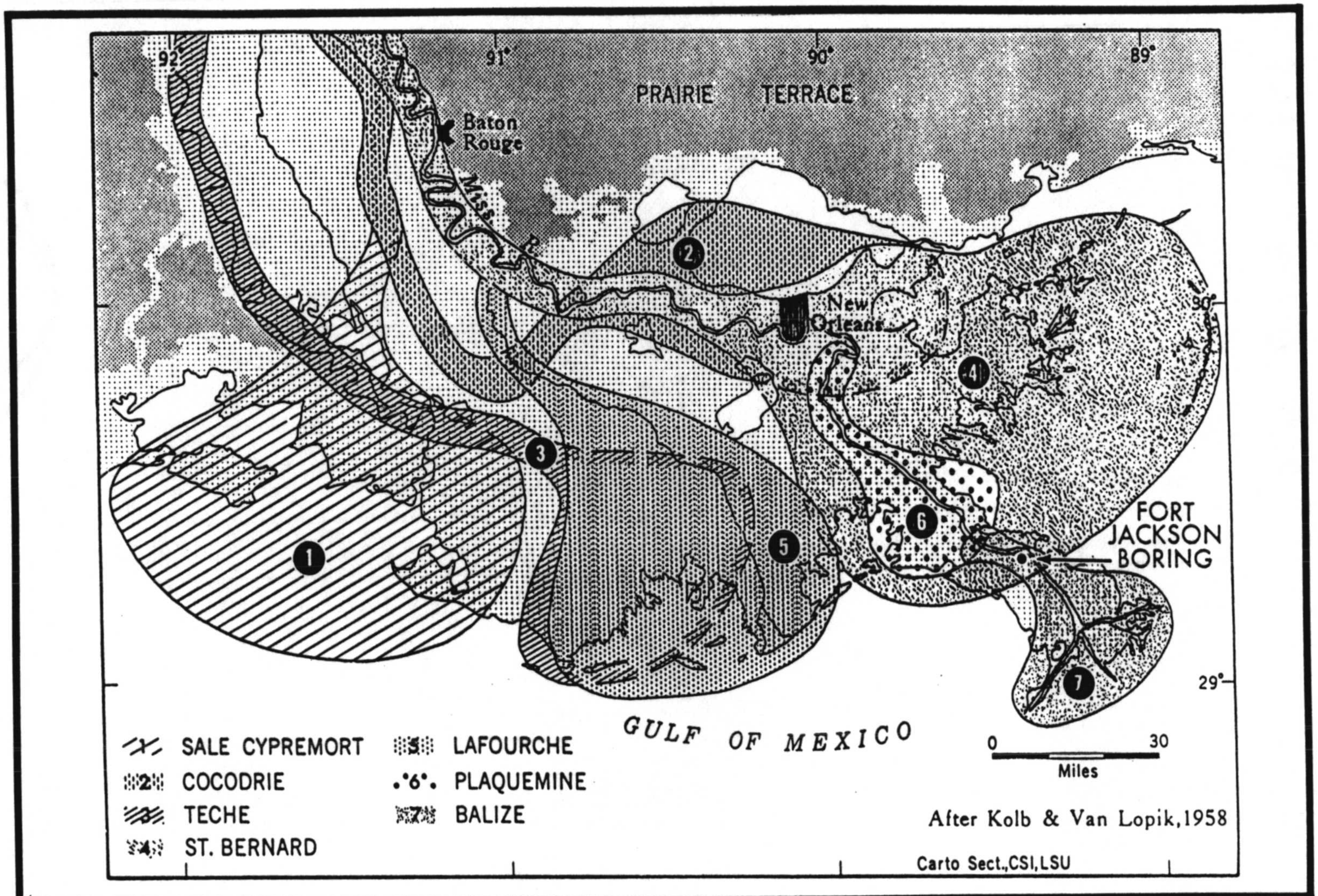


Figure 3.3. Mississippi River Delta lobes (From: Coleman, 1976).

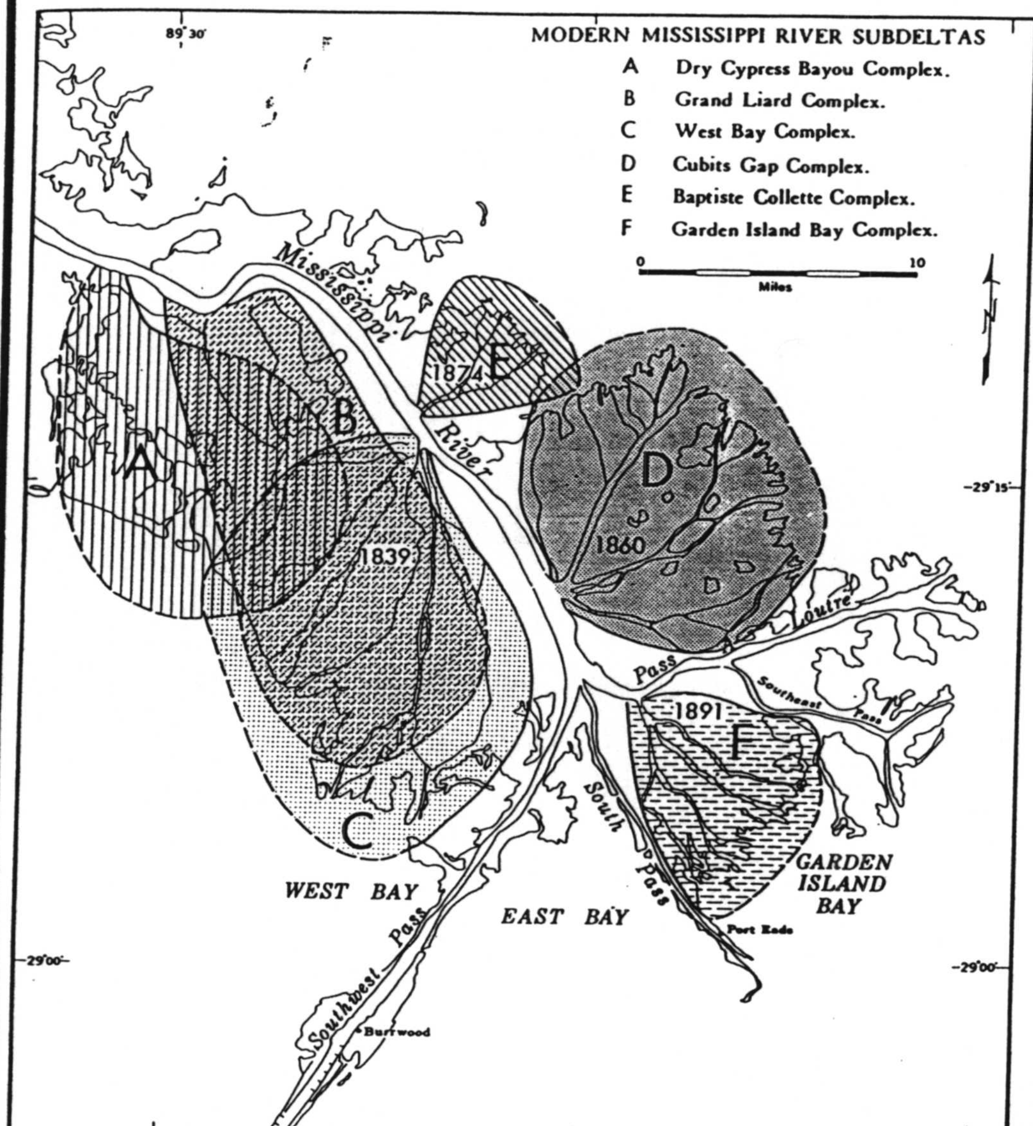


Figure 3.4. Modern Mississippi River subdeltas (From: Coleman, 1976).

sand and shell that have been winnowed by wave action from the sandy muds of the interdistributary bay.

Chenier Plain Province

Physiography. The area between the western shore of Vermilion Bay and Sabine Lake, at the boundary between Louisiana and Texas, is known as the Chenier Plain (Morgan et al., 1953; Van Lopik, 1955; Van Andel and Curray, 1960; LeBlanc, 1972). The plain consists of low ridges of sand separated by marshy swales underlain by sandy muds.

Sediments. The sand ridges (Cheniers) are beach deposits that have formed in a rather unusual manner. LeBlanc (1972) presented a conceptual development model for these beach ridges. Shoreline accretion in this area is mainly by massive influxes of mud and sand from the Mississippi River Delta, which are eroded and transported by longshore currents into the Chenier Plain area where they are deposited as muddy tidal flats. Repeated minor fluctuations in sea level over long periods of time eroded the margin of the mud flats and winnowed the fine sediment particles, leaving a lag of fine sand and silt, with coarser shell debris along the shoreline. Later renewed influx of muds moves the shoreline further seaward and the process is repeated. The very rapid rate of sedimentation in this area has effectively sealed streams such as the Calcasieu and Mermentau Rivers, creating vast coastal marshes and lakes.

Barrier Islands Province

Physiography. The coast between Sabine Pass and Port Isabel, TX is characterized by barrier islands that separate lagoons, embayments, and estuaries from the main body of the Gulf of Mexico (McGowen and Morton, 1979; White et al., 1983, 1985, 1986, 1987). Most of the streams that flow into the Gulf along this stretch of coastline do not drain very large areas, and climate varies from subhumid in the Galveston area to semi-arid south of Corpus Christi. As a result, most streams that drain the area deposit small deltas in the bays and lagoons. Bay depths range from 0.6 to 4.9 m.

Sediments. In addition to the stream input, bay sediments are derived from erosion of Pleistocene outcrops along the bay shores, flood tide deltas, and washover fans created during tropical storms and hurricanes. Locally produced carbonate sediment is in the form of oyster reefs, serpulid reefs, and shells of various kinds. Sediment types in the bays are primarily muds, sandy muds, shelly sandy muds, and muddy sands. Fine sands occur on spoil banks and beaches where waves can winnow out the finer sediments (McGowen and Morton, 1979). The barrier islands prevent the lesser streams in the study area from building deltas on the continental shelf. Their sediments are trapped behind the barrier islands in bays and lagoons. Only after periods of heavy rainfall during tropical storms or hurricanes are plumes of fine sediment seen flowing out of the passes and onto the inner continental shelf.

The growth of the Colorado River Delta across the 7-km wide Matagorda Bay between 1929 and 1956 is an example of spectacular delta growth behind a barrier island (Bouma and Bryant, 1969; Kanes, 1970; Shepard and Wanless, 1971). Normal growth of the delta was retarded by a log jam that was removed by a flood in 1929. In 1936, the U.S. Army Corps of Engineers dug a canal across Matagorda Peninsula, and the Colorado now flows into the open Gulf of Mexico. No delta has developed at the mouth of the river, owing to the rapid removal of sediments by longshore currents.

3.2.2 Geologic Structure

The subbottom strata in the Coastal Region dip gently in a seaward direction. Deep-seated salt domes are scattered across the Coastal Region from east of Matagorda Bay to as far east as the Mississippi River Delta (DeGolyer, 1925; Barton, 1933; Murray, 1961; Overton, 1975; Martin, 1978; Fisher et al., 1973; McGowen et al., 1976; McGowen and Morton, 1979). These piercement structures have surface expressions that range from about 1 m at the Markham Dome, Matagorda County, Texas to as much as 23 m at Damon Mound, in Brazoria County, Texas (Frost and Schafersman, 1978). Growth faults are common in the area, but they are generally inactive.

3.3 CONTINENTAL SHELF

3.3.1 Physiography

The northwestern Gulf, from the Mississippi River to the Rio Grande River, illustrates very clearly the influence of deltaic sedimentation on the character of the continental shelf. The Mississippi River, because of its great drainage area, has been the major contributor of deltaic sediments throughout Cenozoic time and as a consequence has built an extremely wide continental shelf (about 200 km wide measured south of Sabine Pass). Two minor (Brazos-Colorado and Rio Grande) deltas have contributed lesser amounts of sediment to the Texas-Louisiana shelf, which is only about 80 km wide off the mouth of the Rio Grande. The Louisiana shelf narrows very rapidly where the currently active lobe of the Mississippi Delta has built out to the shelf break southeast of New Orleans. The seaward margin of the shelf is a poorly defined break in slope at a depth of about 120 m (Martin and Bouma, 1978). The surface of the shelf is generally smooth, with some local areas of subdued topography remaining from times of exposure due to lowered sea level. Reefs and banks are the most striking topographic features on the shelf. Some are outcrops of Tertiary and Cretaceous siltstone, claystone, and basalt exposed at the seafloor by salt diapirism. Others are carbonate caps on outcrops of Tertiary and Cretaceous bedrock, or coralgal reefs that grew on a Pleistocene carbonate platform.

3.3.2 Sediments

The sediments on the continental shelf reflect the environments of their adjacent coasts. This is a natural relationship, as sea level has risen approximately 130 m during the past 16,000 to 18,000 years and these same environments have migrated across the shelf to their present locations. Consequently, the areas delineated by Curray (1960) to subdivide the continental shelf are still valid for the entire study area. Figure 3.5 illustrates the four major divisions, beginning in the east with the Central Louisiana Area, which is most affected by the Mississippi River outflow. The western boundary of that area lies near a line drawn southward from a point just to the west of Vermilion Bay. The Central Area extends from there to a line drawn to the southeast from the western tip of Matagorda Island. The Western Area extends from the western tip of Matagorda Island to a point about 15 km north of Port Isabel. The Rio Grande Area covers the area of the Rio Grande Delta (outside of the current study area).

Central Louisiana Area

Although the shelf off the western border of Louisiana is over 200 km wide, it narrows rapidly towards the east, and the active lobe of the delta has built out to the shelf break and is depositing most of its load on the upper continental slope. The head of Mississippi Trough cuts into the outer continental shelf about 75 km west of Southwest Pass (Figure 3.5). As result of rapid sedimentation of large volumes of sediment close to the shelf break and on the upper slope, large scale mass movement of sediments is common in those areas. Regional patterns of some of the more common features and their origins have been presented by Bea (1971), Bea and Arnold (1973), Coleman et al. (1974, 1980), Roberts et al. (1976), Suhayda et al. (1976), Garrison (1974), and Whelan et al. (1976). The major types of sediment mass movement in the modern delta are as follows:

- Peripheral faulting and rotational slumping.
- Differential weighting and diapirism.
- Radial graben and tensional faulting.
- Massive mudflows.
- Mass wasting and flowage induced by wave motion and degassing.
- A wide variety of shelf edge arcuate slumps and contemporaneous faulting associated with the shelf edge (Coleman, 1976).

Figure 3.5 shows the sediments of this area to be sands and alternating sands and muds near shore, grading seaward into a large area of muds.

Central Area

After heavy rainfall from the passage of hurricanes or tropical storms, plumes of turbid water can be seen flowing out of the passes in the barrier islands. These plumes are rapidly entrained in the longshore drifts and are generally deposited not far offshore, where their fine fraction is then incorporated in the bottom boundary layer and transported offshore as a nepheloid layer (Shideler, 1978; Sahl et al., 1987). The sediments on the inner continental shelf range from sands and shelly sands on the beaches of the barrier islands to muddy sands and fine sands from a few miles offshore to the shelf break. These sediments are relict nearshore sands deposited during the Holocene rise in sea level. A narrow band of muddy sediment parallels the coast from the mouth of the Brazos River to the southern boundary of the Central

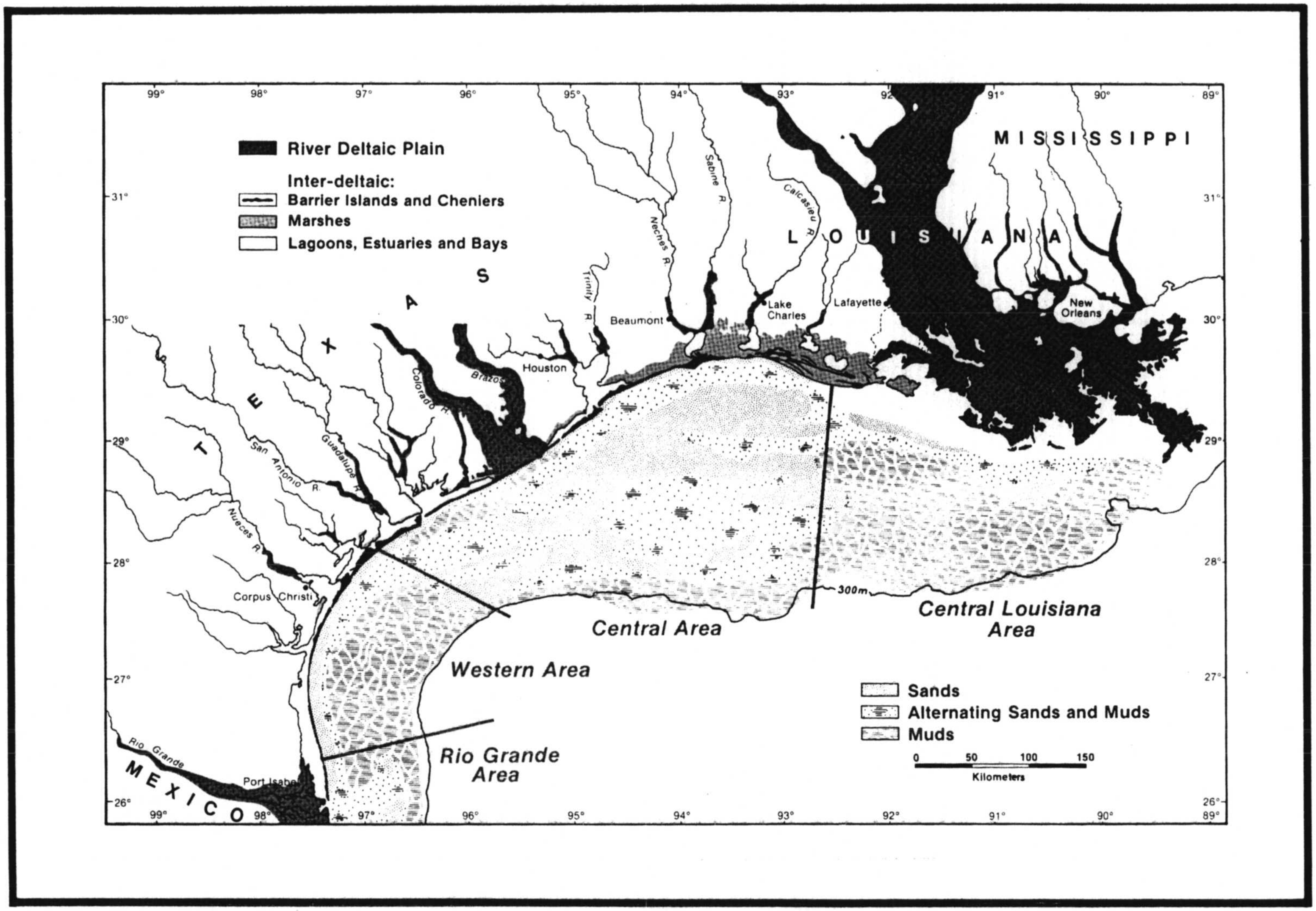


Figure 3.5. Location of areas and general sediment distribution (From: Rezak et al., 1985).

Area. This band lies in the same area where plumes of sediment appear on satellite photos as they are entrained in the longshore drift following heavy rainfall.

Western Area

The Western Area is characterized by predominantly muddy sediments. The beach and nearshore deposits are sands that grade into a narrow band of muddy sand to sandy mud a few miles offshore. Shideler (1977) suggests that the large area of interdelta mud derived from multiple coastal sources. Dead coral reefs on the South Texas shelf yield dates of about 10,500 to 18,000 years BP (Rezak et al., 1985). Their growth and demise will be discussed in Section 3.5.

3.3.3 Geologic Structure

The continental shelf off Texas and Louisiana is characterized by diapiric salt structures from near shore to the shelf break. They are usually subsurface features on the inner half of the shelf, but on the outer half of the shelf, many are seen as topographic features. Some have a relief of 100 m or more. These will be discussed in more detail in Section 3.5.

3.4 CONTINENTAL SLOPE

3.4.1 Physiography

The Texas-Louisiana slope is a 120,000 km^2 area of hill and basin topography (Figure 3.1). It extends from the Mississippi Fan on the east to the abrupt bend to the south off Corpus Christi, where it merges with the Rio Grande slope (Martin and Bouma, 1978). The hill and basin topography is created by salt diapirs, and extends from the shelf break to a depth of 2,800 m (Ewing and Antoine, 1966; Lehner, 1969; Wilhelm and Ewing, 1972; Garrison and Martin, 1973). Bouma (1982) divides the intraslope basin into three basic categories: blocked canyons, interdomal basins, and collapse basins. The Sigsbee Escarpment forms the Continental Rise at the base of the Texas-Louisiana slope. It extends from Alaminos Canyon to the Mississippi Fan.

3.4.2 Sediments

The sediments of the upper continental slope are primarily terrigenous, sandy clays with lesser amounts of nannoplankton. Liquid and gaseous hydrocarbon seeps are numerous off the Mississippi Delta in water depths of 100 to 2,000 m. The normal sediments in these areas are terrigenous clays. However, carbonates are also significant; they occur as highly calcareous hemipelagics, carbonate cemented clays, shell hash, hardgrounds, mounds, and bioherms. The cements are aragonite, Mg-calcite, and minor amounts of siderite (Roberts et al., 1987).

3.4.3 Geologic Structure

Mass movement of sediments as described for the Central Louisiana shelf area in Section 3.3.2 are also common on the upper slope off the Mississippi River Delta (Coleman et al., 1980). N.S. Hardin (1987) delineates four areas along the Texas-Louisiana slope where mass transport deposits were identified on high-resolution seismic profiles. Three of these mass transport features are in the study area. At East Breaks, a single event of large-scale sediment failure created a huge separation scar along an oversteepened delta front. The deposit is 135 m thick and about 55 km long. The large High Island flow-and-slide complex has a maximum width of 35 km and extends downslope at least 58 km. Upslope from the complex are two late Wisconsin shelf margin deltas mapped by Suter and Berryhill (1985). Hardin (1987) suggests that perhaps the two deltas were originally one large delta prior to the mass transport event. The four areas are illustrated with seismic records (Hardin, 1987) and represent the major slope failures in the study area. There are certainly many more.

Coleman et al. (1983) describe mass movement of sediment on a large scale associated with the Mississippi Canyon. A canyon 500 m deep was cut into the shelf during the late Wisconsin. It formed in only 5,000 to 7,000 years and was filled almost simultaneously by late Wisconsin delta lobes north of the trough.

A common type of mass movement that is seen on most seismic reflection profiles that cross the continental slope is the slow sediment creep that appears as parallel ridges moving downslope (Sidner et al., 1978).

Other structures on the upper continental slope include salt diapirs, salt ridges, and growth faults. Salt structures are more common east of 95°W Long. They will be discussed in Section 3.5. Growth faults are down to the basin faults that form contemporaneously with deposition. They begin to form on the upper slope due to the overburden load. Fault surfaces are steep near the surface and tend to level out as the depth increases. This kind of fault is characterized by the downthrown side having thicker sequences than thinner correlative units on the landward upthrown side. Differential compaction and gravity creep are probably the most important factors in growth fault mechanics (Martin, 1978).

3.5 DISTRIBUTION OF HARD AND SOFT SUBSTRATES

A line drawn from Matagorda Bay to the shelf break (Figure 3.6) divides the Texas continental shelf into a southern area of dead coralgal reefs that grew on a Pleistocene to Holocene carbonate shelf and an area of banks situated on salt diapirs to the east (Rezak et al., 1985). The banks to the east of the line are, depending on their location on the shelf, either relatively bare bedrock outcrops, coralgal caps on salt diapirs, or mixtures of the two types.

3.5.1 South Texas Shelf Reefs

Numerous dead coralgal reefs occur on the South Texas shelf between the 60 m and 90 m isobaths. No cores have been drilled into these reefs, but rock dredging and sampling by submersible have recovered dead coral and coralline algae from their surfaces. The reefs vary in

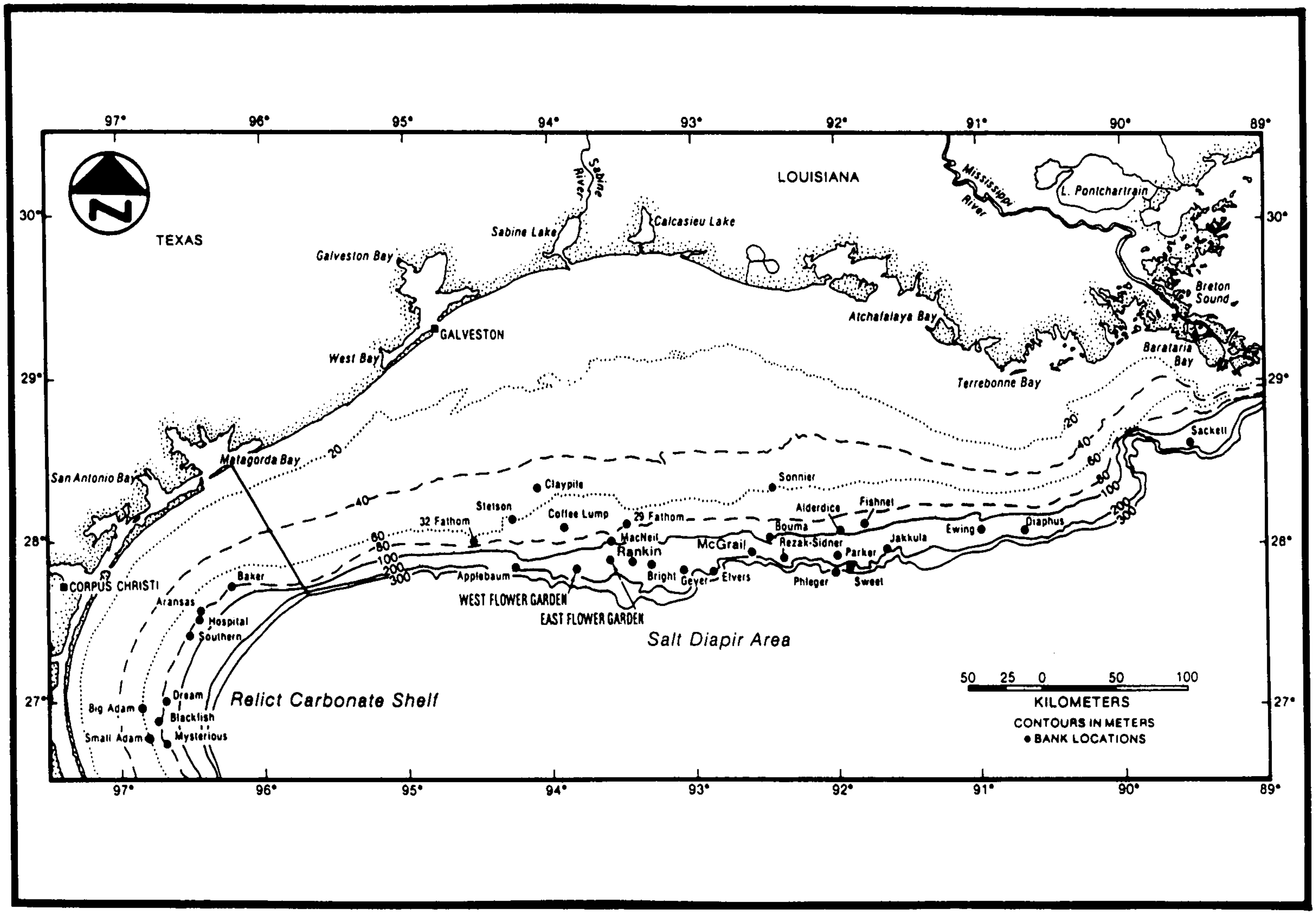


Figure 3.6. Location map of selected banks on the Texas–Louisiana shelf and upper slope (From: Rezak et al., 1985). The line from Matagorda Bay to the shelf break separates the Relict Carbonate Shelf from the Salt Diapir Area.

surface relief from 1 to 22 m. The biota presently growing on the banks is not the same as the one that constructed them (Rezak et al., 1985).

Berryhill et al. (1976) illustrate a seismic profile across Baker Bank (about 110 km east of Corpus Christi) showing continuous flat reflectors beneath the bank (Figure 3.7). Berryhill et al. (1976) illustrate seismic profiles across three other South Texas banks that also show no signs of association with salt diapirs. Rezak et al. (1985), based on work by Lindquist (1978) at Southern Bank, concluded that these reefs were growing on a carbonate shelf during the Late Pleistocene and Early Holocene. The death of the reefs was due to an event that occurred at Southern Bank about 18,000 years BP and reached Dream Bank about 10,500 years BP. The demise of the reef building communities is believed to have been due to the inception of the nepheloid layer, which today covers all but the crests of a few of the higher relief banks. The source of the influx of the terrigenous sediments was most probably the ancestral Brazos-Colorado Delta complex.

3.5.2 North Texas-Louisiana Reefs and Banks

All of the reefs and banks on the north Texas-Louisiana continental shelf and slope are associated with salt diapirs (Rezak and Bright, 1981a) or structures caused by salt tectonics (Rezak and Feeley, 1982) (see Figures 3.2 and 3.8). Most of the banks are circular to ovate in plan view, but many have various other shapes such as tilted fault blocks, isolated ridges, multiple pinnacles in local areas of the sea floor, or a variety of other shapes. Some of the shapes may be inherited from pre-Middle Jurassic structures prior to lateral injection of salt, and others are the result of structural complications by contemporaneous growth faults.

The surface expression and structural character of salt domes is additionally dependent on the depth of the salt below the seafloor, the relative rates of sediment accumulation and upthrusting of salt, and the relative rates of upthrusting and collapse of the overlying cap rock or sediments due to the removal of salt by dissolution. If the rate of sediment accumulation exceeds that of the upward movement of salt, there will be no surface expression of the diapir. Reflection seismic profiles will show nearly horizontal strata near the surface, with a broad doming of the underlying strata beginning at a depth representing the time when the rate of uplift lagged behind the rate of sediment accumulation. However, if the rate of upthrusting exceeds that of sediment accumulation, a piercement structure will develop and when the salt reaches the zone of dissolution (about 300 m below the seafloor; Rezak and Bright, 1981a), removal of solid salt will begin and collapse of the cap rock and overlying sediments into the crest of the diapir soon follows. At that point, collapse and upthrusting are the opposing forces. The resultant of these two opposing forces most probably varies with time, giving rise to crestal grabens that may be filled with sediments at times and uplifted to form high relief at other times.

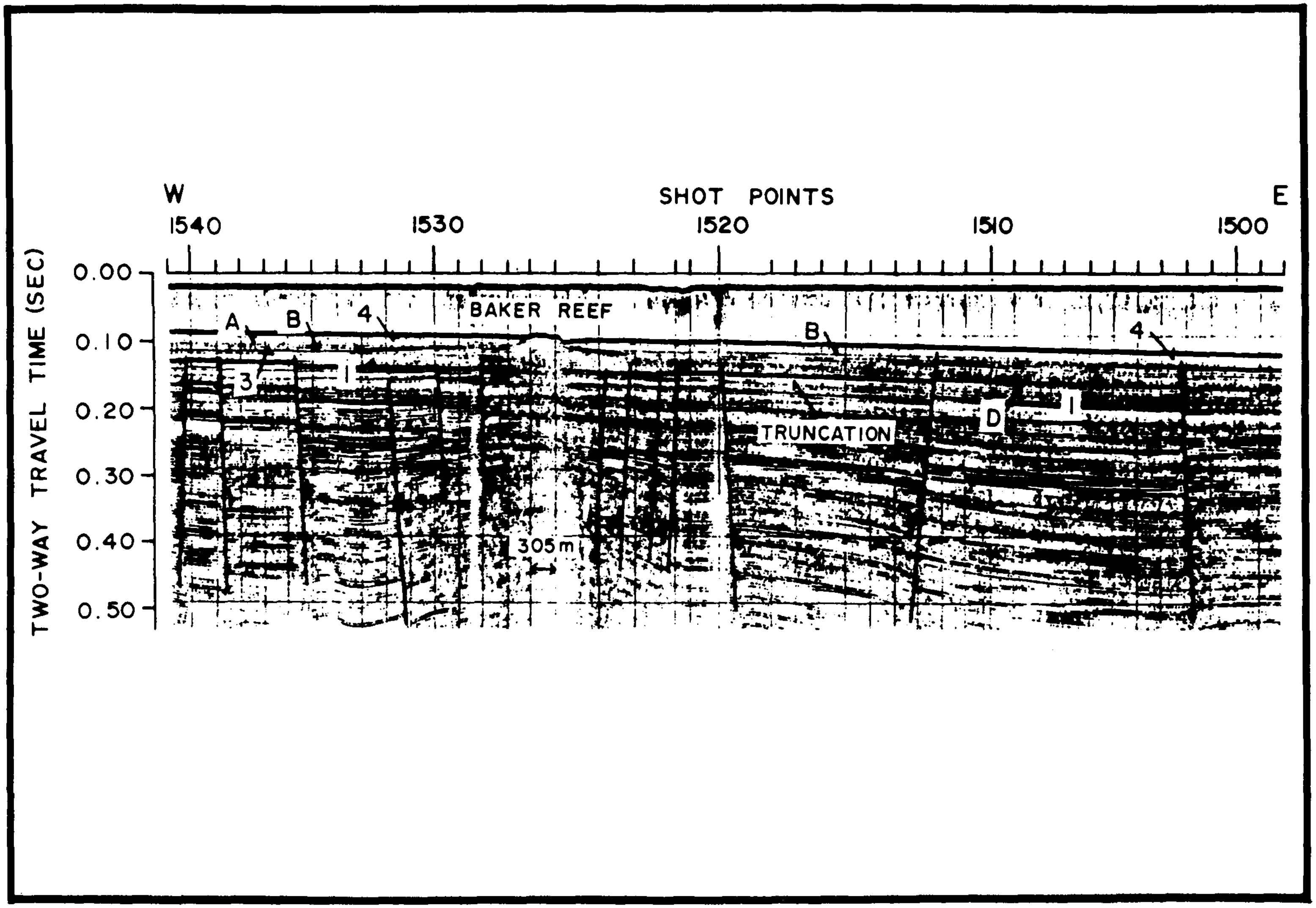


Figure 3.7. Seismic reflection profile across Baker Bank showing continuous reflectors under the bank (From: Berryhill, 1976).

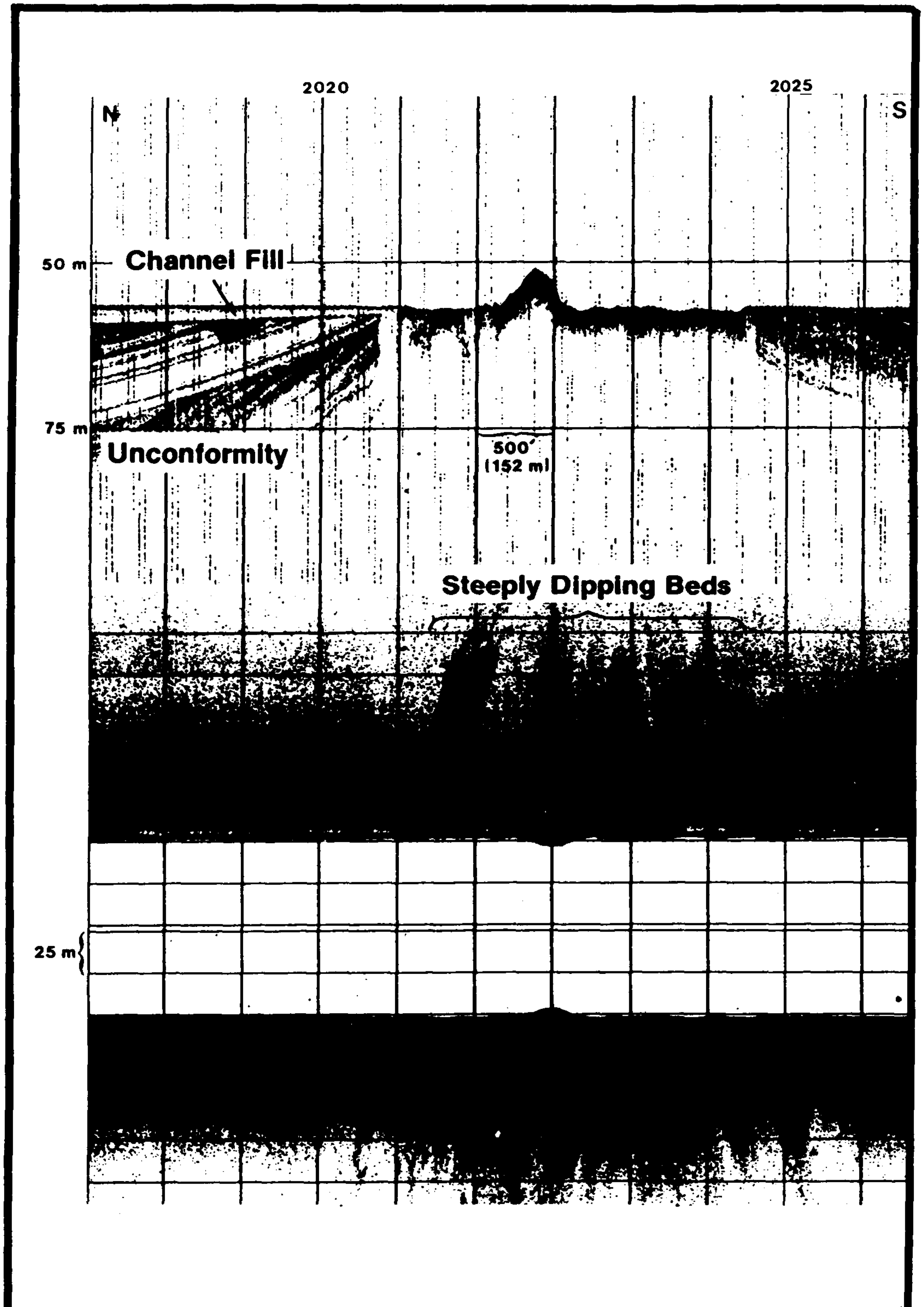


Figure 3.8. A 7-kHz subbottom profile and side-scan sonar record across the east side of Sonnier Bank, a mid-shelf bank (From: Rezak et al., 1985).

Mid-Shelf Banks

Mid-shelf banks are defined as those that rise from depths of 80 m or less and have a relief of from about 4 m to about 50 m (Rezak et al., 1985). These banks are similar to one another in that all are outcrops of relatively bare, bedded Tertiary limestones, sandstones, claystones, and siltstones. Stetson, Claypile, Coffee Lump, Sonnier (Figure 3.8), Fishnet, and 32 Fathom Banks are typical of this category.

Shelf-Edge Carbonate Reefs and Banks

The shelf-edge carbonate banks and reefs are located on complex diapiric structures. They are actually carbonate caps that have grown over outcrops of a variety of Tertiary and Cretaceous bedrock and salt dome caprock. Although all of the shelf-edge banks have well developed carbonate caps, local areas of bare bedrock have been exposed by recent faulting on some of the banks (Rezak and Bright, 1981a). Relief on shelf edge banks varies from about 35 m to 150 m. The East and West Flower Garden Banks are thriving coral reefs. The history of studies on these banks have been described at length by Levert and Ferguson (1969) and Edwards (1971). The geologic structure of these two banks is described in detail in Rezak et al. (1983, 1985).

A common-depth-point seismic reflection survey conducted over the East Flower Garden Bank showed the bank to have developed at the intersection of two salt ridges, rather than at the crest of a single salt diapir. Seismic data indicate the presence of a salt pinnacle rising from the crest of the salt ridge to within 30 m of the reef crest. The salt pinnacle lies about 800 m to the northwest of a brine seep complex that has been described by Bright et al. (1980), Rezak and Bright (1981b), and Rezak et al. (1983, 1985). The primary brine system consists of interrelated components: (1) numerous seeps that feed into (2) a brine lake at a depth of 71 m, which has an outflow into (3) a canyon that contains (4) a mixing stream that dilutes the brine to lower hypersaline concentrations. Based on the measured outflow of the brine lake and the salinity of the brine in the lake, calculations show the amount of solid salt being removed from the crest of the salt dome ranges from 10,765 m^3/year to 21,710 m^3/year. Removal of such large volumes of solids from below the cap rock and the overlying reef must create sizeable caverns. Catastrophic collapse of cap rock and associated sediments can and does occur. It has been documented both in the Recent at Alderdice Bank, off South Marsh Island, Louisiana (Rezak and Tieh, 1984) and in the Oligocene of the Damon Mound salt dome in Brazoria County, Texas (Frost and Schafersman, 1978).

3.5.3 Composition of Unconsolidated Sediments

Recent Sediments

Terrigenous. The composition of terrigenous clastic sediments in the study area is determined by the composition of the sediment load transported by the major rivers flowing into the Gulf of Mexico (Bullard, 1942; Greenman and LeBlanc, 1956; Van Andel and Poole, 1960; Curray, 1960; Davies and Moore, 1970; Berryhill, 1975; Shideler, 1978). The sources of the sediments have been determined by use of heavy mineral suites in the sand and coarse silt fractions of the sediment. The suites of heavy minerals carried by the three major suppliers of sediment to the Gulf are very distinctive. These sources are the Mississippi River, the Brazos-Colorado River complex, and the Rio Grande River. Davies and Moore (1970) point out that in a basinward direction there is no modification in heavy mineral assemblage of the Mississippi River over a travel path of some 3,200 km. However, on the continental shelf of Louisiana and Texas, the dispersal patterns are extremely complex, and it is very difficult to recognize source area by this method. Hawkins (1983) concluded that heavy mineral studies cannot determine unambiguously the extent to which a certain source has contributed to a sediment or, if indeed it has at all. Hawkins used quartz-grain shape analysis to differentiate among the sources that contribute to sediments on the shelf. The purpose of his study was to compare the results of heavy mineral counts and quartz-grain shape analysis (Ehrlich and Weinberg, 1970) to determine sources of the fine sand in the area. Hawkins concluded that much of the sand in the Central Area (Figure 3.5) is a mixture of Colorado River, Brazos River, Trinity River, and Red River sands. His conclusion that the sediments in this area are the result of the Pleistocene progradation of deltas across the shelf agrees with those of Curray (1960) and Winker (1982).

A thin deposit of Recent sediment covers the relict Pleistocene and Holocene deposits on the inner shelf. The thin layer becomes patchy as one proceeds offshore, and near the shelf break, especially in the Central Area (Figure 3.5), large expanses of relict Pleistocene deposits are exposed at the seafloor. The Recent sediments are mostly sandy muds and muddy sands with variable amounts of shell. The sands are all fine to very fine grained. The clay fraction of the mud consists of smectite, illite, and kaolinite in decreasing order of abundance.

<u>Carbonates</u>. Carbonate sediments are found forming caps on topographic prominences and as aprons surrounding the lower flanks of such caps. The production of carbonate sediments on a terrigenous shelf has been discussed by Rezak (1985). Sediment facies at the Flower Garden Banks serve as a typical example of the localized production of carbonate sediments. Figure 3.9 depicts the sedimentary facies distribution in the area of the Flower Garden Banks. It also illustrates the two classifications used in preparing the map: the carbonate classification based on particle types and the terrigenous classification based on particle size distribution. The Molluscan Hash Facies and the Quartz-Planktonic Foraminifer Facies represent transitions between predominantly carbonate sediments and predominantly terrigenous sediments. The facies boundaries in the carbonate sediments roughly parallel the isobaths. The succession of carbonate facies is most complete at the Flower Garden Banks and is used for comparison with other banks that have less complete sequences because their crests are deeper.

<u>Relict Pleistocene or Holocene Sediments</u>

The Beaumont Clay or its equivalents crop out along the coast from the north shore of Corpus Christi Bay to the east end of High Island. Offshore, it occurs beneath a thin cover of Recent sediments as

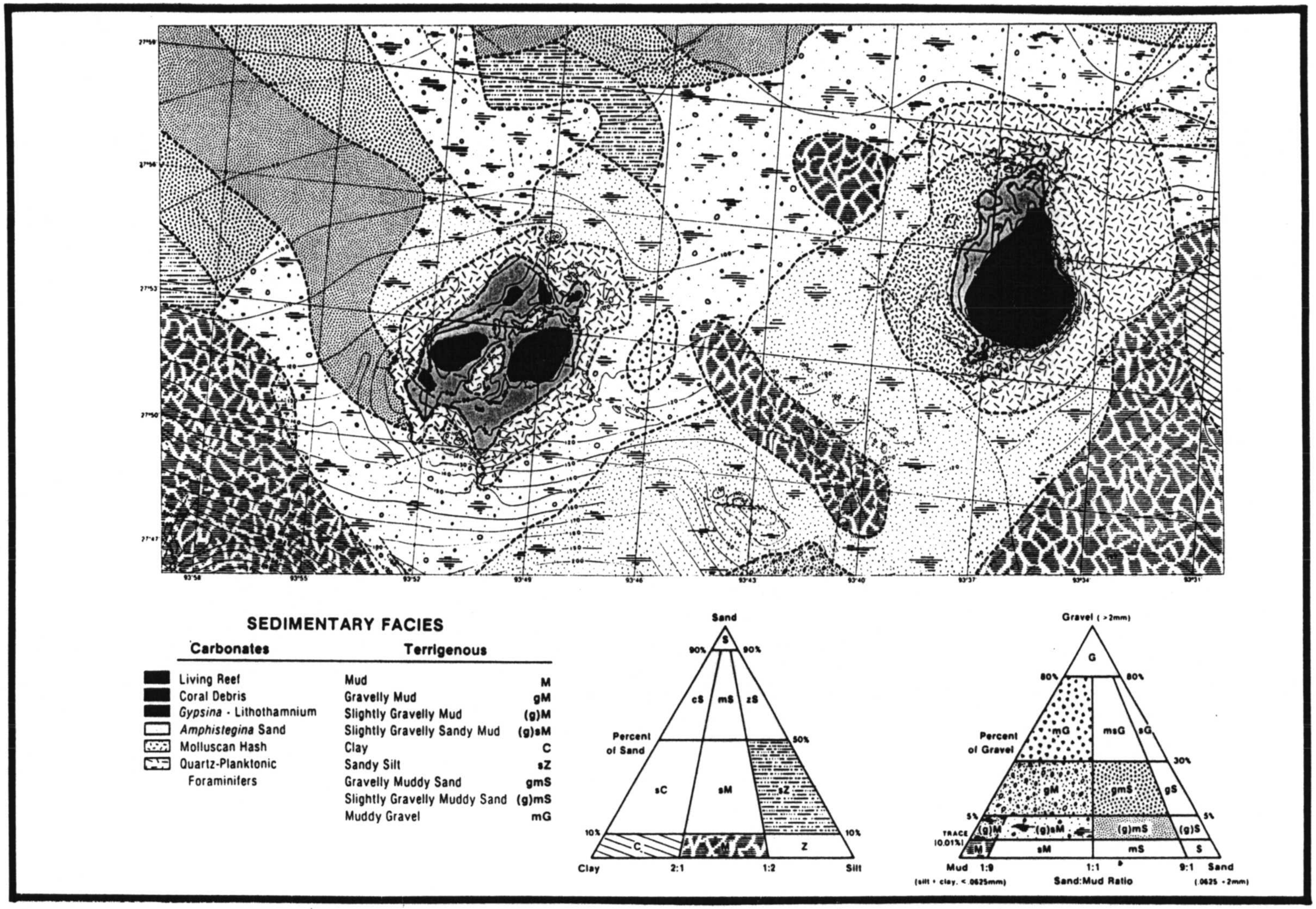


Figure 3.9. Sedimentary facies map of the Flower Garden Bank area (From: Rezak et al., 1985).

far east as the West Cameron Area off Cameron, LA (Roemer, 1976). The Beaumont Clay is a highly overconsolidated, illitic clay with abundant shell content. Subaerial weathering causes calcareous concretions to form at the surfaces of outcrops due to the dissolution of shells in the clay and the evaporation of highly $CaCO_3$-charged pore waters at the surface. This process is so common that the concretions form gravels on the beaches at Baffin Bay, TX.

On the outer continental shelf in the Central Area (see Figure 3.5), Pleistocene sands representing beach and terrace deposits are common. Also, fluvial deposits of muddy sands mark the locations of channel fills leading to near the shelf break that are recognized on reflection seismic profiles. Closer to shore, Heald and Sabine Banks (off Texas) and Ship Shoal (off Louisiana) are believed to represent remnants of Holocene shoreline deposits (Curray, 1960).

3.6 SEDIMENT DYNAMICS

3.6.1 River Sediment Plumes

The major plume entering the Gulf of Mexico is that of the Mississippi River, which sends cells of lower salinity, turbid water as far west as the High Island Area during the few months following its spring floods. Dodge and Lang (1983) attributed what they perceived to be the stressed condition of the Flower Garden Reefs to the impingement of this turbid, fresh water on the reefs. However, McGrail's studies (reported in Rezak et al., 1983) show that low salinity, turbid water never impinges on the reefs. The low salinity water is rarely lower than $31.5^{\circ}/_{\circ\circ}$ at the surface, and salinities at 15 m depth are no less than $35.5^{\circ}/_{\circ\circ}$.

3.6.2 Bottom Nepheloid Layer

The first study of the nepheloid layer on the south Texas outer continental shelf was published by Shideler (1981). The U.S. Geological Survey conducted six cruises at three-month intervals, occupying the same stations on each cruise to study the temporal and spatial variations in the nepheloid layer. Shideler found that the nepheloid layer thickened offshore to a maximum of 35 m near the shelf break, and that the concentration of suspended sediment in the nepheloid layer decreased from a maximum near shore to a minimum at the shelf break. He concluded that the nepheloid layer is generated and maintained by resuspension of muddy seafloor sediment due to bottom turbulence. He demonstrated that gravity waves in calm weather could cause resuspension inshore of only about 10 m depth and storm waves with 10 s periods would not likely be important in resuspension beyond 40 m depths. McGrail (reported in Rezak et al., 1983) indicated that Shideler was correct in his statements about shallow water but that his conceptual model was flawed by a lack of oceanographic data beyond the 40 m depth. McGrail's work on the east Texas-Louisiana shelf demonstrated that the passage of polar fronts during winter months homogenizes the nearshore waters and produces surface gravity waves capable of resuspending sediments at depths as great as 40 m. As a consequence, the nearshore waters are filled with high sediment loads. Frontal passage also creates cold saline waters that sink and flow offshore along the bottom because of their excess density. Sediment entrained in this bottom flow is carried to the outer shelf. The bottom mixed layer and the nepheloid layer thicken in the offshore direction as the bottom waters flow off the sloping shelf and out over water of equal density on the upper slope. The sediment is kept in suspension over much of the inner shelf by swift currents and turbulence. It is then advected to the shelf edge, where episodic deposition may take place. In the summer months, the supply of sediment to the outer shelf is restricted because of a lack of major wind events and the diminished supply of sediments at the coast.

Current meter records from the shelf edge suggest that hurricanes are not the important agent of sediment distribution that Curray (1960) hypothesized (Rezak et al., 1985). Hurricanes occur when the shelf is still stratified and do not directly force the bottom flow on the outer shelf. They appear to produce effects on the outer shelf similar to those of a frontal passage. However, a hurricane's influence in shallow water would be much more extreme.

3.7 DATA GAPS AND INFORMATION NEEDS

3.7.1 Salt Tectonics

Little is known concerning the dynamics of salt tectonics. Section 3.5.2 describes the forces that affect the topographic expression and internal structure of salt domes. We know that the forces are active, but no one has monitored a salt dome to determine what is really happening. Is it a static feature? Is it collapsing on itself, or is it rising? What are the rates of depression or uplift? These are important questions in terms of seafloor stability, especially if a large production platform is located in close proximity. It would be relatively easy to answer those questions by using ocean bottom seismographs and depth calibrated pressure transducers.

3.7.2 Sediment Accumulation Rates

Current knowledge concerning sediment accumulation rates on the outer continental shelf and slope are woefully inadequate. Most estimates are based upon thickness of sediment above the first strong seismic reflector below the seafloor and are really averages over a period of time that may not represent the present sedimentary regime. The lead-210 method used by Holmes (Berryhill et al., 1976) and others gives unrealistic results and should be reevaluated. An accurate knowledge of sediment accumulation rates would aid in interpretation of meiofaunal and macroinfaunal data. It would also be extremely important in modeling the trajectories of solid pollutants in the water column.

3.7.3 Chemosynthetic Communities

The hydrocarbon seeps mentioned in Section 3.4.2 support chemosynthetic communities, including microbial mats that cause the precipitation of carbonate cements in the sediments with which they are associated. The interaction of these bacteria with the inorganic sediment may be an important factor in the stabilization of sediments in the vicinity of seeps.

3.7.4 Shelf Circulation

McGrail's work (reported in Rezak et al., 1985) was just beginning to give us an understanding of the sediment transport processes on the outer continental shelf. A continuation of the accumulation of (1) time series measurements of currents, temperature, salinity, and transmissivity; and (2) seasonal sampling of across-shelf transects for profiles of the same parameters over a larger area of the Texas-Louisiana shelf and over a span of two or three years would improve our ability to predict the fate of particulate pollutants.

CHAPTER 4
PHYSICAL OCEANOGRAPHY AND METEOROLOGY

F.J. Kelly

4.1 INTRODUCTION

Each continental shelf region in the world has a different combination of meteorological, hydrological, astronomical, and deep ocean forces that act in concert with the local topography and geometry to produce a unique set of physical processes and water masses. The characteristics of the Texas-Louisiana shelf waters are determined, principally, by the large input of fresh water from one of the world's great rivers and an annual cycle of prevailing winds acting on a broad shelf with a coast that is arcuate, concave to the southeast (Figure 4.1). Astronomic tides, interaction with eddies and currents in the deep Gulf, and the momentum input and heat and mass exchange across the sea surface caused by intrusions of polar fronts and tropical cyclones, significantly modulate the effects of the principal factors, but do not obscure them.

Although various topics are discussed individually in this chapter, all of the topics are interrelated. Currents, the unifying theme, are presented later (Section 4.8). Some of the many biological, chemical, and sedimentary processes directly related to physical processes are also noted in this chapter, but the details of these interactions are discussed in other chapters.

Figure 4.1 shows the locations of geographic references and study sites from which data are used to illustrate points in the discussion. Bryan Mound, Big Hill, and West Hackberry are sites at which the Department of Energy's Strategic Petroleum Reserve (DOE/SPR) Office conducted environmental studies from 1977 through 1985 for its brine disposal operations. Section 1.1.2 summarizes the DOE/SPR study as well as other major environmental studies conducted off the Louisiana and Texas coasts. As Figure 1.1 indicates, the study area for this synthesis effort formally extends from the Mississippi Delta to Corpus Christi Bay. However, in this chapter some of the discussion includes results of studies conducted in the far southwest region of the shelf because its hydrography and circulation are integral parts of the physical processes on the shelf.

The Minerals Management Service (MMS) Gulf of Mexico Physical Oceanography Program: Year 5 Study, which includes hydrographic transects and an array of moorings along approximately 92°W from near the coast to mid-Gulf, is in progress at the time of this report. It is likely that the results of the Year 5 Study, will address some of the data gaps and questions about dynamic processes noted in Section 4.9, particularly those pertaining to interaction between the shelf and oceanic Gulf waters.

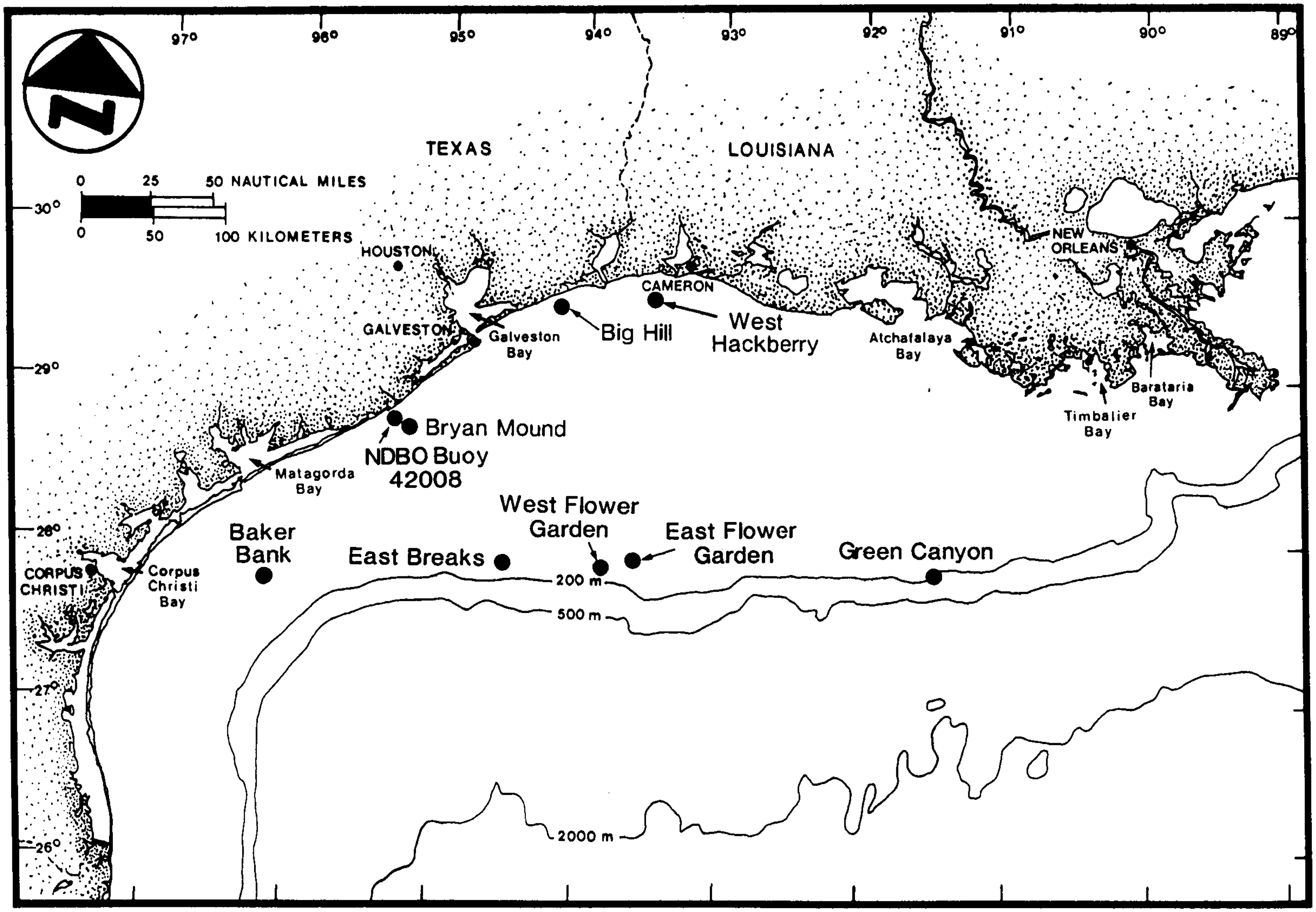


Figure 4.1. Chart of observational and geographic locations referenced in the text. Bryan Mound, Big Hill, and West Hackberry are brine disposal sites of the Strategic Petroleum Reserve.

4.2 METEOROLOGICAL CLIMATE

4.2.1 Air Masses

The following air masses either influence or control the weather over the shelf (Orton, 1964):

- Maritime tropical (mT) air comes from the southeast and south with the circulation around the southwestern extension of the Bermuda high. This air mass dominates the region from March through October and is responsible for the subtropical climate of the Gulf of Mexico.

- Maritime Polar (mP) air comes from the Pacific Ocean, and mP fronts cross the shelf most frequently from late fall through spring. During July and August, the mP fronts are unable to cross the Rockies and push southward through the hot southwest. Most mP fronts have an average orientation when they reach the coast of 40 to 50° from north and, because of the orientation of the coast, they enter the Gulf between Corpus Christi and Galveston (Henry, 1979).

- Continental Polar (cP) air masses push into the Gulf in all months, but most frequently from October through April. Cold fronts, especially cP types, can become quasi-stationary after moving out over the Gulf in winter, a situation favoring cyclogenesis with accompanying low ceilings and continuous rain. According to Henry (1979), the cP fronts (except summer) have an orientation of 60 to 65° from north and enter the Gulf east of Galveston and west of 90°W. Fronts entering the Gulf during the summer are usually cP. They are oriented east-west, because this is their southern-most penetration, and enter to the east of 90°W.

- Continental Arctic (cA) air is very cold and dry, thus the term "blue norther." Invasions of the Gulf by cA fronts are confined normally to the months of January and February. The orientation of cA fronts is similar to that of cP fronts.

From March through September the influence of the Bermuda high dominates the climate over the shelf (Franceschini, 1961). The anticyclonic high pressure system builds during the spring and summer, its western end extending into the eastern Gulf, and mean wind conditions shift gradually from southeasterly to more southerly (Figure 4.2). (Note: the wind roses in Figure 4.2 are constructed using the oceanographic convention for direction. However, in this discussion, meteorological terminology is used, i.e., a southerly wind blows from the south). In the fall the high weakens and the western end retreats from the Gulf. Winds return quickly to southeasterly. In October, an anticyclonic cell, separated from the Bermuda High, lies over northeastern Texas, resulting in more frequent easterly winds. During the winter, as intrusions of polar air masses move out across the shelf, the frequency of strong northerly winds increases. Because the shelf is sufficiently far south to remain under the influence of the Bermuda high,

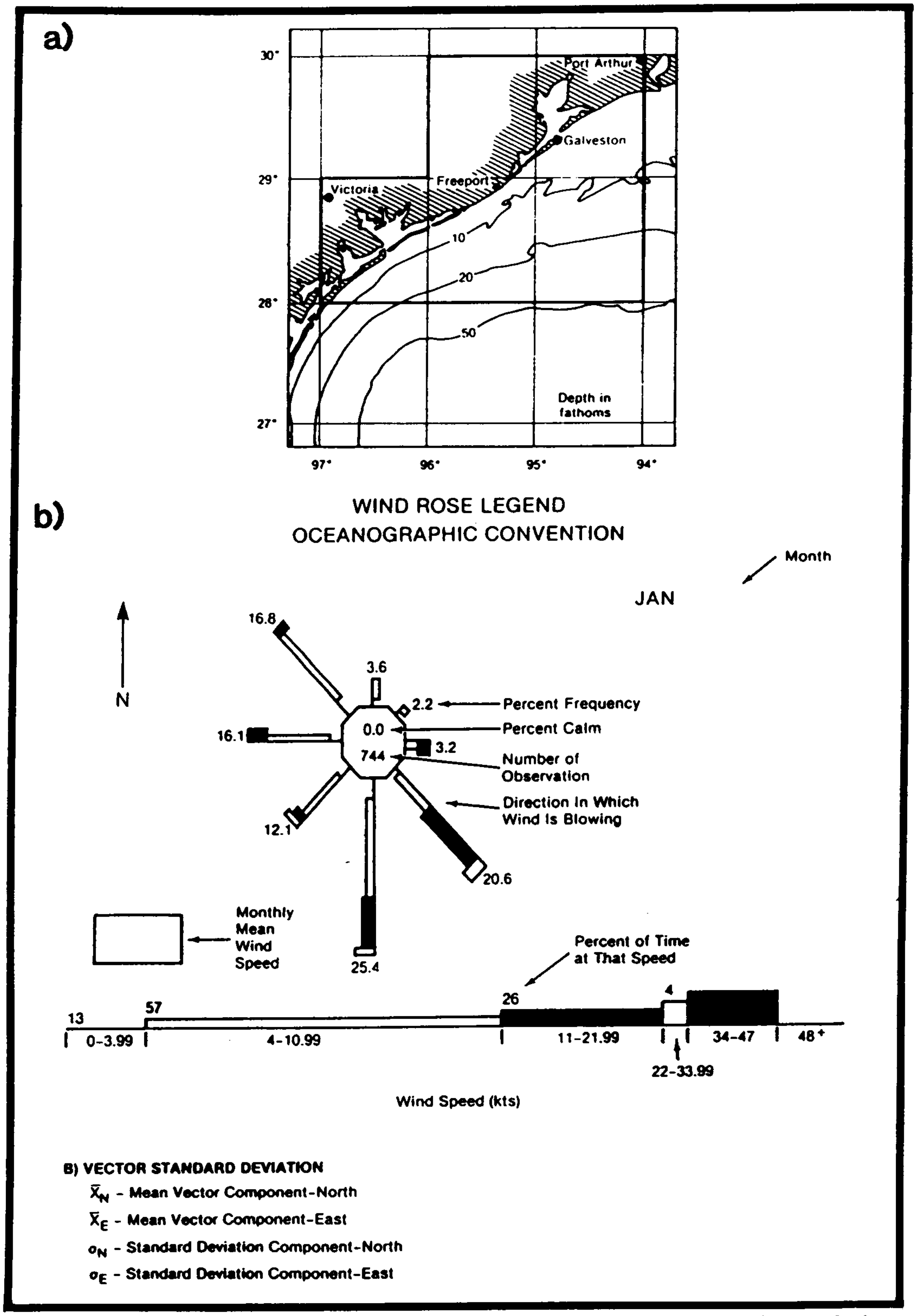


Figure 4.2. Summary of wind observations from transient ships for the period 1900 to 1970. Data were obtained from the Sea Surface Meteorological Observation data base of the NOAA National Climatic Center. a) Area of data collection. b) Wind rose legend. c) February–May data. d) June–September data. e) October–January data.

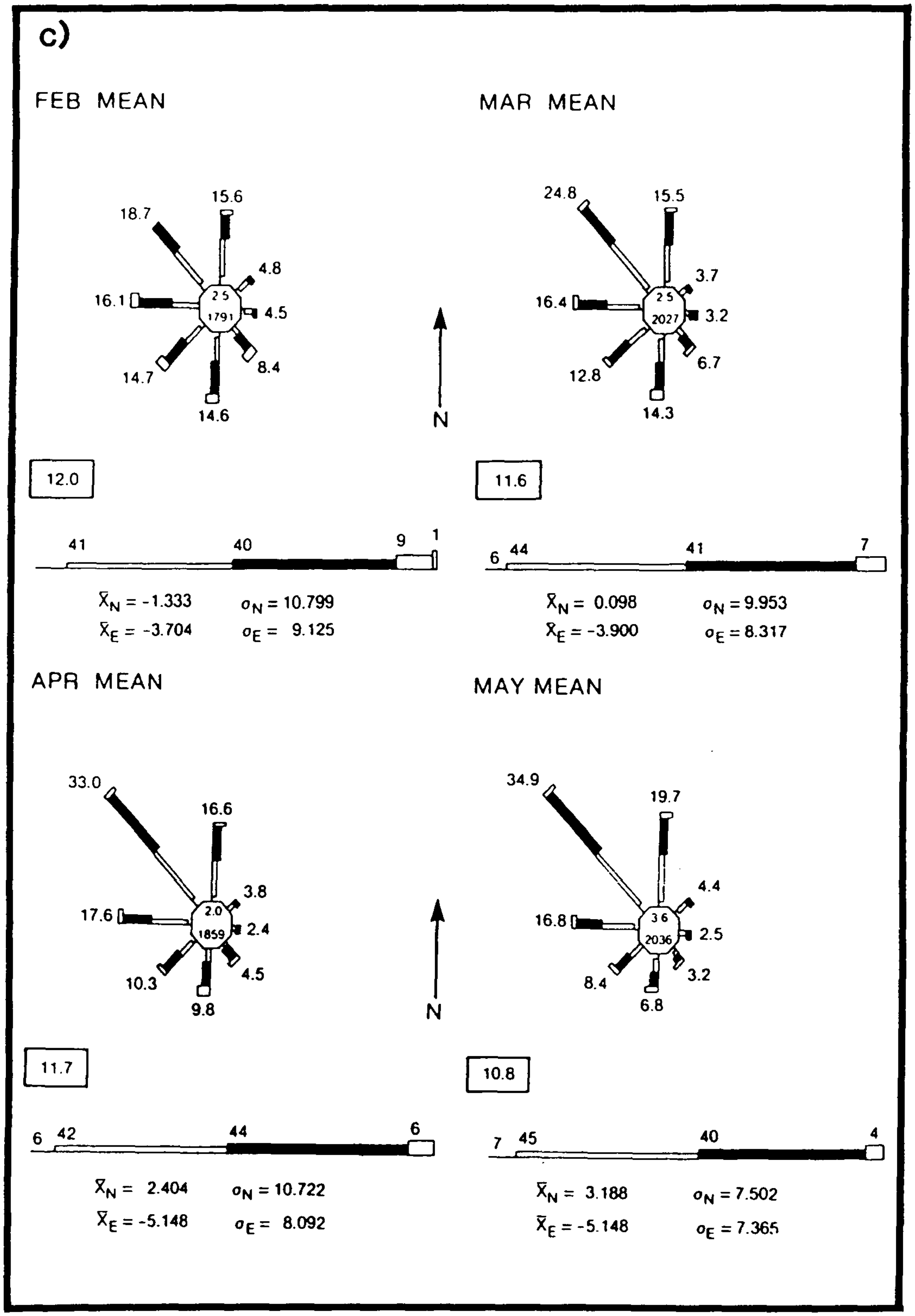
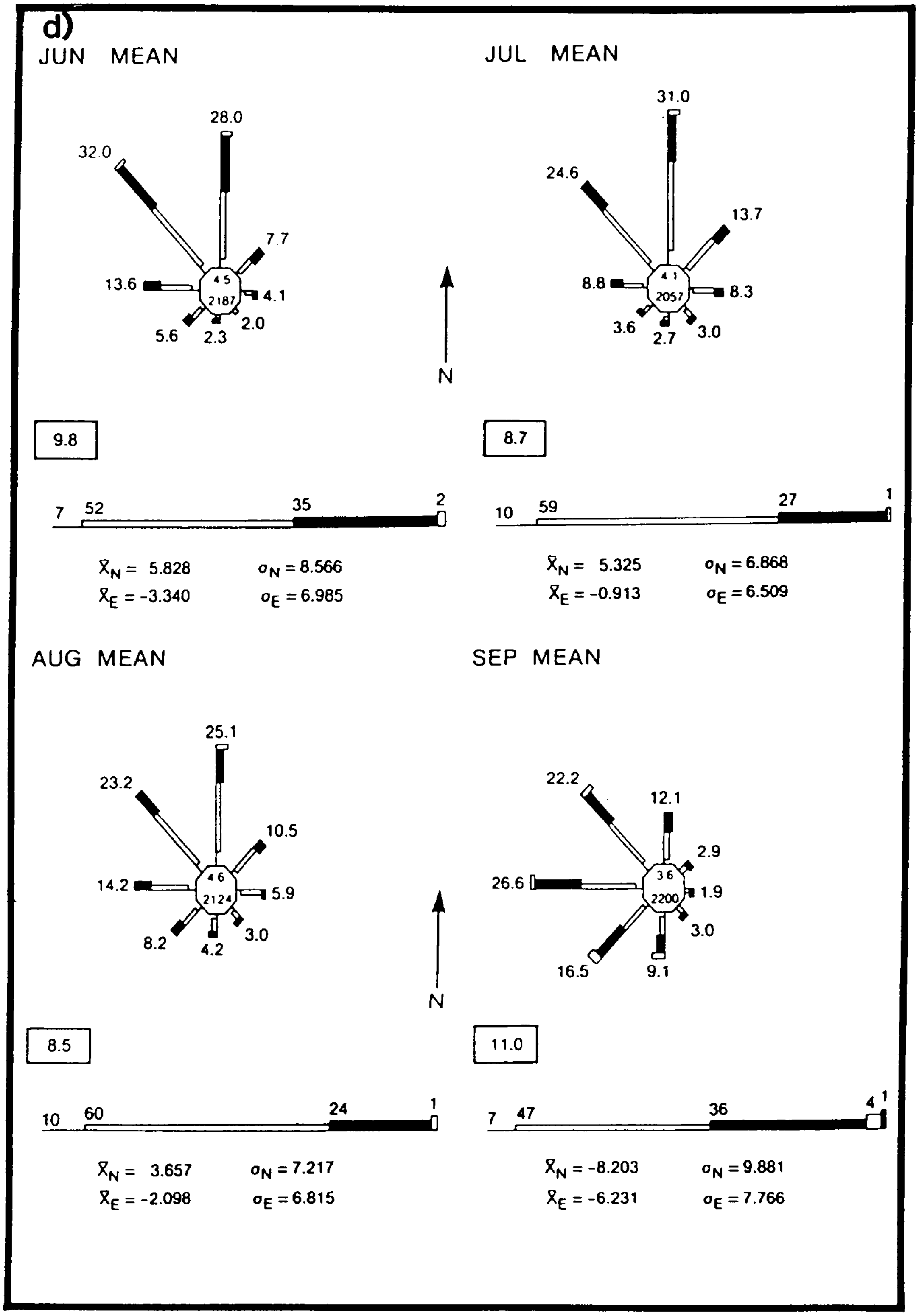


Figure 4.2. (Continued).



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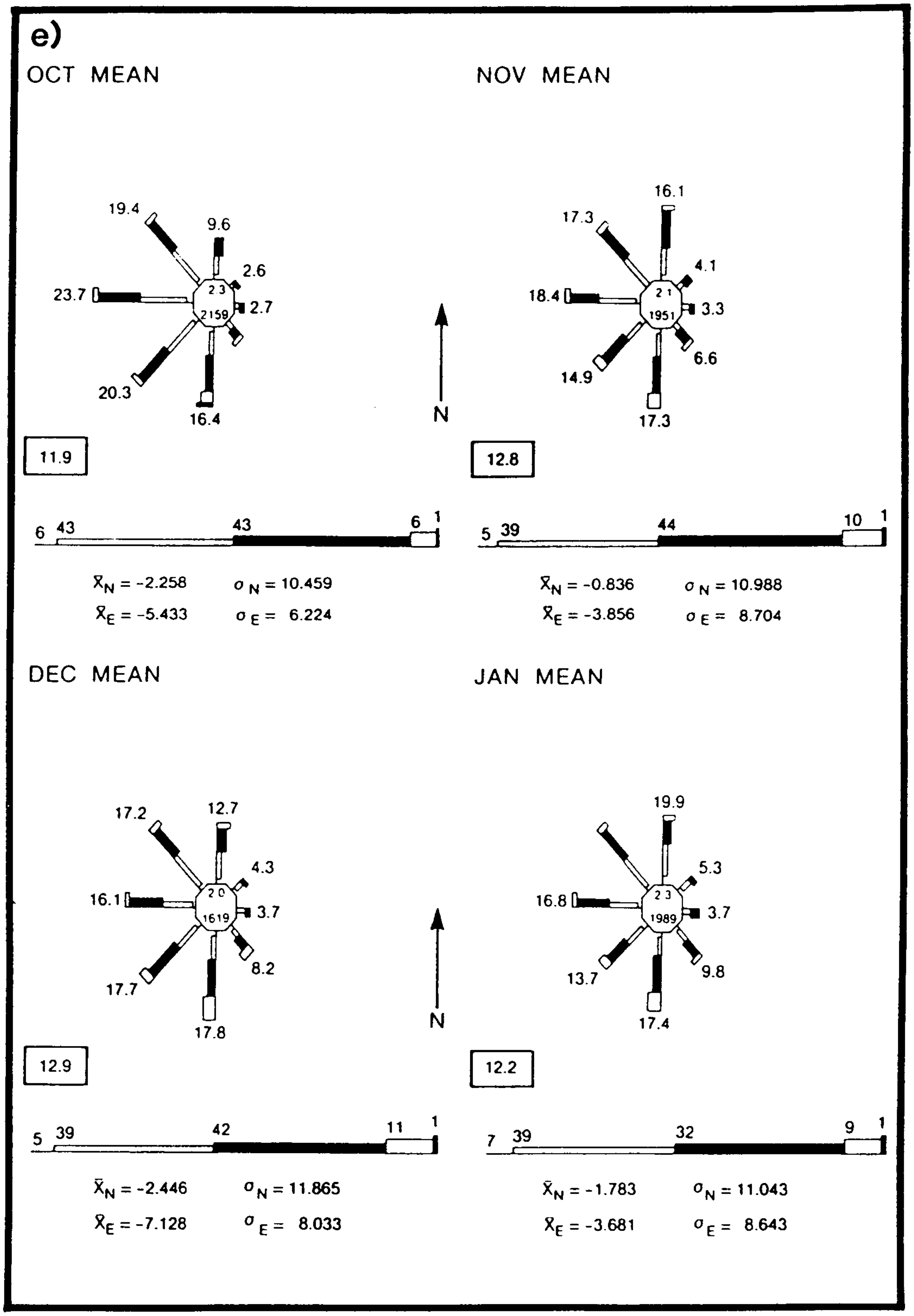


Figure 4.2. (Continued).

winds return to southeasterly after the passage of frontal systems. Therefore, during the winter months (November through February) northerly, northeasterly, easterly, southeasterly, and southerly winds occur with about the same frequency. Thus in Figure 4.2, which uses the oceanographic direction convention, the N, NW, W, SW, and S rose "petals" are about the same length.

4.2.2 Barometric Pressure

Average atmospheric pressure over the inner shelf (Figure 4.3) and outer shelf (Yamazaki and Herbich, 1985) is highest in winter because of continental high pressure systems; pressure averages about 1,019 mb in December. Mean pressure decreases in the spring as the equatorial trough migrates northward and the low pressure system over Mexico deepens. Minimum pressures of about 1,013 mb occur in May and June. In July there is a weak, relative maximum in atmospheric pressure, which Chew (1964) attributes to the maximum westward extension into the Gulf by the Bermuda-Azores high. In August and September there is a second minimum of about 1,014 mb, and then pressure rises as the equatorial trough migrates southward, the Mexican low pressure system fills, and the Bermuda high weakens and retreats.

4.2.3 Air Temperature

According to Orton (1964), mean monthly surface air temperatures during winter (December-February) are about 15.5°C over the inner shelf and 18°C over the outer shelf, and approximately 90% of the actual observations are within 6°C of the mean. For March, the means over the inner and outer portions of the shelf increase to 18°C and 21°C, respectively, and for April they are 21°C and 23°C. From May through September there is very little contrast in air temperature across the shelf from north to south. Also, variability decreases; 90% of the observations are within 3°C of the means. Mean values rise to 24.5°C for May, 28°C for June, reach a maximum of 29°C for July and August, and then decrease to 28°C for September. A north-south gradient reappears in the means for October, which are 24°C and 26°C, respectively, and variability increases. The values of mean air temperature for November are the same as for April.

4.2.4 Precipitation and Humidity

Quantitative measurements of the distribution of offshore precipitation do not exist. Based on ship reports (Orton, 1964), rain occurs most frequently in the Gulf in September. The "wet" season, July through September, is coincident with the season for easterly atmospheric waves and tropical storms. The "dry" season is March through May, with rain reported least frequently in May.

Dinnel and Wiseman (1986) estimated annual precipitation rates over the shelf, between the coast and the 91.5-m isobath and from the Mississippi River Delta to Brownsville, by extrapolating land-based coastal rainfall. They reduced the onshore values by 25% to account for the fact that the meteorological processes that produce rain result in greater precipitation toward the coast than farther offshore. Their

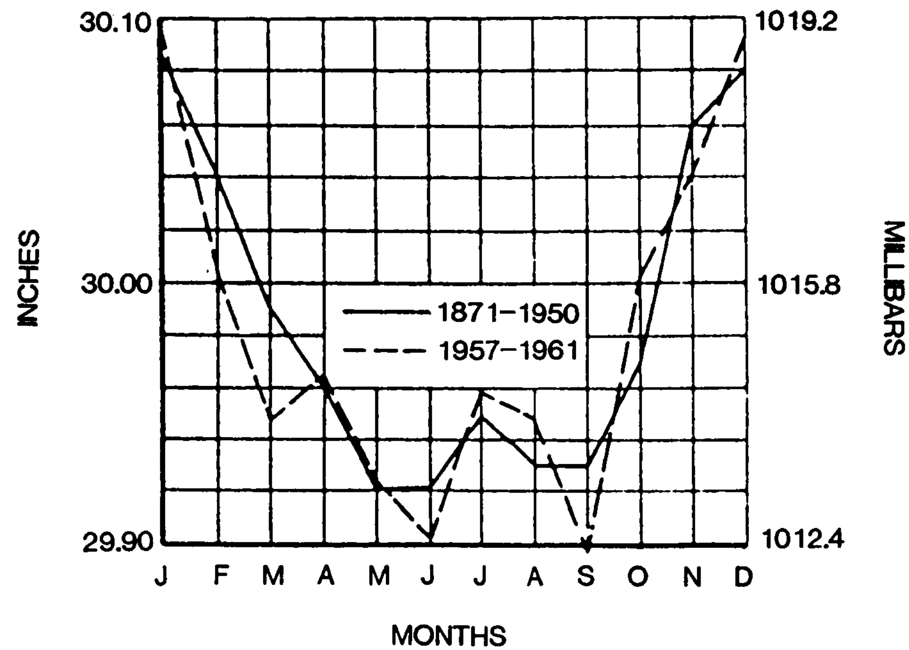


Figure 4.3. Monthly mean sea-level atmospheric pressure at New Orleans. Horizontal lines in legend are positioned at corresponding mean yearly pressures (From: Chew, 1964).

30-year mean value is 108 km^3/year, or, assuming a shelf area of 106,866 km^2, about 101 cm/year.

Fog is produced when warm, moist, Gulf air overrides cooler water. Advection-radiation fog, lasting about three or four hours, occurs most frequently from November through March in near coastal areas. Dense advection fogs (sea fogs) form out over the cold water surface during the winter months, December through February, and may persist for several days.

4.3 METEOROLOGICAL FORCING

4.3.1 Seasonal Variations of Wind Stress

The climate cycle described above produces an annual progression of wind stress patterns over the shelf that is responsible for much of the observed low-frequency circulation. Several estimates of the seasonal patterns of wind stress based on different sources of data are available for the Gulf on a 1° grid. For example, Elliott (1979) calculated his from all available ship observations up through 1972, and Rhodes et al. (1985) produced a wind set based on the Navy's twelve-hourly surface pressure analysis, which is available from 1967 to 1982. Figure 4.4 shows some results of the latter method. In the region of the Texas-Louisiana coast, the Navy Corrected Geostrophic Wind Stress data agree well with the observed wind stresses from coastal and nearshore meteorological stations. Figure 4.5 shows the observed monthly means (vectors) for Brownsville, Galveston, and the 5° quadrangle, 25° to 30°N, 90° to 95°W in the Gulf of Mexico. The sources of the data are given by Cochrane and Kelly (1986a). The lines connecting the tips of the vectors form a "figure 8" and the chronological progression has the same sense.

Monthly mean alongshore components of wind stress are of considerable interest because of their importance to coastal currents (see Section 4.8). Figure 4.6 shows them for a number of fairly evenly spaced locations along the coast. The mean wind components are in the same direction along the coast over long distances. There is, however, a convergence in the wind components. It lies between Port Isabel and Port Aransas in January. It migrates upcoast in spring and early summer, reaching a position east of Calcasieu Pass in July. A downcoast retreat of the feature beginning in August is so rapid that by September it is, if it exists, south of Port Isabel. The convergence of the alongshelf component of wind results not from spatial change in the wind field so much as from the arcuate form of the Texas coast.

4.3.2 Frontal Passages

The maritime tropical atmosphere over the shelf may respond to cold fronts as much as 48 h before their passage. During this period, surface air pressure falls, the dew point rises, and temperature increases. Frontal passages across the shelf are accompanied by dramatic weather events such as gale-force winds, torrential rains and large temperature fluctuations. After the passage of cold fronts, about 36 to 48 h are needed for the air of polar origin to reach a new equilibrium

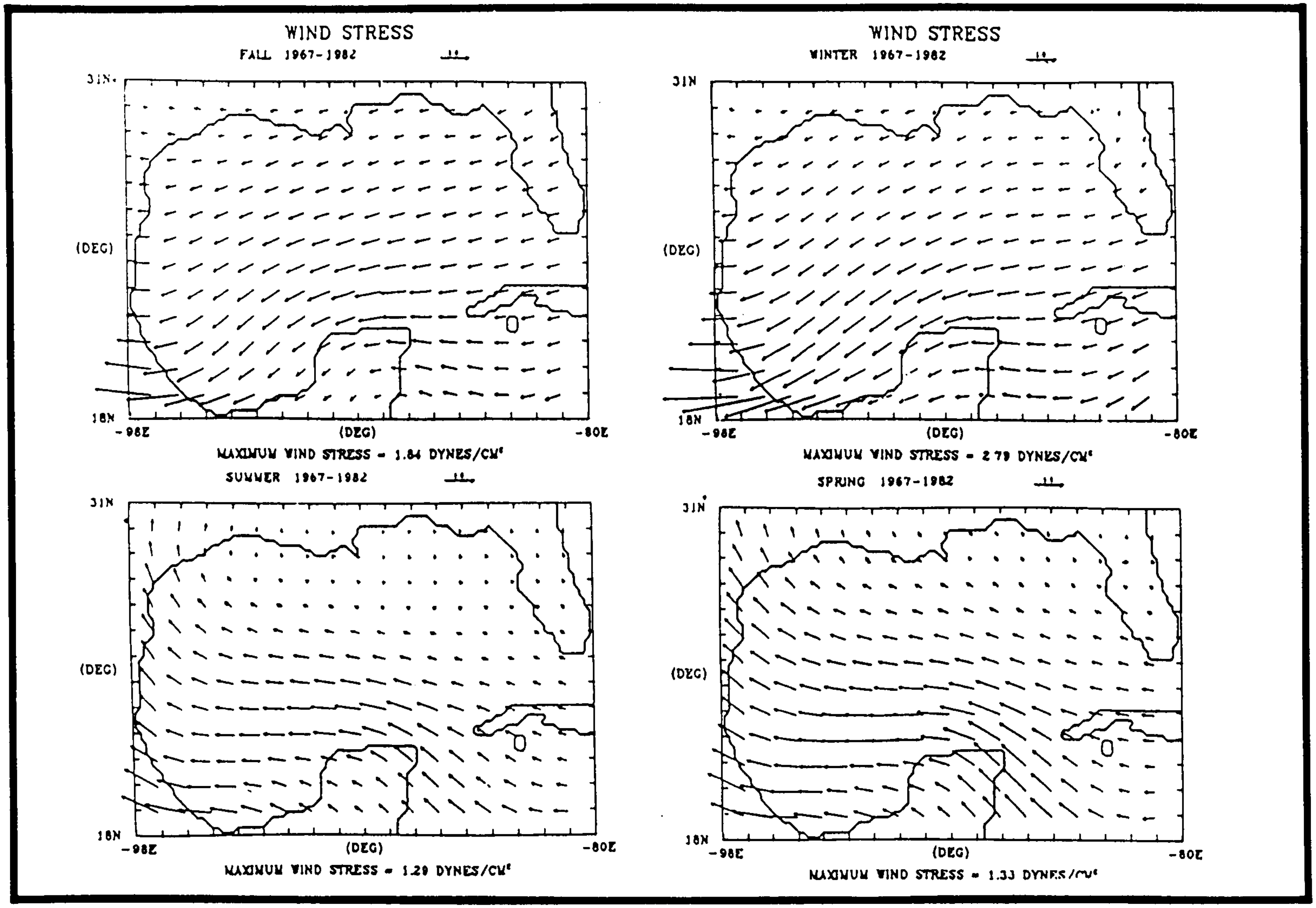


Figure 4.4. Spatial distribution of seasonal mean wind stress over the Gulf of Mexico based on the U.S. Navy's 12-hourly surface pressure analysis for the period 1967 to 1982 (From: Rhodes et al., 1985).

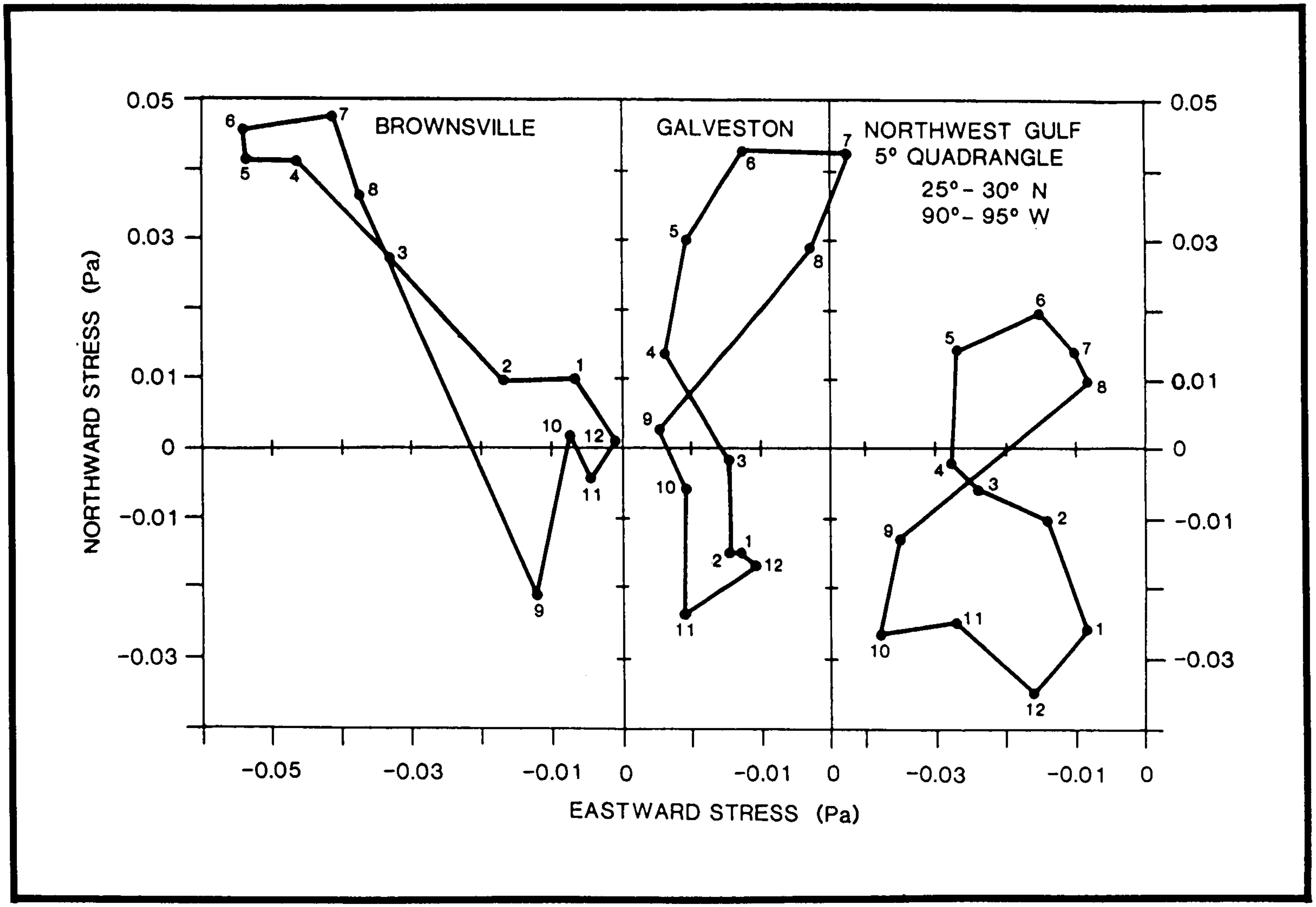


Figure 4.5. Monthly mean wind stress for Brownsville, TX; Galveston, TX; and the 5° quadrangle 25°–30°N, 90°–95°W (From: Cochrane and Kelly, 1986a).

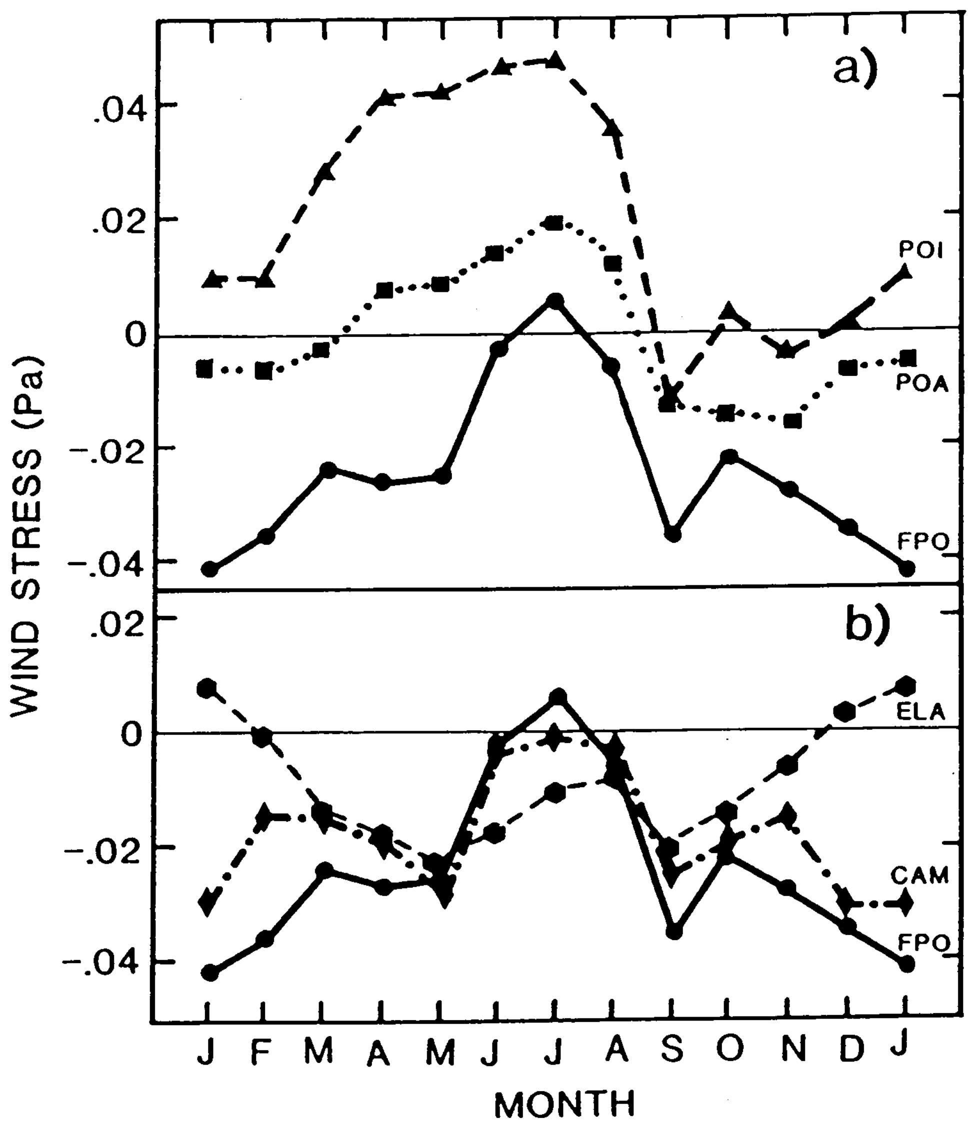


Figure 4.6. Monthly mean alongshore components of wind stress for the waters off a) Port Isabel (POI), Port Aransas (POA), and Freeport (FPO), TX; and off b) Freeport, TX (FPO), Cameron, LA (CAM), and the Louisiana coast between 92°W and the Mississippi River Delta (ELA) (From: Cochrane and Kelly, 1986a).

with the warmer, moister mT air mass. DiMego et al. (1976) analyzed all frontal passages into the Gulf for the period 1965 to 1972 and computed statistics of frequency and duration of frontal systems. Table 4.1 shows the results for the middle of the Texas-Louisiana shelf as interpolated from their maps. The transition from the low-frequency regime of summer to the high-frequency regime of winter is sharp in the fall, occurring between September and October. A more gradual decrease in activity occurs in spring. Henry (1979) also analyzed frontal activity in the Gulf and found a similar pattern, but less frequent frontal activity in winter.

4.3.3 Tropical Storms and Hurricanes

Tropical cyclones produce some of the most extreme meteorological conditions that occur over the Texas-Louisiana shelf. Meteorologists technically define a tropical cyclone (Neumann et al., 1981) as a non-frontal, low-pressure, large-scale system that develops over tropical or subtropical waters and has definite organized circulation. They further classify these cyclones according to wind speed: the sustained surface winds of a tropical depression are ≤61 km/h; a tropical storm, 62 to 117 km/h; and a hurricane, ≥118 km/h. Tropical cyclones draw their energy from the latent heat of condensation of water vapor over the warm waters of the Atlantic Ocean, the Caribbean Sea and the Gulf of Mexico. Tropical cyclones usually have a central "eye," with a geometric radius of 10 to 30 km or more. Winds increase in strength and become tangent to the eye wall (boundary updraft column); inside the eye, winds are light and cloud cover and air pressure are minimum. The high wind stresses, translational motion and low-pressure anomalies of tropical cyclones cause strong currents, high waves, large increases in sea level, intense mixing, and movement of larger sediment fractions. These effects are described in more detail in the appropriate sections.

In the Gulf of Mexico, tropical cyclones have a "season" in that they occur only between the months of May and October. Figure 4.7 shows the tracks of all tropical cyclones that occurred in the Gulf of Mexico in each of these months in the period from 1886 through 1980. They are most frequent in September. In June and July the cyclones tend to develop in western Atlantic, Caribbean and the Gulf of Mexico, but later in the season they tend to form in the eastern Atlantic near the Cape Verde Islands. Ebersole (1985) compiled, for the entire Gulf of Mexico and for the Atchafalaya Bay vicinity, which is centrally located on the shelf area of interest here, the historical frequency of occurrence for the following hurricane properties: heading, forward speed, central pressure and maximum wind (Figure 4.8). The number of occurrences for Atchafalaya Bay (within 100 miles to either side) are too few to define a "typical" hurricane.

As a rough estimate of the frequency of occurrence of landfall by a tropical cyclone of any category along the Texas-Louisiana coast, Figure 4.9 shows a portion of the results from the study of Ho et al. (1975) as presented by Neumann et al. (1981). For the approximately 400 NM of the portion of interest here, the figure suggests about 70 landfalls per 100 years (based on average of about 1.75 landfalls per 10 NM), i.e., not quite one per year. Because of their low frequency of

Table 4.1. Frequency and duration of frontal passages on the Texas-Louisiana shelf, 1965-1972 (From: DiMego et al., 1976).

Month	Passages/Month	Frontal Duration (h)
January	9	24
February	9½	21
March	8	24
April	6½	27
May	4½	30
June	2	24
July	2	24
August	2	42
September	3	48
October	6	30
November	7	24
December	9	30

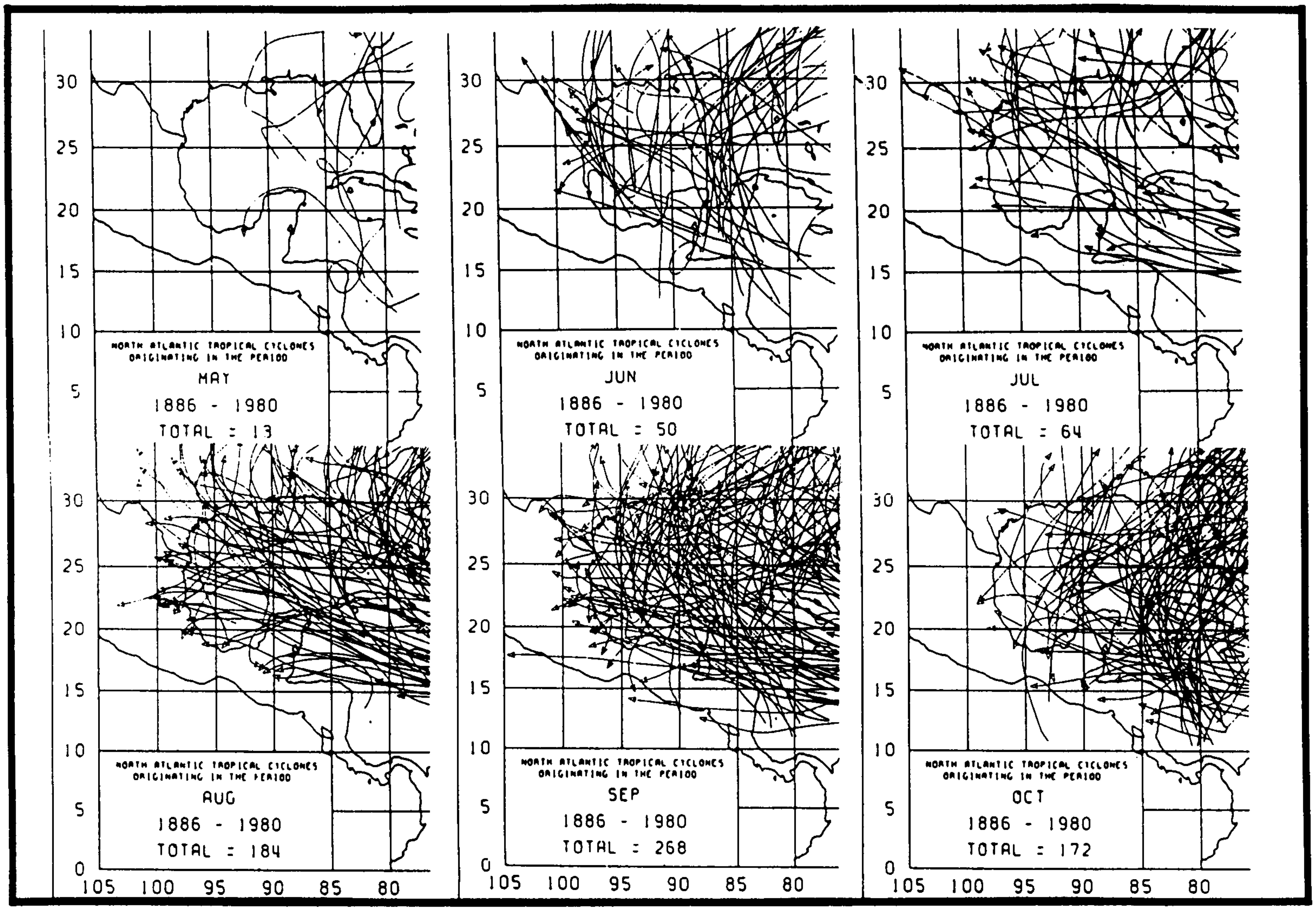


Figure 4.7. Tracks in the Gulf of Mexico of all North Atlantic tropical cyclones originating in each of the months May through September during the period 1886 to 1980.

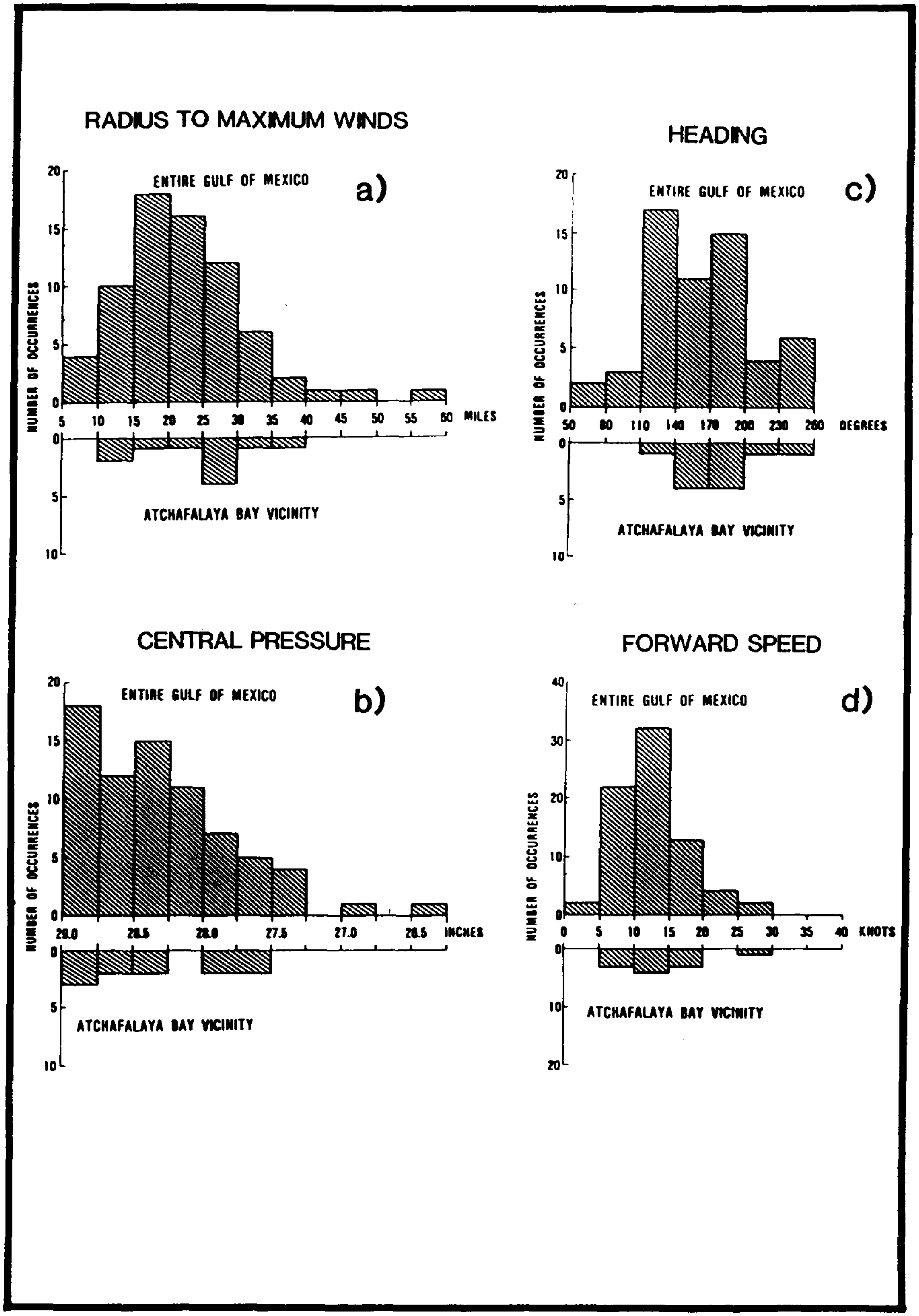


Figure 4.8. Historical (80-year population) frequency of occurrence for a) hurricane radius to maximum winds, b) hurricane central pressure, c) hurricane heading, and d) hurricane forward speed for the entire Gulf of Mexico and the Atchafalaya Bay vicinity (From: Ebersole, 1985).

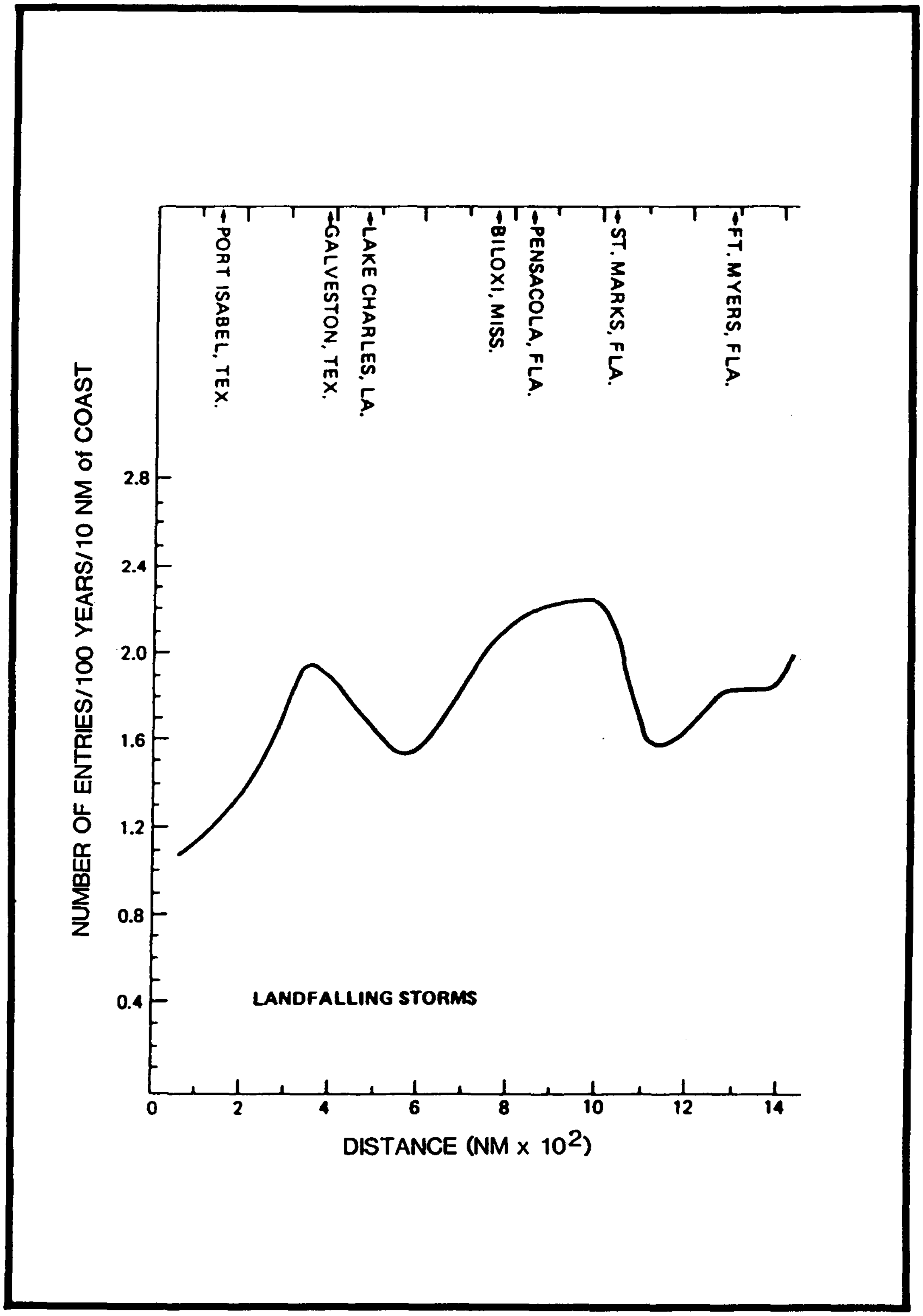


Figure 4.9. Smoothed frequency of landfalling tropical storms and hurricanes (1871 to 1973) for the Gulf of Mexico (Adapted from: Neumann et al., 1981).

occurrence, the oceanic effects of tropical cyclones, although extreme at times, probably are not a significant part of the shelf's current and hydrographic climatology, except perhaps in the area of sediment distribution.

Although the conditions that accompany some of the winter frontal passages are severe enough at times to be compared with tropical storms, northers do constitute part of the regional climatology because of their frequency. The cyclonic storms that sometimes form along the fronts of cP air masses over Gulf waters in winter are termed extratropical. These disturbances tend to be less severe and much larger, spatially, than tropical cyclones and are a distinctly different class of storms. Frey et al. (1981) describe the formation and effects of such winter storms in 1979 at the West Hackberry brine disposal site of the DOE/SPR.

4.3.4 Heat and Mass Exchange with the Shelf Waters

The exchange of heat and water across the sea surface may significantly modify water masses on the shelf, and thus, represents an important forcing factor. Etter et al. calculated a monthly, multi-annual mean heat budget for the Texas-Louisiana shelf, which in symbols may be expressed as

$$Q_R = Q_A + Q_T + Q_V$$

where Q_R is the radiation balance at the sea surface (incoming solar shortwave radiation minus outgoing longwave radiation), Q_A is the net turbulent heat flux from the sea surface (latent plus sensible heat flux), Q_T is the rate of oceanic heat storage, and Q_V is the heat flux divergence due to oceanic motions. They calculated monthly heat storage rates (Q_T) directly using Ulm's (1983) results of a volumetric temperature-salinity census of the shelf waters, and for surface heat exchange (Q_R - Q_A) they used unpublished monthly data of Bunker. The heat budget equation then yielded heat flux divergence values (Q_V) as a residual. Figure 4.10a shows their results. There is a net heat loss across the sea surface from September through February and a net heat gain from March through August. Net heat storage in the shelf waters actually begins in February and continues into September because of the contribution from heat flux convergence (i.e., negative divergence). The heat flux divergence term is negative throughout the year except in June and July, and Etter et al. (1985) argue that this pattern is consistent with the prevailing annual march of the alongshore component of wind stress (Figure 4.10b) and the upwelling and downwelling such a pattern would produce in coastal waters.

The extraction of heat from the water column by winter fronts proceeds in a stepwise manner (Nowlin and Parker, 1974). Each cold-air outbreak cools and deepens the surface mixed layer. This modification is more pronounced in the nearshore waters because the air mass rapidly gains heat and moisture from the ocean as it moves south. Figure 4.11 shows an example of the annual cycle of the cooling and warming of the water column at the West Hackberry DOE/SPR site from March 1981 through April 1982. The water depth is 10 m; instrument depths are 3.7 m (DT) and 7.3 m (DB). The periods of pronounced cooling, e.g., 18 to

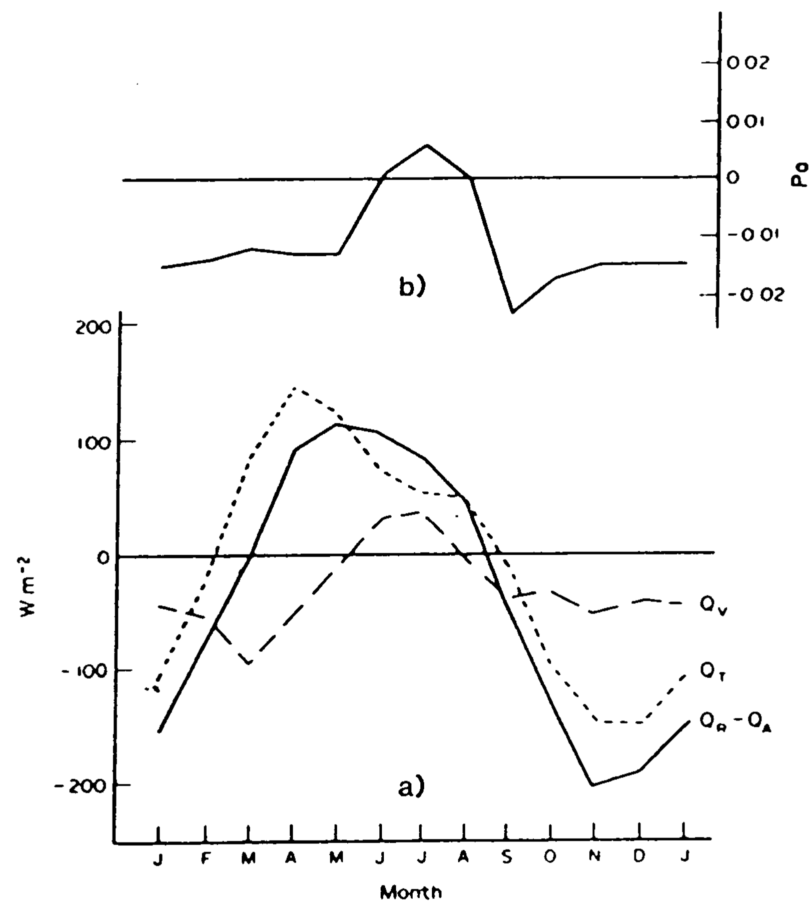


Figure 4.10. **a)** Annual marches (monthly means) of the rate of oceanic heat storage (Q_T), surface heat exchange (Q_R and Q_A), and flux divergence (Q_V) for Texas-Louisiana shelf waters. **b)** Annual march (monthly means) of the alongshore component of wind stress for the entire Texas-Louisiana coast from the Rio Grande to the Mississippi River Delta (From: Etter et al., 1985).

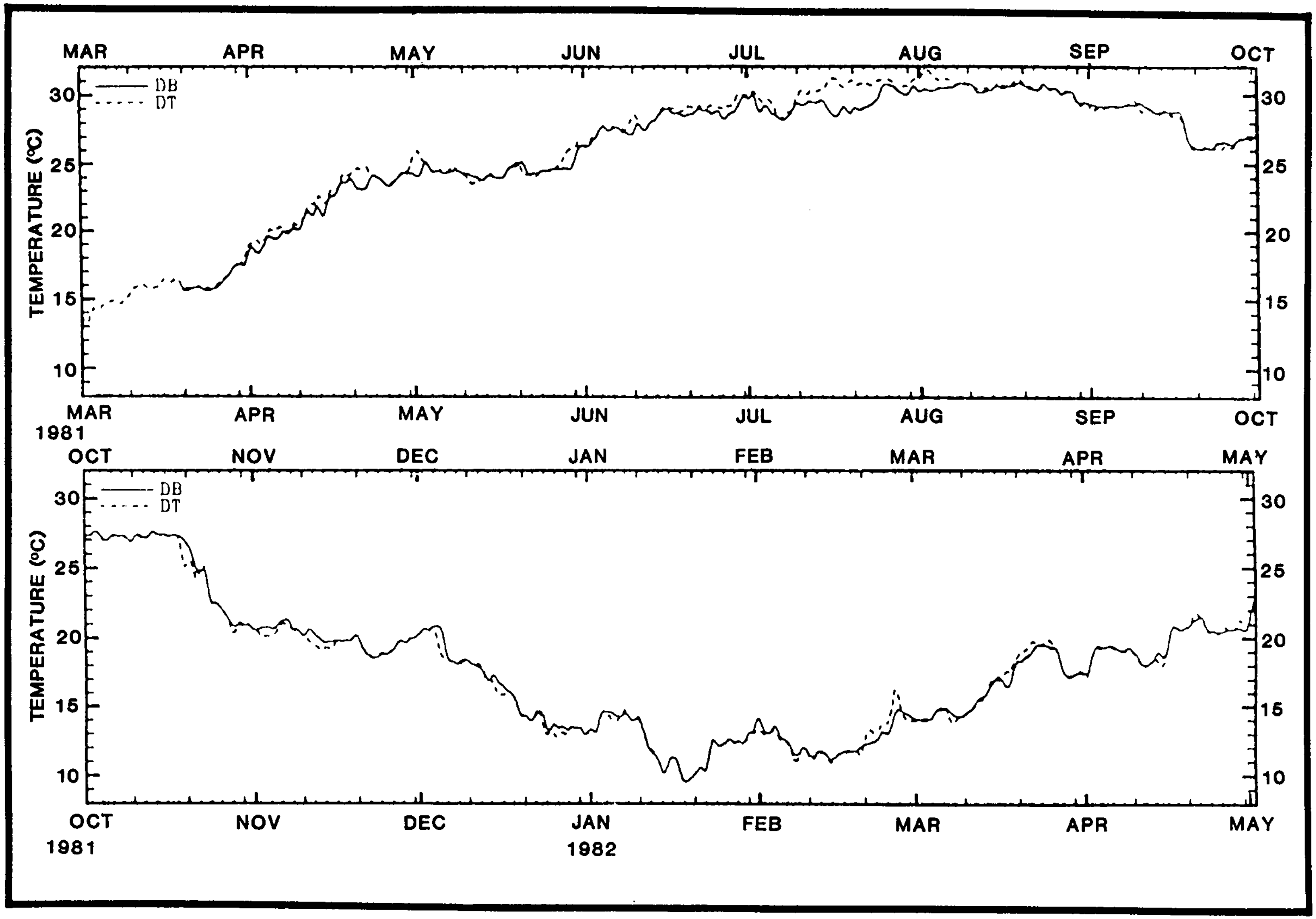


Figure 4.11. Forty-hour, low-pass-filtered time series of temperature measured at the West Hackberry brine disposal site of the Strategic Petroleum Reserve in 10 m of water, at 3.7 m below the surface (DT) and 7.3 m below the surface (DB) during the period March 1981 through April 1982 (From: Kelly et al., 1983b).

20 September, 19 to 28 October, 5 to 7 December 1981, and 10 to 14 January 1982 coincided with the passage of cold fronts through the area (Kelly et al., 1983b). During the cooling event of 19 to 28 October 1981, the temperature decreased by about 6.5°C, or -0.72°C/day. Vertical temperature differences are small, less than 1°C most of the time, except in July and early August 1981 when a difference of up to 3°C was recorded. During the warming period, the near surface temperature is slightly warmer than the near-bottom temperature, and vice versa for the cooling period.

Nowlin and Parker (1974) studied the details of the heat extraction and water mass modification processes during one major outbreak of cold dry air that occurred in January 1966. During the 15-day period between their surveys of the middle portion of the Texas-Louisiana shelf, the rate of cooling of the water column was largest nearshore, about -0.25°C/day, because the continental polar air mass had received a minimum of modification by the sea. The local rate of heat extraction, formed from the product of the local rate of change of vertically-averaged temperature, the local depth, mean density and specific heat, averaged about 400 cal/cm^2/day within 50 miles from shore and generally increased to 700 to 1,500 cal/cm^2/day at the offshore survey limits. They neglected advection. For comparison, Etter's mean monthly heat loss ($Q_R - Q_A$) for January (Figure 4.10A) is about -150 W/m^2 or -310 cal/cm^2/day [negative values correspond to positive heat extraction values of Nowlin and Parker (1974)].

Evaporation and precipitation also modify the shelf waters. Nowlin and Parker (1974) estimated that salinity increased about 1°/$_{oo}$ during the passage of the cold dry polar air. They concluded that the change in temperature-salinity (T-S) relationships before and after the outbreak indicated the possible formation over the shelf of subsurface water types generally found beneath the Subtropical Underwater core in the open Gulf. As noted in Section 4.2.4, observations of evaporation and precipitation over the shelf are generally lacking. Dinnel and Wiseman (1986) review the existing estimates of these parameters over the shelf and calculate their own. Tables 4.2, 4.3, and 4.4, reproduced from their study, summarize the various estimates and compare the characteristics of the Texas-Louisiana shelf with those of the Mid-Atlantic Bight and the South Atlantic Bight. Note that, where data are available, river input, precipitation and evaporation are all larger on the Texas-Louisiana shelf.

4.4 RIVERINE INFLUENCES

The Mississippi River is the principal source of fresh water on the Texas-Louisiana continental shelf. Its mean annual contribution is more than 15 times that of all of the other river sources combined (Cochrane and Kelly, 1986b) and almost four times larger than the contribution from precipitation (Dinnel and Wiseman, 1986). The variability of the flow of the Mississippi River contributes significantly to the variability of the currents, hydrography, nutrients, suspended sediments, chemical properties, and biological processes on the shelf, particularly on the inner third.

Table 4.2. Comparison of the evaporation rate calculated by Dinnel and Wiseman (1986) with global climatic evaporation rates prorated to this study area (Jacobs, 1951; Baumgartner and Reichel, 1975; Bunker, 1976), and with a regional evaporative rate estimated for the study area (Etter, 1975) (From: Dinnel and Wiseman, 1986).

Evaporation Rate (km^3/yr)	Study
148	Dinnel and Wiseman (1986)
128	Jacobs (1951)
160	Baumgartner and Reichel (1975)
214	Etter (1975)
187	Bunker (1976)

Table 4.3. Shelf precipitation rates calculated from onshore coastal data, 30-yr mean values, and climatic annual precipitation estimates for the Texas-Louisiana shelf* (From: Dinnel and Wiseman, 1986).

Year	Onshore	Shelf
1963	105	79
1964	125	94
1965	125	94
30-yr Mean	143	108
Climatic Estimates		85†
		107§
		53#

*1963-1965 were drought years. Values are in km^3/yr.
†Jacobs (1951).
§Baumgartner and Reichel (1975).
#Dorman and Bourke (1981).

Table 4.4. Comparison of Mid-Atlantic Bight and South Atlantic Bight characteristics with those of the Texas-Louisiana shelf* (From: Dinnel and Wiseman, 1986).

	Mid-Atlantic Bight	South Atlantic Bight	Texas-Louisiana Shelf
Area (km^2)	70,656	106,000	106,866
Volume (km^3)	3,108	3,610	3,746
River Input (km^3/yr)			
Long-Term	150	50	382†
Short-Term			320§
Precipitation (km^3/yr)			
Long-Term	49		108#
Short-Term			89**
Evaporation (km^3/yr)	71		148**

*Mid-Atlantic data from Ketchum and Keen (1955), South Atlantic Bight data from Atkinson et al. (1983); values are prorated to a 50-fathom maximum shelf depth.
†Extrapolated value for major rivers.
§Mean 1962-1965.
#Estimate of shelf 30-yr mean.
**Offshore mean 1963-1965.

The waters of the Mississippi River reach the Texas-Louisiana shelf through its two natural distributaries, the main river and the Atchafalaya River. The percentage carried by the Atchafalaya has increased significantly during this century (Gunter, 1979): between 1900 and 1919 the Mississippi proper carried about 85% of the river flow while the Atchafalaya carried about 15%; from 1920 through 1950 the Atchafalaya's share increased to about 30%, with a commensurate decrease in the Mississippi's flow. The U.S. Army Corps of Engineers (COE) now controls the partition by means of its Old River Control Structure. The COE maintains a split of approximately 30/70, but permits the percentage carried by the Atchafalaya to rise sometimes during floods; during the flood year of 1973 the Atchafalaya took over 37% of the flow (Gunter, 1979).

All of the flow from the Atchafalaya contributes to the fresh water budget of the shelf, but only an estimated 53% (Dinnel and Wiseman, 1986) to 65% (Scruton, 1956) of the discharge from the Mississippi Delta consistently flows onto the Texas-Louisiana shelf. Thus, the net contribution from the Mississippi distributary (0.70 X 0.53 = 0.37) is now about the same as that of the Atchafalaya distributary. It is important to note that the total freshwater input to the shelf increased by more than 10% between 1920 and 1950, solely because of the change in the partition of the flow between the two distributaries.

Gunter (1979) analyzed the flows of the Mississippi-Atchafalaya River System for the 79-year period from 1900 through 1978 and found a mean annual flow of 646,304 cubic ft/s (cfs) (1 cfs = 2.832×10^{-2} m^3/s; 1 cfs = 8.932×10^{-4} km^3/year). Table 4.5 shows that most flows were in the 500,000 and 600,000 cfs classes, with 53 of the 79 years, or 67%, below 699,000 cfs. A flood year has, by definition, an annual flow of 700,000 cfs or greater (Gunter, 1979). Flood years are not especially associated, and in several cases low flows and flood years are close together. Corresponding volumes of freshwater flow onto the shelf can be only estimated because of the variable partition between the two distributaries and the imprecise estimates of the percentage of water from the delta that flows onto the shelf; a rough conversion factor is 0.7.

Intra-annual variation, in terms of monthly mean discharges for the Mississippi-Atchafalaya System, follows a cycle that has a strong maximum (spring flood) in April of more than twice the annual mean discharge and a rather flat minimum in October (Figure 4.12). There is considerable inter-annual and short-term variability about this mean progression, as can be seen in Figures 4.13 and 4.14, which show the average daily stream flow for the water years 1977 to 1978 and 1979 to 1980, respectively. (A water year runs from October of the preceding calendar year through September of the given calendar year.) In addition to the April maximum, significant secondary maxima frequently occur in December, January and May. Minimum flow, in these example years, occurs near the month of October, and the lowest value reached varies by more than a factor of two. The annual means for 1977, 1978, and 1980 (541,000 cfs, 671,000 cfs, and 623,000 cfs, respectively) were normal according to Table 4.5. However, the 1979 annual mean of 1,012,000 cfs ranks as the third biggest flood since 1900.

Table 4.5. Annual flows of the Mississippi River for the twentieth century (From: Gunter, 1979).

Class Ranges (Thousands of cfs*)	Number of Annual Flows in Class Range
300	3
400	10
500	17
600	23
700	15
800	6
900	3
1,000	1
1,100	1

*cfs = cubic ft/s

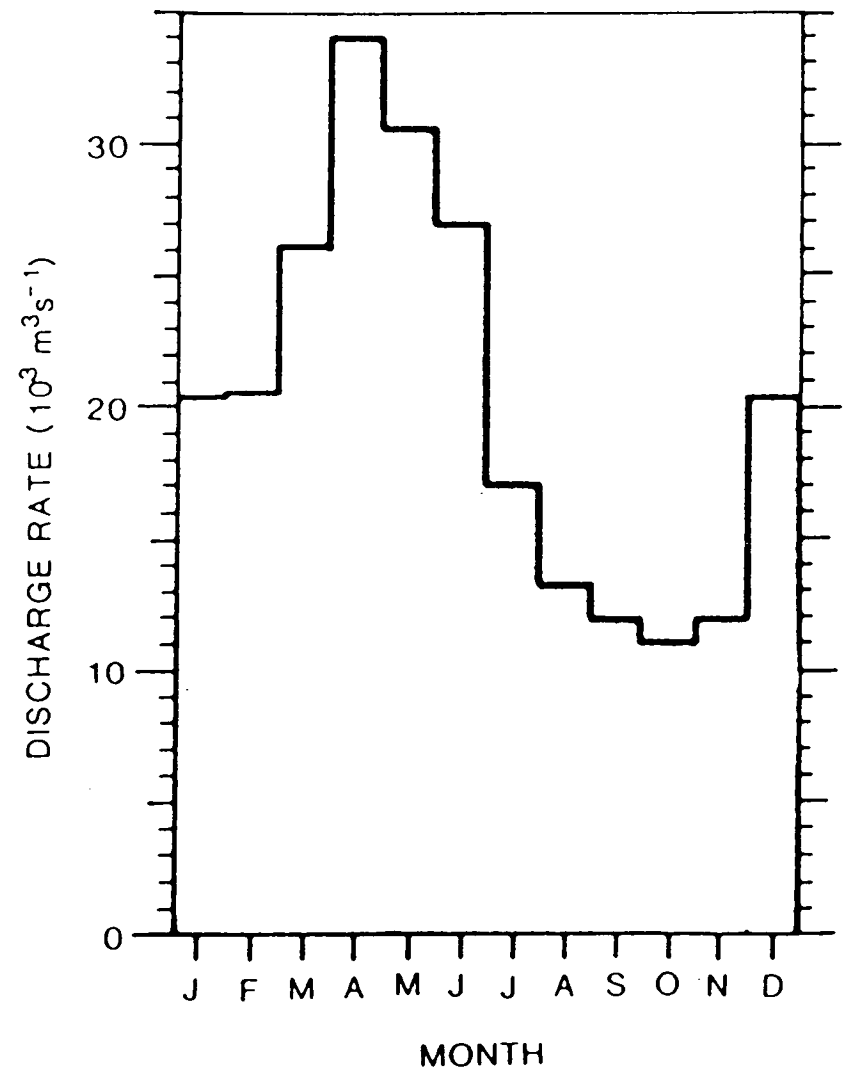


Figure 4.12. Monthly mean discharge rates for the Mississippi-Atchafalaya River system based on the water years 1977 to 1983 (From: Cochrane and Kelly, 1986b).

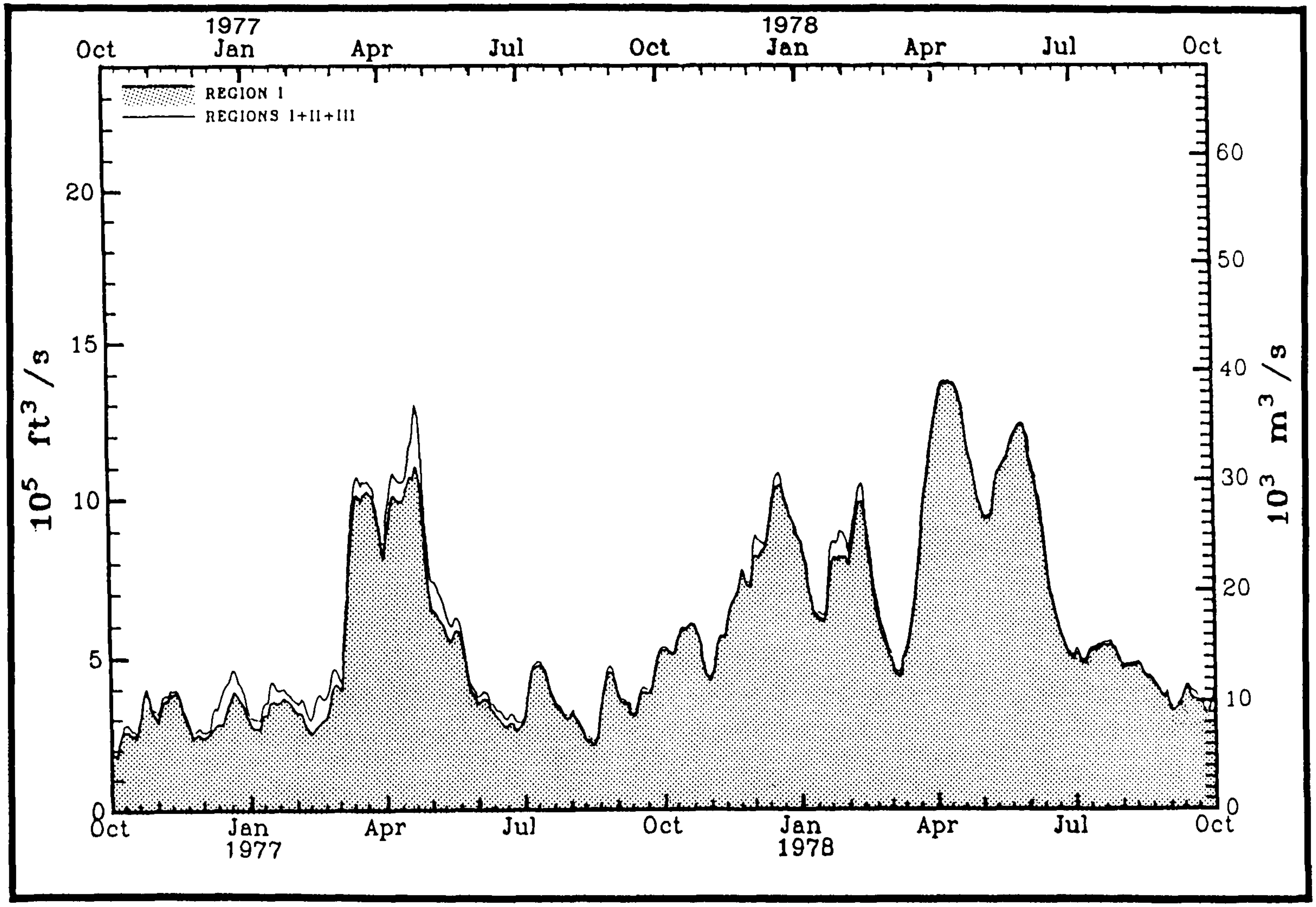


Figure 4.13. Average daily streamflow for water years 1977 and 1978 for the Mississippi-Atchafalaya River System (heavy line) and for this system plus all other rivers from the Vermilion to the San Bernard (light line) (From: Kelly et al., 1981).

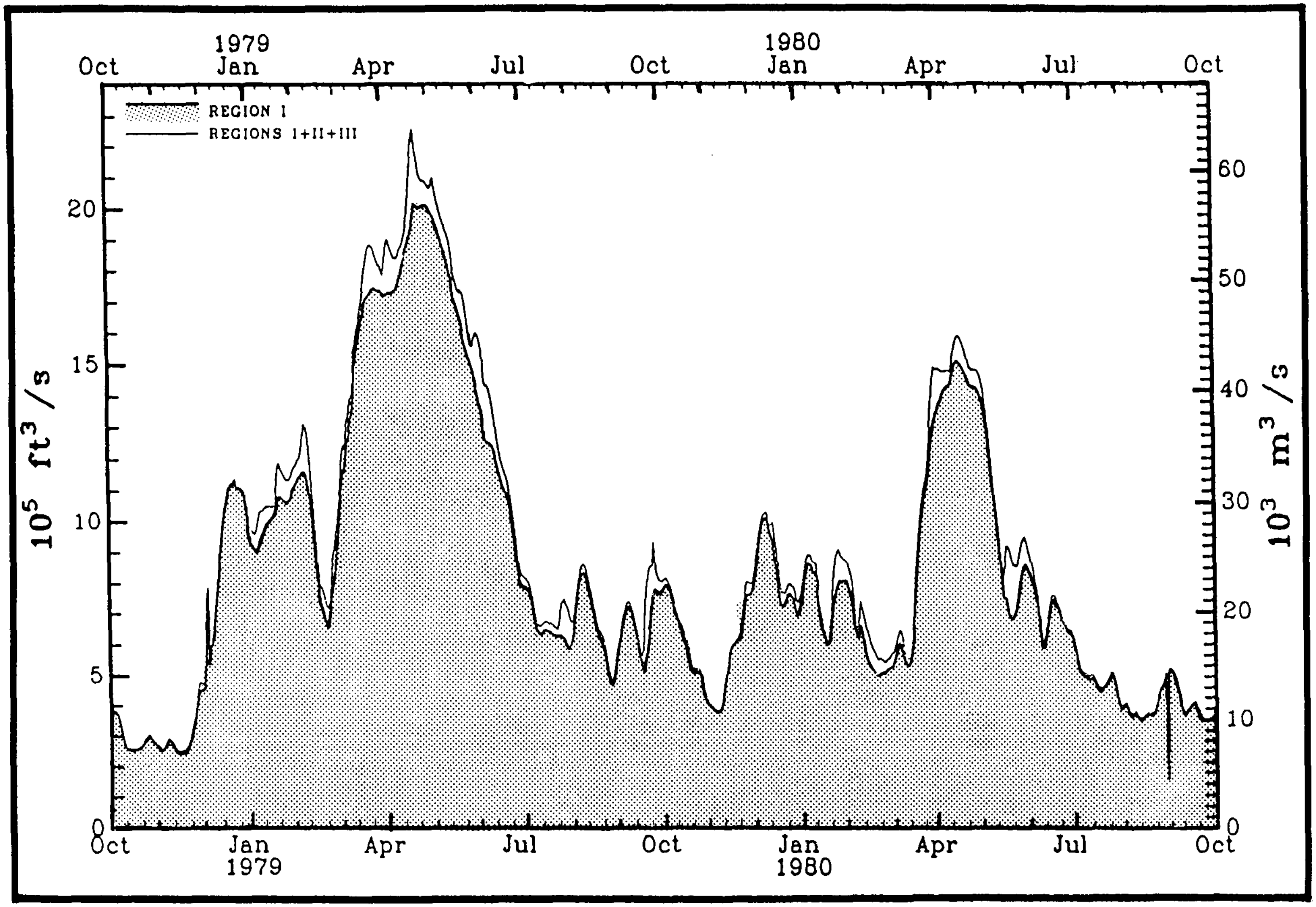


Figure 4.14. Average daily streamflow for water years 1979 and 1980 for the Mississippi–Atchafalaya River System (heavy line) and for this system plus all other rivers from the Vermilion to the San Bernard (light line) (From: Kelly et al., 1981).

The total additional discharge from all rivers and streams from the Vermilion in Louisiana to the San Bernard in Texas is also indicated in Figures 4.13 and 4.14 (light line minus heavy line). The degree to which the Mississippi-Atchafalaya flow dwarfs all other riverine input is evident.

4.5 HYDROGRAPHY

4.5.1 Water Temperature

The spatial and temporal variability of water temperature is caused by advection, turbulent and convective mixing, and the air-sea exchange processes discussed in Section 4.3.4. Temperature is the most abundantly measured of the hydrographic properties, and its variability on the Texas-Louisiana shelf is relatively well documented. For example, Robinson (1973) and Etter and Cochrane (1975) have produced maps of mean temperatures from independent data sets; Ulm (1983) prepared a volumetric T-S census for the waters of the shelf region; the multi-year studies at the various DOE/SPR brine disposal sites along the inner shelf and the MMS environmental studies at the Flower Gardens on the outer shelf have reported the results of continuous sub-surface measurements; and analyses of thermal imagery from satellites have described the synoptic scale spatial variability at the sea surface (e.g., Rezak et al., 1985).

Monthly mean sea-surface temperatures for the northwestern Gulf of Mexico from Robinson's (1973) atlas (Figure 4.15) illustrate the influence of climatology and advection. Shelf waters cool from summer highs near 29 to 30°C to inshore lows of about 14°C in January and offshore lows of about 20°C in February. Warming occurs from March through July. The eastern half of the shelf warms more rapidly and reaches higher temperatures than the western half because of upwelling that begins along the lower Texas coast in May and reaches the west Louisiana coast by July. On the eastern part of the shelf a warm region extends offshore in July and August. (The cold protrusions from Galveston Bay in March and April are probably an artifact of insufficient data, which gives undue weight to flushing events, and probably are not representative of mean conditions.)

Satellite infrared imagery for June through September 1982 (Figure 4.16) illustrates the development of the summer sea-surface temperature pattern over the shelf in greater detail. The June map indicates that upwelling extends as far northeast as Matagorda Bay. During late July and early August, the contrast in temperature between east and west increases markedly, and the warm region in the east grows westward and offshore. However, by mid-September the warm region is pressed against the coast and extends southwestward. The warm region coincides roughly with the summer region of low-salinity surface water (Section 4.5.2). The high stability of the upper layer of the water column in this region facilitates its heating. Figure 4.16 also demonstrates that in the summer months satellite imagery can still detect contrasts in sea-surface temperature on the shelf that are strong enough for useful interpretations to be made.

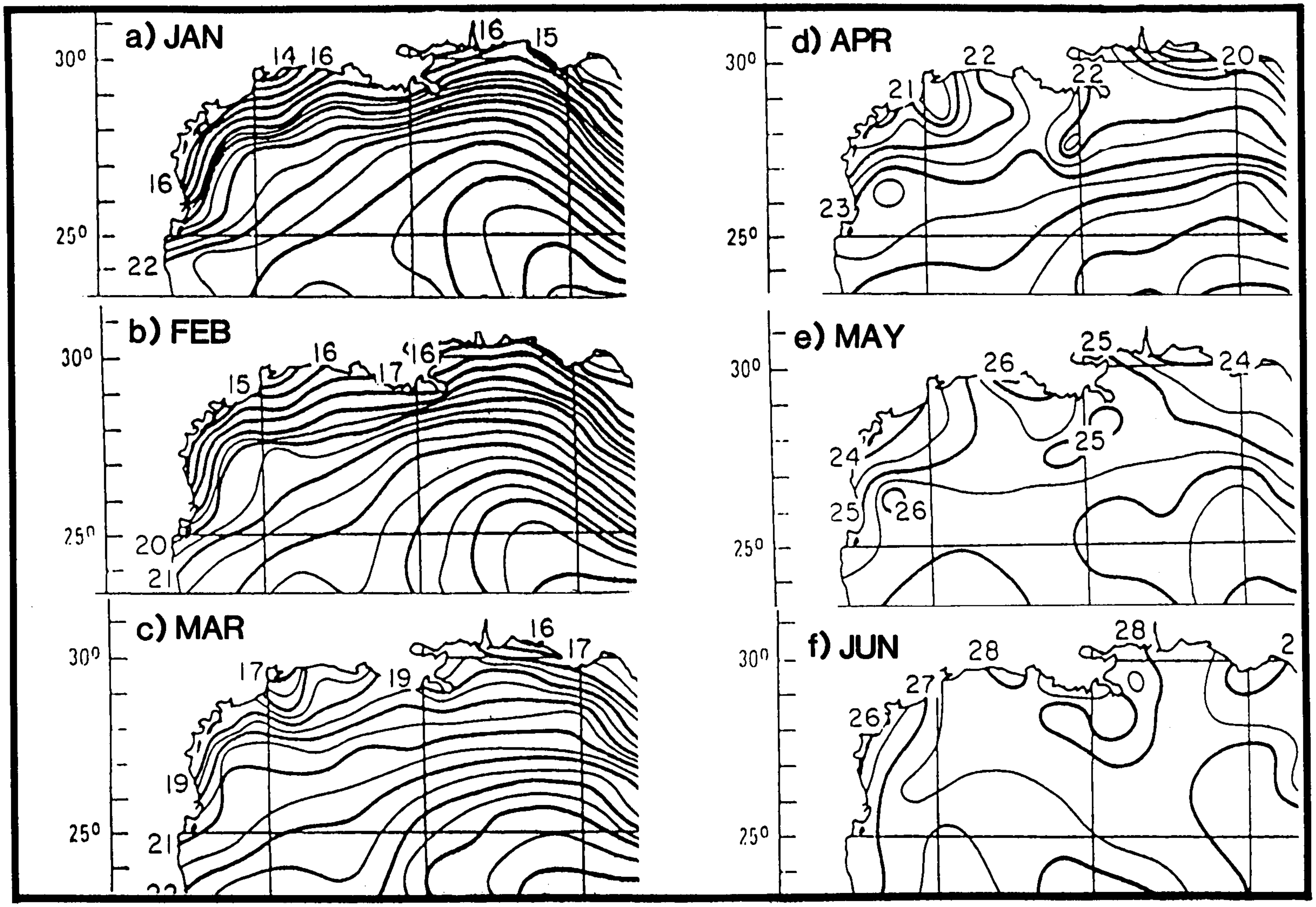


Figure 4.15. Monthly mean sea-surface temperatures for the northwestern Gulf of Mexico, a) January through l) December (Adapted from: Robinson, 1973).

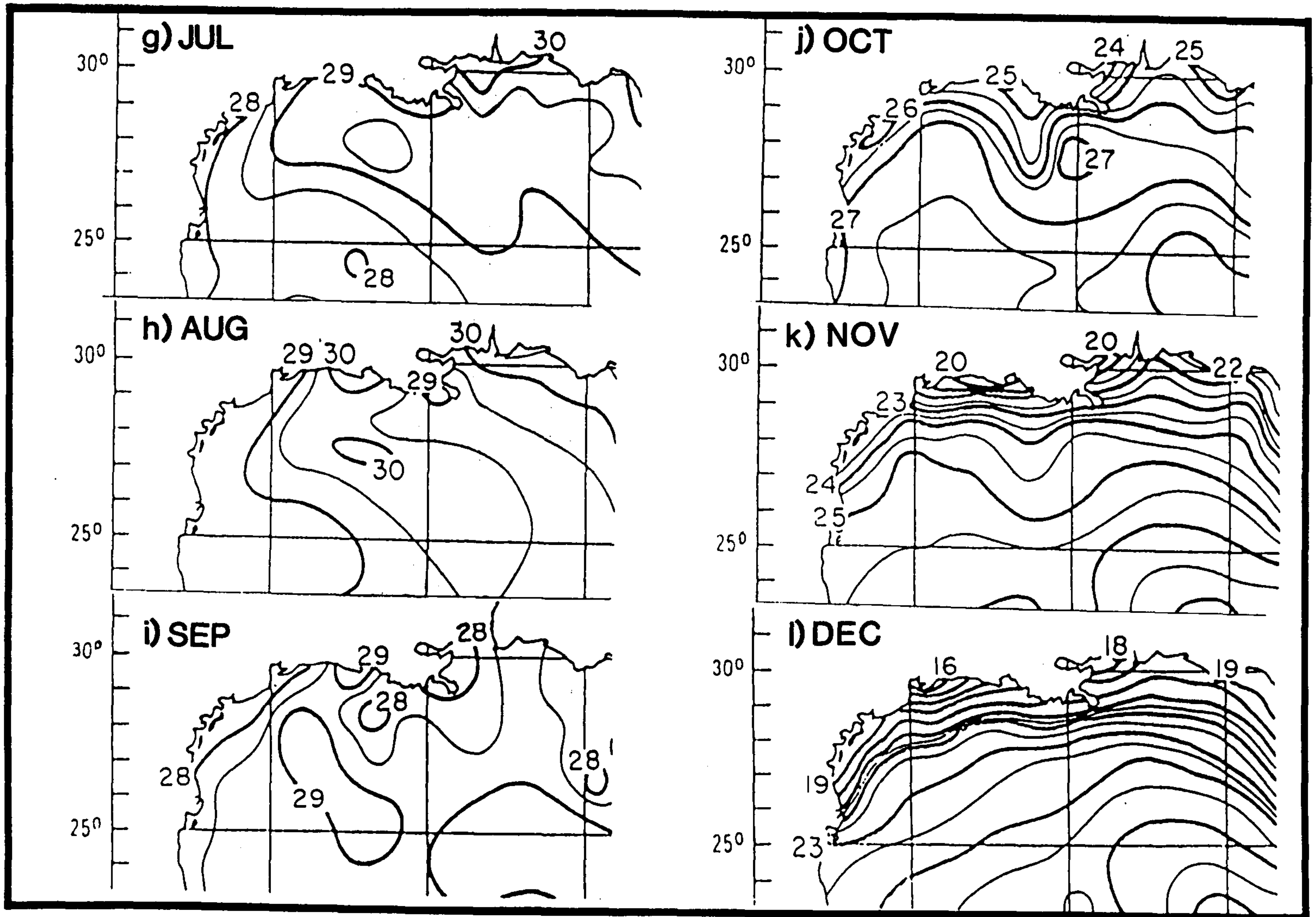


Figure 4.15. (Continued).

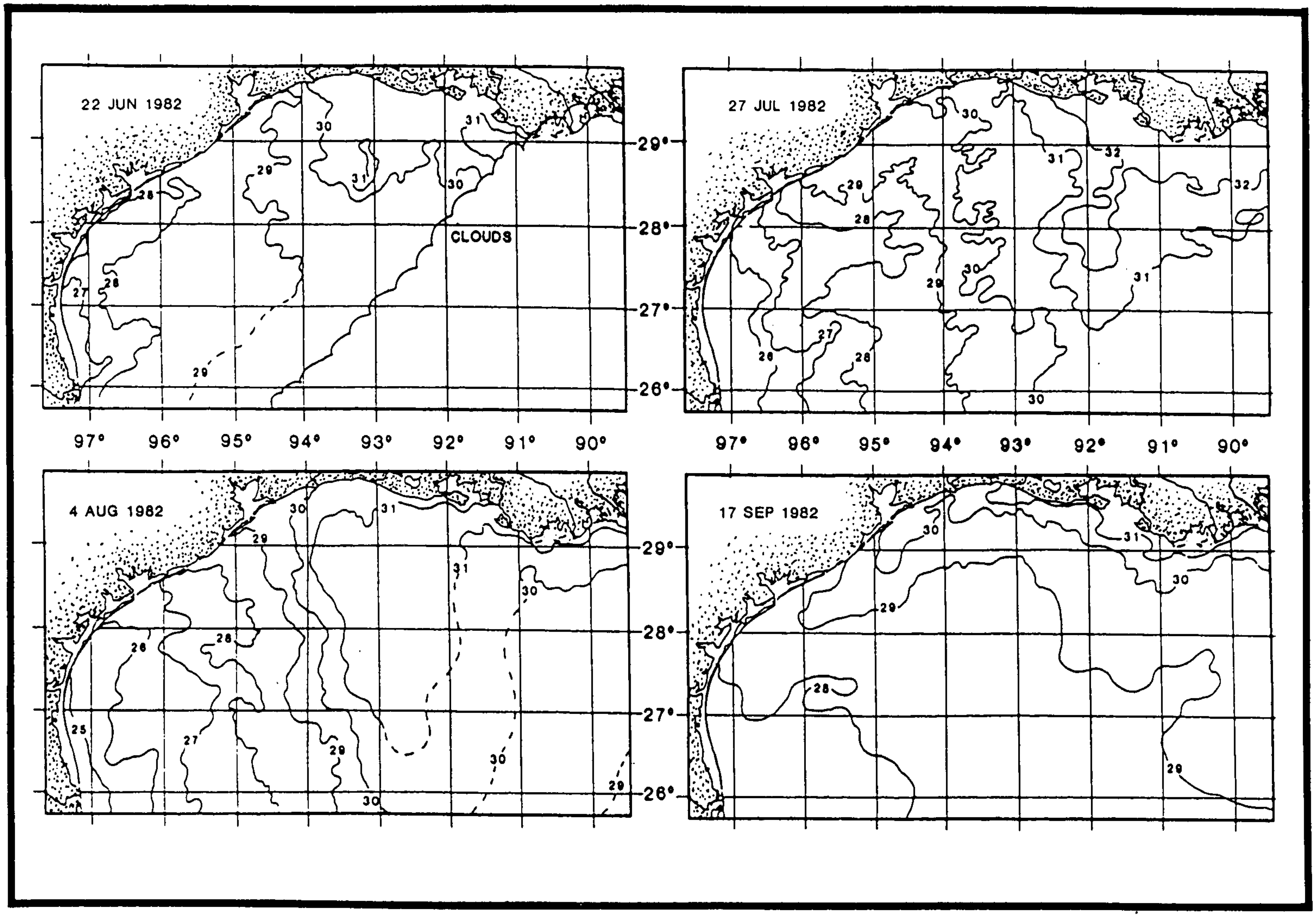


Figure 4.16. Sea-surface temperature based on infrared imagery for days in June, July, August, and September 1982 (From: Cochrane and Kelly, 1986b).

According to Etter and Cochrane (1975), the depth of the mixed layer becomes shallow in the summer, ranging from 10 to 25 m, and deepens in the winter, with a maximum depth of about 75 m over the outer shelf between November and February (Figure 4.17). Within about 25 km of the coast, however, temperature is not a good indicator of mixed-layer depth because the distribution of salinity controls the density field much of the year. Thermocline strength over the outer shelf varies seasonally from a maximum of about 6°C in August to a minimum of less than 2°C in March (Etter and Cochrane, 1975). Rezak et al. (1985) report similar results for mixed-layer depth and thermocline strength near the Flower Garden Banks.

Bottom temperatures over the inner half of the shelf follow sea-surface temperatures to the extent that the mixed-layer depth reaches the bottom, while seaward of about 75 m, bottom temperatures reflect the off-shelf annual variations of the Gulf; seaward of about the 120-m isobath, bottom temperatures vary only slightly (Etter and Cochrane, 1975). Figure 4.18a shows that mean summer temperatures near the bottom are highest near shore and lowest offshore and that the isotherms closely parallel the isobaths. During fall and winter, mean bottom temperatures are low both nearshore and offshore with somewhat higher temperatures in between (Figure 4.18b).

4.5.2 Salinity

Wind-driven currents and freshwater influx from the Mississippi-Atchafalaya River System determine much of the spatial distribution and temporal variability of salinity on the shelf. The best coverage of salinity on the shelf is provided by a series of observations taken during 1963, 1964, and 1965 by the U.S. Fish and Wildlife Service aboard the M/V GUS III (Temple et al., 1977). Figure 4.19 shows the sea-surface salinity distributions for alternate months in 1964, and illustrates an annual sequence that is believed to be fairly typical. A band of low-salinity water lies along the coast from September through June, carried by the inshore limb of the gyre of cyclonic circulation that prevails on the shelf during this time. Minimum salinities occur all along the coast in May after the spring flood of the Mississippi in April. The May distribution also shows fresher water extending from the south Texas coast to the northwest along the outer edge of the shelf, a pattern that is attributed to convergence in the wind stress and current fields near the coast and to the offshore limb of the cyclonic gyre. The band recedes upcoast in June and disappears by August, although brackish water remains along the coast from the delta to about 92°W and in a region extending seaward over the shelf. The absence of low-salinity water west of about 92.5°W is caused by upcoast currents and upwelling driven by the upcoast wind stress in July. In September, currents all along the coast rapidly return to prevailing downcoast flow, bringing with them a coastal band of low-salinity water. The main source of the brackish water must be the extensive region of low-salinity water that lies off eastern Louisiana in July and August, because Mississippi discharge is near its annual minimum at this time.

Dinnel and Wiseman (1986) used the GUS III data set in a study of the freshwater budget of the shelf. They also included evaporation and

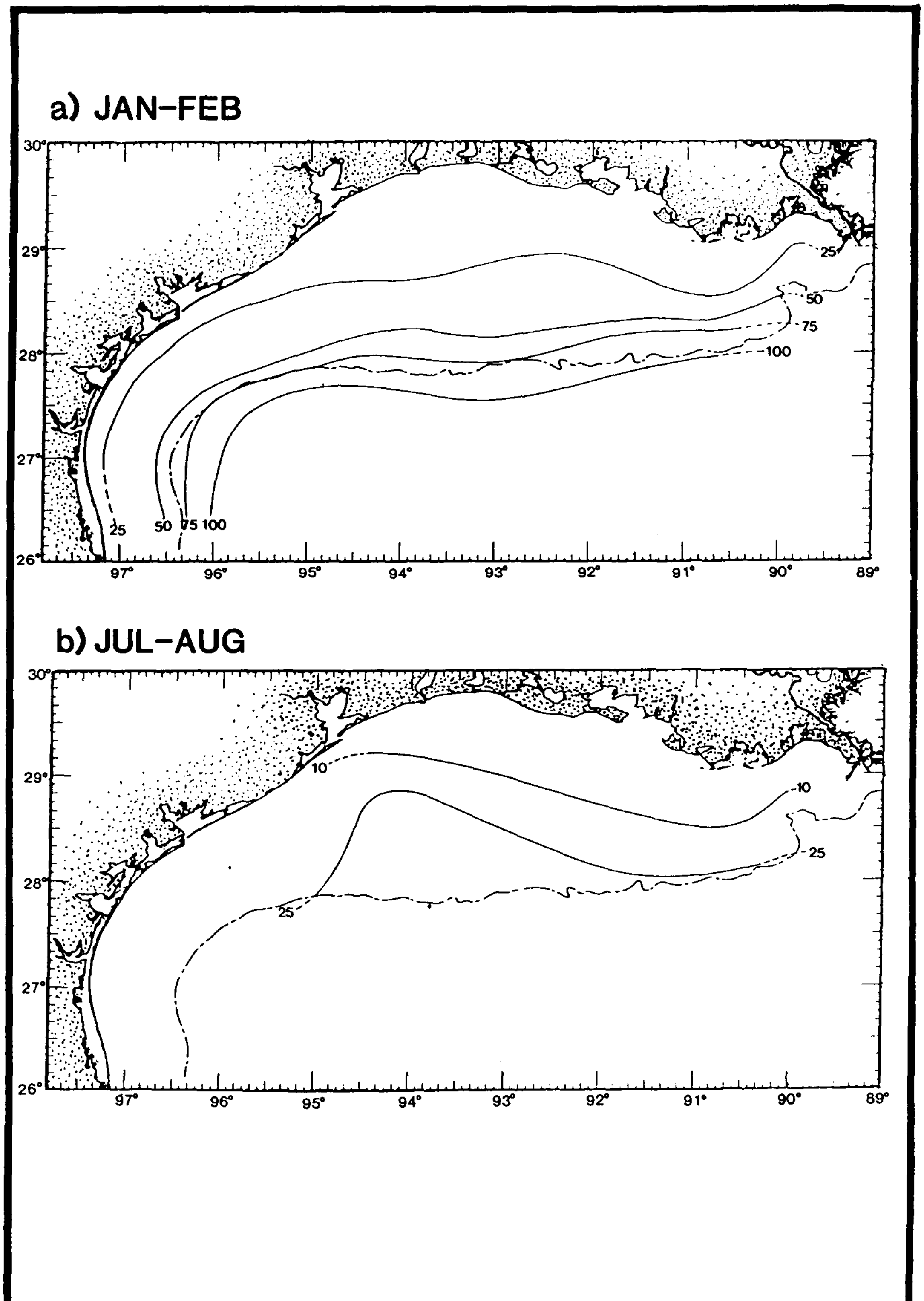


Figure 4.17. Map of mixed layer depths (m) for a) January-February and b) July-August. Dashed lines indicate lack of data, and curvature of these lines suggests most probable tendency (From: Etter and Cochrane, 1975).

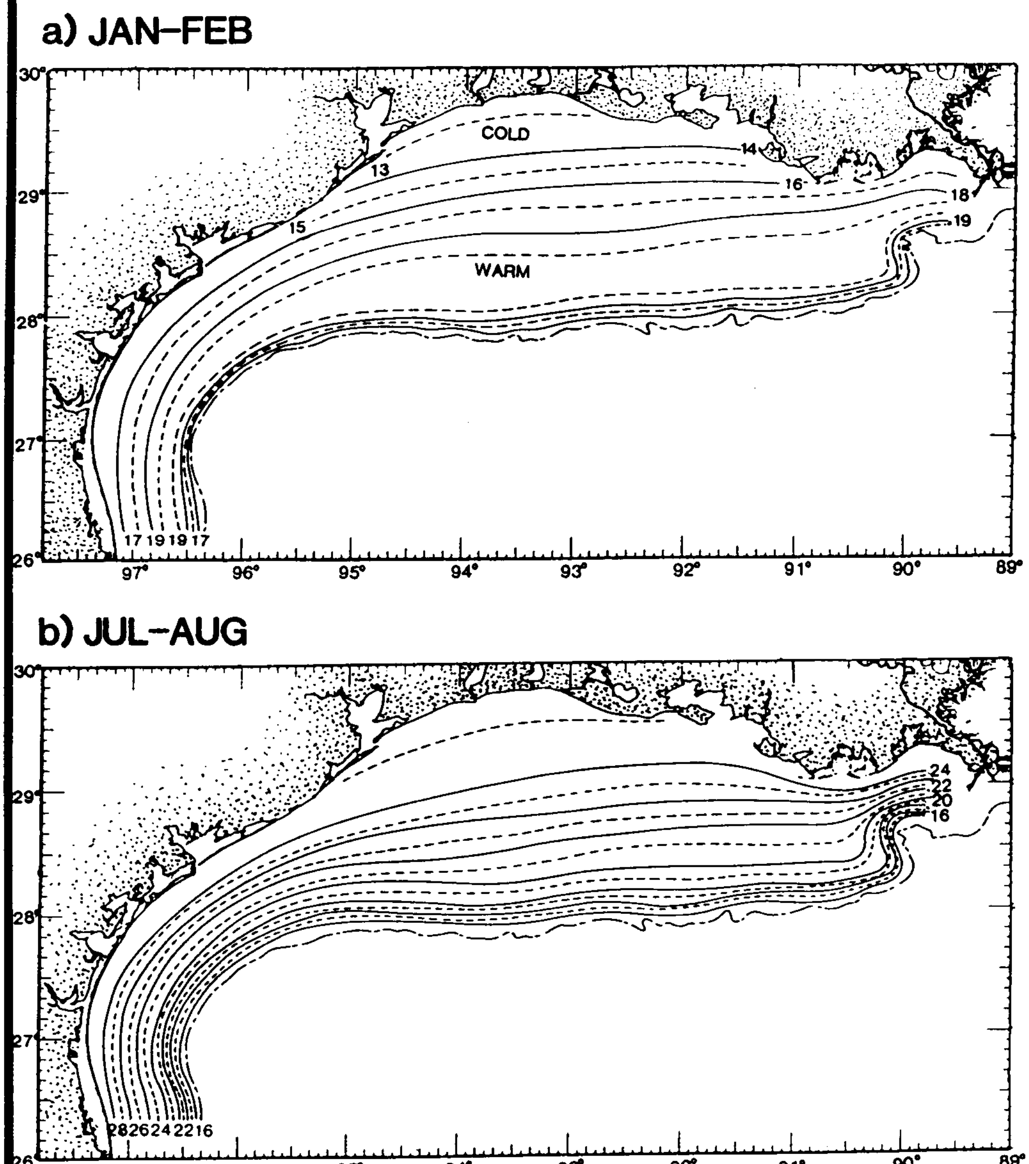


Figure 4.18. Map of mean bottom temperatures (°C) for a) January–February and b) July–August. Solid lines represent even values of temperature, and dashed lines indicate odd values (From: Etter and Cochrane, 1975).

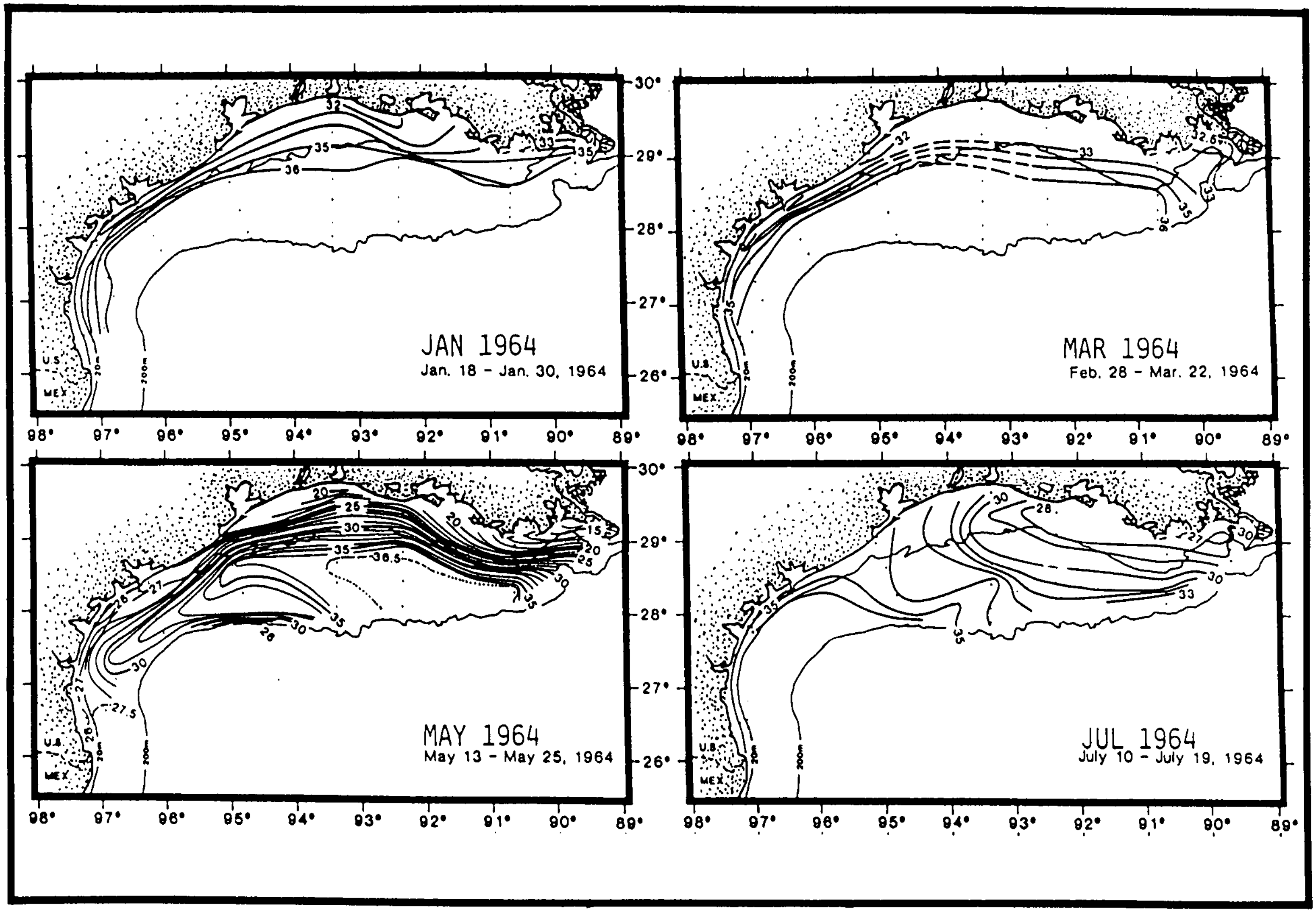


Figure 4.19. Sea-surface salinity (‰) for M/V GUS III cruises in 1964 (From: Cochrane and Kelly, 1982).

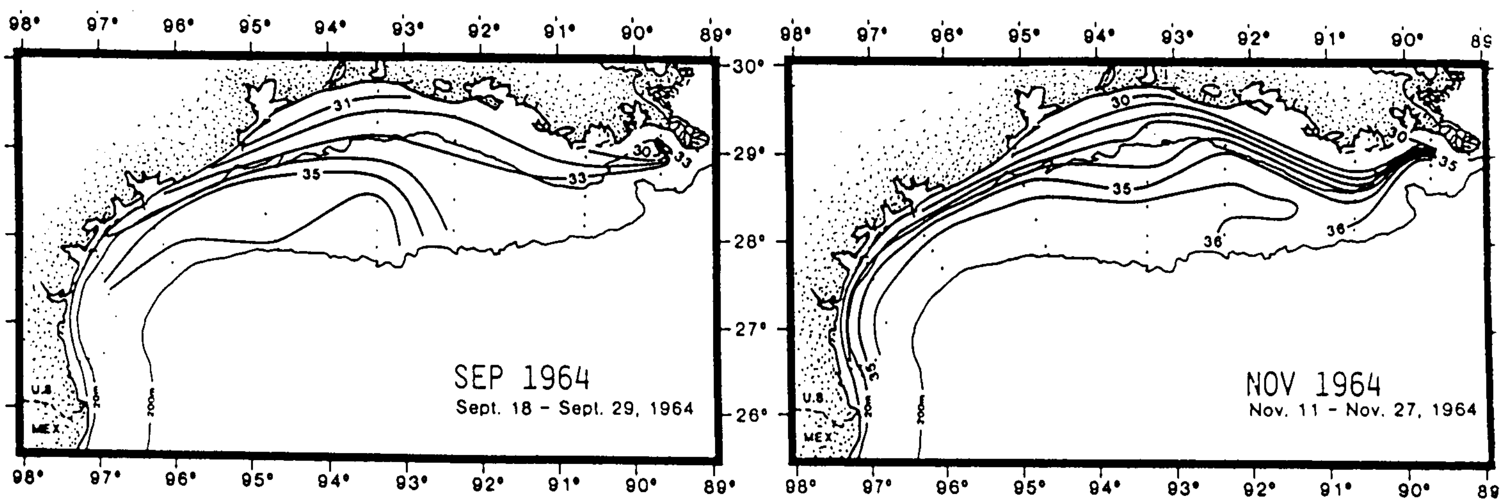


Figure 4.19. (Continued).

precipitation in the budget because evaporation-precipitation is not in balance on the shelf and is comparable to the river discharge term at times. The patterns of distribution of fresh water that they found are consistent with those of low salinity described above, except that the coastal band of maximum freshwater content is displaced slightly seaward of the coast because higher freshwater content is associated with a deeper water column. They found that there was generally a net dispersion of freshwater out of their study area, but that net gains in some spring flood months suggest some additional uncounted flow from the Mississippi Delta. Calculated fill times exhibit an annual cycle, and freshwater volume appears, in most cases, to have originated near the time of the previous spring flood. (Fill time is the length of time required for river runoff, precipitation, and evaporation to account for the volume of excess freshwater on the shelf.)

The slow downcoast change in coastal sea-surface salinity that is found in all of the months shown in Figure 4.19 except July cannot result simply from the local river discharges, which vary widely. Only downcoast advection of Mississippi-Atchafalaya water can explain the very gradual changing. However, floods in the other rivers and flushing of bays and estuaries by strong persistent northers can discharge pulses of relatively fresh water that briefly augment the inshore edge of the coastal brackish band in the near surface layers.

The upwelling current regime acting on the plentiful supply of brackish water in the coastal band produces a dramatically different vertical distribution of the water masses than occurs during downwelling conditions. A typical example of the hydrography of the inner shelf during the downwelling regime is shown by a transect (Figure 4.20) extending 30 km off Freeport, TX. The density field is determined primarily by the salinity field. The strongest part of the frontal zone lies between 10 and 20 km offshore, and the density interface has somewhat of an "S" shape. Contrast this with the conditions during 22 to 23 July 1983. Figures 4.21, 4.22, and 4.23 show the observations along transects running offshore through the Bryan Mound, Big Hill and West Hackberry DOE/SPR brine disposal sites, respectively. Salinity again determines the density field. High salinity water extends shoreward along the bottom almost to the coast, while in the upper layers low salinity water extends seaward past the limits of the transects. The result is extremely strong vertical stratification.

Such stratification also exists over the inner shelf just west of the Mississippi Delta, where Wiseman et al. (1976) observed intense temperature and salinity steps in vertical profiles collected in the river's plume (Figure 4.24).

To provide a more quantitative picture of the annual progressions of temperature and salinity in the coastal regions where the variability is greatest, monthly means for the surface and bottom are shown, together with a representation of both progressions in a T-S diagram, in Figures 4.25 and 4.26 for the Bryan Mound and West Hackberry sites, respectively.

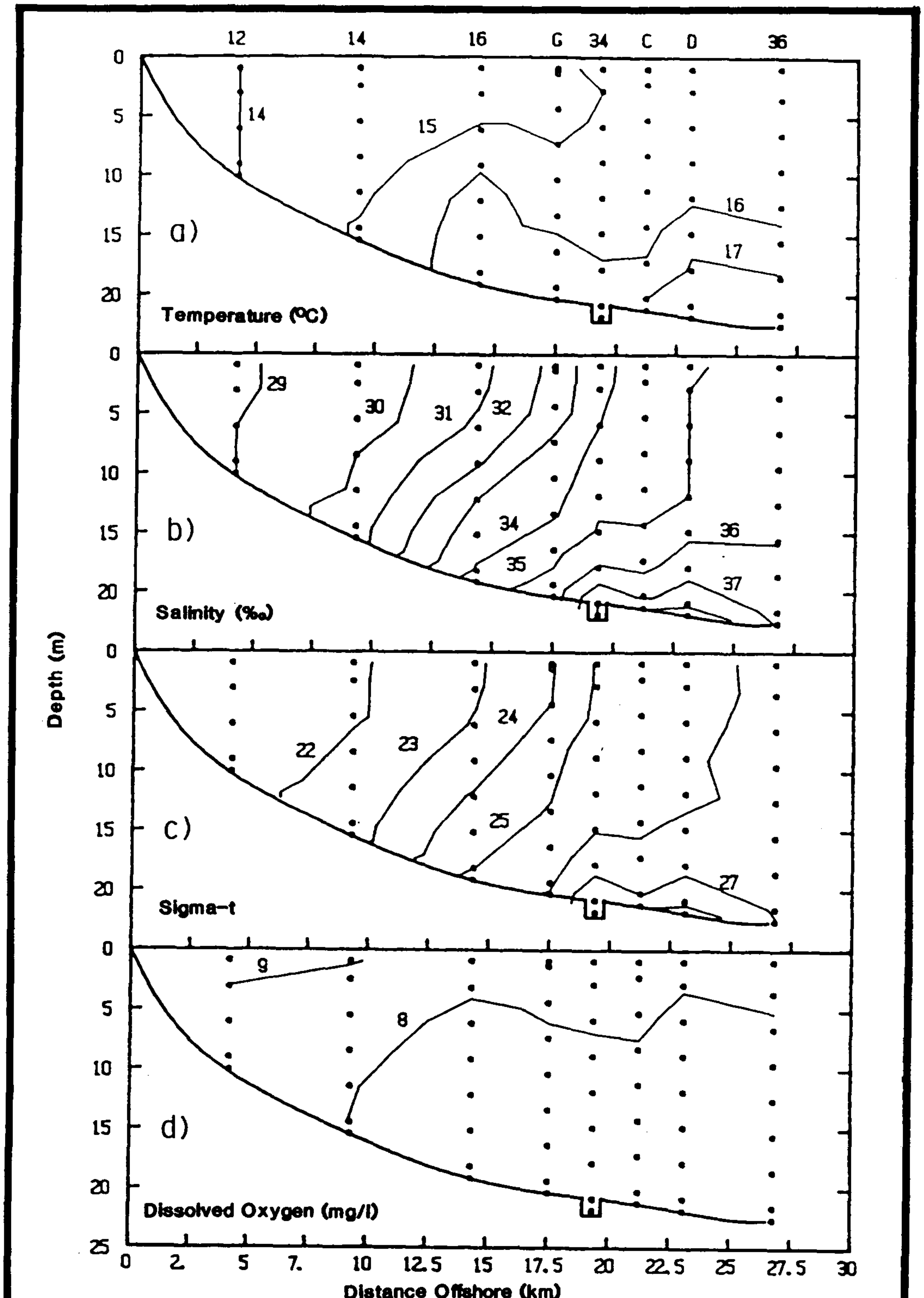


Figure 4.20. Hydrography for the cross-shelf transect offshore Freeport, TX on 4 January 1983 (Note: the salinity values greater than about 36‰ near the bottom in the vicinity of station 34 were caused by the DOE/SPR brine disposal operations) (From: Kelly et al., 1984b).

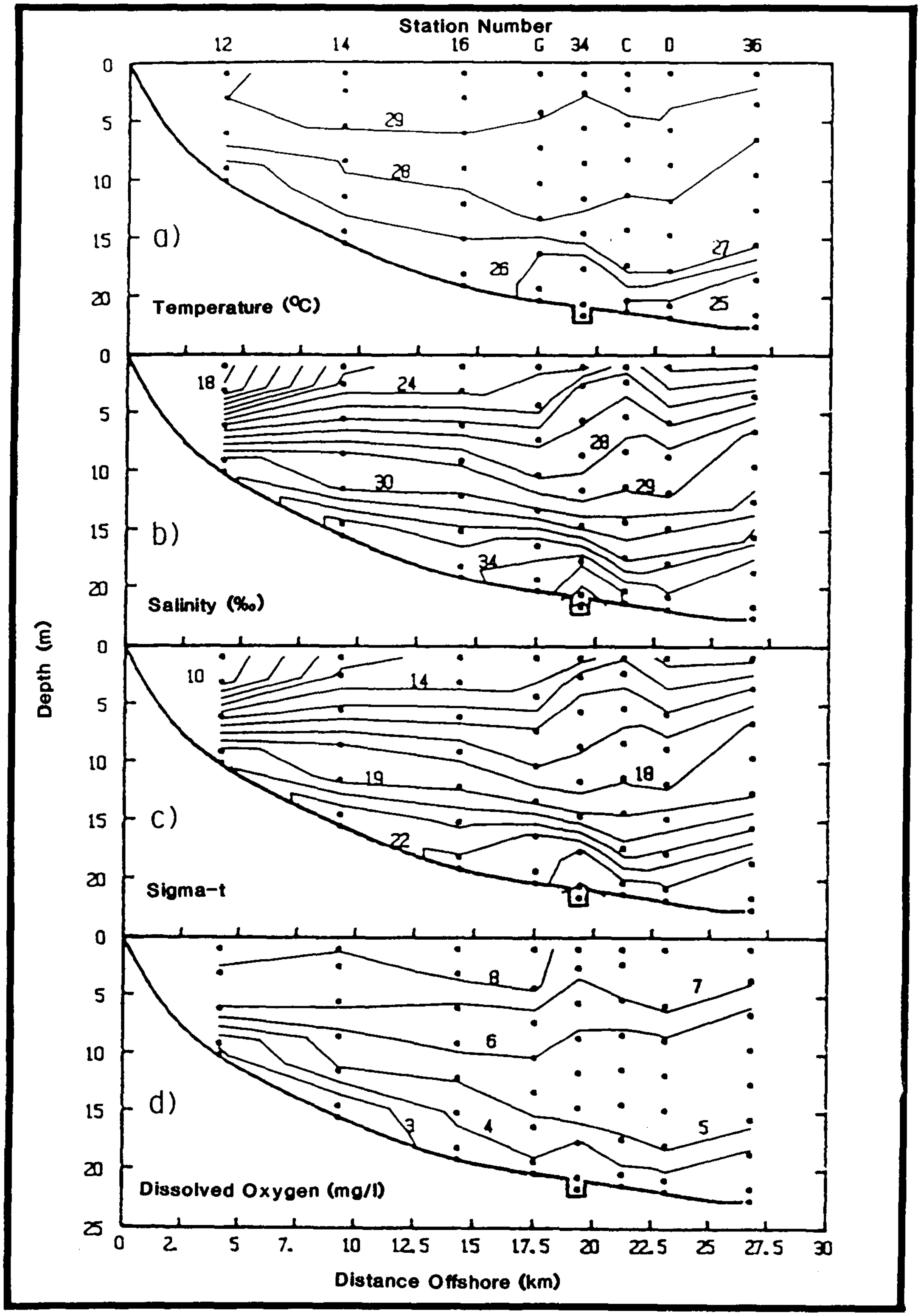


Figure 4.21. Hydrography for cross-shelf transect through the Bryan Mound site on 22 July 1983 (Note: the slightly higher salinity values near the bottom in the vicinity of station 34 were caused by the DOE/SPR brine disposal operations) (From: Kelly et al., 1984b).

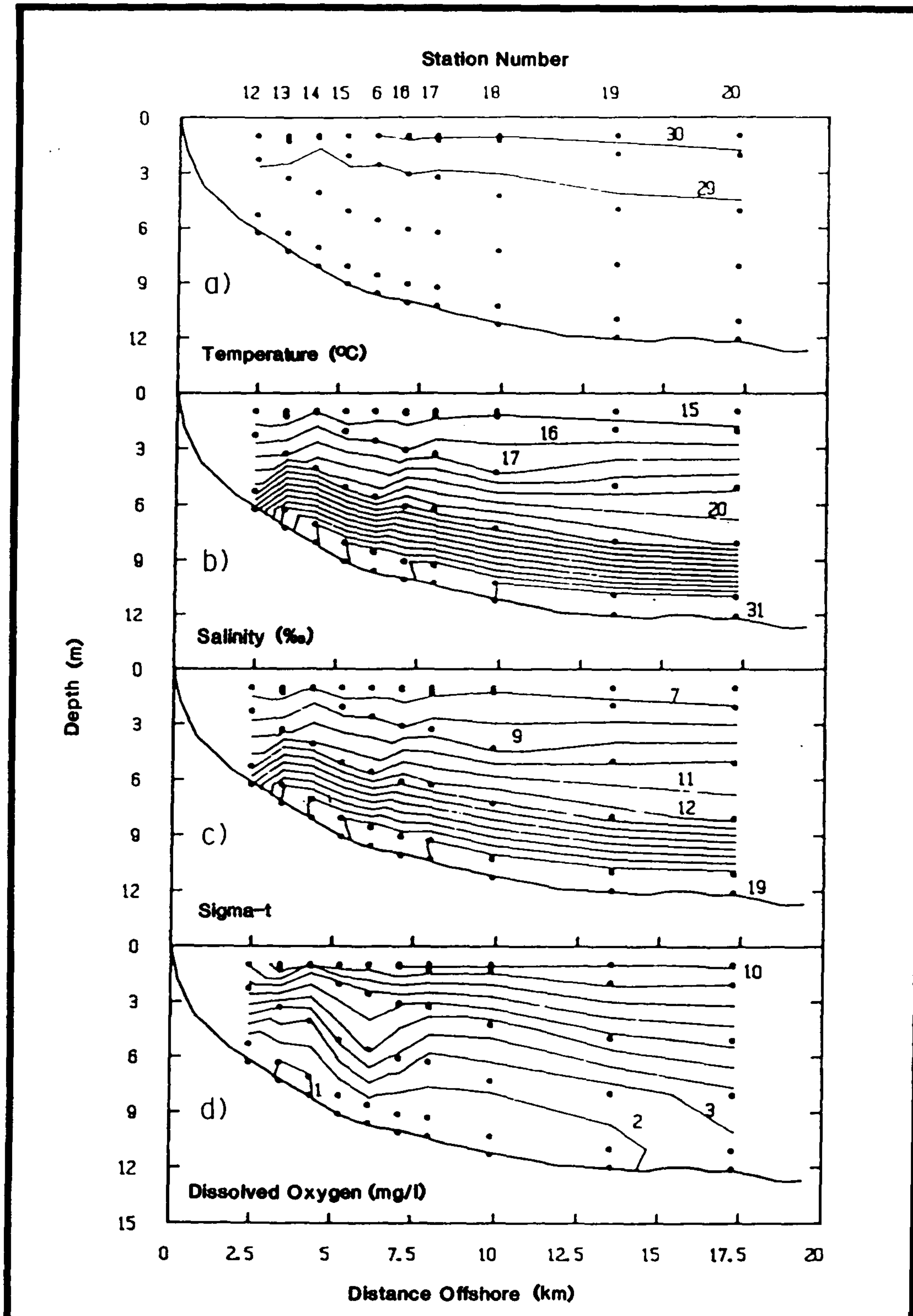


Figure 4.22. Hydrography for cross-shelf transect through the Big Hill site on 21 July 1983 (From: Kelly et al., 1984a).

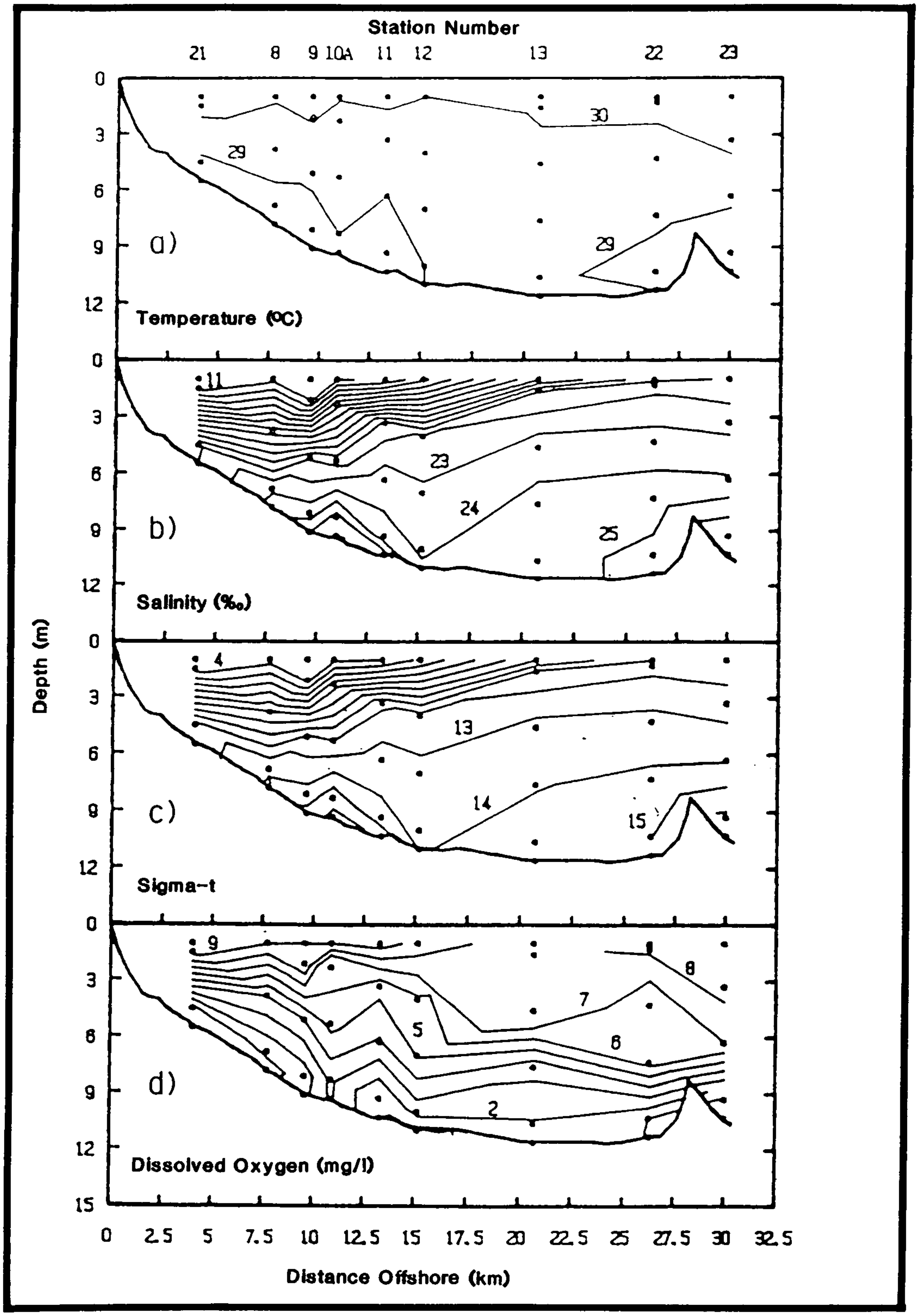


Figure 4.23. Hydrography for cross-shelf transect through the West Hackberry site on 22 July 1983 (Note: the slightly higher salinity values near the bottom at station 10A were caused by the DOE/SPR brine disposal operations) (From: Kelly et al., 1984c).

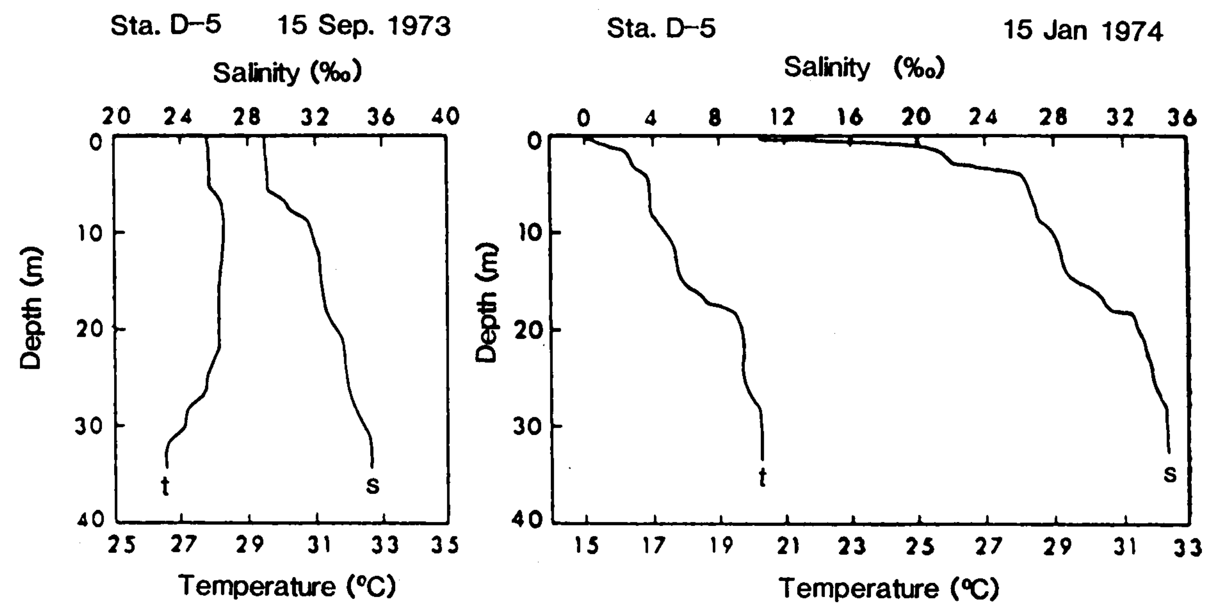


Figure 4.24. Temperature and salinity profiles taken four months apart at the same station in the Mississippi Bight (89° 59′W, 28° 55′N). Note numerous step features in both the temperature and salinity profiles (From: Wiseman et al., 1976).

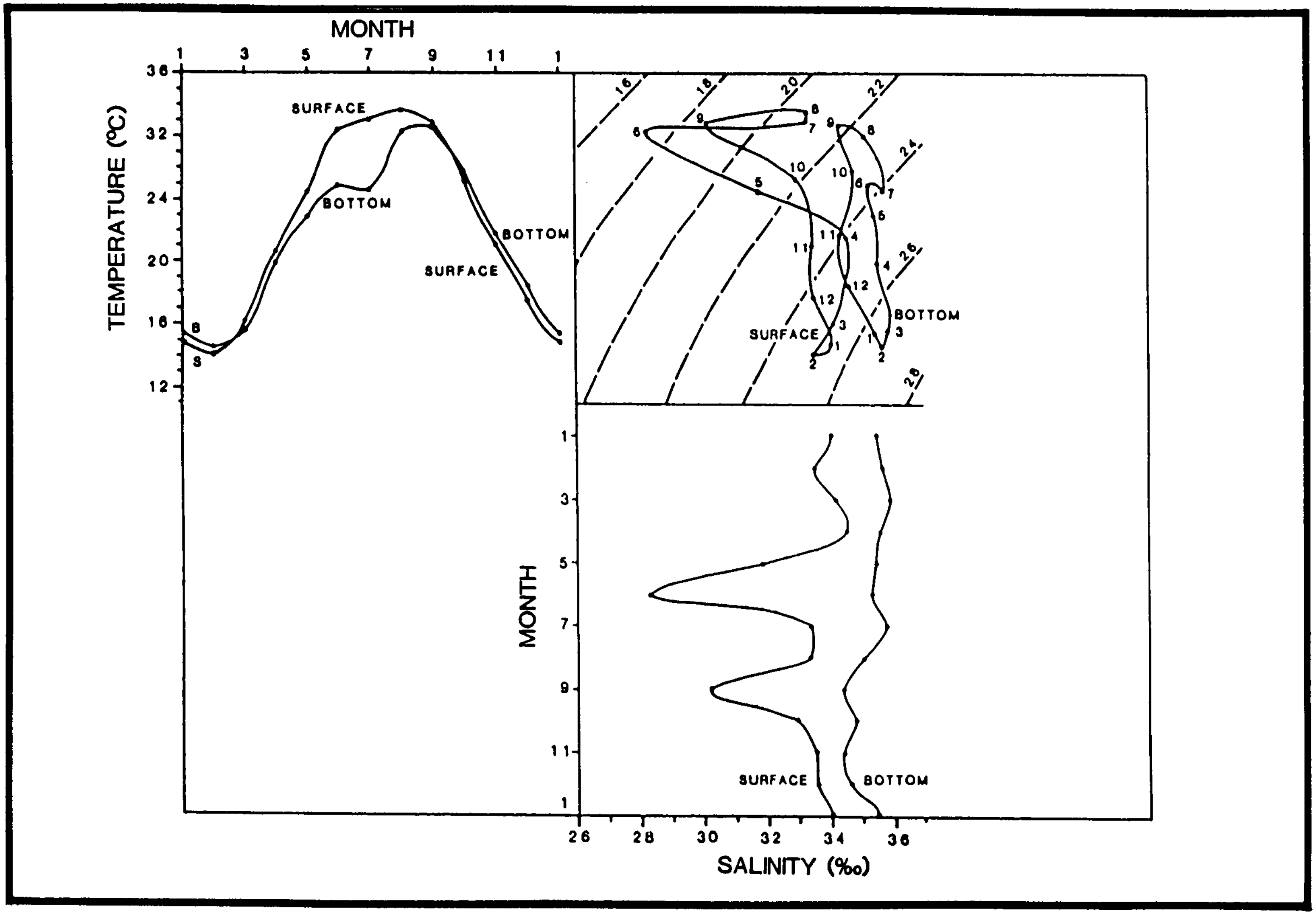


Figure 4.25. Annual progressions of mean salinity (‰) and mean temperature (°C) for near-surface and near-bottom depths for a region about 28 km off Freeport, TX in 22 m of water (Bryan Mound station 36 and GUS III station W-2 data). Data are also shown in a T-S diagram in which sigma-t lines are entered (From: Kelly et al., 1983a).

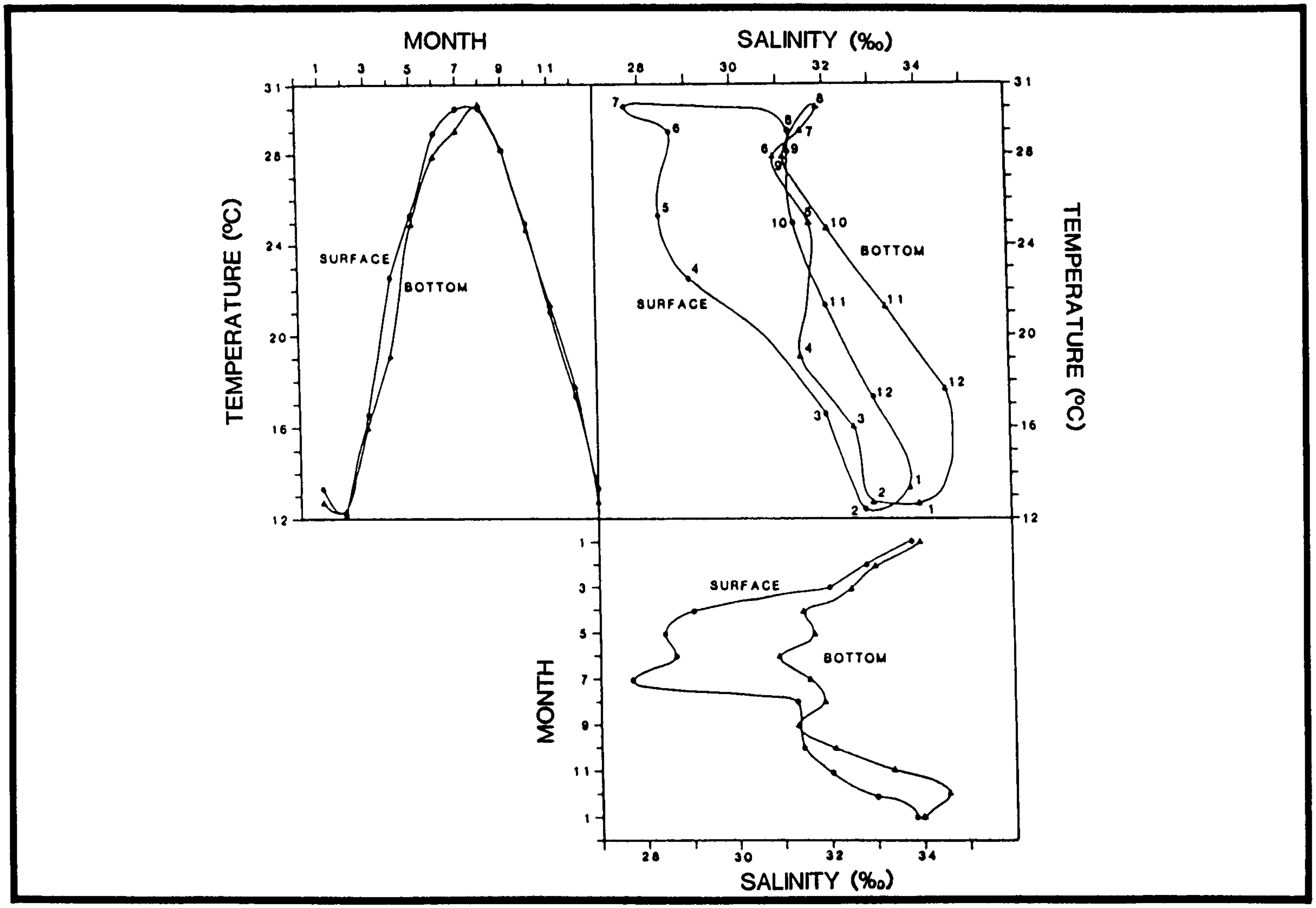


Figure 4.26. Annual progressions of mean salinity (‰) and mean temperature (°C) for near-surface and near-bottom depths for a region about 25 km off Cameron, LA in 10 m of water (West Hackberry station 22 and GUS III station E-1 data). Data are also shown in a T-S diagram in which sigma-t lines are entered (From: Kelly et al., 1983b).

Smith (1980a) also used T-S diagrams to describe the low-frequency hydrographic variability of the central Texas shelf based on data from 23 approximately monthly cruises during 1976 and 1977. He found that minimum salinities occur in late spring, when values decrease to as low as 18°/$_{oo}$ over the inner shelf. Inner shelf salinities during the rest of the year average 31 to 32°/$_{oo}$. Surface salinities over the outer shelf may decrease to 32 to 33°/$_{oo}$ in late spring, but deviate little from 36°/$_{oo}$ at other times. Both the mean salinity and the standard deviation suggest that freshwater runoff effects are restricted largely to inner and mid-shelf waters, within 30 km of the coast. Highest annual surface temperatures were 28 to 29°C across the shelf in late summer. Lowest temperatures in February ranged from 12 to 13°C over the inner shelf to 20 to 21°C over the outer shelf; minima appeared to be highly dependent on the severity of the winter season in a given year. Bottom temperatures were dominated by the annual cycle over the inner shelf. Near-bottom temperatures over the outer shelf varied over shorter time intervals and could not be resolved by monthly sampling.

Examples of the vertical distribution of salinity over the outer shelf are provided by Rezak et al. (1985) for the Flower Garden Banks. In October 1980 and March 1981, they observed relatively isohaline vertical profiles, with salinities slightly over 36°/$_{oo}$. In July 1981, salinity values decreased to about 35.5°/$_{oo}$ in a 13-m thick surface mixed layer. In July 1979, after a major flood by the Mississippi River, salinity values as low as 31.5°/$_{oo}$ were observed at the surface. Values increased to 35.5°/$_{oo}$ at 15 m and to slightly greater than 36°/$_{oo}$ below this depth.

4.5.3 Density

On the shallow continental shelves, density is determined by just temperature and salinity, as the effect of pressure is negligible. On the inner part of the shelf, the annual progression of density near the bottom is controlled primarily by the large annual cycle of temperature, while near the surface, salinity and temperature both contribute to the annual variation of density (Figure 4.25). However, for short periods of days to weeks, temperature variability is small, and density fluctuations and gradients are determined primarily by the highly variable distributions of salinity (Figures 4.20 through 4.23). On the outer half of the shelf, where salinity variability is greatly reduced, temperature largely determines the density field, as can be seen in the cross-shelf vertical section in Figure 4.27.

4.5.4 Dissolved Oxygen

The concentration of dissolved oxygen in the coastal near-surface waters is a function of primarily water temperature and biological photosynthesis and respiration. Values typically range from a high near 9 mg/l in the spring when water temperature is still relatively cool and biological production is strong to a low of 5 to 6 mg/l when water temperature is warmest and biological production is weak (Figure 4.28). In the near bottom waters biological photosynthesis is usually low because of high turbidity, and respiration and chemical oxygen demand are high. Replenishment of dissolved oxygen is dependent primarily on

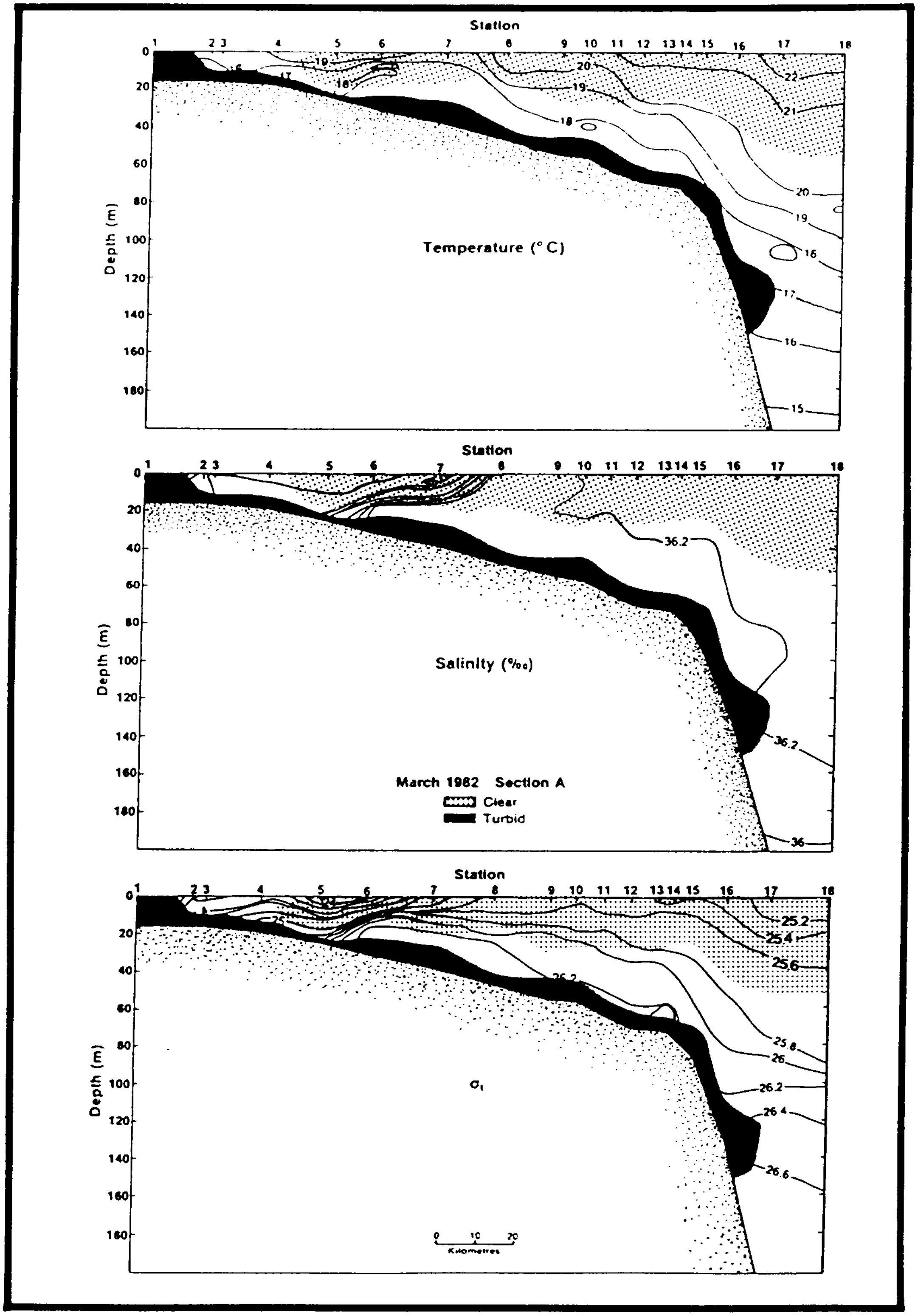


Figure 4.27. Cross-shelf vertical section of temperature, salinity, and sigma-t along a section running south-southeast from Galveston Island, TX, March 1982. Regions of turbid and clear water are indicated by dark and light shaging, respectively; unshaded areas are of intermediate transparency (From: Rezak et al., 1985).

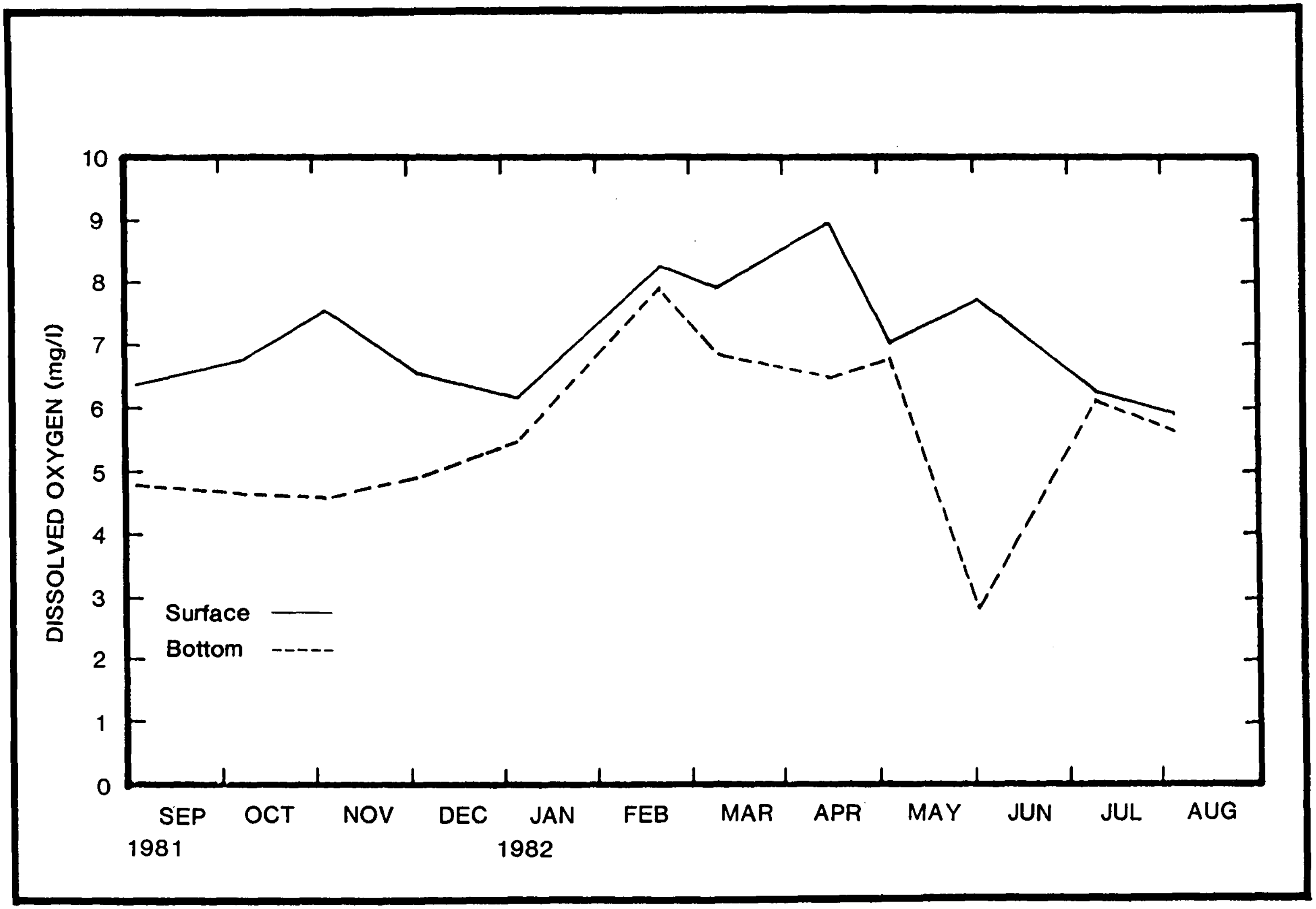


Figure 4.28. Dissolved oxygen concentrations measured at the surface and on the bottom about 25 km off Freeport, TX in 22 m of water by monthly hydrographic cruises (From: Kelly et al., 1983a).

vertical mixing. Values typically range from 4 to 7 mg/l (Figure 4.28), but when strong vertical stratification develops (Figures 4.21 through 4.23), the bottom waters can become hypoxic (i.e., concentrations lower than 2 mg/l) and even anoxic.

Large areas of hypoxia develop almost annually in Louisiana coastal waters west of the delta according to the numerous reports in the literature that are reviewed by Pokryfki and Randall (1987). [Dennis et al. (1984), Rabalais et al. (1985) and Renaud (1985) have produced extensive bibliographies on hypoxia.] Hypoxia also occurs in Texas coastal waters as far west as Freeport, but less frequently. The major flood of the Mississippi in 1979 in conjunction with the summer advent of upwelling favorable winds and currents, produced hypoxic and anoxic bottom conditions in June and July off Freeport, TX that caused mass mortalities of benthic organisms (Harper et al., 1981).

Pokryfki and Randall (1987) measured the spatial extent of hypoxia in coastal waters from Galveston, TX to 74 km east of Cameron, LA in July 1974. Their results for concentrations on the bottom and 4 m above the bottom are shown in Figure 4.29. They note that the hypoxic mass lay entirely inshore of the 20-m isobath and was not an extension of the oxygen minimum layer that impinges on the outer shelf from the deep Gulf. Their study also developed a time-series model that uses river discharge and density gradient to predict concentrations of dissolved oxygen on the bottom during hypoxic events.

Boesch and Rabalais (1988) have systematically studied hypoxia on the northern shelves of the Gulf since 1985. Areas ranging from 7,000 to 10,000 km^2 were hypoxic during mid-summer surveys in 1985, 1986, and 1987. Bottom hypoxic conditions were found on the inner shelf deeper than 10 m and extending to about 30 m, from the Mississippi River Delta to the upper Texas coast. Hypoxic conditions formed as early as April and extended as late as October, depending on hurricane activity. They suggest that the massive enrichment of the Mississippi River discharge in levels of nitrate may have contributed to an intensification of shelf hypoxia since the 1960's. The increase in nitrate is attributable to increased use of agricultural fertilizers, waste discharges, and atmospheric precipitation.

Although the spatial distribution of hypoxia has been mapped with fair resolution at times, virtually nothing is known about its local time-rate-of-change or the advection of hypoxic water masses.

4.6 SURFACE WAVES

A large amount of the total wave energy of the sea surface is associated with gravity waves (gravity is the principal restoring force), which are generated by the action of the wind. Gravity waves are separated into two categories: seas, when the waves are under the influence of wind in a generating area, and swell, when waves move out of a generating area and are no longer subjected to significant wind action (U.S. Army Corps of Engineers, Coastal Engineering Research Center, 1975). Seas on the shelf generally have steep waves with short periods and lengths; the waves associated with swell have relatively long periods

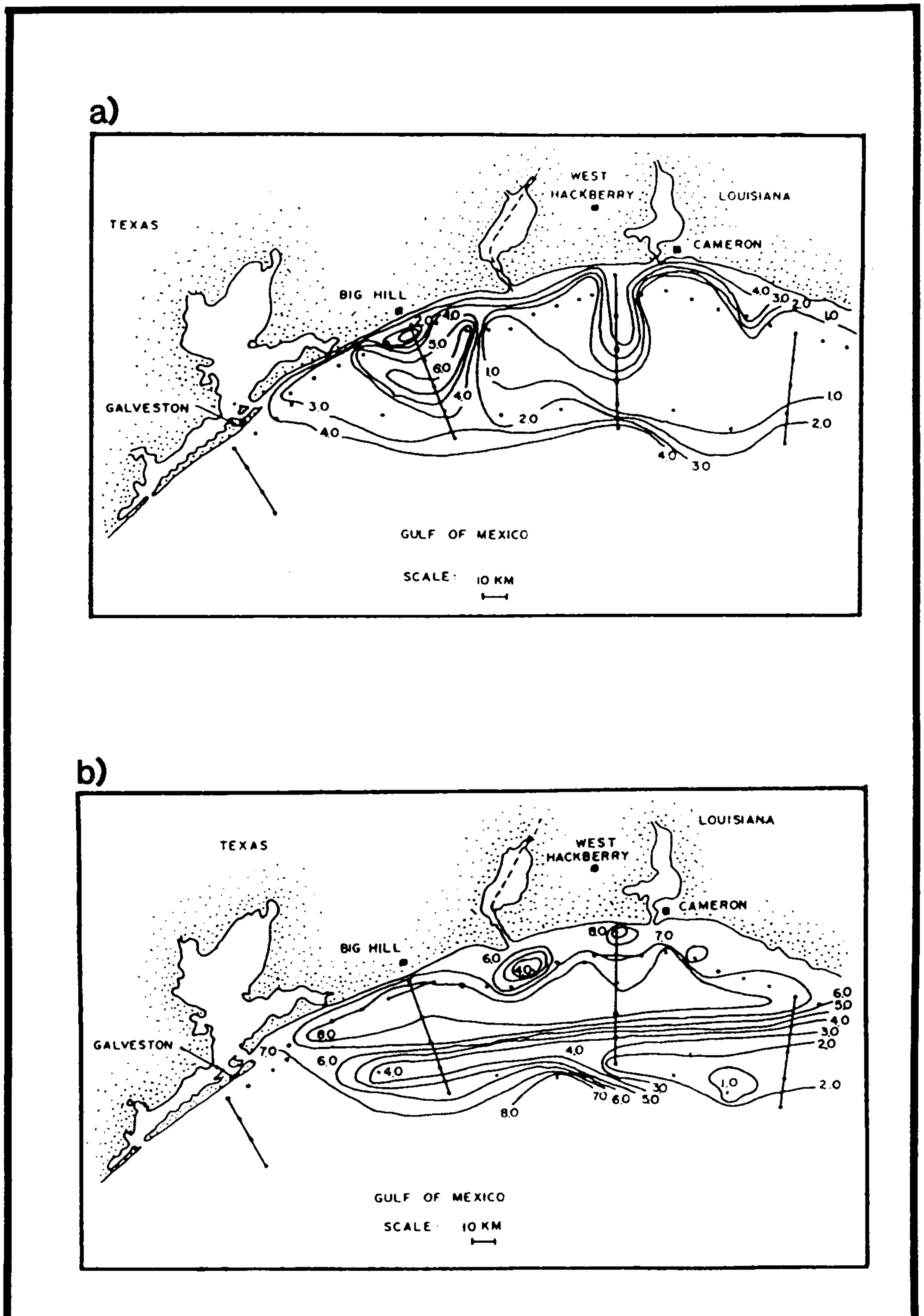


Figure 4.29. Dissolved oxygen concentrations (mg/l) at a) the bottom and b) 4 m above the bottom on 9 to 10 July 1984 (From: Pokryfki and Randall, 1987).

and wavelengths and, until they reach shallow water, low amplitudes. The height, period, and length of wind waves are determined by fetch, wind speed, wind duration, and decay distance. Water depth, if shallow enough, will also affect the size of wave that is generated.

The winds from the southeast and south associated with the flow of mT air around the west side of the Bermuda High have considerable fetch, and are quite persistent at times, but wind speed is typically low to moderate. These winds generate waves that are usually in the range 0.5 to 1.5 m. The fetch of the strong winds from the north associated with frontal passages is small near the coast and increases toward the outer shelf. The northers typically generate 2- to 3-m waves nearshore and 4- to 6-m waves on the outer shelf. The most common periods associated with non-hurricane waves in the Gulf are between 4 and 6 s, with only a very few above 10 s. The extreme wind speeds of hurricanes generate waves of 7 to 10 m or more, with periods of 9 to 13 s.

Wave statistics and climatologies are generated from a variety of data sources, such as ship observations, hindcasts, and direct measurements by various types of instruments. Quayle and Fulbright (1977) gives the annual percent frequency of wave heights in half-meter increments for sea surface meteorological observation (SSMO) areas 27, 28, and 29 based on ship observations (Table 4.6). These three SSMO areas cover the Texas-Louisiana shelf. The COE Waterways Experiment Station has just completed a hindcast of wave climate for the U.S. coastal waters in the Gulf of Mexico as part of its Wave Information Study (WIS). WIS Report 18 (Hubertz et al., 1988), to be released about December 1988, summarizes twenty years (1956 to 1975) of hindcast significant height, peak period, and mean direction for various locations in four data products: percent occurrence tables, wave rose diagrams, mean and largest significant height and 20-year statistics tables, and return period table. Hurricane conditions are excluded. The report also statistically compares the hindcast data with direct observations by gauges and buoys from different periods of time. Hurricane hindcast methodology and wave statistics for the Atlantic and Gulf hurricanes from 1956 to 1975 are given in a separate report, WIS Report 19 (Abel et al., 1988), which is expected to be released about December 1988. Reece and Cardone (1982) also describe and compare examples of extreme wave events in the Gulf of Mexico computed from model hindcasts and measured by calibrated devices.

The wave climatology measured at the Pleasure Pier at Galveston is detailed by Thompson and Harris (1972) and Thompson (1977). Monthly means of significant wave height are less than 0.7 m, monthly maxima are 1 to 2 m, and wave periods are typically about 5 s. (Significant height is defined to be the average of the highest one-third of the waves in a record.) Another example of wave observations in inner-shelf waters is the work of Frey et al. (1981) at the West Hackberry DOE/SPR site in 10 m of water. Figure 4.30 from their work shows the effect on significant and maximum wave heights of the passage of three successive polar fronts. For estimates of wave characteristics near the outer shelf and slope the data from NOAA Data Buoy Office (NDBO) Buoy 42002 are probably applicable, even though the buoy is located about 200 km south of the shelf break. Yamazaki and Herbich (1985) present monthly wave

Table 4.6. Annual percent frequency of wave heights in various categories, based on ship observations in SSMO areas 27, 28, and 29 (From: Quayle and Fulbright, 1977).

Area Number	Wave Height (m) 0	½	1	1½	2	2½	3	3½	4-4½	5-5½	6-6½	7-7½	8-9½	Total OBS	Average Height (m)
27	14.2	25.6	29.7	17.3	7.1	3.4	1.3	0.7	0.6	0.1	0.1	*	*	77,800	1
28	13.9	26.1	30.4	17.1	6.7	3.3	1.2	0.6	0.5	0.1	0.1	*	*	47,507	1
29	8.3	24.2	33.3	18.3	8.2	4.2	1.7	0.9	0.7	0.1	0.1	*	0	13,371	1

*Less than 0.05% but greater than 0.

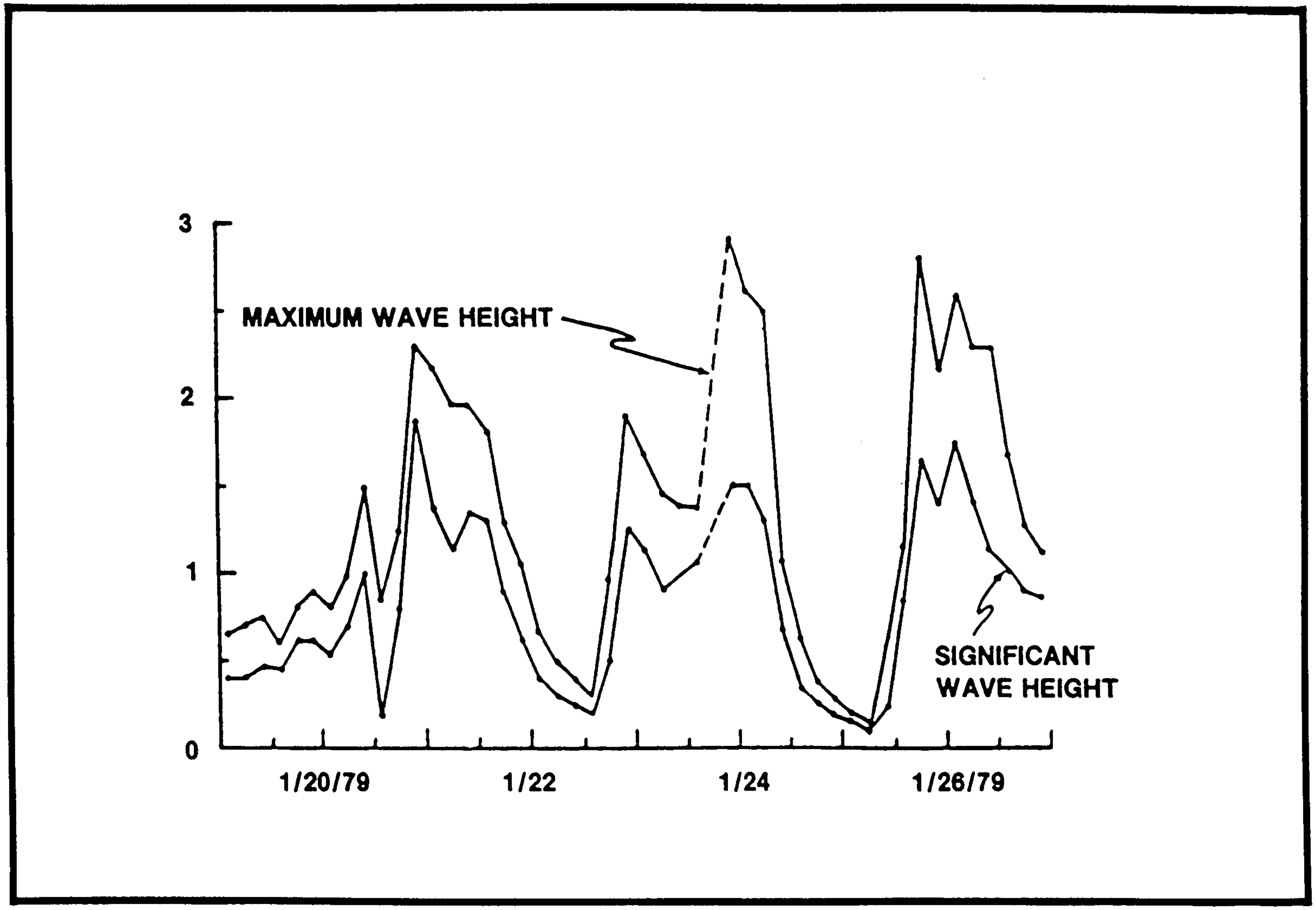


Figure 4.30. Significant wave height and maximum wave height observed at the West Hackberry site during the passage of three successive polar fronts from 19 to 27 January 1979 (From: Frey et al., 1981).

statistics for a 30-month period at NDBO Buoy 42002; monthly mean significant heights are typically 1 to 1.5 m, monthly maximum heights are usually 3 to 4 m but occasionally 6 to 8 m, and average wave periods range from 4.2 to 5.4 s.

4.7 TIDES AND SEA LEVEL

Sea level, the height of the sea surface relative to a fixed datum that is derived by averaging the instantaneous observations (e.g., hourly) of the height of the sea surface over periods of a day, month, year, etc., fluctuates because of the effects of long-period astronomic tides, local winds, local addition of mass, changes in atmospheric pressure, and changes in temperature and salinity, and thus, density, of the water column (steric effect). Marmer (1954) discussed the long-period fluctuations of sea level observed at tide stations around the Gulf of Mexico, and noted annual ranges and month-to-month variations. Along the Texas-Louisiana coast the annual range is about 25 cm. The annual variation has a semi-annual component; the absolute minimum and maximum values occur in January and September, respectively, and relative maximum and minimum values occur in May and July, respectively. Whitaker (1971) computed the seasonal variations of steric and recorded sea level at various stations around the Gulf, including Galveston, TX (Figure 4.31). For Galveston, he found that the regional steric sea levels relative to 150 db and 1000 db accounted for 55% and 77%, respectively, of the recorded sea-level range. However, the variations in steric sea level do not account for the July minimum in recorded sea level. Chew (1964) argued that the July minimum may be related to the upwelling coastal regime driven by local winds, which is consistent with the results of Cochrane and Kelly (1986b).

For periods shorter than one month, coastal variability of sea level is driven substantially by wind forcing. Chuang and Wiseman (1983) examined the sea level response at Galveston and Eugene Island to the wind forcing associated with frontal passages. They found that at Galveston the alongshore component of wind, through Ekman convergence, drives sea-level fluctuations, but at Eugene Island, where a broad region of the shelf is much shallower, the cross-shelf component of wind, through direct wind set-up, drives the sea-level fluctuations.

Tropical cyclones produce extreme changes in sea level. Bunpapong and Reid (1985) investigated the gradual rise in water level along the coast that precedes the arrival of a hurricane (forerunner surge), and hurricane-induced storm surge has been modeled in various ways (Wanstrath, 1975; Ebersole, 1985).

Reid and Whitaker (1981) reviewed the tidal regime in the Gulf of Mexico and developed a numerical tide model that provides good agreement of the important tidal constituents with those deduced from open coastal measurements. Their numerical investigations show that the diurnal tides, K_1 and O_1, have nearly uniform amplitudes and phases over the whole Gulf and are driven primarily by the in-phase volume transports through the Yucatan and Florida Straits. The contribution due to direct forcing is only about 15%. On the other hand, direct forcing accounts for about 55% of the signal of the semidiurnal tides, M_2 and S_2. The M_2

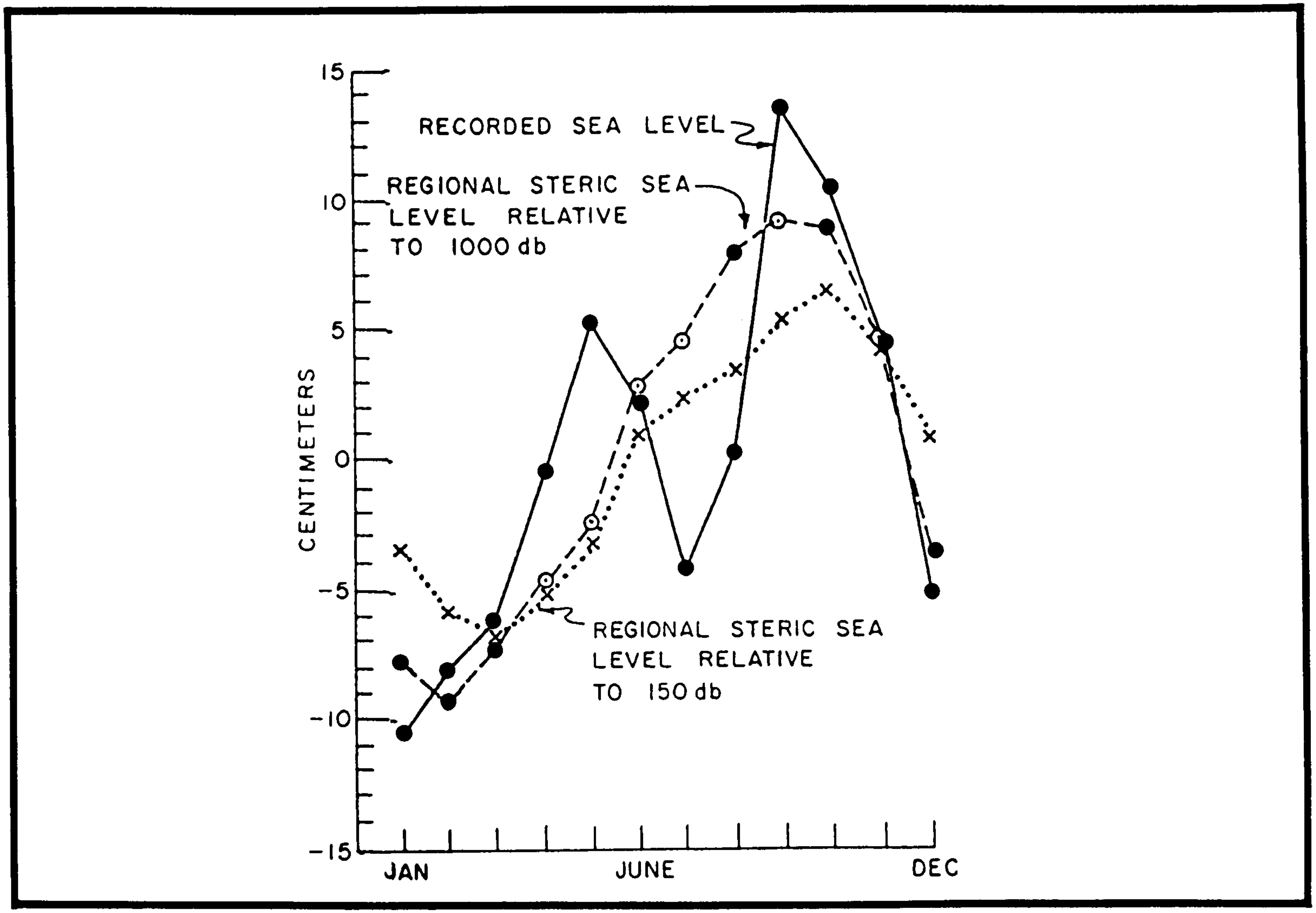


Figure 4.31. Annual variation of recorded sea level, regional steric sea level relative to 150 db, and regional steric sea level relative to 1000 db for Galveston, TX (From: Whitaker,1971).

tide has negligible amplitude in the deep central Gulf and maximum amplitudes along the coast. Phase propagates counterclockwise around the amphidromic point. Table 4.7 gives the observed amplitudes and phases of the major tidal constituents at Southwest Pass, Point au Fer, Galveston, and Port Aransas (Reid and Whitaker, 1981). Along the Texas-Louisiana coast the amplitude of the M_2 tide is largest off Calcasieu Pass and decreases to the east and west. As a result of the relative magnitudes of the diurnal and semidiurnal constituents, the tide is characterized as mixed off Calcasieu Pass and becomes mainly diurnal off the Mississippi Delta and to the west of Galveston (Marmer, 1954; Hicks, 1977; Frey et al., 1981).

Figure 4.32 illustrates several of the processes noted above. It shows the sea-surface elevation for February 1984 at the Bryan Mound site, computed from pressure data measured at the bottom, time series of temperature and salinity at three depths, and atmospheric pressure (the inverted barometer effect is included). The colder water in winter decreased total steric sea level from the long-term mean by about 5 cm. During the last few days of February, winds were strong and directed upcoast and offshore (Kelly et al., 1985a); this wind pattern drove an upwelling event that decreased nearshore sea-surface elevation by about 70 cm (a 10 mb rise in atmospheric pressure forced an additional 10 cm decrease). Tides in Figure 4.32 are mainly diurnal. The maximum range, about 75 cm, occurs during tropic tides, when the K_1 and O_1 tides conspire.

4.8 CURRENTS

4.8.1 Inner Shelf

Wind stress and fresh water influx from the Mississippi-Atchafalaya River System are the dominant factors that control the long-period motion, hydrographic characteristics, and much of the short-period variability of the waters on the inner part of the Texas-Louisiana shelf. The basic features of the circulation on the inner Texas-Louisiana shelf have been known for quite some time. For example, Sweitzer (1898), in discussing the placement of harbor jetties on the Texas coast stated:

> "Hence, it may be concluded that the currents flowing westward are on the northern shore of the Gulf, and those flowing north along the western shore meet at some point near Galveston, the location of which is variable, as it is dependent upon the direction and force of the winds."

Also, Leipper (1954) noted that this convergence is seen in the U.S. Navy pilot charts. Drift bottle studies by Kimsey and Temple (1963, 1964), Watson and Behrens (1970), Hunter et al. (1974), Hill et al. (1975), and Hill and Garrison (1978) provided a more detailed, but still qualitative, description of the inner-shelf circulation. In 1973, Smith (1975, 1977, 1978a, 1979, 1980b) initiated a series of studies off Aransas Pass to directly measure currents and quantitatively describe their temporal and spatial variability, vertical structure, and relation to wind stress.

Table 4.7. Observed amplitude (cm) and phase (relative to Greenwich) for the five principal tidal constituents at four locations along the Texas-Louisiana coast (From: Reid and Whitaker, 1981).

Station	Tidal Constituent				
	K_1	O_1	P_1	M_2	S_2
Southwest Pass	13.5 (20.4°)	13.4 (13.4°)	4.9 (19.5°)	1.7 (127.2°)	0.9 (111.7°)
Point au Fer	16.6 (23.7°)	15.3 (19.7°)	5.6 (18.1°)	9.9 (240.4°)	3.4 (234.7°)
Galveston	16.7 (28.3°)	15.5 (20.3°)	4.3 (13.5°)	13.5 (275.1°)	4.0 (273.0°)
Port Aransas	15.4 (26.4°)	15.1 (20.1°)	4.8 (26.0°)	7.7 (262.3°)	2.2 (264.6°)

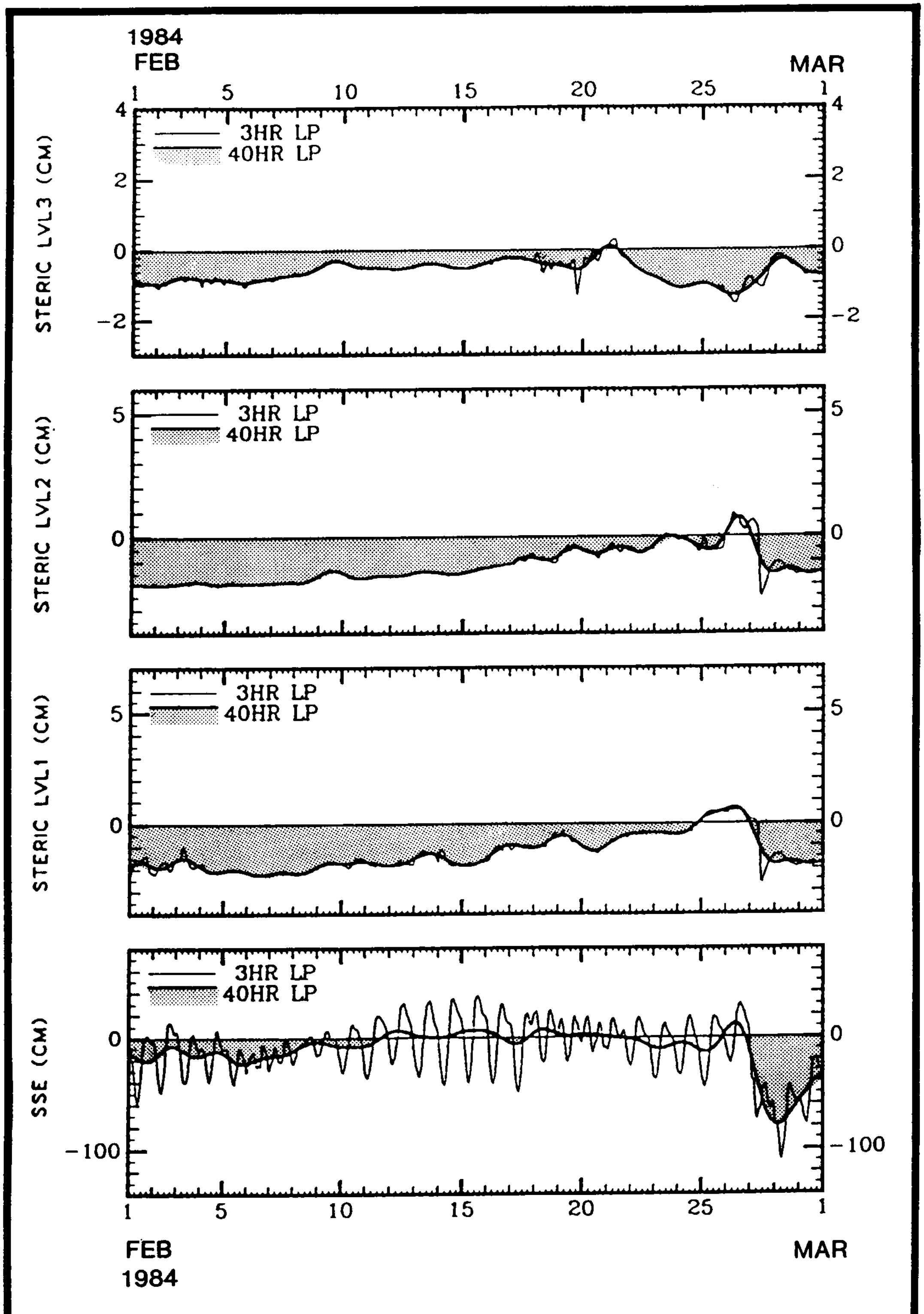


Figure 4.32. Time-series plots, for February 1984, of sea-surface elevation (bottom frame) and the contribution to sea-surface elevation by density fluctuations (cm) in the top, middle, and bottom layers of the water column (From: Kelly et al., 1985a).

Because the annual progression in alongshore wind stress (Section 4.3.1) is similar from Port Aransas to Cameron, the inner-shelf region between these points has a single current regime, which Cochrane and Kelly (1986b) have called the "Freeport regime," with downcoast (southeast) flow prevailing except for a period of upcoast (northeast) flow in spring and summer. Off Port Aransas the period is long, but off Freeport and Cameron it is limited to July.

Currents and Wind Stress off Freeport, TX

Numerous studies of currents along the Texas-Louisiana coast demonstrate the strong coherence between the alongshore components of wind stress and current (Smith 1978a, 1979; Kelly et al., 1982; Crout et al., 1984; Lewis and Reid, 1985; Cochrane and Kelly, 1986b) that results from the combination of wind stress, the Earth's rotation and the presence of the coastal boundary (e.g., Csanady 1982). A visual example of the dynamics comes from observations collected in 20 m of water about 20 km off Freeport, TX at the DOE/SPR Bryan Mound site. In Figure 4.33, the alongshore component of wind stress (Figure 4.33a) during the period 18 to 30 June 1980 is upcoast (toward Louisiana) and drives an offshore directed Ekman transport in the near-surface layer (Figure 4.33c), with a compensating onshore drift in the bottom layer (Figure 4.33d). Water level at the coast (not shown) decreases, and the cross-shelf pressure gradient drives the alongshore component of current (Figure 4.33b) in the upcoast direction. When the alongshore component of wind stress is downcoast (toward Mexico), everything reverses to a downwelling regime, as can be seen in Figure 4.33 for briefer periods earlier in the month. The dramatic effects of downwelling and upwelling on the hydrography of the inner shelf were described in Section 4.5.

The DOE/SPR studies off Freeport, TX and Cameron, LA produced the most statistically reliable evidence of the relation between the alongshore component of wind stress and the coastal currents because of the length of the observations. The seasonal variations of wind stress and the effect of these variations on both the alongshore component and the annual migration of a convergence zone were described in Section 4.3.1. Figure 4.34a shows the annual progressions of alongshore components of wind stress and current off Freeport, TX in terms of monthly means based on hourly values of 3-h low-passed data obtained between August 1978 and September 1984. Both components are positive (upcoast) in July, near zero in June and August, and negative (downcoast) during the rest of the year. By the criterion of standard error, the changes from May to June and from August to September are quite significant, and the values for July are significantly different from zero.

As Figure 4.33 suggests, there is considerable temporal variability about the monthly mean values. Cochrane and Kelly (1986b) examined this variability, and the relation between wind stress and currents for sub-inertial frequencies below 0.5 cycles per day. They applied the methods of cross-spectral analysis to one-year time series of wind stress and top and bottom currents collected at the Bryan Mound site during 1981. Their results agree in most respects with the above model. Alongshore stress drives currents effectively at all sub-inertial

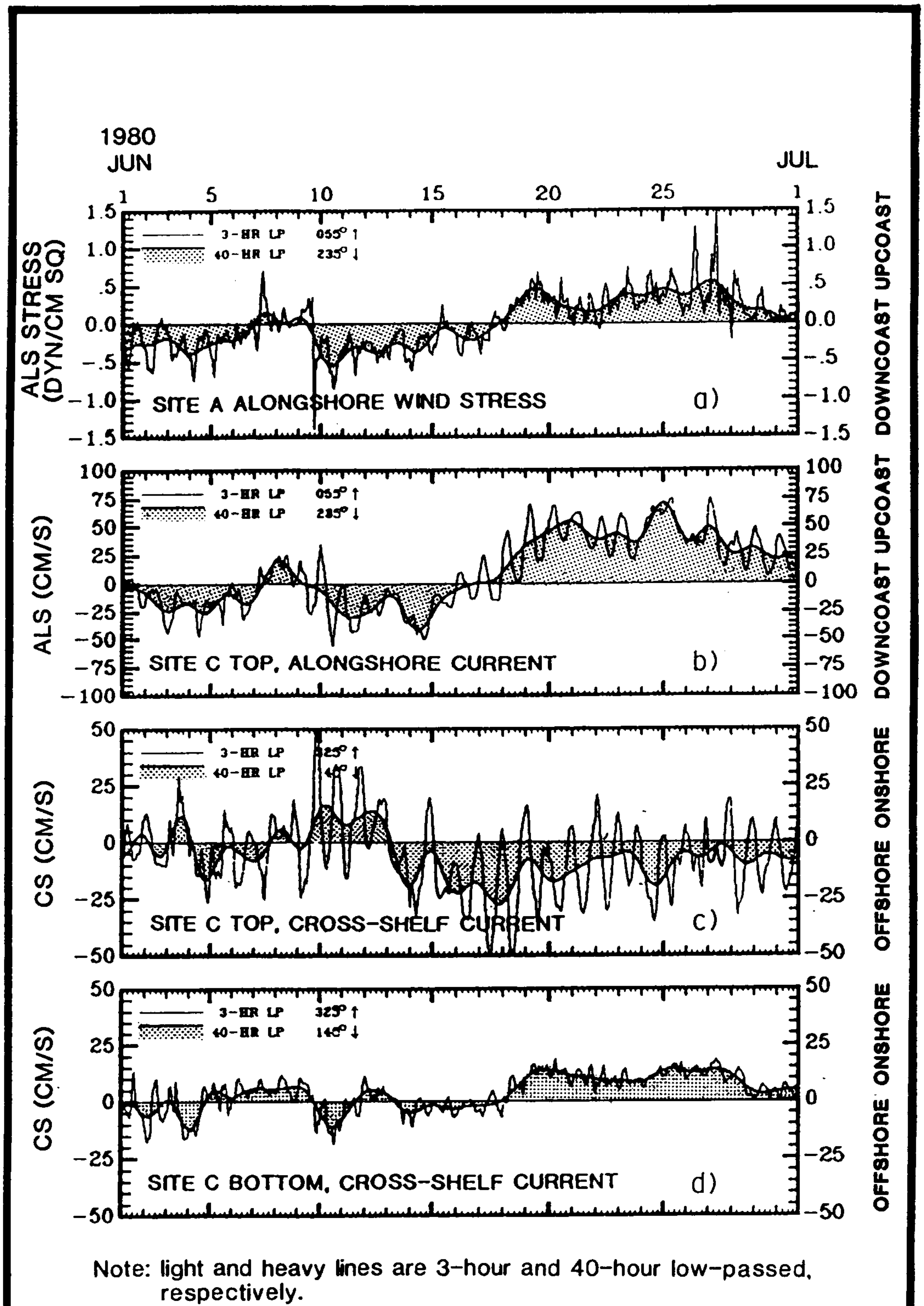


Figure 4.33. An example of the response of currents to the alongshore component of wind stress at Bryan Mound site, water depth 22 m; a) alongshore (positive toward 55° true) component of wind stress; b) alongshore component of near-surface current (3.7 m below the surface); c) cross-shelf (positive toward 325° true) component of near-surface current; and d) cross-shelf component of near-bottom current (1.8 m above the bottom). (Modified from: Kelly et al., 1982).

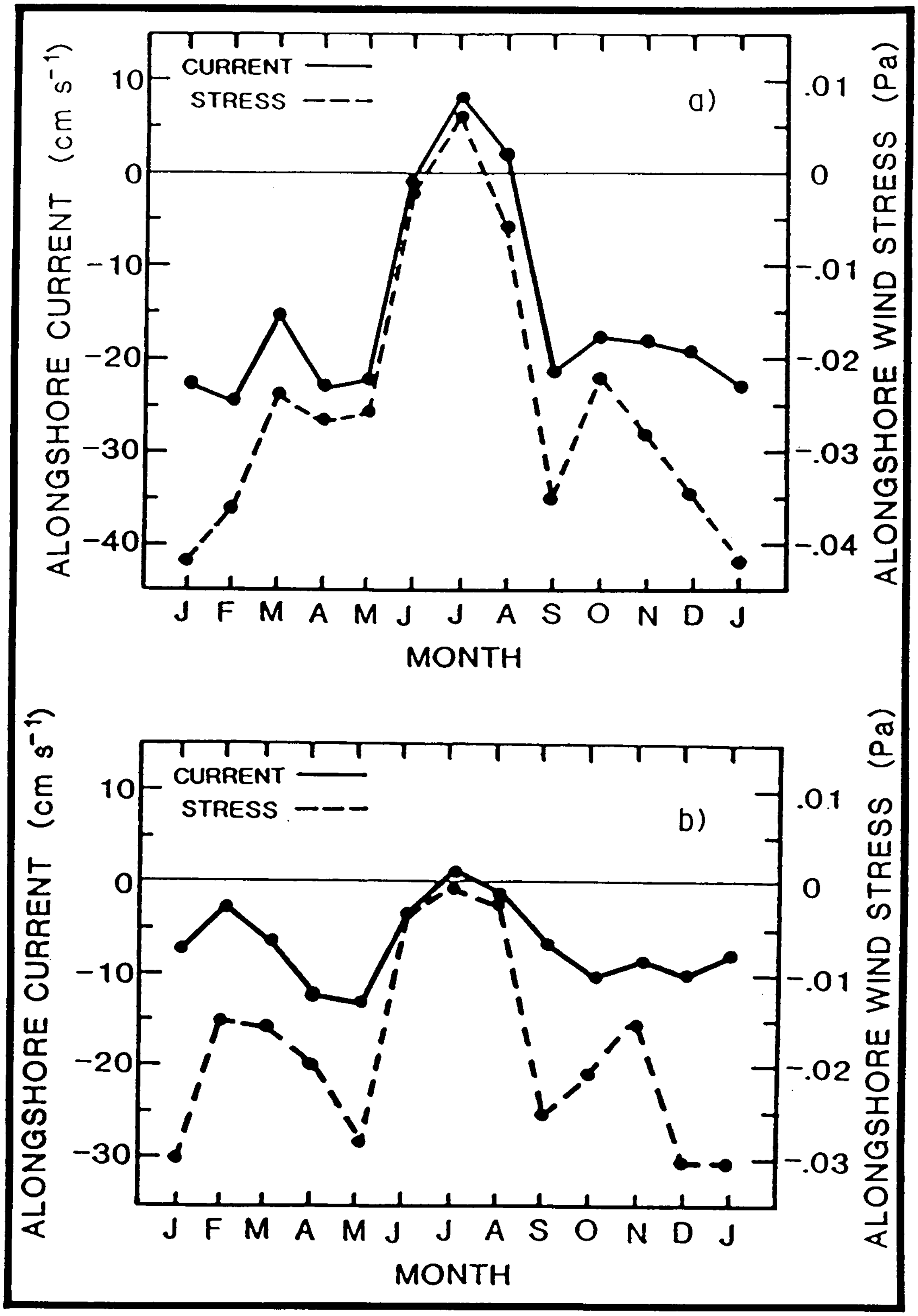


Figure 4.34. Monthly mean alongshore component of wind stress together with monthly mean alongshore component of surface current (3.7 m below sea surface); a) at the Bryan Mound site off Freeport, TX; the positive alongshore direction is 55° clockwise from north; and b) at the West Hackberry site off Cameron, LA; the positive alongshore direction is 86° clockwise from north (From: Cochrane and Kelly, 1986b).

frequencies, but cross-shelf stress does not. (Cross-shelf wind stress induces Ekman transport with a net alongshore direction, and so does not produce a coastal jet.) Alongshore wind stress is coherent with cross-shelf bottom currents, and the phase indicates flow to the left of stress, that is, in the direction expected for upwelling/downwelling regimes described above. The one disagreement with the model is the lack of coherence between cross-shelf currents at the surface and alongshore wind. However, the current meter mooring was located near the mean position of the intense frontal zone separating fresher coastal water from saltier offshore water, and they attribute the low coherence to the effects of the local baroclinic currents caused by the dynamics of the frontal zone.

The DOE/SPR studies amassed a very large data base concerning the characteristics of the inner-shelf region from about Galveston, TX to Cameron, LA. The results are described in a series of annual reports that present the data in a variety of useful formats. However, a comprehensive climatology synthesizing, for example, all of the current meter data does not exist. Therefore, to provide a quantitative example of the magnitudes of the near-surface and near-bottom currents, Table 4.8 shows the basic statistics in intervals of one month from September 1983 through August 1984 for the time series data from the current meters located 3.6 m below the sea surface and 1.6 m above the bottom. It is stressed that the interannual variability is significant at times (Smith, 1978a, 1980b; Kelly et al., 1985a,b).

Currents and Wind Stress off Cameron, LA

The annual progressions off Cameron, LA, from data collected between February 1981 and January 1985, are shown in Figure 4.34B. Similar to the results for Freeport, the means for current are positive (upcoast) only in July, and those for stress are very nearly zero although not positive in July. The two sets of means are clearly correlated. Both the stress and current means are smaller 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 wind. The weaker response of current to alongshore wind in extensive regions of shallower waters (Chuang and Wiseman, 1983) and an increase in bottom friction (Chuang and Wiseman, 1983; Cochrane and Kelly, 1986b) are also factors.

A quantitative example of the basic statistics is provided for a small subset of the data base (Tables 4.9 and 4.10).

Coherence Between Currents off Freeport and Cameron

The West Hackberry and Bryan Mound sites are separated by a distance of about 200 km. Kelly et al. (1983b) investigated the coherence between the near-bottom currents of the two sites using common series of 231-days in length. Their results are shown in Figure 4.35 for the alongshelf components. High coherence exists between the alongshelf components at periods of about 10 days and 3.3 days. They also found significant coherence between the cross-shelf components at 10 days and weaker but still significant coherence at 3.5 days. Smith (1980b)

Table 4.8. Basic statistics by month for the hourly time series of 3-h low-pass filtered current velocity at depths of 3.7 m (CT) and 20 m (CU) at Bryan Mound site C in 22 m of water during the period 1 September 1983 through 31 August 1984 (From: Kelly et al., 1985a). Positive along-shelf direction is toward 55° true, and positive cross-shelf direction is toward 325° true. N = number of observations; MIN = minimum; MAX = maximum; MEAN = algebraic mean; SD = standard deviation.

SITE CT		ALONGSHELF (CM/S)					CROSS-SHELF (CM/S)				
START	STOP	N	MIN	MAX	MEAN	S.D.	N	MIN	MAX	MEAN	S.D.
09-01-83(0000)	09-30-83(2300)	719	-65.	45.	-19.3	21.7	719	-41.	32.	-2.3	13.4
10-01-83(0000)	10-31-83(2300)	744	-60.	23.	-17.7	18.7	744	-39.	38.	0.7	10.5
11-01-83(0000)	11-30-83(2300)	720	-46.	39.	-6.2	15.4	720	-27.	16.	-1.2	5.9
12-01-83(0000)	12-31-83(2300)	744	-58.	30.	-12.0	19.4	744	-36.	17.	-1.1	6.4
01-01-84(0000)	01-31-84(2300)	744	-79.	19.	-29.9	23.7	744	-36.	24.	1.0	8.0
02-01-84(0000)	02-29-84(2300)	696	-52.	78.	-11.7	24.6	696	-24.	51.	2.0	9.9
03-01-84(0000)	03-31-84(2300)	744	-62.	65.	-9.9	26.1	744	-33.	36.	3.0	10.7
04-01-84(0000)	04-30-84(2300)	720	-59.	54.	-8.8	26.7	720	-24.	30.	0.9	9.3
05-01-84(0000)	05-31-84(2300)	744	-71.	18.	-31.6	18.6	744	-37.	44.	1.5	13.9
06-01-84(0000)	06-30-84(2300)	720	-58.	56.	-0.7	30.0	720	-46.	38.	-0.6	14.9
07-01-84(0000)	07-31-84(2300)	744	-59.	62.	8.4	21.3	744	-47.	34.	-0.4	14.2
08-01-84(0000)	08-31-84(2300)	744	-38.	72.	7.6	22.1	744	-37.	38.	-0.8	10.9

SITE CU		ALONGSHELF (CM/S)					CROSS-SHELF (CM/S)				
START	STOP	N	MIN	MAX	MEAN	S.D.	N	MIN	MAX	MEAN	S.D.
09-01-83(0000)	09-30-83(2300)	720	-36.	18.	-9.8	11.8	720	-31.	21.	-3.9	9.7
10-01-83(0000)	10-31-83(2300)	744	-31.	25.	-2.8	12.2	744	-29.	22.	-1.1	7.5
11-01-83(0000)	11-30-83(2300)	720	-31.	32.	-2.4	16.1	720	-15.	25.	1.2	7.7
12-01-83(0000)	12-31-83(2300)	744	-41.	30.	-4.7	15.7	744	-21.	19.	2.8	6.0
01-01-84(0000)	01-31-84(2300)	744	-46.	26.	-8.7	14.8	744	-20.	19.	-0.4	6.8
02-01-84(0000)	02-29-84(2300)	696	-33.	39.	-0.2	14.1	696	-21.	63.	3.0	11.8
03-01-84(0000)	03-31-84(2300)	744	-28.	44.	-0.6	15.4	744	-25.	37.	1.2	11.3
04-01-84(0000)	04-30-84(2300)	720	-43.	28.	-5.8	17.3	720	-24.	20.	-0.3	9.7
05-01-84(0000)	05-31-84(2300)	744	-43.	25.	-3.4	13.0	744	-36.	18.	-1.6	10.5
06-01-84(0000)	06-30-84(2300)	720	-28.	23.	-0.6	12.5	720	-22.	19.	1.0	8.6
07-01-84(0000)	07-31-84(2300)	744	-34.	24.	-3.5	11.6	744	-22.	28.	-1.1	8.9
08-01-84(0000)	08-31-84(2300)	744	-25.	25.	3.3	12.2	744	-20.	23.	3.2	8.5

Table 4.9. Basic statistics in intervals of one month for the hourly time series of 3-h low-pass filtered current velocity at a depth of 3.7 m (DT) at West Hackberry site D in 10 m of water during the period 1 May 1982 through 30 November 1983 (From: Kelly et al., 1984c). Positive along-shelf direction is toward 86° true, and positive cross-shelf direction is toward 356° true. N = number of observations; MIN = minimum; MAX = maximum; MEAN = algebraic mean; SD = standard deviation.

SITE DT		ALONGSHORE (CM/S)					CROSS SHELF (CM/S)				
START	STOP	N	MIN	MAX	MEAN	S.D.	N	MIN	MAX	MEAN	S.D.
05-01-82(0000)	05-31-82(2300)	744	-62.	35.	-11.6	16.5	744	-30.	31.	-0.3	9.6
06-01-82(0000)	06-30-82(2300)	720	-23.	43.	7.3	13.0	720	-19.	22.	1.9	6.7
07-01-82(0000)	07-31-82(2300)	744	-23.	24.	2.8	8.7	744	-22.	26.	0.5	6.6
08-01-82(0000)	08-31-82(2300)	744	-50.	24.	-0.6	12.2	744	-15.	17.	-0.6	5.1
09-01-82(0000)	09-30-82(2300)	720	-76.	19.	-11.8	14.4	720	-28.	26.	2.4	6.9
10-01-82(0000)	10-31-82(2300)	744	-51.	21.	-11.8	12.5	744	-22.	22.	2.3	5.7
11-01-82(0000)	11-30-82(2300)	720	-40.	25.	-10.7	11.5	720	-19.	27.	3.0	7.0
12-01-82(0000)	12-31-82(2300)	744	-67.	31.	-13.4	18.3	744	-18.	30.	3.0	8.4
01-01-83(0000)	01-31-83(2300)	744	-58.	23.	-5.2	17.3	744	-23.	27.	3.1	8.3
02-01-83(0000)	02-28-83(2300)	672	-61.	45.	-0.7	19.1	672	-24.	27.	2.7	9.3
03-01-83(0000)	03-31-83(2300)	744	-85.	28.	-5.3	18.5	744	-18.	28.	1.7	6.9
04-01-83(0000)	04-30-83(2300)	720	-60.	73.	-6.8	22.6	720	-21.	25.	4.0	8.2
05-01-83(0000)	05-31-83(2300)	744	-80.	30.	-20.1	21.6	744	-35.	46.	2.9	12.0
06-01-83(0000)	06-30-83(2300)	720	-60.	24.	-8.5	16.1	720	-33.	29.	-0.3	11.4
07-01-83(0000)	07-31-83(2300)	744	-58.	30.	0.4	14.6	744	-27.	27.	0.4	9.9
08-01-83(0000)	08-31-83(2300)	744	-43.	42.	0.6	12.9	744	-19.	23.	1.6	8.0
09-01-83(0000)	09-30-83(2300)	720	-37.	18.	-5.3	8.9	720	-17.	19.	2.4	5.6
10-01-83(0000)	10-31-83(2300)	744	-27.	26.	-1.7	10.4	744	-16.	21.	2.0	7.0
11-01-83(0000)	11-30-83(2300)	720	-56.	26.	-9.2	13.6	720	-10.	28.	2.9	5.0

Table 4.10. Basic statistics by month for the hourly time series of 3-h low-pass filtered current velocity at a depth of 8 m (DB) at West Hackberry site D in 10 m of water during the period 1 May 1982 through 30 November 1983 (From: Kelly et al., 1984c). Positive along-shelf direction is toward 86° true, and positive cross-shelf direction is toward 356° true. N = number of observations; MIN = minimum; MAX = maximum; MEAN = algebraic mean; SD = standard deviation.

SITE DB		ALONGSHORE (CM/S)					CROSS SHELF (CM/S)				
START	STOP	N	MIN	MAX	MEAN	S.D.	N	MIN	MAX	MEAN	S.D.
05-01-82(0000)	05-31-82(2300)	744	-57.	21.	-4.8	12.5	744	-37.	25.	-2.1	9.1
06-01-82(0000)	06-30-82(2300)	742	-17.	25.	4.0	7.7	742	-27.	20.	0.5	6.9
07-01-82(0000)	07-31-82(2300)	766	-22.	21.	4.4	8.2	766	-18.	16.	0.3	5.7
08-01-82(0000)	08-31-82(2300)	766	-26.	22.	-1.0	8.8	766	-18.	14.	0.4	5.1
09-01-82(0000)	09-30-82(2300)	742	-57.	26.	-6.4	9.4	742	-39.	16.	-0.4	6.5
10-01-82(0000)	10-31-82(2300)	766	-29.	18.	-6.7	9.8	766	-22.	17.	2.0	6.1
11-01-82(0000)	11-30-82(2300)	742	-32.	25.	-6.0	9.8	742	-23.	26.	1.6	6.8
12-01-82(0000)	12-31-82(2300)	766	-49.	24.	-7.4	12.8	766	-42.	25.	1.5	9.2
01-01-83(0000)	01-31-83(2300)	766	-38.	28.	-2.7	11.8	766	-25.	27.	2.5	9.3
02-01-83(0000)	02-28-83(2300)	672	-38.	34.	1.7	11.9	672	-19.	22.	2.2	7.4
03-01-83(0000)	03-31-83(2300)	222	-37.	37.	-4.5	15.8	222	-24.	36.	0.3	9.1
04-01-83(0000)	04-30-83(2300)	742					742				
05-01-83(0000)	05-31-83(2300)	653	-62.	20.	-10.3	13.4	653	-29.	24.	-0.6	9.2
06-01-83(0000)	06-30-83(2300)	742	-34.	32.	-2.0	11.1	742	-27.	18.	-1.0	7.7
07-01-83(0000)	07-31-83(2300)	766	-31.	28.	-1.2	9.5	766	-46.	20.	0.0	10.6
08-01-83(0000)	08-31-83(2300)	766	-36.	26.	-0.8	9.9	766	-26.	22.	-0.2	7.6
09-01-83(0000)	09-30-83(2300)	742	-31.	22.	-0.4	8.6	742	-22.	29.	0.6	6.8
10-01-83(0000)	10-31-83(2300)	766	-26.	22.	-0.4	9.5	766	-21.	19.	1.1	7.1
11-01-83(0000)	11-30-83(2300)	742	-39.	18.	-5.8	10.9	742	-16.	28.	2.9	6.5

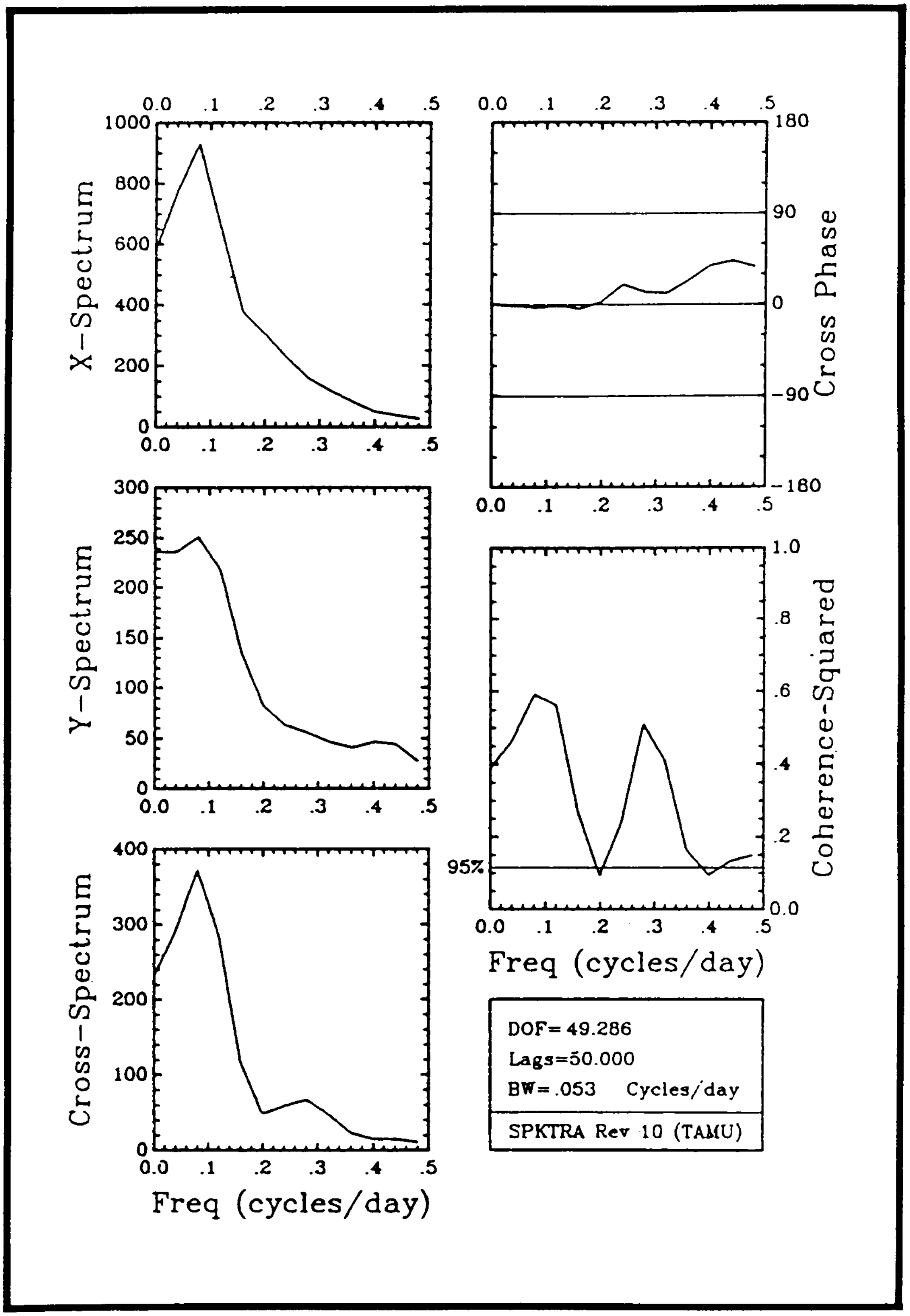


Figure 4.35. Autospectra, cross-spectrum, cross-phase and coherence squared for Bryan Mound site C (X) versus West Hackberry site D (Y) alongshelf components of near-bottom current for the 231-day period from 6 June 1981 through 22 January 1982. Ordinate units are cm^2/s^2/cycle/day. Negative phase means Y lags X (From: Kelly et al., 1983b).

investigated alongshore coherence from a 43-day period in the summer of 1977 at three sites along the central and lower Texas coast. Mid-depth current data in about 20 m of water exhibited an alternating alongshore motion that was coherent with the alongshore component of wind stress and had a net north-northeasterly displacement. Alongshore currents were highly coherent at the longest period resolved (12.5 days), and very nearly in phase over spatial scales in excess of 100 km.

Circulation East of Cameron

East of Cameron, LA there is much less combined wind and current meter data. Most of the observational programs have focused on the bays and estuaries and on the Mississippi Bight. The circulation in the bight is dominated by an anticyclonic drift of the plume from Southwest Pass that appears to be present approximately 70% of the time (Wiseman et al., 1976; Rouse and Coleman, 1976). Daddio (1977) found poor correlation between alongshore wind stress and current in the bight.

East of 92.5°W, the area of shallow depths increases markedly. According to Chuang and Wiseman, a large increase in bottom friction is to be expected in such shallow regions. As the coefficient of friction increases, the vertical-mean current required to balance a given alongshore stress decreases. Thus, even a constant alongshore stress at the coast may produce alongshore divergence in the current. Cochrane and Kelly (1986b) found that flow was directed onshore in this region as a result of divergence in the alongshore current because of a change in bottom frictional resistance, as well as wind stress divergence.

Bottom Ekman Veering

In a fluid with friction, the influence of the earth's rotation appears in the change of the direction of flow with depth, a phenomenon called Ekman veering. That Ekman veering is usually present can be seen in progressive vector diagrams of currents at various depths plotted from a common origin. Figures 4.36 and 4.37 (Kelly et al., 1984a,b) show progressive diagrams of currents at the Bryan Mound and the West Hackberry sites during the period 1 September through 30 November 1982. The various depths are indicated in the figures. From CM down to CZ there is counterclockwise veering in the bottom Ekman layer. In the bottom Ekman layer, the veering is counterclockwise, or to the left looking down, because the stress of friction is directed oppositely to the direction of flow in the wall layer just above the bottom. The mean veering angle at the Bryan Mound site is 52°. At the shallower West Hackberry site the surface and bottom Ekman layers are partially merged, but the counterclockwise veering is still evident and has a mean value of 20°.

Smith (1979) described the vertical structure of currents in 33 m of water off Aransas Pass based on current measurements at four levels above the bottom (2, 7, 16, and 23 m). With increasing distance above the bottom, both the increase in current speed and the clockwise angle (looking down) between the resultant current vector direction and the local alongshore direction were nearly linear when plotted against the

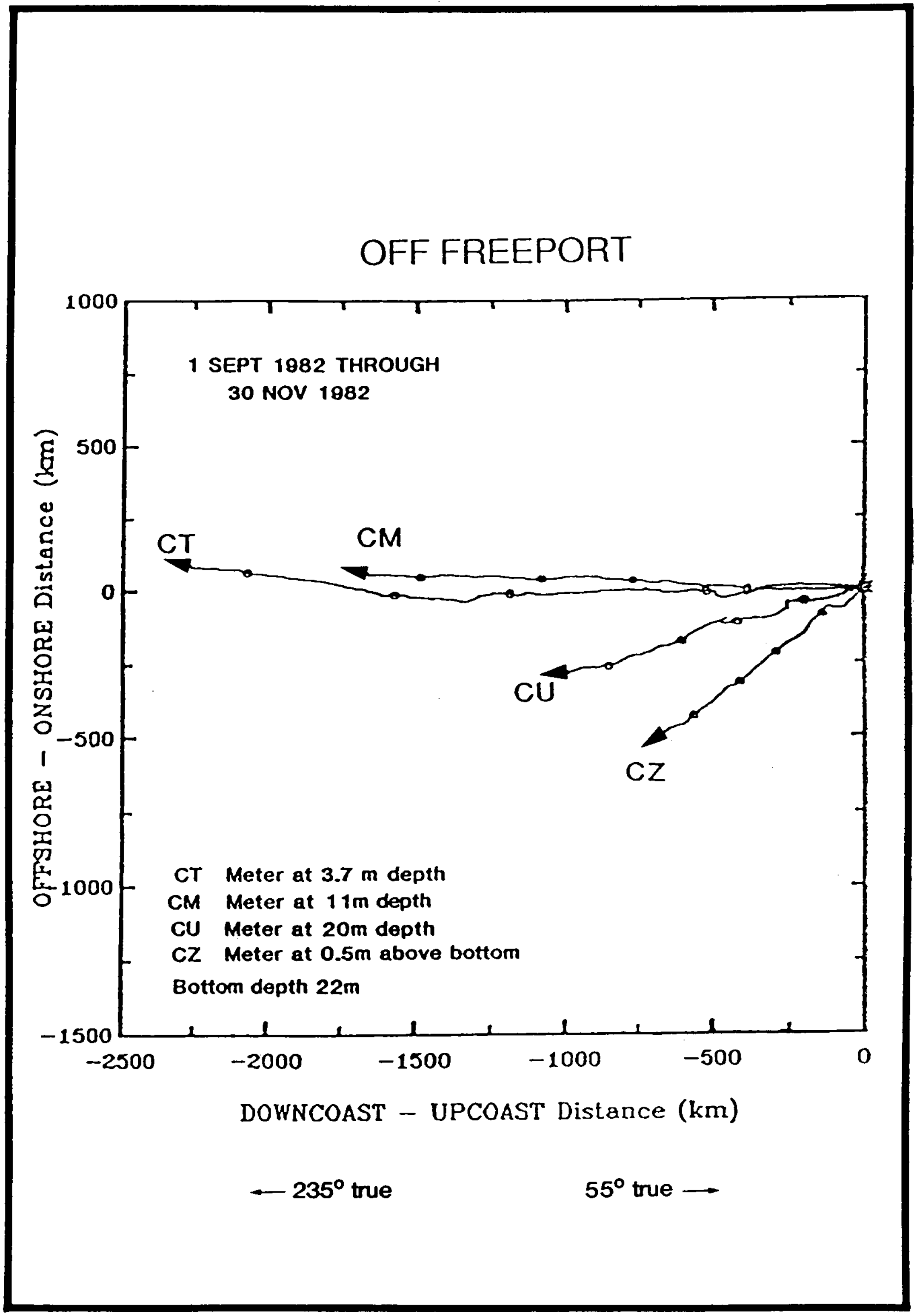


Figure 4.36. Progressive diagrams for currents observed during the period 1 September through 30 November 1982 at Bryan Mound site C at the depths indicated in legend (From: Kelly et al., 1984a). Tic marks are plotted at 20-day intervals.

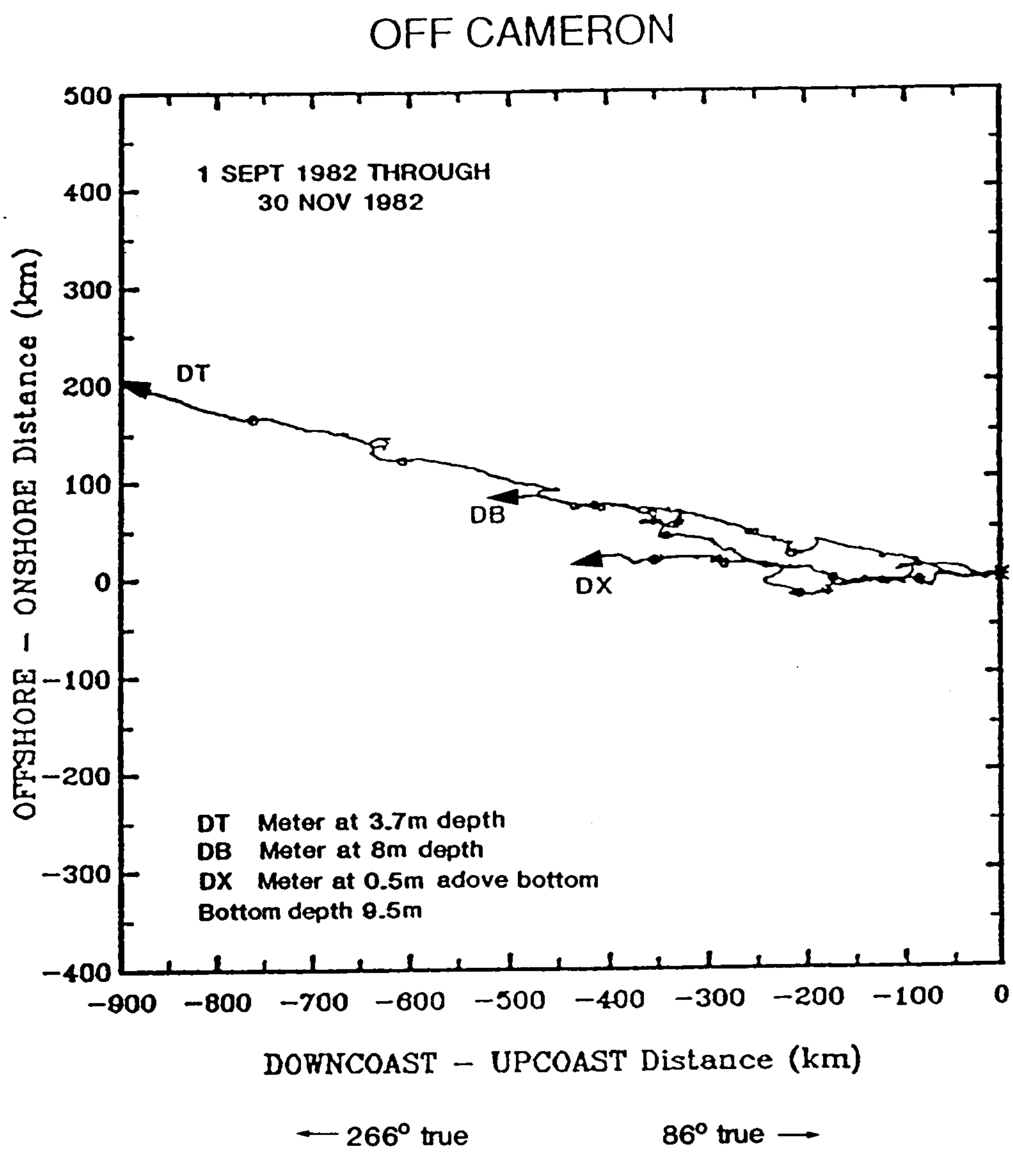


Figure 4.37. Progressive diagrams for currents observed during the period 1 September through 30 November 1982 at West Hackberry site D at the depths indicated in legend (From: Kelly et al., 1984b). Tic marks are plotted at 20-day intervals.

natural log of the height above the bottom, which would suggest a spiral pattern.

Kelly et al. (1985a) evaluated veering at the Bryan Mound site using six current meters between the surface and bottom in 22 m of water during the period 20 July to 8 August 1983. Meters were located at the following heights above the bottom: 0.5, 1.2, 2.1, 5.0, 11.0, and 18.1 m. There were two intervals of relatively steady current conditions, one with an upcoast wind component from 24 through 28 July and the other with a downcoast wind component from 30 July to 1 August. The mean current during the first time interval is shown as a function of depth in Figure 4.38a. The cross-shelf component is directed offshore (shown as positive) at the top current meter and onshore (negative) at all other meters, as might be expected for a wind with an upcoast component (upwelling). The curve is drawn so as to balance offshore and onshore flow. The alongshelf velocity component is quite strong; even at the bottom meter only 0.5 m above the bottom, it is more than 10 cm/s.

To reveal the turning of the current with depth, the mean velocities for the current meters at various depths are plotted in Figure 4.38b on a single polar coordinate grid. In both cases, the bottom two current meters (Z and W) show little turning, and, in the upcoast (July) case, even the third meter from the bottom (U) indicates only a very small turning. The layer with little turning seems to be the wall layer of more or less constant stress in which the velocity is expected to have a logarithmic profile. Above the quasi-logarithmic layer the current turns strongly clockwise with height. For the upcoast case, the turning from the direction at the deepest meter to the direction of the local isobaths (55° to 235°) is 39°. For the downcoast case the turning is 46°. The comparison with the local isobath orientation is made in order to avoid in so far as possible the Ekman veering due to wind stress. The current reaches this orientation somewhere above the current meter (M) at mid-depth. There appears to be no clear separation of the flow into surface and bottom Ekman layers with a geostrophic layer sandwiched between.

4.8.2 Outer Shelf

The prevailing currents in the upper layers on the outer shelf and continental slope flow toward the northeast or east, according to the orientation of the isobaths. The evidence for this comes from hydrographic data and direct measurements of current. Cochrane and Kelly (1986b) review various hydrographic data sets in which vertical sections crossing the outer shelf have isopycnals sloping down in the seaward direction. This implies eastward flow if the currents are quasi-geostrophic.

Direct measurements of currents in the upper part of the water column are available from the following locations along the outer shelf (Brooks et al., 1984): Green Canyon (GC), Flower Garden Banks (FG), East Breaks (EB), and Baker Bank (off Mustang Island) (MI) (see Section 4.8.3). Figures 4.39 through 4.42 display all available data for the respective locations in the form of a current rose and its associated

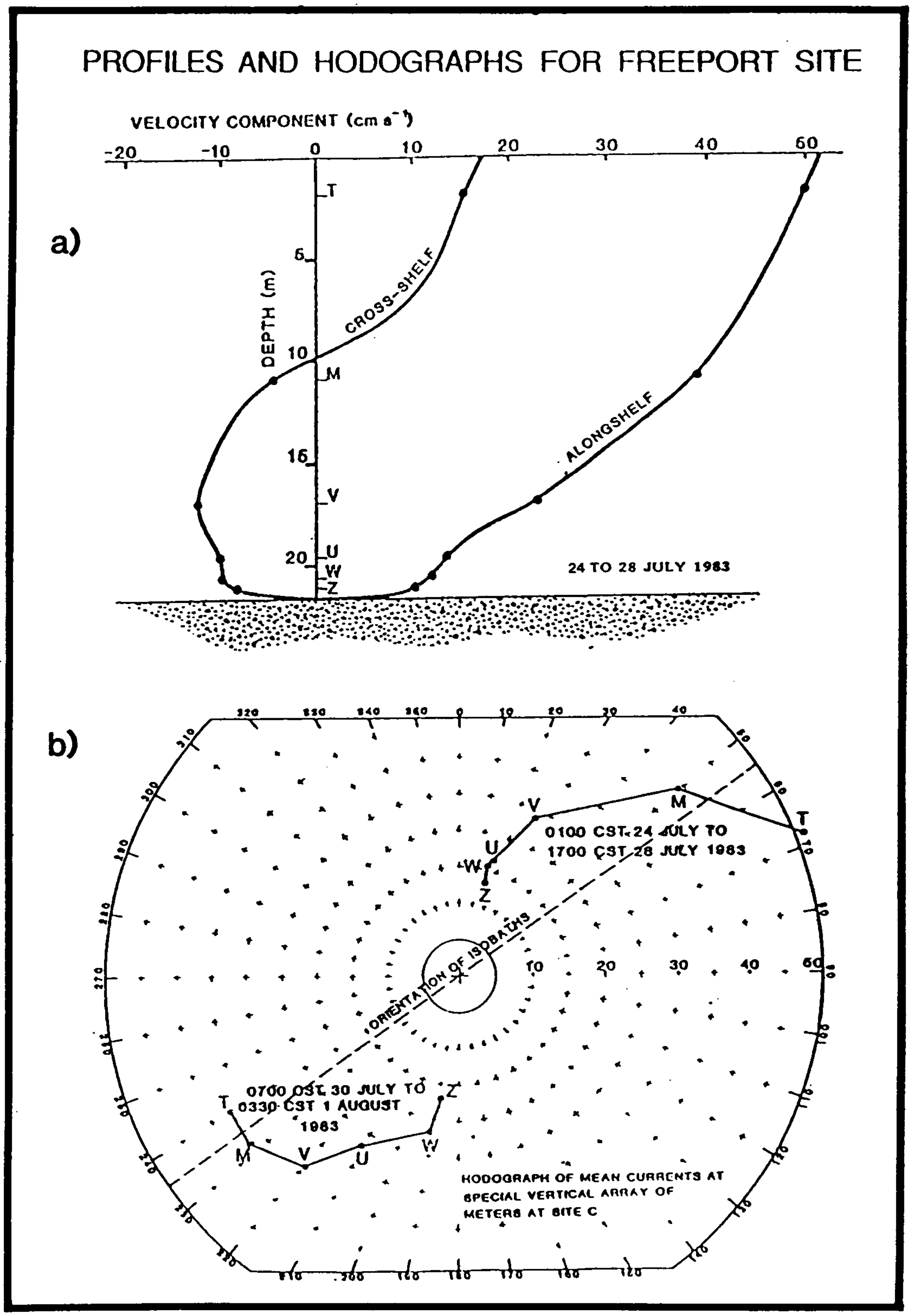
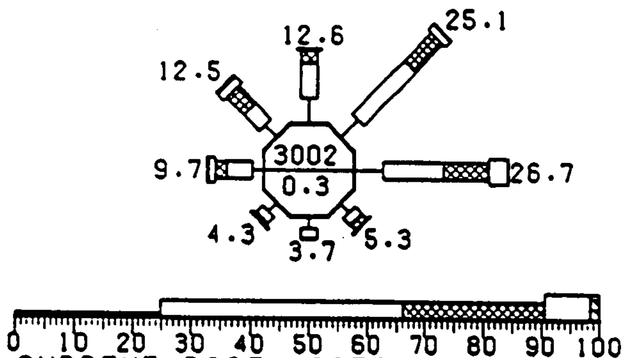


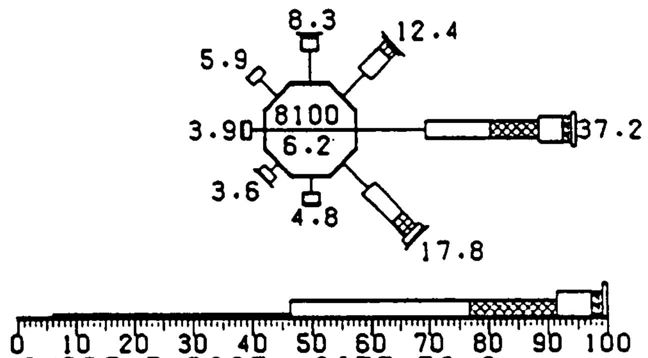
Figure 4.38. a) Mean current for the special vertical array of meters at Bryan Mound site C, 24 to 28 July 1983. Cross-shelf velocity is plotted as positive offshore and alongshelf velocity as positive upcoast (northeastward). b) Time-hodographs (connected points) of mean velocity for two periods. Each point is the head of a vector (starting at the origin) that represents the mean velocity at one of the meters (From: Kelly et al., 1985a).



CURRENT ROSE, SITE GC 1
80/12/18 (0200) - 81/04/22 (0200) (GMT)

DIR	RANGE (CM/S) E.G. 1< V ≤10										AVG SPEED
	0-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80+	TOTAL	
N	4.2	5.9	2.1	0.3	+					12.6	14.0
NE	4.2	12.5	6.8	1.2	0.3					25.1	17.3
E	5.2	10.4	7.7	3.1	0.3					26.7	18.9
SE	2.2	1.5	1.3	0.3						5.3	15.4
S	2.0	1.7	+							3.7	10.3
SW	2.0	1.4	0.4	0.5						4.3	14.0
W	2.0	4.1	2.0	1.1	0.4					9.7	18.7
NW	2.8	3.7	4.0	1.4	0.5					12.5	19.4
TOTAL	24.6	41.2	24.6	7.8	1.6					99.7	17.2
CALM										0.3	

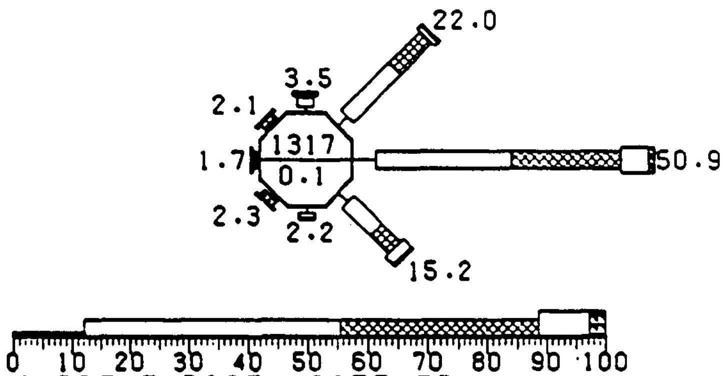
Figure 4.39. Current rose and associated table of joint frequency distribution of speed and direction from 3,002 hourly values of 3-h, low-pass-filtered time-series collected during the period 18 December 1980 to 22 April 1981 at 35 m depth in about 400 m of water in Green Canyon vicinity (From: Brooks et al., 1984). See Figure 4.1 for location.



CURRENT ROSE, SITE FG 3
79/09/12 (0300) - 81/07/15 (2000) (GMT)

DIR	RANGE (CM/S) E.G. 1< V ≤10										AVG SPEED
	1-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80+	TOTAL	
N	5.4	2.1	0.7	+						8.3	9.2
NE	5.5	4.6	1.7	0.5	+	+				12.4	12.8
E	11.9	10.9	8.2	4.1	1.4	0.7	+			37.2	18.2
SE	6.0	6.9	3.3	1.1	0.4	+				17.8	15.5
S	2.8	1.8	0.2							4.8	9.4
SW	1.9	1.4	0.2	+						3.6	10.1
W	2.3	1.3	0.3							3.9	9.6
NW	4.2	1.5	0.2							5.9	7.8
TOTAL	40.1	30.4	14.8	5.7	1.9	0.9	+			93.8	13.6
CALM										6.2	

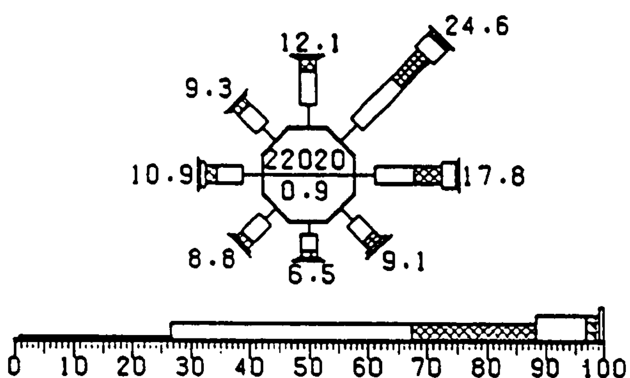
Figure 4.40. Current rose and associated table of joint frequency distribution of speed and direction from 8,100 hourly values of 3-h, low-pass-filtered time-series collected during the period 12 September 1979 to 15 July 1981 at 55 m depth in about 100 m of water just northwest of the West Flower Garden Bank (From: Brooks et al., 1984; data courtesy of D.W. McGrail). See Figure 4.1 for location.



CURRENT ROSE, SITE EB
80/06/19 (0400) - 80/08/12 (2300) (GMT)

DIR	RANGE (CM/S) E.G. 1< V ≤10										AVG
	1-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80+	TOTAL	SPEED
N	1.0	1.4	0.4	0.6	+					3.5	17.2
NE	2.2	11.2	7.4	0.8	0.5					22.0	18.5
E	3.9	22.6	18.7	4.6	1.1					50.9	20.5
SE	2.2	6.5	4.3	1.7	0.5					15.2	19.9
S	1.1	0.8	0.3							2.2	12.3
SW	0.7	0.2	0.9	0.3	0.2					2.3	20.3
W	0.5	0.2	0.5	0.2	0.2					1.7	21.9
NW	0.5	0.4	0.7	0.4	0.2					2.1	23.5
TOTAL	12.0	43.4	33.1	8.6	2.8					99.9	19.8
CALM										+	

Figure 4.41. Current rose and associated table of joint frequency distribution of speed and direction from 1,317 hourly values of 3-h, low-pass-filtered time-series collected during the period 19 June 1980 to 12 August 1980 at 63 m depth in about 280 m of water in East Breaks vicinity (From: Brooks et al., 1984). See Figure 4.1 for location.



CURRENT ROSE, SITE MI
78/03/02 (0500) - 81/03/20 (0700) (GMT)

DIR	RANGE (CM/S) E.G. 1< V ≤10										AVG
	1-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80+	TOTAL	SPEED
N	3.8	5.5	2.2	0.4	+	+				12.1	14.6
NE	4.1	9.6	6.7	3.0	0.9	0.2	+			24.6	20.1
E	3.6	6.7	4.5	2.3	0.5	0.2	+			17.8	19.4
SE	2.9	3.7	1.6	0.5	0.2	0.1	+			9.1	15.9
S	2.1	2.6	1.2	0.4	0.1	+				6.5	15.2
SW	2.7	4.1	1.3	0.5	0.2	+				8.8	15.3
W	3.3	4.5	1.9	0.8	0.3	+	+			10.9	16.8
NW	3.2	4.1	1.5	0.4	0.1	+				9.3	14.4
TOTAL	25.7	40.8	20.9	8.4	2.5	0.8	+			99.1	17.1
CALM										0.9	

Figure 4.42. Current rose and associated table of joint frequency distribution of speed and direction from 22,020 hourly values of 3-h, low-pass-filtered time-series collected during the period 2 March 1978 to 20 March 1981 at 12 m depth in about 73 m of water in Baker Bank vicinity (off Mustang Island) (From: Brooks et al., 1984). See Figure 4.1 for location.

table of joint frequency distribution of speed and direction. The preponderance of flow to the east and northeast is obvious.

Cochrane and Kelly (1986b) argue that the flow along the edge of the outer shelf is a countercurrent or return flow to the downcoast current that dominates the inner shelf except during summer (see Section 4.8.3). The flows on the inner and outer parts of the shelf are connected by cross-shelf flows caused by convergence along the south Texas Coast and divergence in the east.

Near-bottom currents on the outer shelf are less well documented. They were not considered in the study of Brooks et al. (1984). Recently, near-bottom currents on the south Texas continental shelf were monitored during 145 days in the summer, fall, and early winter of 1984 (Science Applications International Corporation, 1986). Current meters were located in water depths of 12, 18, 34, 74, and 140 m along a line perpendicular to Corpus Christi Bay. At the lower frequencies, coherence between the overlying wind field and the bottom currents decreased in an offshore direction. However, there was still some coherence even at the shelf break. Net along-isobath displacements for July to October and October to December periods were downcoast at all locations. Net cross-isobath displacements suggested patterns of convergence and divergence across the shelf. Rezak et al. (1985) and Halper and McGrail (1988) found that at the Flower Garden Banks, near-bottom currents tend to flow toward the east or southeast, and that the stronger the flow, the more southerly it tends to be. They found an overall average of 1.6 cm/s toward the east-southeast for records in the 11 to 18 m above-the-bottom group. These results are not consistent with Ekman veering, which predicts counterclockwise (looking down) veering to the northeast for eastward flowing geostrophic currents above the Ekman bottom boundary layer. Rezak et al. (1985) offer several explanations: orographic effects from the banks, off-shelf flow of cold, dense water formed during frontal passages, and baroclinic shearing.

4.8.3 Prevailing Circulation on the Shelf

To provide a first approximation to the prevailing currents over the whole Texas-Louisiana shelf, Cochrane and Kelly (1986b) computed monthly mean geopotential anomalies (relative to the 70 db) from monthly mean temperatures and salinities for the data from the GUS III cruises. Their charts with streamlines are reproduced in Figure 4.43. In months other than June, July, and August, an elongated region of low geopotential dominates the shelf. On the inner-shelf side of the cyclonic feature, downcoast flow prevails, in agreement with the downcoast wind component discussed above. There is a counterflow (eastward or northeastward) along the shelf break. During the summer months, there is upcoast flow along much of the inner shelf to about 92.5°W, and a high in geopotential lies off the Louisiana coast. Although there is a suggestion of eastward or northeastward flow along the shelf break, it is very weak. The summer situation is, thus, very different from the situation during the rest of the year when there is a distinct "low" in geopotential over the outer shelf. The annual progression of the patterns of geopotential anomaly provide a conceptual framework that is consistent with the various aspects of shelf

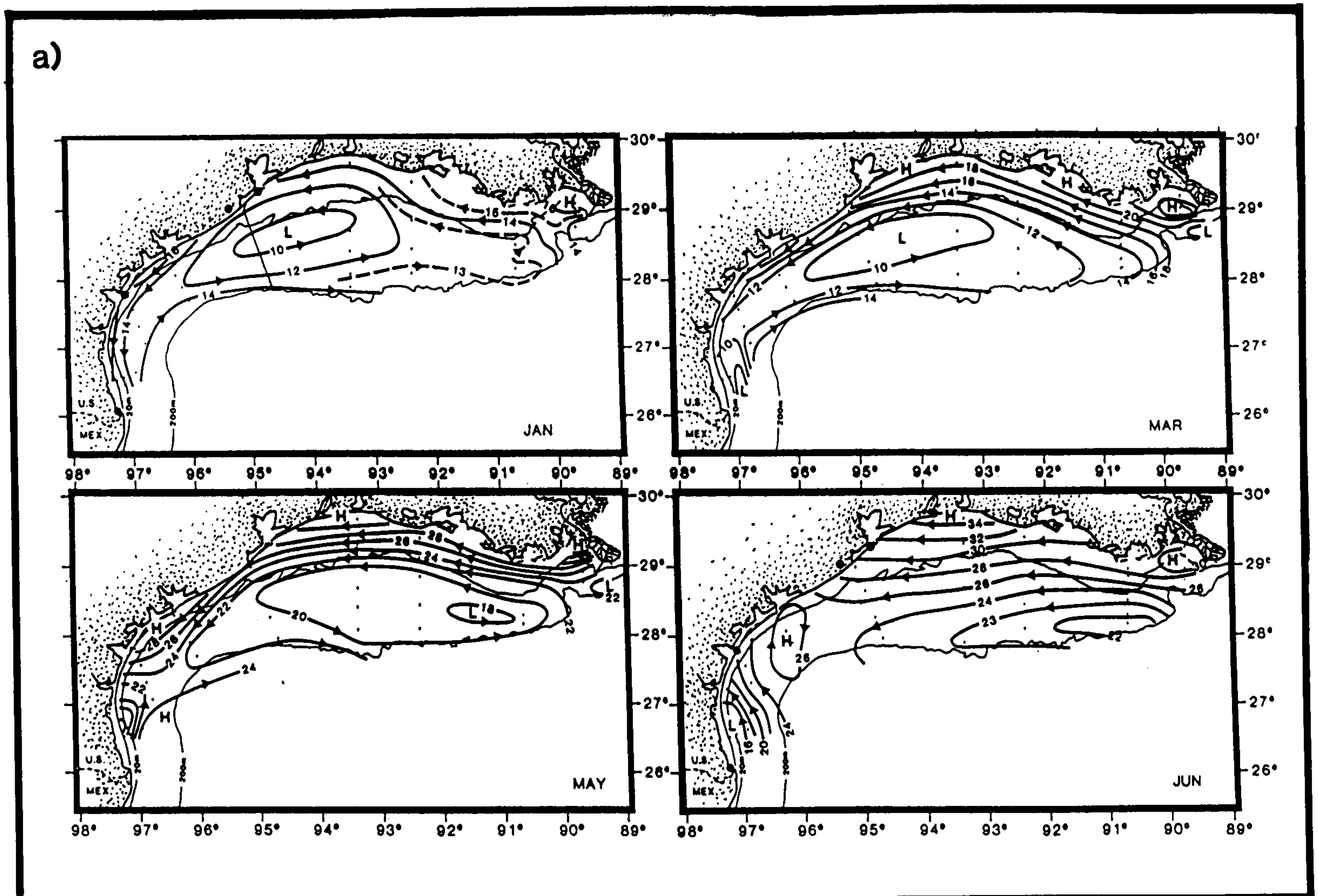


Figure 4.43. Monthly mean geopotential anomaly (dyn cm or 10^{-1} Jkg^{-1}) of the sea surface relative to 70 db or 0.70 MPa based on data taken aboard M/V GUS III in 1963, 1964 and 1965 (From: Cochrane and Kelly, 1986b). a) Data for January, March, May, and June. b) Data for July, August, September, and November.

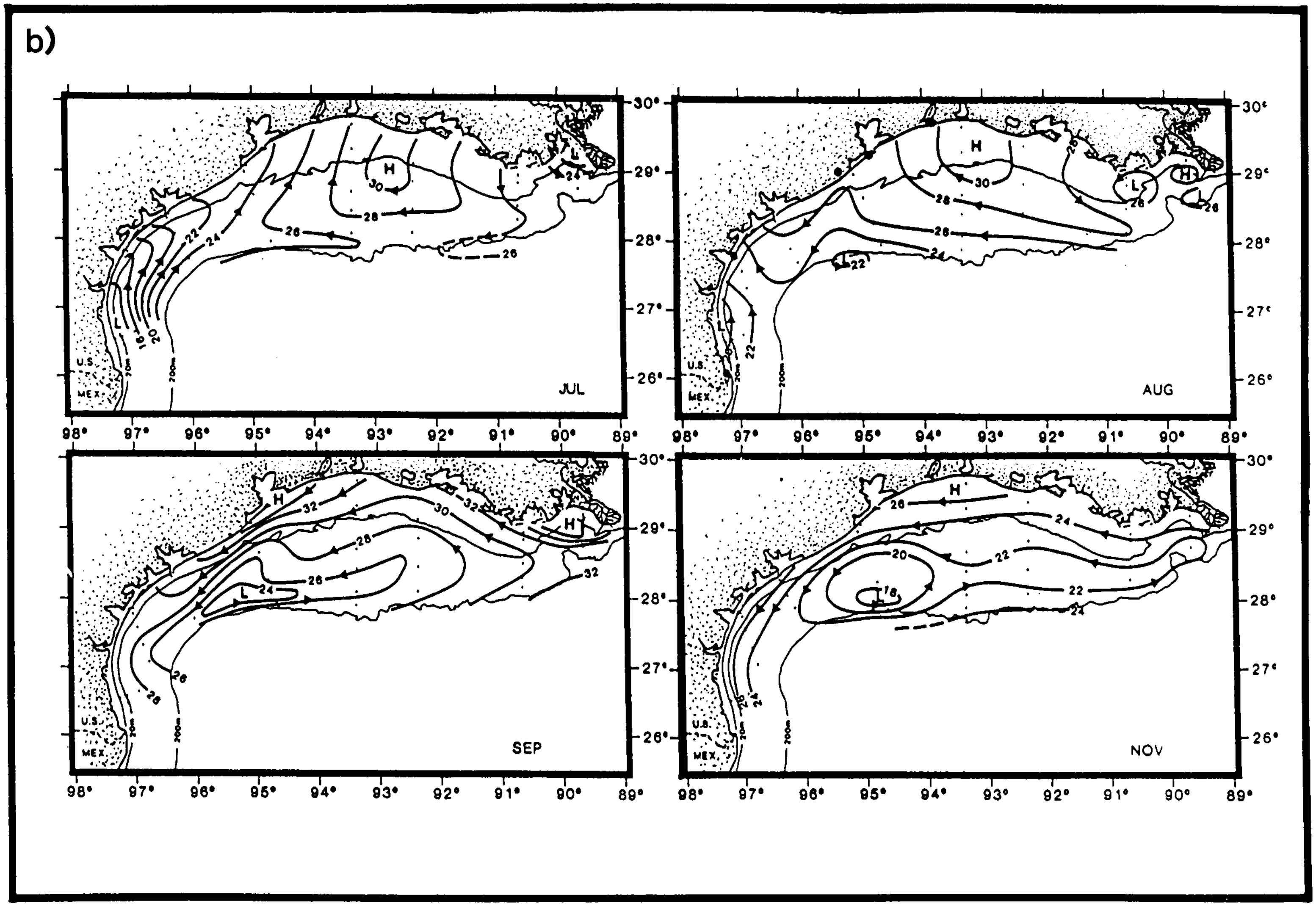


Figure 4.43. (Continued).

circulation and hydrography that have been described in the preceding sections.

4.8.4 Hurricane Currents

Currents generated by tropical storms and hurricanes have been observed at various locations on the shelf. Forristall et al. (1977) describe the effects of Tropical Storm Delia in September 1973 at the Buccaneer platform located in 20 m of water 50 km south of Galveston. Currents exceeded 2 m/s toward the west-southwest (approximately parallel to the local isobaths) at 17 m above the bottom. Peak currents at 3 m above the bottom were 75% of those at the upper level. During part of the time, currents were sufficiently large that the total particle velocities, including the oscillatory wave motion, never reversed direction, which means that steady currents were stronger than the orbital velocities of the highest waves. Forristall et al. (1978) describe these orbital velocities in detail and compare them with theoretically predicted velocities. Maximum observed horizontal wave velocities at 17 m above the bottom were on the order of 150 to 200 cm/s.

Tropical Storm Debra passed about 20 km west of the West Hackberry DOE/SPR site (where the water depth is 10 m) on 28 August 1978 (Frey et al., 1981). At 3 m above the bottom, maximum current speed reached 77 cm/s, and at 1 m above the bottom they were 57 cm/s. Hurricane Anita, during late August and early September 1977, moved west-southwest across the Gulf from its origin, about 250 km south of the Mississippi Delta, to landfall, about 250 km south of Brownsville. Despite the distance of Anita from the central Texas Coast, speeds of up to 80 cm/s were observed on the inner shelf (Smith, 1978b, 1980c; Maresca and Carlson, 1980).

At the Flower Garden Banks, Rezak et al. (1985) observed the effects of Tropical Storm Claudette at 60 m and 90 m in 100 m of water. They conclude that the passage of a hurricane over the banks elicits a three-layer response: a direct wind-driven current down to about the thermocline, an indirectly forced flow extending from the thermocline to about 10 m of the bottom, and a near-bottom flow, probably compensatory to a large degree to that at the surface. Strong inertial oscillations and 2-day shelf waves were also observed.

Hurricane Alicia passed directly over the Bryan Mound DOE/SPR site in 22 m of water (Kelly et al., 1984b). Current meters were moored at nominal depths, i.e., before mooring tilt caused by strong currents, of 3.6 m (CT), 10.9 m (CM), and 20.1 m (CU). Figure 4.44 shows the alongshelf component of currents at these depths after filtering with a 3-h low-pass filter. The effects of Hurricane Alicia were strong but short-lived. Peak currents were downcoast and offshore at all depths and occurred between 1800 and 2400 h CST on 17 August 1983 when the eye passed just east of the mooring. Peak values of the alongshelf component were 160 cm/s at CT, 125 cm/s at CM, and 100 cm/s at CU. Current speeds dropped to less than 25 cm/s at all depths by the end of 18 August and became quite weak for several days. Kelly et al. (1984b) also note that large scale homogenization of the coastal waters did not occur. Prior to Hurricane Alicia, on August 16, the water column at the mooring was very

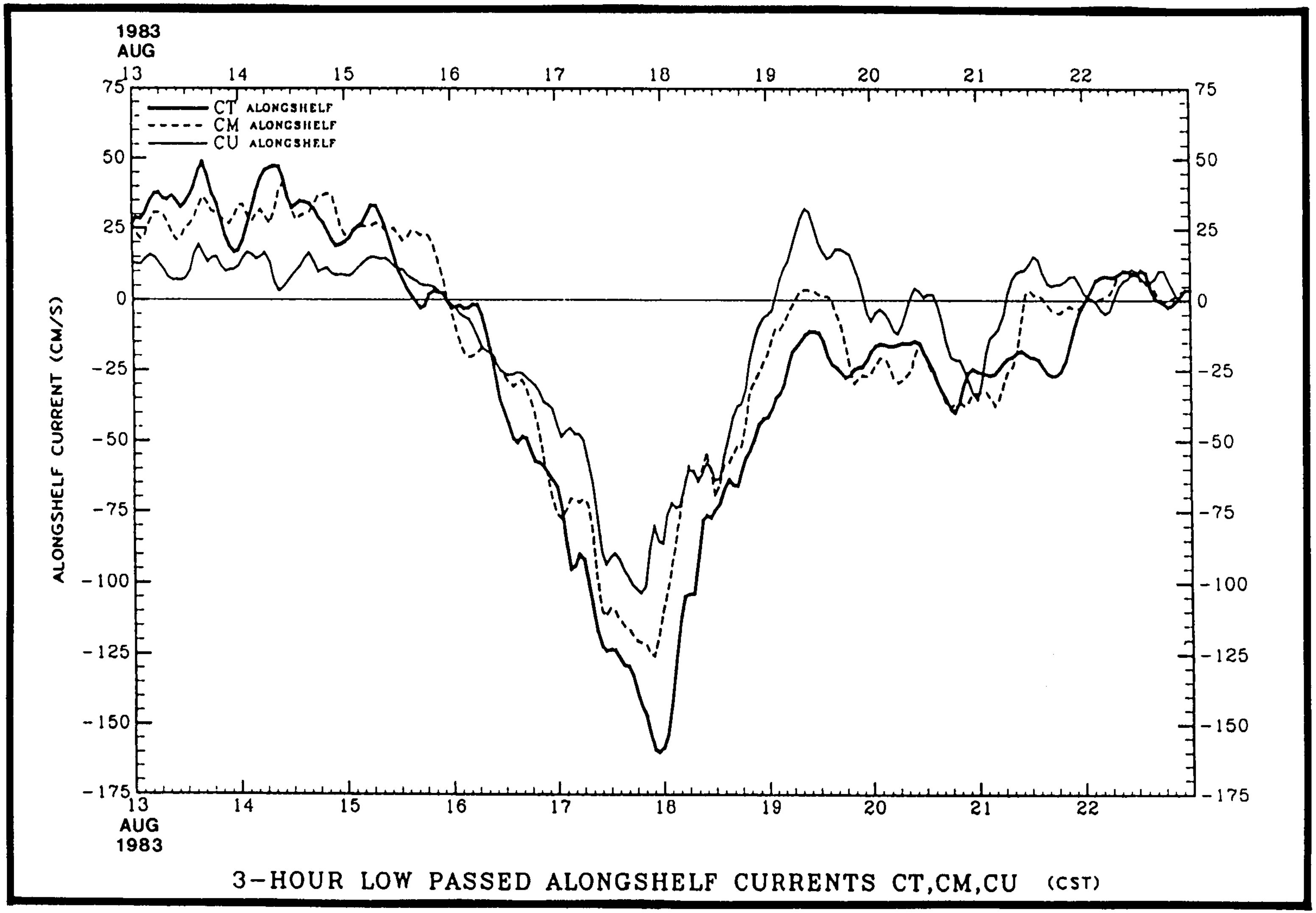


Figure 4.44. Alongshelf components of currents recorded as the eye of Hurricane Alicia passed a few kilometers to the east of a current meter mooring in 22 m of water at the Bryan Mound site. Current meter depths, before any mooring tilt caused by the strong currents, were 3.7 m (CT), 11 m (CM), and 20 m (CU). Original 2-min data were smoothed with a 3-h low-pass filter.

stratified. A thick layer of fresher, warmer water (30 to 32°/$_{oo}$ and 29 to 30°C) overlay a thinner bottom layer of saltier, cooler water (35°/$_{oo}$ and 25°C). The water column at the location of the mooring became homogeneous during the hurricane, but on 19 August salinity stratification had returned, with at top-to-bottom difference of 5°/$_{oo}$. Advection from nearby areas, relatively unaffected by the hurricane, restored the stratification.

4.8.5 Eddy-Shelf Interaction

Large (diameters greater than 200 km), strong (swirl speeds greater than 50 cm/s) eddies, both anticyclonic and cyclonic, are frequently observed near the outer or deep part of the continental slope in the northwestern part of the Gulf of Mexico, but the degree to which they influence the circulation of the Texas-Louisiana shelf and the continental slope out to a depth of about 500 m is little known and poorly understood. Events of strong persistent currents on the upper slope off Louisiana and Texas that suggest the influence of eddies have been reported by offshore industry operations and recorded by current meters. Usually, however, observations of eddies lack concurrent current meter and sub-surface hydrographic observations on the shelf and slope, and vice versa, making it impossible to draw definitive conclusions. For example, Figure 4.45 shows a period of persistently eastward flow at the Flower Gardens during May 1980, when wind forcing at the time was weak and variable, the signature one might expect on the north side of on offshore anticyclonic eddy. Brooks and Legeckis (1982) and Brooks (1984) report that in April 1980 an anticyclone was centered near 25.5°N, 92°W, and its diameter was about 250 km. But if it moved due westward, its northern periphery would have extended only to the 500-m isobath, which is about 50 km south of the Flower Gardens, and so, a connection between the eddy and the currents in Figure 4.45 cannot be proved.

The anticyclonic eddies originate in the eastern Gulf where they separate from the Loop Current. Vukovich and Crissman (1986), in a study of 12 years of satellite infrared data, showed that, after separation, they follow three characteristic paths of westward migration across the western Gulf: a northern one, a mid-Gulf one, and a southwestern one. When an anticyclone follows the northern path its northern side brushes against the Texas-Louisiana slope, and the outer edge of its circulation frequently lies inshore of the 2000-m isobath. The studies during the MMS Gulf of Mexico Physical Oceanography Program: Year 3 (Science Applications International Corporation, 1988) observed an eddy that illustrates this case. Figure 4.46 shows the depth of the 8°C temperature surface, based on a mid-July 1985 expendable bathythermograph (XBT) survey, in an anticyclone that had just separated from the Loop Current. (The depth of the 8°C temperature surface indicates the pattern of the geostrophic flow; deep regions correspond to regions of anticyclonic circulation, and shallow regions to cyclonic circulation.) The eddy's subsequent movement was tracked by satellite infrared imagery, ARGOS drifters and ship surveys. Figure 4.47 shows that by mid-November 1985 the eddy was interacting with both the western and northern slopes and that several small scale cyclonic and anticyclonic features were located around its periphery. During December 1985 and January 1986

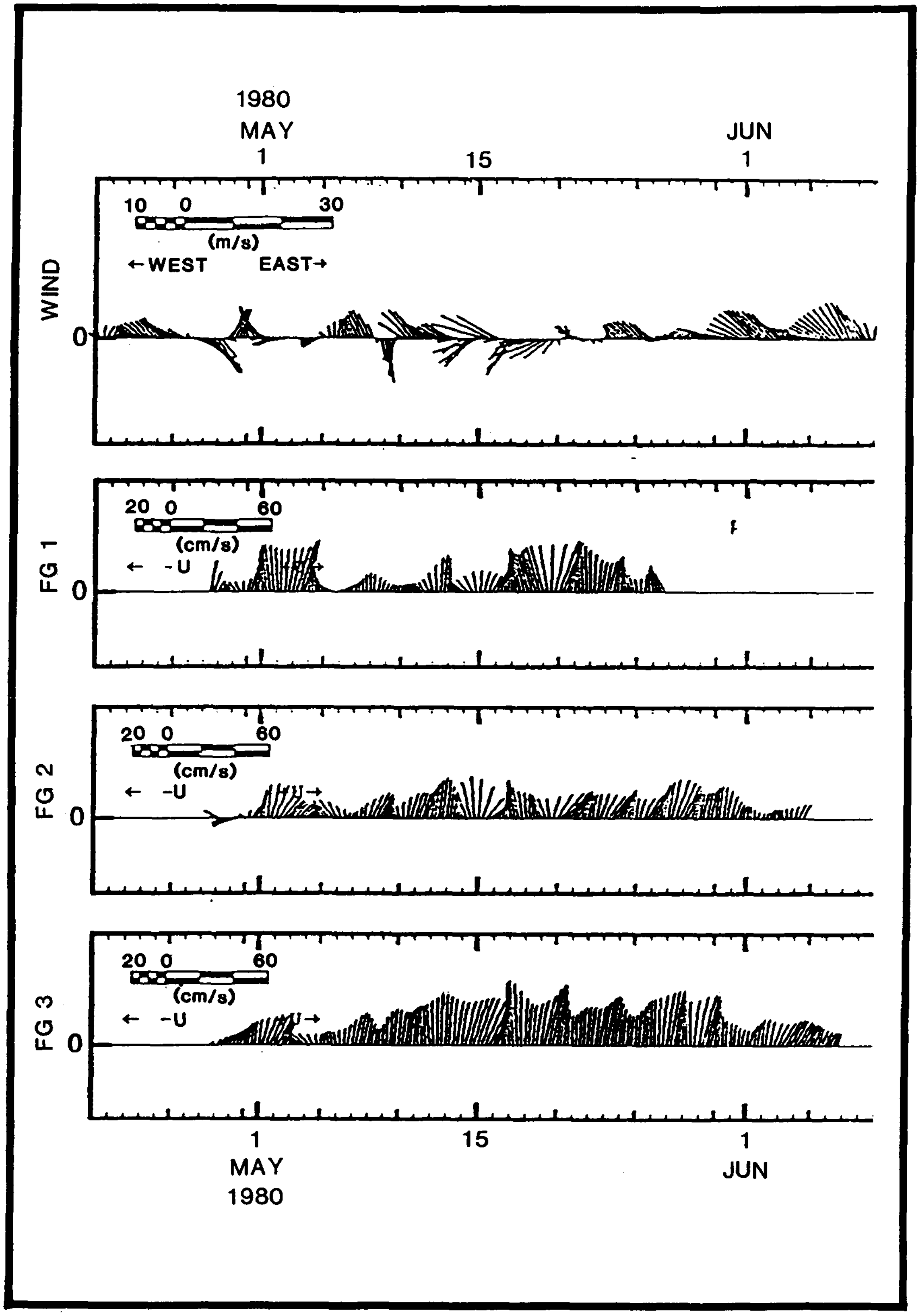


Figure 4.45. Comparative time-series plots of 40-h low-passed stick vectors for wind from NDBC Buoy 42008 (28°47.07'N, 95°18.71'W) and currents from Flower Garden sites 1, 2, and 3 (instrument depths, about 50 m; water depths about 100 m), for May 1980. Vertically up is toward the east for the current stick vectors and towards the north for the wind stick vectors (From: Rezak et al., 1983).

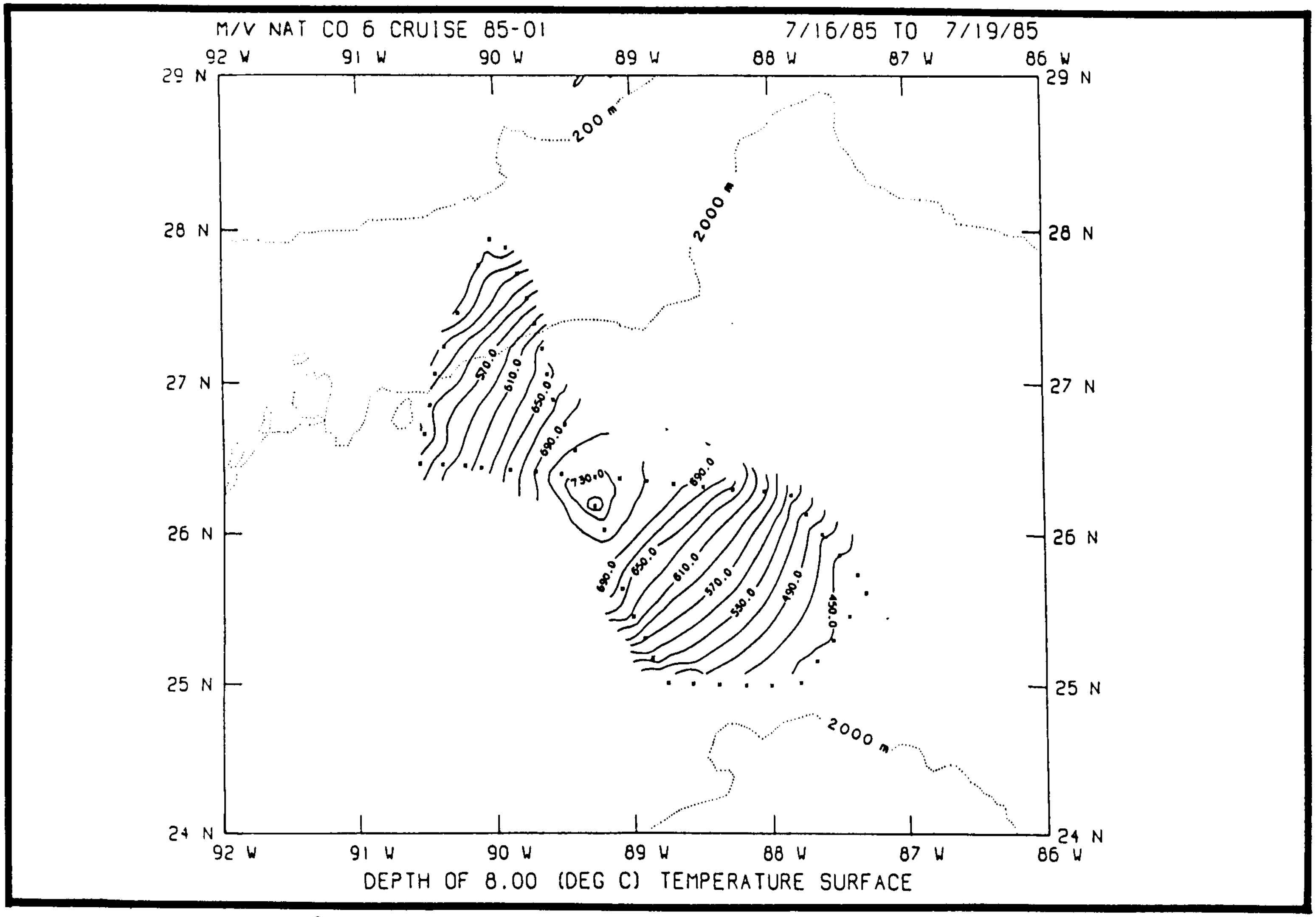


Figure 4.46. Depth of the 8°C temperature surface from XBT data in mid-July 1985 in an anticyclonic, warm-core eddy shed by the Loop Current in late June 1985 (From: Science Applications International Corporation, 1988).

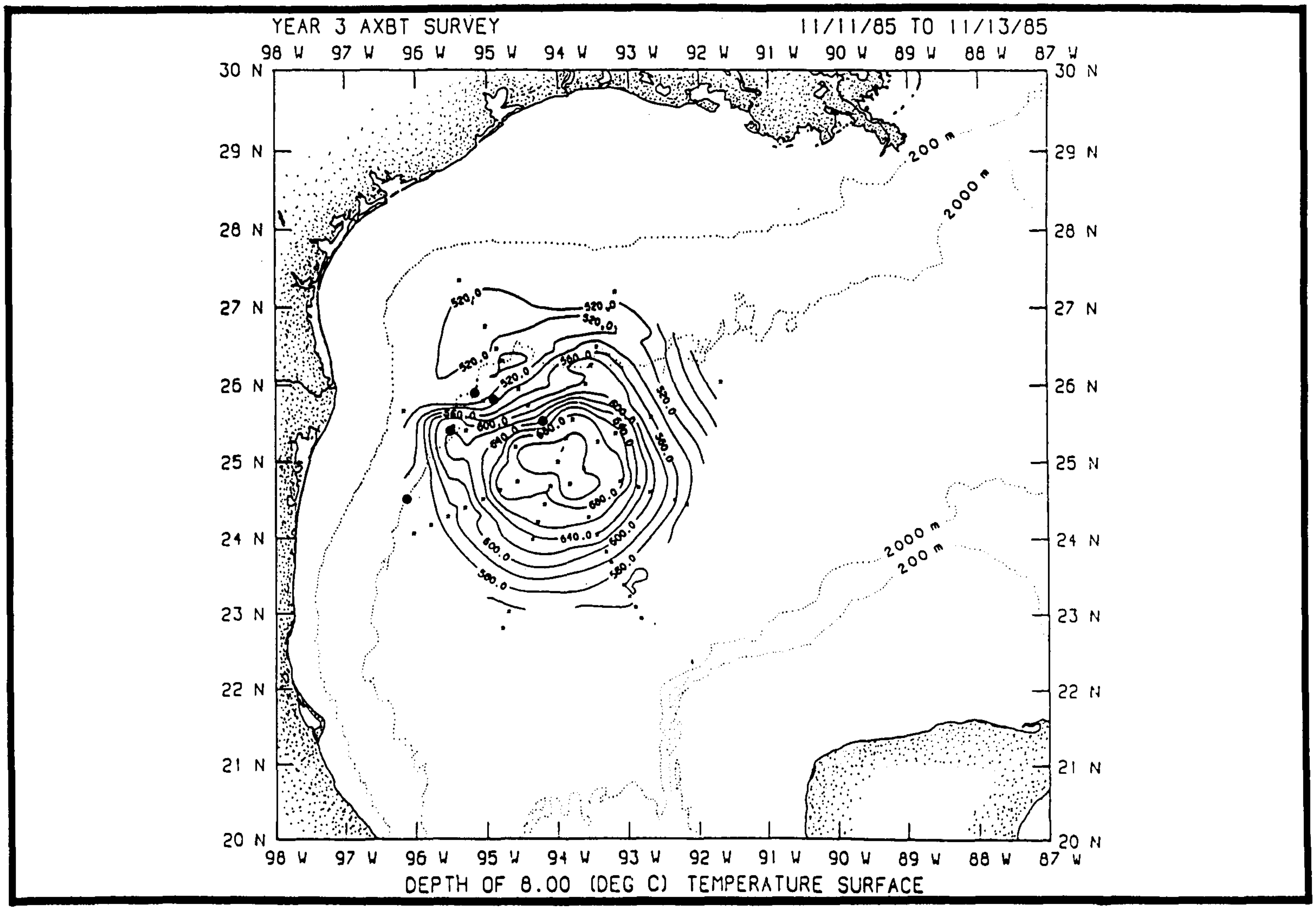


Figure 4.47. Depth of the 8°C temperature surface from AXBT data in mid-November 1985 in the same eddy as in Figure 4.46 (From: Science Applications International Corporation, 1988).

(Figure 4.48), the eddy moved to a position against the western continental slope, and its shape became quite elliptical.

The Texas-Louisiana slope is broad, and the available evidence does not resolve the question of whether an anticyclone's circulation can penetrate inshore of the 500-m isobath and onto the shelf, or instead, influences the shallow regions indirectly through flows associated with filaments, dispersion products, entrainment around the periphery, cross-slope flow between the anticyclone and leading and trailing cyclones, and other secondary mechanisms. Just south of about 26°N, the Rio Grande slope narrows to about half the width of the Texas-Louisiana slope. Here, as Figure 4.48 and the results of Elliott (1982), Merrell and Vazquez (1983), Brooks (1984) demonstrate, the perimeter of an anticyclone can press shoreward to the outer edge of the Mexican shelf, but it is not known if the circulation in the upper layer actually laps onto the shelf.

In the Western Gulf of Mexico, cyclonic eddies are frequently observed in association with Loop Current anticyclones (Elliott, 1979; Merrell and Morrison, 1981; Brooks and Legeckis, 1982; Merrell and Vazquez, 1983; Brooks, 1984). The formation of the cyclonic partner was observed for the first time during the Year 3 phase of the MMS Gulf of Mexico Physical Oceanography Program. Figures 4.47 and 4.48 show that between November 1985 and late January 1986, the small cyclonic feature on the northwest side of a Loop Current anticyclone greatly intensified as the anticyclone migrated onto the continental slope of the western margin. The cyclone's diameter increased to about 200 km and it lay entirely over the continental slope of southwest Texas between the 200- and 2000-m isobaths. The northeastward flow between the pair of vortices drew cool, low-salinity water off the Texas-Mexico continental shelf. Both this example and the studies cited above demonstrate that the vortex pair configuration drives a strong exchange between the western shelf and open Gulf waters. In Figures 4.47 and 4.48, one can also see a partially resolved cyclonic feature on the northeast side of the large anticyclone. Southward flow off the Texas-Louisiana shelf is suggested, but, since the slope is twice as wide as its western counterpart, the influence of this mechanism on the northern shelf may be much weaker.

To summarize, Loop Current eddies interact strongly with the base of the continental slope in the western Gulf of Mexico; they generate cyclonic eddies during topographic interaction; cyclonic eddies act in concert with Loop Current eddies to draw water on and off the shelf; other interactions between eddies and the continental shelf and upper slope are suggested by the existing data base but more information about the mechanisms through which eddies can influence the shelf and upper slope is needed.

4.8.6 Tidal Currents and Inertial Oscillations

These two classes of currents, although dynamically quite different, are grouped together because the period of inertial oscillation at the latitudes of the Texas-Louisiana shelf is very close to the periods of the diurnal tides, and it is difficult to separate

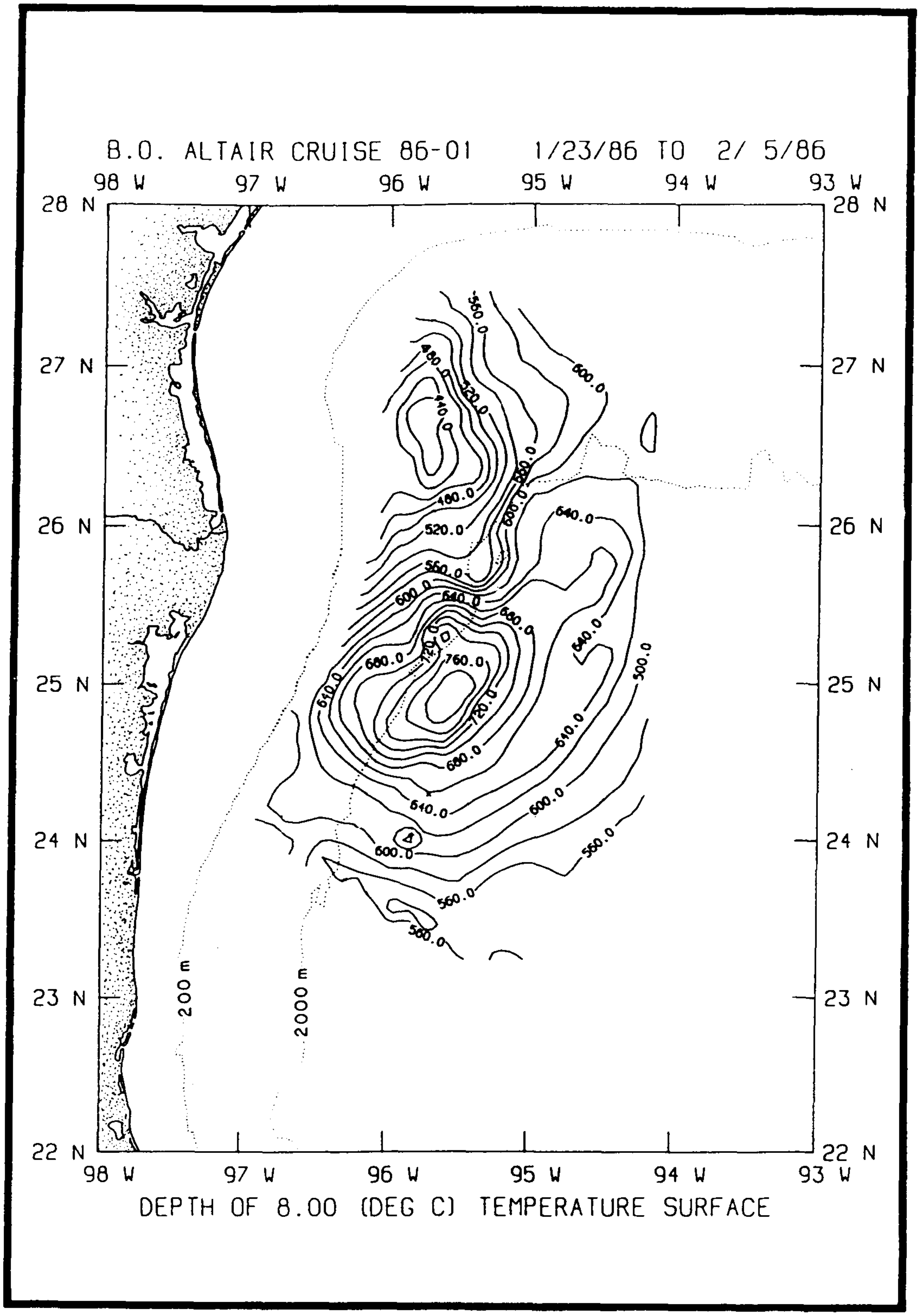


Figure 4.48. Depth of the 8°C temperature surface from XBT data in late January 1986 in the same eddy as in Figure 4.46 (From: Science Applications International Corporation, 1988).

them. Harmonic tidal analyses of current records from locations around the shelf routinely yield amplitudes of 1 to 4 cm/s for the K_1, O_1 and M_2 constituents (Murray, 1976; Frey et al., 1981; Kelly et al., 1983a,b, 1984a,b, 1985a,b; Rezak et al., 1985). Tidal currents near the surface are often larger than those near the bottom, suggesting a baroclinic tidal component (Rezak et al., 1985). The eccentricity orientation and sense of rotation of tidal current ellipses varies by location, degree of stratification, season and depth. Although tidal currents are weak, they are relatively important in the bottom layer of the inner shelf when vertical stratification is strong and/or wind forcing is weak. At such times, tidal currents play an important role in mixing and advection (Kelly et al., 1983b).

Bursts of inertial oscillations lasting from 3 to 10 days or even longer appear in current meter records at most locations on the shelf (e.g., Kelly et al., 1983a,b; Brooks et al., 1984; Rezak et al., 1985). The maximum amplitude of inertial currents is on the order of 20 to 30 cm/s near the surface and 10 to 15 cm/s near the bottom. The oscillations occur most frequently in the late spring and summer months when vertical stratification is strong. An example of inertial currents can be seen in Figure 4.33. Daddio et al. (1978) analyzed two month-long current records, one in February and one in May, from the inner shelf west of the Mississippi River Delta. They demonstrated that the vigorous clockwise motions observed in the near-surface mixed layer were locally wind-induced inertial motions and not diurnal tides. The clockwise current oscillations with diurnal-inertial frequency were associated with strong frontal passages and uncorrelated with the temporal variations of tidal energy. A simple wind-driven model of the mixed layer satisfactorily reproduced the observed oscillations.

4.8.7 Shelf Waves

Low-frequency wave motions, commonly called continental shelf waves or topographic Rossby waves, can exist as a consequence of vorticity dynamics and can propagate current patterns and fluctuations along steep topographic gradients such as the edge of the continental shelf. These waves depend on the topographic gradients, not gravity, for their existence, so their most visible manifestations are horizontal current patterns. They propagate in a direction such that shallower water is on the right (northern hemisphere), have periods of a few days to weeks, wave lengths of hundreds of kilometers, and amplitudes of 5 to 30 cm/s or more. Shelf waves are often excited by atmospheric forcing on synoptic weather-related time scales, which in this shelf region are several days to a week (Table 4.1). Because of the long wavelengths of shelf waves and the distributed effects of wind forcing, it is difficult to separate the free, propagating waves from the locally forced response at a given location. Evidence of phase propagation is often inconclusive or confusing. On the Texas shelf, the phases tend to be further randomized by the irregular topography of the shelf edge, especially near rough areas such as the Flower Garden Banks.

Observations of shelf waves on the Texas-Louisiana shelf are limited. The strong coherence at 3- and 10-day periods between the bottom currents at Bryan Mound and West Hackberry sites along the coast

(Figure 4.35) may be related to shelf waves. Rezak et al. (1985) present evidence from current records at the Flower Garden Banks that suggest shelf waves with periods of 33 h, 2 days and 4 days. The 2-day wave has a wavelength of about 80 km and amplitudes as large as 15 cm/s but normally on the order of 4 cm/s. They also note that analyses of satellite thermal images show wavelike perturbations (onshore-offshore) in sea-surface isotherms at the shelf edge that have a wavelength of about 83 km, which is consistent with the wavelength they estimated for a shelf wave with a 2-day period. Brooks et al. (1984), by means of spectral coherence studies of currents at locations near the shelf edge, also find evidence of westward propagating shelf waves with a period of 2 to 3 days.

4.9 DATA GAPS AND INFORMATION NEEDS

The variability about the mean pattern of surface circulation developed by Cochrane and Kelly (1986b) is largely unknown except in the regions of the DOE/SPR studies. An instantaneous or synoptic picture of the surface currents on the shelf might exhibit several cells of circulation in the central region, rather than one large cyclonic gyre, and complex patterns near the west and east ends of the shelf. Multiple cells of circulation would imply multiple regions in which there is flow across the width of the shelf.

The spatial pattern of mean bottom circulation over the shelf, and its variability, needs to be described and related to the surface circulation and hydrographic variability.

Information about the exchange processes between the shelf and the oceanic Gulf regions is very limited. The influence of Loop Current eddies, the export of water masses created by cold-air outbreaks, the flushing of fresh water discharge on to the shelf, upwelling of deep ocean water masses onto the shelf, and transport of sediment off the shelf are important yet relatively unexplored topics for this shelf.

Our understanding of the effects and fate of the fresh water from the Mississippi-Atchafalaya River System is based largely on the salinity data from the GUS III cruises in the years 1963 to 1965, when river discharge was lower than average. The distribution of salinity on the shelf should be mapped with greater spatial resolution, both horizontally and vertically, during a year with above normal volumes of river discharge.

The structure and the dynamic behavior of the intense frontal zones on this shelf should be studied through a combination of observation and modeling, with a view towards defining the effect that stratification, both horizontal and vertical, has on the mixing, distribution and transport of nutrients, plankton and pollutants.

The rate at which the concentration of dissolved oxygen changes locally in bottom waters when there is vertical stratification is unknown. All terms in the diffusion equation for dissolved oxygen need to be studied: local rate-of-change, advection, production, consumption, and turbulent mixing, both vertical and horizontal.

CHAPTER 5
MARINE CHEMISTRY

B.J. Presley
Paul N. Boothe
(Trace Metals, Radionuclides)

James M. Brooks
(Hydrocarbons, Synthetic Organics)

5.1 INTRODUCTION

The Texas-Louisiana shelf is the most heavily developed area of offshore oil and gas drilling and production in the world. Consequently, alterations in the chemical environment due to oil and gas activities have been widely studied there. This chapter discusses nutrients, trace metals, hydrocarbons, synthetic organics, and radionuclides on the Texas-Louisiana shelf and neighboring areas. The discussion of nutrients is part of a general description of the water masses of the area; related topics of temperature, salinity, and dissolved oxygen have been discussed in Chapter 4. The other topics--trace metals, hydrocarbons, synthetic organics, and radionuclides, are of special interest in evaluating marine pollution resulting from human activities (including oil and gas operations). They are also of more general interest, because the study of their sources, distribution, and transformations can reveal much about chemical pathways in the marine environment and the major natural and human influences on that environment.

5.2 NUTRIENTS

Near-surface nutrient concentrations are low in open Gulf waters (Barnard and Froelich, 1981) and generally increase towards shore, especially in the regions of river runoff (Ho and Barrett, 1977). Factors influencing nutrient concentrations within the study areas include river discharge, coastal currents and winds, intrusions of open Gulf waters, upwelling, biological activity, rainfall, and proximity to coastal marshes (Ho and Barrett, 1977; Barrett et al., 1978; Brooks, 1980; Flint and Rabalais, 1980b; Dagg, 1988). The Mississippi River has a major influence on nutrient levels in coastal waters of the northwestern Gulf. Phosphate and nitrate levels near the mouth of the Mississippi River are at least 8 to 30 times greater respectively than levels found in open Gulf waters (Riley, 1937; Stallworth and Jordan, 1980; Dagg, 1988). Riley (1937) also found surface phosphates eight times higher off the Mississippi River than at stations located along the 18 m contour off eastern Texas and western Louisiana.

Within the study area, near-surface nutrient concentrations are negatively correlated with salinity; that is, the lower the salinity the higher the nutrient levels. As seen in Section 4.5.2, salinities near the coast generally increase from east to west; thus the general trend for nutrient concentrations is to decrease from east to west. As mentioned above, nutrient concentrations are generally high off the

Mississippi Delta, but at the western end of the study area, nutrient concentrations are typically low and representative of open Gulf surface water. Continental runoff can influence south Texas nearshore concentrations, especially in the spring (Flint and Rabalais, 1980b). In addition, after spring and summer phytoplankton blooms, nutrient concentrations along the Texas continental shelf become substantially reduced but are generally replenished during the fall, and reach their maxima in early to mid-winter (Flint and Rabalais, 1980b). In the deeper aspects of the study area, nutrient levels are relatively low in the upper 100 m of the water column, then generally increase in concentration and reach their maxima at around 400 to 600 m, which is within or slightly below the oxygen minimum layer (El-Sayed, 1972; Barnard and Froelich, 1981; Morrison et al., 1983; LGL Ecological Research Associates, Inc. and Texas A&M University, 1986). Table 5.1 presents ranges of nutrient concentrations that have been reported from the study area.

5.3 TRACE METALS

5.3.1 Sources of Trace Metals

Trace metals, unlike pesticides and other synthetic organic compounds, have both natural and anthropogenic sources. Continental rocks, soils, and organisms have variable concentrations of trace metals, some of which are released during weathering, decomposition and destruction of the parent materials. The released trace metals are transported from continents to the ocean, both in the dissolved form and associated with particles of various sizes. In addition to these natural sources of trace metals on the continents, natural sources within the sea itself might, in some cases, supply significant amounts of trace metals to nearshore areas. Human activities, both on the continent and in the sea, can also significantly influence the flux of trace metals to the nearshore marine environment.

For most nearshore environments, such as the area offshore Texas and Louisiana being considered here, most trace metals will come from the nearby land. Marine sources such as undersea volcanos and hydrothermal vents, authigenic mineral formation, manganese nodules, etc. can be neglected. Human activities in the marine environment, such as dumping of wastes, oil exploration and production operations, dredging, construction, and shipping must also be considered. In describing land sources for marine trace metals, a first consideration is their transport to the ocean. The metals can be transported by rivers, the atmosphere, or through human activities (e.g., pipelines, barges, etc.).

Rivers

Rivers are the main pathway by which both natural and pollutant trace metals reach the coastal ocean. Garrels and Mackenzie (1971) estimate that rivers account for 90% of the total seaward transport of dissolved and suspended material. The Gulf of Mexico receives about 69% of the total dissolved material (Leifeste, 1974) and 77% of the total suspended solids (Curtis et al., 1973) transported to the ocean from the continental United States. The Mississippi-Atchafalaya River, in turn,

Table 5.1. Ranges of nutrient concentrations reported for locations within the study area.

Location	Nutrient Concentration (mg/l)		
	NO_3-N	T-PO_4	SIO_4
Corpus Christi* 10 miles offshore	<0.001-0.01	<0.001-0.02	<0.01-0.28
Corpus Christi* 25 miles offshore	<0.001-0.01	<0.001-0.02	<0.01-0.1
Freeport† 10 miles offshore	<0.01-0.67	<0.01-0.12	<0.05-4.2
West of Sabine Pass§ 5 miles offshore	<0.1-0.25	<0.01-0.05	0.1-1.4
Calcasieu Pass§ 5 miles offshore	<0.1-0.5	<0.01-0.07	0.2-1.5
Timbalier Bay# 3-10 miles offshore	<0.1-0.2	<0.01-0.07	--
Barataria Bay** 5 miles offshore	--	<0.2-1.1	0.3-2.4
Louisiana Upper Slope†† Surface Water	<0.001-0.01	<0.001-0.01	0.03-0.05

* Flint and Rabalais (1980b).
† Hann and Randall (1980).
§ Comiskey and Farmer (1981).
# Dagg (1988).
** Barrett et al. (1978).
†† LGL Ecological Research Associates, Inc. and Texas A&M University (1986).

accounts for about 86% of all U.S. riverine transport to the Gulf of Mexico. To characterize the Mississippi River input is, therefore, sufficient to describe a large percentage of the input of continental material to the Texas-Louisiana shelf. Other rivers, such as the Brazos, cannot be ignored, but because they are much smaller than the Mississippi and because less is known of their trace metal contributions, they cannot be discussed in detail here. However, some of these minor rivers may have significant impacts on the immediate area around their mouths, particularly if they drain areas of unusual geology or areas of industrial activity.

Table 5.2 lists recent data on both the dissolved and particulate trace metal concentrations in Mississippi River water. Also given, for comparative purposes, are recent estimates of world average dissolved and particulate riverine trace metals. It can be seen that trace metal concentrations in the Mississippi River are generally less than or equal to those in world average rivers, in spite of the large and highly industrialized drainage basin of the Mississippi. The Mississippi River data are thought to be typical of the river in that the Trefry and Presley (1976b) data are weighted averages of four sampling periods seasonally spaced through 1974 and 1975, and the Shiller and Boyle (1987) data are weighted averages of six sampling times during 1982 to 1984. Dissolved trace metal concentrations in both of these studies were relatively constant with time, with copper and nickel showing only about a 25% variation, but chromium and molybdenum showing larger variations with time. It should be noted that other reported dissolved trace metal data for the Mississippi River are probably in error, due to sampling and analytical artifacts. The U.S. Geological Survey (USGS) data, as published each year in the USGS Water Data Reports, generally give much higher trace metal concentrations, which are judged to be unreliable based on the agreement between the data of Trefry and Shiller and the reputations of these two investigators.

It is generally recognized that dissolved trace metals are much more available to organisms than are particulate metals, and that certain forms of the dissolved metal fraction are more biologically available than others. For example, the ionic form of a dissolved metal is generally more available than a complexed form. Unfortunately, little work has been done on the form of metals dissolved in Mississippi River water, although Andren and Harriss (1975) were able to show that about 65% of the total 40 ng/l dissolved mercury was associated with a <500 molecular weight fraction and that <2% was present as methylmercury.

More work is needed on the forms of dissolved metals in Mississippi River water, including metal-organic complexing and related studies, because the chemical form of the metal determines its behavior and biological effects. Despite the acknowledged importance of the dissolved trace metal load of the Mississippi River, the suspended trace metal load is much greater for essentially all potentially toxic trace metals. Trefry and Presley (1976b) point out that 90% or more of the trace metals they studied were carried by particles. The behavior of these river-borne particulates as they mix with seawater is critically important to the ultimate fate of the trace metals, yet this is a subject that is not well understood. Metals can stay with the particles or

Table 5.2. Mississippi River dissolved and particulate trace metal concentrations.

	Metal										
	Cd	Co	Cr	Cu	Fe	Mn	Mo	Ni	Pb	V	Zn
	Dissolved Metal Concentration (µg/l)										
MISSISSIPPI RIVER											
-(Trefry and Presley, 1976b)	0.1	--	0.5	2	5	10	--	1	0.2	--	--
-(Trefry et al., 1986)	0.013	--	0.28	1.9	--	--	--	1.4	0.11	--	--
-(Shiller and Boyle, 1987)	0.013	--	0.07	1.5	1.7	--	1.1	1.4	--	1.2	0.2
AVERAGE RIVER WATER											
-(Martin and Whitfield, 1983)	0.02	0.2	1	1.5	40	8	0.5	0.5	0.1	1	30
	Particulate Metal Concentration (µg/g suspended matter)										
MISSISSIPPI RIVER											
-(Trefry and Presley, 1976b)	1.3	20	80	46	46,000	1,300	--	55	46	150	180
-(Trefry et al., 1986)	0.68	--	74	32	42,000	1,220	--	46	32	--	--
AVERAGE RIVER SUSPENDED MATTER											
-(Martin and Whitfield, 1983)	(1)	20	100	100	48,000	1,050	3	90	100	170	250
AVERAGE CONTINENTAL SOIL											
-(Martin and Whitfield, 1983) ,	0.35	8	70	30	40,000	1,000	1.2	50	35	90	90

become separated (desorbed) from them during river water-seawater mixing. Trefry and Presley (1976b) found little evidence of desorption of the trace metals they studied at the river mouth, but Hanor and Chan (1977) present evidence for desorption of barium. This subject needs more study.

Table 5.2 shows that many of the particulate trace metal concentrations in the Mississippi River are similar to those of world average river particulates and world average soils. Thus, neither the dissolved nor the suspended load of the Mississippi gives any clear indication of large scale pollutant influences, although cadmium, lead, and zinc seem to be somewhat elevated in both world average and the Mississippi River. As will be discussed later, Mississippi River Delta sediments also seem to be somewhat enriched in cadmium and lead. The pollutant (human-derived) nature of part of the lead carried by the Mississippi River is also demonstrated by a study by Trefry et al. (1985) that shows a decrease in the lead load of the river between 1975 and 1985, attributable to the decreased usage of leaded gasoline during this period.

Spatial and temporal variations in trace metal concentrations in Mississippi River suspended matter are small, according to data by Trefry and Presley (1976b) and Trefry et al. (1986), except at very low river stages when total suspended matter carried by the river is small and more organic rich. The total suspended load varies considerably from day to day and season to season, but its chemical composition remains relatively constant.

In contrast to the relative constancy in Mississippi River trace metal concentrations, Keeney-Kennicutt and Presley (1986) found considerable seasonal variation in both dissolved and suspended concentrations of copper, iron, lead, and manganese in the Brazos River. However, average concentrations were similar to those in the Mississippi River. The Brazos River data did indicate desorption of metals at salinities of about $5^{\circ}/_{\circ\circ}$, and this increases the amount of dissolved metal which is added to the Gulf by the Brazos River. Therefore, it may well be that the dissolved fraction of the trace metal load of many Texas and Louisiana rivers is more important than the particulate fraction, in contrast to the situation in the Mississippi River.

Atmosphere

Numerous studies of transfer of trace metals from continents to oceans through the atmosphere have been conducted in recent years (see for example Buat-Menard, 1986). It is generally recognized that atmospheric transport dominates over riverine transport for open ocean areas far from land. For some metals (such as lead) which have been common in automobile exhaust, atmospheric transport dominates even in coastal regions, especially near population centers. Other processes, such as cement manufacture and coal burning, can also add large amounts of some trace metals to the atmosphere, and for these metals the atmosphere can be a significant transport pathway to the coastal ocean, especially in areas remote from large rivers. Church et al. (1982) suggest that atmospheric sources of several trace metals are as great as riverine sources for the middle Atlantic coast (Delaware area) and Windom (1981) reaches similar conclusions about the Georgia area. Unfortunately, no data are available on atmospheric inputs of trace metals to the Texas-Louisiana shelf. Such inputs might be high, due to extensive industrial activity in this area, but may still be insignificant compared with the large riverine inputs to the area.

Human Activities

Human activities, both on land and at sea, are capable of greatly disturbing the marine environment. Such activities as mining, smelting, manufacturing, energy production and agriculture both can and do mobilize trace metals on the land, which results in enhanced transfer to the sea. Land based activities will not be discussed further here, as they have been covered in the discussion of the transport of trace metals from land to sea. Rather, this section will deal with human activities in the marine environment.

A number of human activities are potential sources of direct addition of trace metals to the study area. For example, ocean dumping of industrial wastes from ships or barges has been a major concern in some places. It is estimated that in 1973 more than 300 industrial facilities in the U.S. were ocean dumping their wastes and that about 5 million tons of wastes were so dumped. At that time, two sites in the Gulf of Mexico were designated as dumpsites by the U.S. Environmental Protection Agency (EPA): one about 90 km from the entrance to Southwest Pass of the Mississippi River in water depths of about 1,000 m, and another about 220 km south of Galveston, TX. About ten different kinds of industrial wastes were dumped at these sites between 1973 and 1978, when dumping was halted (Meyer and Warsh, 1981). It is unlikely that residues from this dumping are still affecting the area of concern in this report, but these dumpsites should be remembered and it should be recognized that industries could request resumption of ocean dumping in the future as land disposal becomes more expensive.

Waste disposal through industrial outfalls is closely related to ocean dumping. Some pipeline discharges of industrial wastes directly enter estuarine or marine waters. These are regulated by EPA but can, nevertheless, degrade the marine environment, especially in view of the difficulty of monitoring compliance with EPA permits. The Texas-Louisiana coast has numerous large industrial plants, petrochemical and others, many of which release wastes to the marine environment.

A listing of industrial outfalls in the Gulf of Mexico should be available through the EPA permitting procedure, but no such summary was available to the authors of this report. Therefore, we can only speculate that trace metal additions to the study area from industrial outfalls is likely to be significant. Certainly, such additions to the Houston Ship Channel are significant and have been documented (Hann and Slowey, 1972). It is essential that data be obtained on trace metal characteristics of industrial and municipal outfalls in the study area so that their influence is not confused with inputs from other sources.

In addition to ocean dumping and pipeline discharges of wastes, two other human activities potentially affect trace metal distributions in the study area. These are (1) petroleum exploration and production, and (2) dredging to create and maintain navigational channels. Both are large-scale activities along the Texas-Louisiana coast, and they are related in that much of the dredging is done in conjunction with petroleum production.

Over 30,000 offshore oil and gas wells have been drilled in U.S. Federal and State waters through May 1988 (American Petroleum Institute, 1982; Dodson and LeBlanc, 1988). Of these, more than 23,000 were drilled offshore Louisiana, and more than 2,500 offshore Texas. If offshore oil well drilling has had an effect on the marine environment anywhere, it should be evident in the area of concern in this report. A number of activities conducted during offshore drilling and production could affect trace metal levels in the area--for example, transporting and constructing drilling platforms, building pipelines, etc. However, the two activities that have received the most criticism are disposal of drilling muds (also known as drilling fluids) and disposal of produced water (also known as formation water, or brine) (Middleditch, 1981).

Drilling muds are essential to oil well drilling. Circulating the drilling mud through the well cools the drill bit, removes cuttings, coats the borehole to prevent fluid loss, controls downhole pressure and performs other functions. Drilling muds are essentially made from freshwater or seawater and bentonite (montmorillonite) clay. However, many chemicals are added to the mud to perform specific functions; as a result, over 1,000 brand name drilling mud additives are on the market. By far the most common additive is barite ($BaSO_4$), which is added to increase mud weight. This compound can amount to 90% or more of the dry weight of a typical drilling mud. Other common additives include chrome lignosulfonate, lignite, and sodium hydroxide. All of these additives contain finite amounts of trace metals; therefore, depending on the amounts and nature of additives, drilling muds contain variable concentrations of trace metals.

The concern that drilling mud disposal might pollute the environment with trace metals stems not from the fact that the muds contain high concentrations of trace metals (except for barium and possibly chromium) but from the fact that very large amounts of drilling muds are used. According to data on 49 wells given by Boothe and Presley (1985), a typical Gulf of Mexico oil well requires drilling mud containing about 600 metric tons of dry solids. Almost all of the used drilling mud is dumped into the sea during or at the conclusion of drilling. Multiplying the 600 metric tons per well released by the roughly 25,000 wells that have been drilled offshore Texas and Louisiana gives a very large number (15×10^6 metric tons) compared with the input of most other substances to the area. For example, the barium contained in the drilling mud that is dumped from the approximately 1,000 new wells that are drilled each year is slightly greater than the barium which is carried down the Mississippi River each year. In the case of barium, then, human activities are drastically changing the entire geochemical balance of the area through offshore oil well drilling. Other trace metals are present in much lower concentrations in drilling mud, but may in some cases be significant additives to local areas of the Texas-Louisiana shelf.

Another substance discharged to the ocean in large amounts is the formation water (brine) that is produced with petroleum and that must be separated from it on offshore production platforms. Over the lifetime of a typical production well in the Gulf, the amount of brine discharged is about equal to the amount of oil produced (Jackson et al., 1981). Since 1954, over 6 billion barrels of oil have been produced on Federal Outer Continental Shelf (OCS) lands off Texas and Louisiana (Risotto and Collins, 1986). Production from State lands and production since 1986 could add substantially to this volume. This enormous volume of brine could have added significant amounts of some trace metals to the Texas-Louisiana shelf, but the chemical composition of the brines is not well known. Most oil well brines are enriched in barium, boron, bromine, fluorine, iron, lithium, manganese, and strontium (Collins, 1975) but the concentrations of rarer and more toxic trace metals, such as cadmium and lead, are not well known. If the produced brines mix rapidly with the large volume of water over the Texas-Louisiana shelf, then even toxic metals would be rapidly diluted to harmless concentrations unless the metals are initially present in very high concentrations, which seems unlikely. Nevertheless, more study of the nature and fate of oil well brines is needed.

Dredging of navigational channels, and dredging to recover sand, gravel, and shell are major operations in the nearshore marine environment off Texas and Louisiana. In terms of volume, dredging is the largest single source of material that is dumped into the sea. During 1983, nearly 58 million m^3 of dredged material was dumped in 51 dumpsites around the U.S. coast. Of this total, 65% was disposed in the Gulf of Mexico--much of this off Texas and Louisiana (National Oceanic and Atmospheric Administration [NOAA], 1985). In many cases, the dredged material contains no harmful pollutants, especially if it is largely sand. In other cases, however, the dredged material can be quite polluted, especially when it is removed from harbors in industrialized areas. The dredged material is likely to be highly reducing and organic rich, and this can result in both high concentrations and high availability of trace metals. Failure to consider nearby dredging operations could seriously complicate interpretation of trace metal data for nearshore areas.

5.3.2 Distribution of Trace Metals

Dissolved in Water

Essentially all data more than ten years old, and much recent data on concentrations of trace elements dissolved in seawater, are high by factors of 10 to 1,000 or more. Bruland (1983) gives a good review of recent dissolved trace metal data and discusses problems with earlier data. He points out that only within the past ten years have sets of dissolved trace metal data for seawater been obtained that conform to known physical and biological oceanographic parameters. For example, a number of metals have now been shown to have "nutrient-like" behavior, whereas in older literature no correlations between trace metals and other oceanographic parameters could be found. It should also be noted that only a few investigators in the world have produced these "oceanographically consistent" dissolved trace metal data sets and even recent data from most investigators should be viewed with extreme skepticism. Researchers who are now able to produce high quality dissolved trace metal data possess no unusual skills or equipment unavailable to other investigators. They simply recognize the need for extreme care in sampling, storing and analyzing seawater and use clean room procedures throughout the process.

Unfortunately, few seawater samples from the Texas-Louisiana shelf have been analyzed for dissolved trace metals with the care required to lend confidence to the data. Data that are almost certainly of high quality have, however, been reported by Edward Boyle and his co-workers. Boyle is one of the most respected and experienced seawater analysts in the world. Boyle et al. (1984) report on two sets of samples near, but not on, the Texas-Louisiana shelf. These will be discussed here, as they are probably the highest quality data available for an area near the Texas-Louisiana shelf.

The first set of approximately 50 surface samples was collected along a cruise track extending from Miami, around the tip of Florida and across the Gulf of Mexico to near Bay Saint Louis, Mississippi. The cruise track crossed the Loop Current and a warm core ring. In spite of these different water masses and the long cruise track, there was almost no difference in concentrations of cadmium, copper, and nickel, the only metals determined anywhere in the open Gulf. The open Gulf surface samples gave concentrations of 0.082 ppb for copper, 0.11 ppb for nickel, and 0.0005 ppb for cadmium--values much lower than those reported by previous investigators (e.g., Slowey and Hood, 1971). However, the half-dozen surface samples collected a few miles off the Mississippi coastline gave higher values, averaging 0.5 ppb for copper and nickel and 0.02 ppb for cadmium. These coastal concentrations, obtained on samples collected in April 1981, are similar to values obtained by Shiller and Boyle (1983) on samples collected further west, in the Mississippi River plume. It thus seems that for these three metals, concentrations are fairly constant in surface coastal Gulf of Mexico water, and although the concentrations are considerably higher than open Gulf values, they are nevertheless much lower than values that have been reported by other investigators, as will be discussed below. Boyle et al. (1984) report cadmium, copper, and nickel data for a second set of samples collected in the northwestern Gulf of Mexico in December 1982. About 20 surface samples were taken off Texas and Louisiana, mostly in water depths of 100 to 1,000 m. Concentrations of copper, cadmium and nickel in these samples were very similar to those of the eastern Gulf samples, with an indication of higher values towards shore, but because no samples were taken nearshore, the increase was not as dramatic as that seen off Mississippi. Boyle et al. (1984) analyzed samples from a few hydrocasts and found increases in concentration of nickel, cadmium, and copper with depth, in response to organic matter degradation and nutrient release. For copper and nickel, however, the increases were irregular and at most a factor of two. Cadmium increased more sharply with depth and some deep samples were ten times richer in cadmium than average surface samples.

Other reported dissolved trace metal values for the Texas-Louisiana shelf are hard to interpret due to possible analytical artifacts. For example, Shokes et al. (1979b) report relatively uniform values for chromium (800 $\pm$ 200 ng/l), mercury (18 $\pm$ 4 ng/l) and zinc (1,700 $\pm$ 200 ng/l) for samples collected 5 to 6 km offshore western Louisiana. Surface and near-bottom water was similar in composition for these metals, but near-bottom water had manganese concentrations as high as 100 μg/l in contrast to 1 to 2 μg/l in surface samples. These high bottom-water manganese values indicate diffusion of manganese out of sediment pore water, a phenomenon that will be discussed further below.

The Shokes et al. (1979b) work was a preliminary phase of the Strategic Petroleum Reserve (SPR) Program, a major monitoring effort funded by the Department of Energy (DOE). Two principal sites were monitored during this five-year program: the Bryan Mound site, centered about 20 km off Freeport, TX in water depths of about 20 m, and the West Hackberry site, located about 11 km southwest of Cameron, LA in water depths of about 15 m. A large body of trace metal data resulted from these studies. As an example of the dissolved trace metal data, Table 5.3 gives data from Bryan Mound (Hann et al., 1985b) for the 1983 to 1984 sampling period and also summarizes previous data from the area. The authors state that the metal levels at the brine discharge (diffuser) were about the same as at the control stations (located about 5 km away) and about the same as pre-discharge values. The reliability of these data is difficult to judge because no actual data are given, only ranges, and in almost all cases the low end of the range is a "less than" value. It seems likely that the high end of the ranges given are in error. The iron, copper, and lead values given are higher than the highest values reported by Keeney-Kennicutt and Presley (1986) for the Brazos River estuary, which is near the Bryan Mound site. The Bryan Mound data are also much higher than data from the Mississippi River and plume discussed above (Boyle at al., 1984).

An example of trace metal data from the West Hackberry site is given in Table 5.4 (Hann et al., 1985a). Samples were collected at a site in the Intracoastal Waterway used for water to leach a salt dome, from the brine pond, from the diffuser site about 10 km offshore, and from a control site about 10 km from the diffuser site. The water column data given for West Hackberry are even more difficult to interpret than the data from Bryan Mound because the West Hackberry data are "total" water column data; that is, the sample was not filtered prior to acidifying to pH 2.5, and thus, part of the "total" metal was dissolved and part was associated with particles. As in the case of the Bryan Mound site, there is no indication that the brine disposal is influencing water column trace metal levels.

The role of diffusion from sediment pore water in controlling trace metal concentrations in overlying coastal seawater has been much discussed, but not enough work has been done to verify its importance for most metals. It seems clear that the phenomenon is important for manganese, which exists in the sediment as an oxide that is easily reduced to the soluble Mn^{+2} form. It was noted above that Shokes et al. (1979b) found high dissolved manganese in near-bottom coastal waters. Trefry and Presley (1982) calculated that manganese was diffusing from

Table 5.3. Range of soluble metal values observed in waters at Bryan Mound diffuser and control stations (From: Hann et al., 1985b).

	Metal Concentration (µg/l)			
	1983-1984 Period		1977-1983 Period	
Metal	Diffuser Area	Controls	Diffuser Area	Controls
Cd	<0.1 - 0.4	<0.1 - 0.4	<0.1 - 3.5	<0.1 - 2.4
Cr	<1 - 6	<1 - 8	<1 - 7	<1 - 5
Cu	<0.2 - 2.4	<0.2 - 1.9	<0.5 - 12.3	0.5 - 9.5
Fe	<1 - 5	<3 - 5	1 - 58	1 - 21
Hg	<0.2	<0.2	<0.1 - 0.7(4)*	<0.1 - 0.4
Ni	<1 - 2	<1 - 2	1 - 11	1 - 11
Pb	<1 - 1	<1 - 2	<1 - 6	<1 - 11
Zn	1 - 22	4 - 45(62)*	<1 - 42(87)*	<1 - 73

*( ) Represents a single value above listed range.

Table 5.4. Total metal concentration in water at the intake structure, brine pond and diffuser; in sediments at the intake and diffuser; and in biota at the diffuser at West Hackberry for 17 April 1984 (From: Hann et al., 1985a).

Station	Metal							
	Cd	Cr	Cu	Fe	Hg	Mg	Pb	Zn
	Water (μg/l)							
Intake	0.12	<0.5	1.7	230	1.0	36,000	1.2	5.5
Brine Pond	0.30	<0.5	2.4	290	<0.1	207,000	2.0	9.1
Diffuser	<0.03	<0.5	0.8	70	<0.1	955,000	<0.3	1.7
Control	0.06	<0.5	0.9	46	<0.1	1,353,000	<0.3	2.2
	Sediment (μg/g dry wt)							
Intake	0.18	13.4	8.0	11,900	0.043	3,310	10.0	31.0
Brine Pond	0.14	4.5	4.9	1,850	0.026	446	8.8	6.0
Diffuser	0.20	21.9	11.1	19,200	0.075	7,080	13.6	65.0
Control	0.24	31.8	16.8	26,100	0.090	10,400	17.9	88.0
	Biota (μg/g wet wt)							
Shrimp (*Penaeus setiferus*)								
Diffuser	0.004	0.06	5.5	16.0	0.03	458	0.12	15.2
Control	0.004	0.08	6.4	24.2	0.02	510	0.13	14.0
Snail (*Polinices duplicatus*)								
Diffuser	0.16	0.16	11.8	85.0	0.03	2,970	0.24	30.0

Mississippi River Delta sediments at a rate of 200 to 1,000 $\mu g/cm^2/year$. This diffusion depletes the delta sediments in manganese by about 50% and should affect bottom water manganese concentrations. Iron is also reduced and mobilized in the sediments, and high iron values are found in nearshore sediment pore water. However, iron flux out of the sediment is less than that of manganese, and fluxes of cadmium, nickel, lead, etc., are no doubt less yet, but this has not been well documented. The Bryan Mound project (Hann et al., 1985b) included trace metals in pore water work and some of those data are given in Table 5.5. It can be seen that metals are generally higher in the pore water than in the overlying water, which would lead to a diffusion out of the sediment pore water. More work is needed on this subject, because benthic organisms would be exposed to sediment pore water and might be affected by high trace metal concentrations or high levels of such chemicals as ammonia and sulfide, which also build up in pore water (Presley and Trefry, 1980).

Suspended in Water

Non-Living Particulate Matter. Most of the particulate matter brought to the sea by rivers settles out very near the river mouth, including even the very fine-grained clay material. Thus, a river plume, such as that of the Mississippi, is highly visible, with a sharp transition from muddy to clear water. Several factors contribute to this rapid settling of river particulates, including the lower current speeds in the ocean and the higher salinity in the ocean, which destabilizes and flocculates clay particles. Zooplankton in the ocean can also aid in sinking of clay particles by packaging them into fecal pellets which sink rapidly.

Total suspended matter (TSM) in the Mississippi, the most important river to our study area, varies considerably from season to season as a function of river flow. At normal and high flow rates, the river water usually has 100 to 500 mg/l of TSM, but can have as little as 10 mg/l at very low flow stages. Other Texas-Louisiana rivers can be expected to have similar TSM values and variability. In contrast to river TSM values, coastal seawater values are low and can vary due to variations in both inorganic and biological particles. Nelsen and Trefry (1986) found 6 to 7 mg/l TSM at a station very near the Mississippi River mouth when concentrations in the river were 180 mg/l. A few miles away at mid-shelf, TSM had dropped to 2 to 3 mg/l and at the shelf break to 0.3 to 0.5 mg/l. Open Gulf of Mexico TSM values are typically 10 to 100 μg/l, that is, 5 to 50 times lower than the shelf break values.

Most TSM values are obtained by filtering a discrete water sample of 100 to 1,000 ml. A problem with this procedure is that it can miss large particles, which sink rapidly and which may carry most of the mass that is sinking towards the seafloor. A second problem arises when the chemistry of the particulate matter is to be determined. If, as is usually the case, this is done by analyzing material caught on filters, the material may not be typical of what is sinking, and the filter is likely to hold so little material that great skill is needed to analyze it properly. For these reasons, there is relatively little information on the chemistry of suspended matter on the Texas-Louisiana shelf and some of the data that are available are of questionable quality.

Table 5.5. Range of soluble metal values in sediment pore waters at Bryan Mound (From: Hann et al., 1985b).

Metal	Metal Concentrations (µg/l)		
	Diffuser	1/2 Mile	Control
Cd	<0.1 - 0.2	<0.1 - 0.7	<0.1 - 0.6
Cr	<1 - 32	<1 - 80	<1 - 62
Cu	0.9 - 3.4(4.3)*	--	0.4 - 2(12.5)*
Fe	7 - 8,300	51 - 4,700	11 - 8,000
Ni	1.8 - 26	<0.5 - 24	0.5 - 26
Pb	<0.5 - 2(16)*	<0.5 - 0.7	<0.5 - 0.6
Zn	<0.5 - 14	2.3 - 28	1.7 - 11.2

*( ) Represents a single value above listed range.

Holmes et al. (1977) have reported data for a suite of suspended matter samples collected on the south Texas shelf, and Shokes et al. (1979b) reported data from off Cameron, LA. These data sets, and data for the Mississippi River Delta from Trefry and Presley (1976b) are given in Table 5.6. Both Holmes and Shokes report sporadically high (>200 μg/g) values for chromium, lead, and zinc, values which seem to be due to contamination during sampling. Holmes' values are generally lower than those of Shokes, which might reflect differences in bottom sediment between south Texas and Louisiana. Shokes sampled four times in one year and did find seasonal differences, but these are difficult to evaluate based on the available data.

Plankton. In addition to the problems discussed above regarding the sampling and analysis of non-living suspended matter, sampling and analysis of plankton presents further problems. Plankton must be sampled with a net, usually attached to a metal wire and pulled by a ship. Metal particles from the wire can be incorporated in the sample, as can paint chips and other debris from the side of the ship. Furthermore, inorganic matter suspended in the water is mixed with the plankton by the net. Few reliable data are available on trace element levels in study area plankton. The only major data set comes from the MMS South Texas Outer Continental Shelf (STOCS) baseline monitoring study, conducted from 1975 to 1977 (Boothe and Presley, 1979; Flint and Rabalais, 1981). Two of the four transects (I and II) sampled three times each year are within the study area for this report. Transect I starts just southwest of Port O'Connor and extends seaward on a line perpendicular to the coastline with the last station (number 3) at a water depth of 135 m. Transect II begins just southeast of Port Aransas and proceeds seaward in the same manner, with the last station (number 7) at 180 m water depth. Because of the mesh size of the sampling net used in this study, only zooplankton, predominately copepods, were collected and analyzed.

Table 5.7 summarizes the three years of zooplankton trace element data from the STOCS study, by station and transect. The overall levels of trace elements in the zooplankton are similar to those in other so-called pristine areas and suggest no significant trace element contamination in the STOCS study area. The only truly meaningful spatial effect observed was an increase in cadmium concentrations offshore. The reason for this trend is not clear, but the finding does not suggest any significant anthropogenic input of cadmium to the nearshore environment. Table 5.8 summarizes the average seasonal concentrations of trace metals in zooplankton observed during the STOCS study. Aluminum, iron, and nickel exhibited significant seasonal trends. These trends probably represent incorporation of clay-rich suspended matter by zooplankton. The concentration of suspended matter in the study area followed the same strong seasonal trend as that of aluminum and iron in the zooplankton.

Pelagic Organisms. Pelagic organisms, primarily fish in this discussion, are consumed by humans and thereby represent both an important economic resource and a public health concern. Consequently, there has been considerable interest in determining trace element body burdens in fish, including those from the Texas-Louisiana shelf. Several baseline and monitoring studies sponsored by the Bureau of Land

Table 5.6. Suspended particulate trace metal concentrations in the Gulf of Mexico.

	Metal Concentration (µg/g suspended matter)									
	Al	Cd	Cr	Cu	Fe	Mn	Ni	Pb	V	Zn
Coastal Texas*			(190)	60	18,000	340		(50)		
Coastal Louisiana†	--	--		45	50,000	1,400				(300)
Mississippi Delta§	88,000	(1.5)	84	56	46,000	1,230	56	(48)	--	(220)

*Holmes et al. (1977).
†Shokes et al. (1979b).
§Trefry and Presley (1976b).
( ) Indicates questionable value.

Table 5.7. Average concentrations of trace elements in zooplankton from the STOCS study (From: Flint and Rabalais, 1981).

			Metal Concentration (µg/g dry wt)									
Transect	Station	No. of Samples	Al	Ca	Cd	Cr	Cu	Fe	Ni	Pb	V	Zn
I	1	18	7,000	35,000	1.4	6.0	14	4,500	8.5	22	21	120
	2	20	2,500	30,000	3.0	4.5	21	1,900	6.0	13	9.5	125
	3	12	2,200	35,000	5.0	2.5	24	1,200	8.0	7.0	7.0	130
II	1	16	5,500	30,000	2.4	4.0	20	3,000	5.0	11	16	130
	2	20	4,000	65,000	3.5	3.5	190	2,100	7.0	11	16	180
	3	12	2,500	30,000	5.0	2.5	21	1,600	6.5	12	14	110

Table 5.8. Average seasonal concentrations of trace elements in zooplankton from the STOCS study (From: Flint and Rabalais, 1981).

		Metal Concentration (µg/g dry wt)									
Season	No. of Samples	Al	Ca	Cd	Cr	Cu	Fe	Ni	Pb	V	Zn
Winter	56	4,500	30,000	3.0	4.0	15	2,300	5.5	15	13	160
Spring	70	1,300	45,000	3.5	3.5	16	950	6.0	7.5	13	130
Fall	68	11,000	50,000	3.0	5.5	70	5,500	9.5	14	25	220

Management (BLM) incorporated trace element analysis of fish as a work element, including the previously cited STOCS (1975 to 1977) studies, the Topographic Features Studies (1974 to 1981) and the Central Gulf Platform Study (1978 to 1979). Another study providing data on trace elements in fish is the DOE/SPR Program.

It is difficult to compare these trace element data sets and evaluate their significance. As discussed above, variability in data quality among studies due to differences in procedures of sample collection and analysis is one important consideration. Another problem is that in many studies, not enough samples of the same fish species were collected at the same site over a sufficiently long time to establish a realistic range of trace element body burdens. This problem is especially true for the Central Gulf Platform Study and the SPR studies. Trying to discern geographical or temporal trends in body burdens by comparing levels in different species or in a few samples is usually counterproductive. A more reasonable approach is to determine trace element levels in the same species for one or more years at several sites over the area of interest. This approach adequately defines the trace element body burden and forms a reasonable basis for comparison with samples from outside the study area or with future samples from the same area.

The approach described above is best demonstrated in the STOCS study. Table 5.9 summarizes trace element data for four species of demersal fish collected annually from the STOCS study area over a three-year period. Many of the trace elements measured (cadmium, chromium, nickel, lead, vanadium) in fish muscle were present in very low concentrations (<0.1 ppm dry weight) and below the detection limits of the analytical procedures used. Still, even for the elements present in detectable concentrations, none of the species exhibited any significant geographical patterns in muscle tissue trace element levels, except for the nearshore species *Trachurus lathami* (rough scad), which varied in concentrations of aluminum and iron, apparently caused by the large seasonal variations in aluminum- and iron-rich suspended sediment in the nearshore area of the STOCS study area.

In an effort to compare trace element data among the studies conducted on the Texas-Louisiana shelf, Table 5.10 gives data for trace elements in fish muscle for two species that were each analyzed in three different studies. The trace element levels are surprisingly similar among the samples of each species, with the main exception being the higher chromium, nickel and lead values from the Central Gulf Platform Study--possibly due to analytical difficulties in that study. These three elements are in low concentrations in fish muscle and can easily be overestimated if the graphite furnace atomic absorption spectrophotometric technique used is not properly applied.

A striking aspect of the data on trace elements in fish muscle is the lack of any significant spatial trends. This situation could be the result of at least two factors. First, fish are mobile, and this mobility would tend to integrate trace element exposures at many sites and dampen any differences between them. Second, geographical trends in trace metal levels within the STOCS study area resulting from human

Table 5.9. Average concentrations of trace elements in muscle of demersal fish from the STOCS study area (From: Flint and Rabalais, 1981).

Transect	Species	No. of Samples	Metal Concentration (μg/g dry wt) Al	Ca	Cd	Cr	Cu	Fe	Ni	Pb	V	Zn
I	*Pristipomoides aquilonaris*	7	25	700	<0.05	<0.05	1.3	4.5	<0.07	<0.04	<0.10	13
	Serranus astrobranchus	4	30	1,100	<0.02	<0.05	0.95	3.5	<0.09	<0.03	<0.10	10
	Stenotomus caprinus	7	20	700	<0.06	<0.05	1.0	5.5	<0.10	<0.08	<0.20	14
	Trachurus lathami	2	19	800	<0.04	<0.03	2.4	9.5	<0.08	<0.05	<0.15	24
II	*Pristipomoides aquilonaris*	23	30	700	<0.03	<0.04	1.4	4.0	<0.08	<0.04	<0.30	8.5
	Serranus astrobranchus	8	30	1,900	<0.03	<0.05	0.90	3.0	<0.08	<0.05	<0.40	10
	Stenotomus caprinus	11	25	700	<0.05	<0.05	1.1	5.0	<0.08	<0.06	<0.10	13
	Trachurus lathami	8	30	750	0.10	<0.05	2.3	15.	<0.10	<0.06	<0.10	24

Table 5.10. Comparison of average trace element concentrations in red snapper (*Lutjanus campechanus*) and croaker (*Micropogon undulatus*) muscle tissue from different Gulf of Mexico studies.

Species	Study (Year)	No. of Samples	Metal Concentration (µg/g dry wt) Cd	Cr	Cu	Fe	Ni	Pb	Zn
L. campechanus	CGPS* (1978)	4	0.085	0.72	0.8	21.	0.82	0.19	13
	STOCS† (1976)	17	0.03	0.03	0.8	5.4	0.06	0.03	12
	TFS§ (1976)	16	0.01	0.03	0.8	5.2	0.06	0.03	12
M. undulatus	CGPS* (1978)	11	0.042	0.32	1.6	19.5	0.835	0.23	19
	SPR# (1977)	9	0.014	0.007	1.7	20.	0.045	0.124	20
	STOCS† (1976)	2	<0.01	0.04	1.4	8.	<0.11	0.06	11

*Central Gulf Platform Study, Tillery et al. (1981).
†South Texas Outer Continental Shelf studies, Boothe and Presley (1977).
§Topographic Features Studies, Boothe and Presley (1978).
#Strategic Petroleum Reserve studies, Science Applications, Inc. (1978).

activities are probably minimal. The levels of trace elements in fish do not suggest any significant pollution, at least on the Texas shelf. Variations in the very low natural background concentrations of many trace elements in fish muscle are difficult to document using current analytical techniques; however, elevated levels due to pollution would be detectable. There remains a need for reliable trace element data on fish and other pelagic species, particularly from the Louisiana shelf, which has by far the most petroleum exploration and production activities on the Gulf coast.

Seafloor Reservoirs of Trace Metals

Sediments. Marine sediments are usually considered to be the ultimate sink for trace metals added to the ocean, and that is certainly true after the trace metals have been buried a meter or so deep in the sediment column. However, trace metals can be returned to the water column from a few centimeters deep in the sediment column by mobilization processes that solubilize them. Either molecular diffusion or physical disturbance within the sediment can transfer the soluble metals to the water column. In spite of processes that can return trace metals to the water column or make them available to organisms living in the sediment, the sediment column represents, in general, a record of past and present trace metal inputs to the marine environment. As such, sediment data provides valuable information to environmental monitoring studies. An example of using sediment analyses for a historical perspective on pollutant inputs to Gulf of Mexico sediments is given by Presley et al. (1980).

One of the first large scale studies of the trace metal chemistry of coastal Gulf of Mexico sediments was that of Holmes (1973). He found highly variable concentrations of a number of trace metals, with high values in the clay-rich sediments off the Mississippi River Delta and low values in sandy and/or carbonate rich sediments from Texas and Florida. Trefry and Presley (1976a) analyzed 51 samples from San Antonio Bay and 72 samples from the Texas-Louisiana shelf for iron, manganese, lead, zinc, cadmium, copper and nickel. These samples too varied in trace metal content depending on clay, sand, and carbonate contents. In order to compare the sediments in a simple way, and to uncover possible areas of pollutant input, Trefry and Presley constructed scatter plots of trace metal concentration versus iron content. These plots gave generally good positive correlations for both bay and shelf sediments, as is shown in Figure 5.1(a) for zinc concentrations in shelf sediments. Some metals in some samples deviated from the linear relationship--for example, some lead samples [Figure 5.1(b)]. Trefry and Presley (1976a) attributed these deviations to pollutant input of lead in the Mississippi River Delta. Much greater deviations were found for obviously polluted areas such as the Houston Ship Channel. Several other pollution-related Gulf of Mexico shelf studies were conducted in Presley's laboratory following the Trefry and Presley (1976a) work--for example, Trefry and Presley (1976b), Presley and Trefry (1978), Presley et al. (1980), Trefry and Presley (1982), and Sheu and Presley (1986). None of these studies found highly polluted sediments, such as those found in the Houston Ship Channel or in some harbors, on the Texas-Louisiana shelf.

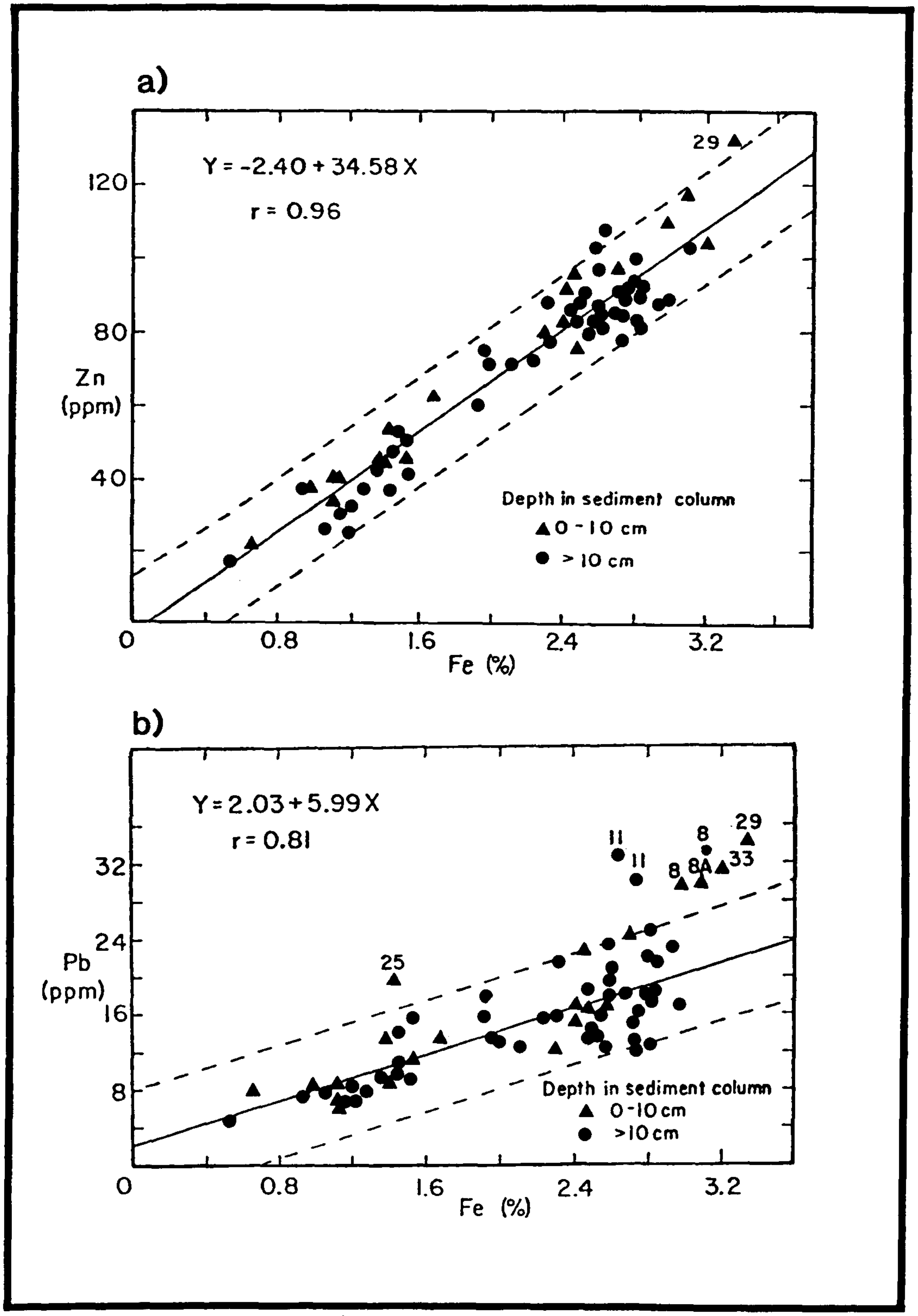


Figure 5.1. Scatter plots of a) zinc vs. iron and b) lead vs. iron for Mississippi Delta and shelf sediments with 95% prediction interval (From: Trefry and Presley 1976a).

In addition to generalized survey work along the Texas-Louisiana shelf, several studies have concentrated on areas immediately around offshore oil drilling platforms. Examples of these studies include Gettleson and Laird (1980), Tillery and Thomas (1980), Middleditch (1981), and Boothe and Presley (1985, 1987). Sediment concentrations of barium were determined in all of these studies, as it is the most abundant metal in drilling muds and therefore provides the most sensitive indicator of the presence of drilling mud in the sediments. Most of the sediment studies also included chromium, as it too can be present in higher concentration in drilling mud than in normal shelf sediment. Some studies included nickel and vanadium, two metals common in petroleum, and some studies included trace metals generally recognized to be highly toxic, such as cadmium, mercury, and lead.

The sediment sampling and analysis program conducted by Boothe and Presley (1985) on six drilling sites in the northwestern Gulf of Mexico was the most intensive such study yet conducted and included several novel features. Sediment cores were collected at 40 stations around each site: 36 stations in a regular circular pattern within 500 m of the site, and four stations on a circle 3,000 m from the site. Sediment type at each station was described in terms of sediment texture and concentrations of organic carbon, calcium carbonate, aluminum, and iron. The influence of drilling activities was characterized by determining sediment concentrations of elements known to be major constituents of drilling muds (e.g., barium) and of trace elements of environmental concern (i.e., cadmium, chromium, copper, lead, mercury, and zinc). Exploration, development and production sites in both shallow and deep water were studied to determine how the amount of drilling, water depth and elapsed time between cessation of drilling and sampling influence the characteristics of surrounding sediments (<500 m).

The Boothe and Presley (1985) study was evidently the first study in which an accurate, three-dimensional mass balance of discharged (excess) barium was determined. This approach estimates all excess barium present in the top 21 to 31 cm of the sediment column sampled within 500 m of each study site. The barium mass balance data clearly shows that only a small fraction of the total barium used (i.e., <1.5% nearshore, <12.0% offshore) was present in near-drillsite sediments. The same is presumably true for similarly behaving drilling mud components. The length of time between cessation of drilling and sampling had little effect on the percentage of the total barium used in drilling activities that was present in sediments near the drillsites. Multiple regression analysis suggests that the distribution of excess sediment barium observed among the six drilling sites is controlled largely by water depth (as an indicator of the magnitude of sediment resuspension and transport) and the total amount of barium used in the drilling activities. In terms of total excess barium, the effect of multiple wells on near-drillsite sediments was directly additive. Discriminant analysis suggested that statistically significant ($p < 0.01$) barium enrichment (greater than twice background levels of 200 to 700 ppm dry weight) existed in surface sediments even at 25 of the 30 control (3,000 m) stations studied.

Despite the large amounts of drilling mud components used at the six drill sites, the more pervasive sediment perturbations attributable to drilling activities were largely restricted to deep-water development and production drilling sites. These two sites had by far the largest total excess (discharged) barium values among the study sites.

Statistically significant elevations in surficial sediment mercury concentrations (i.e., within 125 m of the drillsite, 4 to 7 times mean control levels of 24 and 43 ppb dry weight) were observed at two sites. Barite containing a trace amount of natural mercury contamination is the most likely explanation for these observations. The concentration of mercury in the barite required to cause the elevated sediment mercury levels observed is only 1 to 3 μg mercury/g of barite. Little or no significant elevation in other trace metals was observed. Trends in chromium levels in near-site sediments were largely controlled by the clay content of the sediment, and elevations above control levels were infrequent (patchy) and generally less than twice expected concentrations.

Another study described by Boothe and Presley (1987) was conducted at a drilling site 19 km off Corpus Christi, TX. In this study, sediment was sampled before, during, and after drilling in a "bullseye" pattern around the drill site. The trace metals barium, cadmium, chromium, copper, iron, manganese, nickel, and vanadium were determined. Barium and chromium were the only elements showing significant changes in concentration with both sampling time (before, during, or after drilling) and distance from the drilling site. Lead increased from 19 ppm before drilling to 32 ppm during and after drilling--a small but significant increase. Nickel showed concentrations of 26, 25, and 30 ppm before, during, and after drilling, and the other metals showed no changes that could be attributed to drilling.

The Buccaneer Gas and Oilfield near Galveston, TX was the site of a major three-year environmental study that included analysis of sediment for trace metals (Anderson and Schwarzer, 1979; Tillery, 1980). This study showed concentration gradients in barium, cadmium, chromium, copper, lead, manganese, strontium, and zinc in surficial sediments that decrease with distance from oil well platforms.

Another platform monitoring study was the previously cited Central Gulf Platform Study funded by the Minerals Management Service (MMS) and conducted by Southwest Research Institute in 1978-1979 (Tillery and Thomas, 1980). In this study, 20 platforms and 4 control sites were examined offshore Louisiana in water depths of 20 to 100 m. Four of the platforms were "primary sites" and 16 were "secondary sites". At the primary sites, samples were taken at 100, 500, 1,000 and 2,000 m in four directions from the platform, whereas at the secondary sites, samples were only taken in one direction from the platform. This restricted sampling scheme makes it much more difficult to document influences by the platforms than in the study by Boothe and Presley (1985). Suspected analytical problems in the Central Gulf Platform Study also limit the usefulness of the data. Concentrations of trace metals were found to be similar to those reported by Trefry and Presley (1976a) and to decrease with distance from platforms, at least for some metals (barium, cadmium, chromium, copper, lead, and zinc) and at some platforms.

A large number of Texas-Louisiana shelf sediments were analyzed in conjunction with the DOE/SPR Program, the dissolved trace metal component of which was discussed above. Sediment trace metal data for the West Hackberry site (10 km off Cameron, LA) are given along with water data from that site in Table 5.4. Although this data set is for only one sampling period during the five-year program, the values given are typical for the site and typical for other northwestern Gulf of Mexico shelf sediments. Sediment data for the Bryan Mound site (20 km off Freeport, TX) are given in Table 5.11 for four different sampling periods during 1983 to 1984. These values are lower than most other reported values for Texas shelf sediment, but this is due primarily to the analytical procedure used rather than to a real difference in sediment type. The data were obtained by leaching the sediment with 1 N nitric acid, rather than a more rigorous leach. The data show little difference between control and diffuser sites and little change with time, except for lead, which seemed to increase slightly throughout the project (1978 to 1984).

One of the largest, most systematic, and highest quality trace metal data sets for the northwestern Gulf of Mexico shelf and upper slope is the unpublished data set of Boothe and Presley. Nearly 100 stations were sampled during the period 1976 to 1984. At more than 50 of the stations, both surface and subsurface sediment samples were taken. All samples were analyzed by neutron activation analysis for barium and iron as well as other trace elements (e.g., chromium, cobalt, rare earth elements, etc.). Table 5.12 summarizes mean sediment barium levels as a function of iron concentrations (indicative of sediment texture) in various regions of the Texas-Louisiana shelf and slope.

As discussed previously, the northern Gulf of Mexico is the most heavily explored and developed offshore petroleum hydrocarbon region in the world. The majority of the more than 25,000 petroleum wells drilled in this region have been on the eastern Texas-Louisiana continental shelf (<200 m water depth) between the Mississippi River Delta (89.25°W Long.) and Morgan City, LA (91.5°W). Prevailing currents in this area are westerly, tending to disperse discharged barite (from drilling muds) mixed with native sediments alongshore to the western Texas-Louisiana shelf and cross-shelf over the shelf-slope break (200 m) to the deeper Gulf.

An estimated 250 metric tons of barium are discharged from each well drilled on the Texas-Louisiana shelf. This means that over 6×10^6 metric tons of barium have been discharged into the area since 1947 when offshore petroleum development began. If all of the barium was retained in the discharge area, then the mean surficial sediment barium concentration (<4 cm sediment depth) on the Texas-Louisiana shelf should be elevated >2,500 ppm above background levels (<700 ppm). Comparison of surface and subsurface (circa 1940) data suggests that elevated surface barium is a generalized phenomenon over the entire shelf and slope--a result that is consistent with the widespread drilling and the potential for sediment transport in this area. However, the surface

Table 5.11. Mean sediment metal levels at the Bryan Mound brine disposal site (From: Hann et al., 1985b).

	Metal Concentration (µg/g)*							
	8 Nov 1983		17 Feb 1984		10 May 1984		17 Aug 1984	
Metal	Diffuser	Control	Diffuser	Control	Diffuser	Control	Diffuser	Control
Cd	0.02	0.03	0.02	0.02	0.01	0.02	0.02	0.01
Cu	2.0	3.0	2.3	2.1	1.7	2.2	1.6	1.8
Cr	2.4	3.0	3.1	2.4	2.5	3.7	2.1	2.5
Fe	3,604	5,029	4,481	3,716	3,017	3,776	2,943	3,314
Ni	2.7	4.3	2.6	2.3	1.7	2.4	1.4	1.6
Pb	5.1	8.3	8.3	7.2	8.7	10.3	8.6	8.3
Zn	20.2	23.5	20.7	19.8	16.9	19.1	17.4	17.6
Hg	0.02	0.02	0.05	0.05	0.09	0.10	0.05	0.06

*1 N Acid leach.

Table 5.12. Sediment barium (Ba) concentrations in various regions of the Texas-Louisiana continental shelf and slope as a function of sediment iron (Fe) levels (From: Boothe and James, 1985).*

Area	Water Depth (m)	Depth Interval Range (cm)[§]	Mean Ba concentration ± 1 standard deviation (µg/g dry wt) for samples with range of iron concentrations indicated[†]				
			Fe <1.5%	Fe 1.5-2.5%	Fe 2.5-3.5%	Fe 3.5-4.5%	Fe >4.5%
Miss. River Susp. Matter[#]	---	---	---	307 (1)	394 (1)	460 ± 12 (4)	475 (1)
Eastern Shelf (Delta-91.5°W)	<200	0-2	620 ± 122 (3)	645 ± 95 (10)	600 ± 141 (16)	615 ± 179 (55)	555 ± 42 (13)
		8-29	---	---	420 ± 5 (2)	505 ± 13 (2)	495 (1)
Barataria Bay (89.75°W)	3	0-2	---	725 ± 48 (5)	---	---	---
		20-21	635 (1)	680 (1)	---	---	---
Western Shelf (91.5-94°W)	<200	0-2	320 ± 130 (9)	410 ± 94 (26)	545 ± 85 (30)	511 ± 74 (11)	520 ± 28 (3)
		11-15	---	390 (1)	512 (1)	---	---
Eastern Slope (Delta-91.5°W)	>200	0-2	---	---	470 ± 28 (12)	590 ± 111 (32)	565 ± 68 (13)
		5-20	---	---	415 ± 54 (2)	480 ± 69 (24)	483 (1)
Western Slope (91.5-93.6°W)	>200	0-2	---	535 ± 5 (2)	565 ± 199 (18)	1,000 ± 156 (4)	---
		5-21	---	245 ± 17 (5)	335 ± 29 (5)	445 ± 42 (9)	---
Abyssal Plain	3,350	0-4	---	---	290 ± 25 (5)	---	---

*All samples 500 mg, irradiated 14 h and counted 4,000 s with dead time <10%. Decay time was 10-24 days and sample to detector distances ranged from 4.3 to 9.3 cm. Total number of samples = 329.

†Number of samples in each barium/iron group is given in parentheses.

§Deeper sediment intervals (>4 cm) were deposited about 1940. This year predates the onset of offshore petroleum drilling on the Texas-Louisiana continental shelf by at least five years. This sediment dating is based on sedimentation rates calculated from lead-210 measurements made in this area. This sediment dating does not apply to the Barataria Bay subsurface sample.

#Only unfractionated (whole) Mississippi River suspended matter data are reported here.

elevations observed are generally much smaller (i.e., averaging <160 ppm) than predicted. A combination of large-scale transport of fine-grain sediment off the shelf and dissolution of discharged barite is the most likely explanation for the low retention of discharged barium in shelf sediments. On the eastern shelf, the general lack of a direct correlation between barium and iron is most likely due to discharged drilling mud barium retained in the sediments.

Benthic Organisms. Shrimp are the most important offshore fishery in the study area and as such have been frequently analyzed as part of various studies conducted in the northwestern Gulf of Mexico. The largest sample set is from the STOCS baseline study conducted from 1975 to 1977. Table 5.13 summarizes the trace element in shrimp muscle data for the two STOCS transects that fall within the study area for this report. No significant spatial trends in the data were detected for either species. *Penaeus setiferus* was collected only from the inshore stations, whereas *P. aztecus* was consistently collected from five of the six stations sampled on the two transects during the three-year study. Muscle trace element levels were not significantly different between the two species, and no strong correlations were observed between these data and corresponding sediment trace metal or potential prey organism variables. Aluminum and iron levels in *P. aztecus* muscle were strongly correlated, and both metals exhibited significant correlations with certain sediment texture variables. These results suggest that shrimp are assimilating sediment-derived aluminum and iron into their muscle tissue. Zinc levels in *P. aztecus* did exhibit a significant seasonal effect, with a fall maximum that probably reflects physiological changes in the shrimp prompted by seasonal environmental changes.

Table 5.14 compares the STOCS shrimp muscle trace element data with those from other monitoring studies conducted in the study area. As with the fish samples discussed above, the trace element levels are similar among the studies, with the exception of chromium, iron, lead, and nickel. As discussed above, the differences for nickel and lead are probably related to analytical differences among the studies. The differences in iron may be caused by the differential assimilation of sediment-derived iron, as suggested above in the STOCS study. A similar difference in shrimp muscle iron levels was observed in a rig monitoring study conducted off Corpus Christi, TX (Boothe and Presley, 1987). Shrimp collected during the last few days of drilling had muscle iron levels more than twice those in shrimp sampled before or after drilling. Enhanced iron solubility (bioavailability) in seawater, caused by soluble organic chelating agents in the drilling muds and/or large increases in suspended sediment resulting from drilling, is the most likely explanation for the observed increases. The data in Table 5.14 also shows that the trace element levels in shrimp are low and give no indication of any widespread trace element pollution in the Texas-Louisiana shelf area.

Despite the large number of shrimp samples analyzed from open shelf waters of the Gulf of Mexico, very few sessile benthic organisms have been analyzed. This is in spite of the desirability of analyzing organisms that are fixed to the bottom in the study area. Many oysters and clams taken from Gulf coast bays and estuaries have been analyzed, as

Table 5.13. Average concentrations of trace elements in shrimp muscle from the STOCS study area (From: Flint and Rabalais, 1981).

Transect/ Station	Species	No. of Samples	Metal Concentration (μg/g dry wt) Al	Ca	Cd	Cr	Cu	Fe	Ni	Pb	V	Zn
I/1	*Penaeus aztecus*	3	18	1,200	0.13	<0.05	25.	3.0	<0.10	<0.05	<0.07	45
	Penaeus setiferus	3	20	950	0.05	<0.05	21.	3.5	<0.10	<0.10	<0.05	50
I/2	*Penaeus aztecus*	7	20	1,100	0.08	<0.05	25.	4.5	<0.10	<0.07	<0.20	50
I/3	*Penaeus aztecus*	2	--	--	0.15	--	25.	--	--	--	--	50
II/1	*Penaeus aztecus*	5	36	2,500	0.08	<0.05	24.	3.5	<0.15	<0.15	<0.30	55
	Penaeus setiferus	8	25	1,500	0.05	<0.05	24.	2.5	<0.10	<0.10	<0.05	60
II/2	*Penaeus aztecus*	6	24	950	0.11	<0.05	25.	6.5	<0.10	<0.10	<0.10	50

Table 5.14. Comparison of average trace element concentrations in brown shrimp (*Penaeus aztecus*) and white shrimp (*P. setiferus*) muscle tissue from different Gulf of Mexico studies.

Species	Study (Year)	No. of Samples	Metal Concentration (μg/g dry wt) Cd	Cr	Cu	Fe	Ni	Pb	Zn
P. aztecus	CGPS* (1978)	12	0.12	0.32	24.	47.	0.91	0.17	54
	SPR† (1978)	5	0.17	0.17	26.	48.	0.70	<0.09	62
	STOCS§ (1977)	10	0.03	0.04	23.	5.	0.08	<0.05	53
P. setiferus	CGPS* (1978)	2	0.10	0.21	26.	25.	0.43	0.14	62
	SPR† (1978)	6	0.11	0.17	34.	41.	1.3	0.10	70
	STOCS§ (1977)	9	0.03	0.05	24.	5.	0.06	0.03	55

*Central Gulf Platform Study, Tillery et al. (1981).
†Strategic Petroleum Reserve Studies, Tillery (1980). West Hackberry Site.
§South Texas Outer Continental Shelf Studies, Boothe and Presley (1979).

will be discussed below, and these data, along with the shrimp and fish data discussed previously, will suffice to characterize macro-organism trace metal levels in the area. Organisms living on or in the open shelf sediments are generally too small to allow easy separation of clean tissue samples for analysis. For example, Tillery and Thomas (1980) report that they collected and analyzed 27 different species of organisms by trawling during the Central Gulf Platform Study, but only shrimp and fish were common enough to make comparisons between collection sites.

Tillery (1980) reports data on epibenthic organisms collected at the West Hackberry brine disposal site off Cameron, LA before brine disposal began (Table 5.15). Very few samples were analyzed, and the data are difficult to interpret. One epibenthic species (moon snail) from the West Hackberry site was analyzed during brine disposal. These data, as reported in Hann et al. (1985a) have been given in Table 5.4 along with water and sediment trace element data.

Although suitable benthic organisms for trace metal analysis are hard to find on the open shelf of the Gulf, an almost perfect organism is readily available in bays and shallow water areas; the commercial oyster, <u>Crassostrea</u> <u>virginica</u>. These organisms are relatively easy to collect and prepare for analysis, they have high concentrations of many trace metals (making them easy to analyze), and they are known to change in trace metal content in response to changes in trace metal concentrations in the environment. Even though these organisms are collected from outside the geographic area of main concern in this report, they can provide valuable information on potential transport of pollutants into the study area.

Table 5.16 gives median values for levels of some environmentally interesting trace metals in oysters, along with levels in water and sediment. The next-to-last column in Table 5.16 gives oyster metal levels divided by seawater levels to show the extreme, but variable, enrichment of all of these metals in the oysters. For example, silver is enriched in oysters by a factor of 1×10^6 over dissolved seawater values, and iron and zinc are even more enriched. Chromium and nickel, on the other hand, show lesser enrichment in oysters. The last column in the table compares trace metals in oysters with those in Mississippi River derived sediment. The concentrating ability of the oysters can be seen here too, as they are 43 times richer than sediment with respect to silver and 33 times higher in cadmium.

A large, three-year Mussel Watch program to analyze oysters was funded by the Environmental Protection Agency (EPA) during 1976 to 1978. Data from this program, which included the Atlantic, Pacific and Gulf coasts, can be found in Goldberg et al. (1983). These data suggest site-specific trace metal concentrations in oysters along the Gulf coast--that is, high and low values tended to repeat in the same places each year, with some exceptions. However, it was not possible to correlate high values with known point sources of pollution. The Mussel Watch program was dropped by EPA after three years, but was reinstituted by the NOAA in 1986, with an initial four-year funding commitment. The Gulf coast part of the NOAA Mussel Watch is being conducted by Texas A&M University, with B.J. Presley responsible for trace metal analyses.

Table 5.15. Trace metal concentrations in epibenthic organisms by season at the West Hackberry brine disposal site (From: Tillery, 1980).

			Metal Concentration (µg/g wet wt)												
Season	Species		Al	Ba	Cd	Co	Cr	Cu	Fe	Hg	Mn	Ni	Pb	Sr	Zn
Summer	Portunus gibbesii	Mean	347	115	0.46	2.57	1.12	6.00	182	IS	18.0	2.87	2.33	20.2	14
(I)	n = 2 (10)*	CV%	15	56	11	90	29	23	34	--	72	60	76	141	8
	Polinices duplicatus	Mean	31.6	12.5	0.13	<0.14	0.27	10.6	37	0.011	3.6	0.45	0.14	0.37	19
	n = 1 (6)*	CV%	--	--	--	--	--	--	--	--	--	--	--	--	--
Fall	Busycon contrarium	Mean	80.5	12.1	0.70	0.30	0.39	4.98	88	<0.006	2.8	0.39	0.34	<0.12	28
(II)	n = 1 (2)*	CV%	--	--	--	--	--	--	--	--	--	--	--	--	--
	Thais haemostoma	Mean	93	19	0.86	0.38	0.74	5.07	137	0.014	6.04	0.67	0.44	3.96	33
	n = 4 (19)*	CV%	20	16	59	10	51	12	17	35	16	28	20	12	5
	Cantharus cancellarius	Mean	60	32	1.53	0.40	0.74	17.0	75	IS	8.54	0.52	0.33	<0.12	21
	n = 2 (2)*	CV%	3	33	15	46	50	134	7	--	7	19	24	--	55
Winter	Portunus gibbesii	Mean	13	9.9	0.85	0.57	0.77	17.8	52	0.015	11.8	1.06	1.31	54	9.1
(III)	n = 8 (125)*	CV%	43	33	36	28	94	28	62	66	32	100	80	9	35
Spring	Callinectes sapidus†	Mean	640	157	2.17	0.62	1.20	244	893	0.044	99.4	3.31	2.65	580	81
(IV)	n = 7 (31)*	CV%	23	33	30	59	32	17	36	12	71	44	21	6	10

*n = Number of samples analyzed, ( ) = Number of individuals.

†Concentration in µg/g dry wt.

IS = Insufficient sample.

CV = Coefficient of variation (standard deviation as percent of mean).

Table 5.16. Trace metals in water, sediment, and Gulf of Mexico oysters.

Metal	ARW ($\mu g/l$)	ASW ($\mu g/l$)	ARP ($\mu g/g$)	MDS ($\mu g/g$)	AOY ($\mu g/g$)	AOY/ASW ($x10^{-3}$)	AOY/MDS
Ag	0.3	0.003	0.07	0.07	3	1,000	42.9
As	1.7	1.7	5	6.5	15	9	2.3
Cd	0.02	0.07	1	0.15	5	70	33.3
Cr	1	0.20	100	66	0.5	2	0.007
Cu	1.5	0.25	100	19	150	600	7.9
Fe	40	0.05	5%	3%	400	8,000	0.013
Hg	--	0.001	--	0.1	0.15	150	1.5
Ni	0.5	0.50	90	30	2	4	0.066
Pb	0.1	0.002	100	15	0.5	250	0.033
Se	--	0.15	--	0.3	3	20	10
Zn	30	0.40	250	90	2,500	6,250	27.8

ARW = Average river water dissolved (Martin and Whitfield, 1983).
ASW = Average seawater dissolved (Bruland, 1983).
ARP = Average river particulate (Martin and Whitfield, 1983).
MDS = Mississippi Delta sediment (Presley, unpublished).
AOY = Gulf of Mexico oyster average (Presley, unpublished).

Fifty sites along the Gulf coast from far south Texas to south Florida are being monitored, with three oyster stations at each site. Thirty-two of the 50 sites are in Texas and Louisiana. From each station, 20 individual oysters are collected and these are homogenized into a pooled sample. Thus, 150 pooled samples result. Data on these samples have been reported for the first and second years of the project (Brooks, 1987, 1988) and data from the third year will be available soon.

The large data set resulting from analyzing the NOAA Mussel Watch oysters for 17 different trace metals cannot be presented here, but a few observations on the data will be made in order to impart a flavor for what is being done. Silver concentration in oysters was very high (4 to 7 ppm dry weight) at Copano Bay, TX and at nearby San Antonio and Matagorda Bays during Year I of the program. During Year II, the Copano Bay site, which was highest in silver during Year I, was about 50% lower, but four other sites had higher silver concentrations than the Copano Bay site. The East Matagorda site was similar in concentration during Years I and II and was greatly enriched in silver compared with most all other sites. The other three sites from Matagorda Bay were not enriched in silver. Sabine Lake, TX was very high in silver (7.5 ppm) in Year II, but not in Year I. The south Texas areas of silver enrichment are generally areas of low population density and relatively little commercial activity. There are, however, several large isolated petrochemical plants in the south Texas (Matagorda) area, as well as a large aluminum refining plant (Alcoa). The Sabine Lake area is heavily industrialized and was enriched in several metals (silver, cadmium, copper) in Year II compared with Year I, but slightly depleted in others (chromium, iron, zinc). These large changes in Sabine Lake oysters (e.g., copper changed from a less-than-average value in Year I to a value more than three times greater than average in Year II, whereas zinc was very similar and above average both years) might be due to inputs of specific pollutants. Furthermore, such inputs could affect the offshore as well as the estuarine area, thereby confusing potential inputs from offshore oil wells.

Elsewhere in Texas, silver concentrations from the NOAA Mussel Watch program were variable, with no unusual values. To the east, a high silver value, about twice the Gulf average, was found at Vermilion Bay in central Louisiana in both Years I and II. Farther east, the concentration dropped drastically through the next five sites and reached a minimum at Barataria Bay, just west of the Mississippi River Delta. Moving eastward from Barataria Bay and the Mississippi River Delta, concentrations rose to a high point at Pass Christian, MS in Year I and Breton Sound, LA in Year II, then exhibited both high and low values in Florida.

Barataria Bay, LA and the surrounding bays, which had low concentrations of silver in oysters, have probably been more physically disturbed by human activities than any other bays on the Gulf coast. These are areas of extensive petroleum development, as well as widespread dredging and channel cutting. Furthermore, these bays are directly downstream of the Mississippi River outflow, which is usually considered to be a major source of pollutants to the Gulf of Mexico. Why, then, is silver so low? Also, is this apparent anomalous behavior seen only in silver concentrations? The second question is easy. Several other metals show distribution patterns almost identical to that of silver (e.g., cadmium, copper) in both Years I and II data; other metals (e.g., iron, chromium, selenium, mercury) show similar, but not identical patterns. The first question is more difficult. Something about the muddy, frequently stirred Louisiana bays may be keeping the concentrations of some trace metals in oysters low. Perhaps the large amounts of fine-grained clay from the Mississippi River effectively competes with the oysters by adsorbing dissolved metals. The clay itself would not become greatly enriched in trace metals due to dilution by its large mass and would not be a clear indicator of pollution.

The idea that the amount and/or kind of suspended material in the water might control the concentrations of trace metals in oysters is one of several possible explanations for the pattern seen. It is also possible that local anthropogenic inputs influence trace metal concentration patterns, even though such inputs have not yet been identified. As noted above, it is interesting that oysters from Sabine Lake, TX were greatly enriched in copper in Year II compared with Year I, and also in silver and cadmium, but not in iron, mercury, lead and other metals. Other anthropogenic looking values include high mercury at some Florida sites and higher silver and copper at the Galveston Bay Yacht Club and Breton Sound Sable Island sites. It is possible that some of the tissue metal concentrations are influenced by the oysters themselves through natural processes that are unrelated to pollution. This possibility will be considered as the Mussel Watch program continues, as will attempts to identify specific point sources of pollutant inputs. Any new program dealing with pollutant inputs to the Texas-Louisiana shelf should be coordinated with the ongoing Mussel Watch program.

5.3.3 Transport and Transfer of Trace Metals

Processes that transport trace metals into the study area have been discussed in Section 5.3.1 and transfer of trace metals has been discussed briefly in Section 5.3.2. However, a separate section on transport and transfer seems warranted to emphasize the importance of these processes and to emphasize again that the study area cannot be considered in isolation where trace metals are concerned.

High concentrations of trace metals in some component of the environment within the study area might well be the result of some activity (e.g., oil well drilling, dredging, etc.) within the area. On the other hand, some activity outside the area may be producing metals that are then transported into the study area. The importance of the Mississippi River as a transporter of trace metals was discussed earlier in this report, and other rivers are also important. It should also be noted, however, that the amount of water transported into the Gulf of Mexico from the Caribbean is more than 800 times greater than the Mississippi River inflow. Of course, an almost equal volume of water exits the Gulf, but if some process removes trace metals from the water while it is in the Gulf, concentrations in the Gulf of Mexico would be increased.

Several mechanisms can remove dissolved trace metals from seawater and transfer them to other reservoirs. For example, plankton can extract dissolved trace metals, which can then be transferred up the food chain or to the seafloor. Similarly, dissolved trace metals can be absorbed on clay particles and therefore transferred to the seafloor. The reverse transfer, from particles to water (desorption) is also well documented. No attempt will be made here to explain, or even to list, all the possible transfer pathways by which metals could move into, within, and out of the study area. It is sufficient to note here that such transfers do occur and that they must be considered in evaluating trace metal distributions within the study area.

5.4 HYDROCARBONS

There are two important sources of hydrocarbons to the marine environment: biogenic and thermogenic. Biogenic hydrocarbons are produced by biological systems. Included are the large quantities of methane produced by anaerobic bacteria and the trace quantities of non-volatile hydrocarbons ($>C_{14}$) found in most biological systems. Marine and terrestrial organisms synthesize normal alkanes (predominately with an odd number of carbon atoms, branched alkanes, some branched alkenes, and sometimes small quantities of aromatics). Although considerable literature exists concerning biogenic hydrocarbons, this summary will be restricted to petroleum hydrocarbons. The majority of studies involving petroleum hydrocarbons deal with the immediate and long-term effects of catastrophic events such as oil spills. This emphasis is the result of the deleterious effects of large amounts of oil in a restricted area and the relative ease of analyzing for petroleum hydrocarbons in spill situations.

For the purpose of this summary, petroleum hydrocarbons are defined as those hydrocarbons resulting from thermogenic processes within the sedimentary unit. They are released to the marine environment either by natural or anthropogenic processes. Thermogenic hydrocarbons consist of saturated compounds with straight, branched, isoprenoid and cyclic members containing 1 to 50 (or more) carbon atoms and aromatic compounds containing 1 to 4 (or more) rings. Among the variety of techniques used to characterize oil, gas chromatography (GC) is probably the most widely used for environmental analysis because of the great deal of information obtained from a single sample. The range of compounds analyzed by gas chromatographic techniques depends on the procedure. Gaseous (C_1 to C_5) and volatile (C_5 to C_{14}) hydrocarbons are usually determined by purge and trap or equilibration techniques. Non-volatile hydrocarbons are determined by solvent extraction in conjunction with column chromatography, which is used to separate specific type fractions. Most non-volatile techniques determine saturates containing 15 to $\approx$32 carbon atoms and aromatics with 2 to 4 rings. Although other techniques are employed to measure hydrocarbons, GC in conjunction with mass spectrometry (GC/MS) is the most diagnostic analytical method. Few studies measure the full range of petroleum hydrocarbons (e.g., gaseous, volatile and non-volatile hydrocarbons).

A number of parameters have been suggested for identifying petroleum hydrocarbons. Gaseous hydrocarbons of thermogenic origin contain significant concentrations of C_2 to C_4 saturates. Petrogenic hydrocarbons generally have $C_1/(C_2+C_3)$ ratios smaller than 50, whereas biogenic hydrocarbons have $C_1/(C_2+C_3)$ ratios >1,000. Thermogenic gases can also be characterized by carbon isotopic compositions. The production of volatile hydrocarbons by biological processes is minor. All measurable quantities of volatile hydrocarbons appear to be thermogenic or pyrolytic in origin. Various parameters are indicative of non-volatile petroleum hydrocarbons, including the following:

- The presence of an unresolved complex mixture (UCM) of hydrocarbons (i.e., petroleum has a much broader and tremendously more complex collection of compounds).
- A homologous series of compounds in which the sequential members are of approximately equal abundance (i.e., compounds with consecutive even and odd numbers of carbon atoms).
- The absence of olefinic compounds (except in refined products).
- A greater abundance of both cycloalkanes and aromatic constituents compared to alkanes.
- Ratios of pristane/phytane, pristane/C_{17} and phytane/C_{18} (e.g., incorporation of oil within a sample shifts ratios due to increased isoprenoid concentrations).

When analyzing trace quantities of hydrocarbons, it is often difficult to differentiate between compounds of petrogenic and biogenic origin. This differentiation is complicated by weathering, degradation, and the wide variety of component patterns displayed by hydrocarbons from different sources.

This summary will be, as much as possible, specific to the northwestern Gulf of Mexico and restricted to petroleum hydrocarbons. No attempt will be made to summarize the larger literature on methodologies, fates, and biological effects of hydrocarbons in the marine environment. Several comprehensive works have attempted to summarize much of the existing literature on petroleum hydrocarbons [National Academy of Sciences (NAS), 1975; National Research Council (NRC), 1985]. In this summary, low molecular weight (C_1 to C_4), volatile liquid (C_5 to C_{14}), and high molecular weight hydrocarbons will be abbreviated low molecular weight hydrocarbons (LMWH), volatile liquid hydrocarbons (VLH), and high molecular weight hydrocarbons (HMWH), respectively.

5.4.1 Inputs of Petroleum Hydrocarbons

The major inputs of petroleum to the Gulf include natural seepage, offshore petroleum production and drilling operations, transportation activities, coastal and riverine additions, and atmospheric exchange or fallout (NRC, 1985).

Natural Seepage

Early reports indicated that the Gulf of Mexico was not a region of extensive marine oil seepage. Wilson et al. (1973) estimated a seepage rate for the entire Gulf at 500 barrels/day, 80% of which is along the Mexican shelf. This oil seepage rate is low, even though the Texas-Louisiana region is one of the most prolific areas of the world because the Gulf coast is young and has not been extensively deformed by folding (Link, 1952). Prior to very recent work, only two oil seeps had been reported for the Gulf, although Link (1952) has located over 85 oil seeps within 160 km of the Texas-Louisiana coast.

These early reports may have significantly underestimated Gulf oil seepage, considering recent finds of oil seepage on the Texas-Louisiana continental slope (Anderson et al., 1983; Brooks et al., 1984b, 1986a,b; Brooks and Kennicutt, 1987; Kennicutt et al., 1988a). These authors have reported a number of natural seep sites on the Texas-Louisiana continental slope that contain oil-stained sediment (as much as 15% by weight) and in some cases discrete oil seepage to the ocean surface. The MMS Continental Slope Study collected benthic tar, presumed to be from natural seepage, in most trawls (Brooks, unpublished data). Kennicutt et al. (1988b) reported nine oil-stained cores from the slope of the northwestern Gulf. Thus, there is ample evidence for macro-seepage of oil to the continental slope region of the northwestern Gulf.

However, micro-seepage can also add petroleum hydrocarbons to shallow marine sediments. Brooks and Kennicutt (1987) reported on petroleum hydrocarbons present in marine sediments from 1,954 cores (3,340 analyses) taken for surface geochemical exploration studies in the Gulf. Figure 5.2 shows several hydrocarbon parameters indicative of thermogenic hydrocarbons, plotted for six regions of the Gulf of Mexico. The amount of micro-seepage of thermogenic hydrocarbons into shallow sediments somewhat reflects the production patterns in the Gulf of Mexico, with Louisiana cores having the highest levels of thermogenic seepage. The Texas and Louisiana shelf (designated by "shallow" on the figure) have considerably less thermogenic hydrocarbons in shallow sediments than do the cores on the continental slope (designated by deep). Total UCM and n-alkanes on the Louisiana and Texas shelf averaged 17.7 and 8.0 ppm, and 1,228 and 571 ppb, respectively.

Seepage of gas appears to be a common occurrence in the northwestern Gulf. Acoustical methods have been used extensively to locate many areas of gas seepage (Albright, 1973; Geyer and Sweet, 1973; Tinkle et al., 1973). Many of the seeps are associated with faulting, in many instances along topographic highs in the Gulf. Gas seepage, unlike oil seepage, may have a biogenic origin. Brooks et al. (1974), Bernard et al. (1976), and Brooks et al. (1979b) have reported that of the 21 gas samples collected in the northwestern Gulf, only three had significant petrogenic components, based on molecular and isotopic analyses. The remainder contained principally biogenic hydrocarbons. Brooks (1975) estimated the addition to the Gulf of C_2 to C_4 LMWH from seepage at 2.4×10^9 g/year, and Sauer (1978) estimated VLH inputs at 2.4×10^8 g/year.

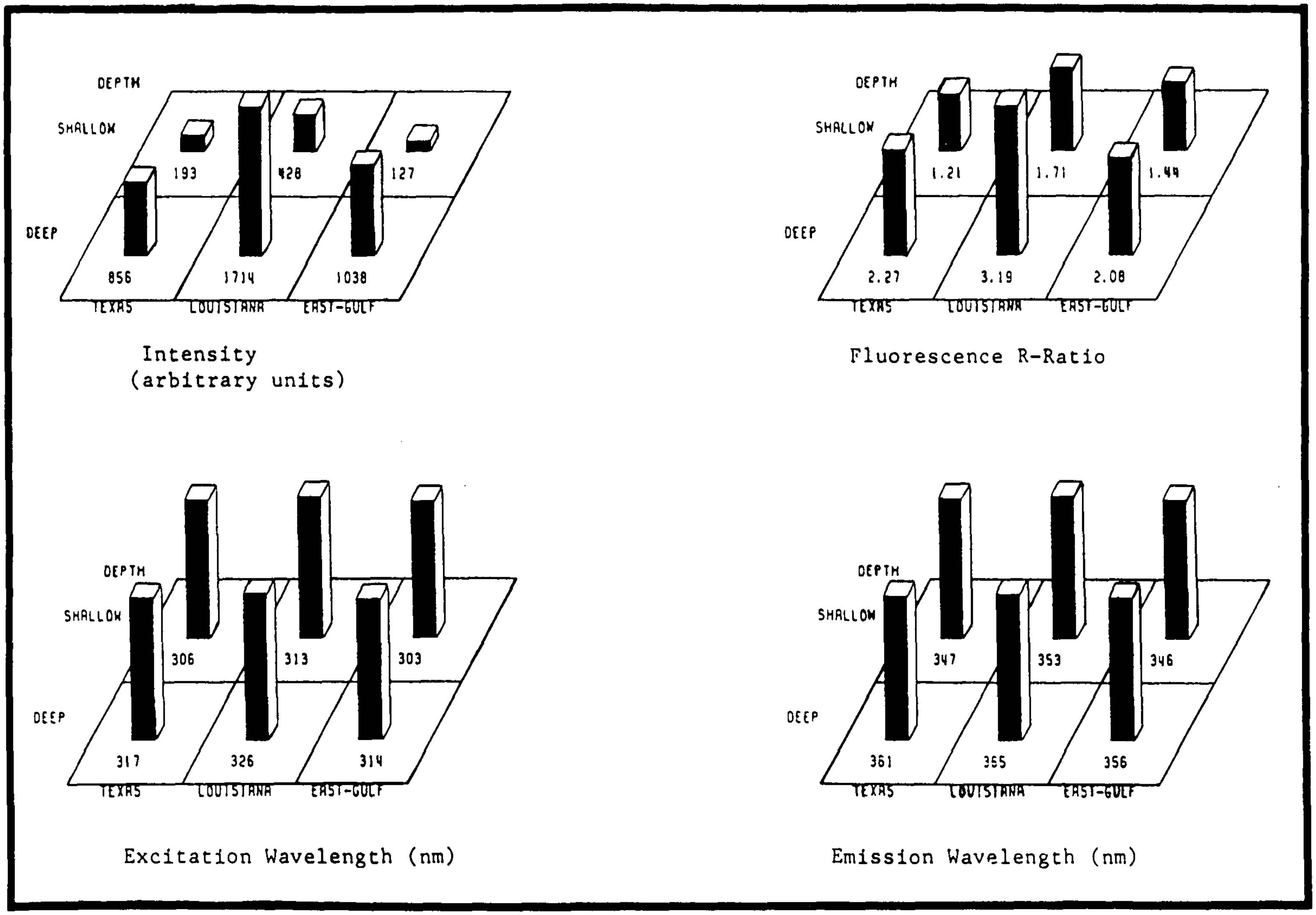


Figure 5.2. Regional averages for HMWH parameters in piston cores from the Gulf of Mexico. Shallow and deep represent cores on the continental shelf and slope, respectively. Numbers in each box represent average concentrations in µg/g dry wt (From: Brooks and Kennicutt, 1987).

Offshore Drilling and Production

The Gulf coast is an area of important petroleum exploration and production. The vast majority of the oil and gas production on the U.S. OCS region is along Texas-Louisiana. Over 90% of the oil and gas produced in the U.S. OCS comes from the northwestern Gulf of Mexico (Horvath, 1987). In the Gulf, mainly represented by the northwestern Gulf, there were 1,644 and 1,298 wells drilled in 1984 and 1985, respectively. Total Gulf OCS oil and condensate production in 1985 was about 0.3 billion barrels (Horvath, 1987).

Oil spillage into U.S. coastal waters is reported to the U.S. Department of the Interior by offshore operators. The spills classified as minor (<50 barrels) amount to about 10% of the reported oil losses, whereas major accidents (>50 barrels) contribute the bulk of the spilled oil. Large spills are the inevitable result of accidents where heavy equipment, flammable materials, large numbers of employees and large scale reliance on complex technology are involved. They result from platform fires, blowouts during drilling, ship-platform collisions, pipeline leaks, barge spills, hurricane damage, and similar incidents. The major cause of offshore petroleum production losses is pipeline accidents, mainly from ships dragging anchors. Estimates of major spills from Gulf OCS platforms between 1971 and 1978 range from 200 to 22,700 barrels/year, or 0.0020% of production (NRC, 1985). Although there have been several well blowouts and platform losses in Gulf waters, only five have resulted in oil and condensate losses estimated at 84,000 barrels of oil. The largest spill effecting the northwestern Gulf was the 1979 IXTOC-I blowout on the Campeche shelf that introduced 0.44 to 1.4 million tons of crude oil. Minor spills in Gulf OCS waters between 1971 and 1978 ranged from 500 to 1,500 barrels/year, or 0.00024% of production (NRC, 1985).

Formation waters (brines) are an important source of petroleum hydrocarbons to Texas-Louisiana shelf waters. Formation waters are produced along with oil and gas. During the lifetime of a Gulf oil producing site, approximately 0.6 to 0.8 barrels of formation water are produced per barrel of oil (NRC, 1985). Thus, about 500,000 barrels of brine are discharged daily into Gulf OCS and coastal waters. Onshore refinery-derived brines are a major contributor of petroleum hydrocarbons to some coastal areas. Shell Oil Company was reported to discharge some 200,000 barrels of formation water per day into Southwest Pass of the Mississippi River (Sport, 1969).

The hydrocarbons in formation waters are partially recovered in oil/water separators before discharge into the environment. However, this recovery is not complete and the oil remaining in solution is discharged into shelf and coastal waters along with the brine. The Federal Water Pollution Act of 1972 regulates these concentrations to <50 ppm of oil. Middleditch and West (1979) found HMWH ranged from 0.8 to 49 ppm in brine from a platform offshore Galveston. Gaseous and volatile hydrocarbons are unregulated in brine discharges and are found in high concentrations depending on the extent of equilibration with crude oil and the amount of dilution. Probably the most immediately toxic component of the brine are the large quantities of light aromatic hydrocarbons. Sauer (1978) estimated that about 6×10^8 g/year and about 2×10^9 g/year of VLH and HMWH are discharged into coastal and OCS Gulf waters from this source.

Underwater venting of hydrocarbons from offshore platforms is an important source of hydrocarbons to many OCS areas. Separation of oil and gas is conducted on offshore platforms to permit single phase transmission of oil and gas through separate pipelines. Depending upon the economics of transportation, the separated gas may either be transported for sale or disposed of by flaring or underwater venting. Natural gas associated with produced oil is sometimes uneconomical to transport. The associated gas at reservoir pressures is dissolved in the oil, but as the pressure is reduced during production, the gases separate from solution. This low pressure gas does not warrant sale, so it is discharged. The petroleum industry at one time considered underwater venting preferable to flaring because venting eliminates fire hazards and allows larger amounts of gas to be eliminated. U.S. Coast Guard data indicates that about 2×10^7 million cubic ft (MCF)/year of gas was vented or flared between 1974 and 1978, representing 3 to 4% of the gas produced (Brooks, 1979).

The venting of waste gas is widespread across the Louisiana shelf. The gases vented underwater contain, in addition to LMWH, significant amounts of aliphatic and aromatic VLH. Brooks (1975) and Sauer (1978) have reported large concentrations of LMWH and VLH around these discharge sites. Sauer (1978) estimated that 0.5 to 1.4×10^9 g VLH/year are contributed to coastal waters by underwater venting, based on the assumption that 70% of the 2×10^8 MCF/year is vented underwater and that 5 to 15% dissolves in the water column before venting to the atmosphere.

<u>Transportation Activities</u>

Worldwide transportation activities are the major source of petroleum hydrocarbons to the marine environment. Estimates of oil inputs from marine transportation range from 1.0 to 2.6 million tons/year (SCEP, 1970; Kash and White, 1973; NAS, 1975; NRC, 1985). The figures reflect that approximately 65% of world oil production is transported by sea. However, the Gulf of Mexico is not one of the heavily traveled tanker routes in the world. The major tanker route in the Gulf passes through the Yucatan Straits to one of the major northern Gulf ports (New Orleans, Houston, and Port Arthur handle over 50% of the traffic). In 1973, 76.5×10^6 metric tons of crude oil and 110×10^6 metric tons of petroleum products were transported to all ports along the upper Gulf coast.

Input of hydrocarbons from transportation activities include tanker and barge accidents, tanker and small boat ballast and bilge discharges, and harbor terminal operations. Just under half of the input from marine operations comes from tanker operational discharges (NRC, 1985). Almost all the tanker discharges from cleaning operations occur at sea, unlike other inputs from transportation, which usually occur in coastal waters. Sauer (1978) estimates that 0.15 to 2.0×10^{10} g/year of VLH are added to the Gulf from transportation activities. Brooks (1975) estimated the addition of LMWH at 6 x 10^9 g/year and C_5 to C_{10} at 4 x 10^{10} g/year. HMWH additions are probably in the same range as VLH additions.

Coastal Contributions

Coastal contributions of petroleum hydrocarbons include river runoff, urban runoff into coastal bays and estuaries, and industrial losses. Approximately two-thirds of the runoff in the contiguous U.S. is received into the coastal region of the Gulf of Mexico, mostly through the Mississippi River. NAS (1975) estimates a HMWH input of 0.2 x 10^{12} g/year for the Mississippi River, based on an annual silt load of about 5 x 10^8 metric tons and a petroleum hydrocarbon concentration of 400 mg/kg of sediment (dry weight) at the mouth of the Mississippi River. This corresponds to a HMWH concentration of 0.3 mg/l of runoff. Sauer (1978) reports VLH concentrations in the Mississippi River range from 0.5 to 1.0 mg/l. Assuming an average runoff of 8.4 x 10^{14} l/year, the amount of VLH contributed from river runoff is 4.2 to 8.4 x 10^8 g/year. LMWH contributions to the Gulf from runoff are estimated at 1.2 x 10^9 and 1.7 x 10^8 g/year for methane and C_2 to C_4, respectively.

Petroleum hydrocarbon inputs from other coastal contributions are nearly impossible to estimate because of the myriad of possible sources (e.g., storm sewer discharges, urban storm drainage, refineries, petrochemical plants, and pleasure craft). In 1975, 3.9 x 10^6 metric tons/day of oil (34% of the U.S. capacity) was processed in refineries along the Texas and Louisiana coasts. Large quantities of petrochemical products are also processed in this region (for example, 4.0 x 10^6 metric tons of benzene and 2.7 x 10^7 metric tons of toluene were produced along the upper Gulf coast in 1972).

Atmosphere

Although the total worldwide flux of petroleum-derived hydrocarbons to the atmosphere is estimated at 68 million tons/year, the amount reaching the Gulf of Mexico is difficult to estimate. SCEP (1970) suggested that 10% of the petroleum input to the atmosphere reached the ocean, but NAS (1975) revised this estimate downward to 1%. NRC (1985) estimated 0.3 million metric tons/year reached the ocean. Sauer (1980) estimated the amount of VLH reaching the ocean at 3 to 30 x 10^9 g/year.

5.4.2 Summary of Petroleum Hydrocarbon Components of Major Multidisciplinary Programs

A number of large, multidisciplinary studies have included investigations of petroleum hydrocarbons, recognizing this topic as a major environmental concern to the northwestern Gulf of Mexico. However, much of the information is found in final reports and is not available in the open literature. Also, much of the analytical data is antiquated relative to current high-resolution GC and GC/MS techniques. Included here is a summary of the hydrocarbon components of the major environmental programs in the northwestern Gulf of Mexico. Most of the petroleum hydrocarbon data in the Gulf of Mexico comes from these programs.

Environmental Studies on the South Texas Outer Continental Shelf (STOCS)

This four-year effort on the south Texas shelf was a consortium program conducted mainly by the University of Texas Marine Science Institute and Texas A&M University for the BLM. Baseline hydrocarbon measurements performed to provide BLM with a data base obtained prior to extensive oil and gas exploration were an important component of this three-year sampling (1975 to 1978) and one-year data analysis effort (1978/1979). HMWH were measured in water, zooplankton, and sediment (Parker et al., 1976, 1977a,b, 1978, 1979) and in benthic macroepifauna and macronekton (Giam and Chan, 1976, 1977a,b, 1978a; Giam et al., 1976a; Giam, 1979). LMWH were measured in water (Sackett, 1976; Sackett and Brooks, 1977a,b, 1978) and sediments (Sackett and Brooks, 1978; Brooks et al., 1979a,b; Bernard et al., 1978). These investigations represented fairly extensive spatial and temporal studies at 25 stations along four transects in the STOCS region.

The STOCS investigations indicated that the area was relatively pristine with respect to anthropogenic inputs of petroleum hydrocarbons. There were no trends in particulate or dissolved HMWH indicating petroleum contamination. Zooplankton samples obtained by oblique tows were the only component of the ecosystem shown to contain quantities of petroleum hydrocarbons. Petroleum contamination in the zooplankton samples was suggested by n-alkanes in the C_{25} to C_{32} range with an OEP (odd-even preference) near unity and the presence of aromatic hydrocarbons in some samples. Petroleum hydrocarbons in this fraction were attributed to micro tarballs in the samples. Figure 5.3 suggests an increase in the contribution of petroleum hydrocarbons to zooplankton samples during the STOCS study period, due most likely to oil tanker traffic. Macronekton showed no indication of petroleum hydrocarbons. Sediment analyses of both bulk sediment and benthic macroepifauna indicated minimal petroleum pollution. Petroleum pollution in the form of tarballs observed in the water column apparently did not contribute measurable quantities to the sediments. No petroleum hydrocarbons were detected around an exploratory drilling site on the shelf.

LMWH also indicated that the STOCS area was relatively "clean" with respect to anthropogenic hydrocarbons. However, an extensive area of possible thermogenic gas seepage was indicated on this shelf by LMWH anomalies in both water and sediment. A gas well blowout (Brooks et al., 1978) about 160 km to the north of the STOCS area may have caused high LMWH levels observed during the winter 1977 sampling.

Buccaneer Gas and Oil Field Study

HMWH were investigated at Buccaneer Gas and Oil Field (50 km south of Galveston) as part of a four-year project funded by the EPA through interagency agreement with NOAA and managed by National Marine Fisheries Service (NMFS) (Harper et al., 1976; Jackson, 1977; Jackson et al., 1978; Middleditch and Basile, 1979). Most HMWH results from the

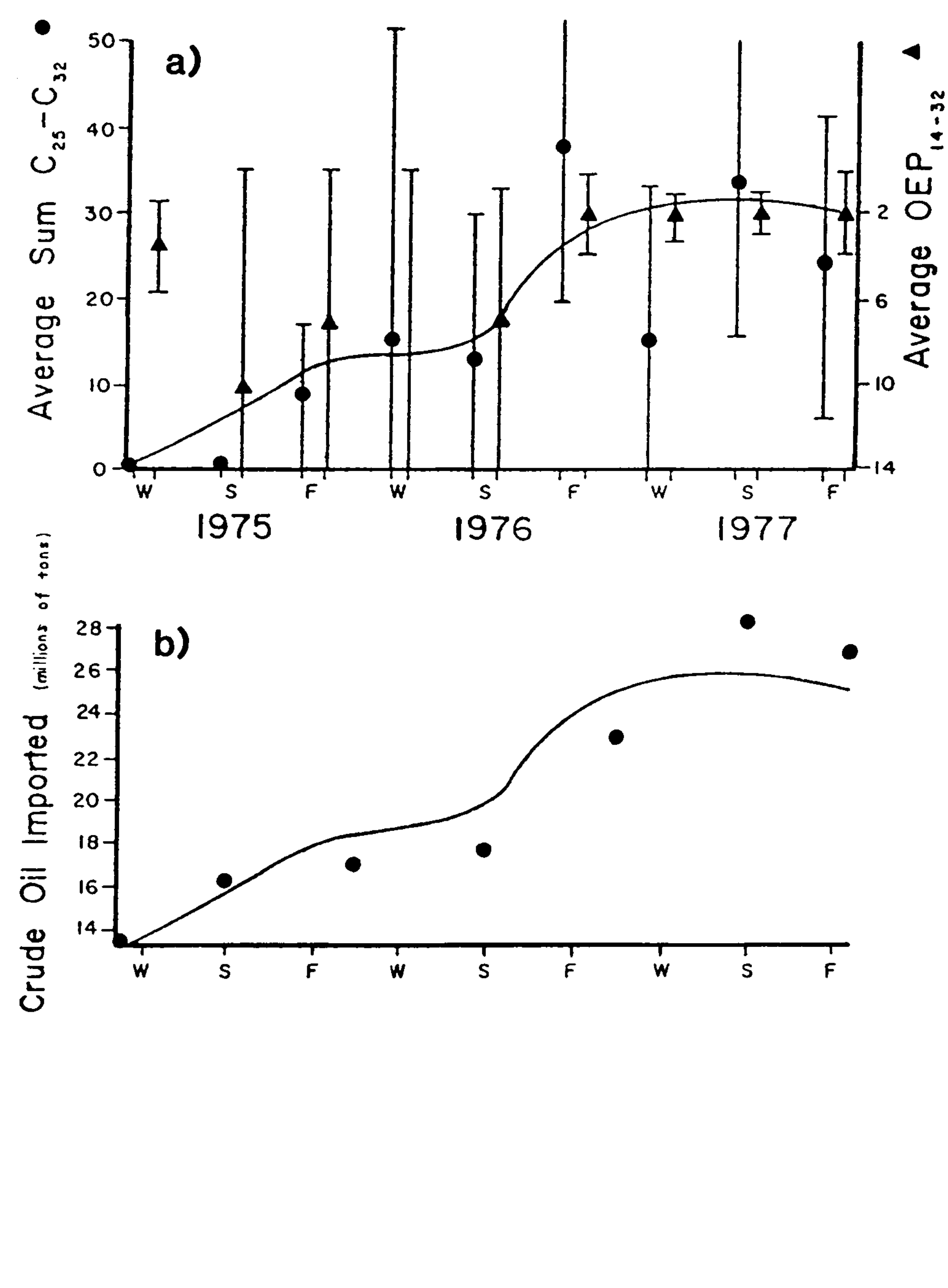


Figure 5.3. a) Average Sum Hi (C_{25}–C_{32}) and average OEP of Zooplankton samples for 1975 to 1977. b) Crude oil imported to the Port of Corpus Christi and Harbor Island 1975 to 1977. The curve from a) has been included in b) for comparison. (From: Parker et al., 1979).

first three years of the project can be found in the literature (Middleditch et al., 1977; Middleditch and Basile, 1978; Middleditch et al., 1978; Basile, 1978; Middleditch et al., 1979a,b,c,d).

The major source of petroleum contamination in the Buccaneer Field was discharged brine. The hydrocarbon components of the produced brine were similar to those of crude oil, ranging up to 29 carbon atoms and representing various members of the alkane and aromatic fractions. Dodecane to pentadecane were usually the highest concentration in the alkane fractions, whereas C_3 and C_4-benzenes were highest in the aromatic fractions. Benzene and toluene were the major VLH in the brine. Although about 200 g/day of LMWH alkanes were present in brine discharges from each of two platforms, a survey of the HMWH in the water indicated that petroleum contamination beyond 200 m of the production platform could not be ascribed to production discharges. Concentrations of alkanes in water samples were found as high as 43 mg/l, not significantly higher than reported for other areas of the Gulf. The petroleum discharged from the brine tended to float at the surface and be dispersed.

Most biota associated with the platform showed some petroleum contamination. Fouling mats on the platform legs contained low concentrations of oil near the air/sea interface (where periodic exposure to sunlight and air apparently promotes evaporation and degradation), but showed high concentrations of fresh oil at three meters. In contrast to the fouling mat, the barnacles contained weathered oil, implying an indirect exposure of oil possibly by filter-feeding on particulates in the water column.

Blennies from the platforms contained fresh oil, whereas the sheepshead contained weathered oil. This difference between fish species reflects their feeding habits (e.g., the blennies feed on the small organisms of the fouling mat, and the sheepshead eat barnacles). The free-swimming spadefish contained lower concentrations of weathered oil than either the blennies or sheepshead. Individual red snappers exhibited a wide range in oil contamination. Some specimens contained no oil, while the mean concentration of oil for all specimens examined was higher than that of the spadefish. The red snapper, in contrast to other species, is not habitat-faithful, indicating that those containing no oil were probably recent arrivals in the region of the Buccaneer Field, whereas those that had resided longer in the oil field had ingested sufficient quantities of contaminated prey to accumulate higher concentrations of oil. In all fish species, oil contamination was higher in the liver than in muscle tissue. Shrimp from the study area were not usually contaminated with oil. Five of nine surface plankton samples collected in the Buccaneer Field contained HMWH alkanes that were probably derived from petroleum.

The major pool of hydrocarbon contamination in the Buccaneer Field was the surficial sediments. Although concentration gradients around the platforms were always present, there was considerable day-to-day flux of these concentrations. This was attributable to periodic resuspension and deposition of surficial sediments. Surficial sediments contained up to 25 ppm of petroleum alkanes. On one occasion, concentration gradients of fresh oil were observed in the field at both production platforms, extending at least 30 m from the platforms. Alkanes in sediments from 0.7 to 11 km from the platforms were mostly of biogenic origin. Sediments outside the immediate vicinity of the production platform did not contain petroleum hydrocarbons.

Strategic Petroleum Reserve (SPR) Brine Disposal Analysis Program

As part of the Energy Policy and Conservation Act of 1975, the DOE implemented the SPR. This program plans to store 1 billion barrels of oil in solution-mined salt cavities near existing petroleum distribution facilities along the Gulf coast. Because large quantities of leachate and brine are produced by this operation, multidisciplinary programs were conducted by NOAA and private firms under contract to DOE at the brine disposal locations. Baseline HMWH measurements were performed at Big Hill, West Hackberry, Weeks Island, and Chacahoula by Science Applications, Inc. (Shokes et al., 1978; Shokes et al., 1979a,b,c) over a 12 to 14 month period in 1977/1978. As a continuation of these programs, ERCO/Energy Resources Company Inc. (Boehm, 1979b) through NOAA (NMFS) performed baseline hydrocarbon measurements at these same sites in 1978/1979. A few measurements at Caplin Sector sites (Weeks Island and Chacahoula) were performed by Carbon Systems, Inc. (through TerEco Corp. and Dames & Moore) in 1978. Texas A&M University measured HMWH at the Brian Mound site off Freeport, TX. Considerable baseline hydrocarbon data for shallow nearshore sites have been produced as part of these programs.

Unlike the STOCS and Florida OCS areas, which contain few indications of petroleum hydrocarbons, the nearshore brine disposal sites off the Louisiana-Upper Texas coast contained petroleum hydrocarbons in water, biota, and sediments. These shallow sites (generally less than 30 m deep) are influenced by Mississippi-Atchafalaya riverine inputs, local hydrocarbon inputs from petroleum operations, transportation activities, and biogenic hydrocarbons. At many of the sites, petrogenic hydrocarbons composed the dominant hydrocarbon fraction, indicating the effects of large-scale petroleum production on the Louisiana shelf.

Both whole seawater (i.e., dissolved plus particulate) and filtered seawater measurements by ERCO/Energy Resources Company Inc. and Science Applications, Inc., respectively, indicated a petrogenic component. Highest petroleum HMWH spectra were found in predominantly bottom waters. Two-ring aromatic molecules (i.e., naphthalenes), which are the more soluble aromatic components in many petroleum products, were dominant. The aromatic compounds were detected by fluorescence (ERCO/Energy Resources Company Inc.) and GC/MS (Science Applications, Inc.). Total hydrocarbon concentrations in seawater averaged 37 mg/l at West Hackberry to 5.8 mg/l at Weeks Island.

Analysis of macrocrustaceans from these sites indicated that petroleum contamination is sporadic and not site-limited. Petroleum contamination was revealed in many samples by the smooth distribution of n-alkanes, a homologous series of isoprenoid hydrocarbons, and an UCM. Shrimp HMWH averaged between 10 to 30 mg/g at most sites. Science

Applications, Inc. noted that most petrogenic hydrocarbons were not concentrated in the shrimp tail. A strong petrogenic nature was not observed in the fall (from either Texoma or Capline sites). This petrogenic pattern was not observed for anchovy. Most aromatic compounds were two-ringed (naphthalenes).

There were drastic sediment compositional differences between brine disposal sites. Sediments hydrocarbons averaged 1.7, 5.0, 14 and 37 mg/g at the Chacahoula, Weeks Island, West Hackberry, and Big Hill sites, respectively. These differences were also reflected in total organic content (e.g., clay content). A significant fraction of the sediment hydrocarbons appeared to be of petroleum origin, based on a large UCM, low OEP, and prominent occurrence of isoprenoids and aromatics. The UCM in most of these samples comprised 70 to 90% of the HMWH. Spectrofluorometry and GC/MS techniques revealed that sediments contained aromatic hydrocarbons from 2 to 5 rings with a possible mixed source of aromatics from combustion (pyrogenic) and petroleum.

Central Gulf Platform Study

This one-year program in 1978/1979, sponsored by the BLM and managed by Southwest Research Institute, was aimed at assessing the long-term, cumulative effects of production operations on the OCS environment. This study involved investigations at 20 platforms and four control sites extending from the Mississippi River Delta to about 160 km offshore and west over 320 km to a line south of Marsh Island. This area was selected to represent a range of production platforms: old and new, nearshore and deep, predominantly oil and gas producers, and wells with various amounts of discharge. Geochem Research Inc. measured C_1 to C_7 hydrocarbons in water column samples and sediment, whereas Southwest Research Institute measured HMWH in fish and bottom fauna. The results were outlined by Bedinger (1979).

Levels of C_2 to C_7 alkanes indicative of major LMWH and VLH contamination were observed at both control and platform locations. Surficial sediments around platforms had a large UCM and detectable amounts of aromatics. Surficial sediments from the study averaged 28.6 mg/g total hydrocarbons, but concentrations as high as 400 mg/g of aromatic hydrocarbons alone were encountered. Implications are that sediment contamination is occurring generally over the entire region with no readily discernible difference between platforms and controls or within samples around a particular platform. Bedinger (1979) suggests that the Mississippi River may be the significant source of petroleum products contaminating the area. Faunal data from the studies indicated no instances of UCM, although aromatic compounds (0.05 ppm or less) were found in some fauna (e.g., spadefish and sheepshead) that live in close association with the platforms. The most common aromatics detected were naphthalene and its derivatives.

Northwest Gulf of Mexico Topographic Features Study

This BLM program, conducted through Texas A&M University, involved surveys and monitoring of many of the hard banks on the Texas-Louisiana shelf. Most of the banks are located between the 50 and

200 m isobaths. Biological sampling was restricted to Spondylus (thorny oyster) and macronekton (Giam and Chan, 1978b,c). No indications of petroleum hydrocarbons were found in these samples, although certain banks such as the Flower Gardens are close to production operations. Sediments also showed no indication of petroleum contamination (Parker, 1978).

Distribution and Behavior of Drilling Fluids and Cuttings Around Gulf of Mexico Drilling Sites

This project, funded by the American Petroleum Institute (API), analyzed sediment around six offshore drilling sites in the northwestern Gulf of Mexico (Boothe and Presley, 1985). The hydrocarbon component of the study was minor, and only extract weights and relative petroleum contamination were provided in the final report. The High Island site exhibited the most petroleum contamination of the six sites investigated. Some of the West Cameron and Vermilion 321 stations contained moderate levels of petroleum. The contamination in surficial sediments at these sites was attributed to the use of diesel oil in oil-based mud systems and the use of lubricants in the drill muds. The other sites in Matagorda and Brazos lease areas showed little or no contamination. Highest extractable (methylene chloride/methanol) weights occurred in close proximity (a few meters) of the platforms, ranging up to 940 mg/g. In terms of extract concentrations, background levels of hydrocarbons were reported as 25 to 50 mg/g for sandy sediment, 100 to 200 mg/g for silty sediments, and 200 to 500 mg/g for clayey sediment.

Fate and Effects of Drilling Fluids and Cutting Discharges in Shallow, Nearshore Waters

This API-funded project is currently being completed by Continental Shelf Associates, Inc. and the Geochemical and Environmental Research Group at Texas A&M University. Aliphatic and polynuclear aromatic hydrocarbons (PAH) are being measured in surficial sediments around a multi-well production platform in 25 m of water, 22 km off Port O'Connor, in the Matagorda Island lease area. Data from this program are not currently available for public release.

Mussel Watch Programs

The EPA Mussel Watch program (1976 to 1978) included sampling of oysters at 26 stations along the Gulf coast for aromatic hydrocarbons. The general consensus of these studies was that oysters near known inputs of petroleum hydrocarbons exhibit aromatic concentrations that are elevated two to three orders of magnitude above those found in remote areas (Farrington et al., 1980, 1982). The relative abundance of phenanthrene and its alkylated analogues was used to distinguish between petroleum and pyrogenic sources. The alkylated analogues are less prevalent relative to the parent compound for pyrogenic sources. Sedimentary aromatic concentrations were found to be elevated near urban areas, over those found in more remote locations. Bivalves generally contained petrogenic aromatic compounds, whereas sediment hydrocarbons were more pyrogenic in nature at a given site. This difference was attributed to the biological availability of pyrogenic hydrocarbons.

The Mussel Watch program was reinstituted in 1986 as part of the NOAA Status and Trends program. The NOAA program in the Gulf of Mexico is being conducted by the Geochemical and Environmental Research Group at Texas A&M University. This four-year oyster and sediment monitoring effort at 65 Gulf Coast estuaries and bays is designed to assess and document the status and long-term changes in the environmental quality of Gulf of Mexico coastal and estuarine environments. In order to meet this goal, a series of systematic observations of selected chemical contaminants (e.g., hydrocarbons, trace metals, pesticides) in representative samples of bivalves and sediments has been undertaken. This program is the highest quality and most comprehensive environmental monitoring program that has been undertaken in the marine environment. Extensive intercalibration with the National Bureau of Standards is an integral component of the study. All PAH concentrations are determined using GC/MS techniques with limit of quantitation of individual PAH of 5 and 20 ppb for sediment and oyster samples, respectively.

Although the results of the Mussel Watch program are generally 5 to 6 km inside the OCS boundary, they are reported here because they are the best and most comprehensive data set from which to assess environmental quality in coastal waters of the northwestern Gulf of Mexico. The total polynuclear aromatic hydrocarbon (ΣPAH) concentrations in sediment and oyster samples from Corpus Christi to the Mississippi Delta are shown in Figure 5.4. At all the Gulf of Mexico sites, ΣPAH in the 1986 sampling ranged from <20 to 18,620 ppb (mean 536 ppb), and from <5 to 36,700 ppb (mean 507 ppb) in oyster and sediment, respectively. Although the concentration averages of PAH in sediments and oysters were nearly the same, the molecular distributions were quite different. Oysters predominantly accumulated lower molecular weight PAH, whereas sediments accumulated higher molecular weight PAH. It is possible that lower molecular weight, more water-soluble, PAH are available to the biota in higher concentrations. The PAH distributions in these coastal waters indicated a predominantly pyrogenic origin with only minor contributions from unaltered petroleum. The "hot spots" for PAH contamination in the Texas-Louisiana area were Galveston Bay, Yacht Club; Galveston Bay, Confederate Reef; and Barataria Bay, Middle Bank.

<u>Other Programs</u>

In response to concerns over the impact of oil spillage from the IXTOC-I blowout, MMS sponsored a study to assess the extent, if any, of damage produced in the offshore Texas benthic environments (Boehm et al., 1983; Boehm and Fiest, 1982a,b; ERCO/Energy Resources Company Inc., 1982). Sediment and biota were analyzed for petroleum hydrocarbons by spectrofluorometry, GC, and GC/MS. Relying on the data base produced by the STOCS program, no significant increase in hydrocarbon content was observed in surface sediments. Sediments contained chronic, low levels of weathered petroleum, anthropogenic saturated hydrocarbons, biogenic n-alkanes, and three- to five-ring aromatic hydrocarbons (1-100 ng/g of individual components). The presence of low-level petroleum pollution in penaeid shrimp was confirmed by GC/MS. Previous STOCS data had indicated that shrimp contained 10 to 70 ppb aromatic hydrocarbons.

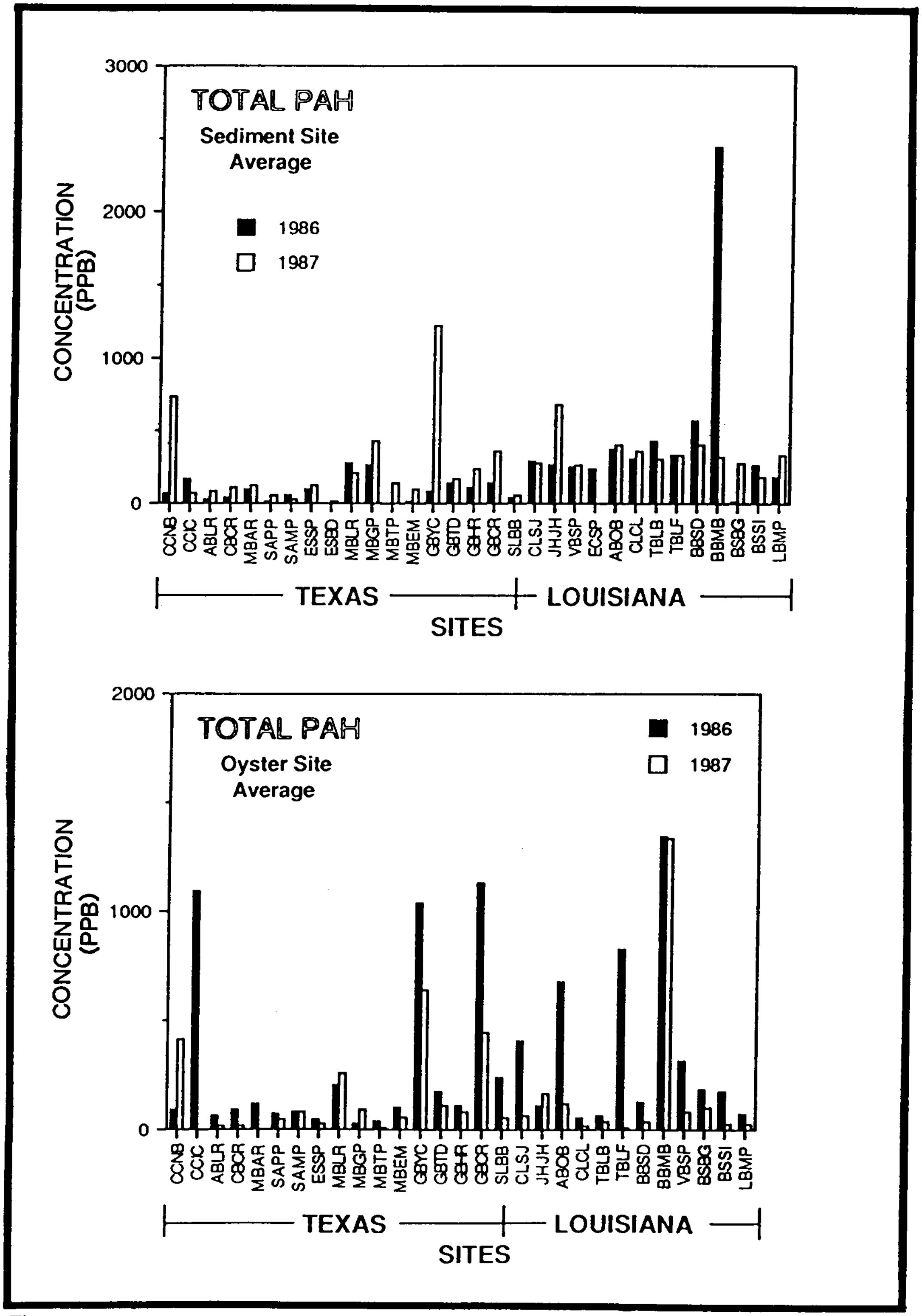


Figure 5.4. Concentrations of polynuclear aromatic hydrocarbons (PAH) at NOAA Mussel Watch stations from Corpus Christi to the Mississippi Delta. Values represent the mean of three samples at each station.

Currently, the MMS is sponsoring a Northern Gulf of Mexico Continental Slope Study. The sediment data from the 1983 to 1985 samplings were published by Kennicutt et al. (1987). They found the sediments of the Gulf of Mexico continental slope contain a mixture of terrigenous, petroleum and planktonic hydrocarbons (Figure 5.5 and Table 5.17). The relative amounts of these three inputs varied as a function of location, water depth, and time of sampling. The hydrocarbon concentrations measured were generally lower than those previously reported for shelf and coastal Gulf of Mexico sediments. Petroleum inputs were measurable at all sites sampled. Natural seepage was considered to be a significant source of hydrocarbons to slope sediments. Hydrocarbon concentrations varied by 1 to 2 orders of magnitude along a given isobath, due to changes in sediment texture and hydrocarbon input. In general, the highest aliphatic hydrocarbon concentrations were associated with the more clayish/organic-rich sediments. Aromatic hydrocarbons were below gas chromatographic detection limits at all sites (<5 ppb), but their presence was inferred from spectrofluorescence analyses, confirming the presence of petroleum related hydrocarbons at all sites.

5.4.3 Distribution of Petroleum High Molecular Weight Hydrocarbons (HMWH)

Water Column

Hydrocarbons exist in the water column in several forms. The first is in a particulate form floating on or near the surface, commonly called tar balls. Hydrocarbons also occur in the dissolved state, although solubilities for HMWH are extremely low (e.g., n-octadecane has a solubility in water of 6 ppb). Other possible states include absorption on marine particulates, and colloidal forms.

Tar Balls. Tar balls are found in most surface neuston tows in the Gulf of Mexico (Koons and Monaghan, 1973; Jeffrey, 1973, 1977, 1979; Jeffrey et al., 1973, 1974; Parker et al., 1979). Jeffrey (1979) determined that the average floating tar concentration in the Gulf of Mexico was 1.35 mg/m^2, based on 220 neuston tows between 1972 and 1976 on nine cruises. No apparent change in tar ball concentration was observed during this period. Highest tar concentrations were observed along the western portions of the Gulf. Koons and Monaghan (1973) estimated the standing crop of tar balls in the Gulf at about 2,000 metric tons (using a concentration of 1.0 mg/m^2), or about 20% of the organic matter in the top 5 cm of the water column.

Until the IXTOC-I well blowout, the two principal sources of tar balls in the Gulf were natural seepage and transportation activities. Jeffrey (1979) found that approximately 30% of the tar balls analyzed were tanker sludge residues, based on a bimodal UCM and a high percentage of high molecular weight alkanes. About 2% were identified as fuel oil residues, and 65% were crude oils from many origins. Only 20% of the floating tar had sulfur content greater than 3%, and these were found primarily in the western and southwestern Gulf. Based on the sulfur content of pelagic tars, Jeffrey et al. (1974) estimated that possibly as much as 60% of the tars did not originate from the upper Gulf

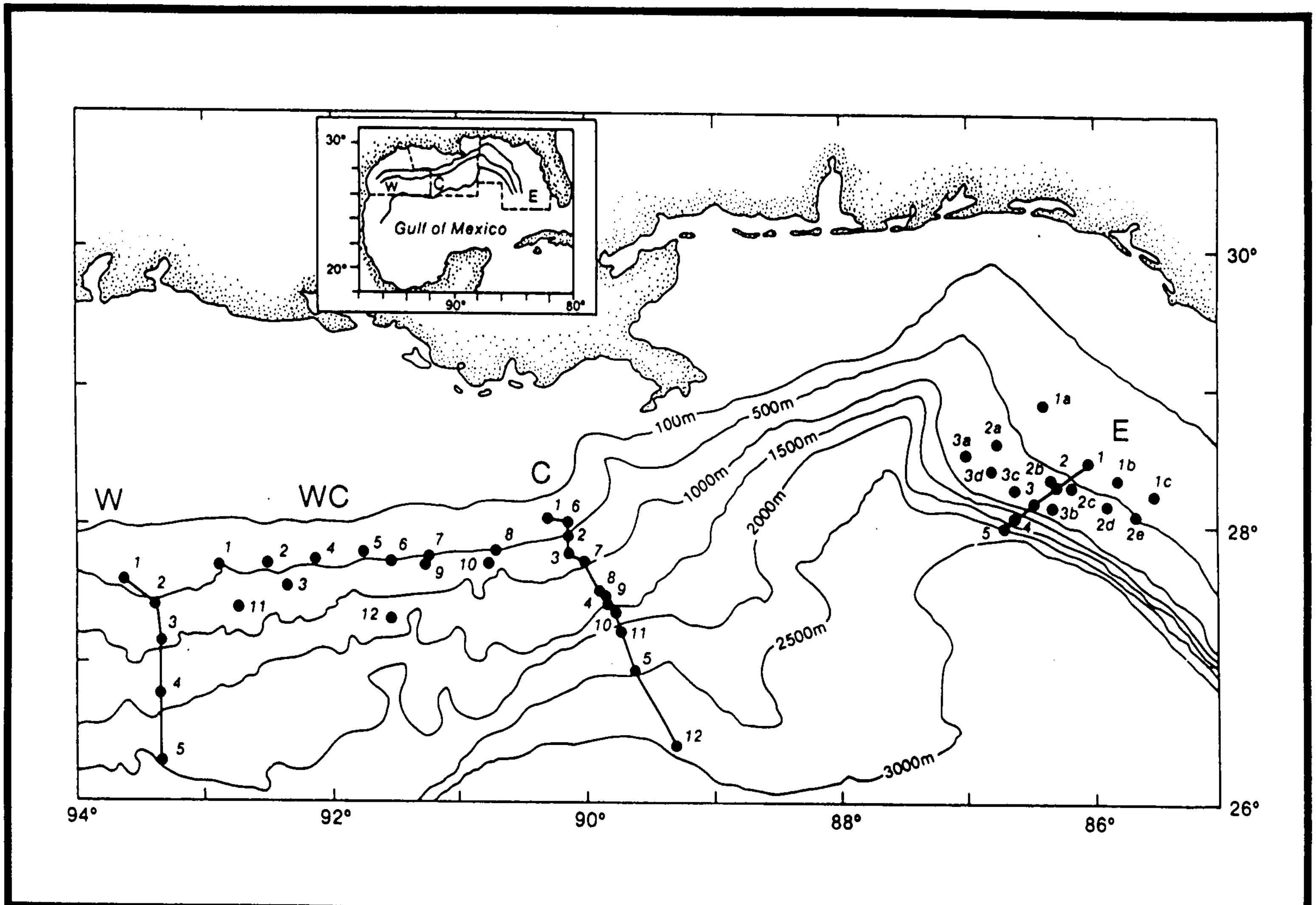


Figure 5.5. Sampling locations for the Northern Gulf of Mexico Continental Slope Study (From: Kennicutt et al., 1987).

Table 5.17. The averages and ranges (values in parentheses) for selected hydrocarbon parameters in Gulf of Mexico continental slope sediments (From: Kennicutt et al., 1987).

Cruise	Location (transect)	Extractable Organic Matter (μg/g dry wt)	Aliphatic Hydrocarbons (μg/g dry wt)	Aliphatic UCM (μg/g dry wt)
I	Central	28.4 (13.9-61.3)	1.6 (1.3-2.0)	23.3 (19.3-29.8)
II	Central	21.7 (18.0-25.2)	1.7 (1.6-1.8)	8.9 (6.0-14.0)
	Western	26.0 (14.0-55.2)	1.1 (0.8-1.3)	11.1 (5.2-11.4)
	Eastern	8.6 (7.6-10.9)	0.7 (0.5-1.0)	5.4 (3.2-7.3)
III	Central	18.1 (4.0-44.4)	1.4 (0.6-4.6)	9.7 (4.4-17.4)
IV	West/Central	30.0 (17.7-94.2)	0.9 (0.4-5.2)	16.8 (4.2-81.4)
V	Eastern	7.2 (4.7-13.4)	0.2 (0.1-0.4)	2.0 (0.5-5.0)

coast, but were probably foreign crudes. Parker et al. (1979) also attributes the petroleum HMWH found in zooplankton samples from the STOCS area to tanker activities. The higher tar ball concentrations observed in the southwestern Gulf are either the result of a large source in the region or floating tar is concentrated in the western Gulf by current patterns. Seepage is supported by the higher seep potentials predicted for the Mexican shelf (Wilson et al., 1973). Koons and Monaghan (1973) suggest that some of the tar balls they analyzed originated from seepage, based on similar carbon isotopic and compositional similarities.

Dissolved and Particulate. As indicated in the previous section, petroleum hydrocarbons were not typically observed in the water column in the STOCS area. Literature values for total hydrocarbons in the open Gulf range from 0.1 mg/l to about 75 mg/l (Parker et al., 1972, 1979; Calder, 1977; Jeffrey, 1977; Iliffe and Calder, 1974; Brown et al., 1973). There is generally a large decrease in HMWH between the surface and a depth of about 10 m (Brown et al., 1973; Parker et al., 1979), below which values are generally <1.0 mg/l. This may suggest that hydrocarbons are present as particulate matter rather than in true solution. In the STOCS area, higher concentrations of particulate HMWH at inshore stations were attributed to terrigenous input through direct addition of particles and increased in situ productivity.

Indications of chronic petroleum pollution in the open Gulf include low aromatic concentrations ranging from 1 to 3 ppb (Brown et al., 1973); 75 ppb of HMWH in the Florida straits containing a larger concentration of n-alkanes above C_{20} than other open Gulf samples attributed to tanker traffic (Iliffe and Calder, 1974), and an unresolved envelope in the gas chromatograms from approximately the C_{15} to C_{30} in open Gulf stations (Iliffe and Calder, 1974). Petroleum hydrocarbons were observed in the water column at the nearshore brine disposal sites and near production platforms (see Section 5.4.2). Parker et al. (1972) observed 18 mg/l and 6 mg/l of saturate and aromatic HMWH, respectively, near a tanker discharging ballast in the open ocean.

Biota

Analyses from the major multidisciplinary programs (see Section 5.4.2) indicate that biota from the northwestern Gulf are generally free of petroleum hydrocarbons, whereas HMWH have been found in association with biota at production platforms and nearshore brine disposal sites. Most of the petroleum HMWH associated with zooplankton appear to result from incorporation of tar balls into the samples (Calder, 1976; Parker et al., 1976). Zooplankton tend to accumulate hydrocarbons by assimilation, modification of dietary components, and direct incorporation of phytoplankton hydrocarbons. Milan and Whelan (1978) and Milan (1978) have reported on the assimilation of petroleum hydrocarbons in a salt marsh ecosystem exposed to steady state oil input. They found benthic organisms, oysters and mussels, demonstrated the greatest enrichment of petroleum hydrocarbons, while the free-swimming fish demonstrated the least petroleum enrichment. The discharged oil in this marsh ecosystem was first absorbed to subaerial marsh vegetation. Subsequent formation of petroleum-containing detritus appeared to be the major transport mechanism of petroleum into the ecosystem. Other reports of petroleum hydrocarbons in northwestern Gulf of Mexico biota represent a few isolated analyses. Parker et al. (1972) found petroleum hydrocarbons in Sargassum from the Louisiana shelf. Brooks et al. (1988) reported PAH concentrations in biota associated with deep water hydrocarbon seepage.

Sediments

Because hydrocarbons are among the most stable of the organic molecules, their presence in marine sediments is ubiquitous. The concentration of hydrocarbons in sediments is orders of magnitude higher than the concentrations above the sediments. STOCS sediments contain 0.2 to 2 ppm saturated hydrocarbons, a range that is lower than concentrations reported for most sediments on the continental margin (Parker et al., 1979). The STOCS sediments appear to contain less petroleum HMWH than do the eastern Gulf sediments, which contain petroleum HMWH in GC chromatograms. Petroleum HMWH contamination appears to be quite common on the Louisiana shelf, both at nearshore stations and in the OCS region. Many of the anthropogenic hydrocarbons in the marine sediments derive from terrigenous sources. An UCM is reported in many chromatograms from the OCS region. The UCM has been associated with weathered (physically, chemically and microbially) petroleum and pyrolytic sources from fossil fuel combustion. Therefore, flux sources can be quite varied (i.e., sewage, urban runoff, refined and crude petroleum, shipping traffic, seepage, air fallout of combustion products). Few techniques are available to address the problem of source differentiation other than GC/MS and possibly high pressure liquid chromatography methods. The literature concentrations in Gulf sediments are summarized in Table 5.18.

5.4.4 Distribution of Volatile Hydrocarbons

Although approximately 30 to 40% of crude oil consists of VLH, there is very little information available on their distribution in the marine environment. This is mostly a result of the difficult methodologies involved (Grob and Grob, 1971; Bellar and Lichtenberg, 1974; Grob and Zurcher, 1976; Sauer, 1978). The VLH are the most immediately toxic component of petroleum, which along with their high water solubilities, may make them as environmentally important as the PAH (Blumer, 1969, 1971; Holcomb, 1969; McAuliffe, 1977). Twenty-nine volatile hydrocarbons and seven volatile aromatic hydrocarbons are on the EPA "Priority Pollutant" list. Much of the marine research involving VLH has been concerned with laboratory studies on the exposure of water-soluble fractions of petroleum to marine organisms. Sauer and Brooks have reported most of the VLH distributions for the Gulf of Mexico (Sauer, 1978, 1980, 1981a,b; Sauer et al., 1978; Brooks et al., 1978, 1981, 1984a; Atlas et al., 1980), although Koons and Monaghan (1973) reported some early C_5 to C_8 distributions.

Sauer et al. (1978) and Sauer (1980) found that open ocean, non-petroleum polluted surface waters contained VLH concentrations of about 60 ng/l, whereas heavily polluted Louisiana shelf and coastal waters reached over 500 ng/l. Aromatic VLH accounted for 60 to 85% of

Table 5.18. Summary of Gulf of Mexico sediment hydrocarbon analyses (concentrations are averages, ranges in parentheses).

Location	Hydrocarbon Concentration (µg/g) Total HC	Saturated HC	Predominant Source[*]	References
Texas/Louisiana-coastal[†]	(20-190)		B/(P)	Smith, Jr. (1952)
Texas/Louisiana-coastal[†]	Low concentrations		B	Stevens et al. (1956)
Gulf of Mexico-coastal[§]	Biogenic waxes		B	Bray and Evans (1961)
Florida (Bay)-sandy sediments[§]	4.4	2.0	B	Palacas et al. (1972)
-muddy sediments[§]	86.0	30.0		
N.E. Coast-sandy sediments[§]	5.8	1.14	B/(P)	Palacas et al. (1976)
	(0.2-19.9)	(0.1-3.8)		
STOCS-coastal[§]	1.14	0.2	B/(P)	Parker et al. (1976)
(Before, during and after drilling activities)	(0.22-5.6)	(0.1-0.5)		
Texas/Louisiana-coastal banks[§]	(0.02-0.80)		B	Parker (1978)
MAFLA-nearshore Florida (<40 m)[§]	1.90	0.86	B	Boehm (1979a)
		(0.29-1.60)		
->40 m Florida[§]	1.39	0.83	B/(P)	
		(0.29-1.89)		
-Mississippi/Alabama shelf[§]	1.61	1.1	B/P	
		(0.28-2.89)		
Freeport, TX-coastal[§]	7.15	0.71	B	Slowey (1980)
	(0.9-45)	(0.1-2.4)		
Texas shelf[§]	1.7	0.5	B	Lytle and Lytle (1979)
	(1.4-2.0)	(0.4-0.5)		
Florida coastal (<60 m)[§]	3.1		B/P	Gearing et al. (1976)
W. of Mississippi R.-coastal (<60 m)[§]	11.7		B/P	Gearing et al. (1976)
Texas/Louisiana-coastal[§]	36.5	21.4	B/P	Nulton et al. (1981)
	(5.71-87)	(3.1-50)		

[*]B = Biogenic; P = Petrogenic.
[†]Method: Gravimetry.
[§]Method: GC, GC/MS.

the total VLH in surface waters. Cycloalkane concentrations were <1.0 ng/l in open ocean water and between 60 and 100 ng/l in polluted waters (about 20% of the total VLH). Total alkanes doubled from approximately 15 ng/l in open ocean water to as much as 40 ng/l in polluted shelf waters. Brine discharges and the underwater venting of waste gases associated with offshore production on the Louisiana shelf were identified as major VLH sources.

Many studies of volatile organic compounds (VOC) in the Gulf of Mexico included their distributions near point sources of pollution, e.g., near wells and blowouts (Brooks et al., 1978, 1981; Wiesenberg et al., 1981) or at disposal sites (Atlas et al., 1980). Surface water near a man-made underwater vent contained VOC with fewer than 10 carbon atoms and generally dominated by n-alkanes (Sauer, 1981b). VOC in formation waters were a complex mixture dominated (≈80%) by aromatic hydrocarbons including alkylated benzenes. VOC determined during the IXTOC-I well blowout on the Campeche shelf were as high as 400 mg/l in surface waters near the wellhead (Brooks et al., 1981). A three-year, NOAA-supported study of VOC concentrations and distributions in Gulf Coast estuaries is one of the most comprehensive studies of VOC in the Gulf of Mexico (Brooks et al., 1984a). A wide variety of VOC were detected in northwestern Gulf estuarine and coastal waters. Although usually less than 10 ng/l, individual component concentrations were occasionally greater than 1,000 ng/l. These higher concentrations were detected at specific point sources (e.g., a chemical outfall). Although various locations were sampled at different times during the year, the range of VOC concentrations were relatively uniform over the upper Gulf Coast estuaries.

Several explanations have been suggested for the relatively low levels of VOC observed in Gulf Coast estuaries and other marine environments (Gschwend et al., 1982; Brooks et al., 1984a). First, the rate of VOC input may be slow and constant at low concentrations. This does not appear to be the case for the Gulf coast region, where VOC sources are ubiquitous and randomly distributed. A second possible explanation is that VOC removal is rapid. There are a number of removal mechanisms: (a) air-sea exchange; (b) adsorption onto particles and subsequent sedimentation; (c) biodegradation; and (d) photolysis. Air-sea exchange in coastal waters appears to be the dominant removal mechanism (Gschwend et al., 1982; Brooks et al., 1984a).

Reports of VOC concentrations and distributions in Gulf of Mexico sediments are limited. A wide variety of VOC have been detected in estuarine and river sediment from the northern Gulf of Mexico with high concentrations at many locations (Brooks et al., 1984a). Sediment VOC concentrations ranged from about 7 to 4,000 mg/kg on the tops of piston cores from the Gulf of Mexico shelf and from 70 to 1,050 mg/kg in the lower Mississippi Delta. The presence of light aromatics and n-alkanes suggested a petroleum source. The source could be anthropogenic or due to natural seepage.

5.4.5 Distribution of Gaseous Hydrocarbons

Brooks, Sackett and co-workers at Texas A&M University (Brooks et al., 1973, 1977, 1978, 1979a,b; Brooks 1975, 1976; Brooks and Sackett, 1977; Sackett and Brooks, 1974, 1975) have shown LMWH are sensitive indicators of petroleum pollution in marine waters. Thousands of analyses by hydrocarbon "sniffing" and discrete sampling have identified ports and estuaries with their associated commercial and petrochemical activities, offshore petroleum operations, and shipping activities, as the major anthropogenic sources of LMWH in the Gulf. The water column for at least one example of each of these three types of inputs has shown LMWH concentrations several orders of magnitude higher than the water column in the open Gulf of Mexico. The underwater venting of waste gases and brine discharges, both associated with offshore platforms, are the major sources of non-methane LMWH to upper Gulf coastal waters. These sources are apparently responsible for the two orders of magnitude increase in Louisiana shelf waters over open ocean levels of the LMWH. Average concentrations of 3,100, 31 and 22 nl/l of methane, ethane, and propane, respectively, have been observed on the Louisiana shelf as compared to concentrations of 50, 3 and 1 nl/l, respectively for other areas of the Gulf. Brooks et al. (1978) reported very high concentrations of LMWH and VLH around a well blowout on the Texas shelf.

Bernard (1978) and Bernard et al. (1978) have reported LMWH in Gulf of Mexico sediments. Most sediment LMWH were biogenic in origin, although one area of possible petrogenic gas seepage was observed on the south Texas shelf (Brooks et al., 1979b). Thermogenic gas seepage has been observed in several blocks of the Green Canyon area.

5.5 OTHER CONSTITUENTS

5.5.1 Synthetic Organics

The most complete and systematic study of chlorinated hydrocarbons and other synthetic organics in the Gulf of Mexico was reported by Giam and co-workers in a series of papers (Giam et al., 1972, 1973, 1974, 1976a,b,c, 1977, 1978a,b). Corcoran (1973) and Corcoran and Curry (1978) reported the presence of chlorinated hydrocarbons and phthalate esters in the Mississippi Delta area. Table 5.19 summarizes the organochlorine residues in biota from the Gulf of Mexico (Kennicutt et al., 1988c).

Samples of plankton and various species of fish, shrimp, and oysters have been analyzed for a variety of organochlorine residues. The organochlorine compounds most commonly found are dichlorodiphenyl-trichloroethane (DDT) metabolites, polychlorinated biphenyls (PCBs), and, occasionally, dieldrin. There is some evidence that estuarine biota contain higher levels of certain residues than do coastal pelagic organisms (Baird et al., 1975; Giam et al., 1978b), but the difference, if any, are masked by large individual and interspecies variations in contaminant concentrations.

Giam et al. (1978a,b) found PCB and DDT residues in virtually all samples. Higher concentrations of pollutants were generally found in

Table 5.19. Average concentrations of organochlorine residues in biota from the Gulf of Mexico and adjacent estuaries and bays (From: Kennicutt et al., 1987).

		Concentration (ng g^{-1})					
Organism	No. of Samples	PCB	ΣDDT	Dieldrin	Others	Location	Reference*
Plankton	29	95	7	--	--	Gulf of Mexico, Northern Caribbean	1
Plankton	5	84	1	12	--	Gulf of Mexico, Mississippi Delta	2
Fish, shrimp, other (whole organisms or muscle)	46	66	62	--	--	Gulf of Mexico	3
Fish (grouper)	18	33	19	--	--	Gulf of Mexico	4
Fish, shrimp, other (whole organisms or muscle)	27	25	10	--	--	Gulf of Mexico	5
Fish (mesopelagic)	27	25	10	--	--	Gulf of Mexico, Mississippi Delta	2
Fish	24	203	18.2	15.2	Toxaphene (200), ethyl parathion (75), methyl parathion (47)	Estuaries of Texas, Mississippi, Louisiana, Alabama and Florida	6
Oysters	9	55	15	0.9	Chlordane (-), endosulfan (-), endrin (-)	Mexican coastal lagoons	7
Fish	7	11	--	--	--	Escambia Bay, FL	8
Fish, crab, oysters	9	--	49	9	--	Aransas Bay, TX	9
Crabs	62	--	16	2.1	--	San Antonio Bay, TX	10
Oysters	30	--	25	8.9	--	San Antonio Bay, TX	10
Clams	43	--	20	2.9	--	San Antonio Bay, TX	10
Shrimp	23	--	2	1.8	--	San Antonio Bay, TX	10
Molluscs, fish	37	--	--	--	Mirex (139)	St. Louis and Mississippi Bays, MS	11

*References: (1) Giam et al., 1973; (2) Baird et al., 1975; (3) Giam et al., 1972; (4) Giam et al., 1974; (5) Giam et al., 1978b; (6) Butler and Schutzmann, 1978; (7) Rosales et al., 1979; (8) Duke et al., 1970; (9) Fay and Newland, 1972; (10) Petrocelli et al., 1974; (11) De la Cruz and Lue, 1978.

organisms from the Mississippi Delta in comparison with offshore biota (e.g., PCB = 20 ng/g offshore, 27 ng/g near the Delta). Two samples taken farthest from shore had high levels of DDT and PCBs. It was suggested that this difference could be explained by the age and nature of the samples at these stations. PCB and total DDT levels were apparently lower than those measured during their 1971 survey (Giam et al., 1972).

Baird et al. (1975) reported organochlorine contamination of mesopelagic fish and zooplankton in the Gulf of Mexico. They analyzed five samples of zooplankton and 24 fish samples that represented 1,052 individuals and 17 species of mesopelagic fish. DDT and its metabolites were found at low levels (average = 18 ng/g) in all but one fish and in two of five zooplankton samples. The concentration of total DDT was compared to that reported by Giam et al. (1972, 1978b). Dieldrin occurred more sporadically than total DDT. PCBs were measured in concentrations one to two orders of magnitude higher than the other organochlorine residues in all samples. The average PCB concentration (203 ng/g) is 2 to 5 times higher than that in other data for fish from the Gulf.

A comprehensive study of organochlorine residues in estuarine fish from 1972 to 1976 was reported by Butler and Schutzmann (1978). Approximately 38,000 fish were analyzed in groups of 25 individuals each (1,524 analyses). The samples were screened for 20 common pesticides and PCBs. The three most common residues were total DDT, PCB, and dieldrin, which occurred in 39%, 22%, and 5% of the samples, respectively. Other pesticide residues appeared only rarely in biota. Along the Texas and Mississippi coasts, toxaphene was measured in 5 of 72 samples with an average concentration of 200 ng/g. Ethyl parathion, methyl parathion, carbophenothion, ethion, endrin, and Dacthal were identified in a few samples in biota from Texas estuaries. Data from the EPA Mussel Watch program (Farrington et al., 1982) reported the concentrations of PCB and dichlorodiphenylethane (DDE) in oysters from several Gulf Coast estuaries. The NOAA Mussel Watch data for total PCB and total DDT pesticide are shown in Figures 5.6 and 5.7.

5.5.2 Radionuclides

Radionuclides in the Gulf of Mexico are both natural and anthropogenic in origin (Scott, 1981). The property that distinguishes these chemical species from all others is their unstable nucleus, which leads to radioactive decay. Each radionuclide decays with a characteristic half-life, and this fact can, in some circumstances, be used as an indication of the rates of certain chemical and physical events. Radioactive decay also results in radiation that can, in some circumstances, be harmful to living organisms. Most studies of radioactivity in Gulf of Mexico waters and sediments have been aimed at determining rates of processes--for example, rates of sediment accumulation, or rates of water movement. Little attention has been paid to possible harmful effects of radioactivity, because the levels of radioactivity in the Gulf are considered to be too low to have measurable effects on organisms. It should be noted, however, that much can be learned about how chemicals, including potentially toxic chemicals, move

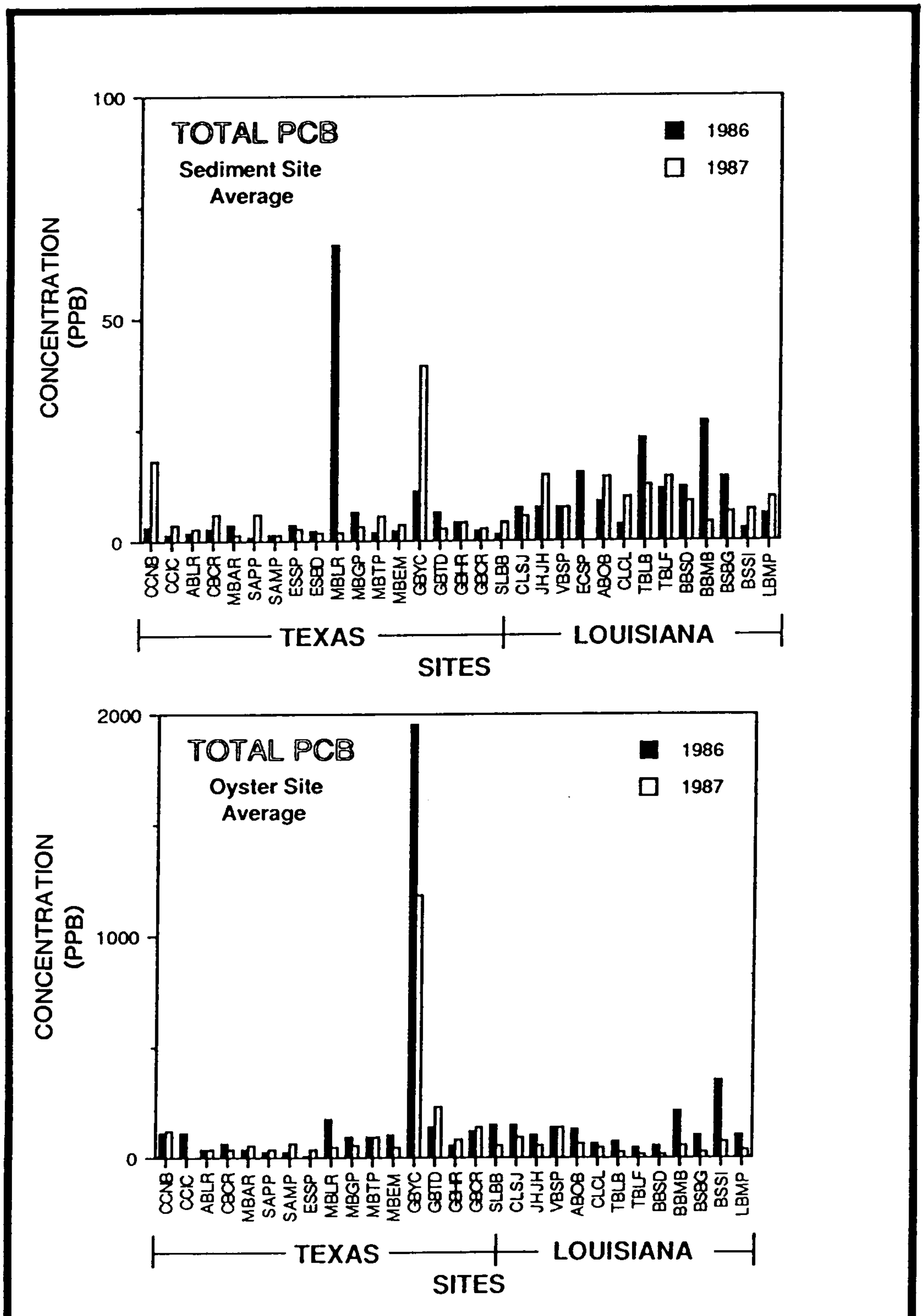


Figure 5.6. Concentrations of total PCB at NOAA Mussel Watch stations from Corpus Christi to the Mississippi Delta. Values represent the mean of three samples from each station.

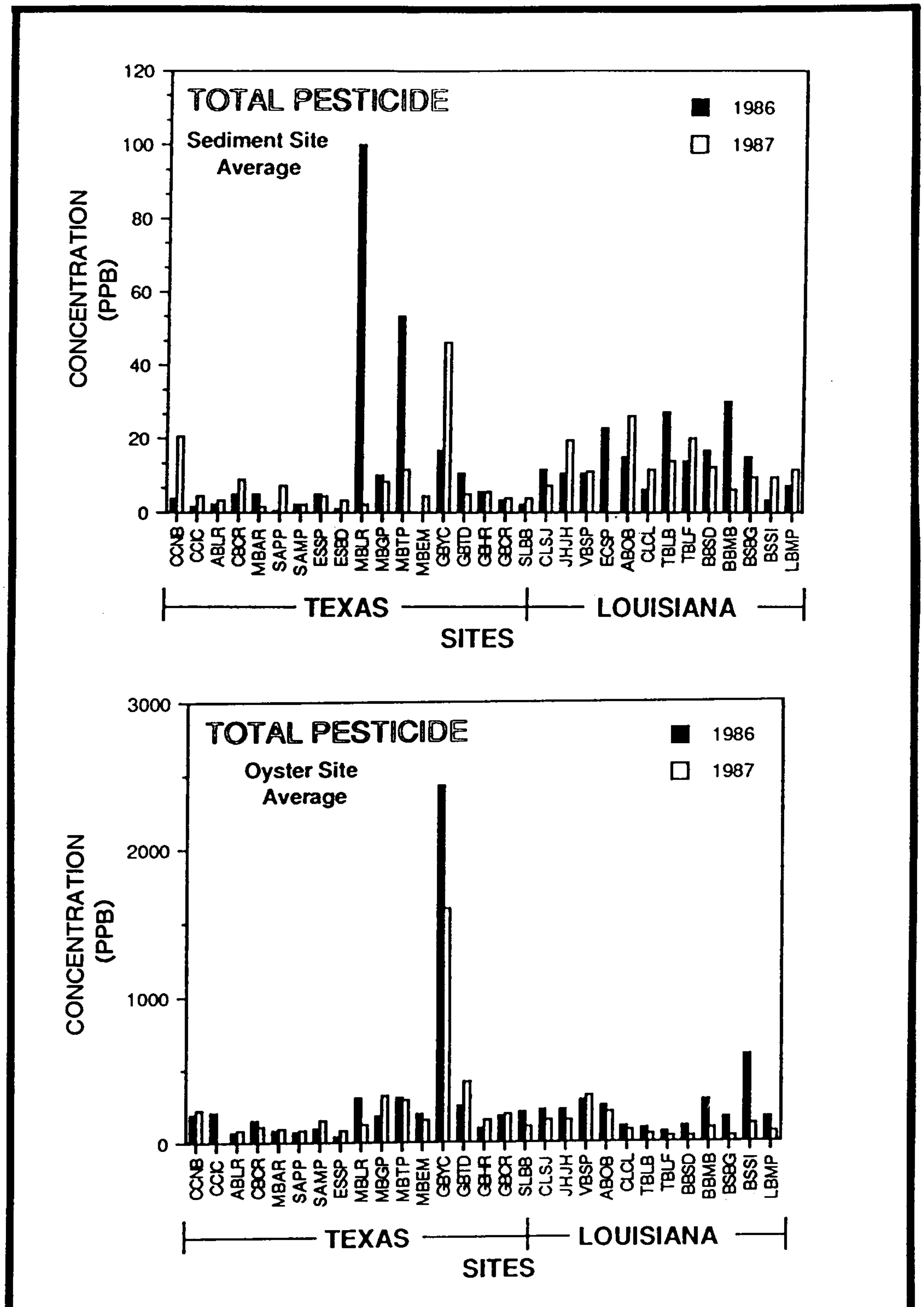


Figure 5.7. Concentrations of total pesticide at NOAA Mussel Watch stations from Corpus Christi to the Mississippi Delta. Values represent the mean of three samples at each station.

through the environment and interact with organisms by studying the behavior of radionuclides, whether the radionuclides have a direct effect on organisms or not.

Reviewing literature on radionuclides can be confusing because so many different units are used to indicate the amount of the radionuclide present. The amount is commonly expressed in "activity" units, that is, in the number of disintegrations of unstable nuclei per unit time, rather than in weight percent or other mass units. The mass of a radionuclide present is directly related to the activity (disintegrations per second or minute) through the half-life or decay constant for the particular radionuclide; thus, conversions can be made. It is also common for researchers to study one or two radionuclides and ignore all others, even though the nuclides they are studying might account for only a very small percentage of the total radioactivity in a sample of water, sediment, or tissue. For example, the primordial radionuclide potassium-40 would probably dominate most samples, but it is only rarely studied in the marine environment. Naturally occurring radionuclides, such as potassium-40 and uranium-238, will contribute much more radioactivity to almost all marine samples than will all anthropogenic radionuclides.

The naturally-occurring radioactive elements uranium and thorium and their radioactive daughter nuclides have been among the most studied radionuclides in the Gulf of Mexico, as well as elsewhere in the world ocean. Those radionuclides have been used in a number of ways to provide a time frame for chemical, physical and biological processes (see Turekian and Cochran, 1978, for a review). Uranium has several sources, sinks, and pathways to and through the Gulf of Mexico. Rona et al. (1956) reported dissolved concentrations in open Gulf waters of about 3.4 μg/l, a value which has been confirmed by considerable later work and which is typical of the rest of the world ocean. Uranium concentrations in nearshore Gulf waters are variable because rivers and other land runoff sources are variable in uranium concentration. Some Texas rivers are enriched in uranium because they drain uranium mining districts, and all rivers draining agricultural areas carry uranium that was associated with phosphate fertilizer.

Scott (1981) has summarized much of the data on radionuclides in the Gulf of Mexico and Gulf coast rivers, including uranium data. She includes data for nearshore Gulf water taken from Sackett and Cook (1969) and given here as Table 5.20. The Mississippi River, like most other Gulf Coast rivers, is contaminated with uranium from phosphate fertilizer, and because of its large size, it has the greatest influence on uranium concentrations in nearshore Gulf waters and sediments. Table 5.21 gives uranium and thorium concentrations in river sediments that are being added to the northwestern Gulf of Mexico. Typical values for nearshore Gulf sediments are similar to these river sediment values.

Natural uranium consists of two isotopes, uranium-238 and uranium-235, with uranium-238 amounting to 99.28% of the total. Both isotopes decay through a complex series of daughter nuclides of variable half-lives. Several of the daughter nuclides, due to their geochemistry, become separated from their parents; then, as they decay unsupported by

Table 5.20. Uranium concentration in Gulf of Mexico waters (From: Sackett and Cook, 1969).

Area	Location	Depth (m)	Uranium ($\mu g/l$)	Salinity ($^{o}/oo$)
Open Gulf	23°45'N, 92°30'W	1	3.5 ± 0.2	36.5
		50	3.5 ± 0.2	34.5
		1,700	3.6 ± 0.2	35.0
		2,900	3.4 ± 0.2	35.0
	28°02'N, 89°44'W	1	3.6 ± 0.2	35.7
	28°39'N, 93°32'W	1	3.5 ± 0.2	34.5
Shelf, Bay, and Estuary	Galveston Channel	1	2.6 ± 0.1	25.0
	Dulce Creek (Near Corpus Christi)	Surface	4.8 ± 0.2	13.7
	Los Alamos Creek (Near Corpus Christi)	Surface	17.3 ± 0.7	40.8
	Baffin Bay (Shore)	Surface	5.6 ± 0.3	27.0
	Baffin Bay (Bridge)	Surface	6.4 ± 0.2	29.4
	Baffin Bay (Pier)	Surface	4.6 ± 0.2	29.0
	Laguna Madre	Surface	3.9 ± 0.2	29.9
	Aransas Pass	Surface	3.0 ± 0.2	29.4
	Copano Bay	Surface	2.1 ± 0.1	12.2

Table 5.21. Uranium and thorium isotopes in river sediments (From: Scott, 1968).

River Sampled and Size Fraction	Element Concentration ($\mu g/g$)	
	Uranium	Thorium
BRAZOS RIVER		
2 - 20 μm	2.42	--
<2 μm	2.56	13.05
RED RIVER		
2 - 20 μm	2.73	7.70
2 - 0.2 μm	3.28	12.42
<0.2 μm	3.05	14.23
MISSISSIPPI RIVER		
2 - 20 μm	3.29	7.93
2 - 0.2 μm	3.84	12.68
<0.2 μm	3.47	15.65

a parent, they give an indication of rates of processes. For example, uranium-238 decays through a series of thorium and radium isotopes, then to radon-222, an inert gas. This gas becomes separated from its parent, and through a series of short half-life daughter nuclides, forms lead-210, an isotope with a 30-year half-life. The long half-life of lead-210 makes it useful for determining the rate of accumulation of recent (past 100 years) sediments. Thus, although lead-210 is not an anthropogenic isotope, and is not a pollutant, it can be very helpful in pollution studies by allowing the sedimentation rate to be determined. Some of the other daughters of uranium-238, uranium-235, and thorium-232 can also be used to time geochemical processes (Turekian and Cochran, 1978).

In addition to the long-lived naturally occurring radionuclides uranium-238, uranium-235, and thorium-232 and their many daughter nuclides, radionuclides are produced in the atmosphere by cosmic rays and by human activities such as bomb testing and nuclear power plant operations. Perhaps the most useful radionuclide produced in this manner is carbon-14, which is produced continuously by cosmic ray bombardment but which was also produced in large amounts by bomb testing in the 1950's and 1960's. Carbon-14 has a half-life of 5,750 years and has been used to time processes such as rates of sediment accumulation and rates of water movement. Much of the earlier work with carbon-14 in the Gulf of Mexico has been summarized by Matthews et al. (1973) and Parker (1977). Little recent use seems to have been made of this isotope in Gulf of Mexico studies.

Like carbon-14, cesium-137 is classified as a "fallout" radionuclide. Most of the cesium-137 was produced by bomb testing in the 1950's and 1960's, and it has been incorporated into soils and sediments worldwide. Its 30-year half-life is similar to the 22-year half-life of lead-210, and like lead-210, cesium-137 is useful for measuring rates of accumulation of recent sediments in nearshore environments. In spite of its potential usefulness and the ease with which it can be measured, cesium-137 has not been used much in studies of northwest Gulf of Mexico environments. Examples of the use of cesium-137 include sediment accumulation studies in Louisiana salt marshes by Delaune et al. (1978), and sediment accumulation studies on the Mississippi River Delta by Pflaum (1982).

Another fallout radionuclide that has been studied in northwest Gulf of Mexico environments is plutonium. This element is generally regarded as being one of the most toxic substances known, but the amounts that have accumulated in Gulf sediments are too low to present any environmental hazard. In spite of its low concentrations, plutonium distributions can give clues to the behavior of other substances. Plutonium is very particle reactive--that is, it has a great tendency to attach to particles rather than to remain dissolved in seawater. In this respect, plutonium behaves like common pollutant trace metals such as copper and lead. In a study of plutonium distributions in Gulf sediments, Scott et al. (1983) found concentrations averaging 13.5 disintegrations per minute per kilogram (dpm/kg) in Mississippi River suspended matter and similar concentrations in deep Gulf of Mexico sediments. However, nearshore sediments in the northwest Gulf had much higher concentrations in their surface layers, up to 110 dpm/kg. Scott et al. (1983) explain this by suggesting that plutonium dissolved in deep Gulf water is removed by particles in the nearshore environment as the deeper Gulf waters are advected toward the shore. Shokes (1976) had earlier explained unusually high lead-210 values in surface sediment near the shelf break in the northwest Gulf of Mexico as resulting from this same phenomenon. Trace metals and other pollutants could conceivably be concentrated by this mechanism.

The only radionuclide that might be added to the northwest Gulf of Mexico in measurable amounts as a direct result of offshore oil and gas operations is radium. It has long been known that radium concentrations are higher in sub-surface brines, such as those from oil wells, than in other natural waters. Kraemer and Reid (1984) discuss some of the earlier data and give their own data and ideas on mechanisms for radium enrichment in Gulf coast formation waters. As had earlier workers, they found radium concentrations higher in more saline formation waters (Figure 5.8). They point out that radium must be continually supplied to the formation waters from its parent isotopes of uranium and thorium, which are contained in the rocks of the formation. Apparently, the higher salinity formation waters are more effective at leaching radium from the rocks and/or keeping it in solution. In some parts of the world, uranium, and thereby its daughter radium, are associated with petroleum itself, but this does not seem to be the case in the U.S. Gulf coast, because those wells that produce only water have just as much radium as those that produce oil.

The possible accumulation by organisms of radium from oil-well produced water appears not to have been studied, so no evaluation of possible biological effects is possible.

5.6 DATA GAPS AND INFORMATION NEEDS

This review has shown that there is a wealth of available information about the marine chemistry of trace metals, hydrocarbons, and other constituents in water, sediment, and biota of the Texas-Louisiana shelf and upper slope. Further information needs are outlined below.

5.6.1 Trace Metals

More information is needed on the sources and fates of trace metals in the study area, including the fate of Mississippi River-derived trace elements and the mass and fate of metals from other sources, such as the atmosphere and industrial discharges. Unfortunately, no data are available on atmospheric inputs of trace metals to the Texas-Louisiana shelf. It is essential that data be obtained on trace metal characteristics of industrial and municipal outfalls in the study area so that their influence is not confused with inputs from other sources.

More work is also needed on the forms of dissolved metals in Mississippi River water, including metal-organic complexing and related studies, because the chemical form of the metal determines its behavior

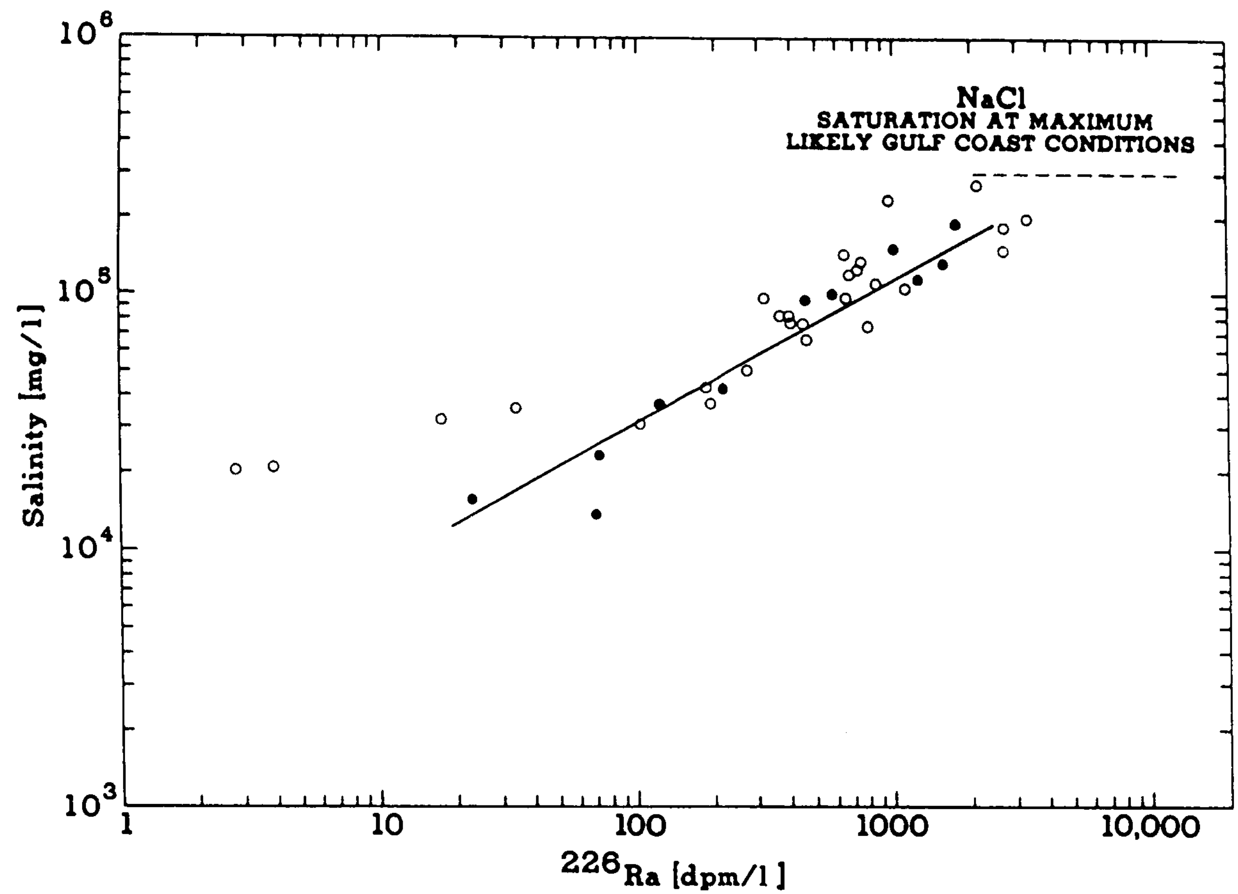


Figure 5.8. Radium-salinity relation in formation water from the U.S. Gulf Coast. Solid circles represent samples from geopressured-geothermal well tests conducted by DOE. open circles represent samples from aquifers which have co-produced oil or gas or both. Solid line represents least-square fit through solid circle data points only (From: Kraemer and Reid, 1984).

and biological effects. Despite the acknowledged importance of the dissolved trace metal load of the Mississippi River, the suspended trace metal load is much greater for essentially all potentially toxic trace metals. The behavior of river-borne particulates as they mix with seawater is critically important to the ultimate fate of the trace metals, yet this is a subject that is not well understood.

Additional data is also needed on the distribution of trace metals in water, sediment, and biota. Concentrations of dissolved trace elements in seawater are poorly known and need to be studied using current methods. Essentially all data more than ten years old, and much recent data on concentrations of trace elements dissolved in seawater, are too high by factors of 10 to 1,000 or more. Unfortunately, few seawater samples from the Texas-Louisiana shelf have been analyzed for dissolved trace metals with the care required to lend confidence to the data. Trace metal concentrations in surficial sediments are much better documented, but information on temporal variability is very limited. There remains a need for reliable trace element data on fish and other pelagic species, particularly from the Louisiana shelf, which has by far the most petroleum exploration and production activities on the Gulf coast. Trace element concentrations should also be measured in organisms and sediments near petroleum seeps.

Effects of bottom water hypoxia on sediment trace metal geochemistry should also be investigated further. The role of diffusion from sediment pore water in controlling trace metal concentrations in overlying coastal seawater has been much discussed (Presley and Trefry, 1980), but not enough work has been done to verify its importance for most metals. More work is needed on this subject, because benthic organisms would be exposed to sediment pore water and might be affected by high trace metal concentrations or high levels of such chemicals as ammonia and sulfide, which also build up in pore water.

Finally, further work is needed on the regional fate of trace metals from drilling mud discharges. Field studies should be accompanied by laboratory work on dissolution of trace metals in seawater.

5.6.2 Hydrocarbons

The distributions of aromatic hydrocarbons in sediments and biota from the northwestern Gulf of Mexico need further study.

More information is also needed on spatial and temporal trends in benthic and pelagic tar distributions. Additional information on the sources of benthic and pelagic tar is needed, as there is little information that is less than ten years old.

Reports of VOC concentrations and distributions in Gulf of Mexico sediments are limited. A wide variety of VOC have been detected in estuarine and river sediment from the northern Gulf of Mexico, with high concentrations at many locations, but there is little data from the open Gulf.

More data are needed on the body burdens of hydrocarbons in benthic organisms around seeps, and on the relationships between seep hydrocarbons and benthic organism body burdens.

5.6.3 Radionuclides

The mass and fate of radionuclides in produced waters needs further study. Also, the possible accumulation by organisms of radium from oil-well produced water appears not to have been studied.

CHAPTER 6
MARINE BIOLOGY

Rezneat M. Darnell

with
David J. Schmidly
(Endangered and Threatened Fauna)

6.1 INTRODUCTION

The region offshore Louisiana and Texas includes a wide variety of habitats for marine biota, both in the water column and on the seafloor. This chapter describes the biota within major groups: plankton, nekton, and benthic and demersal biota. For each group, the composition, standing crop, distribution patterns, and controlling factors are reviewed, and a simple conceptual model is presented. Biologically sensitive areas and endangered/threatened species are also discussed, and major data gaps and study needs are presented.

Major information sources for this chapter include the Bureau of Land Management South Texas Outer Continental Shelf (STOCS) studies (various reports), the Offshore Ecology Investigation (various chapters in Ward et al., 1979), the Central Gulf Platform Study (Bedinger, 1981), the Buccaneer Gas and Oil Field Study (Middleditch, 1981), the Strategic Petroleum Reserve (SPR) Studies (various reports), and the ongoing Minerals Management Service Northern Gulf of Mexico Continental Slope Study (Gallaway et al., 1988). Other studies are cited in the text as needed.

6.2 PLANKTON

6.2.1 Phytoplankton

Information concerning the composition, abundance, distribution, and production of phytoplankton on the Texas-Louisiana shelf is derived primarily from investigations carried out around the Mississippi River Delta (American Petroleum Institute studies), around oil platforms off Timbalier Bay, LA (Offshore Ecology Investigation), near brine disposal sites off Calcasieu River (SPR studies), and along four transects off south Texas (STOCS study). Additional information is provided by remote sensing investigations described below. Only the STOCS involved a regular sampling program with across-shelf transects. Although a variety of techniques have been used by the different investigators, some of the techniques were common to the various studies, and the accumulated results do provide a general understanding of the nature and dynamics of phytoplankton populations of the area.

Composition and Standing Crop

Dominant phytoplankton genera encountered in the major studies of the Texas-Louisiana shelf are shown in Table 6.1. The Simmons and Thomas

Table 6.1. Phytoplankton genera reported to be numerically dominant in studies on the Texas-Louisiana continental shelf.

Genus	Location: Off Mississippi Delta*	Off Timbalier Bay, LA†	Off Calcasieu River§	Off South Texas#
CYANOPHYTA (blue-green algae)				
Trichodesmium				X
CHRYSOPHYTA (diatoms)				
Achnanthes			X	
Asterionella	X	X	X	
Cerataulina		X	X	
Chaetoceros	X	X	X	X
Coscinodiscus			X	
Cyclotella (fw)**	X	X	X	
Guinardia			X	
Leptocylindrus		X	X	
Melosira (fw)	X	X		
Navicula (fw)	X			
Nitzschia	X	X	X	X
Rhizosolenia		X	X	X
Skeletonema	X	X	X	X
Thalassionema	X	X	X	X
Thalassiosira		X	X	
Thalassiothrix	X			
PYRROPHYTA (dinoflagellates)				
Ceratium				X
Gonyaulax		X		X
Gymnodinium			X	
Katodinium			X	
Prorocentrum				X

*Simmons and Thomas (1962).
†El-Sayed and Fucik (1979).
§SPR studies off West Hackberry, LA, various authors.
#STOCS studies, various authors.
**(fw) = freshwater indicator.

(1962) data from just east of the Mississippi Delta are included because these authors differentiated between the freshwater and more marine genera. Thus, the presence of Cyclotella, Melosira, and Navicula in the plankton samples indicates freshwater intrusion onto the shelf. These genera were sometimes dominant at the Louisiana stations off Timbalier Bay and Calcasieu River, but they were not important off south Texas. Clearly diatoms dominate the phytoplankton of the entire Texas-Louisiana shelf, and Fucik (1974) found them to constitute 90% of the phytoplankton off Timbalier Bay. Dinoflagellates become more important as one proceeds south along the coast, and silicoflagellates and blue-green algae are significant off south Texas. Wilson and Ray (1956) reported the red tide organism, Ptychodiscus (= Gymnodinium) breve from south Texas, but recent satellite and ground truth data (Gallegos et al., 1988) show the 1986 red tide extending from Galveston Bay at least as far south as Tampico, Mexico.

Data on the phytoplankton standing crop are available in the form of cell counts and chlorophyll concentrations. Cell counts vary from 10^3 to 10^7 cells/liter, a very wide range. Surface chlorophyll values range from near zero to 43.0 mg chl/m^3, and depth integrated values extend from 15.54 to 283.89 mg chl/m^2. The distribution and significance of these values are addressed in the next section.

Seasonal and Areal Distribution

As a preamble to our consideration of seasonal changes, it is noted that the water masses of the northern Gulf are in a very dynamic state. Cell counts based upon simultaneous samples from nearby stations sometimes give vastly different values. Thomas and Simmons (1960) reported chlorophyll values from the same stations on three successive days as follows: 0.82, 5.7, and 0.97 mg chl/m^3 of surface water (just east of the Mississippi Delta). Similarly, Gallegos et al. (1988) reported dramatic changes in the shape and position of the 1986 Texas red tide event from satellite views taken on three successive days. Thus, plankton concentrations are both patchy and dynamic, and they vary locally on scales of meters and hours.

Off Louisiana in well-mixed waters, cell counts showed little difference from surface to bottom, and the same was true even when there was stratification and the bottom waters were hypoxic. The distribution of phytoplankton cell densities on the Texas-Louisiana shelf are presented in Figure 6.1. Two general gradients exist: the phytoplankton is more abundant off Louisiana than off south Texas, and more abundant nearshore than offshore. Although the nearshore surface values ranged higher than deeper water values, the mean values were not significantly different. The distribution of surface chlorophyll values on the Texas-Louisiana shelf is presented in Figure 6.2. The central coastal Louisiana station (which was the shallowest station, in 10 m of water) gave the highest values and the highest mean value. The Timbalier Bay station, at a depth of 20 m, showed chlorophyll values ranging slightly above 10.0 mg chl/m^3 of surface water. The south Texas stations all ranged much lower. Open Gulf values ranged around 0.20 mg chl/m^3 (El-Sayed and Fucik, 1979). Thus, the surface chlorophyll values indicate that the Louisiana shelf has a much higher and more variable standing

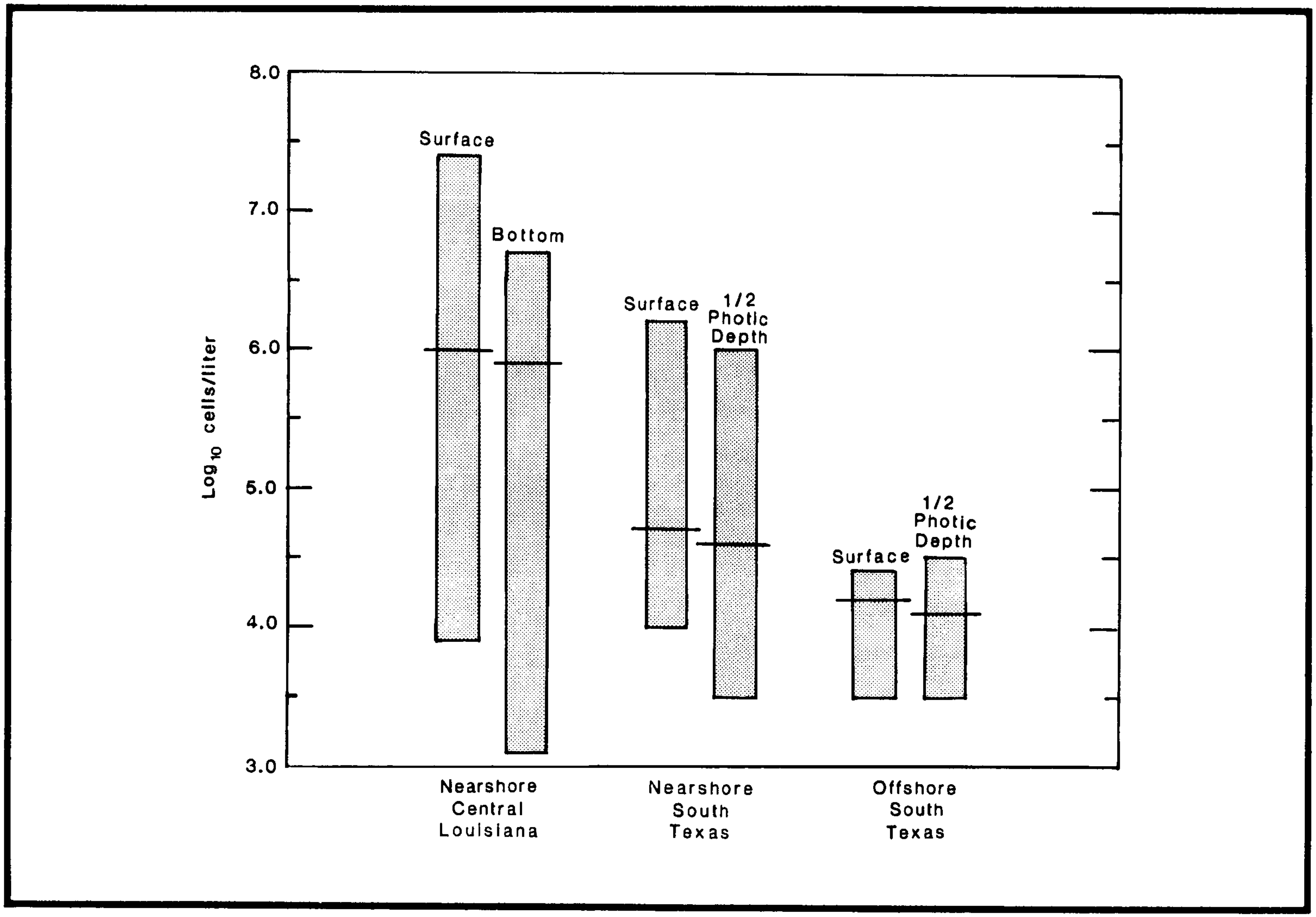


Figure 6.1. Distribution of phytoplankton cell densities on the Texas–Louisiana continental shelf (means and ranges).

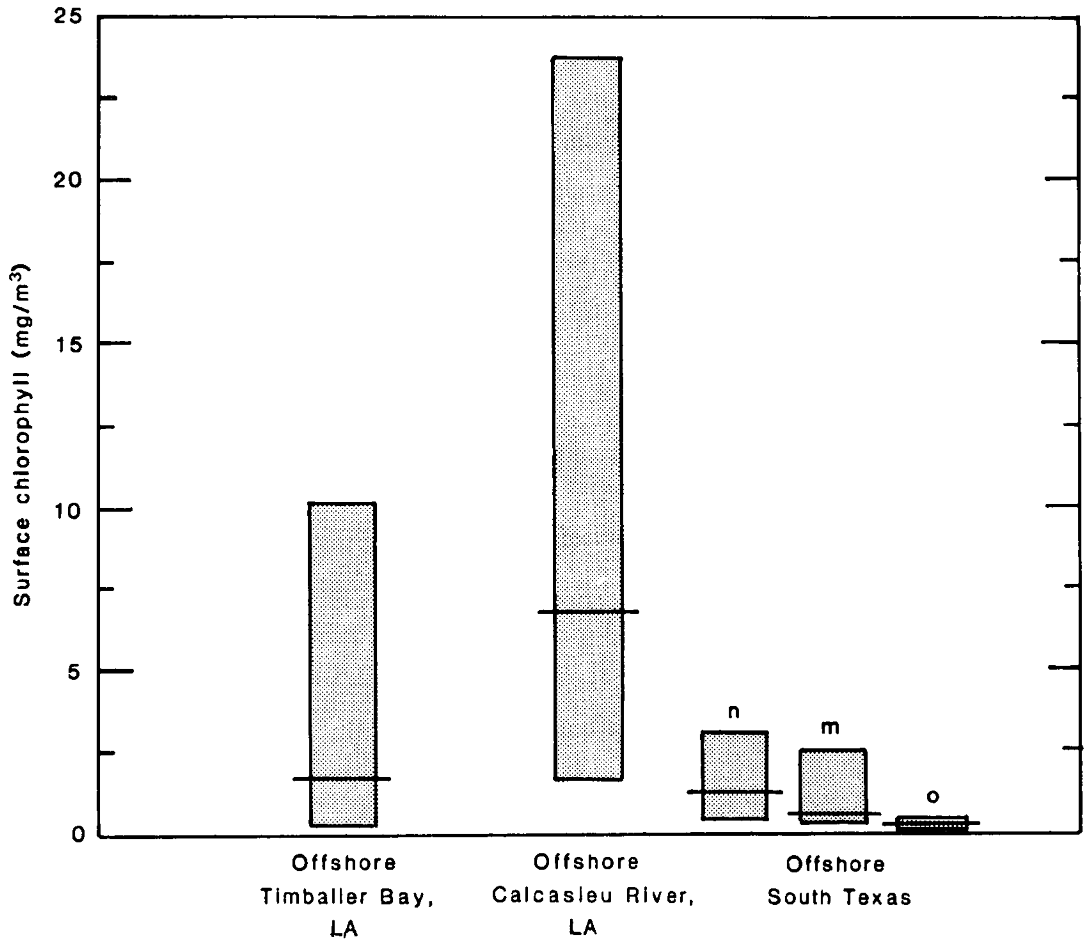


Figure 6.2. Surface chlorophyll values (means and ranges) for three areas of the Texas–Louisiana continental shelf. South Texas stations include nearshore (n), mid-shelf (m), and outer shelf (o).

crop of phytoplankton than does south Texas, and this tends to decrease with distance from shore. These conclusions are substantiated by satellite imagery views of the Texas-Louisiana coast published by El-Sayed et al. (1986). The photographs show surface chlorophyll densities which are highest (at least 5.0 mg/m^3) on the inner half of the Louisiana shelf grading to low (1.0 mg/m^3 or less) on the inner shelf of south Texas. The gradient also extends to about 3.0 mg/m^3 on the outer shelf of Louisiana and less than 1.0 mg/m^3 on the outer shelf of south Texas. Depth integrated chlorophyll values are available only from the Timbalier Bay platform station. Here the values ranged from 5.18 to 84.40 mg chl/m^2 of surface area with a mean value of 23.6 mg chl/m^2. Open Gulf measurements average about 12.4 mg chl/m^2 (El-Sayed and Fucik, 1979).

Off south Texas, the nanno, net, and total chlorophyll values were measured at three depths at all stations on the across-shelf transects. Nannoplankton was found to be quite important at all depths and stations, often equalling the values of the net plankton. Values for the net plankton were generally more variable than those for the nannoplankton, and both were higher and more variable nearshore than offshore. Total plankton showed nearshore peaks in April and in the Fall, and a small offshore peak in February was associated with upwelling in the deeper waters. In the south Texas studies, it was shown that chlorophyll values increase with depth in the water column all along the transects, indicating the association of greater chlorophyll concentrations with the nepheloid layer.

Primary Production

Primary production values have been reported from off Timbalier Bay, LA (El-Sayed and Fucik, 1979) and off south Texas (Kamykowski and Batterton, 1979), and the summarized data are presented in Table 6.2. Surface hourly production values off Louisiana show great variability (2.50 to 87.98 mg $C/m^3/h$) and a very high average production rate (26.54 mg $C/m^3/h$). By contrast, surface values off south Texas show low variability and quite low productivity rates, generally less than 2.0 mg $C/m^3/h$. This is only a little above the average open Gulf rate of 0.328 mg $C/m^3/h$. Both nanno and net plankton were important producer groups off south Texas. Depth-integrated hourly primary production rates have been reported only off Timbalier Bay, LA. These values were highly variable (15.24 to 283.89 mg $C/m^2/h$) and gave a very high mean value (98.82 mg $C/m^2/h$). The latter value contrasts with the hourly average for open Gulf waters of 6.07 mg $C/m^2/h$. Depth integrated daily production off south Texas for a two-year cycle has been provided by Flint and Rabalais (1981) (Figure 6.3). The production values are quite low, ranging from 2.5 to 24.7 mg $C/m^2/day$. The mean of the south Texas values has been calculated to be 8.57 mg $C/m^2/day$. Integrated over a full year, this would come to a total annual production rate of 3.13 g $C/m^2/year$. However, Flint and Rabalais (1981) give the annual estimated production rate as 103 g $C/m^2/year$, which is about 33 times the rate which can be obtained from the values reported in Figure 6.3. The solution of this dilemma is not at hand. One value appears to be too high, and the other too low. Considering the level of fishery production in the area, one might expect annual primary production values to fall in

Table 6.2. C-14 primary production measurements reported from the Texas-Louisiana continental shelf compared with average values from open Gulf waters. Mean value and ranges (in parentheses) are given where available.

	Off Timbalier Bay, LA*	Off South Texas†	Open Gulf§
SURFACE (mg C/m^3/h)	26.54 (2.50 - 87.98)	Total (0.00 - 2.10) Nanno (0.00 - 1.30) Net (0.00 - 1.30)	0.33
DEPTH INTEGRATED - HOURLY (mg C/m^2/h)	98.82 (15.54 - 283.89)	--	6.07
DEPTH INTEGRATED - DAILY (mg C/m^2/day)	1,000	8.57 (2.50 - 24.7)	62.15
DEPTH INTEGRATED - ANNUAL ESTIMATE (g C/m^2/yr)	--	103	--

*El-Sayed and Fucik, 1979.
†Flint and Rabalais, 1981; Kamykowski and Batterton, 1979.
§El-Sayed, 1972; Fucik, 1974.

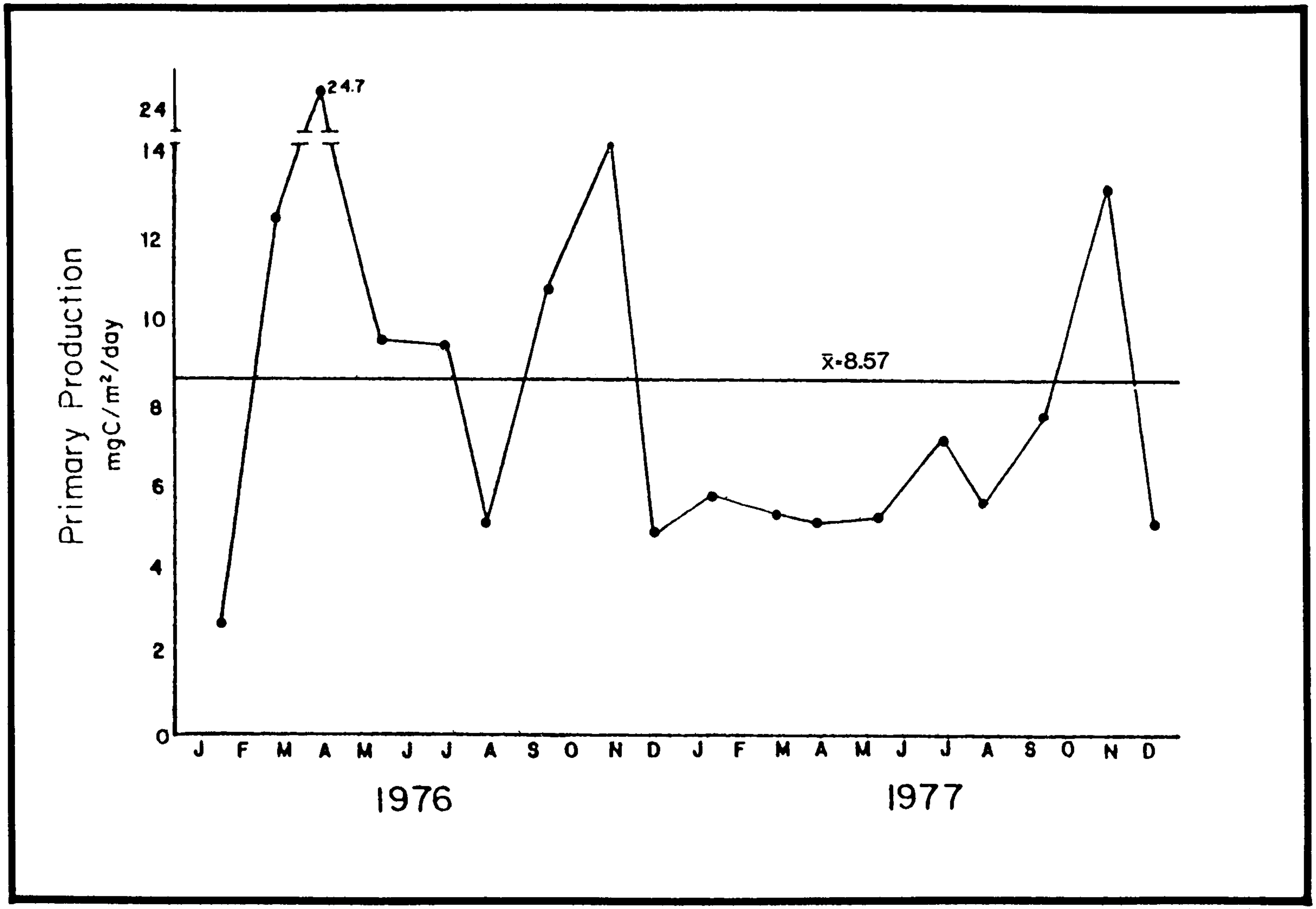


Figure 6.3. The two-year cycle of primary production (carbon fixation) for Texas coastal waters between 1976 and 1977 (From: Flint and Rabalais, 1981). Carbon fixation estimated from chlorophyll measures according to technique of Ryther and Yentsch (1957).

the range of 30 to 50 g C/m^2/year. However, the bay and estuary subsidy of the continental shelf cannot be underestimated. Most of the fishery harvest is based upon estuary related species, and the annual energy outflow from the estuaries in protein alone must be quite high. One fact is quite certain. Primary production in Louisiana shelf waters greatly exceeds that off Texas. Even the hourly production rate off Louisiana exceeds, by an order of magnitude, the estimated daily production rate off Texas.

Controlling Factors

In attempting to understand the role of the various physical and chemical factors controlling the local phytoplankton populations, the study of Fucik (1974) is most informative. His stations were located at a depth of 20 m off Timbalier Bay about 80 km west of the Mississippi Delta. This area is periodically invaded by plumes of Mississippi River water which are quite rich in nutrients and contain heavy loads of fine suspended sediments. These plumes are particularly prominent during the spring months, but they sometimes occur during other seasons, as well. Fucik found that phytoplankton production closely coincided with fluctuations in river discharge. Highest production occurred in April, and the lowest was observed in the summer, fall, and winter months. As a rule, winter phytoplankton levels are light limited due to reduced levels of solar radiation. Summer and fall populations are normally nutrient limited due to reduced river outflow. However, Fucik found that the actual levels observed varied from one year to the next depending upon the river influence. During the second year of his study, a major flood in July brought in a surface layer of fresher water about 5 m deep. As a result, surface phytoplankton populations increased dramatically in response to the nutrient input, but below 5 m production was greatly inhibited due to reduced light levels caused by the suspended sediments. The stimulatory effects of this major nutrient pulse persisted through the following January.

Applying step-wise multiple regression techniques to his data, Fucik (1974) developed a phytoplankton productivity model for the Timbalier Bay area. This is given as follows:

$$Y = 2.75\ (G)^{0.57}\ (e)^{-0.001\ NPS}\ (X)^{0.96}\ (H)^{1.70\ X}$$

where Y = the ^{14}C uptake in mg $C/m^3/h$;
G = the percent of surface light intensity;
NPS = the product of nitrate, phosphate, and silicate concentrations in μg-at/liter;
X = the extinction coefficient as determined by 1.7/Secchi depth; and
H = chlorophyll concentration in mg/m^3.

Thus, the two environmental factors found to be critical were light availability and nutrient concentrations. Temperature, salinity, and other factors were found to be relatively unimportant. Riley (1937) had earlier concluded that phosphorus is the primary limiting nutrient off the Mississippi Delta, but he provided no nitrogen measurements, and the question of which nutrient is actually limiting in this area remains unanswered.

The situation off south Texas is quite complex, but data accumulated during the STOCS project (summarized in Flint and Rabalais, 1981) provide a general basis for interpretation. In general, there is a major spring and a minor fall maximum with a winter low (due to light limitation) and a summer low (due to nutrient limitation). However, the details vary in relation to season, distance from shore, and specific hydrographic circumstances. Shelf circulation in this area shifts seasonally in response to wind and deep Gulf water movements so that portions of the south Texas shelf are alternately bathed by a series of water masses of generally low nutrient levels.

From late fall to early spring (October to March), Louisiana (= Mississippi River) water moves westerly and southerly along the shelf. This flow is more pronounced nearshore, but at times it may cover the entire shelf. Nutrients are gradually replenished and reach a maximum during the winter. Spring and early summer phytoplankton blooms decrease nitrates to below detectable limits. Phosphates and silicates are reduced but are never completely depleted. Thus, nitrogen is the ultimate limiting factor. During the summer, outflow from local rivers brings in some nutrients which aid in supporting nearshore production. At this season, nearshore waters are often stratified, and offshore transport of surface water may generate a return flow of deep-Gulf waters in the near-bottom layer which also may bring in some nutrients. During the summer months, phytoplankton density and production levels are highest near the bottom (i.e., in association with the nepheloid layer). High ammonia levels in this layer suggest rapid nutrient regeneration in the nepheloid layer and on the bottom. Ten percent of the surface radiation can reach the bottom within 50 km of shore. A clear case of upwelling was observed in February, and this temporarily increased nutrient levels all across the shelf.

Light and nutrients (particularly nitrogen) are the two controlling factors for phytoplankton production on the south Texas continental shelf. Nutrient levels depend upon advective transport (from Louisiana, from local rivers, and from deeper off-shelf waters), as well as upon local regeneration (in the nepheloid layer and at the bottom). In turn, advective transport of nutrients is brought about by winds, local and upstream rainfall, and off-shelf ocean dynamics.

Effects of Human Activities

The problem of assessing the impacts of human activities on phytoplankton populations of the continental shelf has been well stated by Fay and Schnitzer (1985). Laboratory studies have indeed demonstrated that high levels of suspended sediments and high levels of a variety of anthropogenic chemicals can adversely affect phytoplankton levels and productivity. However, in the field, natural spatial and temporally variability in phytoplankton parameters is so great that only the most gross effects are likely to be discernible. The vast dilution capacity of ocean water dictates that any effects are likely to be quite local, and the reproductive capacity of phytoplankton is such that any actual effects would become negligible after only a few hours or days. Accordingly, studies to date have been unable to demonstrate any human impact on the phytoplankton populations of the northern Gulf continental shelf. In effect, this is a non-problem, and human impacts are much better assessed using benthic organisms as indicators.

Phytoplankton Production Model

A mathematical model of primary production off Louisiana has already been given. Here (Figure 6.4) we present a generalized conceptual model incorporating the factors shown or presumed to be important in relation to primary production for the entire Texas-Louisiana shelf. Nutrients and light are clearly the proximate factors limiting phytoplankton growth. Nutrient levels in the area are determined by advective transport, upwelling, and regeneration. Light is affected by suspended sediments. Chemical pollutants could inhibit production. Phytoplankton populations suffer losses by advective transport out of the area, zooplankton grazing, and sinking out of the euphotic zone. This simple model summarizes our current knowledge of phytoplankton relations within the study area.

6.2.2 Zooplankton

As in the case of phytoplankton, most of our knowledge of zooplankton composition, distribution, and dynamics comes from studies off Timbalier Bay, LA (Offshore Ecology Investigation), near brine disposal sites off Calcasieu River (SPR studies), and four transects off south Texas (STOCS study). Additional important information on the distribution of penaeid shrimp larvae derives from monthly transect studies across the entire Texas-Louisiana shelf during the early 1960's. Different investigators have employed a variety of gear types and mesh sizes, which confounds exact comparisons between studies. However, from the available data, a reasonable synthesis of the nature and dynamics of zooplankton populations of the area can be constructed.

Composition and Standing Crop

A selected list of zooplankton groups reported from the Texas-Louisiana continental shelf (exclusive of fishes) is presented in Table 6.3. In the south Texas study, the zooplankton fishes were apparently included with the neuston fishes, and a complete list of zooplankton fishes cannot be compiled. As seen in Table 6.3, most of the important marine phyla are represented. Except for the copepods, only a few representative genera have been included. Since considerable quantitative information is available for the copepods, a complete listing of the genera has been provided. Extensive lists are also available for the foraminiferans, heteropods, pteropods, and a few other groups. A complete listing of known species would involve between one and two thousand names, and in many cases the larval forms could not be identified below major group. Thus, the zooplankton of the Texas-Louisiana shelf is a very diverse group, broadly representative of the animal kingdom and particularly rich in protozoans, heteropods, pteropods, and copepods, as well as larval forms representing a variety of phyla.

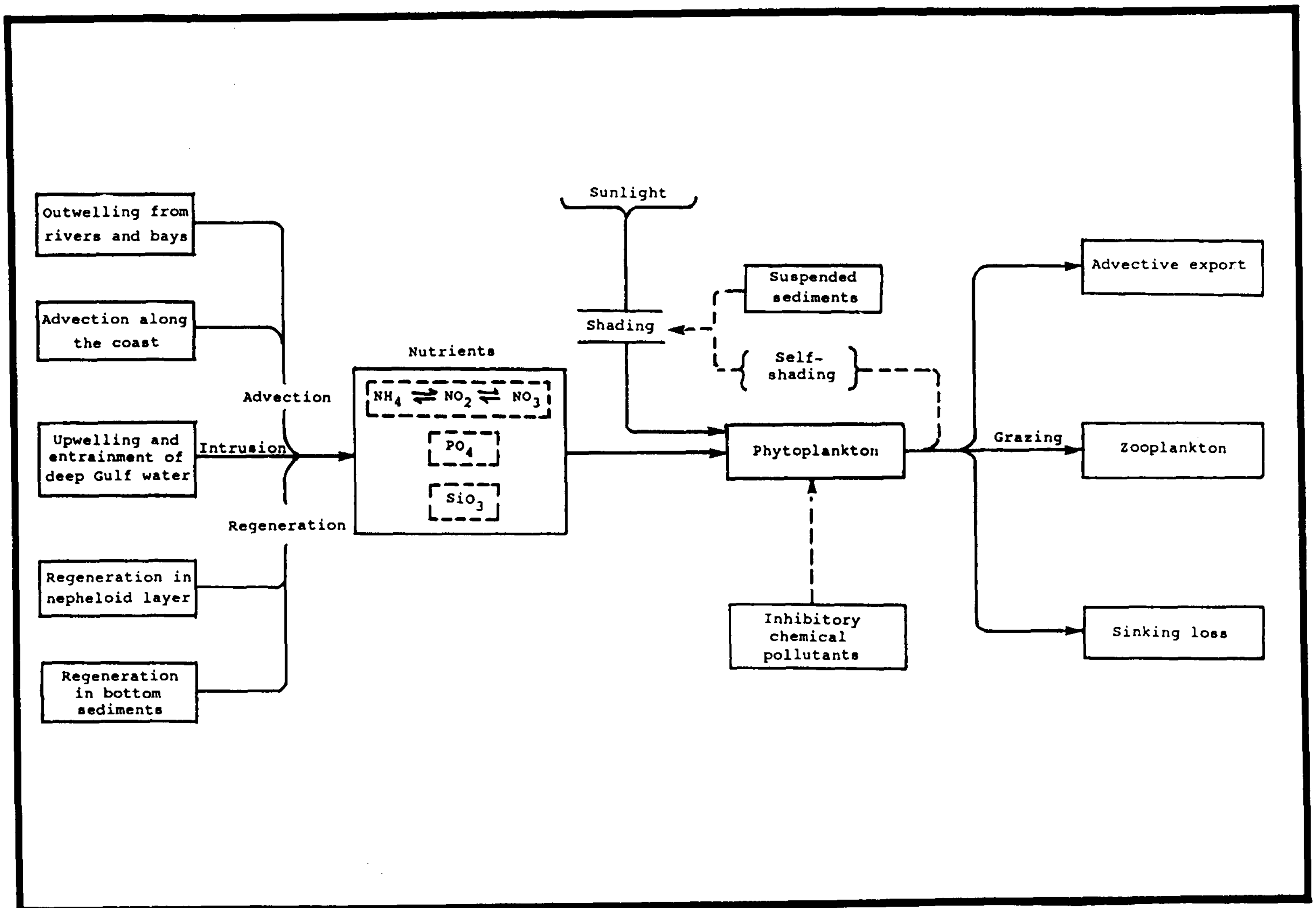


Figure 6.4. Conceptual model of phytoplankton production on the Texas-Louisiana continental shelf.

Table 6.3. A selected list of zooplankton groups reported from the Texas-Louisiana continental shelf (exclusive of fishes).

PROTOZOA
- Ciliatea (several genera)
- Foraminifera (many genera)

CNIDARIA
- Medusae (*Aglaura*, *Bougainvillia*, *Eutima*, *Obelia*, *Phialidium*, others)
- Siphonophora (*Diphyes*, physonectids)

CTENOPHORA (*Beroë*)

PHORONIDA (larvae)

ANNELIDA
- Polychaeta (adults and larvae)

MOLLUSCA
- Bivalvia (larvae)
- Cephalopoda (*Lolliguncula*, larvae)
- Gastropoda (heteropods, pteropods, larvae)

ARTHROPODA
- Crustacea
  - Cladocera (*Evadne*, *Penilia*, *Podon*)
  - Cirripedia (barnacle larvae)
  - Copepoda
    - Calanoida (*Acartia*, *Acrocalanus*, *Aetideus*, *Anomalocera*, *Augaptilus*, *Bradyidius*, *Calanopia*, *Calanus*, *Calocalanus*, *Candacia*, *Centropages*, *Clausocalanus*, *Ctenocalanus*, *Euaugaptilus*, *Eucalanus*, *Euchaeta*, *Euchirella*, *Haloptilus*, *Heterorhabdus*, *Ishnocalanus*, *Labidocera*, *Lophothrix*, *Lucicutia*, *Mecynocera*, *Nannocalanus*, *Neocalanus*, *Paivella*, *Paracalanus*, *Paracandacia*, *Parundinella*, *Phaenna*, *Pleuromamma*, *Pontella*, *Pontellina*, *Pontellopsis*, *Pseudodiaptomus*, *Rhinocalanus*, *Scaphocalanus*, *Scolecithricella*, *Scolecithrix*, *Stephos*, *Temora*, *Temoropia*, *Tortanus*, *Undinula*, *Xanthocalanus*)
    - Caligoida (larvae)
    - Cyclopoida (*Copilia*, *Corissa*, *Corycaeus*, *Ferranula*, *Lubbockia*, *Oithona*, *Oncaea*, *Paroithona*, *Sapphirina*, *Siphonostoma*, parasitic lichomolgid)
    - Harpacticoida (*Clytemnestra*, *Macrosetella*, *Microsetella*)
  - Ostracoda (*Conchoecia*, *Euconchoecia*)
  - Amphipoda (Gammarids, Hyperiids)
  - Cumacea
  - Mysidacea
  - Euphausiacea
  - Decapoda
    - Natantia (adults and larvae) (*Acetes*, *Lucifer*, *Ogyrides*, *Palaemonetes*, *Penaeus*, *Sicyonia*, *Trachypeneus*)
    - Reptantia (mostly larvae) (*Albunea*, *Callinectes*, *Hexapanopeus*, *Menippe*, *Neopanope*, *Pagurus*, *Panopeus*, *Persephona*, *Pinnixia*, *Portunus*, *Rhithropanopeus*, *Sesarma*, *Uca*)
    - Macrura (larvae)
  - Stomapoda (larvae)

CHORDATA
- Larvacea (*Oikopleura*)

Zooplankton standing crop values in the area are not really comparable, because of the variety of gear types and eight different mesh sizes that have been employed in the different studies. The ranges of values which have been reported are given as follows:

- wet weight = 0.66 to 2.5 g/m^3
- dry weight = 3.4 to 122.8 mg/m^3
- volume = 0.1 to 3,500 $\mu l/m^3$
- density = 166 to 1,539,373 individuals/m^3.

Ichthyoplankton

Full consideration of the ichthyoplankton will be deferred to Section 6.2.3 (Neuston).

Holoplankton vs. Meroplankton

Holoplankton includes those species that spend their entire lives in the water column. Meroplankton includes those species that appear in the plankton only during certain life history stages (generally the larval stages) or that appear in the water column only during special periods (such as reproduction). From Table 6.3, it is obvious that both types are abundantly represented in plankton samples of the Texas-Louisiana shelf. However, as a practical matter it is often difficult to determine whether a given species should be referred to one group or the other. For example, some copepod species divide their time between the bottom and the water column. In other cases, such as some cnidarians that practice alternation of generations, the definitions really break down. However, the great bulk of the holoplanktonic organisms are copepods, and in the discussions which follow, the copepods will be used as an indication of the abundance of holoplankton. Reported percentages of copepods in the plankton of the Texas-Louisiana continental shelf range from about 24% to over 98% of the total plankton. If all the holoplankton were considered, the range would likely be from 30 to over 98%, with holoplanktonic species averaging well over half the total zooplankton of the shelf water.

Seasonal and Areal Distribution

Aside from miscellaneous theses, dissertations, and minor reports which provide primarily taxonomic and distributional information, there are three quantitative zooplankton investigations worthy of consideration here. These include the copepod investigations of Marum (1979) off Timbalier Bay, LA (Offshore Ecology Investigation); multi-year zooplankton studies at several nearshore stations off Calcasieu River on the central Louisiana coast (SPR studies); and extensive multi-year investigations across the shelf of south Texas (STOCS studies). These several studies are not exactly comparable due to gear type and mesh size discrepancies. Therefore, the major results of each study will be addressed independently.

In the stations off Timbalier Bay, LA, Marum (1979) found that the total zooplankton biomass values ranged between about 60 and

630 mg/m^3 (Figure 6.5). There appeared to be a seasonal peak in the spring, with a late summer or fall low. Species diversity was highest in the fall and lowest during the spring. The most abundant copepod species, Acartia tonsa, varied between 135 to 2,400 individuals/m^3 with a definite spring peak. In transects extending out to 21 km from shore, Marum (1979) was able to distinguish three groups of copepods which were identified as coastal, shelf, and oceanic species. As shown in Table 6.4, the coastal species tended to dominate the nearshore station, but they sometimes were numerically dominant at the offshore station, as well. This is an area of dynamic hydrographic conditions, and seasonal changes in species composition are often dramatic. In general, species diversity decreased with distance from shore.

Major characteristics of the zooplankton populations off the Calcasieu River are summarized in Figure 6.6. Total zooplankton abundance at these nearshore stations varied from about 365 to 1,539,373 individuals/m^3 with a mean value of 85,408 individuals/m^3. Zooplankton volumes ranged from 10 to 3,500 μl/m^3. Surface values for the most abundant copepod, Acartia tonsa, ranged from 144 to 861,926 individuals/m^3 with a mean value of 47,610 individuals/m^3. This single species constituted 4.8 to 98.3% of the total zooplankton population with a mean value of 55.7%. No consistent pattern of seasonal abundance was evident, but a dramatic population explosion occurred in September of 1983, due apparently to a major storm sweeping the area. Comparison of zooplankton volumes from surface and bottom samples revealed no consistent patterns of abundance, but nighttime bottom values averaged 3.6 times the daytime bottom values (mean values of 1,232 μl/m^3 vs. 359 μl/m^3).

General characteristics of the zooplankton of the south Texas continental shelf are presented in Table 6.5. The nearshore stations showed higher average zooplankton abundance than offshore stations (mean values of 3,496 vs. 1,055 individuals/m^3). Northernmost stations averaged higher than southernmost stations (2,943 vs. 2,008 individuals/m^3). Total copepod abundance showed the same picture as the total zooplankton abundance (nearshore = 2,053 vs. offshore = 607 individuals/m^3 and northernmost = 1,900 vs. southernmost = 974 individuals/m^3). However, the copepod percentage of the total zooplankton showed no consistent pattern. Seasonal characteristics of the south Texas zooplankton are summarized in Figure 6.7 based upon transects off Corpus Christi. Here, there is a definite spring peak and summer low in nearshore and midshelf populations of total zooplankton and total copepods. However, the offshore values were highest in the winter and lowest in the spring and fall. Copepod abundance as a percent of the total zooplankton showed a somewhat confused picture, with inshore values generally exceeding those offshore. As seen in Table 6.6, the south Texas data revealed that individual copepod species tend to fall into several recognizable distribution groups. Ten species appear to be ubiquitous, seven are confined to shallow waters (of which four are most abundant when salinities are low), one species is confined to mid-depths, and seven are deepwater species. Copepod diversities tended to be greatest offshore. A summary of the zooplankton abundance data for the south Texas shelf is given as follows (mean value followed by range in parentheses):

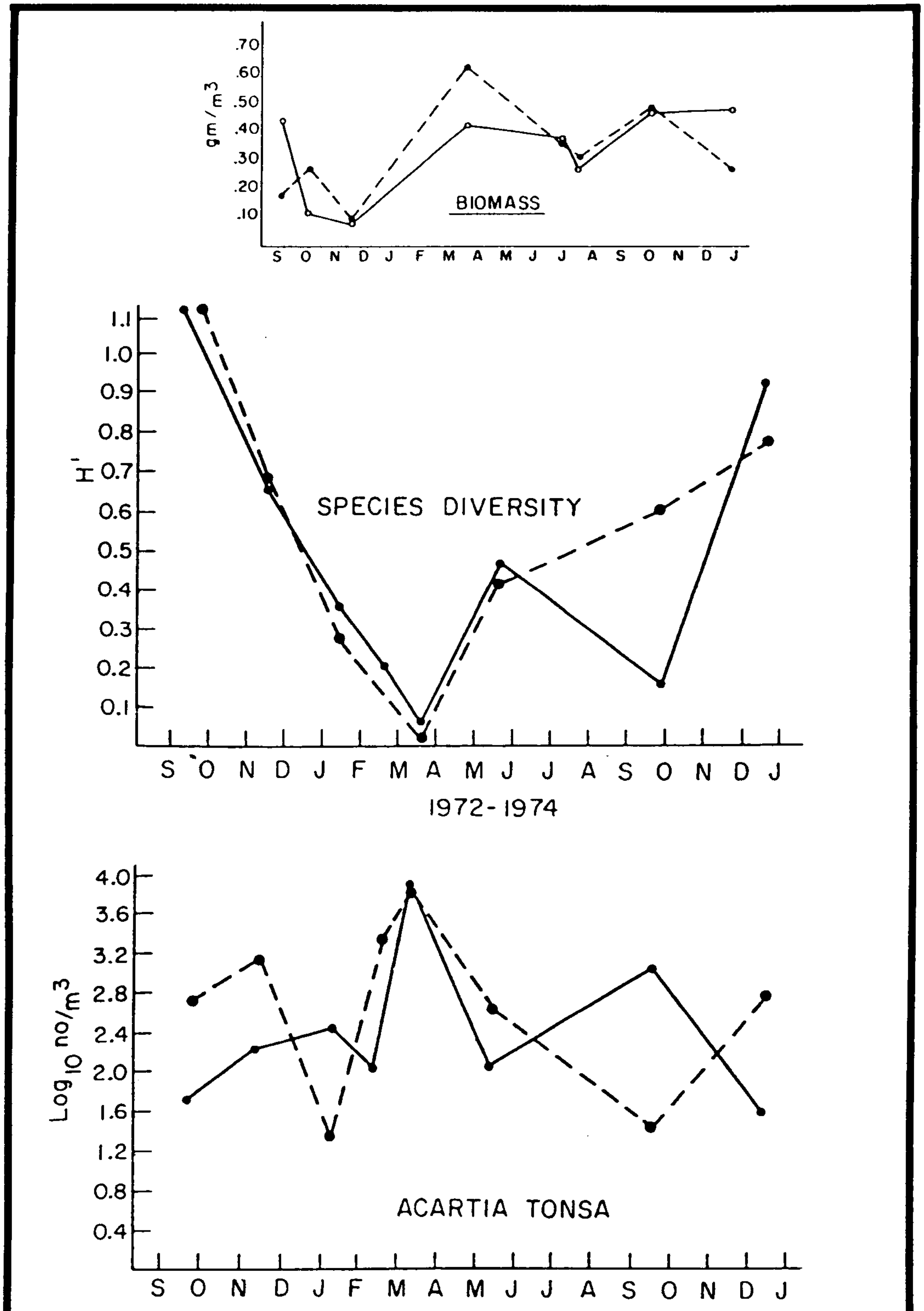


Figure 6.5. Biomass and species diversity (H') of the total zooplankton and numerical abundance of Acartia tonsa off Timbalier Bay, LA. Two nearby stations are compared (dashed and solid lines) (From: Marum, 1979).

Table 6.4. Comparison of copepod species composition at two stations off Timbalier Bay, LA (From: Marum, 1979).

Cruise Date	Species Group*	Percent in Species Group	
		6 km offshore	21 km offshore
October, 1972	C	53	1
	S	42	76
	O	5	23
April, 1973	C	71	49
	S	24	45
	O	5	6
July, 1973	C	98	96
	S	1	3
	O	1	1
October, 1973	C	35	12
	S	59	69
	O	6	19

*C = coastal.
S = shelf.
O = oceanic species.

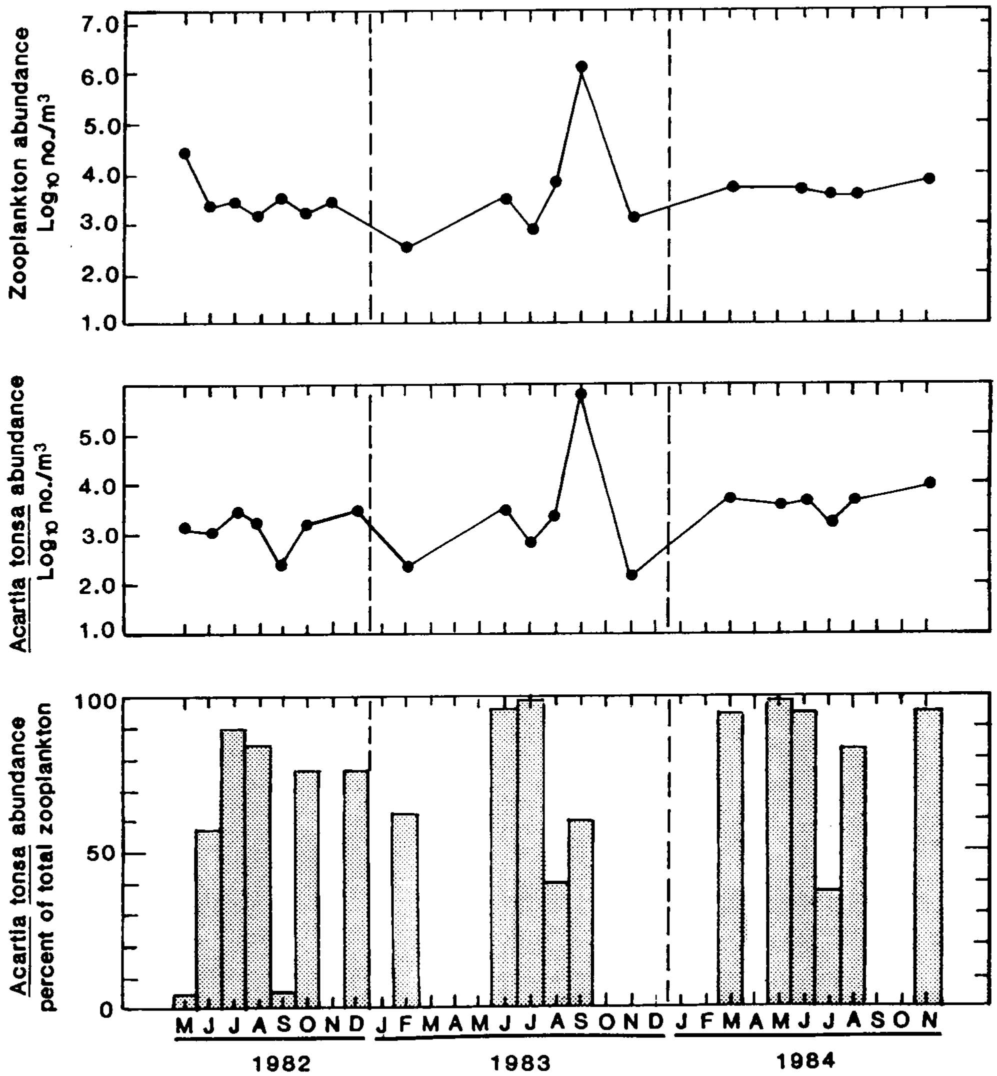


Figure 6.6. Characteristics of zooplankton off the Calcasieu River, LA (Data from: SPR studies).

Table 6.5. Zooplankton abundance and composition on the south Texas continental shelf, giving average values based upon two years of data (1975-1976). Mean values have been calculated by depth and transect (Data from: STOCS studies).

Station	Transect Number I	II	III	IV	Mean
TOTAL ZOOPLANKTON ABUNDANCE (no./m^3)					
1	4,336	3,077	3,377	3,192	3,496
2	3,445	2,250	1,741	1,969	2,351
3	1,049	1,208	1,100	864	1,055
Mean	2,943	2,178	2,073	2,008	
TOTAL COPEPOD ABUNDANCE (no./m^3)					
1	3,791	1,768	1,139	1,513	2,053
2	1,175	1,090	836	796	974
3	736	624	457	612	607
Mean	1,900	1,161	811	974	
COPEPODS/TOTAL (as percent)					
1	71.7	67.1	39.0	49.8	56.9
2	41.8	55.0	49.3	39.0	46.3
3	66.1	54.7	57.1	69.8	61.9
Mean	59.9	58.9	48.5	52.9	

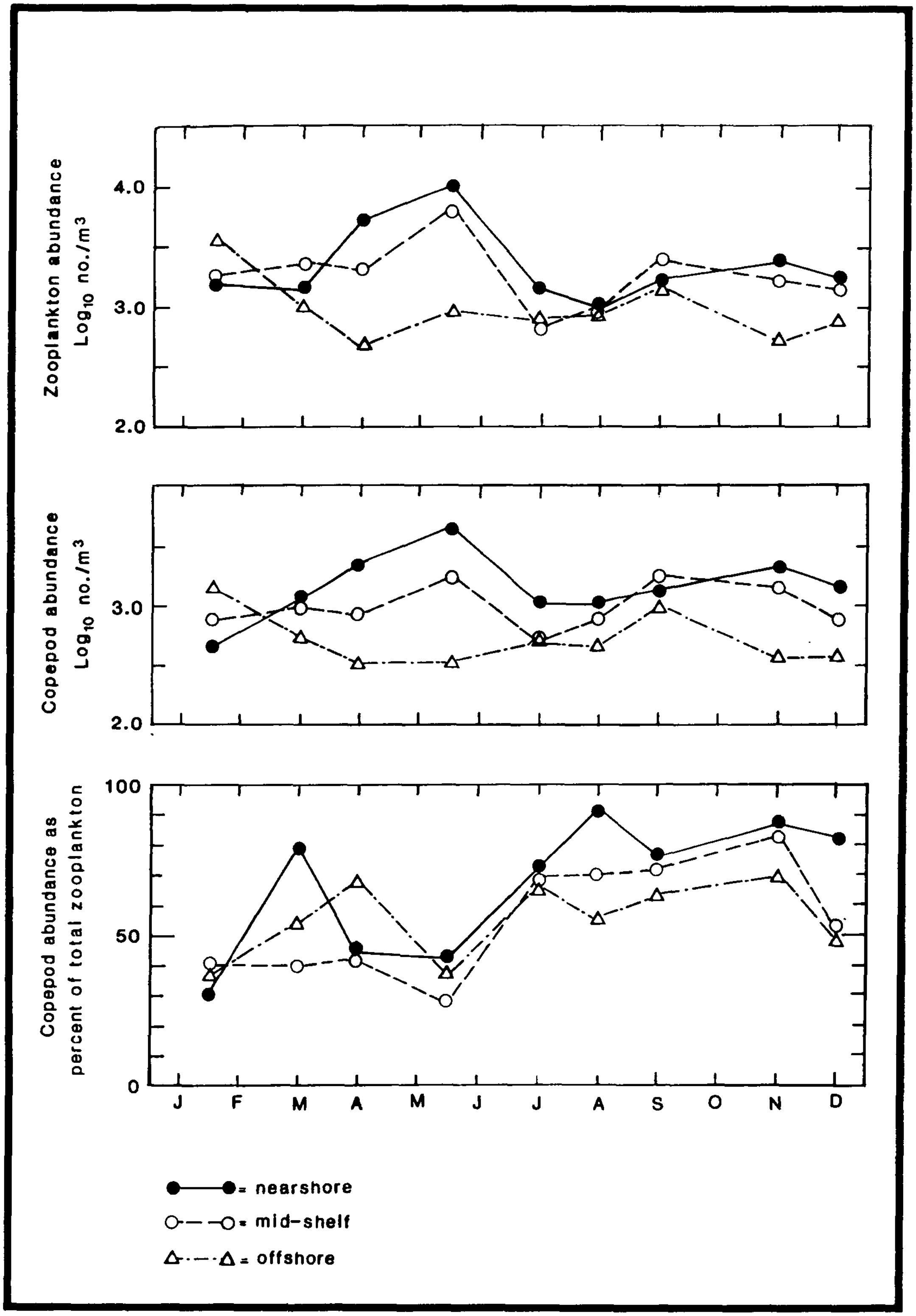


Figure 6.7. Characteristics of zooplankton off the south Texas coast based on a transect off Corpus Christi Bay. Shown are data from three stations sampled during 1976 (Data from: STOCS studies).

Table 6.6. Major copepod species groups encountered on the south Texas continental shelf (Data from: STOCS studies).

UBIQUITOUS SPECIES	
Centropages velificatus	*Oncaea venusta*
Clausocalanus furcatus	*Paracalanus aculeatus*
Clausocalanus jobei	*Paracalanus indicus*
Corycaeus americanus	*Paracalanus quasimodo*
Farranula gracilis	*Temora turbinata*
CONFINED TO SHALLOW WATERS	
Acartia tonsa (ls)*	*Labidocera aestiva* (ls)*
Corycaeus amazonicus	*Oithona nana* (ls)*
Corycaeus giesbrechti	*Paracalanus crassirostris* (ls)*
Eucalanus pileatus	
CONFINED TO MID-DEPTHS	
Nannocalanus minor	
CONFINED TO DEEP WATERS	
Calocalanus pavo	*Oithona plumifera*
Lucicutia flavicornis	*Oithona setigera*
Oncaea mediterranea	

*ls = low salinity species.

- total count = $2,301/m^3$ (166 to $11,030/m^3$)
- total volume = $192.3\ \mu l/m^3$ (34.3 to $792.2\ \mu l/l$)
- total dry weight = $23.3\ mg/m^3$ (3.4 to $122.8\ mg/m^3$)
- copepod count = $1,211/m^3$ (131 to $9,745/m^3$).

Microzooplankton was studied off south Texas using Niskin bottle collections. Microplankton biomass was found to be 3 to 17% of the macroplankton biomass. Species identification revealed great diversity among the microplankton components, and it was found that some of the species and groups are good indicators of water mass. Inshore waters, shallow offshore waters, deep offshore waters, and upwelling are all characterized by typical indicator species and groups.

Investigators at the National Marine Fisheries Service (NMFS) Fishery Laboratory in Galveston, TX have provided seasonal maps showing the density of larvae of the genus _Penaeus_ throughout the Texas-Louisiana shelf waters during the year 1962 (Figure 6.8). The maps are characterized by great seasonal variability in distribution patterns, high density areas, and larval stage composition. Summer and fall months exhibit the highest densities and most widespread distribution patterns, and spring shows the fewest young larval stages. Larvae of the three commercial shrimp species (_P_. _aztecus_, _P_. _duorarum_, and _P_. _setiferus_) are lumped together because of the difficulty in distinguishing their larval stages.

Controlling Factors

Clearly, a major factor affecting the distribution and abundance of zooplankton organisms is the food supply. In the open sea, phytoplankton is the primary food of the zooplankton. On the continental shelf, phytoplankton may be supplemented by suspended organic detritus particles brought down by rivers or resuspended from the bottom sediments. Scanning electron microscope studies of the fecal pellet contents of 11 species of copepods from the Texas-Louisiana shelf reveal that all are primarily herbivores but that some ingest animals and suspended inorganic sediments, as well (Table 6.7). Any organic detritus present would probably not be identifiable by the methods used. As in the case of the phytoplankton, the zooplankton showed greater biomass and numbers off Louisiana than off south Texas. Data are not sufficient to demonstrate zooplankton increases associated with phytoplankton blooms. In any event, biomass and numerical data alone do not provide an adequate basis for relating zooplankton to phytoplankton populations. Dagg and Turner (1982) studied the impact of zooplankton grazing on phytoplankton populations of Georges Bank and the New York Bight using a combination of laboratory and field methods. They concluded that during the spring phytoplankton bloom, grazing could not keep up with phytoplankton production, but that during periods of low phytoplankton production, copepod ingestion rates were often equivalent to or slightly greater than primary production rates. About 50% of the annual primary production was grazed by the copepod community. There is no reason to doubt that this also applies to the Texas-Louisiana shelf. However, the factor of suspended detritus must be considered in the turbid Texas-Louisiana waters, and because phytoplankton abundance off south Texas is greatest

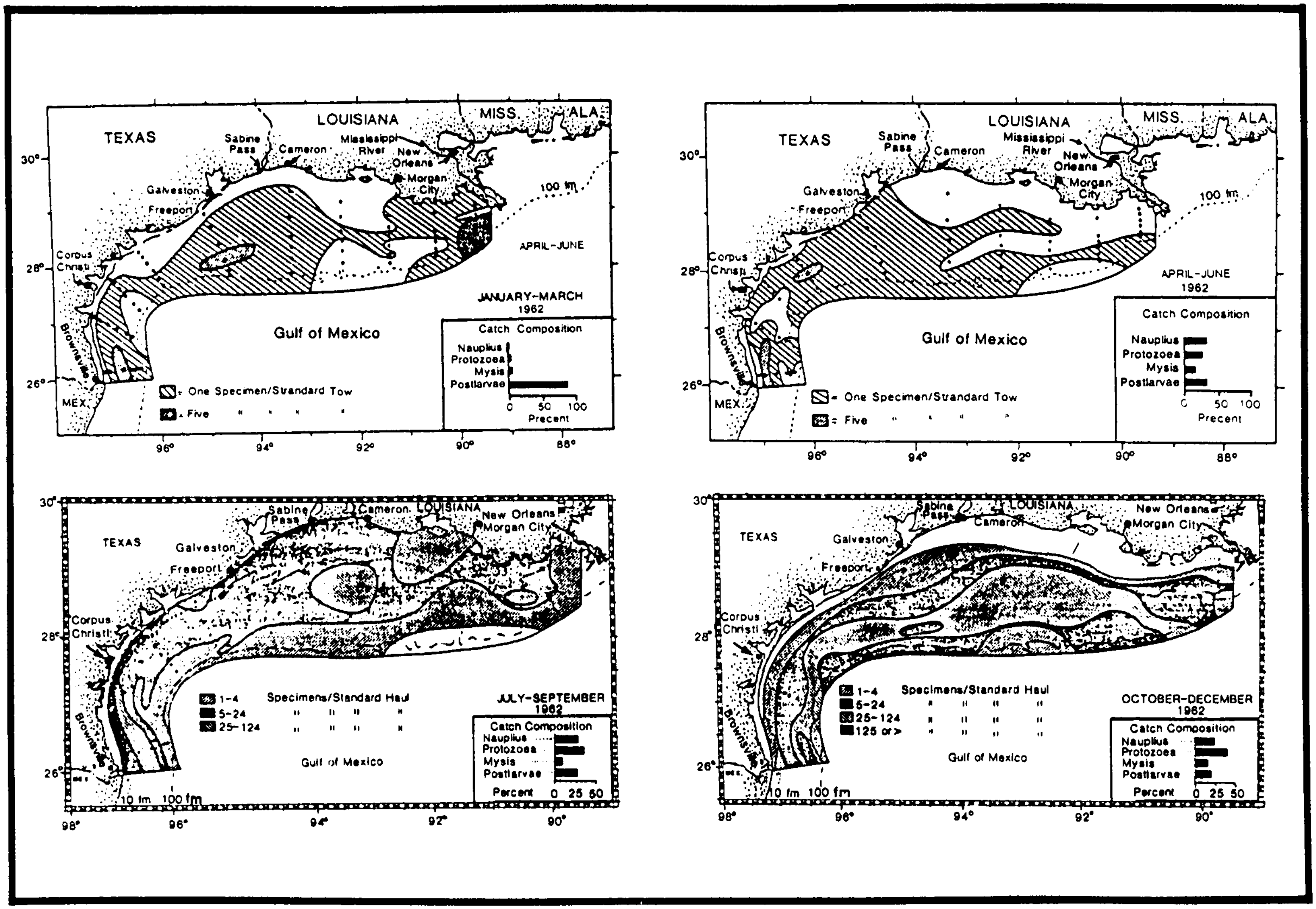


Figure 6.8. Distribution of planktonic stages of Penaeus spp. on the continental shelf of the northwestern Gulf of Mexico during 1962 (From: Temple et al., 1964, and Temple and Fischer, 1965).

Table 6.7. Food and other material consumed by individual copepod species off the Mississippi River Delta and off Galveston, TX, based upon scanning electron microscopic examination of natural copepod fecal pellets. Relative importance of food items is noted by ranking order (1 = most abundant; p indicates that an item was present) (From: Turner, 1984a,b,c; 1985; 1986a,b).

	Identified Fecal Pellet Contents				
Copepod Species	Phyto-plankton	Crustacean Parts	Tintinnids	Detritus/ Sediments	Feeding Type
Acartia tonsa	1	2			Omnivore, suspension feeder
Anomalocera ornata	1				Herbivore
Eucalanus pileatus	1	2	3	p	Omnivore
Labidocera aestiva	1	2			Omnivore, raptorial feeder
Oithona plumifera	1				Herbivore
Oithona simplex	1				Herbivore
Oncaea venusta	1	2			Omnivore, selective, possibly raptorial
Paracalanus quasimodo	1	2			Omnivore
Temora stylifera	1	2		p	Omnivore
Temora turbinata	1	2		p	Omnivore
Undinula vulgaris	1		2		Omnivore, suspension feeder

in the nepheloid layer, nonselective zooplankters there would be forced to ingest the organic and inorganic particles present in the nepheloid layer.

Water mass circulation patterns on the Texas-Louisiana shelf play a significant role in determining zooplankton distribution patterns. Marum (1979) demonstrated the seasonally variable appearance of coastal copepods at the offshore station (see Table 6.4). Somewhat the same picture has been reported off south Texas. Both copepods and microzooplankters (particularly, foraminiferans) are good indicators of water masses, and circulation patterns off south Texas have been interpreted in terms of the zooplankton species present (Casey, 1977).

Many zooplankton species are known to undergo daily vertical migrations. However, most of the studies of the Texas-Louisiana shelf have shown that whereas night time surface collections have more zooplankton per unit volume, the difference is not statistically significant. On the other hand, at the bottom, night zooplankton samples off Calcasieu River, LA averaged 3.6 times the daytime values in terms of zooplankton volumes. This matter has not been thoroughly investigated in the study area.

Breeding seasons must play a significant role in the seasonal appearance of individual zooplankton species, and this is best illustrated by the seasonal distribution patterns of Penaeus spp. larvae as shown in Figure 6.8. The same must apply to other meroplanktonic as well as holoplanktonic species, but actual breeding seasons are not well known, and most of the larval forms are not identifiable to species.

Laboratory studies have shown that in high concentrations, many chemicals, including heavy metals and chlorinated hydrocarbons, can damage and kill zooplankton species. Studies have also shown that natural zooplankton populations of the Texas-Louisiana shelf carry body burdens of a number of types of such chemicals. However, no studies have shown that such chemicals constitute a significant problem for the local zooplankton populations. Mixing and dilution of the chemicals together with the rapid reproduction rates of the species suggest that the holoplanktonic forms, even if temporarily affected, would quickly return to normal. However, benthic adults of meroplanktonic larvae could be seriously affected, and this problem will be discussed in connection with the benthos.

Zooplankton Production Model

From the above discussion it is clear that we have a good general grasp of the zooplankton relations of the Texas-Louisiana continental shelf, and this information is summarized in the conceptual zooplankton model presented in Figure 6.9. The resident zooplankton population feeds upon phytoplankton, suspended organic detritus, and each other. It is supplemented by imported populations of the various water masses which sweep the area and by the addition of eggs and larvae of meroplanktonic species. Zooplankton of the area experiences loss through advective export, predation, self-consumption, and respiration, as well as maturation of meroplankton into nekton or benthos. Inhibitory

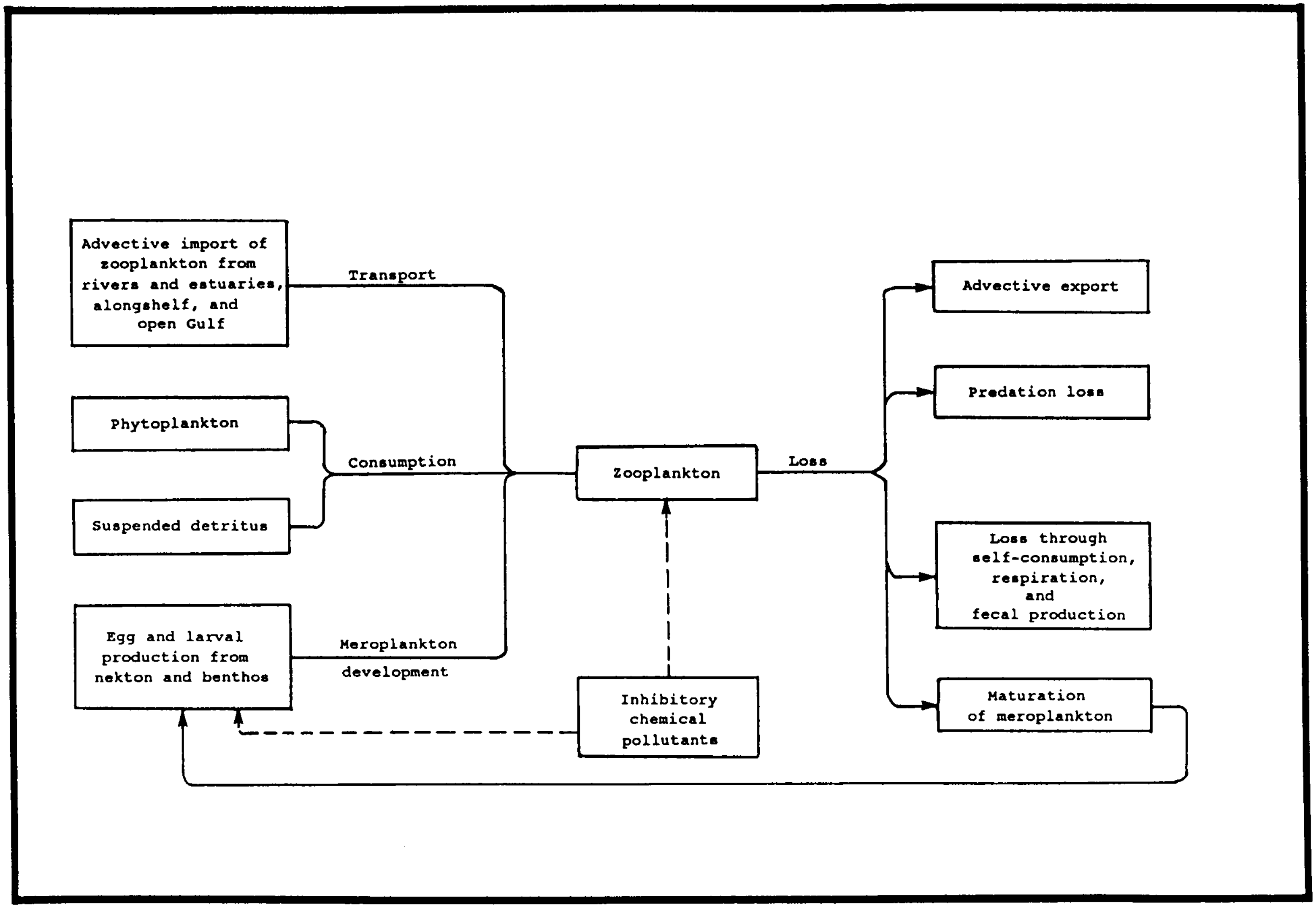


Figure 6.9. Conceptual model of zooplankton production on the Texas–Louisiana continental shelf.

chemical pollutants may affect the zooplankton directly or through the nektonic and benthonic adults which produce the meroplanktonic forms.

Unfortunately, we do not have a good grasp of the details. The species diversity is staggering, and most of the larval forms cannot be identified beyond major taxonomic group. We can roughly allocate species to the holo- and meroplanktonic categories, and we can associate many of the species with general habitats and water mass types. However, factors responsible for major population changes are unexplained, and except for the south Texas shelf area, seasonal and annual changes are not well documented, much less understood. Food habits of only a few species have been investigated. Three general problem areas may be identified:

1) The many factors controlling the zooplankton populations are very complex and only partially understood.

2) It is difficult to identify and repeatedly sample a given water mass to follow the time sequence of a particular population.

3) Zooplankton population changes take place on a scale of only a few days, and frequent sampling is required to ascertain the dynamics of any given group of zooplankters.

The matter is further complicated by the fact that the various groups exhibit different behavior patterns, and vertical migration by some species may take them into different water masses each day. Although detailed understanding of the zooplankton populations is many years away, this can only be achieved in conjunction with studies of water mass movements and a program of sampling at intervals of only a few days.

6.2.3 Neuston

The neuston includes all those plants and animals that live on or just beneath the surface of marine waters. The only neuston investigations carried out in the northwestern Gulf of Mexico to date have been those of Berkowitz (1976) above the continental slope of south Texas, and of the various investigators who examined the south Texas shelf as part of the STOCS studies (Finucane, 1976, 1977; Finucane et al., 1977; Pequegnat and Wormuth, 1977; Wormuth, 1979; Wormuth et al., 1980). The present discussion will summarize the STOCS studies. Included will be both the non-vertebrate and fish fauna. Phytoneuston was not reported except for occasional catches of *Sargassum*.

Composition and Standing Crop

A summary listing of the non-vertebrate taxa encountered in the south Texas neuston samples is presented in Table 6.8. A complete listing would include about a hundred taxa representing ten phyla. Larval forms were well represented, but seldom could these be identified to the species level. Among the identifiable non-vertebrates, the most diverse were the pteropods, copepods, and decapods. A complete listing of the fishes identified in the south Texas neuston studies is presented

Table 6.8. Phylogenetic listing of taxa identified in south Texas neuston samples exclusive of fishes (Data from: STOCS studies).

PROTOZOA	ARTHROPODA
Foraminifera	Cladocera
	Cirripedia larvae
CNIDARIA	Copepoda (37 species + larvae)
Siphonophora (3 species)	Ostracoda
Medusae	Amphipoda
	Cumacea
CTENOPHORA	Decapoda
	Natantia (6 species + larvae of 21 species)
NEMATODA	Reptantia (6 species + larvae of 25 species)
	Euphausiacea
ANNELIDA	Mysidacea (5 species)
Polychaeta (4 families)	Stomatopoda (1 species)
	Insecta (1 species)
MOLLUSCA	
Bivalve larvae	CHAETOGNATHA
Cephalopoda (2 species)	
Gastropoda	ECHINODERMATA (larvae)
Heteropoda (2 families)	
Pteropoda (14 species)	CHORDATA
	Urochordata
	Salps
	Larvae

in Table 6.9. Represented are 45 families, 77 identified species, and around 30 taxa not identifiable to the species level. Included are species characteristic of estuaries, the continental shelf, and the open Gulf. As indicated in the tables, this is a highly diverse fauna.

The general abundance of the total neuston and some of the major components are presented in Table 6.10. Reported are the mean and range of values for the ash-free dry weights and numerical abundance. Copepods were generally the major component, although pteropods, decapod larvae, and tunicates were often well represented. As suggested by the wide ranges of values, numerical abundance varies greatly in relation to locality and time.

Seasonal and Areal Distribution Patterns

The STOCS neuston data show great variability from collection to collection, but when combined they display definite statistical trends. In Table 6.11, the nearshore/offshore data are presented for total catch and a number of the major categories. Three basic trends are discernable:

1) Abundance greatest nearshore and decreasing with distance from shore (displayed by the total catch, copepods, and "other").

2) Abundance greatest at mid-shelf and lowest on the outer shelf (displayed by the mollusca, decapod larvae, fish eggs, and fish larvae).

3) Abundance greatest on the outer shelf and lowest nearshore (displayed by the tunicates).

Seasonal patterns of neuston abundance are presented in Table 6.12. Here, five general patterns are noted as follows:

1) Winter/spring peak, summer high, fall low (fish eggs).

2) Spring peak, all other seasons low or moderate (total catch, copepods, "other").

3) Spring/fall peaks, other seasons low (mollusca, decapod larvae).

4) Winter, spring, and late summer peaks, mid-summer and fall low (tunicates).

5) March, May/June, August, and December peaks, other months low (fish larvae).

All groups appear to exhibit spring peaks, and all except the copepods and "other" category display peaks at other seasons, as well. As each category includes a great many species, it is not surprising that a diversity of pattern types should appear. The nearshore abundance

Table 6.9. Phylogenetic listing of fish taxa identified in south Texas neuston samples (Data from: STOCS studies). Most of these are larvae and juvenile forms of species whose adults are demersal or pelagic.

ELOPIDAE - Tarpons
Elops saurus

MURAENIDAE - Morays
Gymnothorax nigromarginatus

NETTASTOMATIDAE - Duckbill eel
Hoplunnis sp.

CONGRIDAE - Conger eels
Ariosoma sp.

OPHICHTHIDAE - Snake eels
Myrophis punctatus

CLUPEIDAE - Herrings
Brevoortia patronus
Brevoortia sp.
Etrumeus teres
Harengula jaguana
Opisthonema oglinum
Sardinella aurita
Sardinella sp.

ENGRAULIDAE - Anchovies
Anchoa hepsetus
Anchoa mitchilli
Anchoa sp.
Engraulis eurystole

SYNODONTIDAE - Lizardfishes
Saurida brasiliensis
Saurida sp.
Synodus foetens
Synodus sp.

ANTENNARIIDAE - Frogfishes
Antennarius scaber
Antennarius sp.
Histrio histrio

BREGMACEROTIDAE - Codlets
Bregmaceros atlanticus

GADIDAE - Codfishes
Urophycis regia
Urophycis sp.

OPHIDIIDAE - Cusk-eels
Brotula barbata
Ophidion sp.

EXCOCOETIDAE - Flyingfishes
Cypselurus cyanopterus
Cypselurus exsiliens
Cypselurus furcatus
Cypselurus melanurus
Cypselurus sp.
Euleptorhamphus velox
Exocoetus obtusirostris
Hemirhamphus brasiliensis
Hirundichthys rondeleti
Hyporhamphus unifasciatus
Oxyporhamphus micropterus
Parexocoetus brachypterus
Prognichthys gibbifrons

BELONIDAE - Needlefishes
Ablennes hians
Strongylura marina
Strongylura notata
Strongylura sp.
Tylosaurus crocodilus

ATHERINIDAE - Silversides
Membras martinica

CENTRISCIDAE - Snipefishes
Macrorhamphosus gracilis

SYNGNATHIDAE - Pipefishes
Hippocampus erectus
Syngnathus louisianae
Syngnathus pelagicus

SERRANIDAE - Sea basses
Centropristis sp.

RACHYCENTRIDAE - Cobias
Rachycentron canadum

CARANGIDAE - Jacks
Caranx hippos
Caranx latus
Caranx sp.
Chloroscombrus chrysurus
Trachinotus carolinus
Trachinotus falcatus
Trachinotus sp.
Trachurus lathami

CORYPHAENIDAE - Dolphins
Coryphaena equisetis
Coryphaena hippurus
Coryphaena sp.

Table 6.9. (Continued).

LOBOTIDAE - Tripletails	SCOMBRIDAE - Mackerels
Lobotes surinamensis	_Auxis_ sp.
	Scomberomorus cavalla
GERREIDAE - Mojarras	_Scomberomorus maculatus_
Eucinostomus sp.	_Scomberomorus_ sp.
HAEMULIDAE - Grunts	ISTIOPHORIDAE - Billfishes
Conodon nobilis	_Istiophorus platypterus_
SCIAENIDAE - Drums	STROMATEIDAE - Butterfishes
Cynoscion sp.	_Ariomma bondi_
Leiostomus xanthurus	_Nomeus gronovii_
Menticirrhus sp.	_Peprilus burti_
Micropogonias undulatus	_Peprilus_ sp.
	Psenes cyanophrys
MULLIDAE - Goatfishes	SCORPAENIDAE - Scorpionfishes
Mullus auratus	_Scorpaena_ sp.
Mullus sp.	
	TRIGLIDAE - Searobins
POMACENTRIDAE - Damselfishes	_Prionotus_ sp.
Pomacentrus fuscus	
	BOTHIDAE - Lefteye flounders
MUGILIDAE - Mullets	_Citharichthys macrops_
Mugil cephalus	_Etropus crossotus_
Mugil curema	_Etropus_ sp.
Mugil sp.	_Paralichthys_ sp.
POLYNEMIDAE - Threadfins	CYNOGLOSSIDAE - Tonguefishes
Polydactylus octonemus	_Symphurus civitatus_
CLINIDAE - Clinids	BALISTIDAE - Leatherjackets
	Balistes capriscus
	Canthidermis maculatus
BLENNIIDAE - Combtooth blennies	_Monacanthus hispidus_
GOBIIDAE - Gobies	OSTRACIIDAE - Boxfishes
Gobionellus boleosoma	_Lactophrys_ sp.
Gobionellus sp.	
Gobiosoma bosci	TETRAODONTIDAE - Puffers
Gobiosoma robustum	_Sphoeroides parvus_
Gobiosoma sp.	_Sphoeroides_ sp.
MICRODESMIDAE - Wormfishes	DIODONTIDAE - Porcupinefishes
Microdesmus sp.	_Chilomycterus schoepfi_
	Diodon hystrix
TRICHIURIDAE - Cutlassfishes	
Trichiurus lepturus	FAMILY UNKNOWN
	Leptocephalus larva

Table 6.10. Abundance of neuston on the south Texas continental shelf based on transects off Corpus Christi (Data from: STOCS studies).

	Mean	Range
ASH-FREE DRY WT. (g/1,000 m^3)	6.46	0.4 to 16.23
NUMBERS (no./1,000 m^3)		
All species combined	148,690	2,460 to 1,551,790
Mollusca	4,153	0 to 56,280
Copepoda	88,133	109 to 1,251,232
Decapoda larvae	9,178	0 to 102,614
Tunicates	2,919	0 to 66,064
Fish eggs	3,548	0 to 117,838
Fish larvae	1,249	0 to 6,567
"Other"	45,309	324 to 273,480

Table 6.11. Neuston abundance by station depth for a transect across the continental shelf off Corpus Christi. All seasons as well as day/night collections are combined (Data from: STOCS studies).

	Abundance (no. individuals/1,000 m^3)							
Depth	All Groups Combined	Mollusca	Copepods	Decapod Larvae	Tunicates	Fish Eggs	Fish Larvae	"Other"
Nearshore	210,965	3,914	134,469	9,651	1,577	3,792	1,271	56,291
Midshelf	163,391	5,489	96,545	10,101	3,253	5,895	1,503	40,605
Outer Shelf	71,714	3,055	33,386	7,782	3,925	973	972	21,621

Table 6.12. Neuston abundance by season for a transect across the continental shelf off Corpus Christi. All stations as well as day/night collections are combined (Data from: STOCS studies).

	Abundance (no. individuals/1,000 m^3)							
Month	All Groups Combined	Mollusca	Copepods	Decapod Larvae	Tunicates	Fish Eggs	Fish Larvae	"Other"
Jan/Feb	85,584	1,790	47,533	5,138	2,588	8,084	302	20,149
Mar	127,113	3,115	53,132	15,384	6,168	8,036	3,584	37,694
Apr	178,639	5,431	131,436	10,018	3,461	3,740	470	24,083
May/Jun	518,112	14,921	363,442	16,445	9,130	4,279	1,421	108,474
Jul	65,386	983	41,682	5,144	426	3,060	957	13,134
Aug	114,118	7,491	25,967	14,134	1,796	3,345	1,842	59,543
Sep/Oct	54,743	1,547	25,939	4,600	627	372	304	21,354
Nov	71,370	1,085	44,102	4,867	393	517	353	51,317
Dec	123,146	1,011	59,968	6,872	1,678	499	2,009	72,037
Mean	148,690	4,153	88,133	9,178	2,919	3,548	1,249	45,309

observed earlier and the general presence of a spring peak of abundance observed here both undoubtedly reflect the generally greater availability of phytoplankton as a food supply in the nearshore waters and during the spring season.

The relationship between daytime and nighttime collections is presented in Table 6.13. Although considerable variability is observed in individual day/night comparisons, as an overall rule the night collections are more abundant for most of the categories and depths. Only the tunicates at mid-shelf and the fish eggs on the outer shelf do not show a nighttime numerical predominance. Taxa more abundant in daytime samples include the copepod *Anomalocera ornata* and fish larvae of the families Mugilidae, Exocoetidae, and Mullidae. Examples of taxa more abundant at night include foraminiferans, medusae, bivalve mollusk larvae, hyperiid amphipods, barnacle nauplii, decapod and stomatopod larvae, euphausiids, mysids, chaetognaths, most fish larvae, and the adults of several copepods and other crustaceans. Much detailed information is available on the areal, seasonal, and diurnal distribution patterns of individual species and groups.

Although the STOCS studies resulted in a monumental numerical data base, the information is seldom presented in the most useful form in the study reports. The above summary of seasonal and areal distribution of neuston was generated by recalculating from the original computer data sheets in the appendices to the reports. Both detailed and summary information could also be presented in density contour maps, of which an example is presented here. Figure 6.10 presents the density distribution of larvae of the spot (*Leiostomus xanthurus*) during the winter months (as number of larvae/1,000 m^3, averaging data obtained by the 333 and 505-μm mesh nets).

Controlling Factors

Among the many factors that determine the distribution and abundance of the neuston, food supply is perhaps paramount. All groups displayed a spring peak, and most groups were numerically highest in the nearshore waters, suggesting a relationship with the phytoplankton and suspended detritus. However, the relationship may be indirect for some groups. For example, the copepods may be more abundant in the spring because of the phytoplankton blooms, and the fish larvae may be more abundant because of the availability of increased copepods as a food supply. Peaks of several groups occurred at times other than spring, and this probably relates to competitive interaction between species. They cannot all be supported by the same food supply at the same time.

Another major factor determining the distribution and abundance of the neuston is water currents and associated wind patterns. Wind has an effect upon the movement of water masses near the surface, and it has a major role in distributing materials directly upon the surface (sometimes referred to as floaton). Thus, *Sargassum* and its associated biota may be blown in from the open Gulf, and terrestrial insects may be blown out from the neighboring land area. As pointed out earlier, zooplankton is definitely moved around by water currents, and it then becomes available to the neuston community.

Table 6.13. Dominance of nighttime over daytime catches expressed as the percentage of stations at a given depth in which the night catch was greater than the day catch on transects off Corpus Christi, TX (Data from: STOCS studies).

Category	Station Depth			Mean
	Nearshore	Mid-shelf	Outer shelf	
Total catch	55.6	88.9	83.3	75.9
Mollusca	88.9	94.4	66.7	83.3
Copepods	61.1	88.9	83.3	77.8
Decapod larvae	94.4	94.4	94.4	94.4
Tunicates	80.0	50.0	70.6	66.9
Fish eggs	76.5	52.9	16.7	48.7
Fish larvae	77.8	88.9	72.2	79.6
Mean	76.3	79.8	69.6	

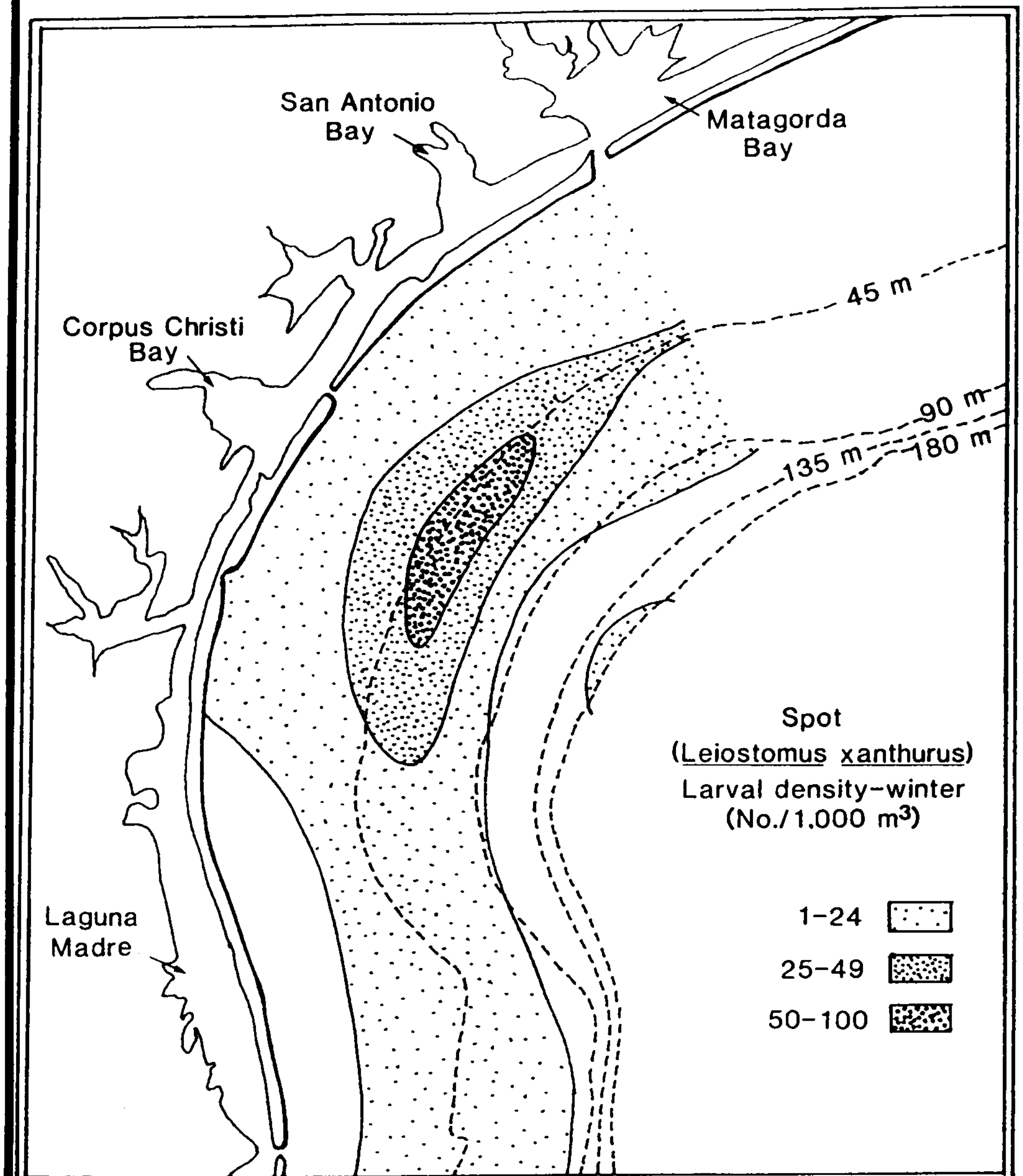


Figure 6.10. Distribution of larvae of the spot (Leiostomus xanthurus) during the winter months. Density values were obtained by averaging the catch obtained by the 333 and 505-μm mesh nets.

Solar radiation includes ultraviolet rays that are lethal to many biological forms. It may inhibit photosynthesis and directly damage tissues. This effect would be greatest during mid-summer, and a definite July minimum was evident for most neuston groups. Day/night variation in neuston abundance was striking for most groups.

Breeding seasons play a major role in determining the seasonal distribution and abundance of individual species. Whereas copepods and other holoplanktonic species may expand rapidly in response to phytoplankton pulses, meroplanktonic species availability depends more upon the set breeding seasons of the nektonic and benthonic adults. These individual breeding seasons seem to be spread throughout the year with concentrations at particular seasons.

Various forms of chemical pollutants within the water column can cause neuston mortality. However, as in the case of zooplankton, the dilution factor of the water column and the rapid reproduction rate of many neuston species suggest that this source of pollution is not likely to be a major factor acting directly upon this system. It can, of course, cause major impacts upon benthic adults that produce mero-neustonic larval forms. The greatest potential problem arises from floating chemical pollutants such as is encountered in major oil slicks. For those species that are holo-neuston, the danger may be small, but for fish eggs and larvae and those of benthic invertebrates, the peril is great. Breeding seasons can be very short, and a major surface slick at the wrong time could wipe out much of the particular year's spawning.

Neuston Production Model

A conceptual model of neuston production on the Texas-Louisiana continental shelf is presented in Figure 6.11. The neuston receives input of floaton, phytoplankton, and zooplankton through active and passive vertical movements of these forms in the water column. Water currents bring additional forms in all three categories from sources outside the area. All of this is supplemented by mero-neustonic forms produced by the nekton and benthos. Neuston is lost through advective export, predation, passive sinking, and vertical migration. Additional biomass losses occur through self-consumption, respiration, and fecal production. Maturation of mero-neuston into nektonic and benthonic adults removes a further fraction. Direct solar radiation is lethal to the body tissues of plants and animals that lack appropriate protective mechanisms. The damaging ultraviolet rays do not penetrate deep into seawater and, thus, do not create a major problem for species that remain one or more meters below the surface. However, surface dwelling forms may suffer damage from this source. Floating chemical pollutants are considered to be a major direct hazard for neuston species. Dissolved and suspended chemical pollutants could affect the neuston directly, but the major impact would be through their effect upon nektonic or benthonic adults.

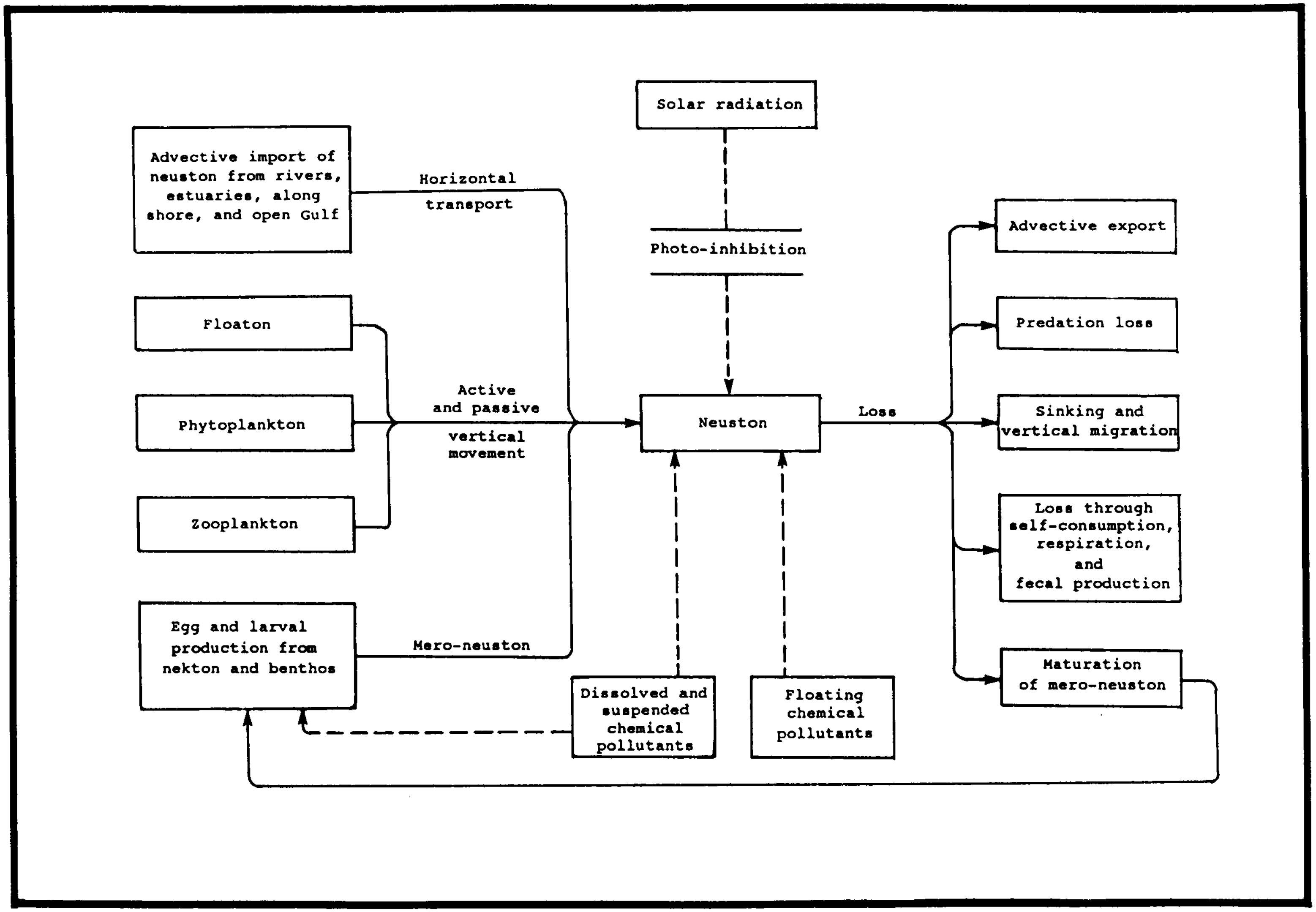


Figure 6.11. Conceptual model of neuston production on the Texas–Louisiana continental shelf.

6.3 NEKTON

As used here, the term "nekton" refers to larger free-swimming animals which, for at least a major portion of their life histories, are found in the water column and not intimately associated with the bottom. Some of the species could also be listed as benthic or demersal, either because part of the life history involves bottom habitat or because in their routine activities they move vertically within the water column. For example, many nektonic species regularly or occasionally feed near or on the bottom.

6.3.1 Composition and Standing Crop

The nekton of the Texas-Louisiana coast consists of many species of fishes and a few species of invertebrates, sea turtles, and cetaceans. A list of the more common species is presented in Table 6.14. Except for the very selective purse seine (Knapp, 1949; Christmas et al., 1960) and hook-and-line (Iwamoto, 1965), there is no collecting gear specific for nektonic animals, and for most nektonic species we do not have even semi-quantitative data concerning the abundance and distribution of the various groups. Recent information from fishing tournaments, aerial censuses, beach strandings, and scuba observations have provided some information for particular species. However, it cannot be said that reliable standing crop data are available for any nektonic species of the area. On the basis of the distribution of primary production, demersal fishes, and menhaden catch, it is likely that the nekton, as a whole, is more abundant off Louisiana than off Texas, but this would obviously vary from one species to another.

6.3.2 Seasonal and Areal Distribution Patterns

Limited information concerning seasonal and areal distribution patterns has been derived from the following sources: fishes--Bogdanov (1969), Hoese and Moore (1977), and Iwamoto (1965); sea turtles--Fritts et al. (1983a), Rosman et al. (1987), and Schroeder (1987); and cetaceans--Fritts et al. (1983b), Schmidly (1981), and Schmidly and Shane (1978). During their life histories, many shelf species move from shallow to deeper water as they mature, and in the deeper water they move up into the water column. This general pattern has been documented for some of the clupeid fishes as well as the striped and white mullet, Atlantic threadfin, and Gulf butterfish, and it undoubtedly characterizes a number of additional species. Many of the coastal species are known to be seasonal migrants that spend only the warmer months in the area. For the most part, these include the larger, faster swimming carnivores among the fishes (several sharks, cownose ray, dolphins, several carangids, scombrids, and billfishes), several of the cetaceans, and possibly some of the sea turtles (although the turtles may undergo hibernation rather than emigration) (see Table 6.15). Yet other species may be characterized as primarily occupying certain depth zones. An inshore and an offshore nekton fauna can be identified, and there may be an undefined mid-shelf nekton fauna, as well. The nearshore group would include adults of the little squid, a number of fishes (spinner, finetooth, bull and bonnethead sharks; scaled sardine; bay anchovy; blackwing flying fish; halfbeak; Atlantic needlefish; rough and tidewater silversides; and

Table 6.14. Common nekton species of the Texas-Louisiana continental shelf (compiled from many sources).

INVERTEBRATES	
Medusae	
Cyanea capillata	lion's mane
Dactylometra quinquecirrha	sea nettle
Stomolophus meleagris	cabbage head
Cephalopods	
Doryteuthis plei	arrow squid
Loligo pealei	common squid
Lolliguncula brevis	little squid
CARTILAGINOUS FISHES	
Carcharhinidae	
Carcharhinus brevipinna	spinner shark
Carcharhinus falciformis	silky shark
Carcharhinus isodon	finetooth shark
Carcharhinus leucas	bull shark
Carcharhinus limbatus	blacktip shark
Galeocerdo cuvieri	tiger shark
Mustelis canis	smooth dogfish
Rhizoprionodon terraenovae	Atlantic sharpnose shark
Sphyrnidae	
Sphyrna lewini	scalloped hammerhead
Sphyrna tiburo	bonnethead
Myliobatidae	
Rhinoptera bonasus	cownose ray
Mobulidae	
Manta birostris	Atlantic manta
BONY FISHES	
Elopidae	
Elops saurus	ladyfish
Megalops atlanticus	tarpon
Clupeidae	
Brevoortia gunteri	finescale menhaden
Brevoortia patronus	Gulf menhaden
Harengula jaguana	scaled sardine
Opisthonema oglinum	Atlantic thread herring
Engraulidae	
Anchoa hepsetus	striped anchovy
Anchoa mitchilli	bay anchovy
Exocoetidae	
Cypselurus cyanopterus	margined flyingfish
Hirundichthys rondeleti	blackwing flyingfish
Hyporhamphus unifasciatus	halfbeak
Belonidae	
Strongylura marina	Atlantic needlefish
Atherinidae	
Membras martinica	rough silverside
Menidia peninsulae	tidewater silverside
Pomatomidae	
Pomatomus saltatrix	bluefish
Rachycentridae	
Rachycentron canadum	cobia

Table 6.14. (Continued).

Echeneidae	
Echeneis naucrates	sharksucker
Carangidae	
Caranx hippos	crevalle jack
Caranx latus	horse-eye jack
Chloroscombrus chrysurus	Atlantic bumper
Decapterus punctatus	round scad
Oligoplites saurus	leatherjacket
Selene setapinnis	Atlantic moonfish
Seriola dumerili	greater amberjack
Seriola zonata	banded rudderfish
Trachinotus carolinus	Florida pompano
Coryphaenidae	
Coryphaena equisetis	pompano dolphin
Coryphaena hippurus	dolphin
Mugilidae	
Mugil cephalus	striped mullet
Mugil curema	white mullet
Sphyraenidae	
Sphyraena barracuda	great barracuda
Sphyraena guachancho	guaguanche
Polynemidae	
Polydactylus octonemus	Atlantic threadfin
Scombridae	
Acanthocybium solanderi	wahoo
Euthynnus alletteratus	little tunny
Scomberomorus cavalla	king mackerel
Scomberomorus maculatus	Spanish mackerel
Thunnus albacares	yellowfin tuna
Thunnus atlanticus	blackfin tuna
Xiphiidae	
Xiphias gladius	swordfish
Istiophoridae	
Istiophorus platypterus	sailfish
Makaira nigricans	blue marlin
Tetrapterus albidus	white marlin
Stromateidae	
Peprilus alepidotus	harvestfish
Peprilus burti	Gulf butterfish
SEA TURTLES	
Caretta caretta	loggerhead
Lepidochelys kempi	Kemp's ridley
CETACEANS	
Globicephala macrorhynchus	short-finned pilot whale
Kogia breviceps	pygmy sperm whale
Stenella plagiodon	Atlantic spotted dolphin
Tursiops truncatus	Atlantic bottlenose dolphin

Table 6.15. Seasonal record of sea turtle strandings on Louisiana and Texas beaches in 1986 (loggerhead and Kemp's ridley turtles only). The data for Kemp's ridleys includes natural as well as "headstart" turtles. The latter includes two from Louisiana and 64 from Texas beaches (From: Schroeder, 1987).

Species and Areas	Month												Total
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	
Loggerhead (*Caretta caretta*)													
Louisiana	-	-	-	1	3	14	3	7	1	-	-	-	29
Texas	-	1	17	35	17	5	10	14	12	16	6	6	139
Total	-	1	17	36	20	19	13	21	13	16	6	6	168
Percent of 1986 Total	-	0.6	10.1	21.4	11.9	11.3	7.7	12.5	7.7	9.5	3.6	3.6	99.9
Kemp's ridley (*Lepidochelys kempi*)													
Louisiana	-	-	-	3	10	26	15	28	9	1	2	-	94
Texas	-	1	25	55	60	27	9	15	10	6	3	-	211
Total	-	1	25	58	70	53	24	43	19	7	5	-	305
Percent of 1986 Total	-	0.3	8.2	19.0	23.0	17.4	7.9	14.1	6.2	2.3	1.6	-	100

Atlantic bumper), as well as the bottlenose dolphin. The offshore group would include most of the larger sharks, round scad, tunas, and billfishes and several cetaceans. An example of the offshore distribution pattern is shown in Figure 6.12, which is based upon data from billfishing tournaments. Most of the remaining nektonic species should be considered to have broad depth distributions on the continental shelf. Encroachment into shelf waters by oceanic species is documented by aerial surveys and beach strandings of larger deep-water fishes and cetaceans.

6.3.3 Controlling Factors

Reproduction and food supply are two of the chief factors determining the distribution and abundance of nektonic species. The Gulf menhaden and other clupeids, striped and white mullets, Atlantic threadfin, Gulf butterfish and some other species apparently spawn well up in the water column on the outer portion of the shelf. Many nektonic species either occasionally or regularly migrate down in the water column to feed upon demersal and benthic organisms. The influx of summer residents appears largely to be a seasonal search for food (Rogers, 1977). Among the hydrographic factors, water currents likely play a significant role in nekton species distribution and abundance, but this has not been documented in the area. However, a case can be made for turbidity as a factor controlling distribution of larger predatory species, such as the tunas and billfishes, which feed by sight and which appear to be more abundant in the clearer waters.

As noted in earlier sections of this report, information is now accumulating on the pollution output of the various rivers (Mississippi, Atchafalaya, Sabine, Brazos, etc.), but the importance of chemical pollutants in restricting nektonic species has not been demonstrated for the Texas-Louisiana shelf. As discussed under the benthic section, sea turtles may be attracted to oil rigs and platforms, where they may be exposed to higher levels of petroleum and drilling effluents. The ingestion of tar balls by hatchlings has been suggested as a possible mortality factor. A number of nektonic fish species are, likewise, attracted to rigs and platforms, thus becoming exposed to higher levels of chemical pollutants. There is evidence that some nektonic fishes may avoid major oil spills. A general problem that must be considered is the possibility of concentrating petroleum fractions, heavy metals, and other chemical pollutants up through the food chain. Many of the nektonic species represent the top carnivore level and would likely be the group most affected by food chain "biomagnification." All of the above pollution problems apply equally well to cetaceans. However, marine mammals, like sea turtles, have a special problem in that they must come to the surface to breathe. The effect of a massive oil slick upon respiration is not known, but it should be considered to be significant unless proven otherwise.

6.3.4 Nekton Production Model

A conceptual model of nekton production on the Texas-Louisiana continental shelf is presented in Figure 6.13. The nekton receives input from zooplankton, demersal, and benthic forms that mature into nektonic

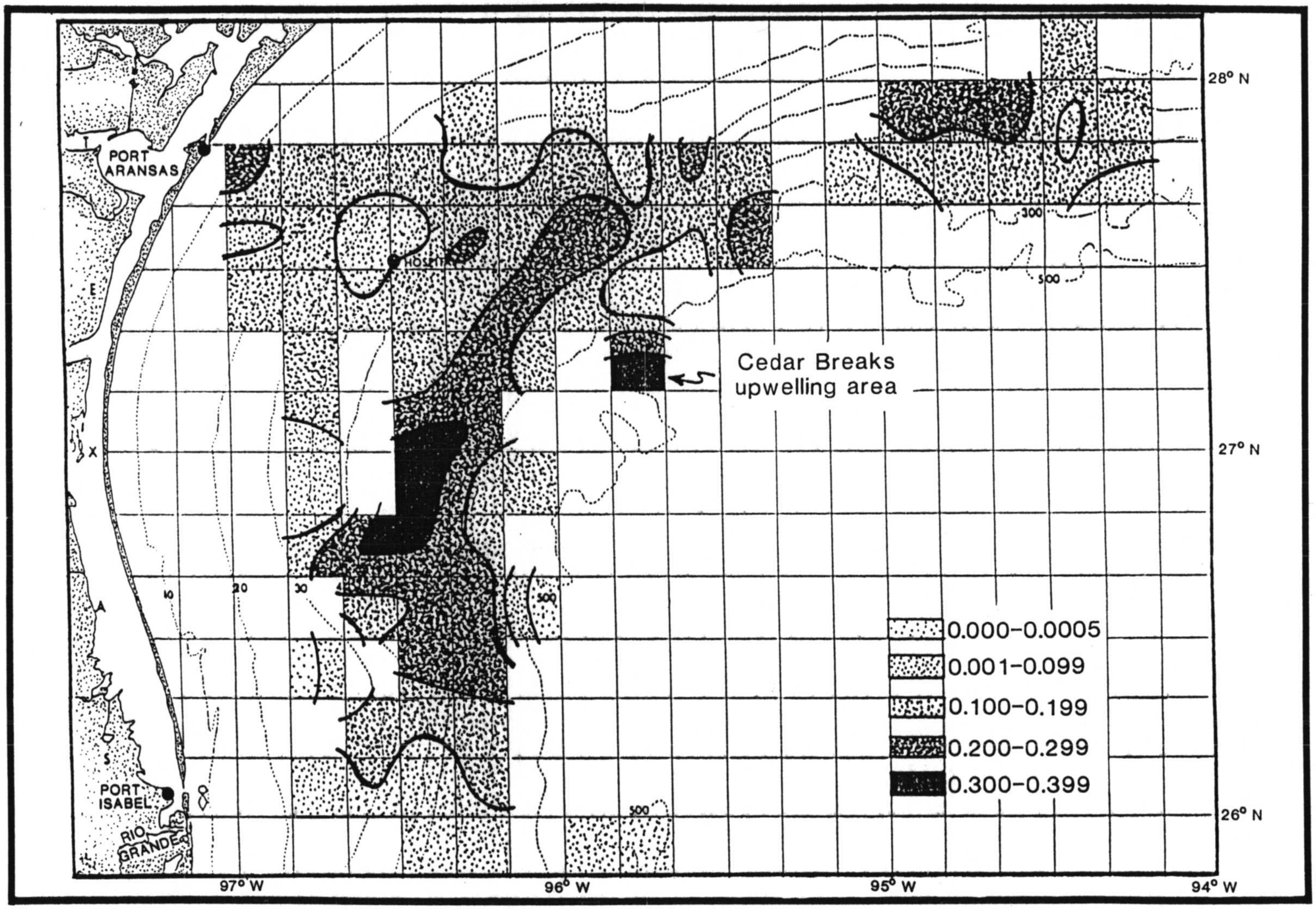


Figure 6.12. Number of billfishes raised per hour of trolling in 1982 (From: Lopez and Pristas, 1982).

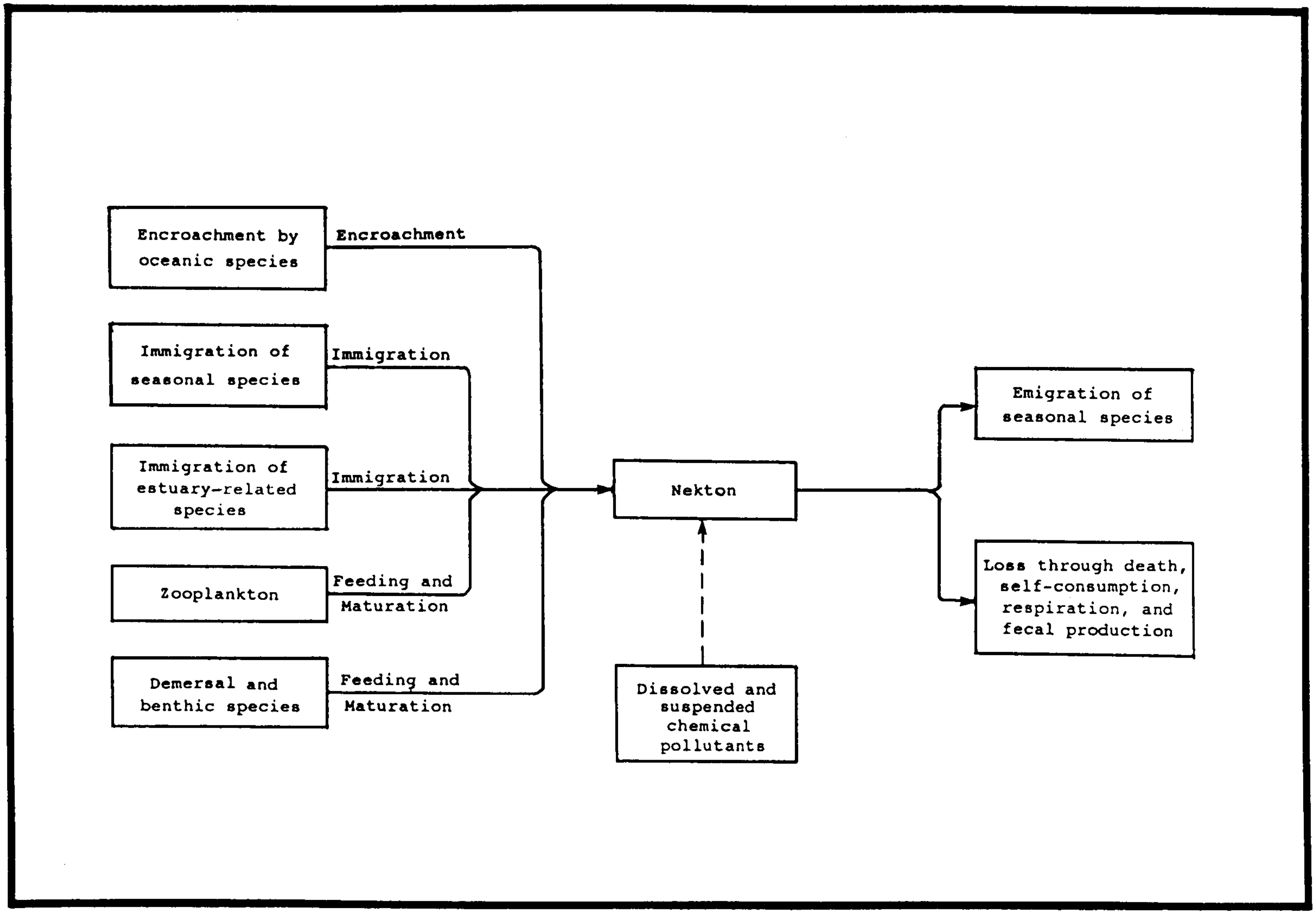


Figure 6.13. Conceptual model of nekton production on the Texas-Louisiana continental shelf.

adults. These are supplemented by immigration of estuary related species and by nekton from other areas that take up local seasonal residence. True oceanic nekton species, such as basking and whale sharks and whales, occasionally encroach upon the shelf. Nektonic species feed upon zooplankton and demersal and benthic species as well as upon each other. Nekton losses occur through emigration, death, self-consumption, respiration, and fecal production. Dissolved and suspended chemical pollutants can directly affect the nekton by causing either physiological damage or avoidance behavior. Floating pollutants may affect respiration in air-breathing species. Pollutants may indirectly affect the nekton by damage to planktonic, neustonic, demersal, or benthic young (as shown in previous models), damage to the food supplies, or concentration up through the food chains. The nekton model emphasizes the local importance of estuary-related species and of chemical pollutants and fishing pressure.

6.4 BENTHIC AND DEMERSAL BIOTA

This section will address those species that spend all or a major portion of their lives in association with the bottom or near-bottom habitat.

6.4.1 Demersal Biota

The demersal biota includes those larger mobile species associated with the near-bottom waters. For practical purposes, it includes those organisms that appear in bottom trawl collections (such as squids, shrimp, galatheids, crabs, stomatopods, and fishes. A wealth of information is available concerning the trawlable species of the Texas-Louisiana continental shelf and upper slope. Among the more important references and data sources are the following: Hildebrand (1954); Moore et al. (1970); Lyon and Baxter (1974); Defenbaugh (1976); Pequegnat et al. (1976); Hoese and Moore (1977); Rogers (1977); Ragan et al. (1978); Wohlschlag et al. (1980); Gallaway et al. (1981b, 1988); Darnell et al. (1983); Pequegnat (1983); Landry et al. (1985); and Pavela and Chittenden (1985). By far the most comprehensive studies are those of Darnell et al. (1983), Defenbaugh (1976), and Moore et al. (1970) for the continental shelf and Gallaway et al. (1981b), Pequegnat (1983), and Pequegnat et al. (1976) for the continental slope. The present discussion draws heavily upon these sources, supplemented as necessary, by other material.

Composition and Standing Crop

The demersal fauna of the Texas-Louisiana shelf and upper slope consists of many species of fishes, a moderate number of shrimp and crabs, and a few species of cephalopods, galatheids, stomatopods, and sea turtles. A list of the more common demersal species of the continental shelf is presented in Table 6.16, and common species of the upper slope are given in Table 6.17. Although inclusion of species in these lists is based upon subjective criteria, a few clear trends can be noted. Out of 69 shelf species, 21 (30%) are estuary related, including one squid, two shrimp, one crab, and 17 fish species. Almost twice as many shelf species are listed as common as on the upper slope (69 vs. 43 species),

Table 6.16. Common demersal species of the Texas-Louisiana continental shelf (0-200 m). (Data primarily from: Darnell et al., 1983; Defenbaugh, 1976; and Hildebrand, 1954).

SQUIDS	
Loligo pealei*	Lolliguncula brevis
SHRIMP	
Penaeus aztecus*	Solenocera vioscai
Penaeus setiferus*	Trachypenaeus similis
Sicyonia brevirostris	Xiphopenaeus kroyeri
Sicyonia dorsalis	
CRABS	
Porcellana sayana	Callinectes similis
Raninoides louisianensis	Portunus gibbesi
Calappa sulcata	Portunus spinicarpus
Callinectes sapidus*	Portunus spinimanus
STOMATOPODS	
Squilla chydaea	Squilla empusa
FISHES	
Clupeidae	
Brevoortia patronus*	Gulf menhaden
Harengula jaguana	scaled sardine
Synodontidae	
Synodus foetens	inshore lizardfish
Ariidae	
Arius felis*	hardhead catfish
Batrachoididae	
Porichthys plectrodon*	Atlantic midshipman
Ogcocephalidae	
Halieutichthys aculeatus	pancake batfish
Gadidae	
Urophycis floridana	southern hake
Serranidae	
Centropristis philadelphica	rock sea bass
Diplectrum bivittatum	dwarf sand perch
Diplectrum formosum	sand perch
Serranus atrobranchus	blackear bass
Carangidae	
Chloroscombrus chrysurus	Atlantic bumper
Selena setapinnis	Atlantic moonfish
Trachurus lathami	rough scad
Lutjanidae	
Lutjanus campechanus	red snapper
Pristipomoides aquilonaris	wenchman
Rhomboplites aurorubens	vermilion snapper
Haemulidae	
Orthopristis chrysoptera*	pigfish
Sparidae	
Lagodon rhomboides*	pinfish
Stenotomus caprinus	longspine porgy

Table 6.16. (Continued).

Sciaenidae	
*Cynoscion arenarius**	sand seatrout
Cynoscion nothus	silver seatrout
*Larimus fasciatus**	banded drum
*Leiostomus xanthurus**	spot
Menticirrhus americanus	southern kingfish
*Micropogonias undulatus**	Atlantic croaker
*Stellifer lanceolatus**	star drum
Mullidae	
Mulloidichthys martinicus	yellow goatfish
Mullus auratus	red goatfish
Upeneus parvus	dwarf goatfish
Labridae	
Hemipteronotus novacula	pearly razorfish
Polynemidae	
*Polydactylus octonemus**	Atlantic threadfin
Trichiuridae	
*Trichiurus lepturus**	Atlantic cutlassfish
Stromateidae	
Peprilus alepidotus	harvestfish
Peprilus burti	Gulf butterfish
Triglidae	
Bellator militaris	horned searobin
Prionotus paralatus	Mexican searobin
Prionotus rubio	blackfin searobin
Prionotus stearnsi	shortwing searobin
*Prionotus tribulus**	bighead searobin
Bothidae	
Ancyclopsetta dilecta	three-eye flounder
*Citharichthys spilopterus**	bay whiff
Cyclopsetta chittendeni	Mexican flounder
*Etropus crossotus**	fringed flounder
Syacium gunteri	shoal flounder
Trichopsetta ventralis	sash flounder
Soleidae	
*Trinectes maculatus**	hogchoker
Balistidae	
Monacanthus hispidus	planehead filefish
Tetraodontidae	
Lagocephalus laevigatus	smooth puffer
Sphoeroides parvus	least puffer

*Estuary-related species.

Table 6.17. Common demersal species of the Texas-Louisiana upper continental slope (200-500 m) (From: Gallaway et al., 1988; Pequegnat, 1983; and Pequegnat et al., 1976).

SHRIMP	
Acanthephyra purpurea	*Parapandalis willisi*
Bentheogennema intermedia	*Parapenaeus longirostris*
Gennadas valens	*Penaeopsis serrata*
Heterocarpus ensifer	*Plesionika tenuipes*
Hymenopenaeus debilis	*Solenocera vioscai*
Hymenopenaeus robustus	*Systellaspis pellucida*
GALATHEIDS	
Munida forceps	*Munida longipes*
CRABS	
Acanthocarpus alexandri	*Myropsis quinquespinosa*
Bathyplax typhla	*Portunus spinicarpus*
Benthochascon schmitti	*Pyromaia arachna*
Cyclodorrippe antennaria	*Raninoides louisianensis*
Ethusa macrophthalma	*Thalassoplax angusta*
Lyreidus bairdii	
FISHES	
Ancyclopsetta dilecta	*Peristedion greyae*
Bembrops anatirostris	*Poecilopsetta beani*
Bembrops gobioides	*Pontinus longispinis*
Coelorynchus caribbaeus	*Pristipomoides aquilonaris*
Coelorynchus coelorhynchus	*Steindachneria argentea*
Dibranchus atlanticus	*Trichopsetta ventralis*
Halieutichthys aculeatus	*Urophycis cirrata*
Hymenocephalus italicus	*Urophycis regia*
Parasudis truculenta	*Ventrifossa occidentalis*

but if exact density figures had been used, the shelf list would have greatly predominated. On the shelf, the fishes outnumber the crustaceans (72% vs. 25%), whereas on the upper slope the reverse is true (42% vs. 58%), and this points to the fact that scavenging for dead material rather than carnivory becomes an increasingly important way of life below the euphotic zone.

Bottom trawls tend to underestimate true density and are selective for certain species and size classes. However, standardized trawl data do provide comparative information on standing crop, as long as these limitations are recognized. Standing crop information is necessarily based upon data from trawling surveys, and this may be expressed as numbers or weights per standard trawl haul or per unit area covered by the trawls. A number of trawl surveys have been conducted for limited areas or seasons, including those of Darnell and Defenbaugh (unpublished), Hildebrand (1954), Ragan et al. (1978), Wohlschlag and Yoshiyama (1980), Landry et al. (1985), and Pavela and Chittenden (1985), but the most extensive survey was conducted by the NMFS (Lyon and Baxter, 1974; Moore et al., 1970). This survey, carried out during the period 1961 to 1965, covered most of the Texas-Louisiana continental shelf and consisted of monthly collections along 11 complete and two partial transects from 7 to 110 m depth (although some adjustments were made during different years). Trawling effort was standardized in terms of trawl type, mesh size, vessel speed, and towing time. Thus, for the Texas-Louisiana shelf there exists a standard, five-year monthly catch record for the penaeid shrimp and a comparable three-year record for the demersal fishes. These data have been partially analyzed by Moore et al. (1970) and more thoroughly by Darnell et al. (1983). Density distribution maps have been prepared for the total shrimp and demersal fish fauna as well as for several families and all abundant species. Where the numbers were sufficient, seasonal distribution maps were made (Darnell et al., 1983). Although these maps are not reproduced in the present report, some of the more important conclusions are provided here.

Information on species dominance in the Louisiana and Texas catches are provided in Tables 6.18 and 6.19. Inshore catches off Louisiana are numerically dominated by the Atlantic croaker, but off Texas, dominance is divided among three species--silver seatrout, southern kingfish, and Atlantic croaker, depending upon season. In waters 27 m and deeper, the longspine porgy dominates off both Louisiana and Texas. The blackfin searobin is consistently an important species on the middle and outer shelf off Louisiana, but off Texas it is replaced by the Mexican searobin and shoal flounder.

To illustrate the types of information available from the NMFS survey, Tables 6.20, 6.21, and 6.22 provide information on standing crops of selected penaeid shrimp and the total fish catch, given by depth for Louisiana and Texas, where the standing crops are expressed as numbers of individuals or pounds per standard trawl haul or as kilograms per hectare. The shrimp data have also been broken down by season. In comparing Louisiana and Texas, the white and brown shrimp catches are almost identical (50.3% vs. 49.7% of the combined catch), the brown shrimp favors Texas over Louisiana (58.3% vs. 41.7%), and the total shrimp catch is greater off Texas (55.9% vs. 44.1%). On the other hand,

Table 6.18. Depth and seasonal distribution of numerically dominant fish species in trawl transects across the Louisiana continental shelf. All species constituting at least 5% of the total catch are included. The numerically dominant species for each season and depth range is underlined (Adapted from: Moore et al., 1970).

	Percent of Catch											
	Inner Zone (7-14 m)				Middle Zone (27-46 m)				Outer Zone (64-110 m)			
Species	W	Sp	Su	F	W	Sp	Su	F	W	Sp	Su	F
Inshore lizardfish						10			10			
Hardhead catfish	10	14	8	8								
Rock sea bass									5	9	6	7
Wenchman												
Longspine porgy	5				22	<u>27</u>	<u>29</u>	20	<u>31</u>	<u>38</u>	<u>54</u>	<u>23</u>
Sand seatrout		6	8			6						9
Silver seatrout								6				
Spot		5	7					5				7
Southern kingfish	7											
Atlantic croaker	<u>51</u>	<u>49</u>	<u>48</u>	<u>66</u>	<u>39</u>	20	21	<u>40</u>	9	9		12
Gulf butterfish												
Mexican searobin												
Blackfin searobin						7	5	5	8	11	5	9
Mexican flounder											6	
Shoal flounder												

Table 6.19. Depth and seasonal distribution of numerically dominant fish species in trawl transects across the Texas continental shelf. All species constituting at least 5% of the total catch are included. The numerically dominant species for each season and depth range is underlined (Adapted from: Moore et al., 1970).

	Percent of Catch											
	Inner Zone (7-14 m)				Middle Zone (27-46 m)				Outer Zone (64-110 m)			
Species	W	Sp	Su	F	W	Sp	Su	F	W	Sp	Su	F
Inshore lizardfish					7	<u>15</u>	9	7	12	16	14	13
Hardhead catfish		10	6	5								
Rock sea bass					6	9				6	6	5
Wenchman									18	12	12	12
Longspine porgy				5	<u>38</u>	<u>15</u>	<u>25</u>	<u>26</u>	<u>29</u>	<u>26</u>	<u>26</u>	<u>27</u>
Sand seatrout	12		9	9	8		7					
Silver seatrout	7	<u>26</u>	7	7		6	9	6				
Spot	19	7						8				
Southern kingfish	<u>26</u>	5	5	<u>23</u>								
Atlantic croaker		15	<u>30</u>	10	5		9	12				
Gulf butterfish						11						
Mexican searobin									9	6	8	8
Blackfin searobin												
Mexican flounder												
Shoal flounder				5	7	14	5	8				

Table 6.20. Depth and seasonal distribution of selected penaeid shrimp on the Texas-Louisiana continental shelf. The combined species total includes all species of the genera _Parapenaeus_, _Penaeus_, _Sicyonia_, _Solenocera_, _Trachypenaeus_, and _Xiphopenaeus_ (Data from: Lyon and Baxter, 1974).

	Shrimp Abundance (no. individuals/h of trawling)											
	White Shrimp				Brown Shrimp				All Penaeid Shrimp			
Species	W	Sp	Su	F	W	Sp	Su	F	W	Sp	Su	F
LOUISIANA												
7-14 m	66	40	49	129	0	21	52	14	484	712	769	1,180
27-46 m	8	3	0	6	50	71	95	84	502	1,284	2,192	1,044
64-110 m	0	0	0	0	57	27	26	36	221	157	206	262
TEXAS												
7-14 m	99	24	19	129	1	36	74	46	944	908	707	1,263
27-46 m	14	2	0	10	56	90	208	130	1,182	1,713	2,329	1,661
64-110 m	0	0	0	0	47	15	9	34	174	58	36	435

Table 6.21. Comparisons of mean annual fish catch (per standard trawling hour) between Louisiana and Texas, within each depth contour and year (1962-1964) (From: Moore et al., 1970).

Year	Depth (m)	Average Catch (lb/h) Louisiana	Average Catch (lb/h) Texas	Significance of Difference (by t-test)
1962	14	379	68	1% level
	27	307	64	1% level
	46	223	109	1% level
	64	184	101	1% level
	82	123	103	n.s.
	110	81	89	n.s.
1963	7	131	52	1% level
	14	221	67	5% level
	27	271	75	1% level
	46	219	76	1% level
	73	121	89	n.s.
1964	7	137	62	5% level
	14	271	72	5% level
	27	229	58	1% level
	46	168	74	1% level

Table 6.22. Comparison of mean annual trawl fish catch (all years combined) between Louisiana and Texas within each depth contour (Calculated from data presented in Table 6.21).

Depth (m)	Trawl Fish Catch (kg/ha) Louisiana	Trawl Fish Catch (kg/ha) Texas	Ratio Louisiana/Texas
7	10.7	4.5	2.4
14	23.1	5.5	4.2
27	21.5	5.3	4.1
46	16.2	6.9	2.3
73	12.2	7.6	1.6
82	9.8	8.2	1.2
110	6.5	7.1	0.9

on a weight basis, the fish catch is far greater off Louisiana than off Texas. In the depth range of 7 to 46 m the Louisiana catch is over twice that off Texas, and in the depth range of 14 to 27 m, it is over four times the Texas catch. However, toward the outer shelf (73 to 110 m) the catches become more equal. Fish catch densities off Louisiana range up to 23.1 kg/ha, whereas off Texas the maximum is 8.2 kg/ha. It is tempting to speculate that the shrimp population off Louisiana should be far higher and that it is kept at a low level by the combined effects of predation by the large fish population, heavy commercial trawling pressure, and extensive summer hypoxia. Rough data on the standing crop of decapods and fishes of the upper slope off Louisiana are provided in Table 6.23. Trawl data indicate that the decapods are about two and half times as abundant as the fishes, but bottom photography suggests that they may be about five times as abundant. Indirect information on sea turtle densities in the area, based upon airplane sightings, strandings, and scuba observations around hard bottoms and other structures, is discussed later in this chapter.

Seasonal and Areal Distribution Patterns

Patterns of seasonal and areal density distribution of penaeid shrimp and fishes have been documented in great detail by Darnell et al. (1983), and for the blue crab (*Callinectes sapidus*) they may, at least, be inferred (Darnell, 1959). Comparisons have already been made between the shelf fauna of Louisiana and that of Texas in terms of species dominance and standing crops, and reference to Tables 6.18, 6.19, and 6.20 will place these parameters in perspective of season and depth. From the vast amount of information analyzed and synthesized in the *Northwestern Gulf Shelf Bio-Atlas* (Darnell et al., 1983) the following generalizations may be set forth.

In order to complete its life history in the face of competition, predation, and available resources, each species has developed a unique strategy for using space and time. These individual spatial/seasonal patterns fall into several roughly distinguishable groupings, several of which are identified below.

1) Spatial patterns:

- Depth-related density distribution patterns.
  - nearshore (0 to 20 m).
  - mid-shelf (20 to 80 m).
  - outer shelf (80 to 120 m).
  - trans-shelf (0 to 110 m).

Table 6.23. Density of demersal decapods and fishes on the upper continental slope (300-500 m) off Louisiana based upon trawls and bottom photography (From: Gallaway et al., 1988).

	Decapod Density (no./ha)		Fish Density (no./ha)	
Transect*	Trawl	Photography	Trawl	Photography
Western	920	--	290	--
West-Central	139	455	63	270
Central	140	1,629	143	160
Mean	400	1,042	165	215

*Western transect, below Calcasieu Lake (Cruise II, spring/summer, 1984).
West-central stations, off central Louisiana (Cruise V, summer, 1983).
Central transect, below Timbalier Bay (Cruise III, fall, 1984).

- Coast-wise density distribution patterns.
  - Regional dominance.
    - Louisiana dominant.
    - Central sector (coarse bottoms) dominant.
    - East and west sectors (fine sediments) dominant.
    - Texas dominant.
  - Aggregation off passes.
  - Population insularization on the Texas shelf.
  - Species concentrations near the mouths of major rivers.

2) Seasonal patterns:

- Minor seasonal changes in density and distribution.
- Seasonal changes in peak abundance.
- Seasonal changes in distributional expansion.
- Seasonal changes in abundance and distribution.
- Seasonal changes in rareness or absence.
- Seasonal changes in depth distribution and/or density.

These patterns relate most clearly with reproduction, feeding, and response to physical factors, of which temperature, substrate type, and availability of inshore nursery areas appear to be the most important.

<u>Estuary Related vs. Non-estuary Related Species</u>

The life history of the typical estuary-related species involves spawning on the continental shelf; transport of eggs, larvae, or juveniles to the estuarine nursery grounds; growth and maturation in the estuary; and migration of the young adults back to the shelf for spawning. This pattern may be obligate or facultative. Post-spawning individuals generally remain on the continental shelf. Most estuary-related species have short life histories of 18 to 36 months, but some (such as the black and red drums) may live for several years. The concern of the present section is the distribution of the adults while on the continental shelf.

Darnell et al. (1983) provided a list of estuary-related species important in trawl collections on the continental shelf off Louisiana and Texas. Included were three shrimp and 33 fish species, and these embrace most of the shelf species of commercial interest (the primary exception being snappers, groupers, and other structure-related species). Chittenden and McEachran (1976) from studies off Galveston and Matagorda Bays concluded that once on the shelf, the estuary-related species tend to remain in the nearshore environment or "white shrimp grounds" located in the depth range of 3.5 to 22 m. However, Darnell et al. (1983) stated that this is only partially true for the lower Texas coast and that it applies for only a few species on the Louisiana shelf. Major exceptions include the brown shrimp, Atlantic midshipman, lane snapper, pinfish, sand seatrout, spot, Atlantic croaker, and Atlantic cutlassfish (which remain demersal), and the Gulf menhaden, Florida pompano, Atlantic spadefish, striped and white mullets, and Atlantic threadfin (which tend to move up into the water column). On the basis of numbers and weight, the estuary-related species do constitute the bulk of the nearshore catch, but for all the species listed above there is a movement toward the middle or outer shelf at maturity, even though the species are short-lived.

Non-estuary related species include all the remaining demersal forms. Some tend to stay within one depth zone or another, but as noted by Rogers (1977), many of the true shelf residents also undergo a movement toward deeper water as they mature. Some remain demersal, while others, such as the Gulf butterfish, become pelagic.

Controlling Factors

It was noted above that distributional patterns of the demersal species related most closely with reproduction, feeding, and response to physical factors, of which temperature, substrate type, and availability of inshore nursery areas appear to be most important. In the absence of detailed knowledge of the life histories of many of the shelf species, it is not possible to state in each case which factor or combination of factors exercise the controlling influences. What we can do is to identify specific instances of such relationships and indicate how further information may be obtained.

If they are to persist through time, all species must successfully produce the next generation, and for continental shelf species, this means that spawning times and places must be synchronized with hydrography in such a way that eggs, larvae, and young arrive at nursery areas at appropriate seasons. Although for most of the demersal shelf species the times and places of spawning are not well known, one good example is provided by the Gulf menhaden. Individuals that use the estuarine nursery areas from the Mississippi River Delta at least as far west as Galveston Bay all apparently spawn during the winter and early spring near the surface over the middle or outer shelf near the Mississippi River Delta. Knowledge of shelf circulation now indicates that this is precisely the right time and place for the floating eggs to be transported by prevailing surface currents westward and shoreward at least as far as Galveston Bay. On the other hand, the finescale menhaden appears to be the dominant species from Matagorda Bay, south. Clearly, its reproductive strategy must be keyed to a different shelf hydrographic pattern. We may theorize that in order to avail itself of the most favorable surface currents, this species should spawn during the late spring and early summer on the middle or outer shelf off the Rio Grande or somewhat further south. Many of the estuary-related species, such as the black and red drums, apparently spawn near the mouths of passes where surface currents may take them directly into the estuaries. Real progress in this general area rests largely in the identification of specific spawning sites and seasons for the various demersal species.

In order to fulfill their energy requirements, all the demersal species must continually exploit the potential food resources. Rogers (1977) has investigated the food of 26 species of common demersal fishes of the Texas-Louisiana continental shelf. However, an effort to correlate the distribution of these species with the distribution of their food supplies has failed for several reasons. The distribution patterns of most of the food organisms are not sufficiently well known; the ones that are well known (such as the penaeid shrimp) are widely distributed; and most of the species analyzed are feeding generalists that are capable of capturing a variety of food items within broad categories. In fact, Rogers selected the abundant and widespread species for analysis, and these are rather generalized feeders. A relationship between the distribution of demersal species and their food supplies must exist, even if it is not demonstrable at the present time. In order to demonstrate such relationships, two types of studies are needed. For food organisms that are not specifically associated with bottom sediment types (small shrimp, near-bottom fishes, etc.), there should be a survey of their distribution patterns with small-meshed nets.

Temperature likely plays a major role in the distribution and spawning of a great many of the shelf species. Here one is concerned with the absolute temperature extremes that must be endured, gradually increasing or decreasing temperatures, and sudden changes in temperature. One example of the likely role of temperature will be provided. Darnell et al. (1983) demonstrated that the majority of the brown shrimp overwinter in the warmest shelf waters (deeper than 40 m where the bottom water temperature remains in the range of 17° to 19°C). Aldrich et al. (1968) showed that postlarval brown shrimp are not active and burrow into the bottom at temperatures below 17°C. Zein-Eldin and Aldrich (1965) demonstrated that the maximum growth rates of the species occurred in the range of 18° to 25°C, and they also indicated that spawning of the species appears to be closely correlated with the appropriate temperatures of the estuarine waters into which the young would be migrating. The white shrimp, on the other hand, which overwinters near shore, is frequently subject to winter mortality associated with cold waves (Farfante, 1969). A combined laboratory and field approach to such problems would doubtless aid in explaining the distribution and seasonal patterns of many of the demersal species.

Substrate type is clearly an important factor in determining the distribution of many of the demersal species. This may operate as a medium for burrowing, a medium determining distribution of food organisms, or in other ways. It has been shown that the rock shrimp (*Sicyonia brevirostris*) reaches its greatest density concentrations on sandy bottoms, whereas the related species (*S. dorsalis*) largely avoids sandy bottoms but reaches great densities on bottoms of silt and clay (Darnell et al., 1983). Similar patterns are in evidence for other demersal species (Darnell et al., 1983).

Additional environmental factors controlling distribution patterns include those associated with depth (as discussed earlier), and the availability of inshore, low-salinity estuarine nursery areas. These estuaries are not only responsible for the production of all estuary-related species, but they are also known to export considerable quantities of organic material, thereby enriching the adjacent continental shelves (Darnell and Soniat, 1979). Thus, in terms of biomass and fishery harvest, such areas are the most productive on the northern Gulf coast.

Chemical pollutants may play a role in determining the distribution of demersal species of the continental shelf, but this has not yet been demonstrated for the species of the area, even though they are of considerable concern within some of the estuaries.

Demersal Biota Production Model

A conceptual model of demersal production on the Texas-Louisiana continental shelf is provided in Figure 6.14. Because this model deviates only slightly from that given for nekton (Figure 6.13), a detailed explanation is not required.

6.4.2 Benthos

The benthic biota includes those organisms that are intimately associated with the bottom, either living primarily within the sediments (infauna) or upon the sediment surface (epifauna). The standard classification of benthos on the basis of size is given as follows:

- microbenthos = <0.062 mm
- meiobenthos = 0.062 mm to 1.0 mm
- macrobenthos = 1.0 mm to 25.4 mm
- megabenthos = >25.4 mm

This classification is particularly convenient because it allows the organisms to be separated by sieves of appropriate mesh sizes. However, the size classification given above is not followed by all authors, and a discussion of the history of benthic size class terminology is provided in Bedinger (1981). It is noted that Hulings and Gray (1971) give the upper size limit of meiofauna as 0.5 to 1.0 mm, and Johnson (1966) simply lists it as 1.0 mm. Boesch (1981) defines the lower limit of the meiofauna as those organisms retained by sieves of 0.063 mm mesh size.

Microbenthos

As defined above, the microbenthos includes those organisms that are less than 0.062 mm. Primarily involved are bacteria, protozoa, some fungi, and some blue-green algae. Within the Texas-Louisiana area under discussion here, studies have been carried out on bacteria and fungi in relation to the STOCS investigations. In their studies of the benthic bacteria of the south Texas shelf, Schwartz et al. (1980) reached the following conclusions. Bacteria were more numerous at nearshore stations and decreased with increasing water depth. They were most abundant in the spring. Hydrocarbon degrading bacteria were present throughout the year and were most abundant nearshore and during the fall. Data on benthic fungi were provided by Powell and Szaniszlo (1980), but no size classes were given, and it is not clear that these all properly belong to the microbenthos. Abundance and diversity of fungi was found to be greatest in the fall. Fungal crude oil degradation potential was greater from inshore than from offshore stations.

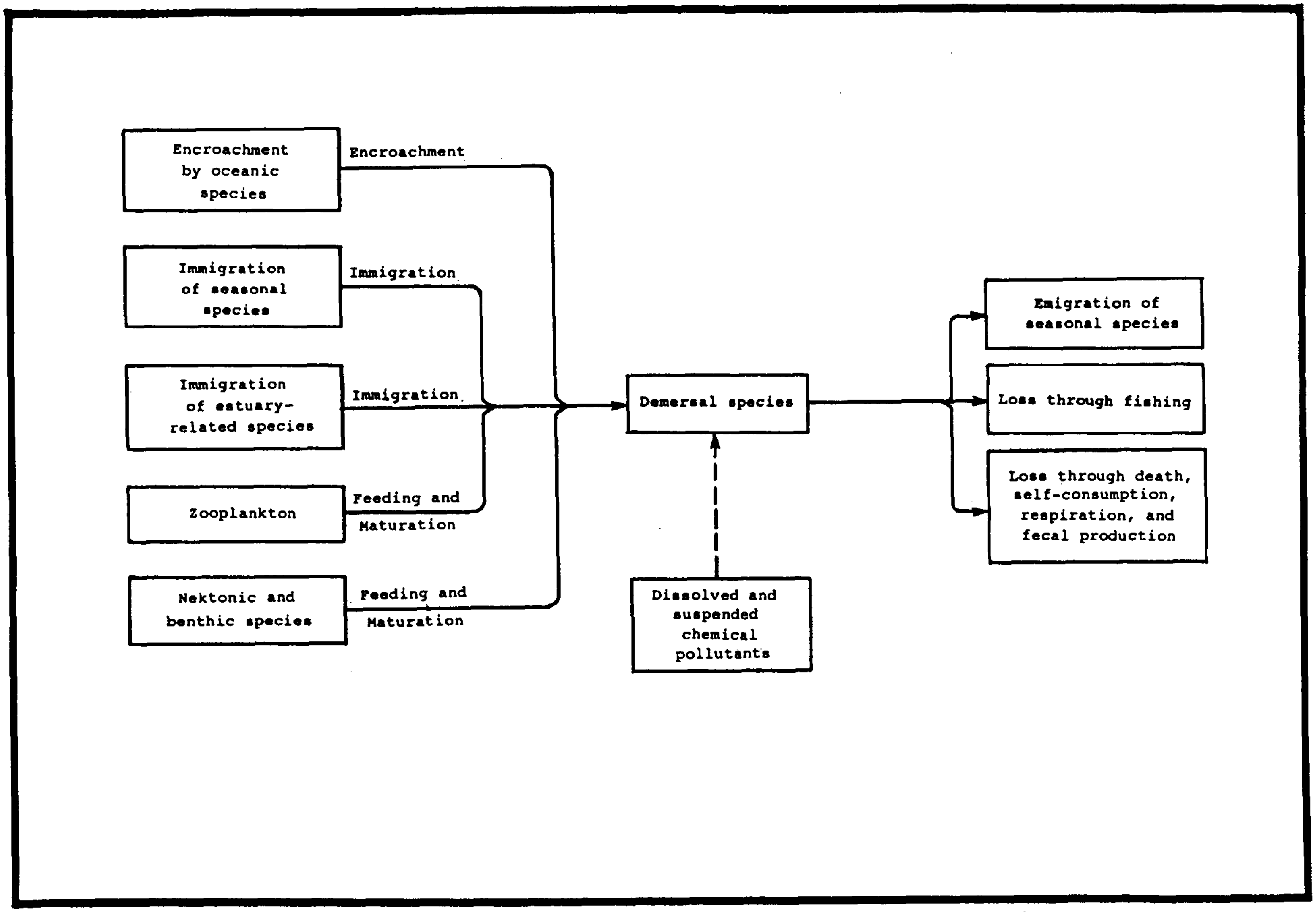


Figure 6.14. Conceptual model of demersal production on the Texas–Louisiana shelf and upper slope.

Meiobenthos

The meiofauna includes those species that pass through sieves of 0.5 to 1.0 mm but are retained by sieves of mesh size 0.063 mm. Two groups are included in the meiofauna: permanent and temporary residents. Permanent residents complete their entire life histories within the sediments and include such forms as the nematodes, kinorhynchs, polychaetes, and harpacticoid copepods. Temporary residents include such forms as copepod nauplii that will pass their adult lives in the water column. Foraminifera and other large protozoans are sometimes included in the meiofauna and sometimes excluded. In either event, it is generally not possible to determine whether the shells contain living organisms when collected, and foraminifera are not discussed herein. Studies in the area have differed in whether to include temporary residents and protozoa.

Four sets of meiofaunal studies have been carried out on the Texas-Louisiana continental shelf and slope. The Central Gulf Platform Study (Bedinger, 1981) involved a series of stations on the Louisiana shelf from the Mississippi River Delta to the level of Marsh Island (west of Atchafalaya Bay) in depths of about 2 to 92 m. Samples were made during three seasons: May, August/September, and January. Many of these samples were taken near the Mississippi River Delta and around oil platforms where contamination was high. Station data were not provided nor were absolute density figures given, limiting the usefulness of the study. The previously cited STOCS study included four seasonal transects across the south Texas shelf (Pequegnat and Sikora, 1977; Venn, 1980). The data are complete and useful. The Buccaneer Gas and Oil Field Study in shallow water off Galveston, TX included a series of stations made seasonally at varying distances from active oil platforms, and at some of the stations the environment was modified by high petroleum levels in the sediments and bleedwater outflow in the water column (Harper et al., 1981). More recently studies have been underway on the upper continental slope off Louisiana that are most comparable to the STOCS studies (Gallaway et al., 1988).

A list of meiofaunal groups encountered off Louisiana and Texas is provided in Table 6.24. Included are many of the marine phyla, several of which are unknown outside of the meiofauna. Vertebrates are not represented. The most abundant groups are the nematodes, polychaetes, harpacticoids, nauplii, and kinorhynchs. Meiofaunal densities and compositions in relation to depth are given in Table 6.25. On the Texas shelf, there is a clear reduction in density with increasing depth. However, meiofaunal abundance is closely correlated with sediment grain sizes, being generally higher when the sand content is over 60% and the interstitial spaces are larger and more well oxygenated. Therefore, the trend toward decreasing abundance with depth off Texas may represent primarily a trend from high to low sand content with depth. On the upper slope off Louisiana, the total meiofaunal density was nearly the same as in shallow water off Texas, which is particularly surprising because the sediments of the Louisiana slope tend to be primarily fine-grained clays and silts with low porosity and low oxygen penetration. Nematodes numerically dominate at all depths followed by harpacticoid copepods, polychaetes, ostracods, kinorynchs, and a diversity of other groups that

Table 6.24. A list of some of the major meiofaunal taxa reported from the Texas-Louisiana continental shelf and slope.

PROTOZOA	MOLLUSCA
Foraminifera	Amphineura
Other	Gastropoda
	Pelecypoda
PORIFERA	Scaphopoda
	Cephalopoda
CNIDARIA	
Hydrozoa	ARTHROPODA
Scyphozoa	Acarina
Anthozoa	Pycnogonida
	Tardigrada
TURBELLARIA	Crustacea
	Ostracoda
NEMERTEA	Copepoda
	Calanoida
ASCHELMINTHES	Cyclopoida
Gastrotricha	Harpacticoida
Kinorhyncha	Nauplii
Rotifera	Mystacocarida
Nematoda	Cirripedia
	Cumacea
PRIAPULIDA	Tanaidacea
	Isopoda
LOPHOPHORATES	Amphipoda
Bryozoa	
Phoronida	ECHINODERMATA
	Asteroidea
SIPUNCULIDA	Ophiuroidea
ANNELIDA	HEMICHORDATA
Oligochaeta	
Polychaeta	CHORDATA
	Urochordata
	Ascidiacea

Table 6.25. Densities and compositions of meiofauna observed in studies off the Texas-Louisiana continental shelf and slope.

Study	Water Depth (m)	Mean Density (no./10 cm^2)	Composition (%) Nematodes	Harpacticoids	Polychaetes	Ostracods	Kinorhynchs	Other
Central Gulf Platform Study*	2 - 92		90	3	2	--	1	4
Buccaneer Field Study†	19 - 20	941	72	15	--	--	--	13
STOCS§	0 - 30	430						
	30 - 60	94						
	60 - 90	64						
	90 - 120	49						
	120 - 140	30						
	0 - 140	133	93	4	4	--	0.5	--
Continental Slope Study# (Louisiana)	300 - 500	416	68	20	7	3	2	--

*Bedinger (1981). Total and depth-related densities were not provided.
†Harper et al. (1981).
§Pequegnat and Sikora (1977); Venn (1980).
#Gallaway et al. (1988).

make up smaller percentages. In general, the meiofauna of the shallow nearshore waters were more abundant during the warmer months, but some variation was noted. Included among the meiofaunal organisms are sediment feeders and carnivores, but otherwise little is known concerning their food habits. Numerous species encountered during these studies were unidentifiable, and many are clearly new to science. In view of the lack of life history knowledge, further generalizations about the meiofauna would be premature.

Macrobenthos

The macrobenthos represents those forms that pass through sieves of 25.4 mm mesh and are retained by sieves of 1.0 mm mesh, and it has been shown that both the composition and abundance of the catch is quite sensitive to the mesh size employed. They are also sensitive to gear type used in collecting the samples. Unfortunately, studies on the Texas-Louisiana continental shelf and slope have used three different minimal mesh sizes (0.3 mm, 0.5 mm, and 1.0 mm), and none seem to have included a maximum mesh. Most frequently, the Smith-McIntyre grab has been used, but many other grabs and box corers have also been employed. Furthermore, some of the studies were deliberately carried out in potentially stressful environments (around oil rigs and brine outflows). For these reasons, the data sets collected from the different studies are not exactly comparable with one another.

Significant information concerning the macrobenthos has been obtained in the following studies: Central Gulf Platform Study, West Hackberry Strategic Petroleum Reserve Study, Buccaneer Gas and Oil Field Study, STOCS Study, and Northern Gulf of Mexico Continental Slope Study. Because these were all referenced and discussed in relation to the meiofauna, they will not be redescribed here. Additionally, the Bureau of Economic Geology of the University of Texas has been carrying out surveys of the State of Texas submerged lands (up to 16.6 km seaward of the Gulf shoreline), including sediment and macrobenthos analyses. Unfortunately, these investigators have employed two different mesh sizes (0.5 mm and 1.0 mm), included hinged dead shells in the counts, and provided no absolute density data. They defined three inner shelf assemblages on the basis of species content, and these were roughly correlated with sediment type.

A list of the major macrobenthic groups encountered off Louisiana and Texas is given in Table 6.26. As in the case of the meiobenthos, most of the marine phyla are represented. Well over a thousand species have been recorded, many of which are new to science. Much effort has been devoted to advanced statistical analysis of the data (equitability, evenness, ordination, cluster analysis, discriminant analysis, etc.), which is somewhat questionable where the taxonomy is often still uncertain. On the other hand, basic information concerning composition and absolute density in relation to depth, season, sediment type, etc. is often difficult to determine from the information provided. Because the various studies do not lend themselves to easy comparison, each is discussed briefly.

Table 6.26. A list of some of the major macrofaunal taxa reported from the Texas-Louisiana continental shelf and slope.

PORIFERA	MOLLUSCA
	Gastropoda
CNIDARIA	Bivalvia
Hydrozoa	Scaphopoda
Scyphozoa	
Anthozoa	ARTHROPOD
Actinaria	Acarina
Alcyonaria	Ostracoda
Scleractinia	Copepoda
	Mysidacea
NEMERTEA	Cumacea
	Tanaidacea
ASCHELMINTHES	Isopoda
Kinorhyncha	Amphipoda
Nematoda	Decapoda
Priapulida	
	ECHINODERM
LOPHOPHORA	Echinoidea
Brachiopoda	Holothuroidea
Bryozoa	Ophiuroidea
Phoronida	
	POGONOPHORA
ECHIURIDA	
	CHORDATA
SIPUNCULIDA	Urochordata
	Ascidiacea
ANNELIDA	
Oligochaeta	
Polychaeta	

In the Central Gulf Platform Study off Louisiana, at depths of 2 to 92 m, macrobenthic densities ranged from 6 to 12,576 individuals/m^2, but an average density value is not available. Densities were highest in May, lowest in August/September, and intermediate in January. In Table 6.27, information is presented on the seasonal pattern of taxonomic diversity and abundance by percent. The average number of taxa encountered per season was 333, being greatest in May and least in January. Both in terms of abundance and species richness, polychaetes were the dominant group, followed by crustaceans and mollusks. Polychaete density was reported to decrease with depth. The area was reported to be a stressed environment due to (1) periodic freshwater and sediment loading from the Mississippi River; (2) cyclonic storms; (3) summer hypoxic events; and (4) widespread chronic heavy metal and petroleum contamination from Mississippi River outfall and petroleum production platform spillage and leakage.

Data from the SPR studies at the West Hackberry site in shallow water off Calcasieu Pass, LA are presented in Table 6.28. Mean seasonal densities varied from 1,510 to 5,262 individuals/m^2, with an annual average of about 2,600 individuals/m^2. Maximum values were observed in February and May, and minimum values occurred in May and June, when they may have been depressed by bottom hypoxia.

In the Buccaneer Gas and Oil Field Study in shallow water off Galveston, TX data were provided on seasonal densities and composition (Table 6.29). Seasonal densities varied from a July high of about 7,300 individuals/m^2 to a January low of about 4,400/m^2, with an overall average of about 6,288 individuals/m^2. Polychaetes dominated the catch, followed by amphipods, bivalves, and nemerteans.

The STOCS studies provided considerable information on macrobenthic composition and density off south Texas in relation to area, season, and depth. Table 6.30 gives information on number of species and number of individuals/m^2 in relation to transect and depth. Here it is seen that both species and individual densities were far greater in shallow water, whereas values for the middle and outer shelf were nearly the same (except on Transect IV). Highest densities were observed near the Rio Grande (to the south). Information on seasonal and depth distribution of densities is given in Table 6.31. Seasonal differences were not great, and they seem to follow no real pattern. Highest species diversities appeared in July, August, November, and December. Highest numerical densities occurred in May/June and August. Composition of the macrobenthos in relation to depth is presented in Table 6.32. Polychaetes were dominant at all depths, but particularly in the shallowest depth zone. Pelecypods, ostracods, and other groups become more prominent on the middle and outer shelf areas.

Studies in progress on the upper slope off Louisiana (Northern Gulf of Mexico Continental Slope Study) have provided information on density and composition. The average density is 3,816 individuals/m^2, which is surprisingly high. As shown in Table 6.33, the fauna is dominated by polychaetes, followed by nematodes, several crustacean groups, mollusks, and others. In the slope studies, a mesh size of 0.3 mm is being employed, which accounts for the presence of nematodes

Table 6.27. Seasonal composition of the macrobenthos of the Louisiana continental shelf west of the Mississippi River Delta in the depth range of 2-92 m (From: Bedinger, 1981).

	Taxa (% of total)*				Individuals (% of total)			
Taxon	May	Aug/Sep	Jan	Mean	May	Aug/Sep	Jan	Mean
Anthozoa	1.9	2.3	2.3	1.7	0.5	0.3	0.0	0.3
Nemertea	0.7	1.0	0.7	0.7	4.9	3.2	4.6	4.2
Polychaeta	29.9	33.6	39.1	28.9	67.7	68.4	70.6	68.9
Gastropoda	9.9	10.3	7.2	9.9	1.4	3.7	0.9	2.0
Bivalvia	10.4	12.0	13.5	12.2	10.3	6.2	5.2	7.2
Decapoda	11.1	8.0	12.0	10.6	0.9	1.3	2.5	1.6
Other Crustacea	15.3	11.0	11.3	14.7	3.4	2.3	3.2	3.0
Sipunculida	1.9	2.3	3.0	1.5	3.4	7.6	4.0	5.0
Echinodermata	3.3	3.6	3.8	3.3	0.7	1.0	0.8	0.8
Other	15.6	15.9	7.1	16.5	6.8	6.0	8.2	7.0

*Total number of taxa collected:

May	424
Aug/Sep	309
Jan	266
Total	545

Table 6.28. Seasonal progression of macrofaunal densities in shallow water (ca. 10 m) off Calcasieu Pass, LA (From: McKinney et al., 1985).

	Density (no. individuals/m^2)						
	Feb	May	Jun	Jul	Aug	Sep	Nov
Maximum	18,736	13,280	6,844	2,388	2,809	2,984	4,958
Mean	5,262	3,350	2,127	1,510	1,665	2,223	2,057
Minimum	1,331	541	226	743	775	1,622	1,046

Table 6.29. Seasonal percent composition of the macrobenthos at the Buccaneer Oil Field site in shallow water (19-20 m) off Galveston, TX (From: Harper et al., 1981).

Taxon	Month: Jul	Oct	Jan	Apr	Mean
Polychaetes	65.7	78.0	75.3	68.1	71.8
Amphipods	19.1	7.5	9.9	21.0	14.4
Bivalves	3.6	4.5	6.8	2.8	4.4
Nemerteans	2.4	2.4	1.7	1.6	2.0
Tanaids	2.6	0.7	0.9	1.1	1.3
Decapods	1.2	1.6	0.9	0.5	1.1
Cumaceans	0.8	1.7	0.3	1.5	1.1
Sipunculids	0.7	0.7	1.1	1.2	0.9
Gastropods	0.7	0.6	0.7	0.5	0.6
Isopods	0.6	0.5	0.8	0.5	0.6
Ophiuroids	0.3	0.5	0.4	0.2	0.4
Ostracods	0.3	0.5	0.2	0.2	0.3
Cephalochordates	0.9		0.2		0.3
Nematodes	0.1	0.1	0.2	0.2	0.2
Hemichordates	0.3				0.1
Anthozoans	0.1				
Hydrozoans				0.1	
Brachiopods		0.1			
Other	0.6	0.6	0.6	0.5	0.6
No. species (mean)	53.7	46.7	39.2	42.7	45.6
No. individuals/m^2	7,300	5,800	4,400	5,700	5,800

Table 6.30. Macrobenthos densities on the south Texas continental shelf in relation to transect and depth. Transect I is located off Matagorda Bay and Transect IV is just above the mouth of the Rio Grande (From: STOCS studies).

Depth Range (m)	Transect: I	II	III	IV	Mean
No. species/m^2					
0 - 39	87	43	110	159	100
40 - 89	55	50	39	63	52
90 - 140	61	51	49	106	67
No. individuals/m^2					
0 - 39	2,740	767	4,671	3,426	2,901
40 - 89	857	350	223	486	479
90 - 140	334	233	258	752	394

Table 6.31. Macrobenthos densities on the south Texas continental shelf in relation to season and depth (From: STOCS studies).

Depth Range (m)	Month								
	Jan/Feb	Mar	Apr	May/Jun	Jul	Aug	Sep/Oct	Nov	Dec
	No. Species/m^2								
0 - 39	37	32	42	41	44	56	41	57	43
40 - 89	37	53	52	56	46	60	47	43	54
90 - 140	28	33	40	48	77	54	59	55	64
Mean	34	39	45	48	56	57	49	52	54
	No. Individuals/m^2								
0 - 39	513	861	751	950	644	904	564	928	790
40 - 89	151	410	313	455	385	546	309	238	345
90 - 140	79	144	118	235	414	306	252	234	316
Mean	248	472	394	547	481	585	375	466	484

Table 6.32. Percentage composition of macrobenthos in relation to depth off the south Texas continental shelf (data from four transects combined) (From: Flint and Rabalais, 1981).

Faunal Group	Station Depth					Mean
	0-30 m	30-60 m	60-90 m	90-120 m	120-140 m	
Polychaetes	81.6	67.6	49.6	53.2	52.6	60.9
Gastropods	1.9	2.5	3.5	2.9	1.9	2.5
Pelecypods	0.3	5.4	29.1	15.1	9.0	11.8
Ostracods	--	0.1	0.4	1.6	8.0	2.0
Isopods	--	--	0.3	5.2	3.0	1.7
Amphipods	9.1	8.5	3.7	6.7	5.6	6.7
Other crustaceans	1.5	8.4	4.0	2.5	4.9	4.3
Other groups	5.6	7.5	9.4	12.8	15.0	10.1

Table 6.33. Percentage composition of the macrobenthos of the upper continental slope (300-500 m) off the Louisiana coast (From: Gallaway et al., 1988).

Taxon	Percent of Total Abundance
Cnidarians	1.0
Nemerteans	1.2
Nematodes	17.2
Polychaetes	46.8
Mollusks	8.1
Ostracods	3.7
Copepods	4.4
Tanaids	4.2
Isopods	4.3
Amphipods	2.5
Bryozoans	3.1
Echinoderms	1.0
Other	2.5

and, to some extent, for the high densities. However, this area receives a major energy subsidy in the form of reduced hydrocarbons (petroleum and natural gas) from subsurface seeps. It may also receive considerable input from the high levels of surface primary productivity. Due to the deviant mesh size, the comparative importance of these subsidies cannot be estimated.

In summary, macrobenthic standing crops off Texas are quite low except in nearshore waters, and seasonal differences are not great. Off Louisiana densities tend to be much higher on both the shelf and the slope. The shelf populations vary considerably in relation to energy subsidies, on the one hand, and stress agents, on the other. On the Louisiana slope the populations and the diversity are high due to energy subsidies, but here the various factors cannot be sorted out in detail. All of the studies show an important relationship between faunal composition and diversity, on the one hand, and sediment type, on the other. Tight-packed clay is the poorest environment for macrobenthic organisms because it has low porosity and low oxygen penetration. Most of the data given in this section relate to infauna, but the collection techniques do not allow separation of infauna from epifauna.

Megabenthos

Technically, the megabenthos includes those organisms associated with the bottom that are retained by sieves of mesh size 25.4 mm. In practice, most authors who have dealt with megabenthos as a group on the Texas-Louisiana shelf have simply given catch data from trawls, Van Veen grabs, etc. In the present report we have listed the squids, penaeid shrimp, larger crabs, stomatopods, and fishes as demersal fauna. There are no sharp dividing lines. Herein, we will focus upon the larger benthic invertebrates, even though there is some overlap with the demersal species. In the STOCS study all larger invertebrates collected by the Smith-McIntyre grabs were listed as "macroinfauna," whereas all organisms collected by bottom trawls were listed as "epifauna." The term "megabenthos" was not employed, even though some of the infauna and most of the epifauna must have been megafauna. Because it is not possible to reconstruct the megafauna from their data and because most of the epifauna is clearly megafauna we have included only the trawl data (= epifauna) in our consideration of megafauna.

The primary study on the larger benthic invertebrates of the area is that of Defenbaugh (1976). He reviewed earlier works in the area, and these need not be addressed here. More recently, Farrell (1979) provided information on the catch from a series of Van Veen grabs off Timbalier Bay, LA. The catch included crustaceans (mainly decapods and amphipods), bivalves, and gastropods as well as a number of less numerous groups. Data from the STOCS study on the epifaunal invertebrates was subjected to cluster analysis, which revealed a series of depth-related species groups as shown in Figure 6.15. Beyond this, the epifauna showed few distinct trends, and this is due largely to the fact that many of the species are quite mobile and move around in relation to life history stage and season of the year.

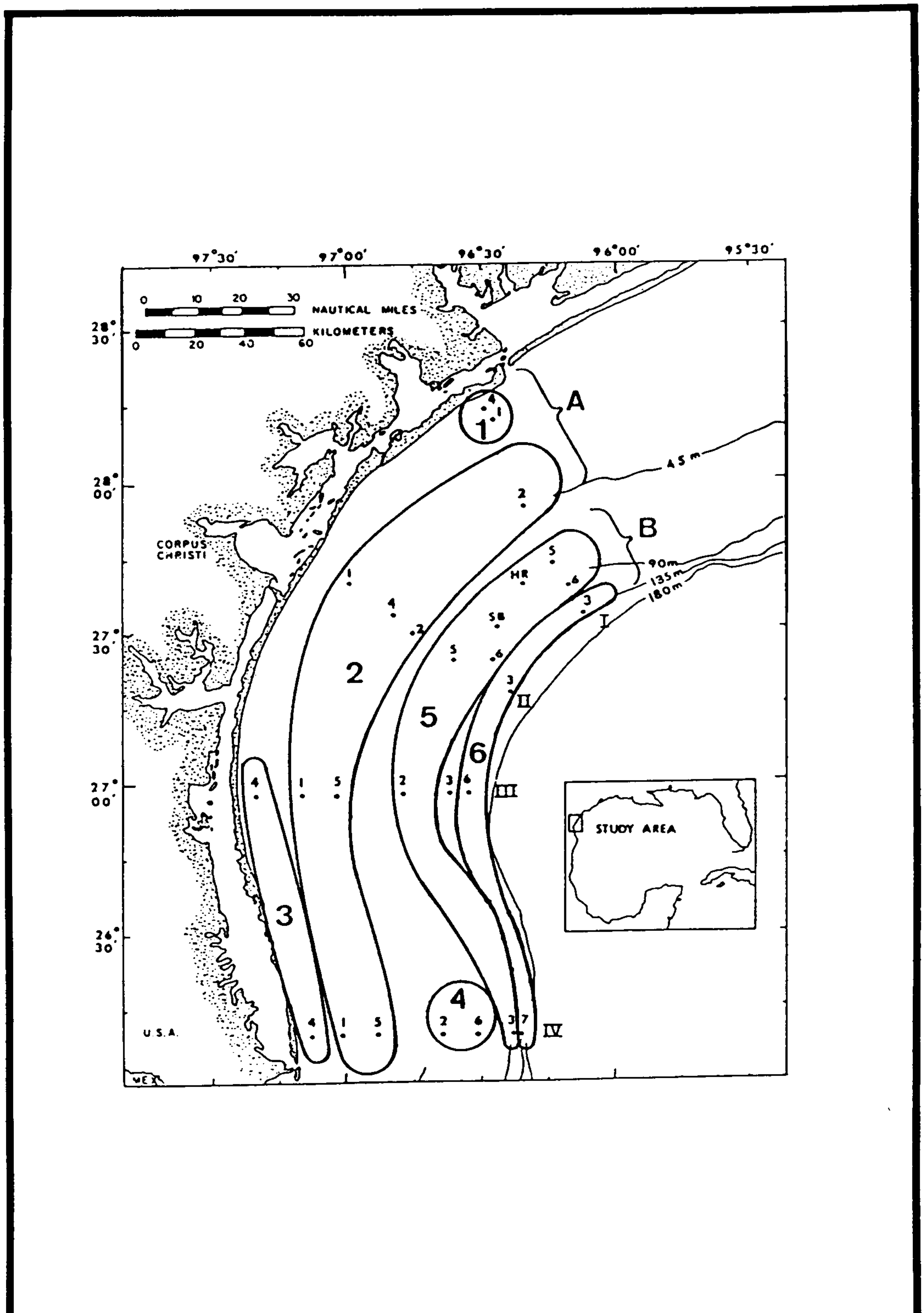


Figure 6.15. Depth-related megafaunal assemblages of the South Texas continental shelf as revealed by cluster analysis (From: Flint and Rabalais, 1981).

The best general summary of the state of our knowledge of the megafauna of the Texas-Louisiana continental shelf and slope is provided by Defenbaugh (1976). He divided the area into a series of depth-related faunal assemblages as follows (Figure 6.16):

A. Inner shelf assemblage. Depth 4 to 20 m; bottom of soft mud, mixed sand and mud, or sand; salinity usually about 36°/oo.

B. Pro-delta fan assemblage. Depth 4 to 20 m; bottom of soft, silty mud; salinity about 30 to 36°/oo. Mississippi River Delta region only.

C. Intermediate shelf assemblage. Depth 20 to 60 m; bottom of soft mud or sand; salinity about 36°/oo.

D. Outer shelf assemblage. 60 to 120 m; bottom typically of soft mud; salinity 36°/oo.

E. Upper slope assemblage. 120 to 200 m; substrate typically soft mud; salinity 36°/oo.

The species characteristics of each of these assemblages are listed in Table 6.34. Although there is considerable overlap, each assemblage does include its own suite of characteristic species. More recent studies would permit expansion of the species lists, particularly of the polychaetes, but the general faunal assemblages would otherwise be little changed. Within the various depth zones, substrate type is an important variable for some species such as the rock shrimp (*Sicyonia brevirostris* and *S. dorsalis*). There is also evidence of a significant tropical element in the megafauna of the south Texas shelf.

The megafauna of the upper slope in the depth range of 300 to 500 m is being investigated by Gallaway et al. (1988). For the most part, this fauna is quite distinct from the "upper slope assemblage" listed by Defenbaugh (1976). For example, among the abundant decapods listed (*Bathyplax typhla*, *Benthochascon schmitti*, *Munida valida*, *Munidopsis robusta*, *Nematocarcinus rotundus*, *Penaeopsis serrata*, *Plesionika holthuisi*, *Rochinia crassa*, and *Stereomastis sculpta*), none appear in Defenbaugh's list. Whether a major faunal break occurs in the depth range of 120 to 300 m cannot be determined from existing information.

For the most part, it is impossible to obtain information on exact megafaunal densities from the existing literature. Most authors have been content to indicate the number of organisms per collection, itself an indefinite quantity. However, in the Louisiana upper slope project, density estimates have been provided based upon trawl collections and bottom photography (Table 6.35). The two methods give quite discordant results that seem to indicate the inefficiency of the trawl in collecting benthic invertebrates.

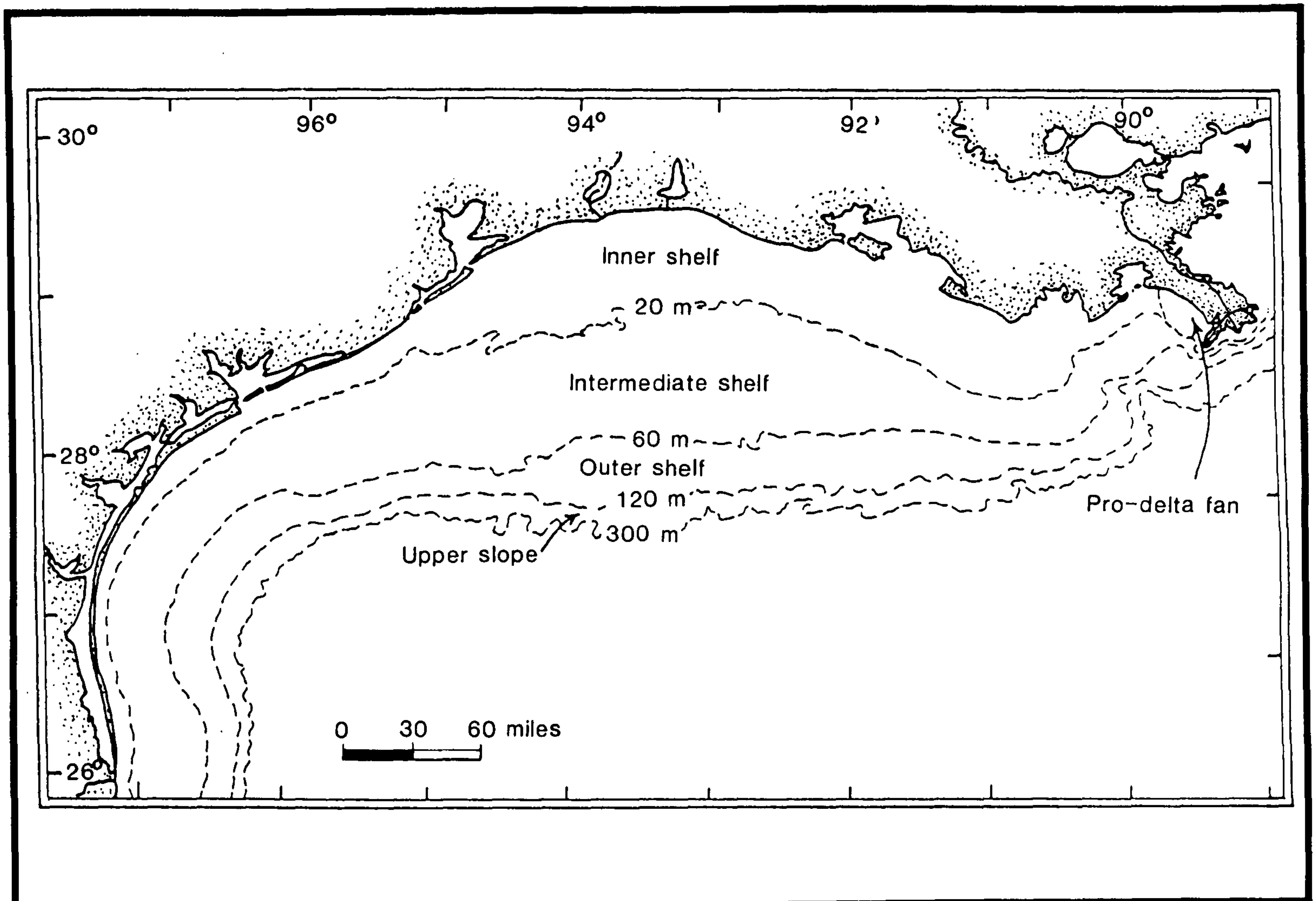


Figure 6.16. Depth-related megafaunal assemblages of the Texas-Louisiana continental shelf (From: Defenbaugh, 1976).

Table 6.34. Depth-related faunal assemblages of the Texas-Louisiana continental shelf and upper slope based upon the larger benthic invertebrates (From: Defenbaugh, 1976).

A. INNER SHELF ASSEMBLAGE

Cnidaria
- *Renilla mulleri*
- *Astrangia astreiformis*
- *Palythoa texaensis*

Annelida
- *Diopatra cuprea*
- *Onuphis eremita oculata*

Gastropoda
- *Architectonica nobilis*
- *Polinices duplicatus*
- *Phalium granulatum*
- *Thais haemostoma canaliculata*
- *Anachis obesa*
- *Cantharus cancellarius*
- *Busycon spiratum plagosum*
- *Nassarius acutus*
- *Oliva sayana*
- *Olivella mutica*
- *Terebra dislocata*
- *Terebra protexta*

Bivalvia
- *Nuculana concentrica*
- *Anadara ovalis*
- *Anadara transversa*
- *Noetia ponderosa*
- *Atrina serrata*
- *Dinocardium robustum*
- *Dosinia discus*
- *Corbula swiftiana*

Natantia
- *Penaeus aztecus*
- *Penaeus setiferus*
- *Sicyonia brevirostris*
- *Sicyonia dorsalis*
- *Trachypenaeus similis*

Reptantia
- *Pagurus pollicaris*
- *Persephona aquilonaris*
- *Persephona crinata*
- *Persephona punctata*
- *Calappa sulcata*
- *Hepatus epheliticus*
- *Callinectes sapidus*
- *Callinectes similis*
- *Portunus gibbesi*
- *Portunus spinimanus*
- *Libinia emarginata*

Stomatopoda
- *Squilla empusa*

Echinodermata
- *Luidia clathrata*
- *Ophiolepis elegans*
- *Mellita quinguiesperforata*

B. PRO-DELTA FAN ASSEMBLAGE

Cnidaria
- *Renilla mulleri*

Gastropoda
- *Cantharus cancellarius*
- *Nassarius acutus*

Bivalvia
- *Nuculana concentrica*
- *Macoma tageliformis*
- *Abra loica*

Reptantia
- *Persephona crinata*
- *Callinectes similis*
- *Portunus gibbesi*
- *Portunus spinimanus*

Stomatopoda
- *Squilla empusa*

Table 6.34. (Continued).

Natantia
- *Penaeus aztecus*
- *Penaeus setiferus*
- *Sicyonia dorsalis*
- *Trachypenaeus similis*

C. INTERMEDIATE SHELF ASSEMBLAGE

Annelida
- *Diopatra cuprea*

Gastropoda
- *Strombus alatus*
- *Distorsio clathrata*
- *Tonna galea*
- *Murex fulvescens*
- *Busycon contrarium*
- *Fasciolaris lilium hunteri*
- *Conus austini*
- *Polystira albida*
- *Pleurobrachaea hedgpethi*

Bivalvia
- *Amusium papyraceus*
- *Argopecten gibbus*
- *Tellina nitens*
- *Tellina squamifera*
- *Pitar cordata*
- *Gouldia cerina*
- *Chione clenchi*

Natantia
- *Penaeus aztecus*
- *Penaeus setiferus*
- *Sicyonia brevirostris*
- *Sicyonia dorsalis*
- *Trachypenaeus similis*

Reptantia
- *Petrochirus diogenes*
- *Persephona crinata*
- *Calappa sulcata*
- *Hepatus epheliticus*
- *Callinectes similis*
- *Portunus gibbesi*
- *Portunus spinicarpus*
- *Portunus spinimanus*
- *Anasimus latus*
- *Libinia emarginata*
- *Parthenope serrata*

Stomatopoda
- *Squilla chydaea*
- *Squilla empusa*

Echinodermata
- *Luidia alternata*
- *Luidia clathrata*
- *Astropecten duplicatus*
- *Ophiolepis elegans*
- *Clypeaster ravenelli*
- *Encope michelini*
- *Echinaster* sp.
- *Stylocidaris affinis*

D. OUTER SHELF ASSEMBLAGE

Gastropoda
- *Turritella exoleta*
- *Distorsio clathrata macgintyi*
- *Polystira albida*

Bivalvia
- *Anadara baughmani*
- *Anadara floridana*
- *Amusium papyraceus*
- *Argopecten gibbus*

Reptantia
- *Munida forceps*
- *Raninoides louisianensis*
- *Myropsis quinquespinosa*
- *Calappa springeri*
- *Calappa sulcata*
- *Portunus spinicarpus*
- *Anasimus latus*
- *Leiolambrus nitidus*

Table 6.34. (Continued).

Pitar cordatus	Stomatopoda
Verticordia ornata	*Squilla chydaea*
Natantia	Echinodermata
Parapenaeus longirostris	*Astropecten cingulatus*
Penaeus aztecus	*Astropecten duplicatus*
Sicyonia brevirostris	*Brissopsis atlantica*
Trachypenaeus similis	*Echinocardium fulvescens*
E. UPPER SLOPE ASSEMBLAGE	
Cnidaria	Reptantia
sea anemone (unidentified)	*Munida forceps*
	Raninoides louisianensis
Annelida	*Myropsis quinquespinosa*
Protula tubularia	*Iliacantha subglobosa*
	Pyromaia arachna
Gastropoda	*Acanthocarpus alexandri*
Sconsia striata	*Calappa sulcata*
Murex beauii	*Portunus spinicarpus*
	Thalassoplax angusta
Bivalvia	*Anasimus latus*
Yoldia solenoides	*Stenocionops spinimana*
Limopsis sulcata	*Parthenope agona*
Cyclopecten nanus	
Cyclocardia armilla	Stomatopoda
Nemocardium perambile	*Squilla chydaea*
Natantia	Echinodermata
Parapenaeus longirostris	*Anthenoides piercei*
Solenocera vioscai	*Luidia elegans*
Hymenopenaeus tropicalis	*Astropecten nitidus*
	Cheiraster echinulatus
	Echinocardium fulvescens
	Brissopsis alta
	Brissopsis atlantica

Table 6.35. Estimates of megafaunal invertebrate density on the Louisiana upper continental slope based upon trawl collections and bottom photography (From: Gallaway et al., 1988).

Group	Density (no. individuals/ha)	
	Trawl	Photography
Porifera	2	139
Alcyonarians	4	153
Actiniarians	19	100
Bivalves	7	0
Decapods	138	861
Asteroids	3	14
Crinoids	1	0
Echinoids	0	25
Holothuroids	5	3
Ophiuroids	17	119
Other	9	96
Total	205	1,510

Controlling Factors

It has already been pointed out that substrate is an important factor in determining distribution patterns of the meiofauna and the macrofauna and for at least some species of megafauna. However, for the mobile megafauna the association is quite loose, and other considerations are probably more important. Life history considerations also loom as a significant factor. Benthic species with planktonic reproductive stages readily invade newly created habitats, and these species would be particularly preadapted to the variable bottom environments off Louisiana and neighboring portions of Texas. Species that lack mobile reproductive stages would be poor colonizers and ill-adapted to highly variable bottom environments. Life histories of some of the megafaunal species involve seasonal migratory movements that take them into different depth zones and bottom types, and for many mobile species the young use the estuarine environment. Depth or depth-related factors are clearly important for many and probably all of the species of the shelf and slope. Food relationships are undoubtedly important, as well, but little can be said about the natural food of most of the benthic species except to classify them as suspension feeders, deposit feeders, scavengers, and carnivores. It is interesting that suspension feeders are not prominent in this area that is characterized by a more or less permanent nepheloid layer. Summer bottom hypoxia has been shown to exert a depressing effect on sedentary benthic populations of the Louisiana and adjacent portions of the Texas shelf. Benthic organisms collected near the Mississippi River Delta and around oil production platforms have been shown to have high body burdens of certain chemical pollutants, including heavy metals. Petroleum hydrocarbons, also abundant in the sediments, have been identified in the tissues of the bottom animals. This is particularly important because some of the aromatic compounds, in particular, are known to induce tissue damage and neoplastic growths. Necropsies of species living on the Louisiana shelf have, indeed, revealed pathological symptoms. On the other hand, petroleum hydrocarbons also provide a nutrient source for bacteria and fungi which, in turn, support benthic populations, and so benthic population levels are sometimes elevated in sediments containing such hydrocarbons. Produced water from petroleum production platforms can inhibit benthic populations. On the other hand, studies of the brine disposal areas of the SPR have shown that elevated salinity resulted in enhancement of the benthic fauna during periods of hypoxic stress, presumably by inducing turbulence and maintaining oxygenated conditions in the near-bottom waters.

Benthic Production Model

A conceptual model of benthic production is presented in Figure 6.17. Relations of the benthos are extremely complex, and the model has been kept as simple as possible by not including all the pathways associated with maturation of benthic young into other categories and by reducing the number of pathways leading to organic detritus production. Both types of information should be rather obvious to the reader. The benthos itself consists of three categories: meiobenthos, macrobenthos, and megabenthos (microbenthos is not discussed here). Through feeding activities, energy and carbon flow from the

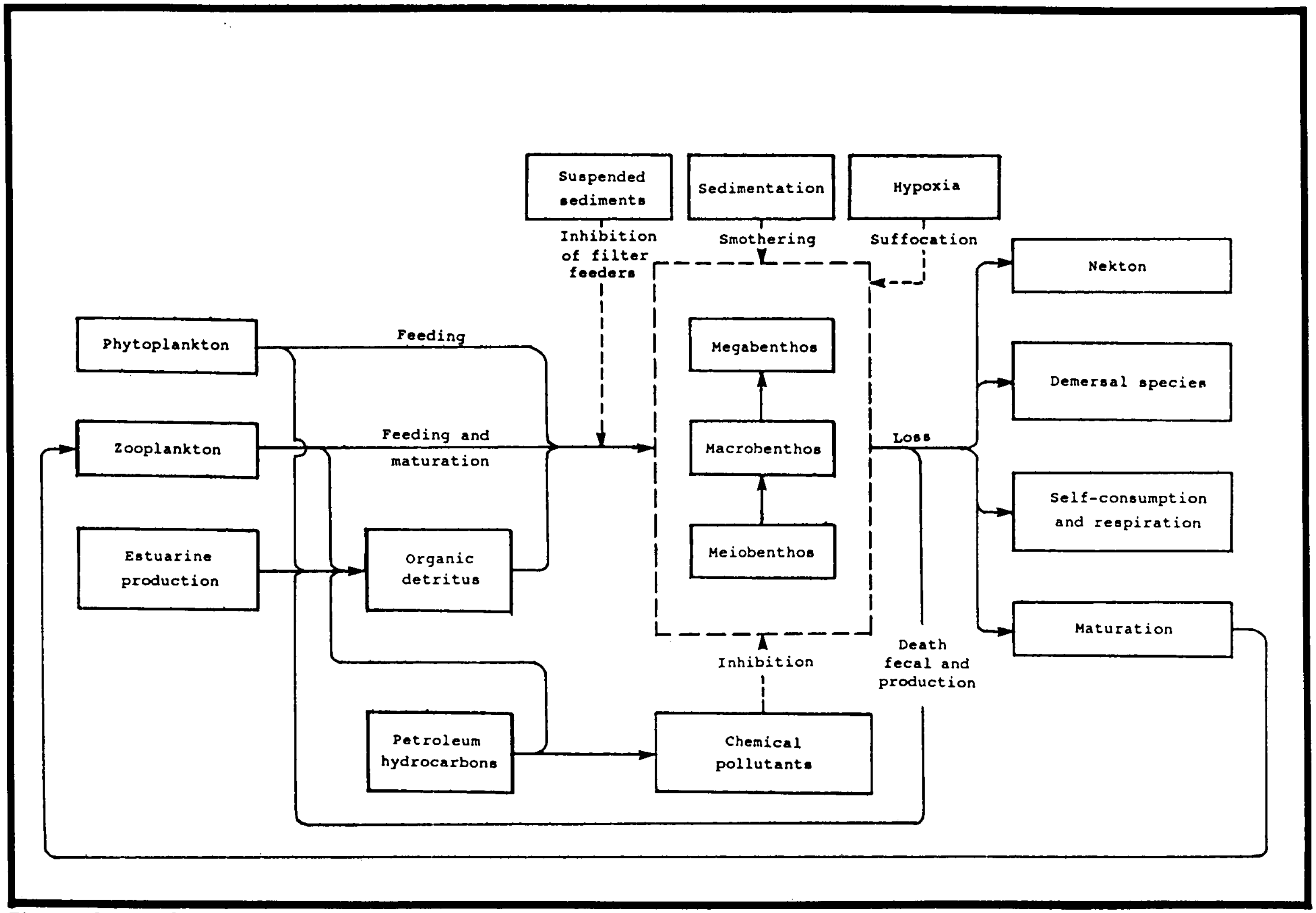


Figure 6.17. Conceptual model of benthic production on the Texas-Louisiana continental shelf and upper slope. Some of the maturation and organic detritus production pathways have been omitted for clarity.

smaller to the larger benthic groups. Three external food sources are shown: phytoplankton, zooplankton, and organic detritus. Benthic filter feeders ingest plankton and suspended detritus. Bottom feeders ingest material from the sediment surface or from within the sediment layer itself. Losses involve maturation or feeding by the nekton and demersal species, death and fecal production, self-consumption and respiration, and maturation into the plankton. A number of external factors have been shown to be particularly important. Suspended sediments inhibit suspension feeders, and heavy sedimentation (as from the Mississippi River) could cause burial and smothering (Saila et al., 1972). Hypoxia in the near-bottom waters is lethal to most sedentary species and induces death or avoidance among the mobile species. Chemical pollutants, including heavy metals, chlorinated hydrocarbons, and other industrial chemicals, can induce pathological conditions and death. Petroleum hydrocarbons have a dual effect. Considered as a form of organic detritus, they support large populations of bacteria and fungi, and so serve as a nutrient source. On the other hand, aromatic fractions, in particular, can have pathological and toxic effects. It should be emphasized that, as complex as this diagram is, it is still a gross simplification of the true dynamics of the benthos.

6.4.3 Structure-Related Biota

The Texas-Louisiana continental shelf and slope consist of a broad, submerged plain carpeted with terrigenous sediments. This plain is punctuated with natural hills and rocky outcrops (topographic high features) and dotted with anthropogenic structures (primarily petroleum production platforms, but also pipelines, submerged shipwrecks, artificial reefs, marker buoys, and other features). Both the natural and anthropogenic structures are populated by special flora and fauna that we collectively term structure-related biota.

Biota Associated with Topographic Highs

Although some of the hard banks of the area have been known to commercial fishermen for about a century, serious scientific research has been limited to the past two decades. A great many research papers and reports have addressed this biota, but the major works of Bright and Pequegnat (1974), Rezak et al. (1983), and Dennis (1985) summarize most of the literature and serve as the primary basis for the present discussion.

The distribution of hard banks in the area is shown in Figure 6.18. The biota of these banks is vertically stratified into zones, which have been described by Rezak et al. (1983). The distribution and depth ranges of these zones on the various Texas-Louisiana banks are shown in Table 6.36. No single bank possesses all the zones, but the East and West Flower Garden Banks lack only the *Millepora* - Sponge Zone. The two Flower Garden banks harbor the most diverse and thoroughly developed offshore hard bottom epibenthic communities in the region. High diversity coral reefs (*Diploria* - *Montastrea* - *Porites* Zone) are not present on any other northern Gulf banks. Lower diversity coral reefs (*Stephanocoenia* - *Millepora* Zone) are

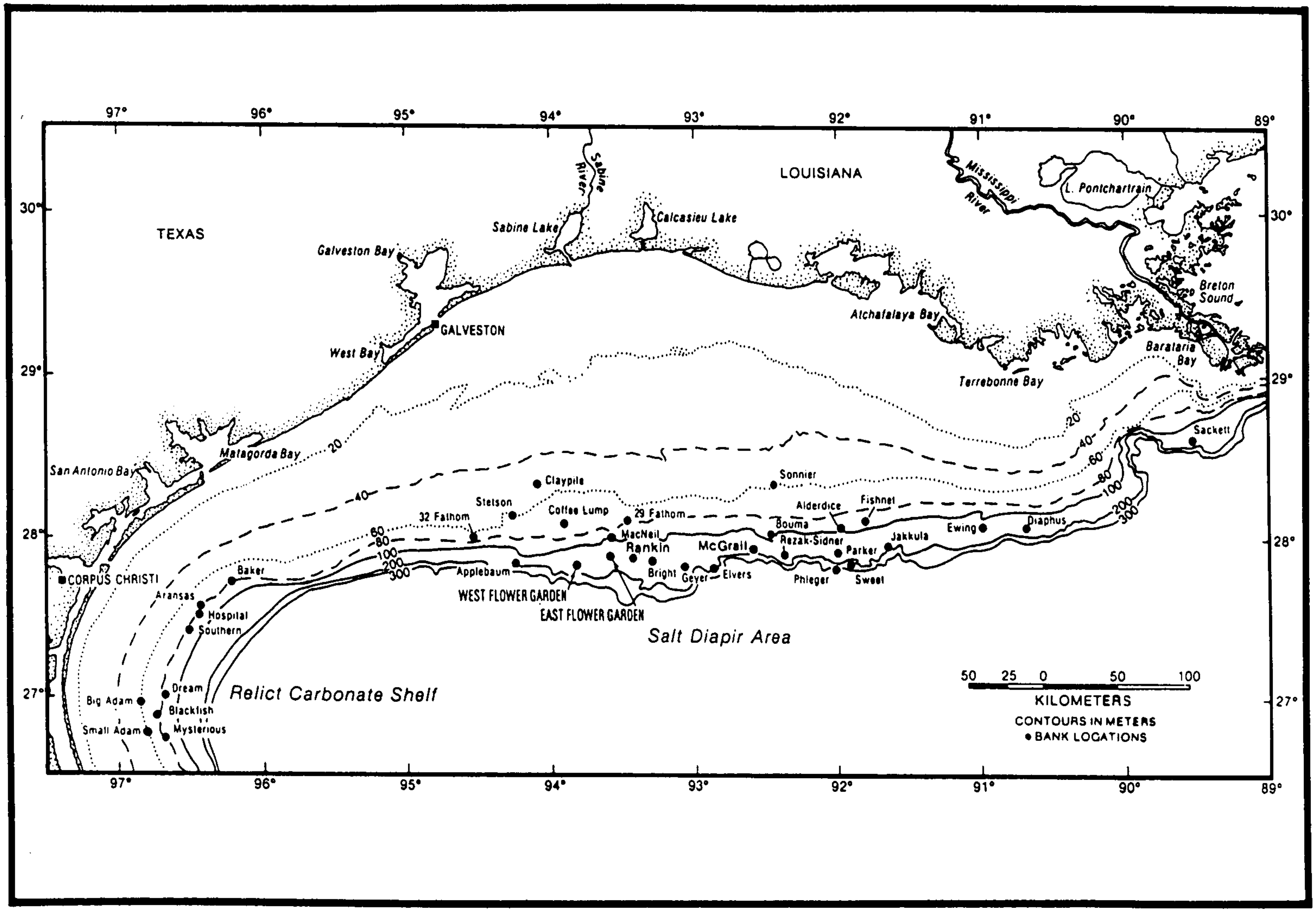


Figure 6.18. Distribution of major hard banks on the Texas-Louisiana continental shelf and upper slope (From: Rezak et al., 1983).

Table 6.36. Depth ranges of biotic zones on hard banks of the continental shelf off Texas and Louisiana. P = zone present, but depth range uncertain (From: Rezak et al., 1983).

Bank	Depth Range of Biotic Zone (m)							
	Millepora Sponge	Diploria-Montastrea-Porites	Madracis	Stephanocoenia	Algal-Sponge	Antipatharian-Transitional	Nepheloid	Soft Bottom
Claypile	40-45	-	-	-	-	-	45+	50+
Sonnier	18-52	-	-	-	-	-	52+	60+
Stetson	20-52	-	-	-	-	-	52+	62-64+
Small Adam	-	-	-	-	-	60?	P	64+
Big Adam	-	-	-	-	-	60?	P	66+
North Hospital	-	-	-	-	-	58-70	70+	68-70+
Aransas	-	-	-	-	-	57-70	70+	70-72+
Baker	-	-	-	-	-	56-70	70+	70-74+
Blackfish	-	-	-	-	-	60?	P	70-74+
Hospital Rock	-	-	-	-	-	59-70	70+	70-78+
Mysterious	-	-	-	-	-	70?	P	74-86+
Southern	-	-	-	-	-	58-70	70+	80+
Dream	-	-	-	-	-	62-70	70+	80+
South Baker	-	-	-	-	-	59-70	70+	80-84+
32 Fathom	-	-	-	-	-	52?	P	55+
Coffee Lump	-	-	-	-	-	62-68	68+	70+
Fishnet	-	-	-	-	-	66-73	73+	78+
Alderdice	-	-	-	-	55-67	67-82	82+	84-90+
Ewing	-	-	-	-	56-72	72-80	80+	85-100+
Bouma	-	-	-	-	60-75	75-84	84+	90-100+
Parker	-	-	-	-	60-82	82-?	P	100+
Sackett	-	-	-	-	*67-82	65-85	85+	100+
East Flower Garden	-	15-36	28-46	36-52	46-82	82-86	86+	100-120+
Applebaum	-	-	-	-	76?	P	P	100-120+
Bright	-	-	-	37	52-74	74-?	P	110+
West Flower Garden	-	20-36	P	36-50	46-88	88-89	89+	110-130+
Diaphus	-	-	-	-	-	73-98	98+	110-130+
McGrail	-	-	-	45-47	45-82	82-?	P	110-130+
Rankin	-	-	-	-	52-92	92-100	100+	110-140+
Jakkula	-	-	-	-	59-90	90-98	98+	120-140+
Rezak-Sidner	-	-	-	-	55-93	93-100	100+	120-150+
Sweet	-	-	-	-	75-80+	P	P	130-200+
Elvers	-	-	-	-	60-97	97-123?	123+	180+
Geyer	37-52	-	-	-	60-98	98-123?	123+	190-210+
Phleger	-	-	-	-	-	?	†122+	200+

*Weakly represented, environmentally stressed.
†Clear water, but biota typical of nepheloid zone.

present at the Flower Gardens and at two other shelf edge banks, McGrail and Bright. The zones are described briefly below.

A. Zone of Major Reef-Building Activity and Primary Production

I. *Diploria*-*Montastrea*-*Porites* Zone: A zone consisting of living, high diversity coral reefs. Hermatypic corals dominant. Coralline algae abundant. Leafy algae limited.

II. *Madracis* Zone and Leafy Algae Zone: The *Madracis* Zone is dominated by the small branching coral *Madracis mirabilis*, which produces large amounts of carbonate sediment. In places, large (possibly ephemeral) populations of leafy algae dominate the *Madracis* gravel substratum (Leafy Algae Zone).

III. *Stephanocoenia* - *Millepora* Zone: A zone consisting of living, low diversity coral reefs. Hermatypic corals limited.

IV. Algal - Sponge Zone: A zone dominated by crustose coralline algae actively producing large quantities of carbonate substratum, including rhodoliths (algal nodules). The zone extends downward, past the depth at which algal nodules diminish in abundance, to the greatest depth at which coralline algal crusts are known to cover a substantial percentage of the hard substratum. This is the largest of the reef-building zones in terms of area of sea bottom. Leafy algae are very abundant.

B. Zone of Minor Reef-Building Activity

V. *Millepora* - Sponge Zone: A zone where crusts of the hydrozoan coral *Millepora* share the tops of siltstone, claystone, or sandstone outcrops with sponges and other epifauna. Isolated scleractinian coral heads may be present, but rare. Coralline algae are rare.

C. Transitional Zones Wherein Reef-Building Activity May Range from Minor to Negligible.

VI. *Antipatharian* Zone: Limited crusts of coralline algae and several species of coral exist within a zone typified by sizeable populations of antipatharians. Banks supporting Algae-Sponge Zones (A, IV above) generally possess something comparable to an Antipatharian Zone and the deeper, turbid-water, Nepheloid Zone of the lower bank.

D. Zone of No Reef-Building Activity

VII. Nepheloid Zone: A zone wherein high turbidity, sedimentation, resuspension of sediments, and resedimentation dominate. Rocks and drowned reefs here are generally covered with veneers of fine sediment. Epifauna are depauperate and variable; deep-water octocorals and solitary stony corals are often conspicuous. This zone occurs in some form on lower parts of all banks below the depths of the Antipatharian and Transitional Zones.

The Flower Garden Banks have been well studied, and detailed species lists for the various taxonomic groups are presented in Bright and Pequegnat (1974). The remaining banks have received less attention, although Dennis (1985) surveyed the fish fauna of twenty three of the banks and obtained a list of 140 identifiable fish species. The vertical zonation and conspicuous biota of the East Flower Garden Bank are shown in Figure 6.19, and similar diagrams are available for several other banks. Darnell and Bright (1983) produced a rough estimate of standing crop and production for the Live Coral and Algal-Sponge Zones of the East Flower Garden Bank (Tables 6.37 and 6.38) as well as mean annual accretion rates for Montastrea annularis, one of the massive corals. Such studies have not been attempted for any of the other banks.

In attempting to assess the factors that control the distribution and zonation of the biota of the Texas-Louisiana banks, three sets of factors loom in importance: the location and nature of the particular bank, its surrounding environmental conditions, and the nature of the available biota. The first set of factors includes the geographic position and nature of the bank itself. Here, proximity to the Mississippi River, latitude, and depth of the water column are important, as are the height of the bank, depth of the bank crest, and nature of the bank substrate (hard vs. soft bottom). The second set concerns the environmental factors surrounding and acting upon the particular bank. Minimum salinity, minimum winter temperature, and turbidity are of particular relevance. Near the Mississippi River, plumes of fresher sediment laden waters may bathe the banks. On the inner shelf, winter temperatures tend to fall below 16°C; beyond mid-shelf, they range 16° to 18°C; and toward the outer shelf and seaward, they rarely dip below 18°C. Near the bottom there is a persistent nepheloid layer. Light penetration is reduced, and substrates here become coated with fine sediments. Light penetration is generally low in the turbid nearshore waters and much higher offshore. On the inner two-thirds of the shelf, the water tends to be fresher and more turbid, the current being predominantly from the northeast and east. Toward the outer shelf, the water is warmer and clearer and comes predominantly from the southwest and west. The third factor is the nature of the biota itself. Most, if not all of the biota is of tropical affinity, and a great many of the species appear to be living at or near their minimum limits of tolerance to temperature and other factors. Populations are precariously small.

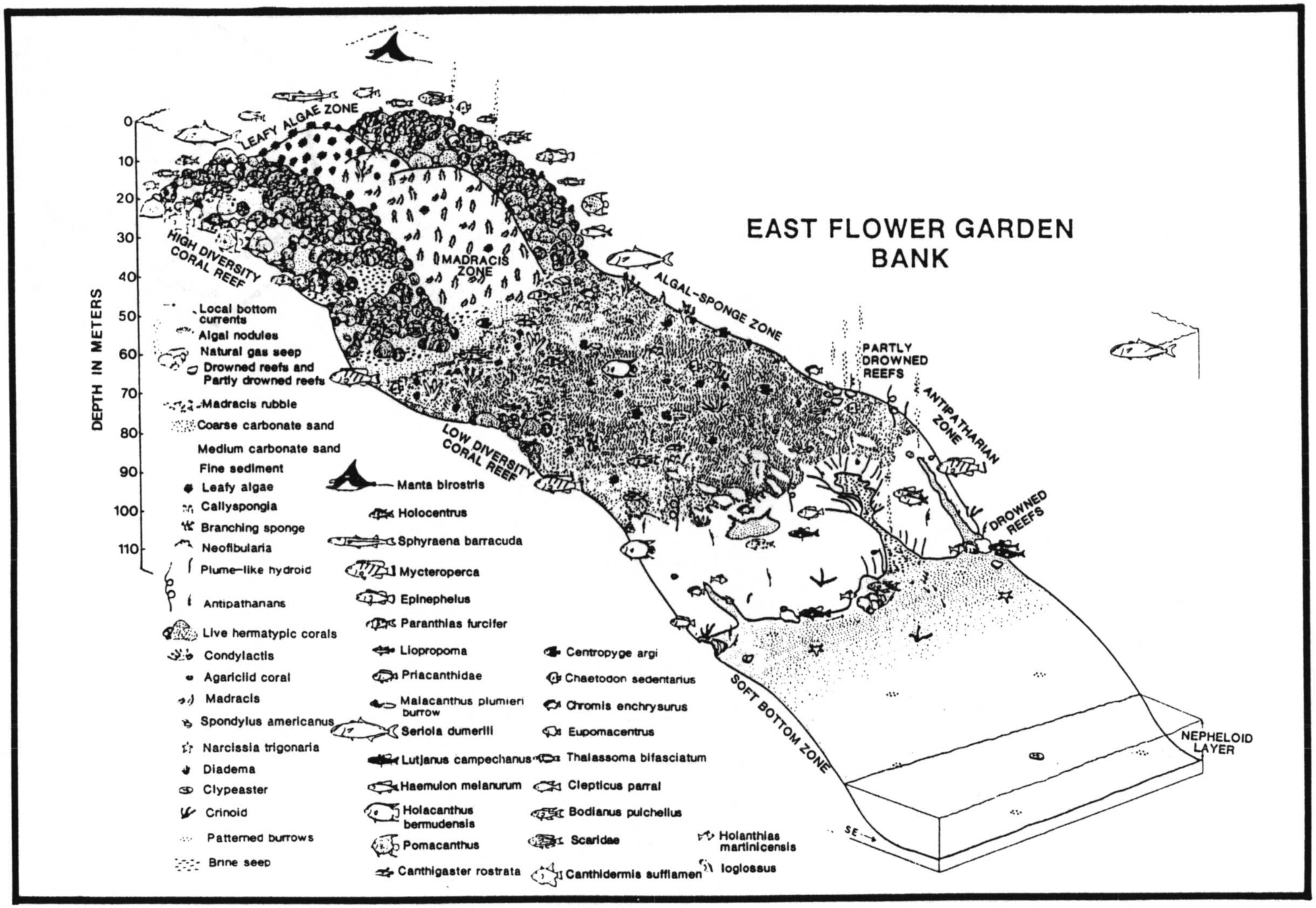


Figure 6.19. Vertical zonation and conspicuous biota of the East Flower Garden Bank (From: Rezak et al., 1983).

Table 6.37. Standing crop and production estimates for the Live Coral Zone of the East Flower Garden Bank (From: Darnell and Bright, 1983).

Measure	Biomass (metric tons dry wt) Min	Biomass (metric tons dry wt) Max	Caloric Equivalent (millions of kcal) Min	Caloric Equivalent (millions of kcal) Max
STANDING CROP				
Producers (tissue only)				
-Zooxanthellae	15.9	31.8	63.6	127.2
-Soft Algae (mean)	4.2	6.9	16.8	27.6
-Coralline and Endolithic Algae	278.9	557.7	1,115.4	2,230.8
Total Producers	299.0	596.4	1,195.8	2,385.6
Coral Tissue	121.3	242.6	448.8	897.6
Other Consumers	255.6	255.6	1,104.3	1,104.3
Total Standing Crop	675.9	1,094.6	2,748.9	4,387.5
PRODUCTION				
Gross Primary Production	13,006		52,022*	
Net Production (58.3% of gross)	7,582		30,329	
Respiratory Loss (41.7% of gross)	5,423		21,693	

*Ratio of gross production to standing crop biomass:

-Using minimum standing crop estimate: 52,022/2,749 = 18.9
-Using maximum standing crop estimate: 52,022/4,388 = 11.8

Table 6.38. Standing crop and production estimates for the Algal-Sponge Zone of the East Flower Garden Bank (From: Darnell and Bright, 1983).

Measure	Biomass (metric tons dry wt) Min	Biomass (metric tons dry wt) Max	Caloric Equivalent (millions of kcal) Min	Caloric Equivalent (millions of kcal) Max
STANDING CROP				
Producers (tissue only)				
-Soft Algae (mean)	54.2	79.2	216.8	316.8
-Coralline and Endolithic Algae	1,038.0	2,077.0	4,152.0	8,308.0
Total Producers	1,092.2	2,156.2	4,368.8	8,624.8
Consumers	--	--	--	--
Total Standing Crop	1,092.2+	2,156.2+	4,368.8+	8,624.8+
PRODUCTION				
Gross Primary Production	49,740		198,860	
Net Production (74.2% of gross)	36,907		147,554	
Respiratory Loss (25.8% of gross)	12,833		51,306	

Three biotic groups are recognized: permanent residents, periodic colonizers, and seasonal transients. The permanent residents maintain persistent populations and must be able to survive and reproduce under the prevailing conditions. Periodic colonizers invade, survive, and may even reproduce for a time, but they are killed by occasional extreme conditions. Most of these have planktonic eggs or larvae, and their erratic appearance represents accidents of dispersal, sometimes from great distances. Seasonal transients include the more mobile fishes, turtles, and invertebrates that appear generally during the warmer months. The association of sea turtles (primarily the loggerhead) with these banks has been documented by Rosman et al. (1987). The distribution of the biotic zones in relation to controlling factors is shown diagrammatically in Figure 6.20. Because most of the biological species are living near their limits of tolerance they must be under considerable stress during portions of the year. This suggests that the species would be particularly vulnerable to anthropogenic threats (especially chemical pollutants) if such challenges occurred in conjunction with naturally-induced stress.

Darnell and Bright (1983) have produced conceptual models and elements of a mathematical model for the East Flower Garden coral reef system, and they have evaluated this model with existing data. No efforts have been made to model any of the other banks. We include here a much simplified conceptual model for the euphotic zone portion of a generalized bank ecosystem (Figure 6.21). A similar model for the aphotic zone would lack the producers (hermatypic corals, leafy algae, and coralline algae) as well as the coralivores and herbivores. This model is appropriate for the zones of major and minor reef building activity discussed above. The taxonomic composition of each of the compartments of the model is detailed in Darnell and Bright (1983). Because of the visual complexity of the model, potential stress factors have been omitted, but they are addressed below. A brief discussion of the model follows. The input of radiant energy and nutrients leads to the production of hermatypic corals, leafy algae, and coralline algae. Phytoplankton and zooplankton swept in by the water currents are consumed by both attached and non-attached plankton feeders. Coralivores and herbivores feed upon the corals and leafy algae, respectively. All categories produce organic detritus that is utilized by the deposit feeders. Omnivores feed upon the various previous categories. Some of the top predators are residents, while others are transient. Both prey upon organisms in the lower consumer levels, and the transients ultimately move out of the area. Not shown are various losses from the system including gametes, eggs, larvae, juveniles, and organic detritus that are swept from the system by strong prevailing currents. Estimates of standing crop and production for the Live Coral Zone and the Algal-Sponge Zone of the East Flower Garden system are given in Tables 6.37 and 6.38. Natural stress factors include primarily low temperature and low salinity water, turbidity (especially, the nepheloid layer), and sedimentation, as well as pathogens and parasites. Anthropogenic stress factors include chemical pollutants and mechanical damage (especially, from anchor dragging) and fishing pressure (primarily for the resident snappers and groupers).

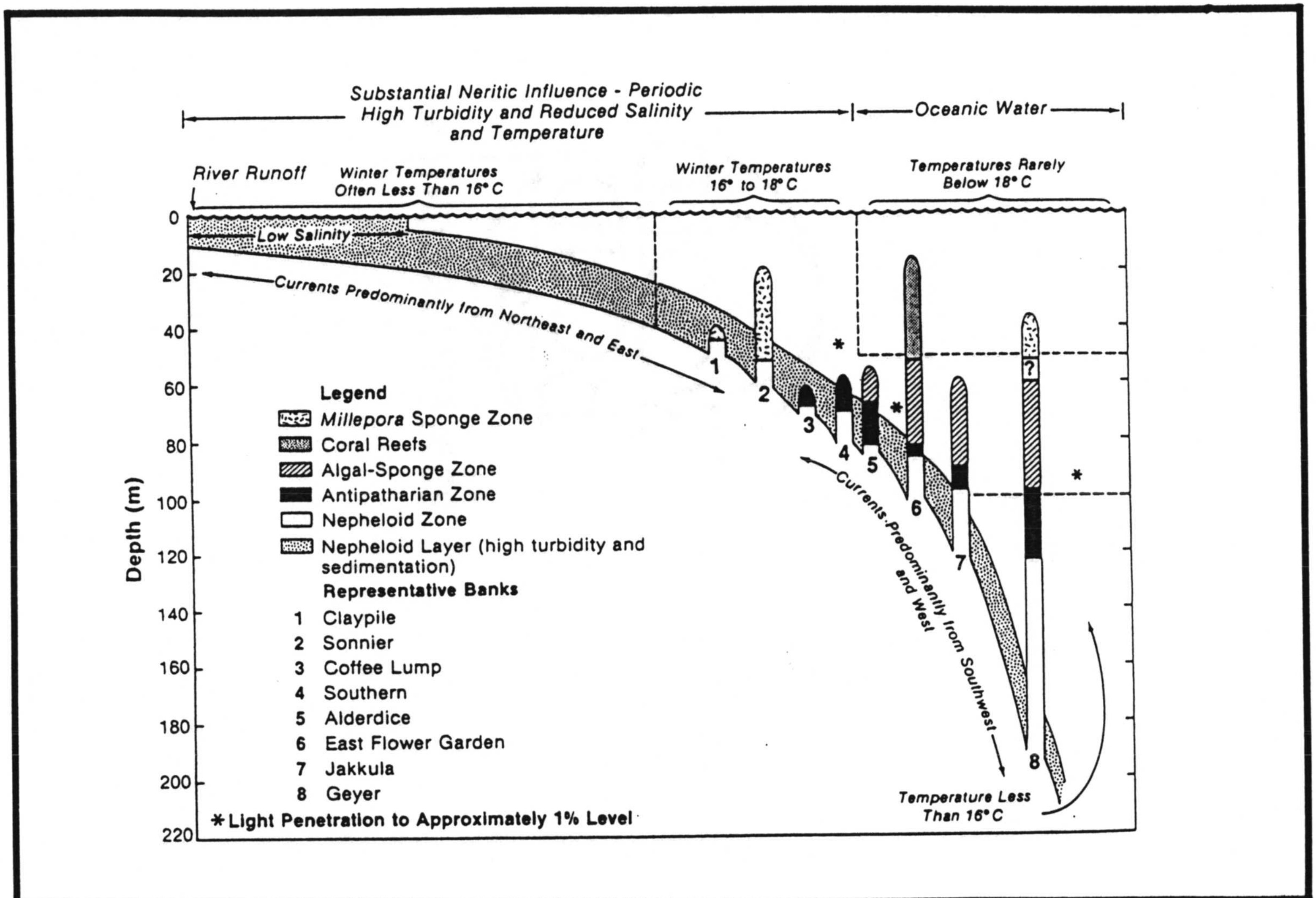


Figure 6.20. Distribution of biotic zones on selected banks in relation to temperature, salinity, turbidity, and light penetration (From: Rezak et al., 1983).

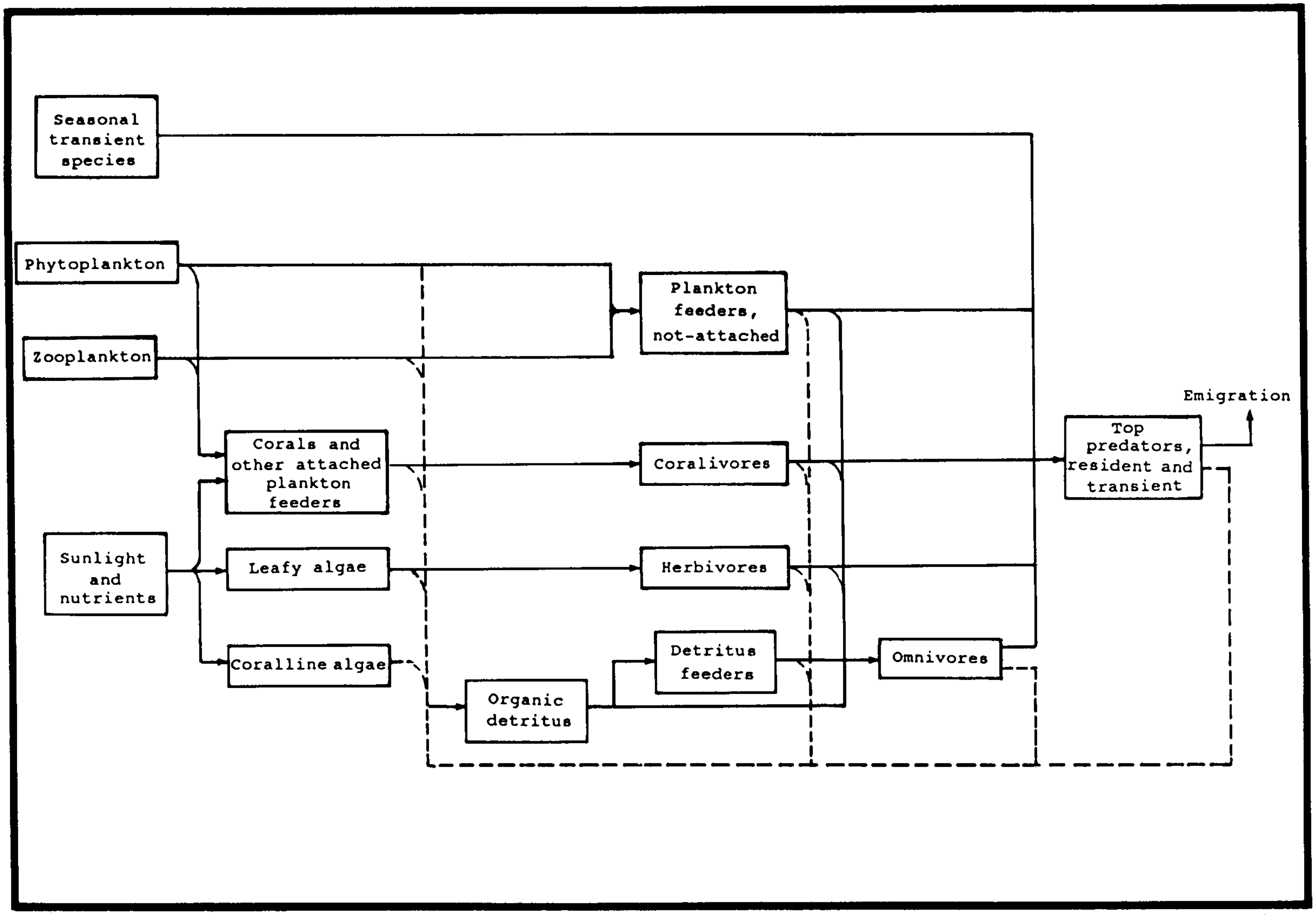


Figure 6.21. Simplified conceptual model of hard bank production in the euphotic zone of the Texas–Louisiana continental shelf.

Biota Associated with Anthropogenic Structures

Prior to the 1940's, the hard surface, fixed structures of the northern Gulf coast consisted of a few docks, jetties, seawalls, pilings, and shipwrecks. During the last half century, the available hard surface has increased dramatically, due largely to the construction of oil and gas related structures on the continental shelf and upper slope. A single platform in 30 m of water has been estimated to provide about 8,000 m^2 of hard substrate. In 1985, the National Research Council reported that over 4,000 oil and gas platforms had been installed in the Gulf of Mexico with most being on the Texas-Louisiana continental shelf. In addition, as of December 1987 there are over 17,000 miles of pipelines on the continental shelf, most of which are exposed. This immense growth in anthropogenic hard surfaces has, in effect, added a large amount of new artificial reef habitat to the waters of the area. This habitat has been invaded by a diverse flora and fauna derived from several sources: previously existing local hard banks and anthropogenic structures, planktonic young from more distant sources, fouling organisms from the hulls of boats and ships that ply the area, and seasonally transient mobile species that now become temporary or permanent residents.

These groups of organisms are normally found in association with the anthropogenic structures: (1) attached species, (2) non-attached species that live in close association with the attached mat, and (3) larger mobile species that inhabit the water column and that are more loosely associated with the structures and the attached community. The attached species include marine algae and a variety of invertebrate groups. These are the biofouling organisms that form the epibiotal mat. The non-attached species that live in close association with the mat include a variety of worms, snails, crustaceans, echinoderms, and other small invertebrates. These may be cryptic, or they may wander about the mat. Included also are a few blenny fishes that are rather sedentary and that find appropriate shelter in old barnacle shells and other niches. The more mobile species include some of the larger crabs and lobsters and the majority of the fishes as well as sea turtles. Some of these are present because they feed upon the biofouling mat or its inhabitants, whereas others appear to be attracted to the structures themselves. Some are residents, whereas others are seasonal transients.

The literature dealing with the biota of artificial structures of the area is not extensive, but it is adequate to provide a generalized picture of the structure-related biotic systems of at least the inner half of the continental shelf. Little is known about the biota of deeper water structures, except by extrapolation from other areas. The marine algae have been studied primarily by Bert and Humm (1979). Invertebrates have been addressed by Gunter and Geyer (1955); Fucik and Show (1979); George and Thomas (1979); Howard et al. (1980); Fotheringham (1981); Gallaway (1981); Gallaway et al. (1981a,b); and Gallaway and Lewbel (1982). The ichthyofauna has been reported by Wickham et al. (1973); Hastings et al. (1976); Sonnier et al. (1976); Gallaway et al. (1981a, b); Klima and Wickham (1981); and Gallaway and Lewbel (1982). The most important references concerning population and community dynamics are those of Fotheringham (1981); Gallaway and Lewbel (1982); Gallaway et al.

(1981a,b); George and Thomas (1979); and Howard et al. (1980). Most of these studies address the biota associated with production platforms, and there is a dearth of literature concerning the biota associated with other artificial structures.

Altogether, several hundred species have been reported from around the platforms. A partial listing of the algae and invertebrates is provided in Table 6.39, and a partial listing of the fishes is given in Table 6.40. These lists include the more common forms, and a complete listing can be found in the references provided. Bert and Humm (1979) listed 120 species of marine algae from shallow water platforms off Timbalier Bay, LA, and these were divided as follows: Cyanophytes = 18%, Rhodophytes = 31%, Phaeophytes = 16%, and Chlorophytes = 35%. All were limited to the euphotic zone (upper few meters). Many invertebrate groups are included, and the hydroids, polychaetes, mollusks, and crustaceans are particularly well represented. Seventy two species of fishes are listed, prominent among which are the sea basses, jacks, snappers, leatherjackets, and various reef-related groups (bigeyes, cardinalfishes, butterflyfishes, angelfishes, damselfishes, wrasses, blennies, and surgeonfishes).

Two basic biofouling community types are recognized--a nearshore coastal water community and an offshore "blue water" community. The environment of the nearshore community is variable and often extreme. The waters tend toward lower salinity, greater turbidity, higher nutrients, and seasonal temperature extremes. The oceanic water that bathes the offshore community is of full marine salinity, clearer, characterized by low nutrient levels, and is warm and seasonally less variable. Between the nearshore and oceanic environments, i.e., in the approximate depth range of 20 to 60 m, the environment is of a transitional nature, and this is inhabited by a transitional type community. The basic characteristics of these community types are displayed in Tables 6.41 and 6.42. The biomass of the biofouling mat, which in surface water of the nearshore zone ranges up to 15.5 kg/m^2, becomes reduced offshore to about 1 to 5 kg/m^2 in the oceanic waters. Inshore, the fully developed mat may be up to 12 cm thick, but in the blue water it is estimated to be 2 to 4 cm thick. Brown and red algae, which are reduced inshore, become more abundant in the clearer oceanic waters. Inshore sessile barnacles dominate, bivalves are most important on the outer shelf, and in the oceanic realm the primary biofoulers are the stalked barnacles. As shown in Table 6.43, biomass tends to decrease with depth in the water column, and the species composition also changes with depth. Marine algae, which require light for photosynthesis, are limited to the upper few meters. Hydroids, anemones, bryozoans, and tunicates become relatively more important below the photosynthetic zone.

Local deviations from these trends have been reported. The highest biofouling biomass recorded in the area (27 kg/m^2) was observed at a transitional zone platform in the Buccaneer Gas and Oil Field about 50 km south of Galveston, TX. This particular area may have been enriched by sewage, petroleum hydrocarbons, or other effluents from the platforms. Gallaway and Lewbel (1982) reported a case in the nearshore waters in which the biomass at 10 m was greater than that at the surface. It appears that, within the general context described above, actual

Table 6.39. Partial list of algae and invertebrates reported from drilling rigs and platforms of the Texas-Louisiana continental shelf.

ALGAE

Cyanophyta - *Microcoleus*, *Oscillatoria*, *Schizothrix*

Rhodophyta - *Acrochaetum*, *Callithamnion*, *Ceramium*, *Polysiphonia*

Phaeophyta - *Ectocarpus*, *Giffordia*, *Sargassum*

Chlorophyta - *Bryopsis*, *Chaetomorpha*, *Cladophora*, *Enteromorpha*

INVERTEBRATES

Porifera - *Cliona*, *Haliclona*, *Halichondria*, *Verongia*

Cnidaria
- Hydrozoa - *Aglaophenia*, *Bougainvillea*, *Obelia*, *Tubularia*
- Anthozoa - *Astrangea*, *Leptogorgia*, *Oculina*, *Telesto*

Nemerteans

Platyhelminthes - *Leptoplana*

Bryozoans - *Acanthodesmia*, *Bugula*, *Membranipora*

Sipunculids

Annelida
- Polychaetes - *Eunice*, *Haplosyllus*, *Neanthes*, *Nereis*

Mollusks
- Gastropods - *Cantharus*, *Crepidula*, *Murex*, *Thais*
- Bivalves - *Arca*, *Crassostrea*, *Isognomon*, *Ostrea*
- Pycnogonids - *Tanystylum*

Crustaceans
- Copepods - *Acartia*, *Labidocera*
- Cirripedes - *Balanus*, *Lepas*, *Megabalanus*
- Amphipods - *Caprella*, *Corophium*, *Jassa*, *Stenothoe*
- Tanaids - *Tanais*
- Isopods - *Limnoria*, *Sphaeroma*
- Decapods - *Callinectes*, *Dromidia*, *Eurypanopeus*, *Hexapanopeus*, *Menippe*, *Neopanope*, *Pachygrapsus*, *Pagurus*, *Panopeus*, *Panulirus*, *Petrochirus*, *Pilumnus*, *Porcellana*, *Portunus*, *Stenorhynchus*, *Synalpheus*

- Echinoderms - *Arbacea*, *Ophiactis*, *Ophiothrix*

Urochordata
- Ascidiaceans - *Enterogona*

Table 6.40. Fish species reported around drilling rigs and platforms of the Texas-Louisiana continental shelf.

Scientific Name	Common Name
ORECTOLOBIDAE	Carpet sharks
Ginglymostoma cirratum	Nurse shark
SPHYRNIDAE	Hammerhead sharks
Sphyrna lewini	Scalloped hammerhead
DASYATIDAE	Stingrays
Dasyatis americana	Southern stingray
CLUPEIDAE	Herrings
Harengula jaguana	Scaled sardine
Sardinella aurita	Spanish sardine
SERRANIDAE	Sea basses
Epinephelus adscensionis	Rock hind
Epinephelus itajara	Jewfish
Epinephelus nigritus	Warsaw grouper
Mycteroperca phenax	Scamp
Mycteroperca rubra	Comb grouper
Paranthias furcifer	Creole-fish
Serranus subligarius	Belted sandfish
GRAMMISTIDAE	Soapfishes
Rypticus maculatus	Whitespotted soapfish
PRIACANTHIDAE	Bigeyes
Priacanthus arenatus	Bigeye
APOGONIDAE	Cardinalfishes
Apogon maculatus	Flamefish
POMATOMIDAE	Bluefishes
Pomatomus saltatrix	Bluefish
RACHYCENTRIDAE	Cobias
Rachycentron canadum	Cobia
CARANGIDAE	Jacks
Caranx crysos	Blue runner
Caranx hippos	Crevalle jack
Caranx latus	Horse-eye jack
Chloroscombrus chrysurus	Atlantic bumper
Decapterus punctatus	Round scad
Elagatis bipinnulata	Rainbow runner
Selene setapinnis	Atlantic moonfish
Selene vomer	Lookdown
Seriola dumerili	Greater amberjack
Seriola rivoliana	Almaco jack
Trachurus lathami	Rough scad
CORYPHAENIDAE	Dolphins
Coryphaena hippurus	Dolphin
LUTJANIDAE	Snappers
Lutjanus campechanus	Red snapper
Lutjanus cyanopterus	Cubera snapper
Lutjanus griseus	Gray snapper
Lutjanus synagris	Lane snapper
Ocyurus chrysurus	Yellowtail snapper
Rhomboplites aurorubens	Vermilion snapper
HAEMULIDAE	Grunts
Haemulon aurolineatum	Tomtate

Table 6.40. (Continued).

Scientific Name	Common Name
SPARIDAE	Porgies
Archosargus probatocephalus	Sheepshead
SCIAENIDAE	Drums
Cynoscion arenarius	Sand seatrout
Cynoscion nebulosus	Spotted seatrout
Equetus umbrosus	Cubbyu
Micropogonias undulatus	Atlantic croaker
KYPHOSIADAE	Sea chubs
Kyphosus sectatrix	Bermuda chub
EPHIPPIDAE	Spadefishes
Chaetodipterus faber	Atlantic spadefish
CHAETODONTIDAE	Butterflyfishes
Chaetodon ocellatus	Spotfin butterflyfish
POMACANTHIDAE	Angelfishes
Holacanthus bermudensis	Blue angelfish
Holacanthus ciliaris	Queen angelfish
Holacanthus tricolor	Rock beauty
Pomacanthus arcuatus	Gray angelfish
Pomacanthus paru	French angelfish
POMACENTRIDAE	Damselfishes
Abudefduf saxatilis	Sergeant major
Chromis multilineatus	Brown chromis
Pomacentrus variabilis	Cocoa damselfish
CIRRHITIDAE	Hawkfishes
Amblycirrhitus pinos	Redspotted hawkfish
LABRIDAE	Wrasses
Bodianus pulchellus	Spotted hogfish
Bodianus rufus	Spanish hogfish
Thalassoma bifasciatum	Bluehead
SPHYRAENIDAE	Barracudas
Sphyraena barracuda	Great barracuda
BLENNIIDAE	Combtooth blennies
Hypleurochilus geminatus	Crested blenny
Hypleurochilis springeri	Orangespotted blenny
Parablennius marmoreus	Seaweed blenny
Scartella cristata	Molly miller
ACANTHURIDAE	Surgeonfishes
Acanthurus coeruleus	Blue tang
SCOMBRIDAE	Mackerels
Euthynnus alleteratus	Little tunny
Scomberomorus cavalla	King mackerel
BALISTIDAE	Leatherjackets
Aluterus schoepfi	Orange filefish
Aluterus scriptus	Scrawled filefish
Balistes capriscus	Gray triggerfish
Balistes vetula	Queen triggerfish
Cantherhines pullus	Orangespotted filefish
Cantherhines sufflamen	Ocean triggerfish
Monacanthus hispidus	Planehead filefish
TETRAODONTIDAE	Puffers
Canthigaster rostrata	Sharpnose puffer

Table 6.41. Development of the biofouling mat in relation to distance from shore. Most of the "blue water" estimates are based upon information for other areas (Data primarily from: Gallaway and Lewbel, 1982).

Measure	Depth Range: Coastal (0 - 20 m)	Transitional (20 - 30 m)	Transitional (30 - 60 m)	Blue Water (Beyond 60 m)
Biomass Range (kg/m^2)	5.4 - 15.5	1.9 - 10.9	--	1.0 - 5.0
Biomass Values (kg/m^2)				
-Near Surface (0-2 m)	9.5	5.6	8.5 - 11.0	--
-Deep (10-13 m)	13.5	2.9	2.0	--
Mat Thickness (cm)	up to 12.0	--	--	2.0 - 4.0
Dominant Groups				
-Barnacles	92%	--	27%	6%
-Bivalves	3%	--	65%	92%
Indicator Species				
-Octocoral (Telesto)	absent	--	present	present

Table 6.42. Dominant organisms (by weight) for coastal, offshore, and blue water biofouling communities.

Assemblage	Dominant Organisms: Scientific Name	Common Name
Coastal	Balanus reticulatus	Reticulated barnacle
	Balanus improvisus	Bay barnacle
	Megabalanus antillensis	Mediterranean barnacle
	Crassostrea virginica	Virginia oyster
	Ostrea equestris	Horse oyster
Transitional	Chama macerophylla	Leafy jewel box
	Isognomon biocolor	Two-toned tree oyster
Blue Water	Conchoderma virgatum	Striped goose barnacle
	Lepas anatifera	Common goose barnacle

development of the biofouling mat depends considerably upon locally prevailing environmental conditions. There is also some question concerning definition of the biomass. Most of the investigations of the area include the non-living shells of mollusks and barnacles in their biomass estimates. As shown in Table 6.43, a fair amount of precipitated sediment may also be associated with the fouling mat. The extent to which this sediment is included in biomass reports is unknown.

Time is also an important factor. Development of a mature climax-type mat community has been estimated to take about three years. The colonization and early development of the biofouling community on new bare surfaces depend upon species availability which, in turn, depend upon the season of the year and the vagaries of dispersal. Studies from other areas have shown that community development may follow any of several alternate pathways leading to the local climax biofouling community, which is largely determined by the prevailing hydrographic climate of the area. George and Thomas (1979) reported on the biofouling accumulation on artificial plates exposed for 60 days in deep water off Timbalier Bay, LA (Table 6.44). The available published information does not permit the development of a clear picture of changes in the biofouling community as one proceeds westward along the coast from the Mississippi River Delta due to the lack of similar studies at comparable depths.

Gallaway and Lewbel (1982) have summarized our knowledge of the non-attached species that live in close association with the attached mat in the following seven points:

1) A diverse assemblage of small and large motile invertebrates utilizes the shelter and food provided by sessile members of the epifaunal community.

2) The most abundant amphipods are tube-dwelling forms such as corophiids and stenothoids, which are typically symbiotic with hydroids and other mat organisms.

3) The most commonly reported polychaetes are syllids, a group often associated with hydroids and sponges.

4) Pycnogonids, another epibiotic group, are frequently found on the fouling mat.

5) Nemerteans are common predators on the other epifaunal invertebrates on platforms.

6) Ophiuroids may be present in very high densities embedded in the fouling mat.

7) Large, conspicuous invertebrates such as lobsters and crabs may be found in low densities around and beneath platforms.

Table 6.43. Comparison of biomass for major taxa of biofouling organisms in relation to season and depth in the water column at a single oil platform ten miles offshore from Timbalier Bay, LA (From: George and Thomas, 1979). Water depth is about 16 m.

Taxon	Biomass (g/m^2) 2.4 m Feb	2.4 m Jul	9.1 m Feb	9.1 m Jul	12.8 m Feb	12.8 m Jul
Algae	25	--	--	--	--	--
Sponges	163	11	82	25	--	--
Hydroids	87	12	19	13	4	4
Anemones	50	19	103	42	--	t*
Flatworms	--	--	--	t*	--	--
Bryozoans	3	18	1	12	4	4
Polychaetes	25	2	36	t*	1	1
Bivalves	6	--	2	--	--	--
Copepods	--	--	7	--	--	--
Barnacles	5,233	5,069	1,525	2,769	30	43
Amphipods	17	9	38	3	--	--
Isopods	--	--	--	--	--	1
Crabs	54	1	57	3	--	--
Total Biomass	5,661	5,141	1,870	2,868	38	49
Sediment	290	362	202	162	25	30

*t = trace amount.

Table 6.44. Biomass accumulation of biofouling organisms on test panels after 60 days of exposure at a blue water site 70 km offshore from Timbalier Bay, LA in about 80 m of water. Data are given for six depths. (Estimates from a figure given in George and Thomas, 1979).

Group	Percent of Total Biomass* 0 m	1.8 m	3.7 m	5.5 m	6.7 m	7.9 m	8.5 m
Algae	20	13	--	--	--	--	--
Hydroids	10	2	2	12	4	20	7
Anemones	3	--	--	17	4	16	16
Bryozoans	28	4	8	34	46	37	51
Polychaetes	7	--	--	12	15	3	14
Barnacles	27	65	73	25	--	7	--
Crustacean larvae	--	--	--	--	27	--	--
Amphipods	5	--	--	--	--	--	--
Decapods	--	16	17	--	4	10	12
Tunicates	--	--	--	--	--	7	--

*Total biomass = 4,150 g/m^2 at surface, and 1,740 g/m^2 at 8.5 m.

In addition, small fishes, particularly the blennies, often reside in old barnacle shells and other niches in the platform mats.

Larger mobile species that inhabit the water column and that have a more loose association with the structures and the attached community include the larger crabs and lobsters, most fishes (Table 6.40), and sea turtles. These may be either resident or transient. Among the residents, some of the crabs and fishes (especially the sheepshead and gray triggerfish) are trophically dependent upon the biofouling mat and its inhabitants. Other residents, including the spadefish, Atlantic moonfish, and creolefish, feed as much upon plankton as on the fouling mat. The snappers and groupers, which are resident, are predators and do not feed directly upon the mat. Most of the transient species are predatory, although a few are plankton feeders. Observations around nearshore platforms have been hampered by poor visibility, but at mid-shelf and deeper water platforms there is a definite vertical zonation of the fish species. There is also a nearshore-offshore zonation of fishes, with the reef species being largely limited to the clear-water offshore platforms. Rosman et al. (1987) have documented the presence of sea turtles around the platform structures.

Not a great deal can be said about the individual environmental factors controlling growth and development of the biota associated with anthropogenic structures on the Texas-Louisiana continental shelf. The most obvious differentiation of the biota is the nearshore-offshore zonation, which is clearly associated with the coastal and oceanic water masses and the intermediate zone of mixing. Because the water masses differ in many characteristics, it is only possible to consider factors operating in combination. Coastal waters, influenced largely by the Mississippi/Atchafalaya Rivers, are characterized by low salinity (surface values seasonally below 25°/∘∘) and high levels of suspended sediments and nutrients. Light penetration is low, and temperature is seasonally variable with winter surface and bottom values falling below 15.0°C. The opposite conditions prevail in the oceanic waters with intermediate conditions occurring in the transition zone. Light penetration limits the depth of the euphotic zone and the depth to which attached algae may grow. Water clarity undoubtedly restricts the distribution of predatory sight-feeding fishes. The combination of low winter temperature and high turbidity may limit the inshore distribution of the tropical reef fishes. Sedimentation on the biofouling mat likely restricts some of the sedentary species as well as some of the small mobile species that feed upon the mat. Produced water and other platform effluents may locally inhibit mat development, but it also has a considerable stimulatory effect a few meters away from the actual discharge point. On the other hand, the fouling mat species develop high tissue levels of petroleum hydrocarbons, and these tend to be passed to those species that feed upon the mat, leading to the development of pathological conditions. Because the platforms concentrate certain species, such as groupers and red snapper, heavy recreational fishing could damage the populations of such reef-faithful species by removal of a large portion of the breeding stocks. Sea turtles sometimes occur around the platforms. In order for a species to become established in an area it must have some means of migrating to the area, and it must encounter favorable habitat once it has made the journey. Thus, from a zoogeographic standpoint, the artificial hard substrates distributed through a variety of depths and water mass types, provide suitable habitat for a wide variety of algae, invertebrate, and fish species which could otherwise not survive off the Louisiana and Texas coasts. In turn, these population centers provide spores, eggs, and larvae for further dispersal throughout the northern Gulf.

Conceptual models of varying degrees of detail and sophistication have been developed for platform communities by a number of authors, including Gallaway and Margraf (1979), Fucik and Show (1981), Gallaway et al. (1981a), and Gallaway and Lewbel (1982). A simplified summary model is presented in Figure 6.22. The biofouling mat includes attached plankton feeders and algae plus the associated small browsers and detritus feeders. It receives input from the plankton and from sunlight and nutrients. The mat produces organic detritus, which may become suspended or fall to the bottom. In the waters surrounding the platform are the various non-attached plankton feeders, mat browsers, detritus feeders, and omnivores, as well as top predatory species. Some of these are resident, whereas others are transients that eventually emigrate. All of these species produce organic detritus, which recycles through the detritus feeders. Not shown in the model are natural stress factors including low temperature and low salinity as well as high turbidity and sedimentation. Also not shown are the potential anthropogenic influences including fertilization, chemical pollution, various forms of mechanical damage, and overfishing. Fucik and Show (1979) developed a mathematical model for the platform community, based on data from the Buccaneer Gas and Oil Field Study. This model provided an elegant method of summarizing the data and of displaying what was already known. However, output from the model did imply that the major flow of organic material through the system comes from the advected phytoplankton and that the major flow of hydrocarbon pollutants to the higher consumers is mediated through consumption of the biofouling mat.

6.5 BIOLOGICALLY SENSITIVE AREAS

6.5.1 Criteria for Judging Biological Sensitivity

Management of public trust lands must take into account areas of special biological sensitivity. This involves the assessment of two sets of factors: importance and sensitivity. Clearly, there is no point in even considering a site unless it displays certain values recognized by human society. The primary consideration in biological resource management is that no species or major genetic strain shall become extinct as a result of human activities. A corollary of this maxim is that if critical habitats and ecological processes are retained intact or with minimal disturbance, the species will generally maintain themselves without special managerial attention. Experience has shown that there are certain kinds of habitats that are of particular concern if one is to retain the biological species and ecological processes. These include known areas of species concentrations or areas important for reproduction, feeding, or migration; areas of high species diversity or high biological productivity; rare or unique habitat types; and habitats of rare, threatened, or endangered species. Sensitivity of such areas to human intrusion relates to several specific factors. An area that is

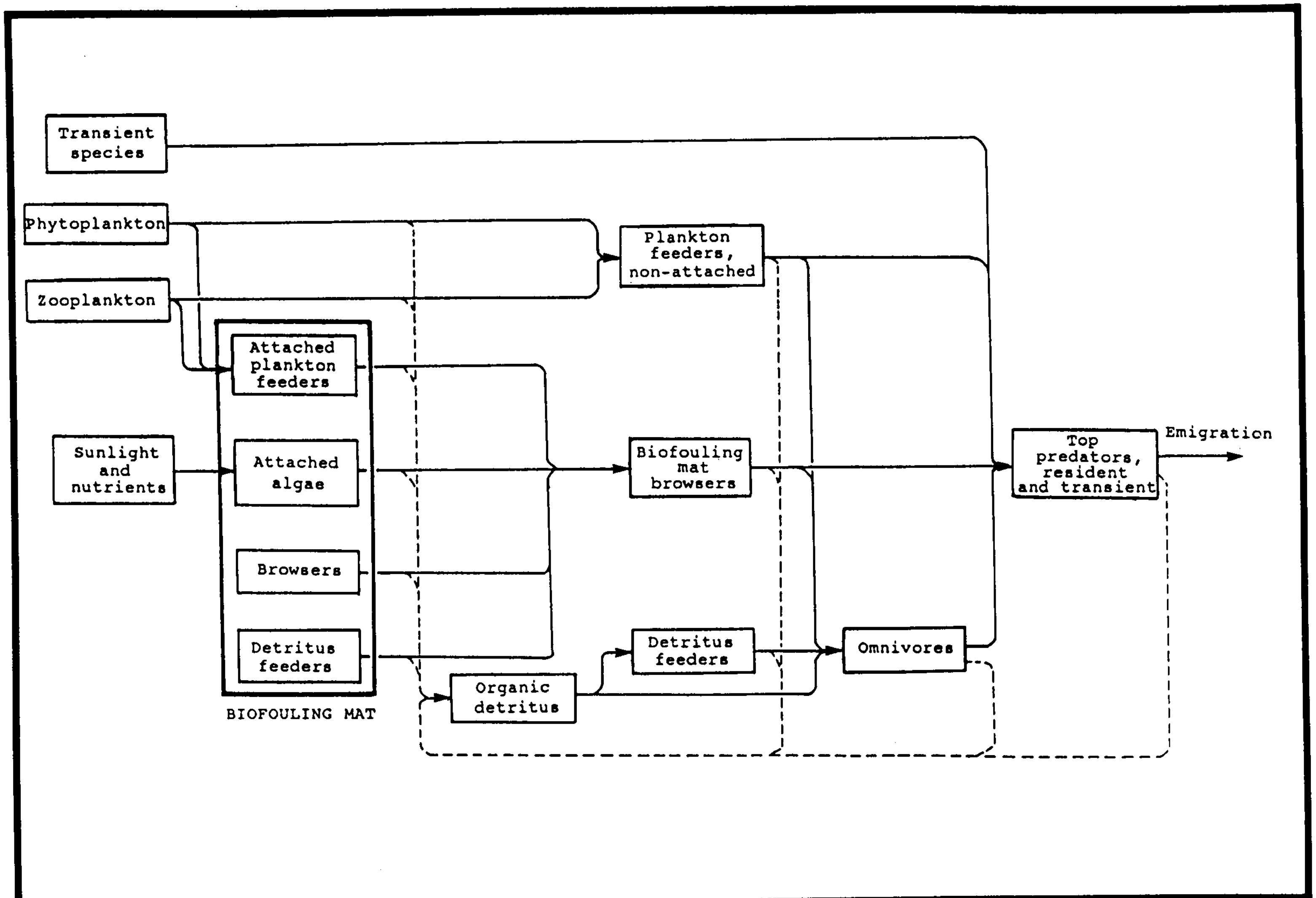


Figure 6.22. Simplified conceptual model of anthropogenic structure production on the Texas-Louisiana continental shelf.

particularly fragile, unique, or of small size is likely to be of special concern. Species living in an area already stressed by natural factors (such as low temperature and/or salinity, high suspended sediments, etc.) may have a limited tolerance for additional stress. The same is true of areas already imperiled by human activities (such as chemical pollution, dumping, anchor damage, drilling operations, etc.).

A systematic method for considering both the importance factors and the sensitivity factors is through matrix analysis (as shown in Figure 6.23). Here, the importance factors are listed in a column on the left, and the sensitivity factors are given along the top. Each box of the matrix represents the coincidence of an importance and a sensitivity factor. The intensity of each particular interaction may be represented by an intensity factor (high, medium, or low). The summation of high intensity boxes provides the primary basis for judging the biological sensitivity of a particular area. Obviously, expertise and good judgement contribute to the successful completion of each site-related matrix. This analytical process is slightly modified from the one recommended by R.M. Darnell to the Marine Sanctuaries Program for the evaluation of sites proposed for designation as marine sanctuaries.

The sensitivity factors listed along the top of the matrix in Figure 6.23 are discussed briefly below.

Endemicity

One measure of the biological sensitivity of an area is the number (or percentage) of rare or endemic species found in the area. Thus, if an area with high endemicity were heavily stressed or destroyed, unique gene pools would be severely reduced or lost.

Fragility

Some species and ecological systems are more sensitive to stress than are others. Fragility is a measure of this sensitivity. For example, hermatypic corals are likely more sensitive to heavy loads of suspended sediments than are certain sponges or mollusks. Knowledge of sensitivities is not always available, and this is an important area for future investigation.

Smallness

In dealing with the problem of biological sensitivity the size of the area determines, to a significant degree, the numerical size of the populations which inhabit it. Large populations are genetically and ecologically conservative, small populations are more sensitive to changes, and very small populations are subject to random gene loss as well as accidental loss due to environmental factor changes. As a rule of thumb, management must consider that all small, isolated populations and ecological systems are more sensitive to disturbance than are larger and more widespread populations and ecological systems.

Proposed area ______________________________

Importance factor \ Sensitivity factor	Endemicity	Fragility	Smallness	Already stressed	Imperiled	Summary	Remarks
Habitat of rare, threatened or endangered species							
Important for species reproduction							
Important for migration route							
Important as feeding area							
Important for species concentrations							
Important for species diversity							
Important for rare or unique habitats							
Important for high biological productivity							

Intensity: H = High, M = Medium, L = Low.

Figure 6.23. Matrix for the analysis of areas of potential biological sensitivity.

Already Stressed

Populations and ecological systems which already exist under natural or artificially-induced stress conditions are clearly likely to be more sensitive to the imposition of additional stress than are populations or ecological systems not living near their limits of tolerance. In the northern Gulf of Mexico many clear-water tropical species are considered to be living near their limits of tolerance for suspended sediments and/or low temperature. These species, in particular, are likely to be more sensitive to additional stress than are those species already adapted to high-turbidity and/or low temperature conditions.

Imperiled

A species population or ecological system that exists in the "path of the bulldozer," so to speak, is considered to be imperiled in the sense that without management intervention the biological values are likely to be destroyed by imminent human activities. Salvage archaeology is a case in point. In evaluating the biological sensitivity of an area, one of the considerations should be the degree to which it is already threatened or likely to be threatened by human activities.

6.5.2 Delineation of Biologically Sensitive Areas

A regional survey of the habitats and biota of the reefs and banks of the northwestern Gulf of Mexico is given in Rezak et al. (1983), and a survey of the general habitats and demersal biota of soft bottoms is provided in Darnell et al. (1983). Taken together, these two publications provide the best information available for making decisions concerning categories of biologically sensitive areas as well as particular sites of potential importance and sensitivity.

In their section dealing with "Management Implications," Darnell et al. (1983) addressed problems of biological importance and recommended habitat types of the northwestern Gulf shelf that should be singled out for special protection. These include: (1) species spawning grounds; (2) tidal passes; (3) reefs; (4) areas associated with the mouths of rivers; and (5) habitat of rare shelf species. Each of these categories will be addressed briefly.

Species Spawning Grounds

Protection of spawning grounds is a generically important consideration. However, the actual spawning grounds of most species are poorly known. This would be a particular concern if it were found that spawning concentrations are quite restricted in terms of space and season of the year. Fortunately, for most species this appears not to be the case, but it may be true for some species.

Tidal Passes

A large percentage of the fauna of the northwestern Gulf shelf is estuary related, and all of these species use the tidal passes as migratory routes. The areas off the mouths of the passes have been shown to be sites of dense species concentrations at certain seasons of the year. These are likely major feeding and spawning grounds, as well. Many of the species are of considerable commercial and/or recreational importance. Although subject to fluctuating environmental conditions and heavy pollution, these areas are considered sensitive because major damage could eliminate spawning or migrating populations.

Reefs

The distribution, biological zonation, and environmental influences on the reefs and banks of the area have previously been discussed in Section 6.4.3 (under Biota Associated with Topographic Highs). In a very real sense, each of the reefs and banks is a unique habitat populated by a singular combination of species. Most are small and fragile. At least some of the banks (those on the outer shelf of Louisiana and upper Texas) are likely under some degree of environmental stress. Most are habitat for sea turtles and other uncommon species. Therefore, as a class the reefs and banks must be considered important and biologically sensitive. No effort is made here to prioritize the importance or sensitivities of the individual banks except to note that the East and West Flower Garden Banks are in a class by themselves, due largely to the extensive development of the hermatypic coral reef community. As an illustration, this area has been analyzed using the importance/sensitivity matrix (Figure 6.24).

Areas Associated with the Mouths of Rivers

It has been shown that the areas associated with the mouths of certain rivers, especially the Mississippi and Rio Grande, are characterized by anomalously high densities of certain species (Darnell et al., 1983). The area around the Mississippi River Delta has been recognized by Defenbaugh (1976) as having a unique faunal make-up (Pro-Delta Fan Assemblage). Most river-mouth areas have not been investigated thoroughly, but enough is known to suggest that these represent areas of particular biological interest and concern, especially because they are likely to be imperiled by human activities. As noted in the case of tidal passes, major damage to these habitats could eliminate endemic species or migrating populations.

Habitats of Rare Shelf Species

Numerous species of the northwestern Gulf shelf are rare in collections, and they may be rare in nature. Most of these cannot be associated with particular habitats and, therefore, cannot be the subject of managerial attention. A number of tropical species appear on the south Texas shelf, and these are clearly at the northern extremes of their ranges. However, it is important to note that outside of the reef and bank areas, no real effort has been made to locate, identify, and investigate special habitats likely to be the haven for rare species. Potential candidate areas include the various Mississippi River Delta environments, Mississippi Canyon habitats, very soft oozy bottoms off Louisiana (habitat for burrowing forms including various eels), and the

Proposed area East and West Flower Garden Banks

Importance factor \ Sensitivity factor	Endemicity	Fragility	Smallness	Already stressed	Imperiled	Summary	Remarks
Habitat of rare, threatened or endangered species	H	H	H	M	M	H	This is a small, unique, and fragile area. It is important in
Important for species reproduction	H	H	H	M	M	H	all categories except migration. It is moderately imperiled, and
Important for migration route	L	L	L	L	L	L	the corals and other tropical forms are living near their
Important as feeding area	H	H	H	M	M	H	minimal temperature tolerance. TOP PRIORITY FOR PROTECTION.
Important for species concentrations	H	H	H	M	M	H	
Important for species diversity	H	H	H	M	M	H	
Important for rare or unique habitats	H	H	H	M	M	H	
Important for high biological productivity	H	H	H	M	M	H	

Intensity: H = High, M = Medium, L = Low.

Figure 6.24. Matrix evaluation of the East and West Flower Garden Banks.

dissected and eroded "hill and valley" areas of the outer shelf and upper slope.

6.6 ENDANGERED AND THREATENED FAUNA

6.6.1 Introduction

The marine environment of the Texas-Louisiana continental shelf area contains a rich and abundant fauna, including several species that are quite sensitive and rare. Within the study area, 14 species of mammals, birds, and reptiles are considered threatened or endangered [U.S. Fish and Wildlife Service (USFWS), 1987]. These include five species of great whales and the West Indian manatee, three species of birds, and five species of marine turtles (Table 6.45).

The decline and unstable status of endangered wildlife from Texas and Louisiana coastlines is attributable to a number of causes, but human activities loom largest. In the case of the great whales, which probably were never common in Gulf waters, massive overexploitation in the early twentieth century all but extirpated many from the world's oceans (Mitchell, 1973; Gambell, 1976). Although whaling in the Gulf of Mexico never developed into the large-scale industry seen in other parts of the world, Gulf populations of these far-ranging mammals may very well have been affected.

The bird life of coastal Texas and Louisiana has undoubtedly been affected by factors such as shoreline development (Thompson, 1982; Haig, 1985); pollution, particularly in the form of pesticides and herbicides contained in runoff (Blus et al., 1975, 1979; King et al., 1977; Nesbitt and Williams, 1978); overhunting, which in the early part of this century contributed to the fragile status of at least one endangered bird in the area (King et al., 1977); and natural events such as hurricanes and disease (King et al., 1977).

Marine turtles were once fairly common along the coastline of Texas and Louisiana, but now are rare. All species of sea turtles have suffered from market hunting for meat and eggs, but loss of nesting habitat (Rebel, 1974), incidental catch (Rabalais and Rabalais, 1980; Fritts et al., 1983a), and pollution (Rabalais and Rabalais, 1980) also cause mortality.

Generally, endangered and threatened species of the area are among the least known of the Gulf fauna. Following are brief summaries of the current state of knowledge for endangered and threatened fauna from Texas and Louisiana marine ecosystems.

6.6.2 Species Accounts

Balaenoptera musculus (blue whale)

Legal Status. The blue whale is endangered over its entire range (USFWS, 1987).

Table 6.45. Endangered and threatened fauna of Texas-Louisiana marine ecosystems.

Species	Common Name	Status*
MAMMALS		
Balaenoptera musculus	blue whale	E
Balaenoptera physalus	fin whale	E
Eubalaena glacialis	right whale	E
Balaenoptera borealis	sei whale	E
Physeter catodon	great sperm whale	E
Trichechus manatus	West Indian manatee	
BIRDS		
Pelecanus occidentalis	brown pelican	E
Charadrius melodus	piping plover	T
Sterna antillarum	least tern	E
REPTILES		
Chelonia mydas	green sea turtle	T
Lepidochelys kempii	Kemp's ridley sea turtle	E
Dermochelys coriacea	leatherback sea turtle	E
Caretta caretta	loggerhead sea turtle	T
Eretmochelys imbricata	hawksbill sea turtle	E

*Status: E = endangered, T = threatened.

Distribution and Abundance. The blue whale is a highly migratory baleen whale known from all oceans of the world. Gambell (1976) estimated that the pre-whaling population of blue whales was 166,400 to 226,000 worldwide. Currently, the worldwide population of blue whales is believed to be approximately 12,000 (Gambell, 1976), with 100 to 1,500 of these present in the North Atlantic (Gulland, 1972; Gambell, 1976). These figures are believed sufficient to allow the blue whale to recover, provided complete protection remains in place (Leatherwood et al., 1976). Only two reports of blue whales are available from the Gulf of Mexico, both strandings on the Texas-Louisiana coast (Schmidly, 1981).

Migratory movements of the blue whale are not known in detail; however, individuals from the northern hemisphere move to arctic feeding grounds in spring and summer, returning to temperate waters in fall for breeding and parturition (Leatherwood et al., 1976). This trend is also followed by blues in the southern hemisphere although feeding grounds are in the antarctic. As the seasons are reversed between the two hemispheres, northern and southern blues are not believed to intermingle in temperate and equatorial waters.

Life History. The blue whale feeds exclusively upon copepods and small, shrimp-like crustaceans known as "krill." Adults strain as much as four tons of krill per day from polar waters (Watson, 1981). Blue whales seem highly selective of species taken, with *Thysanoessa inermis*, *Temora longicornis*, and *Meganyctiphanes norvegica* the only species now recorded from North Atlantic blues (Gaskin, 1982). Additionally, blue whales are thought to feed only in polar waters and therefore, fast during the seven to eight month period of migration and breeding.

Female blue whales give birth to a single calf in temperate or equatorial waters during the winter months. The gestation period is 11 to 12 months, and most females bear young only once every three years (Watson, 1981). Although the birth of a blue whale has never been observed, records from past whaling activities indicate a newborn blue whale is approximately 7.3 m in length and weighs two to three tons (Watson, 1981). Sexual maturity is reached in five to ten years, with the lifespan of blue whales estimated as 30 to 90 years (Yochem and Leatherwood, 1985).

Balaenoptera physalus (fin whale)

Legal Status. The fin whale is endangered over its entire range (USFWS, 1987).

Distribution and Abundance. Fin whales are highly migratory baleen whales known from all oceans of the world. Migratory patterns are similar to those described for the blue whale.

Estimates of pre-whaling population size placed 421,700 to 474,700 fins throughout the world's oceans, with 99,400 to 118,400 present today (Gambell, 1976). The North Atlantic stock is believed to number 2,400 (Gambell, 1976). Leatherwood et al. (1976) state that the fin whale is probably the most numerous and widely distributed of large whales occurring in the western North Atlantic.

Five strandings or sightings of fin whales are known from Gulf waters within the study area (Schmidly, 1981). Schmidly (1981) also indicates that fin whales are present in the northern Gulf of Mexico throughout the year and that a small, isolated population may occur in these waters. No population estimates exist for this area; therefore, additional data are required to establish this group as a separate population.

Life History. The fin whale is second in size only to the blue whale and has the distinction of being the only mammal with asymmetric coloration, the jaw being white on the right side and black on the left. Like the blue whale, fin whales feed predominantly upon krill but also consume a variety of fishes. In the North Atlantic, the diet of fin whales includes herring, cod, mackerel, pollock, sardine, capelin, and squid together with euphausiids and copepods (Gambell, 1985).

The reproductive habits of fin whales are not well known, but females are believed to give birth to a single calf at 2- to 3-year intervals (Schmidly, 1981; Watson, 1981). The gestation period is approximately 11 months, with lactation lasting 6 to 7 months and sexual maturity reached at 6 to 10 years of age, when the calves are 18.3 m (females) and 17.7 m (males) in length (Gambell, 1985). The average lifespan of fin whales is thought to be from 40 years (Gaskin, 1982) to 100 years (Gambell, 1985).

Balaenoptera borealis (sei whale)

Legal Status. The sei whale is endangered over its entire range (USFWS, 1987).

Distribution and Abundance. The sei whale is a medium-sized baleen whale known from all of the world's oceans, although it is rare in tropical and polar waters (Schmidly, 1981). Gambell (1976) estimated the pre-whaling population size of sei whales to be 172,700 to 197,700 worldwide, with 75,700 to 77,700 present today. Approximately 2,700 seis are thought to inhabit North Atlantic waters. Only two records of sei whales are known from the Gulf of Mexico, both of these strandings occurring within the study area (Schmidly, 1981). No estimates of population size are available from the Gulf of Mexico.

Sei whales migrate to high latitude temperate and polar waters during summer and return to warmer waters in winter (Watson, 1981; Gambell, 1985). However, these whales are thought to be year-round residents in some temperate waters (Watson, 1981).

Life History. Sei whales are similar in size and appearance to Bryde's whale (Balaenoptera edeni), a balaenopterid also occurring in the study area but not listed as threatened or endangered. The two are most easily distinguished by the presence of three median head ridges in B. edeni versus the single head ridge of B. borealis.

Sei whales are known to consume a variety of copepod, krill, and fish species. In the North Atlantic, Calanus finmarchicus, Thysanoessa inermis, Temora longicornis, and Meganyctiphanes norvegica comprise the bulk of the diet (Gaskin, 1982) but sardines, capelin, anchovy, cod, and squid are also eaten (Watson, 1981). In contrast to the "lunge-feeding" technique used by most baleen whales, sei whales characteristically "skim" through food concentrations at the water's surface (Watson, 1981).

Breeding activity takes place in warm temperate waters during winter. Adult females calve at 2- to 3-year intervals (Gambell, 1985), giving birth to a single calf after a gestation period of about 12 months (Watson, 1981). The period of lactation is approximately 6 months and sexual maturity is reached at about 10 years of age, when the calves have grown to 13.9 m (females) and 13.5 m (males) (Gambell, 1985). The lifespan of sei whales is estimated at 60 to 70 years (Gambell, 1985; Watson, 1981).

Eubalaena glacialis (right whale)

Legal Status. The right whale is endangered over its entire range (USFWS, 1987).

Distribution and Abundance. Right whales are highly migratory baleen whales inhabiting temperate waters of the North Atlantic, the North Pacific, and the southern hemisphere (Schmidly, 1981). These whales were decimated early by the world's whaling industries, with reliable pre-whaling population estimates unavailable. Gambell (1976) estimates as many as 3,000 right whales may remain in the southern hemisphere but northern hemisphere populations number far less--only 100 to 200 in the North Pacific and "a few hundred" (Mitchell, 1973) or less in the North Atlantic. Only one record of the right whale is available from the study area (Schmidly, 1981). These whales are one of the rarest of great whale species occurring in the Gulf of Mexico.

In winter, right whales move from subpolar regions to lower latitudes, although they avoid equatorial waters. These whales then return to subpolar waters in spring, after mating and calving (Cummings, 1985). Due to the asynchronous seasons of the hemispheres and this species' aversion to equatorial waters, northern and southern hemisphere stocks are not believed to interbreed.

Life History. Although right whales were intensively hunted by early whalers, and the animals pass close to the western North Atlantic coast during migration, little data on the natural history of right whales has been gathered.

Right whales feed upon krill, which they skim from plankton concentrations at the water's surface. Copepods and euphausiids are the primary food items taken with Calanus finmarchicus and juvenile euphausiids known to occur in the diet of North Atlantic right whales (Watkins and Schevill, 1976).

Mating and calving occurs in temperate waters during winter. Female right whales produce a single calf after a gestation period of 9 to 10 months. Calves nurse for approximately 12 months, with sexual maturity reached in approximately 10 years, when the calves are 15 m (males) and 15.5 m (females) in length (Cummings, 1985). The calving interval is 2 to 3 years (Watson, 1981).

Physeter catodon (great sperm whale)

Legal Status. The great sperm whale is endangered over its entire range (USFWS, 1987).

Distribution and Abundance. Great sperm whales are worldwide in distribution, occurring in all oceans including polar waters but are primarily found in temperate and tropical waters of the Atlantic and Pacific Oceans. In the western North Atlantic, these whales are often found along the continental shelf but are rarely observed over the shelf itself as they feed in deeper waters.

Worldwide, great sperm whales numbered over 1 million before large scale whaling, with an estimated 400,000 to 500,000 present today. The current North Atlantic stock is believed to be approximately 22,000 (Mitchell, 1973; Gambell, 1976), but estimates from the Gulf of Mexico are not available. Great sperm whales are the most abundant of great whales occurring in the Gulf of Mexico and have been well documented from the study area (Schmidly, 1981; Fritts et al., 1983b). Collum and Fritts (1985) observed 59 great sperm whales along coastal Texas, Louisiana, and Florida during 1979-1981.

Great sperm whales are highly migratory, with group composition and movements determined by season. Females and calves tend to remain in tropical and subtropical waters in winter, making slight poleward movements in summer (although they rarely leave temperate waters). Large males are found in tropical waters during the winter mating season but move poleward in summer, often as individuals but also in bachelor groups (Gambell, 1967; Berzin, 1972). Males move much farther poleward in migrations than do females. Seasonal movements of sperm whales from the Gulf of Mexico remain undocumented, with migratory habits of these whales unknown for Gulf waters.

Life History. The great sperm whale is the only Odontocete classified as endangered by the USFWS. These whales were exploited heavily by nineteenth and twentieth-century whalers worldwide, including a full-scale whaling operation in the eastern Gulf of Mexico; however, a large-scale whaling industry did not develop in the study area.

Great sperm whales feed at the extreme depths of the ocean with dives of 2,255 m documented and 3,000 m possible (Watson, 1981). The primary food of these whales is squid--up to one ton per day--but other deep water prey items are occasionally taken. These include octopus, lobster, crab, jellyfish, sponge, and several varieties of fish (Schmidly, 1981; Watson, 1981). Due to their deepwater feeding habits, great sperm whales are rarely encountered over the continental shelf but are common along the shelf's outer edge.

Sperm whales may breed and calve at any time of the year although reproductive activity peaks in winter and early spring (Berzin, 1972). Breeding behavior is similar to harem formation--a single, dominant male accompanies a group of females and defends the group against competing males. During this time smaller males are driven off to form their own "bachelor groups" and dominance fights between rival males may occur. Twenty to 30 individuals may comprise a harem with many of the females already pregnant or tending young. In sperm whales, the gestation period is approximately 15 months, lactation may go on for 1 to 2 years, and there is a 10-month "resting period" following weaning. The breeding cycle, therefore, may take as long as 4 years and breeding females are thought to comprise only a percentage of each harem group (Watson, 1981).

Newborn sperm whales are approximately 4 m in length and may weigh 1 ton (Watson, 1981). Although twin calves are known (Watson, 1981), a single calf per female is believed the rule. Sexual maturity is reached at approximately 10 years of age (Berzin, 1972; Watson, 1981), when the animals are 10 to 12 m in length. The maximum longevity of great sperm whales is not known; although specimens have been aged at 35 to 40 years, the maximum lifespan is believed much greater (Berzin, 1972).

Trichechus manatus (West Indian manatee)

Legal Status. The West Indian manatee is endangered over its entire range (USFWS, 1987).

Distribution and Abundance. West Indian manatees are found in tropical and subtropical Atlantic waters of the southeastern United States, the West Indies, and along the Central American coast to the northern coast of Brazil (Powell and Rathbun, 1984; Caldwell and Caldwell, 1985). In the United States, these unusual mammals are rare outside of Florida and the Georgia coast (Hartman, 1979). Only eight locality records exist from the study area (Powell and Rathbun, 1984).

Manatees inhabit both shallow fresh and saline waters and may occasionally wander into open ocean, although rarely more than 1 km from shore (Caldwell and Caldwell, 1985). Hartman (1979) felt that manatees in Florida were migratory and responded to both seasonal and nonseasonal factors in making far-ranging coastal movements. Such movements appeared without distinct pattern or routes, however. Locality records from Texas and Louisiana are probably the result of such movements, with Louisiana specimens thought to have originated in Florida and Texas records coming from tropical Mexico (Powell and Rathbun, 1984).

Life History. West Indian manatees are opportunistic, aquatic herbivores that feed exclusively upon aquatic plants. Hartman (1979) states that the primary foods of manatees in Florida rivers are *Eichhornia crassipes*, *Hydrilla verticillata*, *Vallisneria neotropicalis*, *Ceratophyllum demersum*, *Myriophyllum spicatum*, *Ruppia maritima*, and *Diplanthera wrightii*. In seawater, Hartman (1979) observed manatees eating *Syringodium filiforme*, *Thalassia testudinum*, and *Diplanthera wrightii*.

Manatees in Florida breed year-round (Hartman, 1979). The female bears a single calf approximately at 2.5-year intervals, although a female losing her calf shortly after birth may calve again in as little as 2 years (Hartman, 1979). The age at sexual maturity is estimated as 3 to 5 years, and manatees are thought to live as long as 50 years (Hartman, 1979).

Pelecanus occidentalis (brown pelican)

Legal Status. The brown pelican is endangered over its entire range except the Atlantic coast of the United States, Florida, and Alabama (USFWS, 1987).

Distribution and Abundance. Brown pelicans breed on both the Pacific and Atlantic coasts of the United States, Mexico, and South America (Clapp et al., 1982). In late summer and early fall, Pacific birds tend to disperse northward while Atlantic populations move southward. Most birds winter in the United States, though (Clapp et al., 1982). Gulf of Mexico populations tend to overwinter near breeding colonies.

Along the Gulf coast, this species breeds in Florida, Louisiana, and Texas. Brown pelicans were formerly very abundant in both Texas and Louisiana but experienced a dramatic decline in the early part of this century. Prior to the 1930's, approximately 50,000 brown pelicans inhabited the Texas-Louisiana coast (King et al., 1977) although some estimates were higher. Subsequently, the brown pelican population of this region declined until, by the early 1960's, these birds were extirpated from Louisiana and became extremely rare in Texas.

Oberholser (1938) sighted some 12,000 brown pelicans breeding along coastal Louisiana in 1933; however 30 years later, Van Tets (1965) was the last to document native brown pelicans breeding in Louisiana. Hurricanes, disease, and pesticide contamination (especially endrin poisoning) are thought responsible for this decline (King et al., 1977). Beginning in 1968, nestling brown pelicans were captured from Florida's Atlantic coast and transplanted in Louisiana (Nesbitt and Williams, 1978). A total of 765 nestlings were imported from 1968 through 1976, and a small breeding colony was finally established in Barataria Bay in 1971 (Blus et al., 1979). About 35 to 40% of this population was lost in 1975, probably to endrin poisoning (Nesbitt and Williams, 1978). Since 1975, the Barataria Bay colony has grown and provided birds that were transplanted to the Chandeleur Islands and Timbalier Bay. Breeding colonies are now well established at these three sites in Louisiana and in 1988 produced 3,000 to 4,000 young (T. Joanen, 1988, personal communication, Louisiana Department of Wildlife and Fisheries).

In Texas, brown pelicans numbered approximately 5,000 (King et al., 1977) prior to their decline beginning in the 1920's. The decline of brown pelicans in Texas began much earlier than in Louisiana and is attributed to destruction of nesting colonies and shooting by hunters and fishermen (King et al., 1977). The present population includes only 15 to 25 breeding pairs (Blacklock et al., 1978) but the population is thought to be supplemented by occasional winter migrants from Mexico (King et al., 1977).

Life History. Although brown pelicans may scavenge for fish around piers and fishing boats, and may "beg" from tourists, these birds feed primarily by "plunge-diving" and capturing fish in their large, characteristic bill pouch. Such dives may be from heights as great as 20 m, and the birds may either partially or fully submerge (Clapp et al., 1982). Along the Gulf coast, 90 to 95% of the diet is made up of menhaden (*Brevoortia* sp.), although pigfish (*Orthopristis* sp.), pinfish (*Diplodus* sp.), thread herring (*Opisthonema oglinum*), top minnow (*Gambusia* sp.), crevalle (*Paratractus* sp.), silversides (*Menidia* sp.), sheepshead (*Archosargus probatocephalus*), and mullet (*Mugil cephalus*) are also taken (Clapp et al., 1982).

Brown pelicans are highly sensitive to chemical pollutants, with past die-offs in Louisiana attributed to poisoning by ingesting contaminated fish. The pesticide endrin is believed to be especially toxic to pelicans (Blus et al., 1975; King et al., 1977), although a number of other pesticides have also been isolated from pelican eggs (Blus et al., 1975, 1979) and are known to seriously affect pelican reproductive success.

Brown pelicans are colonial in nesting habits and may nest either on the ground or in trees and shrubbery, with most colonies found on small, offshore islands (Clapp et al., 1982). In Louisiana, pelicans nest in black mangroves (*Avicennia nitida*) and in Texas are found nesting in dense shrubbery or on the ground on islands in San Antonio, Aransas, and Corpus Christi Bays (Schreiber, 1980).

Schreiber (1980) described the nesting chronology of the brown pelican indicating that birds from Texas and Louisiana nest from March through June, although most eggs are laid in April and May. A typical clutch contains two or three eggs and incubation lasts 30 days. Hatching success varies from 53% to 89% in Florida, with fledging success varying from 12% to 59% (Schreiber, 1979).

The presence of organochlorine residues may be a significant detriment to reproduction in brown pelicans from Louisiana and Texas. Blus et al. (1975, 1979) identified the presence of DDE, DDD, dieldrin, PCBs, DDT, and endrin, among others, in brown pelican eggs during two studies of pelican reproduction in Louisiana. These substances are known to reduce eggshell thickness, as well as cause direct poisoning (Schreiber and Risebrough, 1972; Blus et al., 1975, 1979; King et al., 1977).

Charadrius melodus (piping plover)

Legal Status. The piping plover is threatened across its entire range, with the exceptions of the Great Lakes watershed in the states of Illinois, Indiana, Michigan, Minnesota, New York, Ohio, Pennsylvania, and Wisconsin, and the Province of Ontario, where it is classified as endangered (USFWS, 1987).

Distribution and Abundance. Breeding populations of the piping plover are found in the northern plains (Alberta to Manitoba; Montana to Nebraska), the Great Lakes area (Great Lakes states and Ontario), and the Atlantic Coast (maritime provinces and Atlantic Coast states from Newfoundland to North Dakota) (Sidle, 1984). Wintering areas occur along the coast from North Carolina to Florida and Mexico as well as in the Bahamas and Greater Antilles (Sidle, 1984). Haig (1985) indicates that piping plovers occur only sporadically along the Gulf coast, with the major wintering area in this region found on the sand flats adjacent to Padre Island in South Texas.

The breeding population of piping plovers is estimated at 910 pairs for the Atlantic coast (Cairns and McLaren, 1980), 20 pairs in the Great Lakes region (Sidle, 1984), and approximately 600 to 800 pairs on the northern plains (Sidle, 1984). Estimates of wintering populations from Texas and Louisiana are not available, but at least some of these birds are from the northern plains population (Haig, 1985).

Life History. Currently, only three detailed studies of the piping plover are available (Wilcox, 1959; Cairns, 1982; Haig, 1987), with all of this research focusing on the reproductive biology of the birds. Consequently, no specifics are available on feeding habits of the piping plover. Feeding patterns and prey items are probably similar to those for other small shorebirds, however.

Piping plovers inhabit sandy, sparsely vegetated beaches (Wilcox, 1959; Cairns and McLaren, 1980). Nests are slight hollows in the sand, generally spaced 60 m or more apart, and often lined with bits of shell (Wilcox, 1959). A typical clutch contains four eggs and is incubated by both sexes for a period of 27 to 31 days (Wilcox, 1959). Wilcox (1959) also indicated that the birds will re-nest if a clutch is destroyed, but will construct a new nest rather than continue to occupy the old one.

The decline of piping plovers is mainly attributed to loss of ephemeral beach habitat, although human disturbance by recreational activities and increases in predator populations are also blamed (Sidle, 1984; Haig, 1985). Along the Gulf coast, Haig (1985) believed water level manipulation and human recreational activities to be responsible for severe habitat loss, especially as lagoons were stabilized to facilitate the development of shoreline structures.

Sterna antillarum (least tern)

Legal Status. United States populations from the following states are endangered: Arkansas, Colorado, Iowa, Illinois, Indiana, Kansas, Kentucky, Louisiana (Mississippi River and tributaries North of Baton Rouge), Mississippi (Mississippi River), Missouri, Montana, Nebraska, New Mexico, North Dakota, Oklahoma, South Dakota, Tennessee, and Texas (except within 80 km of the coast) (USFWS, 1987).

Distribution and Abundance. Least terns breed along the Pacific, Atlantic, and Gulf coasts of the United States, the Gulf coast of Mexico, and the Atlantic coast of Central America (Clapp et al., 1983). Additionally, an interior race (S. a. anthalassus) breeds along interior river systems of the central United States from Nebraska south to New Mexico and east to northwest Ohio and western Tennessee, thence south through southeastern Texas and central Oklahoma (Clapp et al., 1983). The USFWS considers this interior race as endangered, while the coastal form remains unclassified; however, recent evidence indicates that interior and coastal subspecies may interbreed along the coast of Texas (R.D. Slack, 1988, personal communication, Department of Wildlife and Fisheries Sciences, Texas A&M University), throwing doubt on the taxonomic and protective status of least terns from this region. To date, morphological and electrophoretic data have shown no significant differences between the two subspecies in Texas Parks and Wildlife Department (TPWD) (1987).

Currently recognized as the coastal form, S. a. antillarum, Portnoy (1977) documented 3,530 nesting least terns in Louisiana, while populations from Texas were estimated to be 5,500 to 8,300 breeding pairs (Thompson, 1982). Populations from Texas have declined sharply in recent years (82% decline from 1973 to 1978) (Blacklock et al., 1978; Thompson, 1982), but reasons for this decline are unclear. Predation, limited food supply, and pesticide contamination have not been implicated (Thompson, 1982), but terns along the Texas coast do tend to nest in areas of great human disturbance (Thompson, 1982; TPWD, 1987). In Texas, the interior least tern numbers only approximately 100 birds along the Pecos, Rio Grande, Red, and Canadian Rivers (Downing, 1980).

The winter range of least terns is poorly known, but a portion of the North American population winters off the northern coast of South America from Venezuela to northeastern Brazil (Blake, 1977; Thompson, 1982).

Life History. Least terns feed primarily upon small fish, although they will also take insects and crustaceans. The method of prey capture is by "plunge diving" and "dipping" (Clapp et al., 1983). Clapp et al. (1983) summarize the sparse information available on food habits of the least tern, with silvery anchovies (Stolephorus sp.), Atlantic menhaden (Brevoortia tyrannus), mummichogs (Fundulus sp.), and silversides (Menidia sp.) listed in the diet of Gulf coast terns. Likewise, Thompson (1982) indicates that the diet of least terns from Texas is almost exclusively small fish.

Thompson (1982) studied least terns breeding along the Texas coast, from which the following information on reproductive habits is taken.

Least tern nests are simple, unlined scrapes located on sparsely vegetated, sandy, gravel, or shell substrates near water. A typical clutch contains two eggs and is incubated by both sexes for 20 to 22 days. If the clutch is destroyed the breeding pair will renest in approximately three weeks. The young fledge approximately 20 days from hatching but remain dependent upon their parents for an extended period.

Hatching success may be highly variable in least terns as these birds tend to nest in areas of great potential disturbance, both from natural (high winds and tides) and human (recreational activities) causes (Clapp et al., 1983). Thompson (1982) indicates that development of shoreline properties may benefit least terns by providing additional nesting habitat (i.e., dredged material deposits and construction fill). Poorly drained sites, or those made up of fine particulate matter, pose potential for egg loss, however, as such sites tend to flood.

Chelonia mydas (green sea turtle)

Legal Status. The green sea turtle is threatened across its entire range except the breeding populations in Florida and on the Pacific coast of Mexico, which are listed as endangered (USFWS, 1987).

Distribution and Abundance. The green sea turtle is abundant and widely distributed in tropical and subtropical waters between 35°N and 35°S Lat. (Rebel, 1974). This turtle inhabits comparatively shallow water inside reefs (but not on reefs themselves), with ideal habitat made up of shoals and lagoons that are well provided with marine grasses and algae (Rebel, 1974). Green sea turtles are migratory; however, movements from the Gulf of Mexico are unclear.

The range of green sea turtles includes all areas of the Gulf of Mexico, but they are most frequently observed near Florida (Fritts et al., 1983a), where active nesting beaches are known. This species was formerly common in Texas and Louisiana waters (Rebel, 1974; Rabalais and Rabalais, 1980; Reeves and Leatherwood, 1983); however, over-harvesting has severely reduced their numbers (Rebel, 1974). Also, green sea turtles have suffered heavily from the loss of nesting habitat to development and over-exploitation of eggs (Rebel, 1974). Incidental losses are attributable to shrimp trawling and pollution (Rabalais and Rabalais, 1980). Rabalais and Rabalais (1980) reported ten green sea turtles stranded in South Texas during 1976 to 1979, all of which were fouled with oil. Neck (1978) reported possible nesting of C. mydas near Brownsville in the late 1880's, but no recent nesting has occurred on Texas beaches (Reeves and Leatherwood, 1983), and this turtle has become very uncommon in Texas-Louisiana waters.

Life History. Green sea turtles are predominantly herbivorous, with marine grasses such as Zostera, Cymodocea, Thalassia, and Halophila preferred (Rebel, 1974). These turtles also eat algae, and the young feed upon small molluscs and crustaceans (Rebel, 1974).

Green sea turtles nest in 2, 3, or 4-year cycles (Rebel, 1974). Copulation occurs just off the nesting beaches before and during the laying season. The female then crawls ashore and lays between 100 and 150 eggs in a hollow scooped from the sand. The incubation period is 48 to 78 days after which the young struggle to the sea. Little is known about the early years of the young turtles; they may associate with pelagic Sargassum beds during their first year of life (Fritts et al., 1983a).

Lepidochelys kempii (Kemp's ridley sea turtle)

Legal Status. The Kemp's ridley sea turtle is endangered over its entire range (USFWS, 1987).

Distribution and Abundance. Kemp's ridley sea turtles occur primarily from the Gulf coast of Mexico east to the Atlantic and Gulf coasts of Florida (Rebel, 1974) but also range northwards along the Atlantic coast as far north as southern Canada (Fritts et al., 1983a). These turtles are thought to migrate along the Gulf coast to the Atlantic, and then back again for breeding but such movements remain to be substantiated.

Although Kemp's ridleys occasionally wander into open ocean, they are fairly restricted to shallow, coastal waters of the Gulf of Mexico (Rebel, 1974). The population was once estimated to number over 40,000, but fewer than 1,000 nesting females are thought to remain--making these the most endangered of marine turtles (Fritts et al., 1983a). Nevertheless, Kemp's ridleys, as well as loggerhead turtles (Caretta caretta), are the species most likely to be encountered in open waters along the Texas coast (Reeves and Leatherwood, 1983).

Life History. Kemp's ridley sea turtles prefer shallow waters where they feed upon invertebrates including crabs, gastropods, sea urchins, sea stars, medusae, and shrimp--but they also eat fish (Rebel, 1974).

Lepidochelys kempii nests almost exclusively at one location near Rancho Nuevo, Tamaulipas, Mexico, although nesting activity on Padre Island, TX, has been documented (Rebel, 1974; Fritts et al., 1983a). Copulation takes place in the waters prior to the female's coming ashore to nest. The female may nest up to three times in a season, laying approximately 110 eggs per nest. The incubation period is approximately 50 days.

Kemp's ridleys have suffered great losses to human predation of eggs and adults, primarily due to the turtle's restricted nesting habitat. Additionally, this species' preference for shallow, coastal waters increases its vulnerability to dredging activities, boat collisions, and pollution--especially oil spills (Fritts et al., 1983a). Also, shrimp trawlers cause mortality, as the turtles may become entangled in shrimp nets and drown (Fritts et al., 1983a).

Caretta caretta (loggerhead sea turtle)

Legal Status. The loggerhead sea turtle is threatened over its entire range (USFWS, 1987).

Distribution and Abundance. Loggerhead turtles are distributed in all tropical and temperate seas of the world. In the western North Atlantic, loggerheads occur as far north as Virginia and are found throughout the Caribbean and Gulf of Mexico (Rebel, 1974). These turtles prefer shallow, warm waters among islands, estuaries, and over the continental shelf, but they also inhabit deeper waters near food-bearing ocean currents (Rebel, 1974; Fritts et al., 1983a).

Fritts et al. (1983a) regularly encountered loggerheads during aerial surveys of the Texas-Louisiana coast but believed their numbers to be low. Reeves and Leatherwood (1983) conservatively estimated the total number of sea turtles along the south Texas coast (Aransas to Brownsville, inland coast to 18 m contour) to be 19.0 $\pm$ 0.6 turtles, most of which were probably loggerheads or Kemp's ridleys. Rabalais and Rabalais (1980) recorded 259 sea turtle strandings along the South Texas coast, 202 of which were loggerheads. Caretta caretta appears to be the most common and regularly observed of sea turtles occurring in the study area; however, their numbers are low.

Regular migratory movements are not known for loggerheads (Rebel, 1974). However, Fritts et al. (1983a) noted a decrease in Gulf loggerhead numbers in December and increased numbers in April, possibly indicating migratory movements by Gulf populations.

Life History. Loggerheads are omnivorous and eat a wide variety of foods including conchs, shellfish, barnacles, fish, sponges, jellyfish, marine grasses, crabs, sea urchins, and oysters. In captivity, these turtles have eaten stingrays, octopus, and squid (Rebel, 1974). Rabalais and Rabalais (1980) reported the contents of one loggerhead stomach to contain Sargassum seaweed, bird feathers, and pieces of a plastic bottle.

Nesting beaches in eastern Florida are believed to be the most important breeding areas for the loggerhead turtle, although they are known to nest on beaches of all coastal south Atlantic and Gulf states from North Carolina to Texas (Rebel, 1974). Loggerheads breed at 2- to 3-year intervals and may nest several times during a season. The female deposits approximately 110 eggs per nest, with the interval between nesting lasting 12 to 17 days (Rebel, 1974). The incubation period is about 55 days and like other species, young loggerheads may use pelagic sargassum rafts for food and shelter (Fritts et al., 1983a).

The loggerhead's preference for shallow, coastal waters makes these turtles particularly susceptible to the nearshore activities of humans. The development of petroleum resources of the continental shelf may cause oil contamination of eggs and adult turtles. Additionally, dredging activity and boat traffic has been a cause of loggerhead mortality (Fritts et al., 1983a) and these turtles are known to commonly ingest refuse such as plastic containers, possibly causing mortality. Loggerheads are also drowned or injured by shrimp trawlers when they get caught in the nets. Most strandings along the Texas and Louisiana coasts are attributed to trawling activities (Rabalais and Rabalais, 1980; Fritts et al., 1983a).

Dermochelys coriacea (leatherback sea turtle)

Legal Status. The leatherback sea turtle is endangered over its entire range (USFWS, 1987).

Distribution and Abundance. The leatherback sea turtle is widely distributed in tropical and subtropical seas but commonly strays into temperate waters. Although the leatherback is thought to prefer deep waters (Rebel, 1974) some investigators have shown this species to also use shallow waters (Fritts et al., 1983a). This turtle does not seem to be plentiful in Atlantic waters (Rebel, 1974). Although leatherbacks may wander great distances, regular migratory movements are unknown (Rebel, 1974). As with other marine turtles, leatherbacks suffered heavy losses to market hunting for meat and eggs. Loss of nesting habitat has also contributed to the decline of this species.

Leatherbacks are rare in the study area. Fritts et al. (1983a) observed only two leatherbacks off the coast of Louisiana and none near Texas. Rabalais and Rabalais (1980) recorded only one leatherback from the South Texas coast.

Life History. Leatherbacks feed primarily upon jellyfish and other coelenterates, but they are known to eat a variety of items including fish, eggs, green algae, hydrozoa, and octopus (Rebel, 1974). Fritts et al. (1983a) observed nine leatherbacks in areas of jellyfish (*Physalia* spp. and scyphozoans) concentrations.

Leatherback turtles have a pantropical breeding distribution (Fritts et al., 1983a), although major rookeries are rare. Leatherbacks nest in the Caribbean and both the Atlantic and Gulf coasts of Florida, as well as on scattered beaches of Mexico, Africa, and South America. Nesting of leatherbacks in the western Gulf of Mexico is unknown.

Eretmochelys imbricata (hawksbill sea turtle)

Legal Status. The hawksbill sea turtle is endangered over its entire range (USFWS, 1987).

Distribution and Abundance. The hawksbill sea turtle is confined to tropical seas, although rare records from as far north as Massachusetts are known (Rebel, 1974). Hawksbill turtles are present throughout the Caribbean Sea, but are rarely encountered in the northern Gulf of Mexico. Carr et al. (1966) described the nesting range of hawksbill sea turtles as including or once including "the tropical Gulf coast of Mexico and its islands, and the whole of the West Indies to the northern coast of Cuba and throughout the Bahamas." Dixon (1987) lists seven locality reports of the hawksbill for the Texas coast, only three of which are from the study area.

Rebel (1974) describes typical habitat for hawksbills as "coral reefs, shoals, lagoons, and lagoon channels and bays where a growth of marine vegetation provides both vegetable and small animal food." Also, hawksbills prefer shallow water, usually at depths of 15 m or less (Rebel, 1974).

Although hawksbills may wander somewhat, they are fairly restricted to tropical waters and generally travel less than other sea turtles (Rebel, 1974). Regular migratory movements are not known for this turtle.

__Life History__. Hawksbill sea turtles are omnivorous, but prefer invertebrates such as sponges, sea urchins, and ectoprocts (Rebel, 1974). Known food items include grasses, algae, fish, shellfish, barnacles, and Portugese man-of-war (Rebel, 1974). These turtles are also known to consume plastic bags, possibly causing mortality.

Hawksbill sea turtles breed in waters between 25°N and 25°S Lat. (Rebel, 1974). Only one record exists for the hawksbill nesting on the continental United States (Juno, Florida) (Carr et al., 1966).

Little information is available on the breeding biology of hawksbills but these turtles may nest in 2- to 3-year cycles and may nest several times in a season at two-week intervals (Rebel, 1974). Copulation takes place near shore, and the eggs are laid on sand or fine, gravelly beaches. Hawksbills appear to prefer cleaner beaches with more oceanic exposure than green sea turtles, but the two species are known to have shared the same nesting beaches (Rebel, 1974). An average clutch contains approximately 160 eggs and requires an incubation time of about 58 days (Rebel, 1974).

Hawksbill sea turtles are prized for their shells, which are used to produce a variety of "tortoise-shell" products. Although these turtles, and their eggs, are eaten in some areas the demand for turtle shell is responsible for the endangered status of the hawksbill.

6.6.3 Summary

Three major circumstances are responsible for the endangered or threatened status of 14 mammals, birds, and reptiles from Texas and Louisiana marine ecosystems. These are past excesses in hunting pressure (Rebel, 1974; Gambell, 1976; King et al., 1977), loss of habitat to shoreline development and recreational activity (Thompson, 1982; Haig, 1985), and pollution of Gulf waters, especially by organochlorine residues (Blus et al., 1975, 1979; Nesbitt and Williams, 1978). Although effective legislation has controlled over-hunting where possible, and has reserved key coastal habitats as wildlife refuges and national seashores, the ever increasing popularity of coastal areas for recreation will continue to stress wildlife populations. Also, the continued pollution of Gulf waters may pose serious consequences for the long-term health of the area's wildlife. Currently, the effects of petroleum-related pollution are not as well documented as for organochlorine pollution; however, the ever-increasing development of Gulf Coast petroleum resources call for greater attention to this aspect of Gulf ecology.

Factors affecting the marine environment may also affect nearby freshwater coastal environments. In addition to the species discussed above, five birds from the adjacent freshwater coastal ecosystems are classified as endangered. These are the bald eagle (*Haliaeetus leucocephalus*), wood stork (*Mycteria americana*), whooping crane (*Grus americana*), peregrine falcon (*Falco peregrinus*), and eskimo curlew (*Numenius borealis*). One additional endangered species, the humpback whale (*Megaptera novaeangliae*), has been recorded near the study area and one day may be found to occasionally occur off the Texas-Louisiana coastline. Therefore, a total of 20 threatened or endangered species may be affected by human activities along the Texas-Louisiana coast.

6.7 DATA GAPS AND INFORMATION NEEDS

The Louisiana/upper-Texas continental shelf and slope area has been the subject of a number of intensive biological/ecological investigations, each focusing upon a specific area and with particular, often management-related, goals. Taken as a group, these studies provide a generalized picture of the composition, density, and distribution patterns of large segments of the biota. However, there are major gaps in areal coverage, and the data resulting from the different studies are often not comparable in detail (having been obtained by different collecting gear, different mesh sizes, etc.). With some notable exceptions, the data have not been interpreted within the larger context of the controlling hydrographic and sedimentological factors or in terms of ecosystem dynamics. The interrelationships of the shelf/slope ecosystem are poorly understood. The knowledge base is greatest on the inner third and least on the outer half of the continental shelf.

Three overriding ecological questions beg answers:

1) In quantitative terms, what are the coupling mechanisms between the inshore marshes, bays, and estuaries, on the one hand, and the continental shelf ecological systems, on the other?

2) How do the Mississippi and Atchafalaya Rivers influence and control the shelf ecological systems? What is the extent of these influences in terms of space and time, and how are they related to the meteorological factors?

3) How do the oceanic waters interact with the coastal waters and habitats, and how do they influence the distribution of the biological components of the systems?

Important, but subsidiary, questions include the following:

4) What are the origin, nature, and characteristics of the nepheloid layers, and how do they influence the biological systems?

5) What is the origin and nature of the hypoxic zone of the Louisiana/upper-Texas continental shelf, how does it vary in space and time, and how does it influence the biological systems?

6) What is the nature of the hydrographic and sedimentological environment of the Mississippi Canyon, and what role does it play in the biological economy of the area?

7) The area adjacent to the Mississippi River Delta (essentially, east of a line projected seaward from Barataria Bay, LA) has been recognized as a special habitat with a unique faunal composition (the Pro-delta faunal assemblage). What combination of environmental factors controls this system, what is its biological composition, and how does this system relate to all others?

The state of our knowledge and the lack of information for the various biological groups (phytoplankton, zooplankton, etc.) have been indicated within each section description and need not be repeated in detail here. However, these needs are summarized below.

6.7.1 <u>State of the System</u>

There is a need to develop a coherent overview of the absolute density values of the phytoplankton, zooplankton, neuston, nekton and benthos in relation to depth, distance along the coast, sediment type and/or hydrographic regime, and season. Insofar as possible, collecting gear, mesh sizes, etc. should be identical with those employed in the STOCS studies so that a coherent picture of the entire region will emerge.

Although the demersal fauna and megabenthos have been fairly well studied on the continental shelf, there is a clear data gap in the 120 to 300 m depth range. This depth range should be thoroughly surveyed because a major faunal transition apparently occurs there.

In this connection, it should also be pointed out that our knowledge of the biota is highly biased by the methods used. For example, there is evidence that the near-bottom waters are inhabited by a group of animals (largely small crustaceans and fishes) that are too small to be retained by standard shrimp trawls and too large to be taken efficiently with standard zooplankton nets. These organisms appear in the stomachs of fishes but seldom elsewhere. Collections made with small beam trawls with about 0.5 mm mesh size (at the cod end) should be quite revealing, especially if the catches were made at night when many of the species apparently rise into the water column. Because many of these species are important food items, such a study could reveal areas of high food concentration. A similar case could easily be made concerning our lack of knowledge about larger burrowing forms. Heavy dredges that dig into the bottom with blades or teeth would be required to adequately sample the macroinfauna. Our knowledge of special habitats and the "missing fauna" would be greatly enriched by unconventional studies employing unconventional gear.

Reefs and banks along the outer shelf have been studied with varying degrees of intensity, and some should be examined more thoroughly. However, the banks and reefs both shoreward and seaward of this group are in clear need of identification and study. Most of these shallow and deep banks are relatively unknown at present.

6.7.2 Dynamic Relationships

There is a need to develop a coherent picture of the dynamic relationships within the system and between system components and external controlling factors. The emphasis here is upon physical/biological and biological/biological coupling mechanisms.

6.7.3 Mathematical Models

There is a need to develop comprehensive mathematical models that link together the states and couplings of the various system components as well as the effects of the external driving forces.

6.7.4 Special Habitats and Special Components

Additional investigations should be carried out to examine the environment and biota of special habitats (Mississippi River Delta environments, Mississippi Canyon, oozy bottoms off Louisiana, hill and valley areas of the outer shelf and upper slope). Studies should be conducted to determine the composition and distribution of under-investigated biological components (near-bottom macrofauna, burrowing megabenthos).

Studies should be carried out (presumably by the industry) to find safer methods of platform removal. The current use of bulk-explosive charges can damage or kill sea turtles, which may be attracted to the platforms. In addition to altered methods of platform removal per se, methods for causing the turtles to leave the vicinity of a platform could be investigated so as to minimize the chance of injury or mortality during removal.

Sea turtles are known to frequent offshore platforms, shipwrecks, and natural reefs (Rosman et al., 1987). Further research is needed to determine whether the turtles use offshore structures as resting sites; a study along these lines is planned by the Minerals Management Service. If this is found to be the case, then follow-up research could be conducted to develop turtle docking frames or turtle attracting devices, which could add to the value of these structures as turtle habitat.

CHAPTER 7
SOCIOECONOMICS

Thomas L. Linton

7.1 INTRODUCTION

The Gulf of Mexico is an especially important resource to the nation. One-sixth of the U.S. population lives in Gulf coastal states. Ninety percent of U.S. offshore oil and gas come from the Gulf, and 45% of U.S. shipping tonnage passes through Gulf ports. In addition, the U.S. Navy has eight strategic Homeports proposed for the Gulf. Federal outer continental shelf (OCS) leasing is second only to the Federal income tax as a revenue source for the U.S. Treasury, producing more than $76 billion in revenue between 1956 and 1984. Even with this intensive level of industrial activity, 40% of the nation's commercial fish landings and one-third of the marine recreational fishing activities in the continental U.S. occur here (U.S. Environmental Protection Agency, 1988).

7.2 FISHERIES

The commercial fishery resources of the OCS region off Texas and Louisiana are of national significance in quantity and value of landings. The recreational marine fisheries are also of substantial magnitude, being composed primarily of nearshore, estuarine-dependent species (e.g., sciaenids). The number of private craft capable of going offshore for extended periods of time has expanded greatly in the past ten years. This has resulted in an increasing amount of fishing pressure on reef-inhabiting species.

Historically, the species sought by both commercial and recreational fishermen are estuarine dependent. The fishery landings data that are used in the following characterization were obtained from the National Marine Fisheries Service (NMFS). They cover the area from the beach to the 500-m depth contour offshore of Texas and Louisiana, between Corpus Christi, TX and the mouth of the Mississippi River.

The fishery offshore of Texas and Louisiana is composed of two major components: shellfish and finfish, with shellfish being the most important economically. Shrimp are the most important commercial seafood product in Texas, constituting 82% of the weight and 92% of the ex-vessel value of total seafood landed (Osborn et al., 1986). In Louisiana, shrimp were first in value ($300 million) of all seafood landed in that state in 1987 (Philip Bowman, 1988, personal communication, Louisiana Game and Fish Commission).

7.2.1 Shellfish

The shrimp fishery of the northwestern Gulf of Mexico is based essentially upon two species: white shrimp (*Penaeus setiferus*) and brown shrimp (*P. aztecus*). Historical data on shrimp landings have been compiled by the NMFS. The annual average offshore landings of the white shrimp fishery for the period 1960 through 1982 were 4.8 million pounds from Texas and 16.3 million pounds from Louisiana. The corresponding values for brown shrimp were 26.9 million and 15.4 million pounds (Klima et al., 1987).

More recent data for average annual landings of white and brown shrimp are shown in Figures 7.1 and 7.2, respectively. From 1981 through 1987, white shrimp landings were 3.9 million and 24.0 million pounds for Texas and Louisiana, respectively. The corresponding values for brown shrimp during the same time period were 20.8 million and 17.6 million pounds from the two states. Although the landings fluctuate from year to year, the average values are within the range of historical data reported by Klima et al. (1987). Therefore, the period 1981 through 1987 can be considered reflective of typical conditions in the area with regard to the shrimp fishery.

These landings were accomplished by a varying number of boats over time. The present-day vessels are in excess of 45 ft and are designed for the offshore fishery. In Texas, there were 3,038 licenses sold to Texas residents for vessels longer than 45 ft, or "Gulf shrimp boats," in 1987 (Texas Parks and Wildlife Department, 1988). In Louisiana, there were 2,121 resident and 1,500 non-resident licenses for Gulf-class shrimp boats issued in 1987 (Philip Bowman, 1988, personal communication, Louisiana Game and Fish Commission).

One significant development that has greatly affected the shrimp fishery of the Texas-Louisiana OCS is the Texas Closure. The closure and its influence upon the shrimp fishery of the Gulf are described by Klima et al. (1982) as follows:

> "The implementation of the Gulf of Mexico shrimp fishery management plan (FMP) in May 1981 permitted, for the first time, closure of the brown shrimp fishery from the coastline to 200 nautical miles off the Texas coast. The objectives of the Texas closure management measure were to increase the yield of shrimp and to eliminate waste caused by discard of undersized shrimp in the Fishery Conservation Zone (FCZ). According to the FMP, shrimp yield would be increased by protecting shrimp from fishing during the period when they were predominantly small and were growing rapidly. Discards would be reduced by eliminating the count restriction in order to allow all shrimp caught to be landed."

The Gulf of Mexico Fishery Management Council agreed to continue this seasonal closure of the brown shrimp fishery off the Texas coast in 1982, 1983, 1984, 1985, and 1986. The 1986 Texas Closure was implemented from 10 May to 2 July 1986, but unlike other years, the area closed was only from the coastline to 15 NM off the Texas coast (Figure 7.3). It was determined by the Council that this type of closure would still allow small brown shrimp to be protected from harvest but would also allow the taking of larger brown shrimp by fishermen in deeper waters.

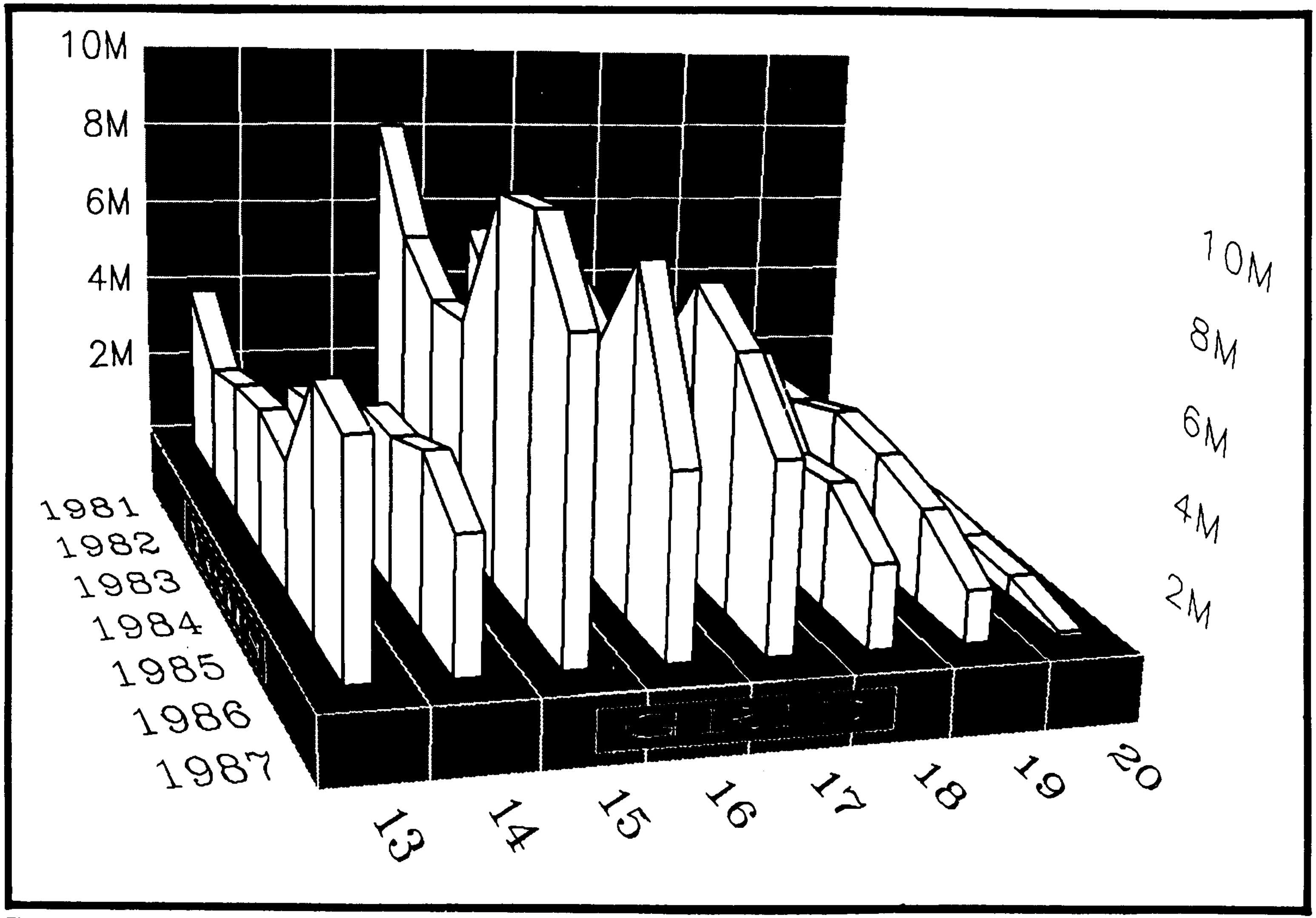


Figure 7.1. White shrimp landings in millions of pounds (M) from NMFS statistical grids 13 through 20 for years 1981 through 1987.

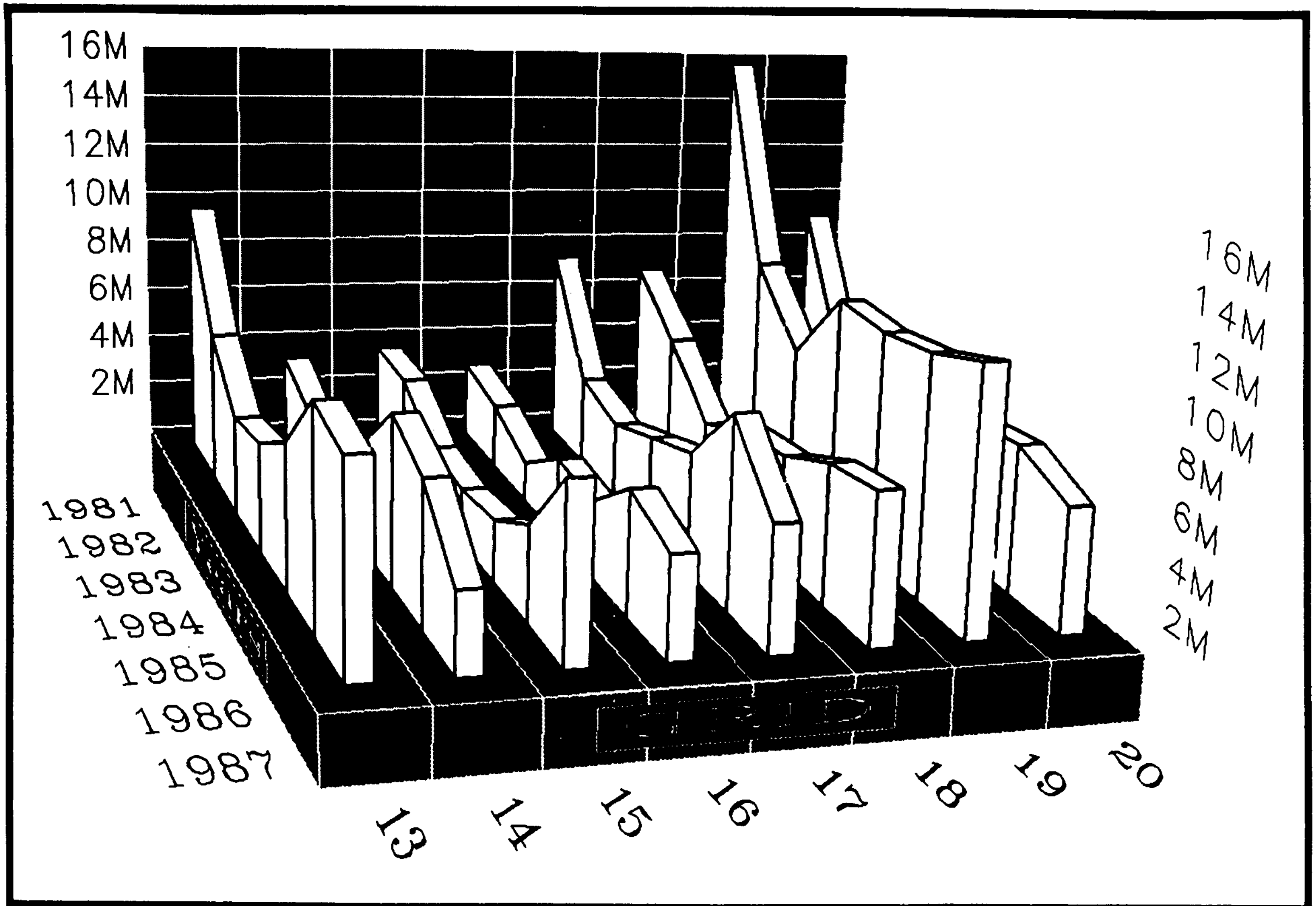


Figure 7.2. Brown shrimp landings in millions of pounds (M) from NMFS statistical grids 13 through 20 for years 1981 through 1987.

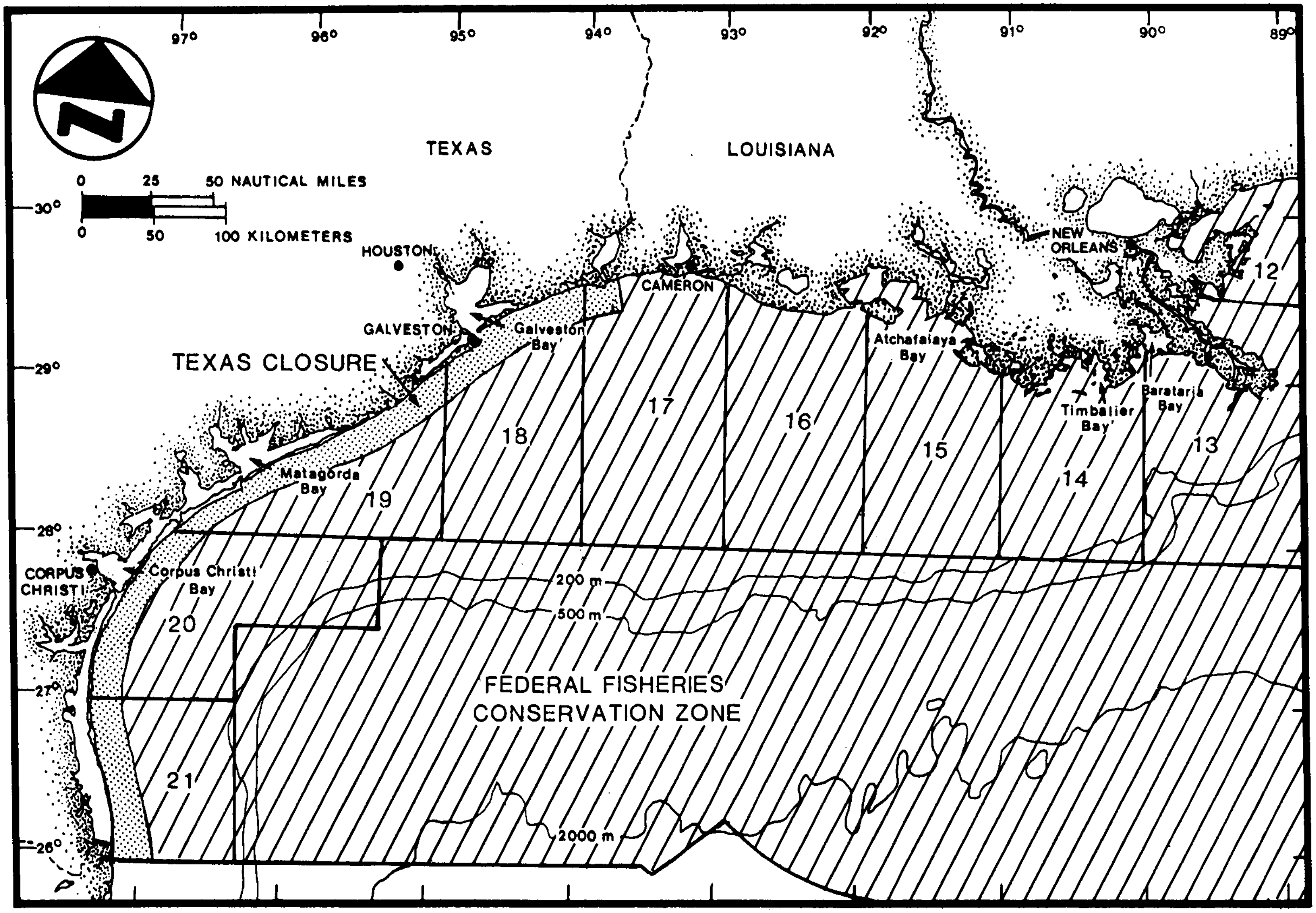


Figure 7.3. Location of the NMFS statistical grid areas (numbers), the Federal Fisheries Conservation Zone (cross-hatching), and the Texas Closure Area (dot pattern).

The Texas Parks and Wildlife Department sets the closing and opening dates for the fishery by assessing abundance, size, and growth rate of shrimp in Texas waters during April and June (Bryan, 1985). Prior to the FMP, Texas law closed the territorial sea from the shoreline out 9 NM for 45 days during mid-May to mid-July from 1960 to 1980 (60 days in 1976). The objective was to ensure that a substantial proportion (>50%) of shrimp in Gulf waters had reached 65 tails/pound or 112 mm total length by season's opening. With the present FMP, the closed portion of the FCZ is closed and opened in conjunction with the Texas territorial sea closure. The 1981 through 1986 closures have all exceeded the historical 45-day closure by 5 to 10 days.

Klima et al. (1987) interviewed shrimp vessel captains from 11 port areas in an attempt to access the socioeconomic impact of the Texas Closure on the shrimp industry in the northwestern and northern Gulf of Mexico. These included six Texas areas (Port Isabel, Brownsville, Port Aransas, Freeport, Galveston/Bolivar, and Sabine/Port Arthur) and three Louisiana areas (Cameron, Delcambre, and Houma). Little difference in fishing habits between 1985 and 1986 was seen among vessels with home ports from Louisiana or Sabine, TX; they fished mainly off Louisiana both years. However, noticeable differences between 1985 and 1986 were seen from the other five port areas in Texas. Vessels with a home port in either the Galveston or the Freeport area showed an almost symmetrical shift in fishing habits when 1985 and 1986 closure periods were compared. In 1985, most vessels fished off Louisiana, and some vessels fished off Texas. In 1986, the reverse was true, with most vessels fishing off Texas.

The effect of the closure on employment in the Texas-Louisiana area was that the incidence of not fishing during closure was high only in the home ports of Freeport, Port Aransas, and Brownsville, TX. Of the four ports where large numbers of captains did not shrimp, unemployment was a problem during 1985 only in the Port Aransas area. During 1986, unemployment was a problem only in the Port Aransas area, with most of the captains at the other ports shrimping elsewhere during the closure period.

7.2.2 Finfish

In regard to the second component of the fishery offshore of Texas and Louisiana, Hoese and Moore (1977) describe in excess of 400 species of fishes that live in the salt water of the northwestern Gulf of Mexico adjacent to Texas and Louisiana. In the Gulf of Mexico a preponderance (41%) of fishes taken by marine recreational fishermen are members of the drum family (Sciaenidae) (U.S. Department of Commerce, 1987a). Of the 51 major species of finfishes taken commercially in the Gulf of Mexico, menhaden was the most important. The largest menhaden processing plant in the U.S. is located in Cameron, LA, and as a result Cameron is the leading port for fish landings in the nation (U.S. Department of Commerce, 1987b). The ports having the second, third and fourth largest landings of finfish in the U.S. are in the Gulf of Mexico--the first two in Louisiana, the third in Mississippi. Louisiana leads all states in volume of fish landed. Louisiana and Texas are second and third to Alaska in value of catch.

Commercial Fisheries

Summaries of commercial finfish landings were developed from data obtained from NMFS for 1981 through 1987. These data are from the eight NMFS statistical grids that encompass the study area (Figure 7.3). Annual landings by species were examined for total weight and dollar value. These data were arranged to highlight those species landed in "substantial quantities" (defined as greater than 100,000 lb. from one or more statistical grids). The data for species landed in substantial quantities for 1981 through 1987 are summarized in Tables 7.1 through 7.7, respectively. A summary of total finfish landings by statistical grid is provided in Table 7.8.

The finfishery off Louisiana and Texas may best be described as consisting of a few species coming from a limited area. The number of species landed in substantial quantities ranged from 13 in 1981 to 18 in 1987, with a low of 11 species in 1984 (Tables 7.1 through 7.7). Only a few of these species consistently exceeded an ex-vessel value of $1 million. Over the seven-year period for which data were examined, those that exceeded $1 million in value were as follows:

Year	Species with over $1 million in landings
1981	menhaden, red snapper, spotted seatrout
1982	menhaden, red snapper, black drum
1983	menhaden, red snapper, black drum, king mackerel, red drum, spotted seatrout
1984	menhaden, red snapper, red drum
1985	menhaden, red snapper, red drum, yellowedge grouper
1986	menhaden, red snapper, red drum, yellowfin tuna, black drum, spotted seatrout, flounder
1987	menhaden, yellowfin tuna, red drum, red snapper, black drum, swordfish, spotted seatrout, bluefin tuna, vermilion snapper

During 1981 through 1987, consistently greater than 60% of the total landings for all grids came from grids 13, 14 and 15, with a high of 94% in 1987 (Table 7.8). Grid 13 consistently had the highest total finfish landings (Table 7.8) and the highest number of species landed in substantial quantities (Tables 7.1 through 7.7). Grids 13, 14, and 15 are off the Louisiana coast (Figure 7.3) in areas that have a greater number of production platforms than the remaining five grids to the west. The nutrient source that Mississippi River provides to this area, coupled with the expanded hard surface habitat that the production platforms provide, may contribute synergistically to the large-scale and expanding production there.

Table 7.1. Finfish landings from NMFS statistical grids 13 through 20 for 1981.

Species*	Landings in Grid (Thousands of pounds) 13	14	15	16	17	18	19	20	Total Landings (Thousands of pounds)	Total Value (Dollars)
Bonito	6	78	135	81	48	0	0	0	355	53,192
Croaker	2,439	84	1	2	0	30	0	1	2,557	802,284
Drum, black	558	1,372	34	72	0	52	43	403	2,535	646,885
Drum, red	609	63	44	122	8	6	93	186	1,131	911,248
Flounders	332	39	7	17	13	0	0	0	409	221,143
Grouper & scamp	6	11	3	6	5	169	27	129	355	284,613
Menhaden	140,000	0	312,000	270,000	225,000	0	0	0	947,325	36,246,515
Mullet, black	11	22	236	0	0	11	55	24	359	38,300
Seatrout, spotted	267	15	19	266	0	86	88	251	992	1,036,295
Seatrout, white	465	5	0	3	0	0	0	16	489	116,045
Sheepshead	174	12	0	0	0	56	32	87	363	73,008
Snapper, red	135	504	65	181	54	289	39	340	1,608	2,299,440
Whiting, king	133	36	8	0	2	8	7	0	194	41,542
								Totals:	958,672	42,770,510

* Only the 13 species with greater than 100,000 lb. in at least one grid are shown. The total number of species reported for the year was 29.

Table 7.2. Finfish landings from NMFS statistical grids 13 through 20 for 1982.

Species*	Landings in Grid (Thousands of pounds)								Total Landings (Thousands of pounds)	Total Value (Dollars)
	13	14	15	16	17	18	19	20		
Croaker	559	102	26	4	5	78	0	0	776	304,018
Drum, black	667	334	137	46	0	77	41	838	2,141	1,048,478
Drum, red	883	213	93	68	0	0	0	0	1,257	832,650
Flounders	278	77	22	8	4	0	0	0	389	188,370
Fluke	0	0	0	0	4	254	167	61	486	471,063
Mackerel, king	229	0	0	0	0	0	0	0	229	217,726
Menhaden	80,322	40,959	412,737	382,541	510,047	17,930	0	0	1,444,536	56,316,568
Mullet, black	4	14	80	0	0	122	11	9	239	60,426
Seatrout, spotted	310	60	51	240	0	0	0	0	661	589,802
Seatrout, white	286	6	3	6	2	2	0	0	306	80,835
Sheepshead	171	34	4	0	1	116	63	104	494	99,442
Snapper, red	126	561	230	275	149	340	38	214	1,933	2,784,267
Swordfish	0	0	0	0	0	0	0	245	245	701,628
Whiting, king	225	25	11	0	2	67	2	0	332	79,535
								Totals:	1,454,024	63,774,808

* Only the 14 species with greater than 100,000 lb. in at least one grid are shown. The total number of species reported for the year was 31.

Table 7.3. Finfish landings from NMFS statistical grids 13 through 20 for 1983.

Species*	Landings in Grid (Thousands of pounds) 13	14	15	16	17	18	19	20	Total Landings (Thousands of pounds)	Total Value (Dollars)
Croaker	124	57	19	8	11	10	1	8	239	95,136
Drum, black	805	242	89	116	1	56	61	1,123	2,493	1,387,208
Drum, red	938	205	77	269	0	0	0	0	1,488	1,097,155
Flounders	144	118	14	30	4	0	0	0	310	172,182
Fluke	0	0	0	0	4	150	123	144	421	393,603
Grouper & scamp	8	20	9	7	26	14	5	180	269	244,830
Mackerel, king	1,250	22	217	0	0	0	0	0	1,490	1,312,975
Menhaden	244,121	25,388	457,709	557,069	353,188	34,906	15,879	0	1,688,264	67,139,448
Mullet, black	17	124	0	0	0	94	25	0	261	30,610
Seatrout, spotted	641	35	17	450	43	0	0	0	1,186	1,086,579
Seatrout, white	138	5	2	13	0	1	1	0	160	62,587
Sheepshead	360	35	9	9	0	67	32	168	681	119,200
Snapper, red	238	682	256	243	371	162	39	369	2,359	3,464,320
Whiting, king	159	86	10	0	2	9	7	1	274	59,723
								Totals:	1,699,895	76,665,556

* Only the 14 species with greater than 100,000 lb. in at least one grid are shown. The total number of species reported for the year was 30.

Table 7.4. Finfish landings from NMFS statistical grids 13 through 20 for 1984.

Species*	Landings in Grid (Thousands of pounds)								Total Landings (Thousands of pounds)	Total Value (Dollars)
	13	14	15	16	17	18	19	20		
Drum, black	487	49	202	155	0	272	26	443	1,635	825,193
Drum, red	1,072	226	119	262	0	0	0	0	1,681	1,437,058
Flounders	124	103	49	66	7	161	127	74	715	548,940
Grouper & scamp	256	16	7	7	13	20	15	6	340	347,010
Mackerel, king	732	19	0	0	0	0	0	0	752	477,505
Menhaden	107,621	14,324	409,271	555,859	427,416	0	0	0	1,514,494	60,055,385
Mullet, black	11	20	140	0	0	60	23	2	255	21,645
Seatrout, spotted	443	15	18	191	9	0	0	0	676	739,438
Seatrout, white	193	5	1	4	0	2	3	0	209	81,845
Sheepshead	327	12	1	4	2	82	14	77	519	74,161
Snapper, red	1,070	501	183	218	288	321	184	77	2,842	4,378,295
								Totals:	1,524,118	68,986,475

* Only the 11 species with greater than 100,000 lb. in at least one grid are shown. The total number of species reported for the year was 41.

Table 7.5. Finfish landings from NMFS statistical grids 13 through 20 for 1985.

Species*	Landings in Grid (Thousands of pounds) 13	14	15	16	17	18	19	20	Total Landings (Thousands of pounds)	Total Value (Dollars)
Drum, black	703	150	516	74	3	120	34	316	1,915	910,100
Drum, red	1,326	219	258	107	2	0	0	0	1,911	2,003,830
Flounders	246	133	81	30	24	180	105	113	911	719,382
Grouper & scamp	461	15	13	5	32	50	186	94	856	1,046,461
Mackerel, king	897	72	0	0	0	2	0	2	973	748,059
Menhaden	97,442	24,089	907,831	168,670	244,650	84,722	0	0	1,527,407	55,910,353
Mullet, black	17	1	71	9	0	170	119	7	395	43,148
Seatrout, spotted	526	37	68	253	1	0	0	0	884	945,124
Seatrout, white	189	12	13	2	0	5	1	1	222	115,573
Sheepshead	372	23	1	4	2	59	27	92	580	84,651
Snapper, red	903	232	180	179	165	288	187	166	2,300	4,265,438
Snapper, vermilion	61	1	19	4	112	42	0	1	240	293,532
Tuna, yellowfin	193	27	1	0	0	47	2	90	360	544,520
								Totals:	1,538,954	67,630,171

* Only the 13 species with greater than 100,000 lb. in at least one grid are shown. The total number of species reported for the year was 58.

Table 7.6. Finfish landings from NMFS statistical grids 13 through 20 for 1986.

Species*	Landings in Grid (Thousands of pounds) 13	14	15	16	17	18	19	20	Total Landings (Thousands of pounds)	Total Value (Dollars)
Amberjack	205	57	58	30	45	15	9	60	478	234,095
Drum, black	1,334	785	863	120	2	33	69	360	3,567	1,655,061
Drum, red	2,940	992	399	253	1	0	0	0	4,585	3,975,684
Flounders	475	158	97	106	30	160	134	167	1,327	1,030,042
Grouper & scamp	137	28	8	7	38	31	37	71	359	393,818
Grouper, yellowedge	442	106	10	0	11	0	0	0	569	741,388
Mackerel, king	270	37	0	0	0	1	0	0	309	231,618
Menhaden	187,371	35,524	472,331	766,646	0	0	0	0	1,458,874	53,522,336
Seatrout, spotted	1,048	112	81	441	0	0	0	0	1,683	1,420,907
Seatrout, white	230	17	4	4	9	5	0	0	268	138,637
Sheepshead	407	107	28	19	5	41	26	56	688	114,057
Snapper, red	887	258	258	165	234	300	97	207	2,406	4,750,120
Snapper, vermilion	277	75	51	45	126	23	0	1	598	818,194
Swordfish	118	3	4	6	1	22	60	2	216	588,597
Tuna, bluefin	127	27	0	1	0	0	1	0	157	476,235
Tuna, yellowfin	1,929	38	74	32	4	1	16	69	2,164	2,954,629
Whiting, king	242	38	37	10	10	12	1	0	351	90,531
								Totals:	1,478,599	73,135,949

* Only the 17 species with greater than 100,000 lb. in at least one grid are shown. The total number of species reported for the year was 76.

Table 7.7. Finfish landings from NMFS statistical grids 13 through 20 for 1987.

Species*	Landings in Grid (Thousands of pounds)								Total Landings (Thousands of pounds)	Total Value (Dollars)
	13	14	15	16	17	18	19	20		
Amberjack	225	113	12	32	31	8	0	0	421	224,485
Drum, black	2,495	1,830	1,879	308	0	0	0	0	6,511	2,212,653
Drum, red	2,476	837	362	116	0	0	0	0	3,792	4,341,712
Flounders	470	135	228	30	34	0	0	0	899	699,196
Grouper, yellowedge	153	151	0	0	0	0	0	0	305	495,718
Mackerel, king	346	171	0	4	1	0	0	0	522	460,170
Menhaden	257,973	13,263	628,252	701,350	0	0	0	0	1,600,837	55,090,733
Mullet, black	129	7	11	10	0	0	0	0	157	51,683
Seatrout, spotted	968	323	126	176	0	0	0	0	1,593	1,410,536
Seatrout, white	189	40	10	11	2	0	2	0	253	120,640
Sheepshead	916	355	53	7	0	0	0	0	1,331	177,778
Snapper, red	619	584	109	98	78	42	0	0	1,530	3,329,719
Snapper, vermilion	295	149	42	123	105	26	0	0	737	1,208,165
Swordfish	630	107	6	4	3	5	2	0	758	2,123,680
Tilefish	97	100	0	9	28	0	0	0	234	264,100
Tuna, bluefin	233	50	12	3	0	0	0	0	297	1,307,380
Tuna, yellowfin	5,121	372	17	77	19	11	0	0	5,617	10,762,634
Whiting, king	251	51	46	1	0	0	0	0	358	95,817
								Totals:	1,621,152	84,376,799

* Only the 18 species with greater than 100,000 lb. in at least one grid are shown. The total number of species reported for the year was 87.

Table 7.8. Total finfish landings in NMFS statistical grids from 1981-1987.

Year	Landings in Grid (Millions of pounds) 13	14	15	16	17	18	19	20	Total	No. of Species
TOTAL FINFISH										
1981	5.3	2.2	0.6	0.8	0.2	0.7	0.5	1.5	11.8	29
1982	3.8	1.4	0.7	0.7	0.2	1.1	0.3	1.6	9.8	31
1983	4.9	1.6	0.9	1.1	0.5	0.6	0.3	2.0	11.9	30
1984	8.0	1.1	0.7	0.9	0.4	1.0	0.5	0.7	13.3	41
1985	6.0	1.4	1.3	0.7	0.4	1.2	1.0	1.0	13.0	58
1986	11.7	4.5	2.0	1.3	0.6	0.9	0.6	1.1	22.7	76
1987	16.6	5.9	3.1	1.2	0.4	0.1	0.08	0.004	27.3	87
MENHADEN										
1981	140	0	312	270	225	0	0	0	947	NA
1982	80	41	413	383	510	18	0	0	1,445	NA
1983	224	25	458	557	353	35	16	0	1,668	NA
1984	107	14	409	556	427	0	0	0	1,514	NA
1985	97	24	908	169	245	85	0	0	1,528	NA
1986	187	33	472	766	0	0	0	0	1,459	NA
1987	258	13	628	701	0	0	0	0	1,600	NA

Table 7.9. Average U.S. crude oil consumption from 1978 through 1987 (From: U.S. Energy Information Administration, U.S. Department of Energy, 1988).

Year	U.S. Consumption (Million bbl/day)
1978	18.8
1979	18.5
1980	17.1
1981	16.1
1982	15.3
1983	15.2
1984	15.7
1985	15.7
1986	16.3
1987	16.6

Table 7.10. The "Rig Count" for 30 May 1988. The Rig Count is a weekly report of the number of drilling rigs in operation in the Gulf of Mexico (GOM), compared with the number active in the previous week, month, and year. (From: Offshore Data Services, Gulf of Mexico Newsletter, 30 May 1988).

	Current (30 May 1988)	Previous Week	Previous Month	Previous Year
Total GOM Fleet	237	237	238	234
Rigs Contracted	137*	134	137	89
Rigs Without Contract	100	103	101	145
GOM Utilization (%)	57.8†	56.5	57.6	38.0
World Utilization (%)	70.8	69.8	70.9	57.3

* GOM Contracted Fleet Breakdown:

Jackups	102
Semis	27
Ships	3
Submersibles	5
Total	137

† In addition, 54 of the 143 (37.8%) platform rigs in the GOM were working as of 30 May 1988.

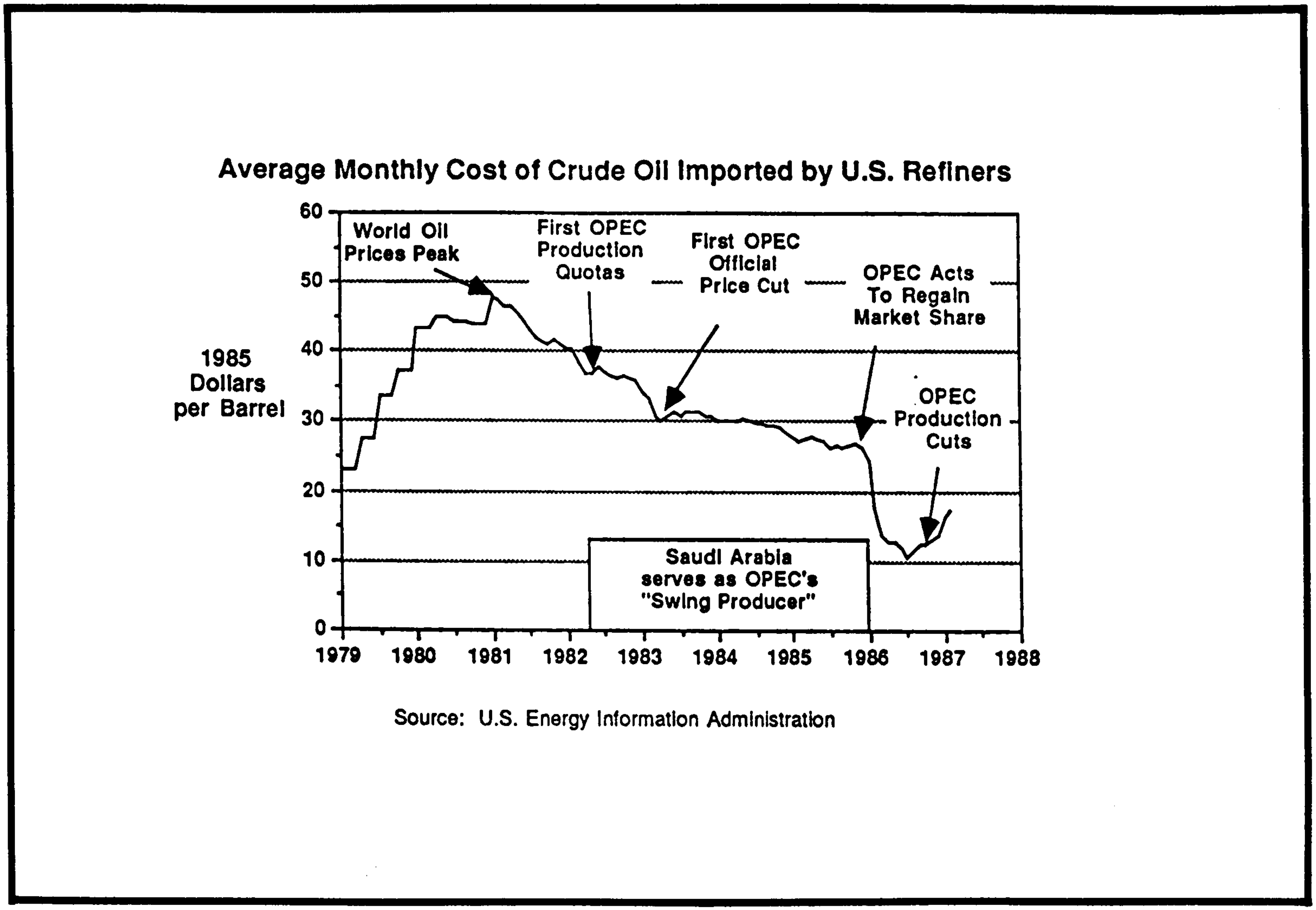


Figure 7.4. Average monthly cost of crude oil imported by U.S. refiners from 1979 through 1987 with factors highlighted that influence prices.

profitable year in 1985, a precipitous drop in prices occurred in 1986 that had pronounced effects upon the domestic segment of the industry (Figure 7.5). By the end of 1986, data from the Bureau of Labor Statistics show that 150,000 oil industry jobs had been lost (U.S. Department of Energy, 1987), with current employment (424,000) falling to about the same level as it was in 1977.

7.3.3 Environmental Effects

In addition to its direct effects on the economy of Louisiana and Texas, the oil and gas industry can generate economic effects through environmental damage--for example, from oil spills. A pertinent example is the June 1979 Ixtoc-I blowout in the Bay of Campeche--the largest and most spectacular oil spill to date (3 to 5 million barrels). By August 1979, currents had carried the oil into U.S. waters, and 25,000 to 70,000 barrels reached the Texas beaches or resided offshore in tar mats; still larger quantities passed through the Texas OCS region in the form of small patches of emulsified oil (mousse) (Boehm, 1982). In an economic damage assessment, Restrepo et al. (1982) reported that the value of lost equipment and oil, damage suits, clean-up and containment costs, and disaster assistance loans was more than $900 million--making the spill the most expensive in history. Most of these expenses were incurred by Mexico; however, costs to the U.S. government were estimated to exceed $8 million. In Texas, the Ixtoc spill also resulted in economic losses in recreation and tourism of about $6.5 million, mostly in the communities of South Padre Island, Port Aransas, and Port Isabel. No significant direct effects on the commercial fishing industry were noted (Restrepo et al., 1982).

The costs of clean-up and damage compensation for oil spills are not easily assigned and collected. At present, there is no legislated means whereby liability and compensation for oil spills can be assigned and collected. A bill has been introduced in the U.S. Senate by Senator John Breaux of Louisiana that would provide a system of liability and compensation for oil spill damage and removal costs; identical legislation is being considered in the U.S. House of Representatives. For the past ten years, legislation that would accomplish these objectives has been considered, but never passed.

7.4 COMMERCIAL SHIPPING

Commercial shipping is conducted out of 14 deep-water ports in the study area. These are listed in Table 7.11, including total tonnage that passed across the docks in each.

The four major ports in this mid-Gulf port region (in addition to the Louisiana Offshore Oil Port, or LOOP) are Corpus Christi and Houston in Texas, and New Orleans and Gramercy in Louisiana. Each of these four ports is described briefly below.

7.4.1 Port of Corpus Christi

The Port of Corpus Christi was first opened in 1926 and consisted of four berths and a 7.5-m deep channel. In its first full year of

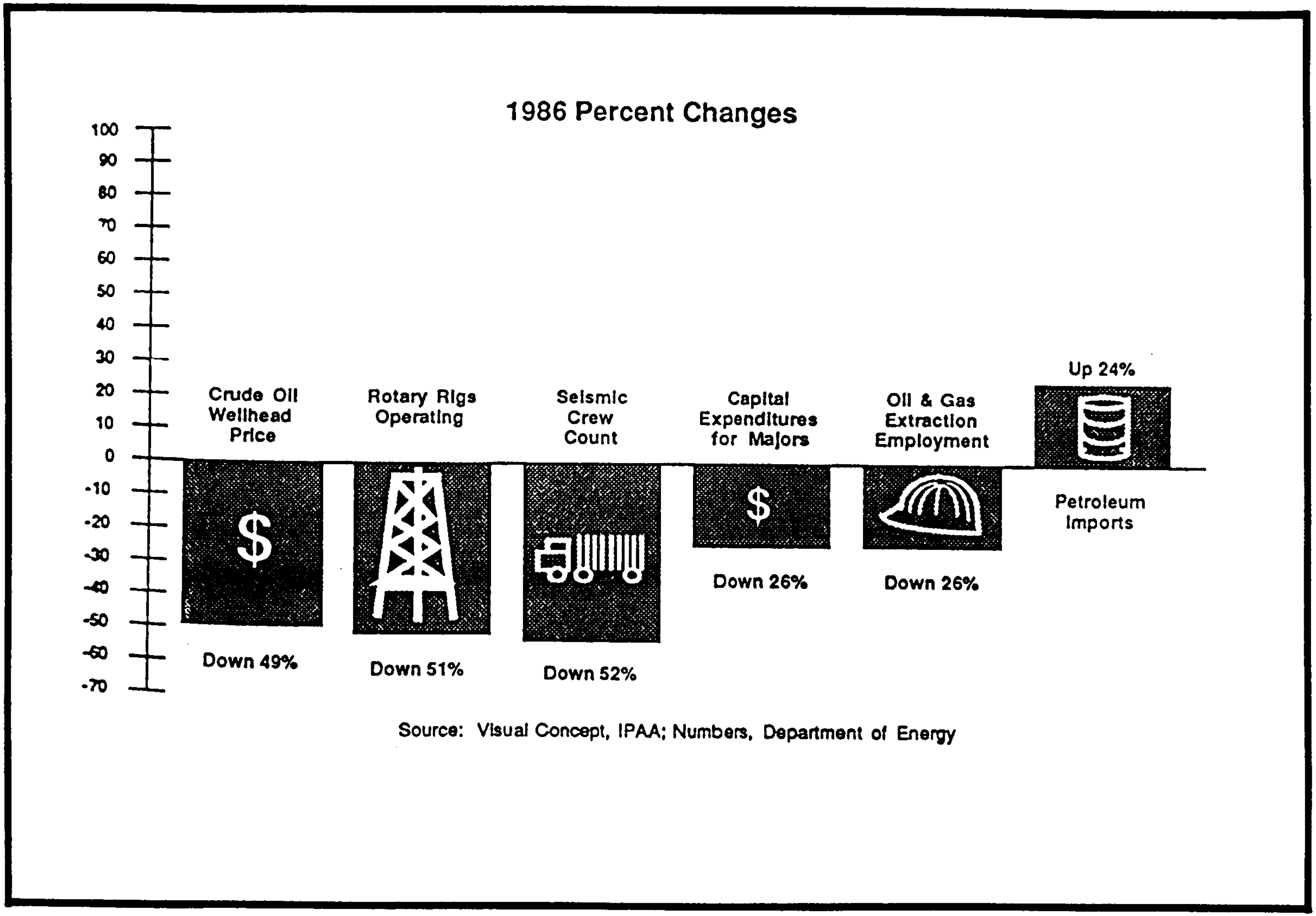


Figure 7.5. The effects of lower world oil prices upon various segments of industry in the U.S. in 1986.

Table 7.11. The 14 major deep-water ports in the mid-Gulf ports region of the Gulf of Mexico, and the import-export tonnage that passed across their docks in 1986 (From: American Association of Port Authorities, Alexandria, VA, October 1987).

Port	1986 Tonnage (Millions of Tons) Import	Export	Total
Houston	31.5	17.6	49.1
LOOP*	41.3	--	41.3
New Orleans	16.8	22.8	39.6
Gramercy	10.9	28.0	38.9
Corpus Christi	23.6	3.8	27.4
Baton Rouge	8.9	14.6	23.5
Lake Charles	14.0	4.1	18.1
Texas City	16.3	1.4	17.7
Port Arthur	8.5	2.5	11.0
Destrehan	0.2	8.1	8.3
Beaumont	4.6	3.4	8.0
St. Rose	1.1	6.8	7.9
Freeport	4.3	1.0	5.3
Galveston	1.2	3.9	5.1
TOTAL	183.2	301.2	301.2

* Louisiana Offshore Oil Port--oil import only (Sharon Dunn, 1988, personal communication, LOOP, Inc., Gretna, LA).

operation, less than 1 million tons of cargo was moved across its docks. Today, it is the deepest port on the Gulf of Mexico, with a 14 m water depth, and over 40 public and private docks (Port of Corpus Christi, 1986a). Approximately 27 million tons of cargo were handled by the port in 1986 on 945 ships and 5,727 barges. Petroleum and chemical tonnage represented 89% of total tonnage in 1985 and 92% in 1986--a 12.8% increase (Port of Corpus Christi, 1986b). The port has been granted Foreign Trade Zone status and is the first in the continental U.S. to include refineries (Port of Corpus Christi, 1987).

The Port of Corpus Christi is ranked seventh largest nationally and directly affects the local area and statewide economy. An exact estimate of this economic impact is the subject of a study that is being conducted by a consulting firm under contract to the Port Authority (Carol Bader, 1988, personal communication, Port of Corpus Christi).

7.4.2 Port of Houston

The Port of Houston is 890 km west of New Orleans and 600 km northeast of Brownsville, TX. It is the nation's third largest in tonnage and fourth in area (Zuniga, 1988). The port area includes the Houston Ship Channel and its tributary channels and basins that extend from Morgan Point, at the head of Galveston Bay, to and including a turning basin within the city limits of Houston; the Buffalo Bayou extending from the turning basin to the Main Street Bridge; and the port facilities at Bayport near Red Bluff on the west side of upper Galveston Bay. All of the port lies within Harris County. The Houston Ship Channel is approximately 80 km long, extending from Bolivar Roads to the Turning Basin. In 1986, approximately 49 million tons moved through the Port of Houston. The top commodities, both imported and exported through the port, were petroleum and petroleum products. The Port of Houston, ranked ninth largest in the world, is estimated to directly affect more than 32,000 jobs in Houston and Harris County and 160,000 jobs through the state (Port of Houston Public Relations Department, 1987).

7.4.3 Port of New Orleans

For over two centuries, New Orleans has been one of the major ports of the U.S. and the world (Port of New Orleans, 1987). Annual general cargo trade over public wharves peaked in 1974 at close to 8 million tons. In 1982, general cargo fell to 5 million tons. Although there has been some recovery, traffic remains at the 6-million-ton level, approximately 25% below its historical peak. Lower traffic flows and the substitution of container ships for breakbulk services have reduced annual dockside labor requirements from 4.0 million hours (1975) to 1.7 million hours (1985). A study to determine local and statewide economic impact through jobs created by port-related activities is currently being conducted for the Port of New Orleans (Clay Miller, 1988, personal communication, Port of New Orleans Public Affairs Department). During 1986, about 40 million tons of cargo passed through the Port of New Orleans, valued at $10.7 billion (Port of New Orleans, 1987). Of the imports, one third was crude petroleum, and approximately 3% of exports were refined petroleum products (e.g., heavy fuel oils, lubricating oils).

7.4.4 Port of Gramercy

Fourth largest in the mid-Gulf region according to the American Association of Port Authorities (Table 7.11) is the Port of Gramercy. It is one of four ports under the jurisdiction of the South Louisiana Port Commission (SLPC). Three parishes constitute the SLPC. Gramercy is the largest of the four ports as a result from it being a custom district and the port of entry for SLPC. The major items of cargo imported and exported through the port of Gramercy are crude/refined petroleum products, grains and chemicals. Approximately 39 million tons of cargo was moved through the Port of Gramercy in 1986 (Table 7.11) (Linda Marmillion, 1988 personal communication, SLPC).

7.5 OTHER MARINE INDUSTRIES

7.5.1 Seismic Exploration Companies

There are currently 20 seismic vessels operating in the Gulf of Mexico (John Laker, 1988, personal communication, Western Geophysical). The average crew compliment is 50 persons per boat--an estimate based on three full crews to allow for "one-on and two-off" operations. The economic impact of the vessels vary, in that some obtain supplies and equipment at the dock site being used at the time, whereas others obtain supplies and equipment from caterers who operate from a central location. Much of the specialized equipment is essentially custom-made by "Mom and Pop" operations (e.g., machine-shops, fabricating shops) that are located in a variety of locations in the coastal area. In addition, the seismic companies develop and fabricate specialized equipment for their own use and for sale to competitor companies.

7.5.2 Offshore Oil Service Companies

The offshore oil service industry, according to Turrentine (1988), is composed of six segments:

1. Drilling contractors.
2. Supply boat operators.
3. Helicopter operators.
4. Construction firms.
5. Manufacturers and suppliers.
6. Rig-based services (cementing, logging, diving and catering).

"In May 1987 while there were 140 rigs operating, there were approximately 190 marine service vessels working out of an existing fleet of some 215. Since that time the number of working vessels has increased, and as of 1 April 1988 there were about 245 vessels working out of a fleet of 258. Since December 1987 service vessel utilization has been above 90%. The present daily rate for conventional 180 ft liquid mud supply boat averages about $2,200" (Ramey, 1988).

7.5.3 Shipyards

There are 69 shipyards in Texas (Hollin, 1988) and 65 in Louisiana (V. Behrhost, 1988, personal communication, LSU Sea Grant Program). These vary in size from those capable of servicing large, ocean going vessels to small, in-shore craft.

7.6 DATA GAPS AND INFORMATION NEEDS

As discussed in Section 7.2.2, it appears that major changes in commercial finfish landings have occurred in the western Gulf of Mexico between 1981 and 1987. The number of species contributing to the catch has increased from 29 to 87, and the number of species with a value in excess of $1 million has tripled. The percentage of the total catch coming from the area off Louisiana was 60% or greater during all seven years, but the highest value (over 90%) was seen during 1987.

These changes in finfish landings raise some important questions that deserve further study. Are these long-term trends, ephemeral events, or only recently recorded events? Or are we seeing a combination of events? Is finfish habitat expansion resulting from the presence of large numbers of production platforms in areas influenced by the nutrient rich waters flowing from the Mississippi River a component? The traditional species in this area have been shrimp and menhaden--species adapted to the muddy conditions that exist in this area. Placement of large numbers of production platforms in these areas provides hard surface habitat that is bathed in nutrient-rich and relatively clear water, a suitable habitat for many of the species that have become important components of the 1987 finfish landings. This provision of new habitat type could be analogous to raft-culture of oysters, wherein expanded growth of aufwuchs occurs when oysters are suspended off-bottom above muddy substrates.

CHAPTER 8
CONCEPTUAL MODELING

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8.1 INTRODUCTION

Previous chapters have reviewed existing knowledge of the marine geology, physical oceanography and meteorology, marine chemistry, marine biology, and socioeconomics of the study area. Data gaps and information needs have been discussed under each category. This chapter focuses on the environmental effects of oil and gas related activities. First, we present a brief synthesis of the accumulated knowledge about the environment, biota, and socioeconomics. This is followed by a discussion of the various aspects of human intrusion onto the continental shelf, including upstream and shore-based operations as well as human activities taking place on the continental shelf. Following this, the focus is entirely upon oil and gas related effects, and these will be examined through narratives and various types of summary models.

There is a voluminous literature on environmental effects of offshore oil and gas operations, based largely on research off Louisiana and Texas. Major, recent sources of information include the proceedings of a symposium on drilling mud and cuttings discharges (Ayers et al., 1980); a review of effects of oil and gas operations on the marine environment by Gettleson (1980); the National Research Council (NRC) reports on Drilling Discharges in the Marine Environment (NRC, 1983), Oil in the Sea (NRC, 1985a), and Disposal of Offshore Platforms (NRC, 1985b); a review of the fate and effects of produced waters (Middleditch, 1984); and a book on The Long-term Effects of Oil and Gas Development edited by Boesch and Rabalais (1987). Several major environmental monitoring programs have been conducted in the study area, including the Offshore Ecology Investigation (Ward et al., 1979), the Central Gulf Platform Study (Bedinger, 1981), the Buccaneer Gas and Oil Field Study (Middleditch, 1981), and several studies at the Flower Garden Banks (Continental Shelf Associates, Inc., 1975, 1978a,b, 1983, 1985; Boland et al., 1983). The Minerals Management Service (MMS) has issued numerous Environmental Impact Statements (EIS) for lease sales in the Gulf, including the regional EIS [U.S. Department of the Interior (USDI), MMS, 1983a)] and the recent EIS for Sales 118 and 122 in the Central and Western Planning Areas (USDI, MMS, 1988). In addition, the MMS has prepared documents addressing particular issues or environmental concerns, such as pipeline installation and operation (USDI, MMS, 1983b), geological and geophysical activities (USDI, MMS, 1984), and platform removal (USDI, MMS, 1987a). Proceedings volumes from recent MMS Information Transfer Meetings also contain much relevant information.

Given this wealth of literature on the subject, it is difficult to say anything new about the effects of oil and gas operations in the marine environment. This discussion is intended to provide an overview of effects of oil and gas operations on major ecosystems (and selected components) of the Texas-Louisiana shelf and upper slope. It is not our intention to present an exhaustive literature review, or to duplicate the kind of analysis presented in recent EISs. The EISs are based in part on many types of information that are beyond the scope of this project, such as development scenarios, probability analyses, and spill trajectories.

To the extent possible, we have avoided lengthy discussions of issues that have been addressed in detail in recent reviews, or that have been summarized in other chapters of this report. Some additional information is contained in the Appendix to this volume, which is a review of major environmental monitoring programs conducted in the Gulf of Mexico.

8.2 SUMMARY OF KNOWLEDGE

8.2.1 The Environment

The coastline of Louisiana and upper Texas, from the Mississippi River Delta to the level of Corpus Christi, is broadly arcuate and concave to the south and southeast. Seaward of this coastline lies the continental shelf, which is about 200 km wide in the center and which narrows at the eastern and western extremes. This shelf consists of a wedge of sediments brought down largely by the ancestral Mississippi River with lesser contributions by the Colorado, Rio Grande, and other streams. Consisting mainly of terrigenous sandstones and shales, the wedge is approximately 15 km thick beneath the present coastline. Sub-bottom strata dip gently in a seaward direction. Diapiric salt structures, which occur from near shore to the shelf break, are usually subsurface features, but on the outer shelf many occur as topographic features with vertical relief sometimes exceeding 100 m. Sand, often mixed with shells, is found along the nearshore bottoms just off the coastal barrier islands, but most of the shelf is composed of sands and muds and mixtures of the two. From the Mississippi River Delta to the level of central Louisiana fine sediments predominate, and from there westward and southward, sands are the principal sediment type, locally mixed with finer materials. East of Matagorda Bay, local areas of subdued topography with sandstone, siltstone, claystone, or basalt outcrops appear associated primarily with salt diapir intrusions. Below the level of Matagorda Bay occasional carbonate banks occur.

Whereas the continental shelf is a broad, smooth, gently sloping plain, the upper continental slope is characterized by complex hill and basin topography which has resulted from extensive salt diapirism, sedimentation, and erosion. Surface sediments of the slope consist of terrigenous sandy clays, swept down from the continental shelf, mixed with calcareous foraminiferal remains. Sediments of the outer shelf and particularly of the upper slope are often unstable and subject to slumping and creeping. Local subsidence, mud flows, and larger downslope mass transport features are not uncommon. Sediments of the continental shelf and slope contain vast reservoirs of natural gas and petroleum hydrocarbons. They are particularly prominent in the eastern half of the area. Some of these deposits are quite near the sediment surface, and many gas and oil seeps have been identified.

During the warmer months (March through October), the area is under the influence of tropical air masses, and most of the winds are from the southeast and south. These winds are persistent but generally of low velocity except during brief tropical storms and hurricanes. These occur from May through October but peak in September. During the cooler months (November through April), polar and arctic air masses become stronger, and winds are frequently from northerly directions. Repeated cold fronts are often accompanied by gale force winds that homogenize the nearshore Gulf waters to depths of at least 40 m. Air temperatures range from nearshore highs of 29°C (July to August) and lows of 15.5°C (December to January) to offshore highs of 29°C and lows of 18°C. Sea fogs occur during the winter months, particularly December through February. Rainfall on the shelf averages about 101 cm per year and is heaviest during the period July through September.

The annual progression of wind stress patterns is responsible for much of the low frequency water circulation on the shelf, and monthly mean alongshore components of wind stress are important in generating coastal currents. During the period September through May, the surface flow on the shelf is cyclonic (counterclockwise) with a downcoast current nearshore and an upcoast counterflow at the shelf break. During June through August, when the wind is more directly from the south, there is a reversal, and for most of the area the flow along the inner shelf is upcoast. At this season, the surface current along the shelf break is quite weak. When the alongshore component is downcoast (during the cooler months), Ekman transport results in a sinking of the nearshore water (downwelling) and a slow seaward drift of the bottom water. When the alongshore component is upcoast (June through August), Ekman transport drives the surface water seaward with a compensating onshore drift of bottom water (upwelling). The downwelling tendency in the winter months is intensified by the episodic passage of cold fronts which chill the nearshore water and increase the salinity through evaporation. Then the dense coastal waters sink and sweep rapidly offshore, transporting large volumes of sediment to deeper water. Because the cold fronts tend to hit primarily the central sector of the coast, offshore transport of bottom water is greatest in this sector. The upwelling tendency during summer is intensified by vertical stratification of the water column at this season. Little mixing occurs, and fresher coastal water extends seaward along the surface while highly saline bottom water extends shoreward almost to the coast. Tropical storms and hurricanes which occur during the summer temporarily upset the stratification in shallow water, but this is reestablished within two or three days after the passage. Little effect is felt on deeper waters of the outer shelf.

The Mississippi/Atchafalaya River system contributes about 73% of the freshwater entering the area. About 20% is contributed by precipitation, and the remaining 7% enters through the smaller streams. During the period of spring floods (April), when the Mississippi River is carrying its maximum load of water and dissolved and suspended materials, the winds are largely from the southeast. Thus, the greatest load of nutrients and sediments is carried westward to be deposited on the Texas-Louisiana shelf. The annual renewal sediment blanket is deposited at least as far west as Galveston Bay. Turbulence in the nearshore waters resuspends the finest particles, creating a nepheloid layer that blankets the entire shelf throughout the year.

Trace metals enter northern Gulf waters from river outflow, the atmosphere, and local human activities. Once in the area, they may be dissolved or suspended in the water column, reside in the sediments, or concentrate in biological tissues. Due to possible sample contamination, most early trace metal analyses of water from the area are suspect, and only recent data appear to be reliable. It would be desirable to be able to construct quantitative budgets for each species of trace metal giving sources, reservoirs, transfers, transports, and sinks, but this is not currently possible. However, we do know roughly where the trace metals come from and how they are moved through the systems of the continental shelf.

In the South Texas Outer Continental Shelf (STOCS) area, concentrations of most trace metals are quite low (in the water column, sediments, and organisms) with local elevations off some estuaries and around some drilling platforms. Off Louisiana and upper Texas, however, trace metal concentrations tend to be much higher, with the greatest concentrations off the Mississippi River Delta, nearshore, and around some rigs and platforms. Clearly the major supplier of trace metals is the sediment brought in by the Mississippi River, and this is supplemented by outflow from some highly polluted estuaries and by drilling muds and other waste associated with oil drilling and production activities. The element barium, of little concern as a pollutant, is of great importance as a tracer. Its distribution clearly indicates that surface sediments of the inner half of the Louisiana and upper Texas shelf are subject to suspension and redistribution by active bottom currents. These sediments and trace metals then become resettled on the outer shelf and upper slope where bottom currents appear to be less active. The Mississippi River contributes many trace metals in nearly their global-average crustal abundance, but some metals such as cadmium, lead, and zinc are enriched in Mississippi River derived material. Nearshore sediments off Louisiana are similar to Mississippi River suspended matter except for a depletion of manganese, which is mobilized by reducing conditions and is thereby lost from the sediment. Sediments around many drilling rigs may have elevated concentrations of trace metals--mainly barium, but also sometimes chromium and others; the concentrations decrease rapidly with distance from the source.

A number of studies have been carried out on trace metal concentrations in organisms and biological tissues. Some zooplankton samples have shown elevated levels of the clay minerals aluminum, iron, and nickel, indicating ingestion of clay particles. Near the Mississippi River Delta, some fishes have shown elevated tissue levels of chromium, nickel, and lead, but the possibility of sample contamination renders these results suspect. Produced (formation) waters, released in quantity around production platforms, contain hydrocarbons, trace metals, and radionuclides (e.g., radium) which quickly become diluted in the Gulf waters. However, the radioactivity may be picked up in some quantity by the fishes closely associated with the structures and which are heavily harvested by commercial and recreational fishermen for human food. This matter has not been investigated. Nor is much known about the effects of dredging and spoil disposal on local trace metal concentrations.

Hydrocarbons enter northern Gulf waters from river outflow, the atmosphere, natural seepage, oil and gas production, local transportation and ship traffic, and oceanic transport from a distance (floating tar balls, etc.). The most important sources are Mississippi River outflow, local oil and gas production activities, and ship traffic (anchor damage to pipelines, bilge and sludge washings, etc.). Hydrocarbons in the sediments and water column tend to be much higher off Louisiana and east Texas than off south Texas (STOCS area). Concentrations are particularly high around the Mississippi River Delta, along the coast, and in the vicinity of some oil platforms and rigs. Louisiana shelf hydrocarbons include both natural petroleum compounds and anthropogenic hydrocarbons (much of which is derived from diesel oils and other drilling mud lubricants).

Tar balls, derived from various crude oils, tanker sludges, and fuel oil residues, reach their highest concentrations in the western Gulf. These are generally floating on the surface, and the concentration in the water column drops off rapidly with depth. High molecular weight hydrocarbons, which are low in sediments off south Texas, are very high in sediments off Louisiana and upper Texas, both in the nearshore and outer continental shelf areas. Many of these are unresolved complex mixtures including both weathered petroleum and anthropogenic fractions.

Volatile hydrocarbons are mostly low molecular weight water soluble compounds. Included in this group are polynuclear aromatic hydrocarbons (napthalenes, etc.) which are often highly toxic. Some cause tissue damage, cancer, and genetic abnormalities. Although of low concentrations off south Texas, these compounds are present in high levels in the sediments and water column of Louisiana and upper Texas. Large quantities are released in the brine discharges and in the underwater venting of waste gases, and some derived from anthropogenic sources are brought in by river flow. Gaseous hydrocarbons show virtually the same distribution patterns as the volatile hydrocarbons. On the upper continental slope, there is much natural gas and oil seepage, particularly near the mouth of the Mississippi River. However, in general, the slope sediments have somewhat lower hydrocarbon concentrations than those of the Louisiana shelf. Many synthetic organic chemicals are brought to the coastal waters by the streams, and off the Mississippi River and the coastal bays and estuaries, high levels of synthetic organics have been observed. These include chlorinated hydrocarbons (many pesticides, polychlorinated biphenyls, and related compounds).

Some studies have been carried out to determine hydrocarbon levels in biological species. At the Flower Garden Banks, no petroleum contamination has been found in the water, sediments, macronekton, or the sedentary American thorny oyster (<u>Spondylus</u>). Off south Texas, hydrocarbons were found in zooplankton tissues, presumably derived from ingestion of micro-tarballs. Off Calcasieu Pass in nearshore waters of central Louisiana penaeid shrimp were found to be sporadically contaminated with petroleum hydrocarbons. At the Buccaneer Oil Field off

Galveston, TX, the biofouling mat at a depth of 3 m was found to contain much fresh petroleum, and this also appeared in the blennies which fed upon the mat. Barnacles had weathered petroleum residues which also appeared in the sheepshead that fed upon the barnacles. Red snappers (which come and go) showed variable levels of contamination, and plankton-feeding spadefish contained lower levels of contamination. Off Timbalier Bay, LA aromatic compounds (naphthalenes and derivatives) were present in tissues of the sheepshead and spadefish. Because seafood is harvested from the vicinity of rigs and platforms of the Louisiana and upper Texas coasts, this subject should be investigated in much greater detail.

8.2.2 The Biota

Nutrient levels on the continental shelf are derived primarily from the Mississippi and Atchafalaya River systems and to a lesser extent from the outflow of other streams and from upwelling. Consequently, phytoplankton levels tend to be much higher and more variable off Louisiana than off south Texas and higher and more variable inshore than offshore. Phytoplankton cell counts average around 1 million cells/m^3 nearshore off Louisiana, about 85,000/m^3 nearshore off south Texas, and about 30,000/m^3 in offshore waters of south Texas. Surface chlorophyll values (in mg chl/m^3) off central Louisiana average 8.5; off nearshore south Texas, about 2.5; and in offshore Texas waters, about 0.6 (only slightly above the open Gulf value of 0.2). Depth integrated primary production (in mg C/m^2/h) off Timbalier Bay ranges from 15.54 to 283.89 and averages 98.82 in comparison with an open Gulf average of 6.07. Diatoms dominate the phytoplankton off Louisiana, with freshwater species being observed on the continental shelf in association with plumes of Mississippi and Atchafalaya River water. Dinoflagellates become more important off south Texas, and red tide blooms, which apparently begin off Galveston Bay, extend along the coast to Tampico, Mexico.

Zooplankton abundance values tend to parallel those for phytoplankton. Zooplankton is much more abundant in coastal waters of Louisiana than off south Texas and more abundant nearshore than offshore. Average standing crop values are as follows: nearshore Louisiana--85,408 individuals/m^3, nearshore south Texas--3,496 individuals/m^3, and offshore south Texas--1,055 individuals/m^3. Copepods make up a large fraction of the zooplankton at all seasons and localities, and nearshore, mid-shelf, and outer shelf groups are recognized. The small estuarine copepod, *Acartia tonsa*, is the dominant nearshore species, and it sometimes makes up over 90% of the total zooplankton.

The neuston has been investigated only off south Texas. This is a very diverse group and is rich in eggs and larvae of invertebrates and fishes. As a whole, neuston is more abundant in nearshore than in offshore waters, but individual taxa may reach their highest levels in nearshore, middle shelf, or outer shelf waters. Most groups peak during the spring months, but some have secondary peaks at other seasons of the year. For most groups, night-time collections show higher concentrations than those made during the day.

Nekton includes a variety of squids, fishes, sea turtles, and cetaceans. Inshore and offshore species assemblages are recognized, and many of the nektonic species are seasonal residents. Quantitative data for nektonic species are lacking.

The demersal fauna of the Texas-Louisiana shelf has been fairly well studied. About 30% of the species are estuary related. The absolute density of penaeid shrimp is about one-third greater off Louisiana than off Texas, and the total fish population is much denser off Louisiana (four times as dense in the 14 to 27 m depth range and two times as dense in the 7 to 46 m range). On the outer shelf, the Louisiana and Texas fish population densities are about equal. Maximum densities of demersal fishes on the Louisiana shelf occur at depths of 14 and 27 m (23.1 and 21.5 kg/ha, respectively) and on the Texas shelf at depths of 73 and 82 m (7.6 and 8.2 kg/ha). In the inshore Louisiana waters, the catch is dominated by the Atlantic croaker, but numerical dominance in the inshore catch off Texas is shared by the Atlantic croaker, silver seatrout, and southern kingfish, all estuary related. At depths of 27 m and beyond, the longspine porgy dominates off both Louisiana and Texas. The white shrimp, which overwinters on the inner shelf, favors Louisiana, while the brown shrimp, which overwinters in deeper shelf waters, favors Texas. For the most abundant demersal species, seasonal depth-related density patterns are known. Food habits of important demersal fishes have been investigated, and trophic ecosystem models have been developed. Density estimates of the demersal fauna of the Louisiana upper slope have been provided.

The meiofauna is dominated by nematodes with a variety of other invertebrates groups present in much lower numbers. At the Buccaneer Oil Field, the average meiofaunal density was 941 individuals/10 cm^2. Off south Texas, mean densities ranged from a high of 430 individuals/10 cm^2 (0 to 30 m) to a low of 30 individuals/10 cm^2 (120 to 140 m). On the Louisiana upper slope, the average meiofaunal density was 410 individuals/10 cm^2. The extent to which these density differences are due to sediment grain size is not clear.

On the south Texas shelf average macrobenthos densities are high nearshore (2,901 individuals/m^2) and low on the outer shelf (394 individuals/m^2). At the Buccaneer Oil Field they are much higher, averaging 6,288 individuals/m^2. In the nearshore waters off central Louisiana, densities up to 18,736 individuals/m^2 were observed, but the mean annual density was low (2,600 individuals/m^2) due to the effects of hypoxic water during the summer months which reduced densities at this season to a low of 266 individuals/m^2. On the Louisiana upper slope, macrobenthos densities averaged 3,816 individuals/m^2, but due to the use of a smaller mesh size, these values are not strictly comparable with the others. As in the case of the meiofauna, the macrofauna appears to be more abundant in shallower than deeper water and more abundant off Louisiana and upper Texas than off lower Texas. The macrobenthos constitutes a major food resource for the demersal fish fauna.

The megabenthos is not sharply distinguished from the demersal fauna, previously discussed. However, five benthic megafaunal species assemblages have been recognized for the Texas-Louisiana coastal waters.

These include the inner shelf (4 to 20 m), intermediate shelf (20 to 60 m), outer shelf (60 to 120 m), and upper slope (120 to 200 m) assemblages, as well as a pro-delta assemblage (4 to 20 m) around the Mississippi River Delta. For each, the environmental correlates and faunal compositions have been provided. Recent studies on the Louisiana upper slope reveal that the megafauna in the 300 to 500 m depth range is distinctly different from that of the previously proposed upper slope assemblage, suggesting a major faunal break in the 200 to 300 m depth range.

The structure-related biota includes those species associated with both natural and artificial hard substrates. The biota of the more prominent natural hard banks of the outer shelf have been studied in some detail. Seven biotic zones are recognized, and these zones are determined by depth in the water column, distance from shore, depth of the nepheloid layer, and related factors. Of particular interest are the well-studied high diversity coral reefs that cap the East and West Flower Garden Banks. No single bank possesses all the zones, but only one zone is missing from the Flower Garden Banks. Many tropical invertebrates and fishes are found in association with the outer shelf banks, and some of these species have not been encountered elsewhere in the area. Numerous smaller banks of the shelf have received little or no attention.

During the past half-century, the availability of anthropogenic hard substrate (particularly on rigs, platforms, and pipelines) has increased dramatically, and such substrate now provides a surface area of at least 40 km^2. This newly available habitat has been colonized by a great many species which together constitute a significant ecological system in its own right. Included are the attached biofouling mats, mat-associated organisms, and mobile species of the water column that are attracted to the structures. Species composition and biomass of the biofouling mat vary in relation to depth in the water column, distance from shore, and distance along the coast from the Mississippi River Delta. Inshore, the mat may be up to 12 cm thick and weigh up to 15.5 kg/m^2, whereas well offshore it is only 2 to 4 cm thick and weighs 1 to 5 kg/m^2. Sessile barnacles dominate inshore, bivalves are most common toward the outer shelf, and stalked barnacles dominate in oceanic water. Marine algae are limited to the euphotic zone, and in the aphotic zone hydroids, anemones, bryozoans, and tunicates are most important. In addition to the mat species, large populations of invertebrates and fishes and some sea turtles find food and haven around the structures. Many of these are also associated with the natural hard banks.

Fourteen species of marine vertebrates of the area are officially recognized as threatened or endangered. These include five species of marine turtles, three species of birds, the West Indian manatee, and five species of great whales. However, exclusive of the birds, only three species are considered to be at all common: the loggerhead and Kemp's ridley sea turtles (which may be found around rigs and banks) and the great sperm whale (which often occurs over the outer shelf and upper slope). Major threats include habitat loss and general disturbance along the coasts (sea turtles and birds), organochlorine pollutants (birds), plastic wastes (sea turtles and marine mammals), and major oil slicks (sea turtles, birds, and whales). Noise and underwater explosions may cause special problems for sea turtles and marine mammals.

In general terms, biologically sensitive areas of the Louisiana/upper Texas coastal waters include species spawning grounds, tidal passes, reefs and hard banks, areas associated with the mouths of rivers, and habitats of rare shelf species. In specific terms, only the Flower Garden Banks have been identified as being particularly important and sensitive. However, no specific search has been made. Potential candidate sites include Mississippi Delta environments, Mississippi Canyon environments, oozy bottoms off Louisiana, and "hill and valley" areas of the outer shelf and upper slope.

8.2.3 Socioeconomics

About 40% of the nation's commercial fish landings and one-third of the marine recreational fishing activity are concentrated in the Gulf of Mexico, and much of this occurs on the Texas-Louisiana continental shelf. The commercial shrimp fishery annually lands about 65 million pounds of brown and white shrimp, which provides the greatest dollar value catch. The finfish fishery has traditionally relied almost exclusively upon the menhaden and several species of the drum family, all estuary dependent. During the 1980's, however, the fishery has expanded with a threefold increase in the number of major species landed. The annual dollar value of the finfish catch now exceeds $84 million, distributed as follows: menhaden--65%, tuna--14%, drums--10%, snappers--5%, swordfish--2%, and the remaining species--about 4%. During the past 15 years, there has also been a major expansion of the marine recreational fishery, with much of this concentrated around the rigs and platforms.

About 90% of the nation's offshore oil and gas is derived from the Gulf of Mexico, primarily from the Texas-Louisiana shelf. During the period 1977 to 1986, this area has produced about 19.5 billion barrels of crude oil and 385 trillion cubic ft of natural gas. During the late 1970's and early 1980's when oil prices ranged from $30 to $46 per barrel, exploration, development, and production reached all-time highs, but since 1986, when oil prices dropped to less than $20 per barrel, the industry has been at low ebb. The oil and gas industry has a good safety record. During the period 1970 to 1979, with around 2,000 structures operating, oil spills averaged only about 11,000 barrels per year (5.5 barrels per structure).

Considerable commercial shipping traffic enters and leaves northern Gulf ports. During 1986, almost 260 million tons of cargo crossed the docks of ports from New Orleans to Corpus Christi, 60% of which was associated with the four major ports (New Orleans, Houston, Gramercy, and Corpus Christi). Much of this cargo was crude petroleum or petroleum products.

The three main marine-related industries of the area (fishing, oil and gas, and shipping) all generate derivative activities in terms of services, supplies, sales, housing, recreation, etc. and thus play a larger role in supporting the economy of the coastal region. It is also clear that these industries are generally compatible with each other and with the natural environment. For example, the heaviest concentrations of commercial and recreation fishing activities are associated with the areas of greatest oil and gas production. Chemical and trash pollution is a continuing problem, but this has not so far resulted in dramatic environmental degradation.

8.3 DEFINITION OF MAJOR ECOSYSTEMS

The major ecological systems of the Texas-Louisiana continental shelf and upper continental slope are presented in Table 8.1 and diagrammed in Figure 8.1. Three basic systems are recognized: the water column, soft-bottom benthic, and hard substrate, structure-related systems. Between these basic types there are transitional systems. Two subsets of each of the major systems are recognized. For the water column system, there are the coastal and the oceanic subsystems. For the soft-bottom benthic system, there are the continental shelf and upper continental slope subsystems. For the hard substrate, structure-related system, there are the natural substrate (hard bank) and artificial substrate subsystems. The general components of each of the major systems are presented in Table 8.1 and have been discussed in some detail in the preceding sections.

The Texas-Louisiana shelf and upper slope area can be viewed as a simple, two-dimensional environmental gradient extending westward along the coast (increasing distance from the Mississippi River discharge) and seaward (increasing water depth and distance from shore). One extreme is in shallow water along the Mississippi River Delta and the other is in deep water at the southwest corner of the area. Although this may be an oversimplified picture, everything that exists or occurs in the area can be interpreted within this general context. It recognizes the overriding importance of the Mississippi River influence as well as the major influences flowing from the low salinity, highly productive Louisiana coastal bays and estuaries. It takes into account natural changes in the water column and benthic environments associated with depth and distance from shore. It recognizes the importance of the transition from continental to oceanic control of ecosystem composition and dynamics. The components of all the major biological systems appear to reflect this double gradient.

However, one cannot classify the systems on the basis of the gradient fields. Whereas the Mississippi Delta environment is somewhat different from that of most of the Louisiana and upper Texas shelf, and that, in turn, may be distinct from the environment off south Texas, not enough information is currently available to define each of these regions in detail or to resolve boundaries, if they exist. In our present state of knowledge, it is most logical to assume that these are continuous gradients.

Transitional systems are extremely important in the area. The widespread nepheloid layer is clearly a transition between the water column and the benthos, and some of the bottoms are so soupy that the bottom surface boundary is almost indefinable. Most of the hard surfaces are subject to sedimentation, and the sediment layer, in some

Table 8.1. Major ecological systems, subsystems, and components of the Texas-Louisiana continental shelf and upper continental slope.

Major Systems	Subsystems	Components
A. Water column system	1. Coastal waters	Phytoplankton
		Zooplankton
	2. Oceanic waters	Neuston
		Nekton
B. Soft-bottom benthic system	1. Continental shelf	Meiofauna
		Macrofauna
	2. Upper continental slope	Megafauna
		Demersal fauna
C. Hard substrate, structure-related system	1. Natural substrates	Hard bank biota
		Biofouling mat
	2. Artificial substrates	Niche fauna
		Structure-associated fauna
D. Transitional systems	Combinations of the above	Mixtures and combinations of the above

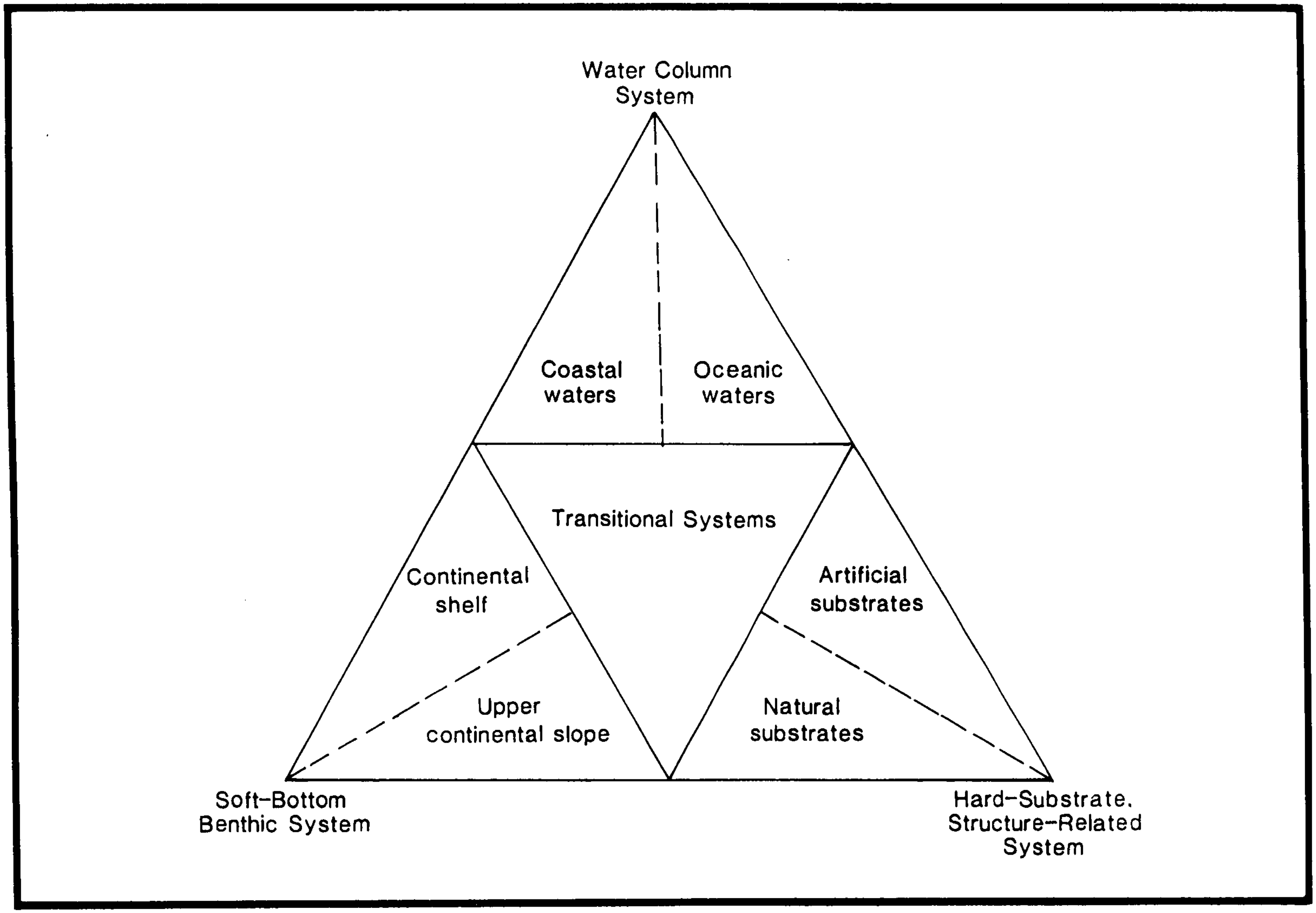

Figure 8.1. Conceptual diagram of the major ecological systems of the Texas-Louisiana continental shelf and upper continental slope.

cases, may be heavy enough to discourage settlement by sensitive fouling species. Whether or not such surfaces support significant meiofaunal and macrofaunal communities has not been determined. Pelagic fishes, normally considered inhabitants of the open water column, often congregate around hard surface structures and become significant elements in the extended fauna of hard surfaces. All of these transitional communities exist in a dynamic relationship that varies over time.

8.4 HUMAN INFLUENCES ON THE CONTINENTAL SHELF

Before proceeding with a discussion of oil and gas related activities and effects, we will briefly review human influences on the continental shelf. The purpose is to provide context and perspective for the discussion that follows.

The emphasis in this section is on human activities other than oil and gas operations. However, oil and gas development is such an integral part of the coastal and marine environment off Texas and Louisiana that many of the activities discussed are related in some way to the petroleum industry.

8.4.1 Onshore Activities

Numerous shore-based human activities can influence coastal and marine environments. These can be divided into inland activities, shoreline construction, and dredging and channelization. The two most significant consequences of these activities are the destruction of coastal wetlands and the addition of nutrients, trace metals, pesticides and other synthetic organic compounds, and suspended particulate matter to the river effluent. Loss or degradation of coastal wetland habitat is important because many species of fishes and invertebrates on the continental shelf depend on the estuarine wetlands at some stage of their life cycle. Addition of pollutants to the river effluent is also important because the Mississippi River outflow has a substantial influence on the physical and chemical characteristics of the Texas-Louisiana continental shelf.

Inland Activities

The inland activities that have the most profound influence on the continental shelf include various types of construction, as well as agricultural, industrial, and municipal development. All of these activities modify the inland streams, and the effects accumulate downstream in the effluent that enters the marine environment.

The environmental effects of upstream construction have been discussed in detail by Darnell (1976). Examples of upstream construction are dam building and impoundment, channelization and stream straightening, leveeing, and floodplain construction. The cumulative results of upstream construction activities include modification of normal streamflow patterns and alteration of the dissolved and suspended loads.

The effects of agriculture include reduced stream flow (especially during dry years when more water is retained for irrigation), increased sediment load due to erosion, and increased concentrations of nutrients and pesticides in waters entering the marine environment.

Industrial uses of rivers and streams also modify the waters flowing into the marine environment, primarily through the addition of industrial chemicals, including heavy metals and synthetic organic compounds.

Shoreline Construction

The effects of minor shoreline structures have been discussed by Darnell (1976) and Mulvihill et al. (1980). Various types of engineering structures are built to protect shorelines from erosion and to protect harbors and shipping channels from shoaling. These include seawalls, revetments, breakwaters, and groynes. Their emplacement can result in loss of local beach and shoreline habitat. Biological effects stem mainly from local habitat loss along the shoreline. These hard surfaces and steep slopes can also intensify the scouring effect of storm waves and result in destruction of nearshore submerged habitats.

Dredging and Channelization

Much has been written about the biological and environmental effects of dredging, spoil placement, and channelization. Among the most pertinent references are Cronin et al. (1971); Darnell (1976); Massoglia (1977); Morton (1977); Mumphrey and Carlucci (1978); Mulvihill et al. (1980); and Pequegnat et al. (1980). There is also a great deal of literature on the more general topic of wetland loss in Louisiana (with dredging and channelization as contributing factors). Pertinent references include Boesch (1982); Louisiana Wetland Protection Panel (1987); and Turner and Cahoon (1988). Much of the dredging and channelization that occurs in coastal Louisiana is associated with oil and gas pipelines (Boesch and Robilliard, 1987).

Major problems arise in connection with both the dredging itself and the disposal of the dredged material. Problems tend to be greatest in bays and estuaries, where the main concern is the loss of nursery habitat. Dredging in coastal marshlands and submerged vegetation beds directly destroys prime nursery areas. Marshland channels and canals can rapidly erode and widen, leading to further wetland loss. Circulation in these channels is often poor and oxygen demand high, leading to hypoxia. Creation of deep holes or channels in open-water estuarine habitat also leads to poor circulation, which may result in hypoxia. In addition to creating the potential for hypoxic conditions, channels facilitate the intrusion of salt water well up into the estuary.

The spoils from dredging operations are often placed either in coastal wetlands as spoil banks, or on the continental shelf. In either case, the main concerns are direct effects of burial and habitat destruction. In coastal areas, poor placement of spoil banks can alter circulation patterns, resulting in mortality of estuarine populations. On the shelf, more widespread effects may also occur through the distribution of resuspended fine sediments by currents. A special problem arises in connection with the disposal of dredge spoil from highly industrialized coastal waters such as the Houston ship channel, where bottom sediments contain high concentrations of heavy metals and organic pollutants. Such materials require special disposal areas, and they cannot simply be placed back into the estuary as run-of-the-mill spoil banks.

Other potential problems are associated with the construction of proposed cross-shelf channels. To accommodate deep-draft vessels, channels have been proposed across a third of the width of the Texas-Louisiana continental shelf. For some of these channels, enormous volumes of sediment would have to be moved. The spoils from these dredging operations must be placed somewhere nearby in order for such a project to become economically feasible, and wherever they are placed there will be major habitat damage due to the faunal burial in the immediate dumping grounds and to the later widespread distribution of fine sediments by the water currents. Across-shelf channels are subject to shoaling and would require frequent maintenance, creating a chronic shelf disturbance problem. These channels could also represent potential barriers to migrating fishes, shrimp, crabs, and other marine life, but the severity of this problem cannot be assessed on the basis of available information.

8.4.2 Offshore Construction

The major construction activities on the continental shelf are the installation of drilling rigs, platforms, and pipelines. These topics, as well as the construction of moorings and offshore ports, are oil and gas related, and are discussed in Section 8.5. Here, we discuss the more general topic of placement of artificial reefs on the shelf.

There are two main consequences of construction activities on the continental shelf: seafloor disturbance (during installation and removal of structures) and the attraction of fish and invertebrates to the submerged structure. The latter is an intentional effect in the case of permitted artificial reefs, but an incidental one for other structures.

Artificial reefs are defined as all large areas of hard substrate placed on the continental shelf, intentionally or otherwise, through human activities. Included in this category are drilling rigs and platforms, pipelines, former dump sites (for construction materials, munitions, etc.), shipwrecks, and designated offshore artificial fishing reefs. There are three small areas of military ordnance disposal along the upper continental slope in the study area (see Figure IV-5 in the EIS for Sales 113/115/116 [USDI, MMS, 1987b]); the locations of old construction material dumps are not documented. The position of over 200 reported shipwrecks are known (Coastal Environments, Inc., 1977), but most of these have not been investigated. Therefore, this section will deal primarily with designated fishing reefs and unidentified bottom obstructions.

In 1984, Congress passed the National Fishery Enhancement Act, which mandated the development of a national artificial reef plan to be developed under the leadership of the U.S. Department of Commerce and with permitting by the U.S. Army Corps of Engineers. Many individual states already had artificial marine reefs, some dating back many years.

The State of Louisiana has recognized the value of offshore structures in the enhancement of commercial and recreational fishing activities, and the Louisiana Artificial Reef Plan was completed in 1987 (Wilson et al., 1987). Phase I of this plan calls for the development of eight offshore artificial reef planning areas, all in Federal waters, with seven located west of the Mississippi River Delta. In Phase II, additional artificial reef planning areas will be established in State waters. Most of the planning areas in Federal waters are on the middle and outer continental shelf. Materials for reef construction will be determined on a case-by-case basis, but it is likely that much of the primary structure of the Louisiana reefs will be decommissioned petroleum platforms that have been stripped down and placed on their sides. Such reefs will be kept away from shipping fairways, channels, and anchoring areas, placed to allow a minimum of 15 m of water clearance, and appropriately marked and lighted (according to U.S. Coast Guard regulations). By the end of September 1988, two artificial reefs had already been established in Louisiana coastal waters, and an additional reef is scheduled to be established by the end of 1988. The reefs all consist of toppled production platforms (Louisiana Coast Lines, October 1988).

The development of artificial reefs off Texas has been discussed by Shepard (1974) and Futch (1981). During the late 1950's, the Texas Fish and Game Commission constructed reefs of car bodies (loosely bound together), which were placed 10 to 16 km offshore in about 20 m of water off Freeport, Port Aransas, and Port Isabel. These reefs were destroyed by Hurricane Carla in 1962. New reefs were built of concrete and clay pipes off Galveston and Port Aransas in 1962 to 1963, and these have persisted. In 1968, several steel barges were added to the Port Aransas site, and a second such reef was constructed of barges farther offshore. Between 1972 and 1976, twelve Liberty ships were sunk between 13 and 58 km offshore. Thereafter, a few small reefs of used tires have been placed in nearshore areas. As a result of all this activity, there are now seven permitted artificial fishing reefs off the Texas coast, four of which are between Matagorda Bay and the Louisiana border, but only three of these lie in Federal waters (USDI, MMS, 1983a, Visual No. 4-II). Currently, there is no formal State program in Texas, and an official State Artificial Reef Plan has not been developed.

The direct, negative effects of these artificial reefs are relatively minor. There can be some local destruction or alteration of the existing bottom habitat at the artificial reef sites. Furthermore, some of the materials can break apart and shift around, as happened with the early Texas car-body reefs. Some temporary leaking of heavy metals (through corrosion of metals) and other chemical pollutants may occur.

A potentially more serious problem associated with the artificial reefs is mounting fishing pressure that could lead to the depletion of certain reef fish stocks. Also, the increased traffic of small boats carrying recreational fishermen magnifies the possibility of marine accidents and adds to the proliferation of garbage, trash, and other wastes in the ocean (see Section 8.4.6).

On the positive side, the artificial reefs support rich communities of biofouling species and attract a rich variety of fishes, including major food and game species. These are supported, in part, by the biofouling communities, leading to greater local fish production. This, in turn, creates the opportunity for increased offshore recreational and commercial fishing activities of types and magnitudes that would be unavailable in the absence of the structures.

There are positive ecological and biogeographic implications, as well, although these have not received adequate study. It is likely that the dense algal mats increase local primary production, and it is certain that the attached algae establishes primary production in a form more usable by the grazing species. Attached filter feeders, such as hydroids, likewise produce major crops and trap marine plankton which together also aid in supporting the grazing fishes and invertebrates. Many new ecological niches are created in the fouling mat for small motile invertebrates and fishes. Periodically, heavy biofouling growth falls to the bottom, opening up new hard substrate habitat for colonization and successional development, and adding to the benthic food resources. The existence of the biofouling community thus creates a greater ecological diversity in a formerly monotonous environment, and it allows for the persistence of species representing all stages of ecological succession. Many of the more mobile fish species were formerly unknown or considered rare in the area, but these are now attracted in quantity and held by the structures and the rich local food resources.

8.4.3 Mineral Extraction

Oil and gas are the most obvious and economically important mineral resources currently being exploited on the continental shelf, and the effects of oil and gas extraction are explored in Section 8.5. There is also some mining of sand, shell, gravel, and sulfur in the study area, as discussed below.

Sand, Shell, and Gravel Mining

Sand, shell, and gravel are surface mineral resources of great economic importance. Sand is used for coastal land fill, and both sand and gravel are used extensively in various construction industries. Shell is used in construction, either as a substitute for gravel or for the manufacture of cement, and it provides a source of lime for the chemical industry. Because shell has a high aragonite content, it is widely used as an additive in chicken feed to enhance egg shell production. Currently, these minerals are taken in quantity by dredges working primarily in coastal bays and estuaries, where the materials are either loaded onto barges or piped ashore. Although the surface mineral resources of the outer continental shelf are considerable, the development of these resources is, at present, uneconomical.

The effects of dredging and removal of sand, shell, and gravel have been described by numerous authors, including the Louisiana Wildlife and Fisheries Commission (1968), Dolan (1972), May (1973), Bouma (1976), Darnell (1976), Mulvihill et al. (1980), and Sikora et al. (1981). Most of the literature deals with effects in bays and estuaries, but attention here is directed toward potential effects on the continental shelf. In operation, the dredge cuts a wide swath through the bottom in advance, removes the coarse-grained sand, shell, or gravel and washes it, and then deposits the unwanted fine sediments behind. If a valuable pocket of shell or gravel is encountered, this is removed to some depth leaving a deep hole. Several dredges can cover a considerable surface area in the period of a year.

Problems stemming from these dredging operations are numerous and can be severe. There is total destruction of the bottom fauna of all size classes in the path of the dredge. The dredge leaves a trench punctuated with deep holes in its wake. Washing of the coarse material creates enormous clouds of highly turbid water containing fine sediments that can contribute to the nepheloid layer, although the use of sediment curtains can reduce the extent of this effect. Over large areas, the formerly coarse-grained bottom becomes overlain with a carpet of fine sediments that settle as a thin clay gel. This sediment type cannot readily be invaded by meiofauna, and it is too soft to support significant development of macrofauna such as mollusks, which sink into the bottom and suffocate. Thus, the bottom can become essentially sterile of food resources for the demersal fauna. The rate of recovery depends upon the rate at which strong bottom currents can replace the gel with coarser sediments. In trenches and holes that are protected from strong currents, full recovery may require many years. Heavy metals and other chemical pollutants, formerly locked in the bottom sediments, become mobilized in the water column and may enter into the marine food chain.

Dredging in front of beaches creates special problems. Here the protective bars and shoals are removed, and the nearshore bottom gradient is steepened. This leads to greater wave impact on the shoreline and hastens beach erosion. This effect becomes particularly severe during storms.

Sulfur and Salt Mining

At present, sulfur mining is active in state waters off Grande Island, LA, but none is going on in Federal waters of the continental shelf. However, there is active interest in developing the offshore sulfur resources, and a lease sale was held in February 1988. Development of the lease is planned for the near future.

Sulfur deposits occur atop some salt domes within and below the cap rock. Large amounts of salt are required for extraction of the sulfur, and this is obtained by solution mining of the salt diapir itself. Diapirs are located by seismic profiling, and then extensive test drilling is carried out to map the distribution and concentration of sulfur in the ore body. During development, wells are drilled from platforms, and a given platform may have up to 60 wells. The extraction process (Frasch process) involves melting the sulfur with concentrated brine heated to a temperature of 163°C and then boosting the molten sulfur through pipes to the surface with compressed air. Once at the surface, the molten sulfur is pumped into barges and transported to shore for storage. Brine for the process is obtained by mixing locally extracted salt with seawater, and this is heated by natural gas piped from shore. Production of a ton of sulfur requires 500 to 7,000 gal of brine. Through a series of bleed wells located around the periphery of the ore body, waste brine mixed with ancient seawater is collected and sprayed onto the surface of the ocean (to dissipate the heat). As sulfur is removed, a massive underground cavern is created, and the overlying rock mass may collapse. This may result in significant surface subsidence, which can cause major or minor structural damage to platforms, wells, and pipelines. Therefore, extensive safety features and procedures are incorporated into the structures and operations.

Development of subsurface sulfur and salt resources is similar in many respects to the development of oil and gas deposits (USDI, MMS, 1987c). Similarities include the seismic survey, construction-related activities (platforms, rigs, pipelines, etc.), drilling and disposal of drilling muds and fluids, dredging of navigation channels, increased ship traffic, minor platform discharges, and disposal of sanitary and domestic wastes as well as trash and debris. The environmental consequences of these activities are discussed in relation to oil and gas operations and will not be repeated here. Due to the small scale of the sulfur-related activities, the environmental effects are localized, and in the large picture, negligible. Of particular concern in sulfur and salt mining, as in the development of oil and gas deposits, is the possibility of a catastrophic blowout due to encountering shallow deposits of high pressure gas. Although most blowouts occasion only minor consequences, the possibility of major damage (including rig collapse, fire, and loss of human life) cannot be ruled out.

Certain activities are specific to the sulfur industry, including the discharge of large volumes of heated brine, accidental sulfur spills, and surface subsidence. Bleedwater containing heated brines, sulfides, and some innocuous chemical additives is sprayed into the air above the surface of the sea. Minor local modification of the temperature and chemical composition of the seawater occurs, but due to dilution, the effect is negligible within a few hundred feet of the platform. Elemental sulfur is a chemically inert substance which, if placed into the sea, would have only minor environmental effects, and these would be mostly physical rather than chemical. Molten sulfur discharged into the sea (through pipe breakage or the sinking of a loaded barge) would have a dramatic but very local effect on water temperature.

Of more concern is the possibility of surface subsidence due to collapse of subsurface caverns created by sulfur and salt extraction. Historical subsidence (over time) has been as great as 20 m, with an average of about 12 m. Although most subsidence is gradual, it can be catastrophic, resulting in major damage to drilling pipelines and surface structures and danger to human life. Built-in safety features and emergency procedures minimize, but do not eliminate, this hazard.

In summary, the two major dangers associated with sulfur and salt extraction are the hazards associated with blowouts and surface subsidence. From an environmental standpoint, the effects are quite localized, and habitat damage is temporary.

8.4.4 Biological Harvesting

About 40% of the nation's fishery landings and one-third of the recreational fishing activities occur in the northern Gulf of Mexico. However, little direct information is available concerning the effects of these activities on the environments or the biota. The discussions that follow will focus attention on three issues: (1) effects on the environment; (2) effects on the target species; and (3) effects on non-target species and the broader ecological systems.

Trawling

Most of the bottom trawling in the northwestern Gulf of Mexico is directed toward the capture of brown and white shrimp, but some trawling for industrial bottom fishes occurs off Louisiana. Although statistics on trawling effort are not available, the average annual yield of these two shrimp species from 1981 through 1987 was about 65 million pounds (see Chapter 7). Brown shrimp made up about 60% of the catch. Most of the white shrimp landings were off Louisiana, but the brown shrimp catch was more evenly divided between Louisiana and Texas. These figures provide some idea of the magnitude of the trawling effort.

Darnell et al. (1983) discussed the effects of bottom trawling on the environment. Nets and trawl doors scour the bottom and raise trailing clouds of fine sediments. Phosphorus and other nutrients in the sediments are released into the water column, temporarily increasing fertility, and some pollutants may also be resuspended. Over time, extensive trawling may spread fine particulates over the coarser-grained sediments of the central shelf area, thereby reducing the areal extent of this habitat type. The clouds of fine sediments probably contribute significantly to the nepheloid layer.

There is no evidence that the enormous harvest on the Texas-Louisiana shelf has damaged either the brown or the white shrimp populations. However, in order to reduce the waste of catching undersized individuals, early summer closed seasons have been instituted for the lower Texas coast (Matagorda Bay to Brownsville) during each of the last seven years.

The spatial and temporal distribution of the non-target fish and shrimp catch by bottom trawls on the northwestern Gulf shelf has been documented by Darnell et al. (1983). Most of the trawlable demersal species are characterized by high fecundity and short life histories, and despite the heavy pressure, there is no evidence that these demersal species have been damaged by trawling activities. The absence of evidence does not mean that there are no effects; the subject simply has not been investigated in detail. The longer range genetic consequences of such heavy "predation pressure" are unknown, as are the potential and possibly subtle effects on the ecosystem. Most of the non-target species are sorted out on shipboard and returned to the water, where they become food for the scavengers.

Effects of fishing gear on sea turtles is of special concern. Death by drowning in shrimp trawls is recognized as a severe problem, and the use of turtle excluder devices on all bottom trawls has been mandated by the National Oceanic and Atmospheric Administration.

Another problem relates to the red drum. Highly sought after to make "blackened redfish" and other haute cuisine, this species is now being taken in large quantities by a variety of gear, including trawls. Unfortunately, this is not a highly fecund, short-lived species, and the capture of too many reproductive adults can quickly endanger the future of the species. The recent heavy fishing pressure on the adults has resulted in the establishment of total catch limits, size-class restrictions, and long closed commercial seasons. It has been determined that a 20% escapement of young from the estuaries to the offshore waters is necessary to maintain the population, and regulations have been established to lower catch limits and increase size limits to increase the survival of nonreproductive stock.

Purse Seining

In the northwestern Gulf of Mexico, most purse seining takes place in nearshore waters of the Louisiana continental shelf. Historically, this has been targeted at a single species, the Gulf menhaden, although in the past few years, purse seines have been used to capture red drum as well (this is now outlawed). The menhaden is the second most valuable fishery resource of the northern Gulf (after penaeid shrimp), and annual catches during the period 1982 to 1986 were about 1.5 billion pounds, with dollar values of $53 to 67 million (see Chapter 7). The menhaden is a schooling, pelagic, plankton-feeding species that is taken in the water column, and there are no known environmental effects associated with its capture. The species is short-lived and very fecund, and as long as there is a significant breeding stock left, there appears to be no danger to the species. Christmas et al. (1960) reported on the non-target species catch of the menhaden fishery in the northern Gulf and listed 62 non-target species, which together constituted less than 3% of the total catch. The effect on the non-target species appears to be minimal. The effects of the total fishery on red drum populations has been discussed earlier.

Long-Lining and Bottom Hook-and-Line Fishing

As discussed in Chapter 7, catch statistics reveal a dramatic shift in Texas-Louisiana landings during the past seven years. This change is probably due in large measure to the development of a long-line fishery and expansion of the commercial bottom and water column hook-and-line fishery. In 1981, commercial landings were given for only 29 species, whereas 87 species were listed for 1987. Newly prominent on the list are swordfish, bluefin and yellowfin tuna (which are taken by long-lines) and vermilion snappers, groupers, amberjacks, and king mackerels (which are taken by hook-and-line, either near the bottom or up in the water column). During this period, the red snapper catch doubled, and the finfish catch, other than menhaden and red snapper, increased five-fold. As early as 1965, Iwamoto discussed the potential for a long-line tuna fishery over the outer shelf and upper slope of the northern Gulf, and development of luminous "light sticks" has enabled fisherman to take swordfishes in deeper waters. The success of recreational fishermen around the drilling rigs and platforms has apparently led the way for expansion of activities by commercial hook-and-line fishermen.

Environmental effects of these operations are unknown. If there are new fishermen involved, then there could be an increase in boat traffic. If former shrimpers have switched to hook-and-line fishing, there may now be less bottom scouring by trawls and reduced pressure on the demersal species. In either event, there is probably more local anchor damage now, and there may be a greater accumulation of fishing line on the bottom around the various structures, which can entangle sea turtles and other bottom animals. Effects on the target species are difficult to assess, but in most cases the stocks are probably able to withstand the current pressure. However, most of the species now being targeted are long-lived and have relatively low reproductive rates (for example, the swordfish and tunas). If the populations of these species are small, the fishery may not be sustainable. Adult groupers are known to be reef-faithful, and without appropriate regulation of the catch, it is conceivable that the adult breeding stocks could be severely damaged by heavy fishing pressure. The same applies, to a lesser extent, to the red and vermilion snapper populations. Effects on non-target species are probably very low.

Recreational Fishing

Approximately one-third of the nation's marine recreational fishing takes place in the Gulf of Mexico, and the activity has been expanding greatly in recent years. It has been estimated that about 20 million fishing trips take place every year in the Gulf, and in 1985 about 145 million fishes were caught by recreational anglers. Much of this activity is centered off Louisiana and east Texas, and relevant information is found in the following references: Ditton and Graefe (1978), Lopez and Pristas (1982), Ditton and Auyong (1984), U.S. Department of Commerce (1986), and Witzig (1987). Considerable recreational fishing takes place from shore or within State waters, but offshore fishing is also actively pursued from party/charter boats as well as private and rented craft. In nearshore waters, anglers typically seek estuary-related species, particularly members of the drum family including sand and spotted seatrouts, Atlantic croaker, and red drum.

Much recreational fishing activity takes place around offshore rigs and platforms, and this effort has been documented by Ditton and Graefe (1978), Ditton and Auyong (1984), and Witzig (1987). For Louisiana residents, 37% of the marine fishing trips are to rigs and platforms, with the peak intensity in March and April. For Texas residents, 28% of the trips are to the rigs and platforms, with peaks in September and October. For the two states combined, 70% of the fishing trips 3 miles or more from shore go to the offshore structures, indicating angler preference for rig fishing. Near the rigs and platforms, 80% of the catch (exclusive of marine catfish) is composed of red snapper, sand seatrout, and Atlantic croaker, whereas away from the structures, 70% of the catch is made up of round scad, grunts, and snappers.

In addition to bottom fishing activities, many anglers seek their quarry in the water column by still-fishing from party boats or by trolling. Here, the catch is composed of a variety of pelagic species including tarpons, cobias, dolphins, amberjacks and other jacks, little tunnys, and billfishes. Lopez and Pristas (1982) reported the results of billfish trolling by boats out of Grande Isle, LA in 1982. During 3,092 h of trolling effort, the boats hooked 79 blue marlin, 73 white marlin, and 5 sailfishes. Except for the increased small boat traffic, anchoring, and over-the-side trash disposal, there appear to be no significant effects of the recreational fishery on the environment, target species, or the ecosystem.

8.4.5 Ship Traffic

From the standpoint of ship and boat traffic, the Texas-Louisiana coast is a very busy area, and directly or indirectly, much of the traffic is associated with the offshore rigs and platforms.

Information concerning waterborne traffic and commerce involving the ports and waterways of the northern Gulf coast in 1984 is available in U.S. Army Corps of Engineers (1986b). During the 12-month period, almost 160,000 passages were recorded, with about 53% of the total passing through Texas ports. This is an average of about 435 boat passages per day. Inbound and outbound traffic was approximately equal. Almost 40% of this traffic flowed through the Sabine River Channel, followed by Calcasieu River, Galveston Harbor, and the other waterways. These ships carried a combined total of about 300 million tons of cargo. Although a variety of cargo materials was transported, by far the largest bulk cargo was crude petroleum, with petroleum-related materials also constituting a large percentage of the total load. Much of the traffic of smaller vessels apparently consisted of work boats servicing the offshore rigs and platforms. To the above totals should be added the smaller commercial and recreational fishing boats whose passage is not included in the above statistics.

Although there are specific regulations that apply to vessels operating in coastal waters, enforcement at sea is virtually impossible. Considering the volume of ship traffic, the density of rigs and platforms, and the often heavy seas, even the most careful and conscientious boat crews could be expected to generate a fair amount of fuel spillage and leakage, to create a great deal of subsurface noise, and to become involved in occasional accidents. However, without enforcement these problems become magnified, and to these should be added the deliberate discharge of bilge washings, domestic wastes, garbage, trash, and other solid and semi-solid refuse.

Ship traffic can have a wide range of influences on the shelf environment and biota (see further discussion in Section 8.5 under oil and gas activities). Chronic spillage of hydrocarbons, bilge washings, and domestic wastes simply adds to the mounting chemical pollution of continental shelf waters. Occasional major accidents of ships running into each other, colliding with rigs or platforms, or damaging pipelines with their anchors creates the hazard of more widespread effects associated with major spills of petroleum and other chemicals. Cumulatively, the general noise and disturbance from heavy ship traffic can interfere with orientation, feeding, migration, and spawning of various marine species, particularly sea turtles and cetaceans. Occasional collisions of ships with marine mammals and sea turtles are known to occur.

8.4.6 Dumping of Trash and Debris

The dumping of trash and debris in marine waters from boats, ships, and offshore platforms is becoming a very serious problem. The trash and other refuse causes a variety of effects, depending upon the nature of the materials. Plastic sheeting, bags, and other such refuse have been directly implicated in the deaths of sea turtles and cetaceans. Non-floatables pollute the bottoms where they land, and non-degradable plastics and other such materials are swept widely around the shelf by bottom currents. Vast quantities of floatable materials ultimately wind up as debris on the beaches lining the northern Gulf coast.

Two studies of beach litter are relevant. In September 1987, the Louisiana Geological Survey organized a one-day Statewide beach clean-up to determine the quantity, nature, and probable sources of the beach litter (Louisiana Department of Natural Resources, 1988). Approximately 3,300 volunteers filled 16,000 bags with an estimated 798,000 pieces of trash. This was composed of plastic (63%), metal (13%), glass (12%), and other materials (12%). The five most common items in order were styrofoam drinking cups, pieces of styrofoam, plastic cups and lids, milk jugs, and plastic bags. An estimated 85,000 styrofoam cups, 71,000 soft drink cans and bottles, 50,000 beer cans and bottles, and 31,000 milk and water jugs were collected. Likely sources of the litter include the offshore oil and gas facilities, shrimpers, commercial and recreational fishermen, merchant ships (some of the items were of foreign origin), daily beach users, and local residents. A small fraction (2 to 4%) was definitely linked to the offshore oil and gas industry (55-gallon drums, write-protect rings, pipe-thread protectors, industrial-size supplies, work vests, hard hats, etc.), and other items were likely associated with oil and gas activities (drink containers, food trays, work gloves, plastic bags, rope, etc.).

The second relevant study is the litter survey and clean-up of about 90 km of beach in the Padre Island National Seashore in 1985 (USDI, MMS, 1986). In the March survey, it was estimated that there were about 142 tons of litter on the beach, of which 40 tons were related to the oil and gas industry. In the August survey, it was estimated that the beach contained 253 tons of litter, of which 130 tons were oil and gas related. Of great concern was the presence of 306 30- to 55-gallon drums at various stages of decomposition, and 56% of these contained hazardous chemicals. The cost of pick-up, storage, and handling of the drums averaged $1,125 apiece, but the potential dangers for marine life and human users of the beach was considered far greater than the clean-up cost. The incidence of large drums on the beach has steadily decreased since 1986. However, despite laws and regulations, a cure is not in sight for this increasingly serious problem.

8.4.7 Recreational Diving

Recreational diving occurs regularly around some of the nearshore drilling rigs, platforms, and artificial fishing reefs, and irregularly around the Flower Garden Banks. The only significant environmental effect from the diving activities around the rigs, platforms, and fishing reefs is the removal of certain species by spear fishing. There is some indication that the red snapper, jewfish, and black grouper populations of the northern Gulf are already over-fished, and this could soon be true for other reef-faithful species.

Recreational diving can create several problems at the Flower Garden Banks. Anchoring of boats on the high diversity reef can cause extensive damage to the corals and other sessile fauna. Several instances of apparent damage from anchors, cables from mooring buoys, or other diving-related activities were noted in the Bureau of Land Management surveys of these banks by Texas A&M University researchers (e.g., Bright et al., 1976; Bright and Rezak, 1978a). Effects of a specific anchoring incident (though not connected to recreational diving) were documented by Continental Shelf Associates, Inc., (1984). At this site, the major concentration of red snappers is too deep to be reached effectively by scuba divers, but some spear-fishing does occur. Also, specimens of some of the attractive marine life (corals, mollusks, etc.) are taken by divers as trophies. Any touching or abrasion of the coral heads may cause local damage to the living coral tissue leading to infections. In addition, human intrusion may cause disturbance to the local sea turtle populations.

The scuba diving pressure on the Flower Garden Banks is limited at present due to their relative inaccessibility, but this pressure is likely to increase in the future. No governmental agency is currently monitoring or regulating such activities in this highly sensitive area. However, the Flower Garden Banks are again under consideration for National Marine Sanctuary status. If they are so designated, use by scuba divers would certainly increase, but the effects could be better controlled. Emplacement of mooring buoys would eliminate the anchoring problem, and regulation and enforcement could at least reduce damage to the valuable components of this unique ecological system.

8.5 OIL AND GAS OPERATIONS: ENVIRONMENTAL EFFECT MECHANISMS

In this section, we discuss major pathways of influence of oil and gas activities on the marine environment off Texas and Louisiana. Major information sources are listed in the Introduction to this chapter. We also reviewed major environmental monitoring programs conducted in the northern Gulf of Mexico (see the Appendix).

8.5.1 Phases of Oil and Gas Operations

Oil and gas activities can be grouped into four main phases: Evaluation, Exploration, Development and Production, and Post-Production. Each phase involves a number of activities that may affect the biota and ecosystems of the continental shelf. The phases and major activities or processes that can affect the environment are shown in Table 8.2 (referred to as the "main model"). The table lists major activities and events during each phase, along with their "primary results." These primary results are not environmental effects per se, but rather major factors that can lead to environmental effects. Each primary result is explored further in a submodel that is listed in the right hand column of the table. The 12 submodels (A through L) are presented individually as Figures 8.2 through 8.13.

The four phases are described briefly below, and the primary results for each phase (Table 8.2) are noted. The submodels showing derived effects are discussed in the next section.

Many of the activities discussed below are regulated, either by the MMS, the Environmental Protection Agency, or other agencies. Regulations, permitting, and inspection help to minimize adverse environmental effects. Here we are concerned mainly with describing pathways of effect, rather than evaluating the severity of effects or the effectiveness of regulations. For a discussion of the regulatory context of Outer Continental Shelf (OCS) oil and gas activities, read a recent EIS (e.g., USDI, MMS, 1988).

Evaluation

During the evaluation phase, lease blocks are surveyed with geophysical equipment (e.g., side-scan sonar, subbottom profilers) and sometimes bottom sampling equipment (e.g., corers) in order to evaluate hydrocarbon potential, identify prospective drillsites, and map shallow drilling hazards. The main sources of potential effects are ship traffic and noise (from seismic equipment such as air guns and sparkers) (USDI, MMS, 1984). Geophysical vessels, their trailing gear, and the associated noise may interfere with commercial fishing activities. There may also be some minor, localized seafloor disturbance from bottom sampling.

Exploration

During the exploration phase, one or more wells are drilled to evaluate the hydrocarbon potential of a lease tract. This phase consists of two main groups of activities: drilling rig installation and removal, and routine drilling operations. The main potential sources of effects during routine exploratory activities are boat and ship traffic, seafloor disturbance (mainly from rig installation and removal), noise, presence of structures (drilling rigs, anchor chains, etc.), drilling mud discharges, drill cuttings discharges, other liquid waste discharges (cooling water, desalinization brine, sanitary and domestic wastes, etc.), and release of solid debris. Possible accidental occurrences

Table 8.2. Main model of OCS oil- and gas-related operational phases, activities, and primary results. Derived results are illustrated in submodels A through L.

Operational Phase	Activity/Event	Primary Result	Submodel for Derived Effects
EVALUATION	Geological and geophysical surveying	Boat and ship traffic	A
		Seafloor disturbance	B
		Noise	C
EXPLORATION	Drilling rig installation and removal	Boat and ship traffic	A
		Seafloor disturbance	B
		Noise	C
		Presence of structures	E
	Routine drilling operations	Boat and ship traffic	A
		Seafloor disturbance	B
		Noise	C
		Drilling mud discharges	F
		Drill cuttings discharges	G
		Other liquid waste discharges	I
		Release of solid debris	J
		*Minor spills (e.g., fuel)	K
	Blowout*	*Seafloor disturbance	B
		*Noise	C
		*Release of solid debris	J
		*Major or minor oil spill	K
DEVELOPMENT AND PRODUCTION	Platform installation	Boat and ship traffic	A
		Seafloor disturbance	B
		Noise	C
		Presence of structures	E
	Routine drilling operations	Boat and ship traffic	A
		Seafloor disturbance	B
		Noise	C
		Drilling mud discharges	F
		Drill cuttings discharges	G
		Other liquid waste discharges	I
		Release of solid debris	J
		*Minor spills (e.g., fuel)	K
	Blowout*	*Seafloor disturbance	B
		*Noise	C
		*Release of solid debris	J
		*Major or minor oil spill	K
	Routine production operations	Boat and ship traffic	A
		Noise	C
		Produced water discharges	H
		Other liquid waste discharges	I
		Release of solid debris	J
		*Minor oil spills	K
	OCS pipeline installation and routine operation	Boat and ship traffic	A
		Seafloor disturbance	B
		Noise	C
		Presence of structures	E
		*Minor oil leaks or spills	K
		Dredging and channelization	L
	Moorings and offshore ports	Boat and ship traffic	A
		Seafloor disturbance	B
		Noise	C
		Presence of structures	E
		*Minor oil spills	K
	Pipeline rupture*	*Major or minor oil spill	K
	Tanker/barge accident*	*Major or minor oil spill	K
POST-PRODUCTION	Platform removal	Boat and ship traffic	A
		Seafloor disturbance	B
		Noise	C
		Explosions	D
		Release of solid debris	J
	Platform disposal	Boat and ship traffic	A
		Seafloor disturbance	B
		Noise	C
		Presence of structures	E

*Indicates an accidental event or result. All others are either intentional, or a normal consequence of routine activities.

CAUSES/ SOURCES	PRIMARY RESULT	DERIVED EFFECTS		OTHER SUBMODELS
DIRECTLY RELATED TO OIL AND GAS:		Physical Environment	Seafloor disturbance (anchoring)	B
			Noise	C
• Seismic surveys • Rig, platform construction and removal • Routine drilling and production operations • Pipeline installation • Tanker transport • Moorings and offshore ports	---> Boat and Ship Traffic --->	Chemical Environment	Chronic, low-level pollution (nutrients, trace metals, hydrocarbons, etc.)	
		Biological Environment	Possibility of collisions with sea turtles, marine mammals	
			Possibility of damage to corals on hard banks (anchoring)+	
			Transport of biofouling species	
OTHER SOURCES:		Human Environment	Release of trash and debris	J
• Commercial fishing*			Possibility of collisions with other vessels ---> oil spills	K
• Recreational fishing*			Possibility of damaging/rupturing pipelines ---> oil spills	K
• Scuba diving*			Need for dredging navigational channels	L
			Conflicts with commercial fishing	

*Partly or indirectly related to offshore oil and gas development.
+Effect may be lessened or avoided through existing regulations.

Figure 8.2. Submodel A relating oil and gas activities to the derived effects of boat and ship traffic.

CAUSES/ SOURCES	PRIMARY RESULT	DERIVED EFFECTS		OTHER SUBMODELS
DIRECTLY RELATED TO OIL AND GAS: • Geological sampling • Rig, platform construction and removal • Drilling • Pipeline installation • Anchoring of tankers, support vessels, etc. • Blowout **OTHER SOURCES:** • Commercial fishing (trawling)	---> Seafloor Disturbance --->	Physical Environment	Damage to rock outcrops/hard banks (by anchoring)* Resuspension of bottom sediments Altered seabed topography	
		Chemical Environment	Mobilization of nutrients, trace metals, etc. from resuspended bottom sediments	
		Biological Environment	Crushing, burial, removal of benthic organisms Alteration/loss of benthic habitat Interference with filter feeding (resuspension of sediments)	
		Human Environment	Loss of offshore structures (in the event of a blowout) Damage to pipelines (by anchoring)	

*Effect may be lessened or avoided through existing regulations.

Figure 8.3. Submodel B relating oil and gas activities to the derived effects of seafloor disturbance.

CAUSES/ SOURCES	PRIMARY RESULT	DERIVED EFFECTS		OTHER SUBMODELS
DIRECTLY RELATED TO OIL AND GAS: • Seismic surveys • Rig, platform construction and removal • Routine drilling and production operations • Pipeline installation • Ship traffic • Blowouts **OTHER SOURCES:** • Other ship traffic • Military operations	---> Noise --->	Physical Environment	Propagation of sound waves	
		Chemical Environment	None	
		Biological Environment	Startle response, altered behavior of fishes, mammals, turtles Interference with communication, echo-location (cetaceans) Auditory discomfort or hearing loss (for bursts of noise)	D
		Human Environment	None significant on the OCS	

Figure 8.4. Submodel C relating oil and gas activities to the derived effects of noise.

CAUSES/ SOURCES	PRIMARY RESULT	DERIVED EFFECTS		OTHER SUBMODELS
DIRECTLY RELATED TO OIL AND GAS:		Physical Environment	Noise Shock wave	C
• Platform removal • Blowouts		Chemical Environment	Minor chemical pollution from combustion gases	
	---> Explosions --->	Biological Environment	Mortality or injury to fishes, marine mammals, sea turtles* Auditory discomfort or hearing loss (marine mammals, sea turtles)	
OTHER SOURCES: • Military operations • Artificial reef placement		Human Environment	Possible interference with commercial fishing (disruption of fish schools) Hazard to human life (in the event of major blowout)	

*Effect may be lessened or avoided through existing regulations or permitting and inspection.

Figure 8.5. Submodel D relating oil and gas activities to the derived effects of explosions.

CAUSES/ SOURCES		PRIMARY RESULT		DERIVED EFFECTS		OTHER SUBMODELS
DIRECTLY RELATED TO OIL AND GAS:				Physical Environment	Addition of hard substrate, vertical relief Local changes in flow field ---> scouring of bottom sediments	
• Drilling rig and platform construction • Pipeline installation • Moorings and offshore ports				Chemical Environment	Minor leaching of metals through corrosion of structures	
	--->	Presence of Structures	--->	Biological Environment	Attraction of sessile invertebrates (biofouling species) Attraction of reef fishes and pelagic fishes Benthic enrichment (biological "fallout" from structures) Interference with migrations of demersal species (pipelines) Concentration of biota near contaminant sources	
OTHER SOURCES: • Shipwrecks • Artificial reefs* • Other solid debris				Human Environment	Increased recreational and commercial fishing Possible depletion of some fish stocks (over-fishing) Interference with trawling; gear damage† Hazards to navigation†	

*Partly or indirectly related to offshore oil and gas development.
†Effect may be lessened, avoided, or compensated through existing regulations.

Figure 8.6. Submodel E relating oil and gas activities to the derived effects of the presence of structures.

CAUSES/ SOURCES	PRIMARY RESULT	DERIVED EFFECTS		OTHER SUBMODELS
DIRECTLY RELATED TO OIL AND GAS: • Routine drilling operations	---> Drilling Mud Discharges* --->	Physical Environment	Water column turbidity Local alterations in sediment grain size, mineralogy	
		Chemical Environment	Local, intermittent increases in barium conc. in water column More persistent elevations in conc. of trace metals (mainly barium) in sediments Some release of other contaminants (e.g., hydrocarbons from diesel fuel)	
OTHER SOURCES: • No other sources of drilling muds; however, Mississippi River is major source of fine sediments		Biological Environment	Possible smothering of benthic organisms Altered benthic habitat (sediment grain size) Interference with filter feeding Shading of light-sensitive species (e.g., corals) due to turbidity Possible interference with benthic larval settlement	
		Human Environment	None	

*Effects may be lessened or avoided through existing regulations and permitting.

Figure 8.7. Submodel F relating oil and gas activities to the derived effects of drilling mud discharges.

CAUSES/ SOURCES	PRIMARY RESULT	DERIVED EFFECTS		OTHER SUBMODELS
DIRECTLY RELATED TO OIL AND GAS: • Routine drilling operations **OTHER SOURCES:** • No other sources of drill cuttings; however, disposal of "clean" dredged material is analogous	---> Drill Cuttings Discharges* --->	Physical Environment	Altered seafloor relief, topography (cuttings piles) Altered sediment grain size, mineralogy	
		Chemical Environment	Release of small amounts of trace metals or other contaminants from adhering muds Increase in biochemical oxygen demand	
		Biological Environment	Burial, smothering of benthic organisms Altered benthic habitat (sediment grain size) Attraction of fishes, motile invertebrates to cuttings pile with possible "halo effect" of predation by these animals on surrounding benthic communities	
		Human Environment	None	

*Effects may be lessened or avoided through existing regulations and permitting.

Figure 8.8. Submodel G relating oil and gas activities to the derived effects of drill cuttings discharges.

CAUSES/ SOURCES	PRIMARY RESULT	DERIVED EFFECTS		OTHER SUBMODELS
DIRECTLY RELATED TO OIL AND GAS: • Routine production operations	---> Produced Water Discharges┼ --->	Physical Environment	Local elevation in water temperature	
		Chemical Environment	Local elevation in salinity Local increase of trace metals, hydrocarbons, other organics, and radionuclides Biochemical oxygen demand	
OTHER SOURCES: • Brine seeps* • Brine disposal* (Strategic Petroleum Reserve)		Biological Environment	Reduced fouling community on platform legs Bioaccumulation of metals, hydrocarbons in some platform-associated biota Local depression of benthic fauna (in shallow areas)	
		Human Environment	None	

*Brines similar to produced waters in composition.
┼Effects may be lessened or avoided through existing regulations and permitting.

Figure 8.9. Submodel H relating oil and gas activities to the derived effects of produced water discharges.

CAUSES/ SOURCES	PRIMARY RESULT	DERIVED EFFECTS		OTHER SUBMODELS
DIRECTLY RELATED TO OIL AND GAS: • Routine drilling and production operations • Ship traffic **OTHER SOURCES:** • Other ship traffic (source of some domestic and sanitary wastes, engine oil, etc.)	--> Other Liquid Waste Discharges* • cooling water • desalinization brine • domestic and sanitary wastes • deck drainage -->	Physical Environment	Locally elevated temperature (cooling water) Locally elevated salinity (desalinization brine)	
		Chemical Environment	Small amounts of nutrients, trace metals, hydrocarbons, other contaminants Biochemical oxygen demand	
		Biological Environment	Minimal or no effects	
		Human Environment	None	

*Effects may be lessened or avoided through existing regulations and permitting.

Figure 8.10. Submodel I relating oil and gas activities to the derived effects of other liquid waste discharges.

CAUSES/ SOURCES	PRIMARY RESULT	DERIVED EFFECTS		OTHER SUBMODELS
DIRECTLY RELATED TO OIL AND GAS:		Physical Environment	Altered seafloor relief and topography (debris piles)	E
• Routine drilling and production operations • Routine vessel traffic • Accidents (e.g., blowout, collision)		Chemical Environment	Low-level pollution from corrosion of metals Leakage of toxic chemicals from waste drums	
--->	Release of Solid Debris* --->	Biological Environment	Entanglement of marine mammals, sea turtles, fishes (e.g., with fishing line, plastic six-pack rings, netting, etc.) Mortality of marine mammals, sea turtles, fishes through ingestion of debris (e.g., plastic bags, styrofoam, etc.) Attraction of fish and invertebrates to benthic debris	E
OTHER SOURCES: • Other ship traffic • Military operations		Human Environment	Obstructions to trawling Debris/litter on beaches Hazardous chemicals on beaches (waste drums)	

*Effects may be lessened or avoided through existing regulations and permitting.

Figure 8.11. Submodel J relating oil and gas activities to the derived effects of the release of solid debris.

CAUSES/ SOURCES	PRIMARY RESULT	DERIVED EFFECTS		OTHER SUBMODELS
DIRECTLY RELATED TO OIL AND GAS:		Physical Environment	Surface slick, mousse, tarballs, etc. Reduced light penetration in water column Coating of surfaces	
• Routine drilling and production operations (minor spills) • Routine pipeline operation (minor leaks) • Routine vessel traffic (fuel spills) • Blowouts (major or minor spills) • Pipeline ruptures (major, minor spills) • Tanker accidents (major, minor spills)	---> Oil Spills --->	Chemical Environment	Increased hydrocarbon concentrations in water, sediments Biochemical oxygen demand	
		Biological Environment	Mortality/injury through coating, smothering Destruction/alteration of benthic habitats Ingestion of tarballs (e.g., by sea turtles) Acute toxicity Chronic and sublethal effects (e.g., morphological, cytologic, histopathologic, and behavioral abnormalities) Increased microbial activity Community and ecosystem level effects	
OTHER SOURCES: • Natural seeps • Other ship traffic		Human Environment	Clean-up costs Interference with commercial, recreational fisheries Reduced tourism (beaches)	

Figure 8.12. Submodel K relating oil and gas activities to the derived effects of oil spills.

CAUSES/ SOURCES	PRIMARY RESULT	DERIVED EFFECTS		OTHER SUBMODELS
DIRECTLY RELATED TO OIL AND GAS:		Physical Environment	Seafloor disturbance (anchoring) Noise Habitat destruction	B C
• Pipeline installation • Ship traffic (requires dredging of navigational channels)		Chemical Environment	Mobilization of nutrients, trace metals, etc., from resuspended bottom sediments	
-->	Dredging and Channelization* -->	Biological Environment	Crushing, burial, smothering of benthic organisms Community effects through destruction/alteration of benthic habitats Indirect effects through destruction of nursery habitat (coastal wetlands) Interference with filter feeding (by resuspended sediments)	
OTHER SOURCES: • Other major ship traffic		Human Environment	None	

*Effects may be lessened through existing regulations and permitting.

Figure 8.13. Submodel L relating oil and gas activities to the derived effects of dredging and channelization.

during exploratory activities include minor fuel spills and (very rarely) blowouts resulting in major or minor spills of crude oil.

Development and Production

During the development and production phase, platforms are installed to extract oil and gas. Transportation of oil and gas by pipelines, tankers and barges, and construction and operation of offshore ports (e.g., LOOP) are also considered part of this phase. Factors potentially producing environmental effects during routine development and production activities include ship traffic, seafloor disturbance (mainly from platform and pipeline installation), noise, presence of structures (production platforms, quarters platforms, flare stacks, pipelines, etc.), drilling mud and cuttings discharges, produced water discharges, other liquid waste discharges, release of solid debris. Accidental occurrences of concern (in addition to minor fuel spills or pipeline leaks) include blowouts, pipeline ruptures, and tanker and barge accidents, all of which can result in major or minor oil spills.

Post-Production

Potential effects in this phase are associated with the removal and disposal of spent production platforms.

Platform removal and disposal is a topic of increasing concern, because the industry is reaching a stage such that the number of platforms to be removed is expected to increase dramatically (NRC, 1985b). The production life of an offshore platform is generally about 20 to 25 years (NRC, 1985b). Currently, there are about 3,400 offshore oil and gas platforms and related structures on the northern Gulf of Mexico OCS, and about 55 to 65 platforms are removed annually (USDI, MMS, 1987a). In the past, most platforms have been removed by using bulk explosive charges to sever platform legs. The shock waves from these explosions are propagated through the surrounding waters and can kill or injure fishes, turtles, and marine mammals, or interfere with communication and echolocation. Alternative removal methods are available, including the use of shaped charges, mechanical cutters, or underwater arc cutters (USDI, MMS, 1987a).

There is increasing interest in using obsolete platforms as artificial reefs (NRC, 1985b; Reggio, 1987). Transportation and placement of the platforms inevitably involves some ship traffic, seafloor disturbance, and noise.

A related issue concerns residual debris left on the bottom after platform removal. By regulation the debris fields should be cleaned up after platform removal, but in practice some bottom obstructions may remain and this debris can destroy trawls of commercial fishermen. A Fishermen's Contingency Fund administered by the National Marine Fisheries Service has been established to deal in a monetary way with this problem.

8.5.2 Discussion of Submodels

This section discusses 12 submodels illustrating environmental effects of oil and gas operations:

A. Boat and Ship Traffic
B. Seafloor Disturbance
C. Noise
D. Explosions
E. Presence of Structures
F. Drilling Mud Discharges
G. Drill Cuttings Discharges
H. Produced Water Discharges
I. Other Liquid Waste Discharges
J. Release of Solid Debris
K. Oil Spills
L. Dredging and Channelization

Each submodel (Figures 8.2 through 8.13) is a diagram showing the causes or sources on the left, the primary result in the center, and the derived environmental effects on the right. The causes are divided into oil and gas related causes and others. The environmental effects are divided into effects on the physical, chemical, biological, and human environments.

Boat and Ship Traffic (Submodel A, Figure 8.2). Boat and ship traffic is associated with all phases of offshore oil and gas operations, as well as numerous other human activities on the continental shelf--especially recreational and commercial fishing. Much of the recreational fishing and scuba diving, and some of the commercial fishing, is associated with offshore oil platforms and is therefore indirectly related to petroleum development.

The direct physical effects of ship traffic are primarily noise and seafloor disturbance from anchoring. Noise is of concern because it may affect the behavior of acoustically sensitive animals, such as cetaceans. Anchoring disturbs bottom sediments and bottom dwelling organisms, which is of particular concern at the offshore hard banks (e.g., Flower Garden Banks). This topic is discussed briefly below under biological effects.

Chemical effects from ship traffic include chronic, low-level inputs of hydrocarbons, trace metals, nutrients, etc. from bilge washings, domestic wastes, and other discharges. These effects are of little concern individually, especially in the open ocean, but the cumulative effects in areas of limited dispersion (e.g., shallow bays and harbors) can be significant.

The direct biological effects of boat and ship traffic include possible collisions with marine mammals and sea turtles, possible damage to reef corals through anchoring on offshore hard banks, and transport of biofouling species that colonize offshore structures. Some vessels have been known to anchor on the Flower Garden Banks, with severe damage to coral heads from the anchor and chains (Continental Shelf Associates, Inc., 1984). Although oil and gas lessees are prohibited from anchoring on the banks, some tankers and other vessels passing through the area probably anchor there on occasion.

Ship traffic can also affect the human environment. Vessel traffic from OCS oil and gas operations may conflict with commercial fishing activities. Boat and ship traffic also involves a chance of a marine traffic accident (e.g., tanker or barge collision, or anchor damage to pipelines) that can result in major or minor oil spills. In addition, ship traffic requires dredging and maintenance dredging of navigational channels.

Seafloor Disturbance (Submodel B, Figure 8.3). There are many sources of seafloor disturbance associated with oil and gas operations, including rig and platform installation and removal, drilling per se, anchoring of supply vessels and other boats, and pipeline installation. The most significant of these is pipeline installation, which is discussed in detail under submodel L (Dredging and Channelization). Another major source of seafloor disturbance that is not directly related to oil and gas operations is trawling (see Section 8.4.4).

The main physical effects of seafloor disturbance are possible damage to hard bottom areas (e.g., by anchoring), resuspension of bottom sediments, and alteration of seafloor configuration or topography (e.g., anchor scars, etc.). There are no direct chemical effects, but resuspension of bottom sediments can lead to remobilization of nutrients, trace metals, and other contaminants into the water column.

Direct biological effects of seafloor disturbance include crushing, burial, smothering, and direct removal of benthic organisms; habitat loss or alteration, and interference with filter feeding (through resuspension of sediments).

Human-induced seafloor disturbance does not have any direct effects on the human environment. However, two accidental events that may occur during drilling--blowouts and sediment slides--can cause loss of structures and/or loss of life. Also, seafloor disturbance in the form of anchoring can damage pipelines.

Noise (Submodel C, Figure 8.4). Noise is produced during all phases of oil and gas operations. Here, we are concerned with two types of noise: general background noise, and loud bursts of noise. General background noise is produced by engines, machinery, etc. Bursts of noise are produced during geophysical surveys by air guns, sparkers, etc.

Noise carries little energy and does not have any direct physical or chemical effects of bursts of noise on the environment, other than the propagation of sound waves. Some biological effects have been cited, including disturbance or frightening of fishes, marine mammals, and sea turtles; interference with communication and echo-location of marine mammals; and changes in migration patterns or other behavior of acoustically sensitive species. Acute bursts of noise may also cause hearing loss in some species.

Explosions (Submodel D, Figure 8.5). Explosions are produced during removal of obsolete production platforms (by bulk explosive charges). Explosions could also result from a major accident such as an uncontrolled blowout. The only other likely sources of explosions on the continental shelf are military operations and placement of artificial reefs (e.g., sinking of an old ship by detonating explosive charges in the hull).

In contrast with background noise, explosions cause high-energy shock waves to travel over a short range. Chemical effects are limited to combustion products entering the water. Typically, the combustion products are gases that travel to the surface and are released into the atmosphere, but some may become solubilized (USDI, MMS, 1988).

Direct biological effects of explosions are of the most concern, especially in the case of platform removal with explosives. The effects can include mortality or injury to fishes, marine mammals, and sea turtles around the platform (USDI, MMS, 1987a; Young, 1987). The industry is currently researching alternative platform removal methods to minimize this problem, and the MMS is sponsoring a study to determine whether sea turtles can be harmlessly driven away from platforms prior to removal.

There are several possible effects on the human environment as well. Explosions resulting from an accident (blowout) are of obvious concern--i.e., the safety of personnel on the rig or platform. There is also some concern that seismic pulses may interfere with commercial fishing activities by breaking up schools of fish. Some research has been conducted into this question, but the problem is very difficult to study and has not been resolved.

Presence of Structures (Submodel E, Figure 8.6). Major oil and gas related structures on the OCS include drilling rigs, production platforms (and associated structures such as quarters platforms, satellite platforms, and flare stacks), and pipelines. Other structures include shipwrecks, artificial reefs, and other solid debris dumped on the seafloor. The oil and gas related structures are by far the major physical structures on the shelf. As of December 1986, there were over 3,400 petroleum production structures on the OCS (USDI, MMS, 1987a). OCS pipeline length, as of December 1987, was over 28,000 km (USDI, MMS, 1988).

The physical effects of submerged structures are the addition of hard substrate and vertical relief and local alterations in the current field. The addition of hard substrate and vertical relief is the cause of the "artificial reef" effect discussed below. The altered flow regime may result in erosion of bottom sediments surrounding the structure. Behrens (1981) estimated that a 1 to 2 m thickness of surface sediments had been eroded away within the Buccaneer Gas and Oil Field, apparently due to scour around the production platforms and accessory structures in the field. Macroinfaunal communities beneath the production platforms were relatively sparse and distinct in species composition, and scouring of surficial sediments was cited as a possible contributing factor (Harper et al., 1981).

Other than some minor leaching of chemicals from metal objects, there are no direct chemical effects of structures. However, by concentrating fishes and invertebrates (see below), the production platforms and pipelines may lead to exposure of marine organisms to platform effluents (e.g., produced waters, drilling muds) and pipeline leakage. These can result in elevated body burdens of trace metals and hydrocarbons in some species (Bedinger, 1981; Middleditch, 1981).

The most significant biological consequence of these structures is the artificial reef effect (Fotheringham, 1981; Gallaway, 1981; Gallaway et al., 1981a; Gallaway and Lewbel, 1982). Biofouling epibiota such as algae, barnacles, bivalves, bryozoans, hydroids, and ascidians attach to the submerged structure and create a dense fouling mat that is home to numerous cryptic epifauna. Numerous reef fishes, including commercially or recreationally important species (e.g., groupers and red snapper) are attracted to the shelter and food provided by the structures. Additional demersal fishes and macroepifauna may be attracted to biological fallout from the rig or platform (e.g., clumps of barnacles) and/or cuttings piles, which accumulate beneath rigs and platforms (Wolfson et al., 1979; EG&G Environmental Consultants, 1982).

Negative biological effects of the oil and gas structures include possible interference with migrations of demersal species by pipelines; concentration of biota in areas where they may be exposed to contaminants from produced water discharges, drilling mud discharges, and leakage from pipelines; and shading under the structures. Also, the scouring of bottom sediments around structures can lead to a depressed macroinfauna, as noted above.

The structures have an obvious influence on the human environment in the form of increased recreational fishing and scuba diving opportunities. This concentrated fishing effort carries a risk of overfishing of some reef fish stocks, particularly red snapper (Gallaway et al., 1981a). Also, the structures (rigs, platforms, and exposed pipelines) can interfere with trawling, resulting in gear damage.

Drilling Mud Discharges (Submodel F, Figure 8.7). Drilling muds (drilling fluids) are specially formulated mixtures of clays and/or polymers, lignosulfonates, and other additives that serve the following major functions (NRC, 1983):

- Removing formation solids (cuttings) from beneath the drill bit, and transporting them to the surface, where they can be separated from the muds.
- Cooling and lubricating the drill bit and drill string.
- Coating the borehole wall with an impermeable filter cake to prevent fluid loss in permeable formations.
- Helping to support the weight of the drill string.

- Maintaining pressure in the borehole to prevent formation fluids from entering the wellbore.

Generally, about 200 to 1,000 metric tons of drilling fluids are discharged to the ocean during the drilling of an offshore well (Neff, 1987), with an average of about 600 metric tons (see Chapter 5).

Oil and gas drilling operations are the only source of drilling mud discharges on the OCS. However, there is another major source of fine sediments to the shelf in the form of suspended solids in the Mississippi River effluent. The total annual input of drilling muds discharged to the OCS is <1% of the annual average Mississippi River sediment load (NRC, 1983); however, drilling is obviously a major, local source of fine sediments in some areas, particularly those removed from the direct influence of the Mississippi River (e.g., western part of the study area). Also, drilling muds constitute a major source of barium to the study area as a whole (see Chapter 5).

There are two main physical effects of drilling mud discharges: intermittent turbidity in the water column, and altered sediment grain size and mineralogy on the seafloor. In both cases, these are local concerns (within a few kilometers of drillsites).

The main chemical effects of drilling mud discharges are alterations in the trace metal content of suspended particulates (temporary effect during discharges) and bottom sediments (longer lasting effect). Barium, and to a lesser extent chromium, are the metals most likely to be affected, and the changes are most likely to be detected within 1,000 m of drillsites. However, the cumulative effect of all the drilling that has taken place on the Texas-Louisiana shelf has resulted in a regional increase in sediment barium concentrations (see Chapter 5). It should be noted that barium is not considered a toxic or dangerous metal; it is simply a tracer of drilling muds.

The biological effects of drilling muds have been widely studied and debated. There is a general consensus that toxicity of drilling muds currently allowed for discharge on the OCS is low and that biological effects are more likely to result from water column turbidity and physical changes to the substrate properties (grain size). Turbidity is mainly of concern in relation to benthic species that require light for photosynthesis (e.g., hermatypic corals at the Flower Garden Banks). Accumulations on the seafloor could result in localized smothering and interference with filter feeding, and other effects mediated by altered substrate. In most field studies, it has proven difficult to document effects on the benthos that are specifically attributable to drilling muds (EG&G Environmental Consultants, 1982; Battelle New England Marine Research Laboratory and Woods Hole Oceanographic Institution, 1983; Nekton, Inc. and Kinnetic Laboratories, Inc., 1984).

A subtle mechanism by which relatively small accumulations of drilling muds could affect benthic communities is through inhibition of larval settlement (Menzie, 1984). Many larvae of benthic organisms rely on specific chemical cues present on the substrate surface to stimulate settlement. If the larva's ability to detect the appropriate cues is confounded by the presence of an unusual sediment type (drilling mud) or another chemical that interferes with the chemosensory process, then settlement in that area might be prevented. Over time, this could change the composition of the benthic community, especially if drilling muds and cuttings persist in the sediments around drillsites.

Field evidence for possible inhibition of larval recruitment comes from a monitoring program off the mid-Atlantic coast (EG&G Environmental Consultants, 1982; Menzie, 1984). In that study, densities of the ophiuroid Amphioplus macilentus were reduced within about 50 m (164 ft) of the wellsite, both immediately after drilling and one year after drilling; also, a much smaller percentage of small individuals was observed during the post-drilling surveys than during the pre-drilling survey. This suggests that inhibition of settlement near the wellsite may have been responsible for the reduced ophiuroid population there. Decreased densities of polychaetes in areas of high clay content (>10%) may also have been due to this mechanism, but the results were equivocal because similar decreases occurred at stations much farther removed from the influence of drilling discharges.

Some laboratory evidence for effects of drilling mud on larval recruitment has been presented by Tagatz and Tobia (1978) and Tagatz et al. (1978). They showed that mixtures of drilling mud (or barite, a major component of drilling mud) and natural sand could result in lower number of organisms settling on the substrate in flow-through aquaria. The strongest effects were usually noted when the mud or barite was layered on top of the natural substrate. Different groups of organisms (annelids, molluscs, coelenterates, etc.) were affected to different degrees by the substrate alteration.

Drill Cuttings Discharges (Submodel G, Figure 8.8). Discharges of drill cuttings (formation solids from the well) generally accumulate in a pile beneath the drilling rig or platform. Drilling operations are the only source of these particular sediments; however, disposal of "clean" dredged material may be considered as an analogous process with similar environmental effects.

The main physical effects of drill cuttings are altered sediment composition and altered bottom topography underneath the drilling rig or platform.

Chemically, cuttings are considered fairly innocuous, except for small amounts of drilling muds that adhere to the cuttings and are discharged with them. The cuttings may increase oxygen demand in bottom sediments of the cuttings pile.

Cuttings discharges may bury benthic fauna near the rig or platform and can result in more subtle effects on the benthic fauna due to altered bottom substrate. In particular, the cuttings pile has been shown to attract numerous motile invertebrates and fishes (Zingula and Larsen, 1977), which can result in a halo effect on benthic communities around the rig or platform (Wolfson et al., 1979; EG&G Environmental Consultants, 1982). Fallout of biological debris (shells, dead organisms, etc.) from the drilling rig, platform, and anchor chains can add to the artificial reef effect.

Produced Water Discharges (Submodel H, Figure 8.9). During the production of oil and gas, produced water (also known as connate, fossil, or formation water) is often pumped from the oil and gas formation. Following treatment, much of this water is released to the ocean. The amount generated during production operations varies with well location, field characteristics, and production methods; Neff (1987) reports that offshore oil production platforms may discharge up to 1.5 million liters of produced water per day.

Oil and gas production operations are the main source of produced waters on the OCS. However, a similar brine is produced through leaching of onshore salt domes for petroleum storage (Strategic Petroleum Reserve), and the brine has been discharged to coastal waters at two sites (West Hackberry and Bryan Mound) within the study area. In addition, there are localized brine seeps on the continental shelf (e.g., East Flower Garden Bank).

Produced water has some physical and chemical characteristics that can affect the local environment near the discharge point. These characteristics include elevated salinity and altered ion ratios; elevated temperature; low dissolved oxygen content; presence of organic compounds creating a biochemical oxygen demand; and contamination with petroleum hydrocarbons, other organic compounds, trace metals, and radionuclides (Middleditch, 1984; Neff, 1987; USDI, MMS, 1988).

The most likely biological effects of produced water discharges are reductions in the fouling biota on platform legs and local reductions in the benthic fauna, particularly in shallow areas with limited dispersion. During the Central Gulf Platform Study, reductions in the fouling community on platform legs were noted near produced water discharges (Bedinger, 1981). Similar effects were noted on fouling biota during the Buccaneer Gas and Oil Field Study, with the effects being limited to 1 m vertically and 10 m horizontally from the discharge point (Gallaway et al., 1981a). Armstrong et al. (1977, 1979) reported that benthic populations were depressed around a platform discharging produced water in a shallow, coastal bay; they attributed the effect to accumulation of naphthalenes in sediments. A study of produced water effects on benthic communities off the Texas coast has been conducted by the American Petroleum Institute, but the results are not available as of this writing (November 1988).

Produced water discharges can also result in low-level trace metal and hydrocarbon contamination of platform-associated epibiota and fishes (Bedinger, 1981; Gallaway et al., 1981a). However, the contaminant levels measured in platform-associated biota during the Central Gulf Platform Study and the Buccaneer Gas and Oil Field Study were not high enough to be of concern from a human health perspective (e.g., humans eating contaminated fish) (Bedinger, 1981; Gallaway et al., 1981a).

Other Liquid Waste Discharges (Submodel I, Figure 8.10). Other routine discharges include cooling water, desalinization brine, deck drainage, and sanitary and domestic wastes. Sanitary and domestic wastes are disinfected, and deck drainage is passed through an oil-water separator, prior to release.

Cooling water may be several degrees warmer than receiving waters, and create a local elevation in temperature. Chemically, the various other wastes may result in slight, local, and temporary elevations in metals, hydrocarbons, and nutrients. None of these discharges are considered to have a significant effect on receiving waters (USDI, MMS, 1988), and no biological effects are postulated here.

Release of Solid Debris (Submodel J, Figure 8.11). The dumping of trash and debris in marine waters from boats, ships, and offshore platforms is becoming a serious problem, as discussed in Section 8.4.6. The offshore oil industry is not the only contributor, but the Offshore Operators Committee has recognized that trash and debris from offshore operations is part of the problem and has taken steps to educate industry personnel (Kewley, 1987).

The main physical effects of solid debris are local alteration in bottom topography (for heavy objects) and damage to fishing gear.

Chemically, the solid debris may release trace metals or other pollutants to the environment. Also, some drums have been found to contain hazardous chemicals.

The biological effects of solid trash and other refuse released into the marine environment have only recently come to light. Plastic sheeting, bags, and other such refuse have been implicated in the deaths of sea turtles and cetaceans through ingestion and entanglement, and this is considered to be a very serious problem. Non-floatables pollute the bottoms where they land, and non-degradable plastics and other such materials are swept widely around the shelf by bottom currents.

Release of trash and solid debris affects the human environment as well. Vast quantities of floatable materials ultimately wind up as debris on the beaches lining the northern Gulf coast. Aside from the obvious negative effect on the enjoyment of the beach, this material costs money to clean up, and some can present a health hazard (e.g., chemical waste drums).

Oil Spills (Submodel K, Figure 8.12). Minor spills (e.g., diesel fuel) can be expected to occur occasionally during routine drilling, production, and transfer operations. Minor leakage of oil from pipelines is also inevitable. Major spills can result from a tanker or barge accident, a pipeline rupture (e.g., due to anchoring, or sediment slumping), or a blowout. Other sources of oil in the marine environment include natural seeps, municipal and industrial wastes and runoff, and marine transportation other than tankers and barges (NRC, 1985a).

The fate and effects of oil in the marine environment have been studied and discussed extensively. The reader is referred to a recent, major review by the NRC (1985), as well as papers by Capuzzo (1985) and Spies (1985). In addition, Boehm (1982) provides information about the fate and effects of oil from the Ixtoc-I blowout off the Mexican coast, which resulted in transport of substantial quantities of oil into the Texas OCS region.

The physical effects of minor spills and leaks are negligible. Chemical effects include local increases in hydrocarbons in the environment. Taken individually, these spills are not of much concern, but cumulatively they can alter the chemical environment, especially in areas of shallow water with limited circulation. Also, minor spills that result in contamination of coastal marshes can have persistent effects on these areas.

The physical effects of a major oil spill include formation of surface slicks, mousse, and tarballs; reduced water clarity; and coating of surfaces. Chemical effects include increased biochemical oxygen demand and increased concentrations of hydrocarbons in water and sediment.

The biological effects of a major spill are of serious concern. Although effects on benthic organisms of the open shelf may occur, none were detected on the south Texas shelf in the aftermath of the Ixtoc-I blowout (Boehm, 1982). The main concern is for oiling of beaches and coastal wetlands. Effects may include smothering, acute toxicity, and chronic and sublethal effects (behavioral, morphological, cellular, and histopathological abnormalities). Damage or alterations to coastal habitats could result in effects on continental shelf populations and communities because estuarine areas serve as nursery habitat for many shelf species.

<u>Dredging and Channelization (Submodel L, Figure 8.13)</u>. Under this heading we include installation of pipelines both on the OCS (which usually requires trenching and burial) and in coastal wetlands. Also, dredging of navigational channels for shipping (both oil and gas related, and other) is included.

Installation of pipelines on the OCS is probably the most significant source of oil and gas related seafloor disturbance because of the sheer size of the area affected. The network of pipelines on the Texas-Louisiana OCS and adjacent state waters is the most extensive in the world. As of December 1987, there were over 28,000 km of pipeline on the OCS in the Gulf of Mexico (USDI, MMS, 1987a). Over 90% of the pipeline is in the Central Planning Area (primarily off Louisiana), with the remaining 10% in the Western Planning Area (Risotto and Collins, 1986). Data from Boesch and Robilliard (1987) and Risotto and Collins (1986) indicate an average figure of about 900 to 1,000 km of new pipeline installed each year on the northern Gulf of Mexico OCS.

During pipeline placement, tugboats move the lay barge along the pipeline route, continually repositioning their anchors. This anchoring disturbs bottom sediments and may kill or damage benthic organisms in a swath up to 46 m wide along the pipeline route (USDI, MMS, 1983b). In addition, pipeline burial (which is required on the OCS in most cases where water depth is less than 61 m) requires a special jet sled that moves along the pipeline and fluidizes bottom sediments, allowing it to sink into the resulting trench. Backfilling is usually left to natural processes. Biological effects may occur through habitat destruction and modification, resuspension of bottom sediments, and (in polluted areas) remobilization of nutrients and contaminants from resuspended bottom sediments along the pipeline route.

Although our focus here is on the continental shelf and slope, the network of OCS pipelines cannot be considered in isolation from the corresponding onshore pipeline network. Dredging of canals in the coastal zone of Louisiana (both for oil and gas pipelines, and other uses) has been shown to affect coastal environments through direct and indirect habitat destruction and alteration (Boesch, 1982; Boesch and Robilliard, 1987; Turner and Cahoon, 1988). Continued loss of coastal wetlands, both from oil and gas operations, other human activities, and natural processes, must eventually be reflected in alterations in the ecology of the continental shelf.

Likewise, the direct effects of navigational dredging are seen mainly in the bays, harbors, and other nearshore areas where the dredging occurs. However, disposal of the dredged material on the continental shelf can crush, bury, and smother biota and cause local habitat alteration and turbidity. In addition, proposed cross-shelf channels (as described in Section 8.4.1) could directly affect the shelf biota.

8.6 POTENTIAL EFFECTS ON ECOSYSTEMS AND SELECTED COMPONENTS

In this section, we apply the information on effect pathways from the preceding section to the major ecological systems defined in Section 8.3. Along the way, we try to distinguish between effects that are (or should be) of serious concern, those that are of little concern, and those for which we do not have enough information. First, we want to make a distinction between local and widespread effects.

8.6.1 Local vs. Widespread Effects

The environmental effects of oil and gas related activities can be divided into two classes: local effects (whose influence extends only tens to a few hundreds of meters from the activity, such as a rig or platform) and widespread effects (whose influence may extend to hundreds of kilometers).

In general, local effects are of concern only where (1) a rare or unique species or resource is present near a site of oil and gas activity, or (2) where many local influences in an area may accumulate. As an example of the former, the effects of anchoring and drilling mud discharges are local, but they are a serious concern at the Flower Garden Banks because of the unique nature of the reefs found there. Similarly, effects of explosions during platform removal are local, but they are a serious concern if endangered or threatened sea turtles are present. An example of cumulative effects is the chronic, low-level contamination of bays and coastal waters due to a combination of waste discharges from boats and ships, oil and gas operational discharges, municipal and industrial outfalls, and runoff. Another example is the destruction of coastal wetlands, a few acres at a time, due to dredging and channelization.

Widespread, or regional, effects are of obvious concern. For example, a major oil spill has the potential for widespread effects on the continental shelf and adjacent coastal areas. Likewise, trash and debris from oil and gas operations can be widely distributed and result in effects over a wide area.

8.6.2 Potential Effects on the Major Ecosystems

Three major ecosystems of the Texas-Louisiana continental shelf and upper slope were identified and defined in Section 8.3: water column, soft-bottom benthic, and hard substrate/structure-related systems (as well as transitional systems).

Tables 8.3, 8.4, and 8.5 detail the main existing and potential effects of oil and gas operations on the three major systems. In each case, the effects listed are of three types: widespread effects (W), those that may affect a large area; local effects that are of concern where rare species or unique resources are present (LR); and local effects that can cumulatively be considered important (e.g., in heavily developed areas, or in shallow water where dispersion is limited) (LC).

Water Column Ecosystem

Table 8.3 summarizes the main existing and potential effects of oil and gas operations on the water column ecosystem.

Effects of potential widespread importance to the water column ecosystem are major oil spills and release of trash and debris. In both cases, the material released can be widely dispersed and result in effects over a wide area. Local effects on rare species or unique resources include potential collisions of boats and ships with marine mammals; effects of noise on marine mammals; and mortality or injury of marine mammals and sea turtles due to explosions during platform removal. Local effects of possible cumulative significance in areas of limited dispersion include turbidity from dredging and channelization, other seafloor disturbances, and drilling mud discharges; and chronic, low-level contamination of the water column by produced water discharges and wastes from boats and ships. Another local effect of cumulative importance is the concentration of fishes near structures, which leads to enhancement of recreational and commercial fisheries. In some instances, this effect could also lead to over-fishing of certain species.

Soft-Bottom Benthic Ecosystem

Table 8.4 summarizes the main effects and potential effects of oil and gas operations on the soft-bottom benthic ecosystem.

The only widespread effects of concern are those resulting from major oil spills. All other effects listed are local influences on the benthic communities that may be significant cumulatively in certain

Table 8.3. Main existing and potential effects of OCS oil and gas operations on water column ecosystems of the Texas-Louisiana continental shelf and upper slope.

Submodel	Main Environmental Effects of Concern	Nature of Concern* W	LR	LC
A. Ship Traffic ---------->	Chronic, low-level pollution			x
	Potential for collisions w. marine mammals, turtles		x	
	Potential for oil spills	x		
B. Seafloor Disturbance -->	Turbidity, pollutant release through resuspension of bottom sediments			x
C. Noise ----------------->	Disturbance/altered behavior of marine mammals		x	
D. Explosions ------------>	Mortality, injury to marine mammals, turtles		x	
E. Presence of Structures >	Enhancement of recreational and commercial fishing			x
	Possible over-fishing of some species			x
F. Drilling Mud Discharges ------------>	Intermittent turbidity			x
G. Drill Cuttings Discharges ------------>	Negligible effects			
H. Produced Water Discharges ------------>	Local elevations in hydrocarbons, metals, radionuclides, etc.			x
I. Other Liquid Waste Discharges ------------>	Negligible effects			
J. Release of Solid Debris ---------------->	Mortality of fishes, mammals, turtles through entanglement, ingestion	x		
K. Oil Spills ------------>	Toxicity, sublethal effects, etc.	x		
L. Dredging and Channelization -------->	Turbidity, pollutant release through resuspension of bottom sediments			x

*W = Widespread effects.
LR = Local effects on rare species or unique resources.
LC = Local effects that can accumulate, particularly in heavily developed areas, or in shallow water where dispersion is limited.

Table 8.4. Main existing and potential effects of OCS oil and gas operations on soft-bottom benthic ecosystems of the Texas-Louisiana continental shelf and upper slope.

Submodel	Main Environmental Effects of Concern	Nature of Concern*		
		W	LR	LC
A. Ship Traffic ---------->	Chronic, low-level pollution of sediments			x
	Potential for collisions, oil spills	x		
B. Seafloor Disturbance -->	Crushing, burial of benthos			x
C. Noise ---------------->	Negligible effects			
D. Explosions ------------>	Mortality, injury of benthic organisms			x
E. Presence of Structures >	Habitat alteration (hard substrate)			x
	Benthic scouring			x
F. Drilling Mud Discharges ------------>	Shading of light sensitive species (e.g., benthic algae) due to turbidity			x
	Altered sediment grain size, mineralogy			x
	Smothering, interference with filter feeding			x
G. Drill Cuttings Discharges ------------>	Burial, smothering of benthos			x
	Attraction of fish and motile invert. predators			x
H. Produced Water Discharges ------------>	Possible local depression of benthic fauna			x
I. Other Liquid Waste Discharges ------------>	Negligible effects			
J. Release of Solid Debris ---------------->	Altered benthic habitats (heavy solid debris)			x
K. Oil Spills ------------>	Acute toxicity and chronic, sublethal effects, smothering, coating, etc.	x		
L. Dredging and Channelization -------->	Crushing, burial of benthos			x
	Habitat alteration			x
	Indirect effects through destruction of nursery habitat (coastal wetlands)			x

*W = Widespread effects.
LR = Local effects on rare species or unique resources.
LC = Local effects that can accumulate, particularly in heavily developed areas, or in shallow water where dispersion is limited.

Table 8.5. Main existing and potential effects of OCS oil and gas operations on hard-substrate, structure-related ecosystems of the Texas-Louisiana continental shelf and upper slope.

Submodel	Main Environmental Effects of Concern	Nature of Concern*		
		W	LR	LC
A. Ship Traffic ---------->	Anchor damage to reef corals on hard banks		x	
	Potential for collisions, oil spills	x		
	Transport of biofouling species	x		
B. Seafloor Disturbance -->	Damage to reef corals (anchoring)		x	
C. Noise ---------------->	Negligible effects			
D. Explosions ----------->	Destruction of platform associated biota during removal			x
E. Presence of Structures >	Provision of additional habitat			x
	Enhancement of recreational and commercial fishing			x
	Possible over-fishing of some species			x
F. Drilling Mud Discharges ----------->	Shading of light sensitive species (e.g., hermatypic corals) due to turbidity		x	
	Altered substrate on hard banks		x	
	Smothering, interference with filter feeding		x	
G. Drill Cuttings Discharges ----------->	Burial, smothering of benthos		x	
	Altered substrate on hard banks		x	
H. Produced Water Discharges ----------->	Minor, local reduction in platform fouling community			
	Bioaccumulation of contaminants by platform associated species			x
I. Other Liquid Waste Discharges ----------->	Negligible effects			
J. Release of Solid Debris --------------->	Negligible effects			
K. Oil Spills ----------->	Toxicity, chronic and sublethal effects, coating, smothering, etc.	x		
L. Dredging and Channelization -------->	Habitat destruction (if allowed to occur on hard-bottom area)		x	

*W = Widespread effects.
LR = Local effects on rare species or unique resources.
LC = Local effects that can accumulate, particularly in heavily developed areas, or in shallow water where dispersion is limited.

areas. Examples include dredging and channelization (particularly for pipeline installation on the OCS and in coastal wetlands), crushing and burial of benthic organisms by seafloor disturbance, scouring of sediments around production field structures, and shading of light-sensitive species due to drilling mud discharges. The effects of operational discharges--particularly drilling muds and produced waters--are considered to be of possible concern, especially in heavily developed areas where dispersion is limited (e.g., coastal bays).

Hard Substrate, Structure-Related Ecosystem

Table 8.5 summarizes the main existing and potential effects of oil and gas operations on the hard substrate, structure-related ecosystem. Widespread effects include those resulting from major oil spills and transport of biofouling species by ship traffic. The latter is a positive influence, in that ship traffic helps to bring in potential colonizers of exposed hard substrate. Local effects on rare species or unique resources include anchor damage to reef corals at the Flower Garden Banks; effects of drilling mud and cuttings discharges on reef biota at the Flower Garden Banks (if allowed; currently, all discharges must be shunted, thereby preventing exposure); and effects of dredging and channelization (if allowed to occur in a hard-bottom area). A local effect of great cumulative importance is the presence of structures, which provide habitat for the biofouling community and which attract fishes, leading to enhancement of recreational and commercial fishing. Concentration of fishes near structures may expose some fish populations to over-fishing, however. The concentration of reef epibiota and fishes on and near platforms can also result in bioaccumulation of contaminants in some species. Another local effect of possible cumulative importance is the mortality to platform biota (both the biofouling community and associated nekton) during platform removal.

8.6.3 Potential Effects on Selected Components

We now turn to some selected ecosystem components for further discussion: (1) the East and West Flower Garden Banks, (2) white and brown shrimp, (3) groupers and red snapper, (4) sea turtles, and (5) marine mammals. These components were chosen on the basis of their ecological and/or economic importance, the degree of environmental concern about them, and the amount of available information on them. Some existing and potential environmental effects on these components have been discussed in earlier sections. These points are reiterated below, and other potential effects of concern are discussed.

East and West Flower Garden Banks

The major environmental effect of human activities at the Flower Garden Banks is anchor damage to reef corals. Oil and gas companies holding leases near the banks are prohibited from anchoring on them, but tankers and other vessels may knowingly or unknowingly anchor there. This is not entirely an oil and gas industry problem. Other sources of disturbance to the reef corals include other ship traffic and recreational divers.

Drilling mud discharges from exploratory and production operations near the Flower Garden Banks have been a concern in the past. However, theoretical calculations indicate (and monitoring studies confirm) that when muds and cuttings are shunted to within 10 m of the bottom beyond the base of the banks, these materials are not transported upward into the coral reef zone (McGrail et al., 1982b; Continental Shelf Associates, Inc., 1985). As long as the lease stipulations requiring shunting are continued, there should be no problem with effects on reef corals atop the banks.

White and Brown Shrimp

White and brown shrimp are not known to be severely affected by any oil and gas related activities. Potential effects of intermediate concern relate to chemical pollution, heavy sedimentation, and the influence of linear barriers (dredge channels and pipelines) on migration patterns. On the positive side, the presence of physical structures on the bottom probably provides some sanctuary from bottom trawling.

Groupers and Red Snapper

Groupers and red snapper are attracted to rigs, platforms, and other vertical structures where the resident adult breeding populations are potentially, if not actually, subject to over-fishing and mortality or injury from explosions during platform removal. Of less concern are the effects of chemical pollution, suspended sediments, and heavy sedimentation. Whether noise and other habitat disturbances affect the behavior of these fishes is not known. The over-fishing issue is discussed in Gallaway et al. (1981a) and Gallaway and Lewbel (1982).

Sea Turtles

A number of potential effects on sea turtles are of concern. Oil spills can affect the turtles by coating, toxicity, and reduction of food supplies. Explosions during platform removal may result in mortality, injury, or behavioral interference. This issue has not been raised with respect to seismic surveys, which are a more widespread influence; indeed, this topic would prove very difficult to study in the field. Solid and semi-solid debris may result in mortality through ingestion and entanglement. Attraction to physical structures (where the turtles may be harassed and damaged) and effects of chemical toxicity are of intermediate concern. The effects of low-level noise on sea turtle behavior are not well understood but cannot be overlooked.

Marine Mammals

Marine mammals are also potentially affected by several types of oil and gas related activities. Major oil spills may affect them through coating, ingestion, and respiratory damage. Explosive and low level noise can interfere with communication, echo-location, and other behavioral activities. Plastic bags, sheets, and other such materials may be ingested, causing choking, digestive tract blockage, and death. Other effects of less concern include non-petroleum chemical toxicity and possible avoidance of areas of high turbidity.

8.7 CONCLUSIONS

The preceding discussion has highlighted the major concerns about the environmental effects of offshore oil and gas development on the Louisiana and Texas continental shelf and upper slope. In addition to the obvious effects cited above, there is always the possibility of more subtle, indirect effects through food supply modifications, food chain transfers of pollutants, etc., but these are not well documented. Also, the possible additive and synergistic effects of several low level factors acting in combination are not well known.

In this section, we summarize the main concerns. Again, the effects are divided into widespread effects; local effects on rare species or unique resources; and local effects that may accumulate in heavily developed areas, or in shallow water where dispersion is limited.

8.7.1 Widespread Effects

The widespread effects of most concern are as follows:

- A major oil spill resulting from a tanker or barge accident, pipeline rupture, or blowout. Although there could be direct effects on continental shelf biota, the main concern is fouling of the coastal wetlands that serve as nursery areas for many species of fish and invertebrates.

- Proliferation of trash and debris, particularly plastic items. Ingestion and entanglement are the main problems, and effects on endangered or threatened sea turtles and marine mammals are of particular concern.

8.7.2 Local Effects on Rare Species or Unique Resources

The following environmental effects (or potential effects) are the result of activities that probably are not of much concern except when carried out in the presence of rare species or unique resources. In most cases, the likelihood or severity of effects is not well known or documented.

- Effects of explosions (during platform removal) on fishes, marine mammals, and sea turtles.

- Collisions of boats and ships with marine mammals and sea turtles.

- Effects of noise on behavior of marine mammals and sea turtles.

- Anchor damage to reef corals at the Flower Garden Banks.

- Surface discharges of drilling mud and cuttings at or near the Flower Garden Banks (if allowed). Under the current stipulations requiring shunting, these discharges are not expected to affect the corals atop the banks.

- Dredging or channelization on or near hard bank areas (if allowed).

8.7.3 Local Effects of Possible Cumulative Significance

- The presence of thousands of structures on the continental shelf and upper slope has provided hard substrate for biofouling communities and attracted many nektonic and demersal species, including groupers, red snappers, and sea turtles. On the positive side, the structures have enhanced recreational and commercial fisheries. On the negative side, some fishes such as the groupers and snappers, which become residents, can become vulnerable to over-fishing. Also, association of sea turtles with the platforms can lead to mortality during platform removal.

- Continued destruction of coastal wetlands through dredging and channelization for OCS pipelines. Although oil and gas activities account for a fraction of the total wetland loss in Louisiana, the cumulative losses could have significant, long-range effects on the biota of the continental shelf because many of the shelf species are estuarine dependent.

- Chronic chemical pollution of heavily developed, shallow areas where dispersion is limited, by contaminants from ship traffic and OCS operational discharges (drilling muds, produced waters).

- Chronic water column turbidity resulting from drilling mud and cuttings discharges and various sources of seafloor disturbance (resulting in sediment resuspension). This effect would be of particular concern in shallow areas with limited dispersion, and especially those not already influenced heavily by turbid outflow from the Mississippi River.

- Effects on benthic communities in the immediate vicinity of drilling rigs and platforms. These effects may result from operational discharges (drilling muds, cuttings, produced waters), scouring of sediments around structures, and/or predation by fish and motile epibenthos attracted to the structures and to biological debris and cuttings piles on the bottom.

8.8 DATA GAPS AND INFORMATION NEEDS

Many of the data gaps and information needs discussed in the earlier chapters would help in evaluating existing and potential environmental effects of oil and gas operations. Some other information needs are discussed below.

Three main types of effects were discussed above--widespread effects; local effects on rare species or unique resources; and local effects of possible cumulative importance. Further scientific research can be of most use in understanding and minimizing the third type of effect.

For the two major widespread effects cited above (oil spills and proliferation of trash and debris), further research is not particularly going to help the problem. We hope that there is no occasion for further research on major oil spills in the study area; what is needed is continued improvement in prevention and cleanup measures. Concerning the proliferation of trash and debris in Gulf of Mexico waters and on coastal beaches, further studies could help to identify the sources of wastes (in some cases). However, to the extent that the oil and gas industry is a contributor, specific measures should be (and are being) undertaken to reduce that contribution (Kewley, 1987).

For known or suspected local effects on rare species or unique resources, it would seem prudent to implement protective measures as soon as possible, even if full scientific understanding of the problem is not at hand. The prime example of this principle in the Gulf of Mexico is the protection of coral reefs at the Flower Garden Banks through lease stipulations requiring shunting of all mud and cuttings discharges to within 10 m of the bottom (for wells drilled near the banks). Despite all of the monitoring studies in the last 13 years, no one really knows what the effects of unrestricted surface discharges of drilling muds near the Flower Garden Banks would be. But there is no overriding need to know, as long as it can be shown that a relatively simple alteration in discharge practices (shunting) will prevent exposure of the corals to drilling muds.

The issue of the possible effects of explosions during platform removal on endangered and threatened sea turtles is a similar case in point. The association of sea turtles with offshore structures should be documented and studied. However, from a regulatory viewpoint, there is no need to wait for further scientific studies before proceeding with measures to prevent sea turtle injury/mortality by (1) developing alternative platform removal methods; and (2) surveying platforms for sea turtles prior to removal, and shooing them from the area during removal operations. According to DeMarsh (1987), past platform removal practices have been determined almost entirely by cost considerations, with little thought for possible environmental effects. Therefore, it may be possible to minimize effects of explosions or to use other removal methods with relatively little effort.

No further research on the effects of anchoring on reef corals at the Flower Garden Banks is needed. Although few specific incidents have been documented, it is obvious that anchoring can be very destructive. Protection of the banks through education, appropriate regulations, and strict enforcement is the only solution to this problem.

Further research on the cumulative significance of the many local effects of oil and gas development is needed. For example, there are lingering concerns about the biological consequences of chronic, low-level contamination in heavily developed areas. Also, the cumulative effects of local destruction and alteration of benthic habitats during pipeline installation, and local effects on benthic communities around drilling rigs and platforms need to be evaluated. In general, these effects are of most concern in shallow water, especially where dispersion is limited--rather than in open shelf waters. Some research on the effects of drilling mud and cuttings discharges in shallow water off the Texas coast is currently being sponsored by the American Petroleum Institute, and the results (not yet available) should provide valuable information on the effects of individual drilling operations. Perhaps this sort of information can then be extrapolated to determine cumulative significance.

Continuing research should also focus on the platform-associated biota and the relationships between the oil and gas industry and recreational and commercial fisheries. The biogeographic implications of the added hard substrate for the distribution of biofouling species should also be studied further.

CHAPTER 9
CONCLUSIONS AND RECOMMENDATIONS

9.1 DATA GAPS AND INFORMATION NEEDS

Each chapter has included a brief section discussing data gaps and information needs. Here, we highlight the major points from each chapter.

9.1.1 Marine Geology

Data gaps were identified in four main areas: salt tectonics, sediment accumulation rates, chemosynthetic communities, and sediment transport.

- Salt Tectonics. Little is known concerning the dynamics of salt tectonics. We know that the forces affecting the topographic expression and internal structure of salt domes are active, but no one has monitored a salt dome to determine what is really happening.

- Sediment Accumulation Rates. Current knowledge concerning sediment accumulation rates on the outer continental shelf and slope is woefully inadequate. The lead-210 method used by Holmes (Berryhill et al., 1976) and others gives unrealistic results and should be re-evaluated. An accurate knowledge of sediment accumulation rates would aid in interpretation of meiofaunal and macroinfaunal data. It would also be useful in modeling the trajectories of solid pollutants in the water column.

- Chemosynthetic Communities. Hydrocarbon seeps support chemosynthetic communities, including microbial mats that cause the precipitation of carbonate cements in the sediments. The interaction of these bacteria with the inorganic sediments may be an important factor in the stabilization of sediments in the vicinity of seeps.

- Sediment Transport. McGrail's work (reported in Rezak et al., 1985) was just beginning to give us an understanding of the sediment transport processes on the outer continental shelf. A continuation of the accumulation of the same kinds of data over a larger area of the Texas-Louisiana shelf and over a span of two or three years would improve our ability to predict the fate of particulate pollutants.

9.1.2 Physical Oceanography and Meteorology

Five main areas of information needs were identified in the physical oceanography/meteorology chapter: circulation patterns; exchange processes between the shelf and open Gulf waters; river discharge effects on salinity; structure and behavior of frontal zones; and dynamics of changes in dissolved oxygen concentrations.

- Circulation Patterns. The variability about the mean pattern of surface circulation developed by Cochrane and Kelly (1986b) is largely unknown except in the regions of the Department of Energy Strategic Petroleum Reserve studies. The spatial pattern of mean bottom circulation over the shelf, and its variability, also need to be described and related to the surface circulation and hydrographic variability.

- Exchange Processes. Information about the exchange processes between the shelf and the oceanic Gulf regions is very limited. The influence of Loop Current eddies, the export of water masses created by cold-air outbreaks, the flushing of fresh water discharge on to the shelf, upwelling of deep ocean water masses onto the shelf, and transport of sediment off the shelf are important yet relatively unexplored topics for this shelf.

- Effects of River Discharge. Our understanding of the effects and fate of the fresh water from the Mississippi-Atchafalaya River System is based largely on the salinity data from the GUS III cruises in the years 1963 to 1965, when river discharge was lower than average. The distribution of salinity on the shelf should be mapped with greater spatial resolution, both horizontally and vertically, during a year with above-normal volumes of river discharge.

- Frontal Zones. The structure and the dynamic behavior of the intense frontal zones on this shelf should be studied through a combination of observation and modeling, with a view towards defining the effect of both horizontal and vertical stratification on the mixing, distribution, and transport of nutrients, plankton, and pollutants.

- Dissolved Oxygen. The rate at which the concentration of dissolved oxygen changes locally in bottom waters when there is vertical stratification is unknown. All terms in the diffusion equation for dissolved oxygen need to be studied: local rate of change, advection, production, consumption, and turbulent mixing, both vertical and horizontal.

9.1.3 Marine Chemistry

Several major information gaps were noted in the Marine Chemistry chapter. These are presented separately for trace metals, hydrocarbons, and radionuclides.

Trace Metals

- **Sources and Fates of Trace Metals**. More work is needed on the forms of dissolved metals in Mississippi River water, the behavior of river-borne particulates as they mix with seawater, and the fate of Mississippi River-derived trace elements. Also, the mass and fate of metals from other sources, such as the atmosphere and industrial discharges, need further study. Effects of bottom water hypoxia on sediment trace metal geochemistry should also be investigated further.

- **Distribution of Trace Metals**. Concentrations of dissolved trace metals in seawater are poorly known, as few seawater samples from the Texas-Louisiana shelf have been analyzed with the care required to lend confidence to the data. Trace metal concentrations in surficial sediments are much better documented, but information on temporal variability is very limited. Data on trace metals concentrations in biota from the east Texas and Louisiana continental shelf and slope are lacking. Trace metal concentrations also need to be measured in sediments and biota near petroleum seeps.

- **Fate of Drilling Mud Discharges**. Further work is needed using trace metals to study the fate of drilling mud discharges, particularly in the near-field around drillsites.

Hydrocarbons

- **Aromatic Hydrocarbons**. Distributions of aromatic hydrocarbons in northwestern Gulf sediments and organisms need further study. Regional and temporal distributions of aromatic hydrocarbons should be studied using National Oceanic and Atmospheric Administration "Status and Trends" methodologies.

- **Tar**. More information is also needed on spatial and temporal trends in benthic and pelagic tar distributions. Additional information on the sources of benthic and pelagic tar is needed, as there is little information that is less than ten years old.

- **Seep Hydrocarbons**. More data is needed on the body burdens of hydrocarbons in benthic organisms around petroleum seeps, and on the relationships between seep hydrocarbons and benthic organism body burdens.

Radionuclides

- **Radionuclides in Produced Waters**. The mass and fate of radionuclides in produced waters needs further study. Also, the possible accumulation by organisms of radium from oil-well produced water appears not to have been studied.

9.1.4 Marine Biology

Data gaps and information needs identified in the Marine Biology chapter can be divided into four categories: general information, local influences, biological gradients, and special systems and components. The long-term goal is the development of a complete understanding of the major ecosystems of the area, possibly leading to the construction of predictive mathematical models.

General Information

- **Coupling Mechanisms**. Information is needed on the coupling mechanisms between the inshore marshes, bays, and estuaries, on the one hand, and the continental shelf ecological systems, on the other.

- **Influence of the Mississippi and Atchafalaya Rivers**. More information is needed to understand the influence of the Mississippi and Atchafalaya Rivers on shelf ecosystems. The spatial and temporal extent of these influences, and the relationships to meteorological factors, need to be investigated.

- **Interactions of Oceanic Waters with Coastal Systems**. Interactions of oceanic waters with coastal waters and habitats need to be better understood, and their influence on the distribution of the biological components of the systems needs to be determined.

- **Nepheloid Layer**. Relationships between the nepheloid layer and biological systems of the shelf and upper slope need to be studied.

Local Influences

- **Hypoxic Zones**. Influences of hypoxic zones on biological systems need to be studied.

- **Oxygen Minimum Layer**. Relations of the oxygen minimum layer with shelf/slope biota are not well known.

Biological Gradients

- **Water Column**. Quantitative information is needed on the seasonal and areal distribution of phytoplankton, zooplankton, and neuston, especially in relation to water masses.

- **Benthos**. Quantitative information is needed on the density and distribution of meiofauna, macrofauna, and megafauna in relation to sediment types.

Special Systems and Components

- **Hard Banks**. The outer shelf banks have been well studied, but hard banks of the middle shelf and upper slope are not well known. The distribution and biological characteristics of these banks need to be documented.

- **Sea Turtles**. Additional research is needed to develop safe methods of platform removal. Current methods involving bulk explosive charges can injure or kill sea turtles. In addition to developing alternative removal methods, it would be desirable to find methods to keep sea turtles away from the vicinity of platforms during removal.

- **Special Systems**. Information is needed on the composition and ecological characteristics of certain areas: the Mississippi River near-delta environments [e.g., Pro-Delta Fan Assemblage (Defenbaugh, 1976)], Mississippi Canyon environments, areas of oozy bottom off Louisiana, and hill-and-basin environments of the outer shelf and upper slope.

9.1.5 Socioeconomics

The major topic for further study cited in the Socioeconomics chapter concerns the nature of changes in commercial finfish landings over the last seven years. These changes raise some important questions that deserve further study. In particular, the possible relationships between these changes and the high density of petroleum platforms off Louisiana need to be investigated.

9.2 SUGGESTIONS FOR FUTURE FIELD STUDIES

Based on the information needs identified in the various chapters and highlighted above, we can make suggestions for future field studies of the Texas-Louisiana shelf and upper slope. These suggestions are general recommendations concerning study locations, scheduling, and design considerations. It is premature to make specific recommendations for study components, sampling equipment, and methodologies.

We suggest that the study area should extend from the Mississippi River Delta to Brownsville, TX, and from the shallow sublittoral to the 500-m isobath. Based on the data gaps that have been identified and an understanding of the dynamics of the study area, we suggest that primary sampling transects for future studies should extend from nearshore to the 500-m isobath at three locations:

- south-southeast from Freeport, TX.
- south from Cameron, LA.
- southeast from Isles Dernieres, LA (90°50'W).

These proposed transects cross areas containing major data gaps in most of the oceanographic disciplines. In addition, the two transects off Louisiana are shoreward extensions of transects occupied during the Minerals Management Service Northern Gulf of Mexico Continental Slope Study. About five or six stations should be located along each transect, and a full oceanographic sampling program should be conducted at each station, including long-term current meter arrays. To support the interpretation of results gathered from the above transects and stations, it is recommended that (1) seasonal, high resolution, quasi-synoptic hydrographic surveys be conducted within the suggested study area; (2) two meteorological recording stations be installed at approximately the 200- to 300-m isobath at about 92°W and 95°W Long.; and (3) an additional line of current meter arrays be concurrently located off south Texas along about 27°N Lat. Location of offshore stations should be chosen to complement data sets from ongoing or planned deep-sea investigations.

In order to build a credible data base and to document temporal variations, there should be three years of field sampling, followed by one to two years of data integration and synthesis. Year 1 activities could concentrate on sampling the primary transects, placement of meteorological sensors, and performing high-resolution hydrographic surveys. Years 2 and 3 could continue sampling of primary transects and high-resolution hydrographic surveys, and add the south Texas current meter array and biological and chemical sampling in special interest locations--e.g., Mississippi River near-delta environments, Mississippi Canyon area, and macro oil- or gas-seep regions on the upper slope (200 to 500 m), and selected hard banks.

Due to the dynamic nature of the Texas-Louisiana continental shelf and the interrelationships of its biological, chemical, geological, and physical environments, it is essential that any large-scale study be an integrated data collection program. Concurrent collection of data within these different disciplines will ensure the maximum usefulness of the data sets produced. In general, the biological, chemical, geological, and physical data should be collected at the same transects and stations, with some exceptions for special studies that may be needed in each discipline.

Previous studies have used various sampling methods and laboratory analyses whose results are not necessarily comparable (e.g., different mesh sizes for sieving macroinfauna). In order to make the most of the existing data in any future synthesis effort, it would make sense to standardize the methods to match or closely approximate those of one of the previous major studies. Alternatively, if new and different methodologies are to be used, then the relationships between the data sets produced by the old and new methods should be established.

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APPENDIX

REVIEW OF MAJOR ENVIRONMENTAL MONITORING STUDIES

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REVIEW OF MAJOR ENVIRONMENTAL MONITORING STUDIES

During the past 15 years, several major environmental studies of the Texas-Louisiana continental shelf have provided information about the effects of oil and gas development and other human intrusions. Six groups of studies are reviewed below:

- Offshore Ecology Investigation.
- Central Gulf Platform Study.
- Buccaneer Gas and Oil Field Study.
- Bureau of Land Management (BLM) rig monitoring programs under the South Texas Outer Continental Shelf (STOCS) and Mississippi-Alabama-Florida (MAFLA) baseline studies.
- Monitoring studies at the Flower Garden Banks and other shelf-edge banks.
- Strategic Petroleum Reserve (SPR) studies.

The Offshore Ecology Investigation, Central Gulf Platform Study, and Buccaneer Gas and Oil Field Study were major, multidisciplinary studies funded by government agencies to evaluate contaminants and biological effects around platforms in existing production fields. The rig monitoring programs under STOCS and MAFLA were sponsored by the BLM to evaluate effects of drilling single exploratory wells in shallow water off the Texas coast. Most of the monitoring studies at the Flower Garden Banks and other shelf-edge banks were funded by petroleum companies under lease stipulations (or other agency directives) requiring monitoring around biologically sensitive features; these studies focussed on the fate of drilling effluents from exploratory or production wells and effects on nearby hard-bank communities. The Strategic Petroleum Reserve studies were designed to monitor the effects of brine disposal off the Texas and Louisiana coasts.

The experimental design of three of these studies (Offshore Ecology Investigation, Central Gulf Platform Study, and Buccaneer Gas and Oil Field Study) have been critically examined by Carney (1987). Other problems are cited below, and major conclusions are summarized at the end of the review.

OFFSHORE ECOLOGY INVESTIGATION

This investigation, conducted by the Gulf Universities Research Consortium, was the first major study specifically directed toward determining the long-term effects of oil drilling and production on the marine environment. During 1972 to 1974, field studies were carried out in Timbalier Bay, LA and the adjacent nearshore continental shelf, a heavily developed "oil patch" area. Results were initially reported in unpublished technical reports, then compiled in a book (Ward et al., 1979). The compilation volume included an overview of study design

(Menzies et al., 1979) and an independent appraisal of study findings (Bender et al., 1979).

The Offshore Ecology Investigation included studies of hydrography, nutrient and pollutant chemistry, surface sediments, phytoplankton and zooplankton, benthic marine algae, foraminifera, macroinfauna, demersal fishes and macroinvertebrates, and platform biofouling communities. In general, the summary reports in Ward et al. (1979) indicated either that (1) there were no effects of oil production on the biota, or (2) effects, if present, could not be detected because of problems in design, sampling adequacy, and overwhelming natural variability. The latter conclusion is perhaps the most appropriate epitaph for this study.

The design, organization, methods, and conclusions of the Offshore Ecology Investigation have been criticized by a number of authors (see Carney, 1987). Individual parts of the study varied greatly in quality and thoroughness, and there was little coordination of sampling efforts or interpretation. In addition, the suitability of the control stations was questioned because the large amount of offshore drilling and production in the study area may make an unexposed control impossible. However, taken as a whole, the investigation provided an important baseline of taxonomic data and standing crop information about this very productive and previously uninvestigated area near the Mississippi River Delta. It also provided considerable information on the spatial and temporal variability of populations of this region, which is highly influenced by outflow from the Mississippi River.

CENTRAL GULF PLATFORM STUDY

The Central Gulf Platform Study was conducted in 1978 to 1979 in the highly developed "oil patch" area just west of the Mississippi Delta. The study, directed by Southwest Research Institute under the sponsorship of the BLM, was intended to evaluate effects of oil and gas production platforms on the surrounding environment. The approach was to (1) compare environmental and faunal characteristics at platform and "control" sites and (2) examine environmental and faunal gradients around platforms. In addition, there was a separate study of biofouling communities and fishes at selected platforms. Study methods and results are presented in the final report edited by Bedinger (1981).

Twenty-four sites were sampled: 4 primary platform sites, 16 secondary platform sites, and 4 control sites (no platforms). The sites represented a range of water depths (6 to 75 m) and environmental conditions, from turbid, estuarine waters to the open ocean. The primary platforms and control sites were sampled on three cruises: April to May 1978, August to September 1978, and January 1979. Secondary platforms were sampled only on the second cruise. Artificial reef studies were begun during a separate cruise in June 1978 and completed during the August to September 1978 cruise.

At the primary platform sites, stations were sampled at distances of 100, 500, 1,000, and 2,000 m on four radial transects extending north, south, east, and west from the platform. At the secondary platforms, only the northern transect was sampled. Control sites were sampled as single stations. Vertical profiles of temperature, salinity, dissolved oxygen, and transmittance were taken at each site on each cruise. Grab samples were collected at all stations on one or more cruises, and subsamples were analyzed for sediment texture, total organic carbon, clay mineralogy, hydrocarbons, trace metals, microbes (various abundance and activity measures), meiofauna, and macroinfauna. Demersal fishes and invertebrates were collected by trawl sampling (all sites) and angling (platforms only), and specimens were analyzed for trace metals, hydrocarbons, and histopathological abnormalities. In addition, water samples were collected at each site on all cruises and analyzed for hydrocarbons. On the artificial reef surveys, divers photographed and scraped biofouling epibiota on platform legs and videotaped reef fish populations around the platforms.

The physical and chemical measurements showed that the water, sediment, and biota around some production platforms were contaminated with petrogenic hydrocarbons and trace metals. Elevated concentrations of low-molecular-weight hydrocarbons (LMWH) were present in the water column throughout the study area; several platforms had particularly high concentrations, probably due to production-related activities such as brine discharge and gas venting. Sediments from around most platforms had high-molecular-weight hydrocarbons (HMWH) of diverse origin, with the concentrations depending on sediment type, proximity to river discharge, and in some instances, platform activities. There was evidence of petrogenic and pyrogenic hydrocarbons in sediments around several platforms. There were also localized elevations in concentrations of some trace metals, primarily at the stations nearest to the platforms (100 m). At several platforms, there was a gradient in trace metal concentrations with distance from the platform, but no relationship to platform age or the number of wells was discerned.

Chemical analyses of fish and epibiota indicated no major contamination problems. However, the hydrocarbon analysis results suggested that many organisms had been exposed to low levels of petrogenic and pyrogenic hydrocarbons. The incidence of histopathological abnormalities was higher at some platforms (particularly in the eastern part of the study area) than at other platforms and the control sites; however, interpretation was confounded by the differences in species collected at the platforms vs. control sites.

Benthic faunal analyses were not conclusive regarding effects of the platforms or contaminants, in part because of confounding with other major influences, such as the presence of extensive areas of anoxic bottom water, or "dead bottom" during the spring and summer. The anoxia is apparently caused by the oxygen demand created by nutrients and organic matter entering the area from Mississippi River runoff. The main influences on benthic populations in the study area were apparently water depth, distance from shore, salinity, sediment texture, dissolved oxygen, and proximity to Mississippi River discharge.

The artificial reef studies documented the presence of characteristic biofouling communities on platform legs and associated reef fishes attracted to the submerged structures. Three zones of fouling communities were proposed: coastal (<27 m), offshore (27 to 64 m), an blue water (>64 m). Some localized adverse effects of produced water discharges on the epibiota of platform legs was noted.

The Central Gulf Platform Study has been critiqued by Carney (1987), who listed four major failings: (1) a lack of prior hypotheses about impacts; (2) faunal surveys that made little use of the experimental design to evaluate impacts; (3) an inadequate attempt to accommodate natural variability in the treatment of replicates and in the analyses; and (4) a tendency to state opinion as fact when the findings were equivocal. Nevertheless, the study was a great improvement in design and execution over the Offshore Ecology Investigation.

BUCCANEER GAS AND OIL FIELD STUDY

Another major investigation was the Buccaneer Gas and Oil Field Study (1975 to 1980), funded by the U.S. Environmental Protection Agency (EPA) through an interagency agreement with the National Oceanic and Atmospheric Administration (NOAA), and administered by the National Marine Fisheries Service (NMFS), Southeast Fisheries Center in Galveston, TX. The final year of the study produced six "milestone" or synthesis reports edited by Jackson and Wilkens (1980). A symposium was held in 1980, and the proceedings were published as a book edited by Middleditch (1981).

The study site, a production field located 50 km south of Galveston, had been in operation for 15 years prior to 1975, providing an opportunity to examine long-term effects of oil and gas development and production activities. Because the production field was isolated from others, the investigators were able to sample unaffected "control" areas nearby--a distinct advantage over the Offshore Ecology Investigation and the Central Gulf Platform Study, which were in highly developed areas. The Buccaneer Gas and Oil Field Study consisted of two production platforms and numerous other structures, including quarters platforms, satellite platforms, and flare stacks. "Control" areas were located 9.3 km to the northeast and southwest of the field.

The Buccaneer Gas and Oil Field Study was multidisciplinary (like the Offshore Ecology Investigation) rather than interdisciplinary (like the Central Gulf Platform Study). That is, sampling programs of various investigators were conducted independently (with some exceptions during the later years). The study included current and hydrographic measurements; various analyses of water samples and suspended particulate matter; analyses of platform effluents for hydrocarbons, trace metals, and sulfur; analyses of sediment samples for grain size, mineralogy, total organic carbon, stable carbon isotopes, hydrocarbons, and trace metals; grab sampling of macroinfauna and meiofauna; trawl sampling of demersal fishes and macrocrustaceans; studies of biofouling communities and platform-associated fishes; bacteriological, histopathological, and toxicological analyses; observations of marine birds; and hydrodynamic and ecological modeling efforts.

According to Gallaway et al. (1981), the most significant environmental effect demonstrated during the Buccaneer Gas and Oil Field Study was the "artificial reef" effect of the submerged structures. The platforms and other submerged structures provide attachment surfaces for fouling communities and attract numerous pelagic and reef fishes. Localized adverse effects of produced (formation) water discharges on the fouling community on platform legs were documented (within 1 m vertically and 10 m horizontally from the discharge point). Possible localized effects on benthic macrofaunal communities near the two production platforms were also identified (e.g., reduced abundance, distinct species composition), but causes were not determined; unfortunately, the macrofaunal sampling was discontinued after the first full study year (Harper et al., 1981). There was some bioaccumulation of contaminants (alkane hydrocarbons), mainly in fouling community organisms, but no evidence of a general build-up of contaminants in the food web or in organisms eaten by humans (Gallaway et al., 1981).

The Buccaneer Gas and Oil Field Study [or more specifically, the benthic sampling program reported by Harper et al. (1981)] has been criticized by Carney (1987) on several grounds. First, the faunal and environmental data were not collected concurrently or at the same stations, limiting the ability to correlate exposure and response variables. Second, neither the treatment of replicates nor the analyses presented dealt effectively with natural variability. Carney (1987) did not review the discussion by Gallaway et al. (1981), which was a more thorough and integrated attempt to evaluate environmental effects in the Buccaneer Field. However, the comments about lack of coordination among sampling programs is well taken. In addition, the termination of infaunal sampling after the first study year was unfortunate, as a better understanding of effects might have been obtained through further sampling (particularly if environmental samples were collected concurrently at the benthic biological stations).

BLM RIG MONITORING PROGRAMS

Two rig monitoring programs were conducted between 1975 and 1977 as part of the BLM STOCS and MAFLA baseline studies. Both programs focused on the short term environmental effects of drilling a single exploratory well in a water depth of about 35 m off Corpus Christi, Texas.

The MAFLA rig monitoring program was described by Alexander et al. (1977), and additional information on trace metals in sediment and organisms is provided by Boothe and Presley (1987). A single exploratory well was drilled between December 1975 and January 1976, and surveys were conducted before, during, and three months after drilling. Stations were sampled at distances of 100 m, 500 m, and 1,000 m along eight radial transects extending from the drillsite. Sediment samples were collected and analyzed for texture, clay mineralogy, trace metals, and HMWH. Macroepifauna (mainly shrimp) collected by trawling were analyzed for trace metals, hydrocarbons, and histopathological abnormalities. Foraminiferans were identified and counted in sediment samples. Reported effects of drilling were as follows:

- Changes in sediment texture were noted.

- Visible accumulations of cuttings occurred at four 100-m stations and one 500-m station during and after drilling.

- Elevated barium and chromium concentrations were detected in sediments at some stations at 100 m, 500 m, and 1,000 m, with the largest changes (up to 7.5-fold increase in barium) near the drillsite.

- Shrimp muscle tissue had elevated iron concentrations during drilling.

- Abundance of forams declined at 100 m, 500 m, and 1,000 m distances during drilling, with some recovery by three months after drilling.

The STOCS rig monitoring program was similar in design. A single exploratory well was drilled from December 1976 to January 1977, and surveys were conducted before, during, and after drilling (Groover, 1977). Stations were sampled at distances of 100 m, 500 m, 1,000 m, and 2,000 m on 16 radial transects (although not all parameters were sampled at each station). The program included current and hydrographic measurements, water sampling (for LMWH, suspended sediment mineralogy, and suspended sediment trace metals), sediment sampling (for texture, trace metals, and hydrocarbons), grab sampling of macrofauna and meiofauna, and trawl sampling of fishes and macroepifauna and fishes (for taxonomy, trace metals, and hydrocarbons). Major results were as follows:

- Accumulations of "foreign material" (presumably cuttings) were seen at the drillsite.

- Sediment concentrations of barium, cadmium, and zinc increased at the drillsite.

- Petroleum hydrocarbon contamination was detected in one of three sediment samples from the drillsite.

- Macroinfaunal populations were depressed at the drillsite.

Some other changes were noted between surveys, including declines in the abundance of meiofauna at some stations and declines in abundance of trawl-caught fishes and invertebrates within the 1-km radius of the drillsite. However, these changes were not conclusively attributable to drilling. The summary report concludes that physical, chemical, geological, and biological effects were primarily in the immediate vicinity of the drillsite (within 100 m) (Groover, 1977).

MONITORING STUDIES AT THE FLOWER GARDEN BANKS AND OTHER SHELF-EDGE BANKS

Several environmental monitoring studies have been conducted at the East and West Flower Garden Banks and other shelf-edge banks to evaluate effects of exploratory or production drilling in nearby lease blocks. These monitoring programs differ from those described previously in several respects:

- Most of the studies were not funded by government agencies, but by oil companies. The monitoring studies were required by regulatory agencies for drilling near the Flower Garden Banks and certain other banks on the Texas-Louisiana shelf.
- In most cases, the regulatory agencies required that drilling muds and cuttings be shunted to within 10 m of the seafloor to minimize the chance that corals and other reef biota atop the banks would be exposed to drilling effluents.
- The studies were mainly concerned with the fate of drilling effluents (mud and cuttings) and their effects on the biological communities atop the bank, rather than effects on the biota surrounding the rig or platform.

Most monitoring to date has been conducted at the East Flower Garden Bank in conjunction with exploratory and production drilling in High Island Area Block A-389. The drillsites were within about 2,000 m to the southeast of the 85-m depth contour taken as the boundary of the East Flower Garden Bank. In 1975, two wells were drilled, and a monitoring program was conducted by Continental Shelf Associates, Inc. (1975). Two more exploratory wells were drilled and monitored in 1977 (Continental Shelf Associates, Inc., 1978a; Gettleson, 1978; Gettleson and Laird, 1980). Finally, a production platform was installed in September 1981, and six production wells were drilled between April 1982 and April 1983. Production drilling was monitored under a program funded by Mobil (Continental Shelf Associates, Inc., 1985a) and a separate study of reef fish populations funded by EPA under interagency agreement with the NOAA, NMFS Southeast Fisheries Center, Galveston Laboratory (Boland et al., 1983).

All three of the Mobil-funded studies in Block A-389 included current measurements, hydrographic profiles, sediment sampling, sediment trapping, and visual observations and photographic sampling of corals (coral reef zone). The monitoring program for production drilling was the most complex, consisting of a pre-drilling survey, three during-drilling surveys, and a post-drilling survey. The program included continuous current measurements; vertical profiling of temperature, salinity, dissolved oxygen, and transmissivity; analysis of drilling muds for trace metals (barium, chromium, cadmium, copper, lead, and zinc) and hydrocarbons; analysis of bottom sediments, trapped sediments, and bivalves for trace metals (barium, chromium) and hydrocarbons; visual observations, repetitive photographic examination of coral margins, coral vertical growth measurements, transect photography, and larval colonization studies within the coral reef zone of the East Flower Garden Bank.

The most significant results emerging from the Mobil-funded monitoring programs in Block A-389 were as follows:

- Current measurements indicated that drilling effluents (released within 10 m of the bottom) were rarely transported toward the bank. This is consistent with previous studies showing topographic steering of currents around the base of the bank.

- Sediment trap results indicated that drilling muds were not deposited on the coral reef zone of the bank. The observational evidence was supported by calculations (McGrail, 1981) which indicate that sediments discharged into the nepheloid layer could not be transported into the coral reef zone even under worst-case conditions (high velocity currents directed toward the bank).

- Visual observations and photographic analyses of corals in the coral reef zone did not reveal any changes attributable to drilling.

During 1980 through 1982, additional studies of reef fish populations were conducted at the East Flower Garden Bank and at the production platform in Block A-389 as part of an EPA-NOAA monitoring program (Boland et al., 1983). These studies did not detect any effect of drilling on the reef fish communities of the East Flower Garden Bank, a result consistent with the lack of exposure to drilling effluents cited above (Continental Shelf Associates, Inc., 1985a). The most significant aspect of production activities was the installation of the platform, which attracted reef fish species commonly found on the bank as well as some other species not previously seen there (Boland et al., 1983).

Two other studies of exploratory drilling have been conducted at the Flower Garden Banks. In the first (Continental Shelf Associates, Inc., 1978b), the drillsite was about 2,000 m northeast of the 85-m isobath of the East Flower Garden Bank; drilling muds and cuttings were discharged near the surface (not shunted). Sediment samples were collected around the drillsite, but no sediment or sediment trap samples were collected on the bank, and there were no biological studies in the coral reef zone. However, current measurements indicated that discharged material was not likely to be transported toward the bank (Continental Shelf Associates, Inc., 1978b; Gettleson and Laird, 1980). In a later study conducted at the West Flower Garden Bank, the results were very similar to those reported above for monitoring in Block A-389: (1) currents were rarely directed toward the bank; (2) drilling muds did not reach the coral reef zone; and (3) no effects on the coral community were detected (Continental Shelf Associates, Inc., 1983).

The monitoring studies at the Flower Garden Banks have not provided any information about effects of drilling effluents on coral communities. However, the studies have shown that when drilling discharges are shunted to within 10 m of the bottom, the material does not reach the coral reef zone of these high-relief banks. This finding has prompted the Minerals Management Service (MMS) to uniformly require shunting of all drilling discharges within a 4-NM zone from the boundary (taken as the 100-m depth contour) of the East and West Flower Garden Banks (USDI, MMS, 1988).

There have been several monitoring studies at other shelf-edge banks (e.g., Alderdice, Applebaum, Baker, Stetson, and Rankin Bank; Bright and Rezak, 1978a,b; Continental Shelf Associates, Inc., 1985b, 1986; Gettleson, 1980; Gettleson and Laird, 1980), but none have involved quantitative biological sampling. In most cases, shunting of drilling effluents was required, and no drilling mud was detected on the banks being monitored. However, in two cases involving surface (unshunted) discharges, small quantities of drilling muds have been detected in sediment traps on hard bank communities after exploratory drilling. One study was conducted near Applebaum Bank (Continental Shelf Associates, Inc., 1985b), the other near Rankin Bank (formerly 28 Fathom Bank) (Continental Shelf Associates, Inc., 1986). In both cases, the biological studies consisted of towing a video camera and still camera across the bank to record qualitative observations before and after drilling. Therefore, biological effects of the exposure (other than catastrophic changes, which were not seen) could not be evaluated on the basis of the field studies.

STRATEGIC PETROLEUM RESERVE (SPR) STUDIES

The underground storage of up to a billion barrels of crude oil for the SPR has required the creation of vast solution caverns in coastal salt domes. This, in turn, has necessitated the release into nearshore waters of the Louisiana/Texas shelf of up to 400 x 10^6 bbl/year of saturated brine with salinities seven to eight times that of normal seawater at each of three reserve storage sites. In order to assess the environmental effects of such massive brine release, the Department of Energy sponsored extensive field studies between 1977 and 1985 at two coastal locations: the West Hackberry site (11 km off southwestern Louisiana) and the Bryan Mound site (18 km off the Texas coast west of Galveston Bay). At both sites, pre-release studies were carried out to provide baseline data, and the environmental studies were continued through several years of brine discharge. Included were investigations of physical oceanography, water and sediment chemistry, and biology (phytoplankton, zooplankton, benthos, and "nekton" = trawlable invertebrates and fishes). Controls included data from the pre-release studies as well as from "test" stations located some distance from the brine release sites and which were likely unaffected by the brine. Data analysis was characterized by thorough statistical treatment and modeling procedures. Although some effects on water and sediment quality were observed, the brine was rapidly mixed and diluted, and the effects were neither widespread nor persistent. Some very local biological changes were observed in the vicinity of brine release, but these could not be definitely attributed to the brine. High natural biological variability, summer hypoxia, and infrequent sampling tended to confound the analyses and preclude possible detection of subtle effects. From a regional standpoint these studies are of considerable interest because they provide an invaluable multi-year data base, and they document biological responses to summer bottom-water hypoxia in both areas.

CONCLUSIONS

All of the studies reviewed had problems in experimental design, execution, analysis, and interpretation, or in discerning effects of oil and gas operations from natural variability. Carney (1987) has reviewed many of these problems and suggested improvements in study design. However, despite the problems, many of the study findings are valid. When the results of the studies are compared and synthesized, several major conclusions emerge:

- The most obvious biological consequence of oil and gas development on the Texas-Louisiana shelf is the artificial reef effect of the platforms--i.e., the development of fouling communities on the submerged structures, and the attraction of reef fishes.

- Effects on the benthos in the immediate vicinity of a drilling rig or platform have been documented. In both the Buccaneer Gas and Oil Field and STOCS rig monitoring studies, infaunal populations near the rig (or platform) were depressed. Possible contributing factors include burial and smothering by drilling discharges, erosion of sediments around platforms, increased predation by fishes attracted to the structures, and chronic exposure to contaminants in sediments.

- Biological effects beyond the immediate vicinity (few hundred meters) of a rig or platform have not been demonstrated convincingly, because of experimental design problems, high natural variability, and the subtle nature of the effects to be detected.

- The presence of contaminants (trace metals, petrogenic hydrocarbons) in biota around production platforms has been demonstrated in both the Central Gulf Platform Study and the Buccaneer Gas and Oil Field Study. However, in both cases, the contaminants were primarily in species directly associated with the platforms or the fouling community food chain, and contaminant levels were not high enough to pose a health threat to human consumers.

- Effects of drilling effluents on hard bank communities have never been evaluated in a monitoring program. At the Flower Garden Banks, exposure of the reef corals has been prevented through shunting of drilling effluents. At two other shelf-edge banks (Applebaum and Rankin), the bank communities have been exposed to small amounts of drilling effluents during exploratory drilling, but there was no quantitative monitoring of the biota.

- There are lingering uncertainties about the effects of long-term, chronic exposure to low levels of contaminants from oil and gas activities, particularly in heavily developed areas or where dispersion is limited.

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