A. Robertson

Proceedings of a Symposium

on

# ENVIRONMENTAL RESEARCH NEEDS IN THE GULF OF MEXICO (GOMEX)

KEY BISCAYNE, FLORIDA, 30 SEPTEMBER--5 OCTOBER 1979

Volume IIA

May 1981

U.S. DEPARTMENT OF COMMERCE

National Oceanic and Atmospheric Administration

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Donald K. Atwood, Convener



Atlantic Oceanographic and Meteorological Laboratories

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Malcolm Baldrige, Secretary

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James P. Walsh, Acting Administrator

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CONTENTS

Page

Volume IIC - Summary Papers

# GULF OF MEXICO: A SOCIOECONOMIC VIEW OF COMPETING RESOURCES

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# 1. INTRODUCTION

The socioeconomic environment of the coastal region of the Gulf of Mexico is highly varied in terms of human quality. Although specific data on the coastal region socioeconomic patterns, trends, needs, and uses are essentially unavailable, sound policy development and effective management are dependent upon correct assessment of these factors. The purpose of this paper is to provide a socioeconomic basis for assessing man's impact on the marine environment and to describe the socioeconomic processes that relate to marine pollution concerns.

This review of existing data summarizes what is known about the socio-economic activities that effect the greatest alteration in the Gulf of Mexico region. These activities include demographic changes, industrial development (petroleum, waterborne transportation, and ocean dumping), and commercial fishing. Data are included for five states: Texas, Louisiana, Mississippi, Alabama, and Florida.

The primary ways in which socioeconomic sectors interact with coastal processes are: (1) generation of wastes (industrial and domestic) that are discharged into the environment; (2) habitat modification, such as impounding, draining, polluting, and filling wetlands; and (3) natural resource exploitation, including water use. Various socioeconomic sectors, such as transportation and mineral extraction, may generate the same kinds of activities, so the environmental impact of one sector is often difficult to distinguish. Further, the impact of one sector is almost always in parallel with that of other sectors; increased industrial activity not only generates additional industrial wastes but also may increase domestic pollutants as the labor force increases.

A recent study of the Mississippi deltaic plain region shows the extensive impact that socioeconomic factors have had on habitats in the area between 1955 and 1975 (U.S. Department of the Interior, Fish and Wildlife Service, 1979). Because of erosion, subsidence, road building, canal dredging, levee construction along the Mississippi River, and numerous other factors, large areas that were fresh marsh in 1955 had become either brackish or salt marsh, or open water by 1975.

While socioeconomic factors affect fish and wildlife habitats, changes in habitats also have direct socioeconomic results, such as effects on entire tax structures; e.g., fresh marsh (in Louisiana) is taxed at $3/acre/year, brackish marsh at $2/acre/year, and salt-marsh at $1/acre/year. If an area becomes open water, the title to the land reverts to the state.

Fresh marshes are the primary region for trapping, and their loss means the decline of a profitable economic activity. Changes in marsh habitats affect commercial fishing and shrimping activities, as well as recreational fishing and hunting. Marshes also act as a buffer between settled areas and the Gulf during hurricanes, and marsh loss leaves residents far more vulnerable to flood and wave damage.

## 2. DEMOGRAPHIC PATTERNS

The population factor may be considered a basic ingredient of any region's economy because of the far-reaching impact of demographic changes. In general, there has been rapid population growth in the South during the last decade, with the greatest rates of increase occurring in the coastal states and, within them, in the coastal belt itself.

Between the years 1965 and 1975, the population of the United States increased by approximately 10 percent. The South accounted for less than one-third of the nation's population growth in the first 5 years of that period, but accounted for more than half in 1970-1975 (U.S. Department of the Interior, Bureau of Land Management, 1978). In the states that border the Gulf Coast, population increases ranged from less than half to more than four times the national rate (Table 1). By 1975, the populations of Texas, Louisiana, and Mississippi were already greater than had been projected for 1980.

Figures for statewide increases generally mask the proportionately greater growth in the coastal counties. In Texas, for example, the state's population was expected to increase by approximately 15% between 1970 and 1980, while the coastal population was projected to increase by 22% in the same decade (General Land Office of Texas, Texas Coastal Management Program, 1975).

Demographic changes in the Gulf states also include shifts in patterns of distribution. Consolidation of agricultural operations and an associated increase in mechanized operation have contributed to a decline in farm population; at the same time, urban growth and suburban sprawl have pushed into formerly rural areas.

The major urban concentrations in the Gulf coastal zone include Houston, Galveston, Port Arthur, and Beaumont, Texas; New Orleans and Baton Rouge, Louisiana; virtually the entire Mississippi/Alabama Gulf coast from Bay St. Louis to Mobile; and Tampa/St. Petersburg and Pensacola, Florida (Figure 1). Numerous smaller urban areas are scattered along the coast.

Increasing industrial development and employment have paralleled urban growth and rural decline in the South. For all the Gulf coastal states, employment in industry increased rapidly between 1965 and 1975, while farm employment declined (Table 2). During the same decade, per capita income more than doubled in all five states. The petroleum industry, a major field of employment, expanded production in Alabama, Louisiana, Texas, and Florida, although production in Mississippi declined.

Three population trends for the Gulf Coast region may be extrapolated to the year 2000: there will be (1) continued absolute growth, with a small natural increase of population; (2) continued net in-migration at a rate lower than in the early 1970's; and (3) stabilization of urban populations (within the present urban limits), while suburban populations continue to grow.

## 3. ECONOMIC DEVELOPMENT

Commercial and industrial resource uses in the Gulf area are most closely associated with petroleum and petrochemical production, commercial fishing, recreation, and agriculture. Of these, activities associated with the petroleum industry have generated the greatest economic development and also have the greatest environmental impact on the region.

A recent study of the Chenier Plan (southwest Louisiana and southeast Texas) by the U.S. Fish and Wildlife Service (1979) compared the impacts of the major activities of various economic sectors. The types of waste generation, habitat modification, and natural resource exploitation associated with each major commercial and industrial activity are shown in Table 3.

The study also compared the annual values of major resources exploited by several economic sectors. The dollar value of minerals extracted in 1974 was six times the total value of renewable resources. Although these statistics do not represent all areas of the Gulf coast equally, the comparisons may be applied directly to much of the region and are related to the socioeconomic environment of the region as a whole.

For the purpose of discussing economic development, the Gulf coastal zone may be subdivided as follows: Texas - western Gulf; Louisiana - central Gulf; Mississippi, Alabama, and western Florida - eastern Gulf. (For the several states, available data vary in date, detail, and scale.) In general, the density of industrial development, particularly petroleum and petrochemical industries, is much greater in the western and central Gulf than in the eastern Gulf. Although some heavy industry (shipbuilding and metal fabrication) is a major activity in Mobile, Alabama, and Pascagoula, Mississippi, lighter industries such as textile production and food processing are more typical of the eastern Gulf as a whole.

### 3.1 Petroleum Refineries and Support Industries

The production of hydrocarbons in the coastal region of the Gulf states has led to the development of an extensive system of production, transportation, refining, and manufacturing facilities. Oil and gas resources include crude oil, condensate, natural gas, and liquified natural gas. In 1975, about 65% of all U.S. oil was produced in the Gulf coastal states (U.S. Department of the Interior, Bureau of Land Management, 1978). Crude oil production declined in the three major petroleum areas (Louisiana, Texas, and Mississippi) during 1973-1975 (Table 4).

On January 1, 1977, the crude oil capacity of petroleum refineries on the Gulf coast was about 37% of the total U.S. capacity (Table 5). By far the greatest refinery capacity was on the western and central Gulf coast (Texas and Louisiana). Additional crude oil refining capacity under construction in the Gulf coastal area amounts to about 58% of the capacity under construction in the United States (Table 6).

By 1972, the western Gulf coast had the nation's greatest concentration of chemical plants, producing more than 40% of every basic petrochemical, 80% of the synthetic rubber, and 60% of the nation's sulphur (U.S. Department of the Interior, Bureau of Land Management, 1978). Support industries for petroleum production include shipyards that supply the oil and gas industry with drilling platforms, tugs, barges, crewboats, and other specialized vessels. Other oil field service companies supply mud, cement, logging services, casing, valves, bits, transportation, and technical expertise such as directional drilling, mapping, and geological and geophysical services.

The production of crude oil and condensate in the Gulf coast area declined between 1973 and 1975 (Table 4). Slight increases in Alabama and Florida were more than offset by decreases in Texas, Louisiana, and Mississippi, reflecting the national trend.

Industry leaders have ranked the factors deterring growth of petrochemical firms or plants in Texas (Table 7). The principal deterrents were lack of feedstocks (raw materials), remoteness from markets, and the poor availability of energy.

Petrochemical industry representatives also ranked the factors that could change the future level of activity of their operations (Table 8). Additional technological factors that could affect the petrochemical industry include new or improved processes or products, environmental control costs, and alternative fuel sources.

Trend projection must take into account the reasons for location of industry in the past. The major factors to date have been the impetus of an early start and the availability of existing facilities, proximity to raw materials, nearness to markets, and the availability of land, labor and transportation.

The Department of Energy (DOE), through the Strategic Petroleum Reserve Program, has developed plans for storing more than a billion barrels of petroleum in solution-mined salt cavities (salt domes) along the Gulf of Mexico coast (Figure 2). Water quality is a serious environmental issue associated with the plan, as large quantities of brine will be produced in leaching the cavities and in evacuating existing cavities. Disposal of brine into the Gulf is the alternative considered most feasible (Figure 2).

Environmental concern regarding marine disposal of concentrated brine focuses on several anticipated problems. A major issue is the possible creation of a large volume of seawater with salinity exceeding the tolerance limits of indigenous biologic populations. An additional concern is the possibility of stable vertical stratification of seawater, as the brine may contain dissolved solids of 250 ppt. and an average density of 1/2 g/cm$^3$, in contrast with an average ambient seawater salinity of 30-35 ppt. and density of about 1.025 g/cm$^3$. In the relatively shallow nearshore marine environment, the brine may create a dense lens that would sink and spread over the bottom, filling topographic depressions and becoming a semipermanent bottom feature (U. S. Dept. of Commerce, NOAA, 1978). NOAA has provided DOE with preliminary information that could be used to facilitate selecting environmentally appropriate locations, configurations, and sizes of brine disposal diffuser systems. These reports covered the Bryan Mound, West Hackberry Capline Sector, and Big Hill discharge sites, and also provided information regarding surface brine disposal at two selected offshore domes (Figure 2). Baseline monitoring field programs have been implemented at the Bryan Mound, Texoma, and Capline Sector brine discharge sites to undertake monthly physical oceanographic sampling, assessment of nekton and benthic communities, collection of sediment cores, and bioassay studies on selected fauna and flora considered to be representative of the disposal core in an effort to determine the acute toxicities resulting from brine discharge.

The immediately critical socioeconomic and strategic concern that has given impetus to development of the Petroleum Reserve Program has been the threat of interruption in the supply of foreign oil. Plans originally provided for the storage of 100 million barrels by December 22, 1978, and 1 billion barrels by December 22, 1985. Stored oil would be withdrawn when necessary, and caverns would be refilled after foreign oil supplies resumed normal levels.

## 3.2 Waterborne Commerce

The Gulf of Mexico coastal region is served by an extensive waterborne transportation system, as well as by other forms of transportation, that connect all major ports with inland areas. For the western, central, and part of the eastern (Mississippi/Alabama) Gulf region, most waterborne traffic is connected with petroleum and petroleum-related industries. (For Florida, the data are treated separately, inasmuch as the character of the shipping is very different.)

In 1977, 622 million tons of freight passed through the 16 major ports and harbors along the Gulf coast from Brownsville to Mobile (Table 9). Approximately 354 million tons (321 million metric tons), or more than 50%, were crude oil and petroleum products. Of this tonnage, 284 million tons (258 million metric tons), or approximately 45%, moved in foreign trade. More than half of the foreign tonnage was crude petroleum. The contribution of foreign petroleum imports to total tonnage has increased rapidly in recent years.

Several of the nation's largest ports are within the Gulf coastal area. The Port of New Orleans is the nation's second largest port, Houston is the third largest, and Corpus Christi is ninth. Data on port facilities and marine transportation may be categorized, by states, as follows:

### Texas

Deep water ports in Texas include: Beaumont, Brownsville, Corpus Christi, Freeport, Galveston, Houston, Orange, Port Arthur, Port Isabel, Point Comfort, Texas City, and Sabine Pass Harbor.

Texas ports handle foreign, domestic, and internal waterborne traffic. Of the ocean traffic, approximately two-thirds is domestic commerce and the remainder is in foreign trade. Most of the outbound tonnage consists of liquid petroleum products. Of total tonnage, 64% is shipped out; 36% is received.

Most of the waterway traffic in Texas is on the Gulf Intracoastal Waterway, which extends from Brownsville, Texas, to Apalachee Bay, Florida. The Intracoastal Waterway comprises 1791 km of canals; 681 km are in Texas. The Intracoastal Waterway connects all ports on the Gulf of Mexico to an extensive (9654 km) inland waterway system centering on the Mississippi River. Industrial expansion in the Texas coastal zone has been related to the waterway, with more than 80% of additional tonnage of waterborne traffic developed in the last 15 years occurring on the canal. No locks are required on the Intracoastal Waterway in Texas because all portions of the canal are at sea level.

Of the total tonnage transported on the Texas sections of the Intracoastal Waterway, approximately 22% consists of crude petroleum, and 33% consists of petroleum and related industries. Including the petrochemical industry, approximately 85% of all tonnage handled at Texas ports consists of crude oil or petroleum products.

## Louisiana

The major waterways in Louisiana are the Mississippi River and the Gulf Intracoastal Waterway. Other waterways that are important for commerce are the Calcasieu, Atchafalaya, Mermentau, Vermilion, and Pearl Rivers; Barataria Bay, Bayou LaFourche, the Houma Navigation Canal, and the Mississippi River-Gulf Outlet.

The major ports for Louisiana are New Orleans, Baton Rouge, and Lake Charles. New Orleans is the largest port on the Gulf of Mexico. Baton Rouge, located on the Mississippi River upstream from New Orleans, ranks as the nation's seventh largest port in terms of tonnage. Lake Charles ranks twentieth among the nation's ports. For all of these ports, petroleum and petroleum products comprise much of the bulk cargo. Grains, ores, and other bulk cargo are also important.

A deepwater offshore oil terminal has been licensed for Louisiana, to be located 18 miles off LaFourche Parish in the Gulf of Mexico. A large (420,000 Mcf per day) liquid natural gas terminal is planned for Lake Charles.

## Mississippi

The major navigation channel in coastal Mississippi is the Gulf Intracoastal Waterway, which links all ports along the Mississippi Gulf Coast with inland waterway systems that empty into the Gulf of Mexico. Other major waterways include the Pascagoula River, Jourdan River, Pearl River, and the Bayou Portage Channel.

The principal ports on the Mississippi Gulf coast are Pascagoula Harbor and Gulfport. In 1973, these ports, together with Biloxi, handled a total of 15,112,000 short tons of freight traffic. Of the total, 3,787,000 short tons were in foreign trade.

Alabama

Alabama's only coastal port is the Port of Mobile, which is served by a 42' X 600' channel approximately 1-1/2 miles long across Mobile Bay, a main channel that extends 35 miles from the Gulf of Mexico through Mobile Bay into Mobile River. The Mobile/Tombigbee-Black Warrior River system accommodates barge traffic northward from the Port of Mobile to Port Birmingham.

Florida

The major coastal navigation channel on the Florida Gulf Coast is the Gulf Intracoastal Waterway that links ports on the State's west coast with Gulf ports in Texas, Louisiana, Mississippi, and Alabama. The major Florida ports on the Gulf include Tampa Harbor, Port St. Joe, Panama City, and Pensacola.

## 3.3 Nuclear and Fossil Fuel Electric Generation Plants

Present power generating facilities in the Gulf coastal region include a number of affiliates with interconnected facilities. The major companies are, among others, Central Power and Light and Houston Power and Lighting in Texas; Louisiana Power and Light Company and Gulf States Utilities in Louisiana; and the Southern Company and its affiliates, particularly Mississippi Power Company, Alabama Power Company, and Gulf Power Company, the latter serving the panhandle of Florida. Florida Power and Light provides power for the southern Gulf coast of Florida.

In the western Gulf coast region (Texas), power is generated primarily by natural gas. A coal-fired generating plant is under construction by Central Power and Light at Coleto Creek, Texas. Houston Lighting and Power has one coal project in operation near Richmond, Texas, 25 miles southwest of Houston. The two companies (Central Power and Light and Houston Lighting and Power) are in a joint venture with the city of Austin (a municipal power agency) and City Public Service of San Antonio to build a nuclear power facility, called the "South Texas Project," near Bay City. This plant is now under construction. Impact studies have been done and permits applied for to build a nuclear facility at Allen's Creek, Texas. No nuclear facilities are currently in operation.

In the central Gulf coastal region (Louisiana), natural gas has been the major fuel for steam-electric generating stations. In 1961, Louisiana Power and Light constructed the world's first steam-electric generating station capable of fully automatic operation at a site called "Little Gypsy", on the Mississippi River approximately 25 miles upriver from New Orleans. Louisiana Power and Light has also constructed another facility, Nine-mile Point, a steam-electric generating station in Jefferson Parish approximately nine miles upriver from downtown New Orleans.

Other Louisiana Power and Light power plants have been constructed at Buras, in Placquemine Parish, and at Thibodaux, in LaFourche Parish. Louisiana Power and Light is planning to build its first coal-fired generating unit for operation in the mid-to-late 1980s.

The first nuclear-fueled electric generating plant in Louisiana is under construction by Louisiana Power and Light Company at Taft, Louisiana, across the river from the Little Gypsy facility. After completion, 1.4 billion gallons of cooling water will be pumped from the Mississippi River to the plant each day, and returned to the river. (This is about 0.5% of the mean daily flow.) The plant, Waterford 3, was approximately 56% complete at the end of 1978 and is scheduled to go into operation in late 1981.

The eastern Gulf coastal zone relies more heavily on coal and nuclear energy for electric power than does the western or central Gulf region. The Southern Electric System is one of the nation's three largest users of coal.

Approximately 62% of the power by the Mississippi Power Company (MPC) in 1978 was supplied from coal-fired generators, 29% from oil-fired generators, and 9% from natural gas-fired generators. The MPC electric system consists of five generating stations, four steam and one gas-fired combustion turbine; in southeastern Mississippi, MPC also has a 40% interest (with Alabama Power Company) in a coal-fired steam-electric plant in Greene County, Alabama. Although only two of MPC's four steam-electric facilities are located on the coast (Plant Watson at Gulfport and one at Escatawpa, north of Pascagoula), power from all four facilities is available for coastal use.

For Alabama, coal is the primary fuel, accounting for about 65% of the total electricity generated by the Alabama Power Company (APC) in 1978. Hydroelectric plants produced about 11% of APC's total energy output, with oil and gas accounting for only 2%. In 1978, for the first time in the company's history, nuclear power accounted for a substantial amount, 22%, of APC's total energy generation. That year was the first full year of service by Unit No. 1 of Plant Farley, located on the Chattahoochee River near Dothan.

In 1978, Alabama had seven steam-electric generating stations powered by coal and one more under construction, one nuclear steam-electric generating station, two combustion turbine-electric generating stations, and thirteen hydroelectric generating stations, with one more hydroelectric station to be installed by 1982. Several new facilities are planned by Alabama Power Company (Table 10). Most of the new plants will be powered by coal.

Gulf Power Company, serving the panhandle of Florida, has limited facilities. The company has ownership in three coal-powered steam-electric generating stations, with one more under construction, and one combustion turbine-electric generating station. Coal supplies 88% of the fuel requirements for the company's generating plants. Florida Power and Light has two plants, one at Manatu and one at Ft. Meyers, that serve the Gulf coastal area. The company plans to build near the Okeechobee area two large coal plants that potentially could provide power to the eastern coastal area.

Increased costs of natural gas and coal and increasingly stringent environmental regulations have affected the potential for future power-source development. The average cost of coal, for example, has increased from $6.42 a ton in 1968 to $33.92 a ton in 1978. Costs are expected to increase at a rate of 10 to 12 percent a year.

For most power companies in the Gulf coastal region, the peak demand for electricity set all-time records in 1978. Demand on the Gulf Power electric system represented an increase of 6.5% from the previous year, and despite conservation efforts, the demand is expected to increase in future years at an average annual rate of approximately 4.9%. Protecting environmental quality for air, water, and land resources will be a difficult issue as power generating facilities increase.

## 3.4 Offshore Resources

The Gulf of Mexico, in addition to being one of the world's most productive fishing areas, is the scene of intense commercial and industrial activity. Numerous fairways and shipping lanes bisect the entire Gulf. Oil and gas development, primarily offshore from Louisiana and Texas, now extends out to water depths of 1000+ feet and distances of 200+ miles offshore. Additional thousands of miles of pipelines have been laid to transport oil and gas to onshore facilities.

The Gulf also contains numerous cultural resources, such as shipwrecks, and possible habitation sites and special biological resources, e.g., South Texas fishing banks, Flower Garden Reefs, Florida Middle Grounds, and numerous other fishing banks. These resources plan an important role, monetarily, aesthetically, and biologically, in any development that may occur in the Gulf.

## 3.5 Commercial Fishing

By weight the Gulf states accounted for 33%, or 1.75 billion pounds, and by dollar value 29%, or $389 million, of the total U.S. landings in 1977. (U.S. Department of Commerce, NOAA, 1977.) The number of full-time and part-time fishermen probably is 30,000, operating 5,000 vessels (5 net tons or more). (U.S. Department of Commerce, NOAA, 1977.)

The principal ports for the Gulf states fishing industry and their rank nationally are given in Table 11. These ports also serve as the locale for processing and transporting products.

In summary, the fisheries of the Gulf of Mexico are adapted to particular physical, chemical, and biological regimens. The conditions vary within defined geographical and temporal limits, but, with time, the system achieves a balance. Some of the human activities that seem insignificant can drastically upset the balance and have far-reaching, adverse and long-term effects. Some of the little-noticed changes with potential for severe adverse effects include: (1) changes in salinity due to increased or decreased circulation or to changes in the amount of freshwater inflow; (2) reduced inflow of nutrients from marshes, swamps, and upstream watershed; (3) reduced organic matter in wetland soils as a result of drainage and subsequent oxidation; (4) excessive amounts of organic matter in water due to the trapping of vegetation uprooted by storm tides or floods in altered drainage and levee systems; and (5) soil deterioration resulting from monoculture, irrigation, and drainage (U.S. Dept. of the Interior, Fish and Wildlife Service, 1979).

## 3.6 Pollutants

### 3.6.1 Ocean Dumping

The United States Environmental Protection Agency (EPA) regulates ocean dumping under the 1972 Marine Protection Research and Sanctuary Act. EPA published the "Final Revision of Regulations and Criteria for Ocean Dumping" in the Federal Register of January 11, 1977 (Vol. 42, No. 7, pp. 2462-2490).

In the past, EPA listed two "Approved Interim Dumping Sites" in the Gulf of Mexico. One is approximately 130-150 statute miles offshore south of Galveston, Texas, and the other one is about 60-75 statute miles offshore from the mouth of the Mississippi River.

Another past "Approved Ocean Dumping Site" was for the incineration of organochlorine wastes. It is located about 180-225 statue miles offshore southeast of Galveston, Texas.

Additionally, tankers discharge their ballast (often oil-contaminated) in offshore areas, ostensibly outside the 50-mile limit, which results in considerable pollution and tar balls. This practice is a common problem in many areas.

### 3.6.2 Dredging

The development of ports and navigable waterways that could accommodate deep-draft vessels was due to the marine transport of huge tonnages of materials. Extensive dredging of large volumes of sediment each year has occurred along with the maintenance and development of these ports and waterways. The United States Army Corps of Engineers (Corps) has the principal responsibility for dredging operations. The EPA, which is responsible for water quality, has designated a number of "Dredged Material Sites"; their locations are contained in the aforementioned Federal Register. These are all inshore in the vicinity of the Intracoastal Waterway or in dredged channels and harbors.

Dredging operations are carried out annually in major harbors and along the Intracoastal Waterways. There are variations in the disposal of the dredged material in open ocean dumping sites, diked areas nearshore, and onshore dumping sites, depending on approval of Corps permit by various Federal and State agencies.

### 3.6.3 Solid Waste

The management of solid waste is considered a state and local problem. The Federal government has jurisdiction only over disposal practices at Federal installations. However, there is a provision of grants for research, the development of new methods of collection, and disposal and purchases of recycled materials. In the past, the Federal government has funded demonstration projects for new technologies and has tried to eliminate discriminatory interstate transportation rates.

Regional or county management plans specifying conditions and future alternatives are required by most states. Cooperation between regions and counties is encouraged so as to share the financial burden and to maximize the use and efficiency of disposal facilities. The most acute problems are in population centers where density is high, waste volumes are large, and disposal sites are scarce.

The range of the solid waste generated per person is from 3.3 lb/day to 6 lb/day (Snyder, 1974). Included in the 3.3 lb/day figure are wastes generated in households, commercial and business establishments, and institutions. The higher figures are due to the incorporation of wastes generated by industrial processes and agricultural, construction, demolition, and municipal sewage wastes.

Of the solid wastes, more than 90% is disposed of on land: in open and burning dumps or sanitary landfills. Other disposal methods include incineration, use of materials to build structures such as artificial reefs, and collection and recovery. The preferred method is sanitary landfilling, which involves the disposal of solid wastes on land by spreading them in thin layers, compacting them to the smallest practical volume, and covering them with soil.

To help alleviate solid waste disposal problems, the Resource Conservation and Recovery Act of 1976 (P.L. 94-580) was passed. The Act's objectives are to promote the protection of health and the environment and to conserve valuable material and energy resources. Methods include:

- Providing technical and financial assistance to state and local governments for development and implementation of solid waste management plans.
- Providing training grants in solid waste occupations.
- Prohibiting future open dumping on land requiring upgrading, or closing of existing open dumps.
- Regulating the treatment, storage, transportation, and disposal of hazardous wastes.
- Promulgating guidelines for solid waste management practices and systems.
- Conducting a research and development program for improved solid waste management and resource conservation techniques.
- Demonstrating improved solid waste management and resources conservation and recovery systems.
- Establishing a cooperative effort among Federal, State, and local governments and private enterprise.

3.6.4 Air Emissions

The quality of waste disposal is temporarily degraded by the multiple and massive use of air in a limited area. To evaluate the potential impact of proposed additional use of air necessitates knowledge of the restrictions on additional impacts, the capability of the air to receive additional impacts, and the extent of proposed impacts.

Areas in which specific controls and standards are applied (but administered by Federal and State jurisdictions) are defined by interstate air quality control regions (AQCR). The Federal ambient air standards are listed in Table 12. It is required that all individual states adopt standards as stringent as, or more stringent than, the Federal standards.

EPA Region IV in Atlanta, Georgia, has compiled estimates of air pollution emissions for each AQCR and for coastal counties. These data are listed in Tables 13 through 15. Quantities of pollutants being emitted into the air are given by these emissions data, and some indication of the likelihood that the emissions will not be satisfactorily dispersed is given by the air pollution potential. However, these data do not given a true picture of the air quality of a given AQCR or county; most of the data available are from urban centers. This presents a picture of region-wide problems when in reality it is only an urban problem. Measurements are being initiated in non-urban areas but data have not yet been obtained from these areas.

The counties and the point sources responsible for the highest emission for particulates, $SO_n$, $NO_n$, hydrocarbons, and carbon monoxide, are listed in Table 16. It is generally noted that: (1) industrial processes such as mineral and wood products, area burning, fugitive dust, and paved roads cause these particulate emissions; (2) combustion of coal, oil, or natural gas causes $SO_n$ and $NO_n$; (3) carbon monoxide emissions result from the use of gasoline for transportation; and (4) hydrocarbons indicate petroleum storage, refining, or other petroleum-related activities.

Although the general air quality in the Gulf Coast region is good, the counties with major urban areas show high pollution concentrations that indicate that an increase in pollutants directly correlates with an increase in the population of an area.

A small but significant amount of air pollutants resulting from stationary combustion or from venting produced gas is generated by offshore oil operations.

The oil storage on the production platform ($136 \times 10^3$ mg/yr) and from gas processing vents ($93 \times 10^3$ mg/yr) is the major source of total hydrocarbon emissions. Over 70% of the total non-methane hydrocarbons (29,403 mg/yr) emitted offshore are accounted for by these sources.

Several methods and control technologies are available for major emission sources: combustible modifications, waste heat utilization, dilution, stack vapor recovery systems, and smokeless combustion flares. However, the best method for emission control is waste heat utilization, which totally eliminates emission sources from direct-fixed heaters.

A great potential for the occurrence of air quality problems has been created in areas of high concentrations of population and industry in the western Gulf. The city of Houston and dense concentrations of industries along the Houston Ship Channel are the two most critical locations. The Beaumont-Port Arthur-Orange areas and the Corpus Christi area are other western Gulf sites where frequent air pollution problems endanger the health and well-being of the public.

## 4. SUMMARY AND CONCLUSIONS

### 4.1 Florida

In the past twenty years, Florida has undergone rapid growth pressures with a transition from an agricultural economy to an urban economy. Tourism became the major industry of the state.

In this twenty-year period (1950-1970), the population increased by four million. The rate of arrival in the 1970's was more than 6,000 people per week. The estimated population in the coastal planning area for 1976 was 6.4 million with projections as follows: 1980 - 7 million; 1985 - 8 million; 1990 - 8.8 million.

The coastal zone counties' annual per capita income for 1974 ranged from $2,331 (Franklin County) to $6,662 (Palm Beach County). The per capita income in nine coastal counties was above the state average of $4,412 with three coastal zone counties having a per capita income below $3,000 per year.

Over $9 billion was spent in 1975 by the 25 million visitors to the state. A major source of public revenue comes from the sales tax on expenditures. However, a majority of the employment in the southern half of the state stems from tourism-related trades and services.

In 1975, six billion dollars was added by manufacturing in the coastal zone. Located in the coastal zone are fourteen of the state's fifteen largest industries; however, these industries are concentrated in the larger urban areas. Only five coastal counties show manufacturing as one of the top five sources of personal income.

Of considerable economic importance are the commercial and sport fishing industries. In 1975, $73.7 million was added to the economy by commercial fish landings. Another $156 million was added by fish processing and marketing. An estimated $500 million is expected to be added annually by salt-water sport fishing.

In 1975, 15 deep-draft ports of authorized depths of 32 feet or greater handled over 85 million tons of freight, and well over one million passengers were served by them. The coastal zone also has nine shallow-draft, or barge, ports.

Over 550,000 acres (6%) of land area in the coastal zone is used by eleven military and defense bases. In 1975, $1 billion was spent on military payrolls with civilian payrolls at the bases amounting close to $7 million.

About 30% of the coastal land area is urban or built-up, 57% being for residential and institutional purposes. Twenty-one percent of the coastal land area is used for agriculture; 49% is classified as vacant land and natural areas. Less than 1% is designated as public park and recreation areas (excluding the Everglades National Park); 6% of the coastal zone is subdivided but not developed.

A vast majority of coastal land is privately owned, accounting for approximately 78% of coastal land ownership. The Federal government owns about 17% and state and local governments own the remainder.

Primarily due to the demand for residential development near the water, the cost of land in the coastal areas has sky-rocketed. In 1941, the total value of Florida real estate was $2.1 billion; in 1970 it jumped to $51.2 billion. The coastal areas have had even more dramatic increases.

There are variations in demand and supply characteristics in the coastal zone for support services (including water supply, sewage treatment, and solid waste disposal facilities, transportation, and recreational facilities). The two most serious support service problems in Florida's coastal areas are solid waste disposal and water supply. There is an inadequacy of sewage disposal, transportation facilities, and park and recreational areas in many urbanized regions, especially those experiencing rapid growth.

## 4.2 Alabama

The Alabama coastal coastal was described by that state's Legislature, in the Alabama Coastal Area Act of 1976, as follows:

(a) The coastal area is rich in a variety of natural, commercial, recreational, industrial, and aesthetic resources of immediate and potential value to the present and future well-being of the state.

(b) There are increasing and competing demands upon the lands and waters of the coastal area occasioned by population growth and economic development, including requirements for industry, commerce, residential development, recreation, extraction of mineral resources and fossil fuels, transportation and navigation, waste disposal, and harvesting of fish, shellfish, and other living marine resources.

(c) The coastal area and the fish, shellfish, other living marine resources, and wildlife therein are ecologically fragile and consequently vulnerable to destruction by man's alteration.

(d) Important ecological, cultural, historic, and aesthetic values to the coastal area are essential to the well-being of all citizens.

(e) Special natural and scenic characteristics may be damaged by ill-planned development.

(f) There is a state interest in the effective administration, beneficial use, protection and development of the coastal area.

(g) In light of competing demands and the urgent need to balance development for the preservation of the natural systems in the coastal area, the key to more effective protection and use of land and water resources of the coastal area is to encourage the state to exercise its authority for improved and better methods of utilizing the lands and waters in the coastal area by developing, in cooperation with counties and municipalities and other vitally affected interests, land and water use programs for the coastal area, including unified policies, criteria, standards, methods, and processes for dealing with land and water use.

The coastal area of Alabama has some 400,000 acres of bays and estuarine waters, 121,000 acres of wetlands, 130 identified species of birds, a commercial fishing catch with an annual value estimated at $148 million, and a registration of over 23,300 recreational boats. The area also has major industrial and municipal sources discharging daily 170 million gallons of various waste products into coastal waters, a rapidly growing second home construction business throughout the area's waterfront, a maintenance dredging requirement producing 7 million cubic yards of spoil material annually, the prospect of increased energy-related development (coal and oil), and the possibility of additional growth related to the Tennessee-Tombigbee Waterway. As competition for resources becomes more intense, special effort must be made to resolve potential conflicts in order to give fishermen the opportunity to harvest the rich coastal fishery yields; at the same time, industries use the water resources for process water, transportation, and some waste assimilation to provide employment opportunities for local residents. A balance must be achieved that sustains economic development on the one hand and protects natural resources on the other.

## 4.3 Mississippi

The distance along the Mississippi coast between Louisiana and Alabama is approximately 70 miles. Coastal shorelines, including the Barrier Islands, is approximately 370 miles in length. Hancock, Harrison, and Jackson counties comprise the entire coast of Mississippi.

Two distinct physiographic regions cross the Gulf counties: the coastal meadows and the coastal plains. The coastal meadows extend across the three counties along the Mississippi Sound from the shoreline to approximately 25 feet in elevation. This topographic region encompasses one-third of Harrison County, one-half of Hancock County, and one-half of Jackson County. The coastal plain covers the remaining portion of these counties.

Population data for 1972 indicate that 259,990 people resided in the three-county area, 91% of that population (236,526) being near the coastal section. This coastal section comprises 33.8% of the land, which is 607 square miles. The coastal section is roughly defined as 5 miles in from the coastline. Population projections for the urbanized areas (coastal section) of these counties indicate that there will be an urban population of 305,635 residents in 1984 and 416,009 in 1997; a 36% urban population increase is projected between 1984 and 1997.

Existing land use reflects historical land use, economic development, and current attitudes toward land use control. The land use and economy for most of the coast's history have involved forestry, fishing, and the tourist industry. Because of the threat of hurricanes, this coastal area developed slowly through the 19th century and the early part of the 20th century. The threat of hurricane damage has continued to be a deterrent to growth, although potential storm damage has lessened with the development of advance warning systems and Federal financial aid to natural disaster areas. This Mississippi coastal region has been transformed from a rural economic base to an expanding urban economic base having diversified industrial and commercial development. Historically, land use controls were not implemented, so over-utilization of natural resources occurred, e.g., the devastation of virgin timber stands. In the past 40 years, sound resource management and land use control policies have been implemented. These policies include reforestation, county-wide subdivision ordinances, and comprehensive land use planning. The economy of the Mississippi Gulf coast shows a decline in agricultural, fishing, and forest industries. They are being replaced by manufacturing and service industries. This change in the economic base is reflected in increasing coastal urbanization, which requires continued comprehensive land use planning and land use controls.

### 4.4 Louisiana

The Mississippi River, which over the past 5,000 years has shifted across the southern part of the state from west to east, has produced the Louisiana coastal marshlands. Considerable variation in the physiography of coastal Louisiana is due to the seven Mississippi River delta systems. Winds, tides, currents, and hurricanes have reworked the soils deposited by the Mississippi into the Gulf of Mexico. As a result, a wide variety of land features have formed in the coastal zone.

Intimately related to the area's land features are human activities. Development has occurred along the natural levee ridges, which have relatively firm soils and high elevations. Water access, transportation routes, and drainage ways are provided by distributary channels. Valuable natural resources and flood protection are provided by the fringing swamps and marsh basins. A buffer against eroding tides and dangerous storms is provided by the coastal barrier islands, chenier ridges, and oyster reefs.

The Louisiana coastal zone is comprised of 8.5 million acres, 15% being dry land. The wetlands of this state account for about 25% of the nation's wetlands. Fifteen percent of the coastal zone is covered by swampland. A variety of marsh types (saline, brackish, intermediate, and fresh), comprising about 70% of the Louisiana coastal zone, make up the remaining wetlands.

The Louisiana coastal zone is one of the largest and richest estuarine regions in the world because of its lakes, bays, tidal channels, and other coastal water features. Rapid growth of vegetation and wildlife is due to the warm, humid climate and mixing of fresh and salt water. Major breeding and nursery grounds for many commercially important fish and shellfish are in the Louisiana estuaries. The estuarine marshes retain valuable nutrients. Importantly, they serve to reduce the impact of storms upon development farther inland.

A dramatic variation of salinity levels, water circulation patterns, and rates of soil erosion and accretion is seen in the Louisiana marshes, which are subject to natural impacts caused by hurricanes and storms, flooding, rainfall, and climate. This part of an invaluable ecosystem is characterized by biological production, wildlife refuge, recreation, conservation, and many types of development.

Louisiana's coastal zone contributes significantly to the economic system of the nation. It has a great magnitude and variety of natural and human resources. A large share of the nation's energy comes from the petroleum and natural gas reserves of the Louisiana coastal zone. The greatest U.S. Outer Continental Shelf oil and gas contribution comes from the Louisiana coastal zone. Twenty-eight percent of the nation's fishery harvest is produced by Louisiana's estuarine system, and much of the country's sugar and rice is produced by Louisiana. The Mississippi River and the Gulf Intracoastal Waterway are vital commercial arteries to the interior of the United States. Of primary importance to the people and economy of the state and nation are the coastal and marine resources of the Louisiana coastal zone, including living and non-living resources, recreation, fish and wildlife, and estuarine, water, and land resources. There has been a coordinated effort by State agencies for development and protection of Louisiana's most valuable resource--its coastal zone. The expanded use of the coastal zone for industrial and commercial development, water resources development, recreation, tourism, urbanization, and transportation has created many conflicts. These conflicts will diminish the natural capacities of the marshlands to provide nutrients essential to estuarine productivity, to serve as a buffer against flooding and erosion of upland areas, and to aid in the assimilation of pollutants in the coastal zone. One step taken by the people of Louisiana to diminish these problems is the development of the Louisiana Coastal Resources Program.

### 4.5 Texas

The Texas coastal zone contains approximately 30,000 square miles. Many of the most productive fish and wildlife habitats comprise only small portions of the total area. For example, according to Bureau of Economic Geology estimates, salt marshes constitute only one percent of the area, brackish-to-fresh marshes constitute approximately 2.2%, and fresh marshes cover less than 1%, as do marine grassflats and swamps. These habitats not only are relatively scarce in the coastal area, but they are very susceptible to alterations caused by urban and industrial development activities.

Approximately 60 square miles of the coastal area are occupied by industrial facilities, while urban development occupies approximately 1,000 square miles. One-third of the entire state's industrial activities, and a similar share of the state's population, are concentrated in the coastal area, which comprises only 8.1% of the state's land area.

Because of the array of resources located in the Texas coastal zone, many diverse demands are placed on the area. Industry finds it to be advantageous to locate near coastal water transportation routes. Agriculture, fisheries, and cattle ranching are important coastal activities. The mineral and oil reserves of the coastal area generate substantial economic activity, and there are unique recreation and tourist attractions as well. To a number of local, State, and Federal agencies, this range of demands on the region's resources is a continuing source of concern.

The coastal bays and their associated wetlands, which comprise such small portions of Texas' land resources, provide huge dividends for a small investment. In one year's time (1975), sport fishing took almost 6 million pounds of finfish from coastal bays. This harvest afforded approximately 13 million person-hours of recreation. In 1975, the commercial fisheries harvest in Texas was 86 million pounds, valued at nearly $93 million; the economic impact upon the State's economy was conservatively estimated at $231.6 million.

Urban and industrial development can affect coastal resources in many ways. There is an increasing subjugation of wetlands and agricultural lands by urban use, and fish and wildlife habitats have suffered severe consequences. For example, according to the Bureau of Economic Geology, more than 500 square miles of Texas' bays are closed to oyster harvest because of sewage discharge. Lavaca Bay has been contaminated by mercury pollution, and fish and shellfish harvests from that area have been curtailed since 1970.

Industrial and related urban expansion have caused increased diversion and consumption of surface and ground water supplies, which are essential to the maintenance of the fragile coastal ecosystems. Water development projects have generally resulted in fish and wildlife resource losses by inundation of riparian habitats such as hardwood bottomlands, by reduction of instream fisheries below damsites, by reduction in the replenishment of delta marshes, and by increased salinity concentrations within the coastal bays.

Wildlife depends on healthy water systems and vegetation for food and cover. Both of these necessities are affected by human use of coastal zone resources. Industries and cities may release toxic wastes into water supplies. Extensive agricultural areas in monoculture may be detrimental to or incompatible with certain types of wildlife. Dams reduce the nutrient and sediment supplies and freshwater inflows needed by estuarine systems. Channelization and dredging required to maintain navigation routes often have adverse effects on fish and wildlife. At the present time, three proposed deepwater facilities are being given serious consideration. The Freeport monobuoy system is being considered to the extent that the Texas Deepwater Port Authority was recently established to supervise regulatory proceedings in establishing this deepwater channel facility. A 55-foot channel into

Galveston Harbor has been proposed to accommodate supertanker navigation. The "DEEPORT" 80-foot channel, extending 27 miles into the Gulf of Mexico, has been proposed to help accommodate supertanker navigation in the Corpus Christi-Harbor Island area, and Brownsville is considering port expansion and channel deepening activities. Each of these proposed facilities will provide tremendous amounts of dredge material, and the location of spoil sites will be critical to the coastal area's wetland habitats.

Concern for the coastal fish and wildlife resources, expressed at national, state, and local levels in recent years, is very real and well-founded. The recently expanded authority for the Corps of Engineers to control development in the nation's wetlands is due to a general recognition of the productivity, scarcity, and vulnerability of these habitats. Texas' Department of Parks and Wildlife was recently successful in using the Texas State Legislature to set allowable red fish catch limits for each major bay system for the entire Texas Gulf coast (Adopted Rule of June 26, 1979); this ruling became effective in October 1979. An additional expression of concern for coastal zone resources is a major study on the means for insuring freshwater inflows into the coastal bays to optimize fish and wildlife resource productivity. The findings are to be released in the fall of 1979 by the Texas Department of Water Resources, Planning and Development Division.

Table 1. Gulf of Mexico Coastal States, Population Changes

| State | Population (Thousands) 1965 | 1975 | % Change 1965-1975 | Projected 1980 |
|---|---|---|---|---|
| Texas | 10,388* | 12,237 | 17.8 | 12,167 |
| Louisiana | 3,496 | 3,791 | 8.4 | 3,744 |
| Mississippi | 2,246 | 2,346 | 4.5 | 2,328 |
| Alabama | 3,443 | 3,614 | 5.0 | 3,747 |
| Florida | 5,594 | 8,857 | 40.4 | 8,926 |

*Estimated from 1960 and 1970 figures.

Source: Federal Reserve Bank of Atlanta (1976).

Table 2. Economic Activities in the Gulf of Mexico

| | Petroleum Production (Million Barrels) | Employment Manufacturing | Employment Construction | Employment Farm | Per Capita Income (Personal) |
|---|---|---|---|---|---|
| Texas** | | | | | |
| 1965 | 943 | 497 | --- | 415 | $2,052 |
| 1975 | 1,222 | 835 | 299 | 255 | $5,631 |
| Louisiana* | | | | | |
| 1965 | 595 | 158 | 77 | 121 | $2,134 |
| 1975 | 655 | 182 | 90 | 68 | $4,729 |
| Mississippi* | | | | | |
| 1965 | 56 | 153 | 29 | 179 | $1,684 |
| 1975 | 47 | 198 | 36 | 92 | $4,041 |
| Alabama* | | | | | |
| 1965 | 8 | 277 | 52 | 120 | $1,987 |
| 1975 | 13 | 320 | 68 | 91 | $4,557 |
| Florida* | | | | | |
| 1965 | 1 | 252 | --- | --- | $2,402 |
| 1975 | 42 | 328 | 161 | 95 | $5,517 |

Source: *Federal Reserve Bank of Atlanta (1976).
**Texas Almanac and Industrial Guide (19 ).

Table 3. Socioeconomic Components and Ecologically Sensitive Activities Generated by Them. The Matrix Identifies Major Activities Associated With Each Section of the Economy.

| | Ecologically Sensitive Activities | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Waste Generation | | | Habitat Modification | | | | | Natural Resource Exploitation | | | |
| Economic Sectors | Point source | Agriculture runoff | Urban runoff | Filling and draining | Impoundments | Construction/land | Canal dredge and spoil | Construction/water | Wildlife harvest | Surface water use | Ground water use | Refuge creation |
| Mineral extraction | ● | | ● | | | ● | ● | ● | | ● | ● | |
| Commerce and industry | ● | | | ● | ● | ● | | | | ● | | |
| Commercial fishing and trapping | ● | | | | | | ● | ● | ● | | | |
| Recreational fishing and hunting | | | | | | | ● | ● | ● | | | ● |
| Agriculture | | ● | | ● | | ● | ● | | | ● | ● | |
| Port and navigation | | | ● | ● | | | ● | ● | | | | |
| Highways, rails, airports | | | ● | ● | ● | ● | ● | | | | | |
| Resident population | | | ● | ● | | ● | ● | | | | | |
| Government services | ● | | | | ● | | ● | ● | | ● | ● | ● |

Source: U.S. Department of the Interior, Fish and Wildlife Service (1979).

Table 4. Production, Producing Wells, Average Production Per Well

| | 1973 | 1975 |
|---|---|---|
| Texas (Gulf Coast area only) | | |
| Crude Petroleum Production[1] | 253,296 | 234,365 |
| No. Producing Oil Wells | 14,199 | 14,108 |
| Average Production Per Well[2] | 46.6 | 45.3 |
| Average Value Per Barrel | $4.11 | $7.96 |
| Louisiana (Gulf Coast area only) | | |
| Crude Petroleum Production | 791,760 | 613,502 |
| No. Producing Oil Wells | 13,086 | 12,535 |
| Average Production Per Well | 162.4 | 132.4 |
| Average Value Per Barrel | $4.00 | $7.10 |
| Mississippi | | |
| Crude Petroleum Production | 56,102 | 46,614 |
| No. Producing Oil Wells | 2,901 | 2,237 |
| Average Production Per Well | 50.4 | 56.9 |
| Average Value Per Barrel | $3.81 | $6.66 |
| Alabama | | |
| Crude Petroleum Production | 11,677 | 13,477 |
| No. Producing Oil Wells | 586 | 608 |
| Average Production Per Well | 56.6 | 62.1 |
| Average Value Per Barrel | $3.58 | $10.13 |
| Florida | | |
| Crude Petroleum Production | 32,695 | 41,877 |
| No. Producing Oil Wells | 147 | 143 |
| Average Production Per Well | 619.9 | 822.4 |
| Average Value Per Barrel | $4.59 | $11.71 |
| United States (Total) | | |
| Crude Petroleum Production | 3,360,903 | 3,056,779 |
| No. Producing Oil Wells | 497,378 | 500,333 |
| Average Production Per Well | 18.3 | 16.8 |
| Average Value Per Barrel | $3.89 | $7.56 |

[1]Thousands of barrels

[2]Average production per well per day (barrels)

Table 5. Operable Petroleum Refineries (January 1, 1977), Gulf of Mexico Region, Bureau of Mines Refining Districts.

| Operator | Location | Crude Capacity Barrels Per Day |
|---|---|---|
| Texas | | |
| American Petrofina | Port Arthur | 110,000 |
| Amoco Oil | Texas City | 348,000 |
| Atlantic Richfield | Houston | 306,000 |
| Champlin Refining | Corpus Christi | 125,000 |
| Charter International | Houston | 70,000 |
| Coastal States Petrochemical | Corpus Christi | 185,000 |
| Crown Central Petroleum | Pasadena | 100,000 |
| Eddy Refining | Houston | 3,088 |
| Exxon | Baytown | 390,000 |
| Gulf | Port Arthur | 312,100 |
| Marathon | Texas City | 66,000 |
| Mid Texas | Hearne | 3,000 |
| Mobil | Beaumont | 335,000 |
| Monsanto | Alvin | 8,500 |
| Phillips | Sweeney | 104,000 |
| Quintana Howell (Joint Venture) | Corpus Christi | 44,559 |
| Saber Refining | Corpus Christi | 9,950 |
| Shell | Deer Park | 294,000 |
| South Hampton | Silsbee | 18,100 |
| Southwestern Refining | Corpus Christi | 120,000 |
| Sun | Corpus Christi | 57,000 |
| Texaco | Port Arthur | 406,000 |
| Texaco | Port Neches | 47,000 |
| Texas City Refining | Texas City | 74,500 |
| Union Oil of California | Nederland | 120,000 |
| Independent Refining Corp. | Winnie | 13,490 |
| Subtotal | | 3,670,287 |
| Louisiana | | |
| Canal Refining | Church Point | 4,800 |
| Cities Service | Lake Charles | 268,000 |
| Continental Oil | Egan | 15,000 |
| Continental Oil | Westlake | 83,000 |
| Evangeline Refining | Jennings | 5,000 |
| Exxon | Baton Rouge | 510,000 |
| Good Hope Refineries | Good Hope | 70,000 |
| Gulf Oil | Belle Chasse | 195,900 |
| Gulf Oil | Venice | 28,700 |
| Hill Petroleum | Krotz Springs | 5,000 |
| La Jet | St. James | 15,000 |

Table 5. Operable Petroleum Refineries (January 1, 1977), Gulf of Mexico Region, Bureau of Mines Refining Districts. (Cont'd)

| Operator | Location | Crude Capacity Barrels Per Day |
| --- | --- | --- |
| Louisiana (Cont'd) | | |
| Marathon | Garyville | 200,000 |
| Murphy Oil | Meraux | 92,500 |
| Placid | Port Allen | 36,000 |
| Shell | Norco | 240,000 |
| Tenneco | Chalmette | 86,000 |
| Texaco | Convent | 140,000 |
| Subtotal | | 1,944,900 |
| Mississippi | | |
| Chevron U.S.A. | Pascagoula | 280,000 |
| Alabama | | |
| Marion Corp. | Theodore | 19,200 |
| Louisiana Land and Exploration | Mobile | 39,636 |
| Subtotal | | 58,836 |
| Florida | | |
| Seminole Asphalt Refining | St. Marks | 6,000 |
| TOTAL GULF OF MEXICO | | 6,010,023 B/D[1] |

[1] B/D - barrels per day

Source: U.S. Department of the Interior, Bureau of Mines (1977).

Table 6. Additional Crude Oil Refining Capacity Under Construction on January 1, 1977

| Operator | Location | Additional Crude Capacity Barrels Per Day |
|---|---|---|
| Texas Gulf Coast | | |
| Texas City Refining | Texas City | 46,000 |
| Tipperary Corp. | Ingleside | 5,000 |
| Exxon | Baytown | 250,000 |
| Subtotal | | 301,000 |
| Alabama Gulf Coast | | |
| Marion Corp. | Theodore | 1,900 |
| Louisiana Gulf Coast | | |
| La Jet, Inc. | St. James | 15,000 |
| Tenneco Oil Co. | Chalmette | 29,000 |
| Subtotal | | 44,000 |
| TOTAL GULF OF MEXICO | | 348,800 |

Table 7. Deterrents to Growth in Texas

| Factors | Rank |
|---|---|
| Shortage of feedstocks | 1 |
| Remoteness from main market area | 2 |
| Energy (fuel) availability and cost | 3 |
| High state and local taxes and inequity in taxes | 4 |
| Transportation costs including high rail taxes | 5 |
| Raw material costs | 6 |
| Saturation of some type of processing plants | 7 |
| Labor costs | 8 |
| Pollution abatement laws too stringent | 9 |
| Land transportation to markets | 10 |

Source: Whitehorn (1973), with permission of the author.

Table 8. Economic Factors Which May Change the Future Level of Petrochemical Activity in Texas

| Factors | Rank |
| --- | --- |
| Availability and cost of feedstocks | 1 |
| Availability and cost of energy sources | 2 |
| Product demand and prices | 3 |
| Labor costs | 4 |
| Foreign imports and competition | 5 |
| Government regulations (safety, environment, price, etc.) | 6 |
| Transportation costs | 7 |
| Tax levels | 8 |
| Environmental costs | 9 |
| Product distribution costs | 10 |

Source: Whitehorn (1973), with permission of the author.

Table 9. Freight Traffic at Major Gulf Coast Ports, Mobile - Brownsville, 1977

| | Foreign and Domestic Trade | | | Foreign Trade | | |
|---|---|---|---|---|---|---|
| Port | Total (*) | Crude Petroleum (*) | Petroleum Products (*) | Total (*) | Petroleum (*) | Petroleum Products (*) |
| Mobile | 35,944 | 3,983 | 5,309 | 13,688 | 45 | 00.3 |
| Pascagoula | 23,833 | 8,738 | 7,842 | 11,192 | 8,631 | 77 |
| Biloxi | 1,716 | 10 | 109 | 00 | 00 | 00 |
| Gulfport | 1,095 | 00 | 28 | 991 | 2 | 00.2 |
| New Orleans | 162,992 | 29,365 | 29,596 | 64,287 | 17,498 | 27.2 |
| Baton Rouge | 70,008 | 12,174 | 18,771 | 25,505 | 9,234 | 36.2 |
| Lake Charles | 25,401 | 12,743 | 7,796 | 9,660 | 7,963 | 82.4 |
| Orange | 1,003 | 67 | 85 | 25 | 00 | 00 |
| Beaumont | 48,919 | 28,524 | 12,840 | 26,804 | 23,787 | 89 |
| Port Arthur | 30,754 | 15,227 | 11,113 | 16,610 | 384 | 02 |
| Houston | 104,291 | 31,776 | 33,965 | 51,041 | 29,310 | 57 |
| Texas City | 33,584 | 15,391 | 11,361 | 13,054 | 12,116 | 93 |
| Galveston | 9,564 | 510 | 303 | 7,575 | 510 | 07 |
| Freeport | 15,333 | 10,294 | 994 | 11,417 | 9,957 | 87 |
| Corpus Christi & Harbor Island | 56,041 | 27,105 | 18,030 | 31,611 | 23,092 | 73 |
| Brownsville | 2,130 | 5 | 677 | 1,132 | 409 | 36 |
| TOTAL | 622,608 | 195,912 | 158,819 | 284,592 | 142,938 | 619.3 |

Source: U.S. Department of the Army, Corps of Engineers (1977).

Notes: *Short tons x 1,000

Table 10. Alabama Power Company Planned Power Facilities

| Plant | Generating Capacity (kilowatts) | Estimated Date of Completion | Type of Plant |
|---|---|---|---|
| Farley, Unit No. 2 | 860,000 | 1980 | Nuclear |
| Harris Dam, Unit Nos. 1 and 2 | 135,000 | 1980 | Hydro |
| Miller, Unit No. 2 | 660,000 | 1981 | Coal |
| Miller, Unit No. 3 | 660,000 | 1982 | Coal |
| Miller, Unit No. 4 | 660,000 | 1983 | Coal |

Source: The Southern Company (1978).

Table 11. Commercial Fishery Landings at Certain U.S. Ports, 1978

| Port | Quantity (Million Pounds) | Rank |
|---|---|---|
| Cameron, La. | 606.0 | 1 |
| Pascagoula-Moss Pt., Miss. | 334.8 | 2 |
| Dulac-Chauvin, La. | 300.2 | 4 |
| Empire-Venice, La. | 292.8 | 5 |
| Biloxi, Miss. | 37.8 | 20 |
| Brownsville-Port Isabel, Texas | 24.0 | 27 |
| Aransas Pass-Rockport, Texas | 23.0 | 28 |
| Bayou La Batre, Ala. | 22.2 | 29 |
| Golden Meadow-Leeville, La. | 22.1 | 30 |
| Freeport, Texas | 16.0 | 36 |
| Ft. Myers, Fla. | 15.2 | 38 |
| Delcambre, La. | 15.1 | 39 |
| Lafitte-Barataria, La. | 13.1 | 42 |
| Apalachicola, Fla. | 12.4 | 44 |
| Bon Secour-Gulf Shores, Ala. | 7.3 | 50 |

| Port | Quantity (Million Dollars) | Rank |
|---|---|---|
| Dulac-Chauvin, La. | 46.7 | 6 |
| Brownsville-Port Isabel, Texas | 43.0 | 7 |
| Aransas Pass-Rockport, Texas | 39.0 | 8 |
| Cameron, La. | 34.2 | 9 |
| Freeport, Texas | 28.0 | 11 |
| Empire-Venice, La. | 26.4 | 13 |
| Bayou La Batre, Ala. | 25.1 | 15 |
| Pascagoula-Moss Pt., Miss. | 19.4 | 21 |
| Golden Meadow-Leeville, La. | 19.1 | 22 |

| Port | Quantity (Million Pounds) | Rank |
|---|---|---|
| Delcambre, La. | 16.7 | 24 |
| Apalachicola, Fla. | 13.3 | 26 |
| Ft. Myers, Fla. | 13.1 | 27 |
| Lafitte-Barataria, La. | 11.5 | 29 |
| Bon Secour-Gulf Shores, Ala. | 10.0 | 32 |
| Biloxi, Miss. | 6.5 | 40 |

Source: U.S. Department of Commerce, NOAA (1979).

Table 12. Federal Ambient Air Quality Standards

| Parameter | Standard Primary | Standard Secondary |
|---|---|---|
| Particulate Matter: | | |
| Annual geometric mean | 75 $\mu g/m^{3+}$ | 60 $\mu g/m^3$ |
| 24-hour maximum | 260 $\mu g/m^3$ | 150 $\mu g/m^3$ |
| Sulfur Oxides: | | |
| Annual arithmetic mean | 80 $\mu g/m^3$ | |
| 24-hour maximum | 365 $\mu g/m^3$ | |
| 3-hour maximum | --- | 1,300 $\mu g/m^3$ |
| Carbon Monoxide: | | |
| 8-hour maximum | 10 $mg/m^{3++}$ | 10 $mg/m^3$ |
| 1-hour maximum | 40 $mg/m^3$ | 40 $mg/m^3$ |
| Photochemical Oxidants: | | |
| 1-hour maximum | 160 $\mu g/m^3$ | 160 $\mu g/m^3$ |
| Hydrocarbons: | | |
| 3-hour maximum | 360 $\mu g/m^3$ | 160 $\mu g/m^3$ |
| Nitrogen Dioxide: | | |
| Annual arithmetic mean | 100 $\mu g/m^3$ | 100 $\mu g/m^3$ |

$^{+}\mu g/m^3$ = micrograms per cubic meter

$^{++}mg/m^3$ = milligrams per cubic meter

Source: Adapted from U.S. Environmental Protection Agency (1976).

Table 13. Air Pollution Emissions Estimates for Alabama Coastal Counties

| Counties | Particulate | Emissions in Tons/Yr. $SO_n$ | $NO_n$ | HC | CO |
|---|---|---|---|---|---|
| Mobile | *11870 | *10366 | *18860 | *33911 | *140107 |
| Baldwin | 1454 | 1183 | 5287 | 12336 | 43388 |

*Highest Recorded

Source: U.S. Environmental Protection Agency (1977a).

Table 14. Air Pollution Emissions for Selected Mississippi Counties

| Counties | Particulate | $SO_n$ | $NO_n$ | HC | CO |
|---|---|---|---|---|---|
| Amite | 751 | 93 | 1207 | 1869 | 7696 |
| Hancock | 622 | 61 | 1050 | 2922 | 13268 |
| Harrison | 5607 | *75265 | *22141 | *14975 | *67228 |
| Jackson | *7446 | 14193 | 8343 | 25173 | 58197 |
| Marion | 1202 | 96 | 1486 | 2912 | 12947 |
| Pearl River | 971 | 112 | 1921 | 3205 | 14746 |
| Pike | 653 | 197 | 2291 | 4184 | 17299 |
| Walthall | 203 | 53 | 1067 | 1193 | 4727 |
| Wilkinson | 165 | 74 | 863 | 1002 | 3510 |

*Highest Recorded

Source: U.S. Environmental Protection Agency (1977a).

Table 15. Air Pollution Emissions for West Coast Florida Coastal Counties

| | Particulate | Emissions in Tons/Yr $SO_n$ | $NO_n$ | HC | CO |
|---|---|---|---|---|---|
| Bay | 11699 | 57664 | 15133 | 9367 | 53873 |
| Charlotte | 846 | 113 | 843 | 4337 | 13990 |
| Citrus | 8905 | 49917 | 18307 | 3861 | 12336 |
| Collier | 4328 | 126 | 1946 | 9679 | 45290 |
| Dade | 14185 | 47493 | 47067 | *77940 | 100687 |
| Dixie | 296 | 94 | 712 | 1387 | 3857 |
| Escambia | 15208 | 125166 | 36215 | 16704 | 38078 |
| Franklin | 360 | 31 | 245 | 2180 | 7733 |
| Gulf | 6644 | 14037 | 4114 | 2250 | 50155 |
| Hernando | 740 | 148 | 1122 | 2309 | 9292 |
| Hillsborough | *27302 | *243982 | *69004 | 61409 | *289877 |
| Jefferson | 148 | 39 | 718 | 997 | 4051 |
| Lee | 2596 | 16078 | 20907 | 16884 | 79057 |
| Levy | 1501 | 1003 | 2323 | 3256 | 11868 |
| Manatee | 2254 | 7483 | 19627 | 10952 | 51875 |
| Monroe | 717 | 770 | 5693 | 10011 | 42160 |
| Okaloosa | 1982 | 467 | 5371 | 10775 | 47716 |
| Pasco | 1187 | 3277 | 5856 | 8268 | 35896 |
| Pinellas | 6350 | 34072 | 37691 | 56028 | 264505 |
| Santa Rosa | 7559 | 32100 | 13799 | 17951 | 33217 |
| Sarasota | 1315 | 472 | 7095 | 15313 | 69008 |
| Taylor | 9418 | 3588 | 4005 | 4441 | 18145 |
| Walton | 446 | 78 | 1469 | 3672 | 15716 |

*Highest recorded

Source: U.S. Environmental Protection Agency (1977a).

Table 16. Point Source Emissions for Selected Counties

| State | County | Emission | Source |
|---|---|---|---|
| Texas | Harris | Particulate | Industrial fuel - bituminous coal |
| | | $SO_n$ | Commercial and institutional fuel |
| | | $NO_n$ | Gasoline - land vehicles |
| | | HC | Industrial processing - evaporation |
| | | CO | Gasoline - land vehicles |
| Louisiana | St. Tammany | Particulate | Mineral products |
| | Plaquemines | $SO_n$ | Industrial fuel |
| | Jefferson | $NO_n$ and HC | Gasoline - land vehicles |
| | St. Mary | CO | Chemical manufacturing |
| Mississippi | Jackson | Particulate | Industrial processing - wood products |
| | Harrison | $SO_n$ and $NO_n$ | Fuel combustion - bituminous coal |
| | | HC and CO | Gasoline - land vehicles |
| Alabama | Mobile | Particulate | Industrial fuel |
| | | $SO_n$ and $NO_n$ | Commercial and industrial fuel |
| | | HC and CO | Gasoline - land vehicles |
| Florida | Hillsborough | Particulate | Fuel combustion - bituminous coal |
| | | $SO_n$ and $NO_n$ | Gasoline - land vehicles |
| | | HC and CO | Gasoline - land vehicles |

Source; U.S. Environmental Protection Agency (1977a).

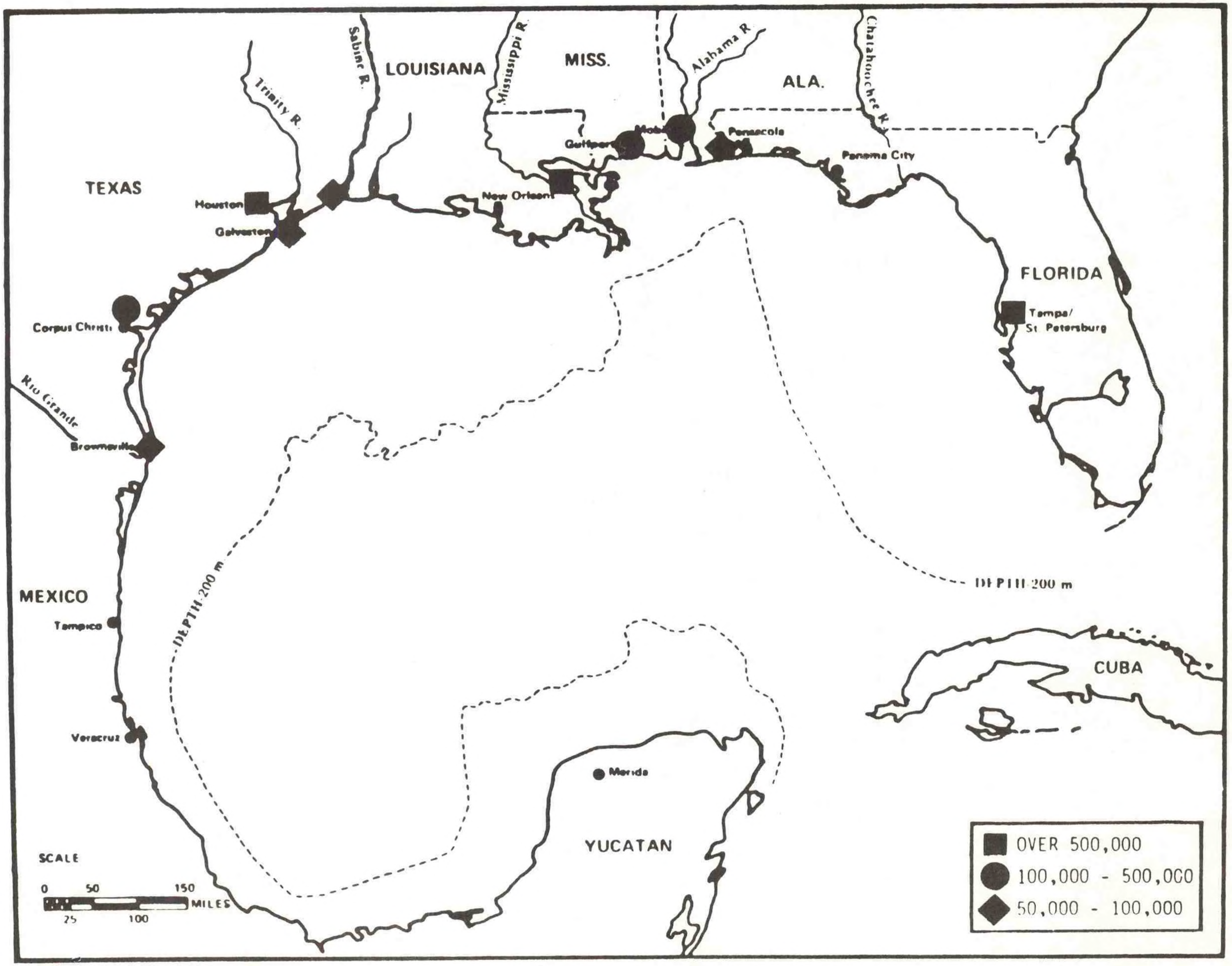


Fig. 1. Major Urban Areas.

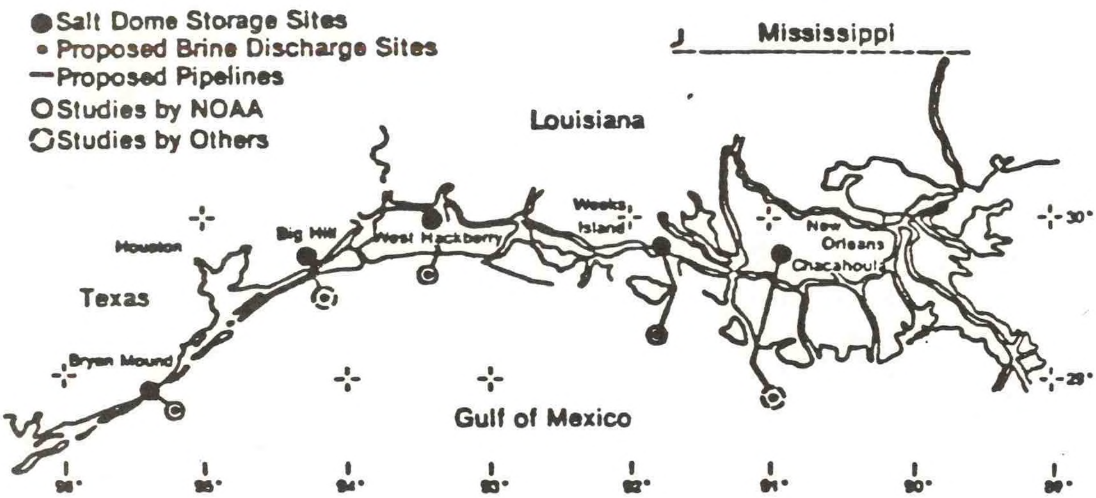


Fig. 2. Proposed Brine Disposal Locations.

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# CIRCULATION IN THE GULF OF MEXICO

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## 1. INTRODUCTION

This summary on circulation in the Gulf of Mexico has been written in an attempt to be concise, yet cover the essential information. In many cases, the choice of which papers to give as references has been rather arbitrary, and to those people whose work has been slighted, we apologize. The material here covers what is usually called circulation, with no mention of internal or surface waves, tides, or inertial motion. It is difficult to prepare "background material" when one has no clear idea about the specific problems to be addressed. The difficulty is especially acute in the area of diffusion and mixing. Specific mention is made, where appropriate, about mixing processes that seem important. A brief section is included to cover a few topics on mixing, but it should be obvious that this is "where the action is," and cookbook formulae may not give answers that are worth the effort.

A summary was prepared previously (Jones et al., 1973). In an attempt to be "recent and fresh," we have tried to avoid covering the same ground over again.

## 2. LOOP CURRENT

The strongest single feature in the Gulf of Mexico is the Loop Current (Fig. 1). As is well known, this flow enters the Caribbean and eventually becomes the Gulf Stream. The path that it takes, however, is highly time-dependent, and this portion of the pre-Florida Current is known as the Loop Current. Figure 1 shows that the dynamic height signal across the current is 60-70 cm. This current is important, not only in its own regard, but also in that it injects pinched-off rings into the interior of the Gulf. These rings carry with them momentum, salt, and nutrients, which are major contributions to the balances of the interior and western portions of the Gulf. The Loop Current and its variability is likely to be important to understanding the exchange of deep water between the Gulf and the Caribbean. The Loop Current also may act as a significant external driving mechanism for adjacent areas of the west Florida shelf. Pinched-off rings are discussed in the next section; the deep water of the Gulf is discussed in Section 5.

On a cross-section between Tampa and Yucatan, Figures 2 and 3 show temperature and salinity sections, which are combined in Figure 4 on a t,s diagram. It is important to note on these cross-sections that a temperature surface (and a salinity surface) will change depth by roughly 500 m in the region of strong flow. This suggests that any dissolved or suspended material that can be mixed along a constant density surface can change its depth in a region of strong flow by many hundreds of meters, yet there will be no work required; this, of course, is at the heart of the idea of mixing along constant density surfaces.

Morrison and Nowlin (1977) have made repeated nutrient, oxygen, and STD sections through the Loop Current and have described several water masses. Their Figure 10 shows that several water properties (maxima, minima) in the Loop Current follow density surfaces in a cross-section, adding support to the idea that mixing takes place preferentially (but not exclusively) along these surfaces. Their figure 11 shows characteristic diagrams (of oxygen, silicate, and phosphate) vs Sigma-t for the eastern Gulf, and they find fairly "tight" curves. Figure 1a is an attempt to use averages of the hydro data. It shows averaged NODC data (Molinari, Festa, and Behringer, 1978).

Figure 5 shows a velocity cross-section measured by Brooks and Niiler (1977) at the Key West section. Note that this is an "instantaneous" section and is not the smoothed picture obtained from geostrophic calculations. The stippled area shows flow into the Gulf along the Florida coast, a feature found frequently.

The mooring records displayed by Duing, Mooers, and Lee (1977; their figure 13) in the Florida Straits show bursts of southerly flow at depths of 100 to 500 m; the southerly "flow" seems to be associated with shelf wave-like events that are probably weather forced. But the wave-like events do not merely slosh back and forth. The eddy fluxes of momentum and heat, $\overline{u'v'}$, $\overline{u'T'}$, $\overline{v'T'}$, show an eddy flux of heat to the north and to the east, as shown in figure 5a. Most of the cross-spectral energy is found at periods of 10 days or longer.

There is a widely held notion that the Loop Current has an annual cycle. Figure 6, adapted from Vukovich et al. (1978), shows variability of the position of the Loop Current in different months. The variability is large; the average positions from one month to another are not that much different. Figure 7, however, suggests that there is a seasonal cycle that has a period of roughly one year, but that the cycle is not very regular.

It is not well known what forcing mechanisms control the position, growth, or decay of the Loop Current. Soong and Hsueh (1978) have shown that vorticity models that include some measure of the surface velocity can well account for the path of the Loop Current if its initial conditions in the Yucatan are known. Their models even suggest when the Loop Current will form a ring. But the information required for a real understanding of Loop Current variability is enormous. It is a substantial effort at present to determine the velocity distribution at one section. The earlier work of George Maul in tracking the Loop Current was very time-consuming, whereas with satellite coverage, the work is much simplified. Unfortunately, the months of June - October show a uniformly warm surface layer in the Gulf, the present infra-red technology is of little use during the summer. When satellite altimeters become as readily available as the infra-red data are now, modeling features such as the Loop Current will be done with much greater ease. There are suggestions that altimetry data may be useful to ~4 cm rather soon.

The "conventional wisdom" is that the Loop Current pinches off a ring every time it makes an intrusion into the far northern part of the Gulf. However, this is open to question, owing to the small number of careful continuous sets of observations. It sometimes appears that a ring will pinch off and attach itself again to the main flow.

## 3. PINCHED-OFF RINGS

It is well known that in the region downstream from Cape Hatteras the Gulf Stream meanders about, eventually closes back upon itself, and pinches off large eddies, or rings. (The term "eddy" has come to mean large features that are clearly wave-like, saving the term "ring" for a feature that appears to be detached from this pinching-off process.) The Loop Current in the Gulf of Mexico pinches off rings, as suggested in Figure 7. Elliot (1979) has compiled data on rings drifting to the west and concludes that they take approximately one year to drift from their formation region to the western side of the Gulf. A model by Flierl et al. (1975) of the western propagation of an eddy is shown in Figure 8. The eddy is "self-propagated" to the west, and it tends to decrease in amplitude as it moves along. The decrease is accomplished because the eddy radiates energy, as shown in the trail of temperature fluctuations that it leaves radiated behind it. Eddies have been tracked (sometimes more successfully than at others) by various means. Richardson et al. (1977) have shown that a surface radio-transmitting buoy can be tracked in a Gulf Stream ring for many months. Other investigators have found that markers placed in eddies are sometimes thrown out; the same fate has befallen Swallow floats placed at mid-depth in Gulf Stream rings.

A previous result given by Carruthers (1972) may be relevant here. Figure 9 shows a set of departures from a standard t,s curve in the Gulf of Mexico. Region 1 is in the inflow near Yucatan, and regions I-VI get farther toward the west. The t,s diagram used by Carruthers as a basis was simply the one at Yucatan. Figure 9 shows the increase in the salinity at temperatures of about $8^{o}$ and a corresponding decrease in salinity at temperatures above about $14^{o}$. Referring to Figure 2, we can see that this is the region of very strongly sloping isotherms. The salinity maximum at temperatures near $20^{o}$ obviously is losing salt; the temperature minimum at temperatures near $6^{o}$ is gaining salt. But the maximum increase in salinity, as viewed on a t,s curve, is obviously not in the region of minimum salinity but at $8\text{-}10^{o}$, which is the region of strongly sloping isotherms. This should indicate something about mixing along sloping isotherms.

## 4. WESTERN GULF

The western Gulf of Mexico is a difficult area to describe, owing to the paucity of observations and to the complexity (and a lack of knowledge) of the pertinent dynamics. There appear to be two important driving mechanisms: the wind field and rings propagating from the east. Unfortunately, the picture is further complicated by the fact that the wind stress and the curl of the wind stress have strong seasonal variability. Rings come into the region at irregular intervals.

The ship data over the western Gulf, whether for surface currents, wind observations, or basic research data, are notoriously sparse. The data sets are sometimes badly aliased by high frequency events (such as fronts moving through), and the answer one gets depends strongly on which data set is used. There is obviously room for improvement.

The dynamic height pictures, as shown in Figure 1, show a large gyre in the western Gulf, having the same sense of rotation as the Gulf Stream system -- and the same sense of rotation as pinched-off rings. Work by Vasquez (1975) suggests that this gyre is always present in the western Gulf. A large tracer experiment conducted by the Mexican government recently showed that oil released into the ocean in the Bay of Campeche proceeds rapidly up the western side of the Gulf of Mexico to Corpus Christi. Figure 10 shows hydrography taken from an airborne XBT survey in July of this year. The depths of the isotherms suggest that the flow approaches the coast at approximately 22-23$^{o}$ N and stays near the western boundary all the way to the continental shelf in the north before a recirculation (or meander?) begins. Satellite photographs in the winter have sometimes shown, however, that this flow leaves the coast at approximately 26$^{o}$N, at the mouth of the Rio Grande river.

It has been suggested (Sturges and Blaha, 1976) that the western gyre may be a western boundary-like feature driven by the curl of the wind stress. Figure 11 shows a map of the curl of the wind stress done by meteorologists during GATE (from Krishnamurti, 1978). The wind stress shows strong seasonal variations. Figure 11a shows monthly wind stress estimates (presented as Ekman transport) derived from atmospheric pressure at sea level. Additionally, Figure 11a shows the seasonality of the stress and curl of the wind stress curl in the western Gulf. The seasonality implies that the western gyre is constantly either spinning up or spinning down. Work has been done on spin-up at mid latitudes. The most applicable work may be by Anderson et al. (1979). They have studied the spin-up of the North Atlantic using a numerical model. This is a topic of present work.

A view held by some investigators is that the gyre in the western Gulf is merely the remnant of rings pinched off from the Loop Current that have propagated into the area. Elliot (1979) has studied the problem and concluded that the western gyre is (roughly) half driven by the curl of the wind stress and half driven by the introduction of one new large ring per year. However, what happens when a ring moves into the region is really moot, as no good observations exist. Sturges is now sponsoring a sequence of AXBT surveys in the western Gulf.

The work of Blaha and Sturges (1978), as shown in Figure 12, suggests that the longshore currents on the Mexican-Texas border (as indicated by tide gauge signals) are about half coherent with the longshore wind stress and about half coherent with the curl of the wind stress over the western Gulf.

## 5. DEEP WATER

The deep water of the Gulf is determined almost entirely by the inflow at Yucatan. Some water enters through the Straits of Florida, appearing on velocity sections as a counter-current just beyond the edge of the shelf break (e.g., Figure 5).

Temperature and salinity sections and a typical t,s diagram were shown earlier (Figures 2-4). Figure 13a shows a comparison between the vertical temperature distribution in the Gulf of Mexico and that in the western

Caribbean. The Gulf water is the same temperature as the Caribbean water at depths near 1600 m, but it is warmer from that point down. The identical temperatures suggest that the inflow to the Gulf of Mexico is unimpeded above 1600 m, but that below 1600 m, separation between the two waters is severe. The sill is fully 200 m deeper, so the inflow (and outflow) near sill depth must be weak or sporadic.

Figure 13b is a composite showing western Caribbean temperature-salinity characteristics that are derived from the Atlantic, and those in the Gulf of Mexico below 1400 m. The Caribbean pictures are from Sturges (1965), the Gulf data from McLellan and Nowlin (1963). In Figure 13b, the vertical dashed line marked C is the coldest water in the Caribbean at the depth of the sill at Yucatan (about 1800 m). The little arrow marked G shows the average temperature in the Gulf at 1800 m, as determined from Figure 13a. It is clear that the Caribbean water that spills over the sill at Yucatan enters the Gulf surrounded by water that is appreciably warmer and lighter, so that as every inflow "event" happens, there must be substantial mixing and turbulence as the water sinks. The t,s diagram essentially points to the water mass that enters.

Observations in the deep part of the Yucatan channel have been made by several groups (e.g., Texas A&M, NOAA). These (unpublished) observations show a substantial amount of southerly flow. Maul (1979) has suggested that when the Loop Current advances into the Gulf, the water behind the Loop must displace resident Gulf water; this mechanism forces deep water out through Yucatan. This mechanism seems highly plausible, but our data base to verify and understand it is obviously very scanty.

Studies of Atlantic water overflowing into the Caribbean (Sturges, 1975) have shown that the characteristics of the entering water mix very rapidly. The largest amount of mixing takes place on scales of roughly 10 km near the sill. The observation that the t,s diagram over the entire Gulf of Mexico at all depths below the sill has very little scatter (e.g., Figure 4) suggests that such rapid mixing also happens near Yucatan. The narrow envelope of "Gulf" water shown in Figure 13b contains all of the observations of the 62-H-3 cruise in the Gulf below 1400 m.

When a ring becomes detached from the Loop Current and drifts toward the west, it carries with it a salinity excess in the upper water and a salinity deficit in the water below about $14^{o}$ (e.g., Figure 9). Maul (1979) has made estimates of a salinity budget. Simple models of a closed basin (such as the early Box Models of Atlantic and Pacific waters by Stommel, et al. (19 ) may give useful insight into basin residence times. However, brine seeps have been reported at various depths in the Gulf (300 feet, East Flower Gardens; 2900 m, etc.), where the "salinity" of the seep is ~200 $^{o}/_{oo}$. Such flows seem to be weak, but no calculations appearing in the open literature suggest whether the seeps are important; it will probably be necessary to ask a specific question to learn (in salinity-budget ideas) whether the seeps are important relative to something else. Perhaps other investigators know of estimates of the total flux rate of the seeps?

## 6. CONTINENTAL SHELVES

In recent years, the data base on continental shelf circulation has increased substantially. It sometimes happens that there are strong external forces, e.g., the Gulf Stream, near Miami, that affect the longshore flow. But when such forces are absent, the dominant mechanism is local wind. It has been observed in many locations that the longshore wind drives the longshore current; see Winant (1979), Winant and Beardsley (1979).

We can learn much from the results of the Coastal Upwelling Experiment (CUEA) that is applicable to the Gulf of Mexico (see for example Smith, 1974; Mooers, Collins, and Smith, 1976). Huyer (1976) compares the wind-driven currents on the Oregon coast to those off the coast of northwest Africa. (Strangely, the shelf off the coast of northwest Africa is much more like the shelf in the Gulf of Mexico than is the coast of Oregon.) Figure 14 shows the observed flow in the longshore and onshore components. These currents are transients, of course, having essentially the periodicity of the wind field: roughly ten (10) days.

We know that longshore winds drive longshore currents; the currents come into geostrophic balance fairly rapidly (within half a day or so) and the slope of the sea surface causes a change in sea level, which is recorded at tide gauges. This change in sea level is fortunate because current meter observations are very sparse compared with tide-gauge data. Figure 15a shows a simple comparison between longshore winds and sea level near St. Petersburg. Figure 15b shows a summary of data at different tide gauges.

Observations of currents on the west Florida shelf have been reported by Niiler (1976), Weatherly and Martin (1978), and Price, Mooers, and Van Leer (1978). A progressive vector diagram of measured currents north of Tampa, shown in Figure 16 (Hsueh, Weatherly, and Sturges, unpublished manuscript), shows that the tides contribute small amounts of back and forth motion, yet, the events that have much larger spatial scales are associated with the week-or-so time scale of the passage of frontal systems.

When large storms come by, currents at the bottom are sometime found to be as large as 4 knots (Forristall et al., 1967). Observations on the Texas shelf have been reported by N. Smith (1977). Blaha and Sturges (1978) found that along the north Texas coast (e.g., Galveston), longshore sea level was highly coherent with longshore winds. The tide gauges along the Mexican and southern Texas coast were only about half coherent with longshore winds, half coherent with the curl of the wind stress, hence, with the larger, basin-wide scales.

The longshore flow does not merely go back and forth, however. Figure 17 is a schematic of surface circulation on the shelf during a wind event. The longshore winds have a net Ekman transport onto (or off of) the shelf. In Figure 17, we see a surface layer being moved offshore by the wind stress. To replace this water, deeper water is brought toward shore, largely in a bottom boundary layer, in which there is stress against the bottom and mixing within a bottom boundary layer. Very near the coast, in a boundary layer roughly 10 km wide, the flow is very turbulent, with much mixing taking place. Thus, some deeper water that came up onto the shelf has been mixed with considerably lighter water during the (back and forth) wind event.

An analytical model that has recently been presented by Csanady (1978) is summarized in Figure 18. The wind stress is indicated as extending only from the origin to a distance 180 km along the coast and then being stopped abruptly. The model shows the change in sea level along the coast to a maximum at the down wind (or downstream) end of the region of wind stress, and decaying away thereafter. In the lower part of the figure, the velocity distribution is suggested. There are few good observations of currents on the shelf to verify such models, although the need for them is very apparent.

There is a great need for a clearer understanding of how mixing takes place during these events (as well as during a tidal excursion, etc.). Currently, attempts are being made to learn what these motions are, what forces them, and what the important balances are.

A further mechanism deserves mention. Differences in density along the coast can also give rise to a longshore pressure gradient and an induced flow, at frequencies much lower than the wind event time scale. Figure 19 shows a summary of surface temperature data around the Gulf by Goulet and Haynes (1978) (an equivalent salinity or density diagram is not given). We expect that, on fundamental grounds, the low-salinity Mississippi River outflow should induce a residual flow to the west along the northern coast. The mean wind stress along the coast is also to the west (see Blaha and Sturges, 1978, Figs. 11a, 11b, 11c), so it is not clear which mechanism is dominant. Chase (1979) has described the variations in longshore pressure gradient associated with density changes and wind (along the Atlantic coast; see also Csanady, 1979). Both driving mechanisms are found to be important, as is the influence of the position of the Gulf stream.

## 7. NUMERICAL MODELS AND MIXING

A number of numerical models of the Gulf of Mexico have been run in the past, using large horizontal friction in an attempt to let the Loop Current "drive" the western Gulf. Since it appears that the curl of the wind stress and pinched-off rings are the important forcing mechanisms, modern numerical modelling has begun to incorporate wind into full Gulf models. Hurlburt and Thompson (unpublished; private communication) have gone to great lengths at NORDA to try to account for the two open boundaries in the system, which makes the numerical model exceptionally difficult. A second large numerical model is being done by George Mellor (supported by OTEC); we look forward with great eagerness to seeing the results of these two quite different numerical models.

If mixing of tracers such as nutrients is the object, numerical models using large horizontal "friction" must be viewed with great care. The use of a large horizontal eddy viscosity causes mixing of mass, momentum, and tracers to be along level surfaces instead of along density surfaces. This is especially a problem where isopycnals slope steeply; significant but unrealistic cross-isopycnal transport will be induced. Veronis (1977) points out that a numerical model of the North Atlantic using a large horizontal eddy viscosity predicted a vertical velocity in the interior of the ocean opposite in sign to that suggested by thermocline theory. Veronis attributes this to unrealistic cross-isopycnal mixing. He noted that another version of the same numerical model using a smaller horizontal eddy viscosity predicted a vertical velocity consistent in sign with "traditional wisdom."

Numerical modelling of some special features of the flow has been very successful. Weatherly and Martin (1978) have modelled mixing in the bottom boundary layer on the west Florida shelf with good results. The wind-mixed surface layer on the west Florida shelf has been studied by Price et al. (1978).

When studying "mixing" in the Gulf, it would be prudent to look for the most general work, as turbulent models in the Gulf would be expected to have a great deal in common with models of other regions. In the classical method, a term involving mixing of some property (momentum, heat, salt, etc.) is introduced rather arbitrarily into an appropriate conservation equation, using a term of the form (for the heat equation, for example)

$$\frac{\partial}{\partial x}\left(A_H \frac{\partial T}{\partial x}\right)$$

where the term $A_H$ is the horizontal eddy viscosity coefficient. Similar terms involving a vertical coefficient, $A_V$, may be used. The game then becomes one of "solving" for $A_H$ and $A_V$.

Physical oceanographers are somewhat embarrassed about the use of the term eddy coefficients. This term, and the term mixing, are euphemisms for our ignorance about the mechanisms or dynamics of processes that are going on beyond our ability (or desire) to observe and understand. It is particularly awkward to construct ocean models that duplicate the interior of the ocean, in which, in many respects, you can either ignore vertical diffusion or ignore horizontal diffusion. It has recently been suggested (e.g., in the work of Rooth) that the role of horizontal diffusion in the ocean is substantially more important than was previously thought, and that vertical diffusion in the ocean at mid-depths may be less important. Perhaps, the two are of roughly equal importance. (See, for example, Veronis, 1977.)

Models, either analytical or numerical, must parameterize mixing in some way. Even the so-called "eddy-resolving" models can only resolve scales of tens of kilometers, whereas the actual mixing mechanisms take place at scales of perhaps tens of centimeters, or less. (See, for example, the excellent discussion by Woods, 1977, in the recent workshop volume edited by Kraus, 1977.) Figure 20 is taken from Woods (1977).

Some models use turbulence closure schemes to solve, explicitly, for those terms that are in principle beyond solution using the basic equations in a turbulent flow (e.g., Weatherly and Martin, 1978; Mellor, 19 ).

If an eddy coefficient is used, we know that it must be a function of the horizontal scale of motion; Figure 21 shows Okubo's (1971) result. This is to be expected, because the derivative is being taken on larger and larger scales. Unfortunately, when careful observations are used to "solve" for eddy coefficients, they have a way of going negative (for good reasons) where processes are interesting.

Although we know that intense mixing takes place on very small scales, such as in frontal systems, the amplitude of the observed eddy-like motions grows with horizontal scale. Figure 22, from Dantzler (1977), shows the vertical amplitude of the displacement of the thermocline at eddy-like scales (~100 km). We see that it varies greatly with horizontal position. We would expect largest values in the Gulf near the Loop Current. Figure 23, Katz, from (1977), shows a wave number spectrum from a single location (MODE, near Bermuda), showing that the amplitude of the motion falls off radically as the horizontal scale decreases. Figure 24, from Wilson and Dugan (1978), shows the same results in the Pacific Ocean. The amplitude is a function of latitude, and is largest near the Kuroshio, but the amplitude increases with scale only out to a wavelength of about 300 km.

Weatherly (1972) has summarized the conditions of a bottom boundary layer, as applied to the Florida Current. The velocity distribution is approximately logarithmic with height above the bottom in a thin layer (about 5-10 m); the thickness of bottom boundary layer is approximately

$$H \sim \frac{.4u^*}{f} \qquad (1)$$

if the water is not stratified, where $u^*$ is the friction velocity (the bottom stress divided by density, to the 1/2 power) and f is the coriolis parameter. Thus, for a "typical situation" with the speed of the freestream flow just outside the boundary layer, approximately 10 cm/s, a value of $u^*$ is approximately .4 cm/s; the Ekman layer depth H is approximately 25 m. Weatherly and Martin (1978) showed that, if the water is stratified, the thickness is found to be reduced, and

$$H \sim \frac{u^*}{f(1 + N^2/f^2)^{\frac{1}{4}}} \qquad (2)$$

where N is a measure of the vertical stability. For N = 0, the answer is the same as before.

The depth of the Ekman layer at the sea surface is roughly the same as the Ekman layer at the bottom, if the stress are approximately equal. We, thus, see that in waters of approximately 50 m depth, there are surface and bottom layers in which friction is an important parameter throughout the entire water column.

The effect of the wind in forming surface mixed layers, together with the effect of solar heating, is an important problem. A recent review of one-dimensional thermocline models is given by Niiler (1977). Application of a one-dimensional model to several ocean weather stations, for example (by Camp and Ellsbury, 1978), has shown that if a reasonable amount of historical data are available, the depth of the upper mixed layer can be forecast quite well.

## 8. APPENDIX I

Ongoing Data - The question arises: where are data available from recent ongoing (or proposed) programs that are not yet in the open literature? The following summary is intended to allow an interested party to contact the Principal Investigator.

| Area | Type of Data | Investigator |
|---|---|---|
| Yucatan Passage | Deep Currents | G. Maul |
| Cuban Coast | | R. Claro |
| West Florida Shelf | Hydrographic observations, summary; Recent current observations; OTEC current moorings | M. Rinkel, W. Sturges, Y. Hsueh, G. Weatherly, R. Molinari |
| North Florida, Alabama Shelf | OTEC current moorings | R. Molinari |
| Texas Shelf | Hydrographic data Currents | W. Merrell, A. Amos, D. Brooks |
| East Coast Mexico | Currents, hydrographic data | W. Sturges, A. Amos |
| Southwest Gulf of Mexico | Hydrographic data | I. Emilsson, A. Vasque |
| Loop Current | Positions | S. Baig US Coast Guard |
| Various Interior | Ships of opportunity | S. Cook |

## 9. ACKNOWLEDGMENTS

We are especially grateful to Ms. P. Arnold for her skill and help in preparing this manuscript, and to the Office of Naval Research and the National Science Foundation who have supported our studies.

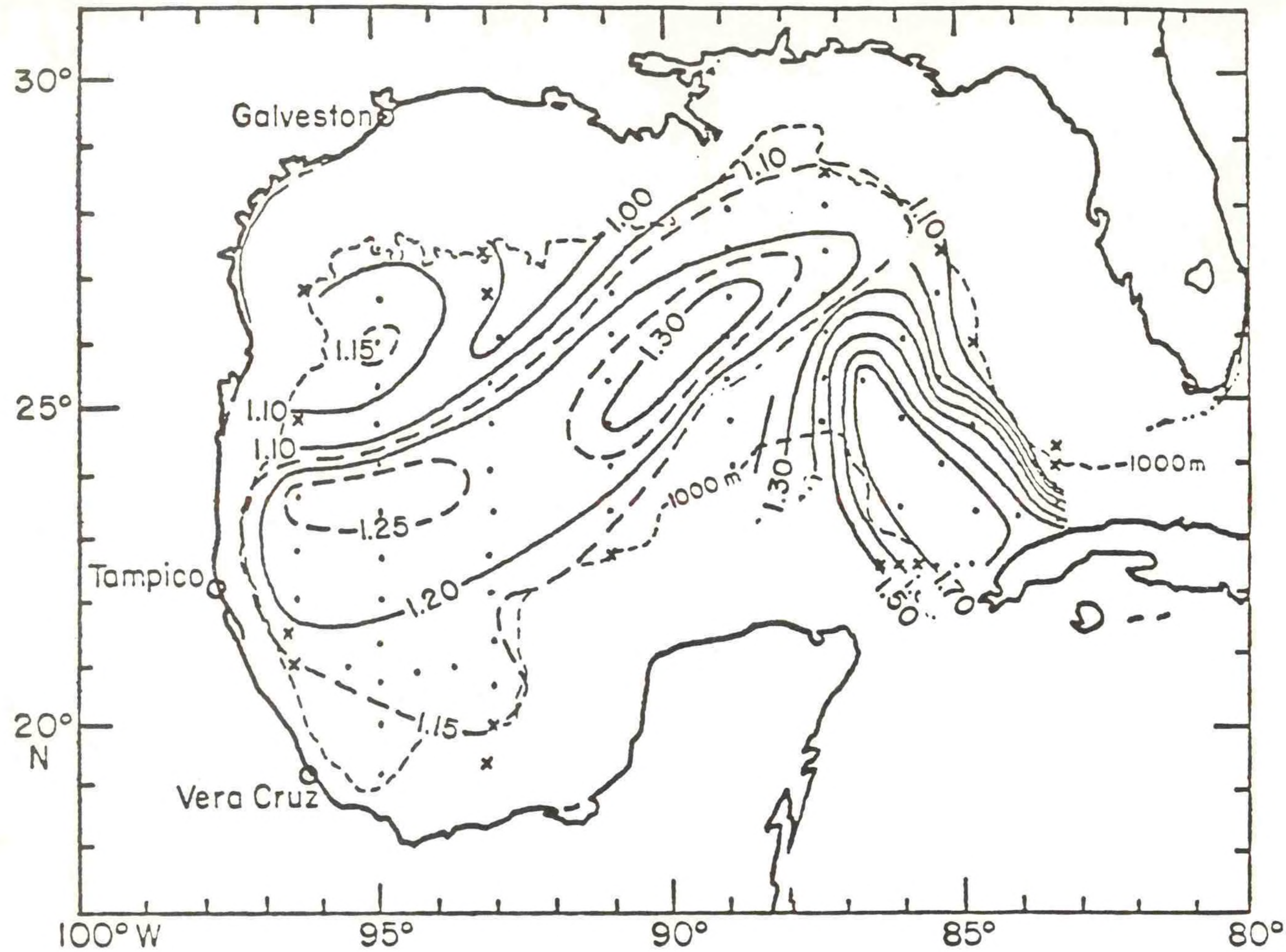



Fig. 1. Dynamic Height of the sea surface, meters relative to 1000db. (From Sturges and Blaha, 1976, adapted from Nowlin and Mclellan, 1967.) The Loop Current is in an "average" position. This simply shows the average density of the water between (about) 1000m and the sea surface. The surface stands higher where the water is warmer or fresher. Data from Hidalgo cruise, 62-H-3, Feb., March 1962. (Sturges and Blaha, Science 192:367-369, April 1976, Copyright 1976 by the American Association for the Advancement of Science; adapted from Nowlin and McLellan, 1963, J. Mar. Res. 25(1):25-29. Reprinted with permission of the American Association for the Advancement of Science and the Foundation for Marine Research.)

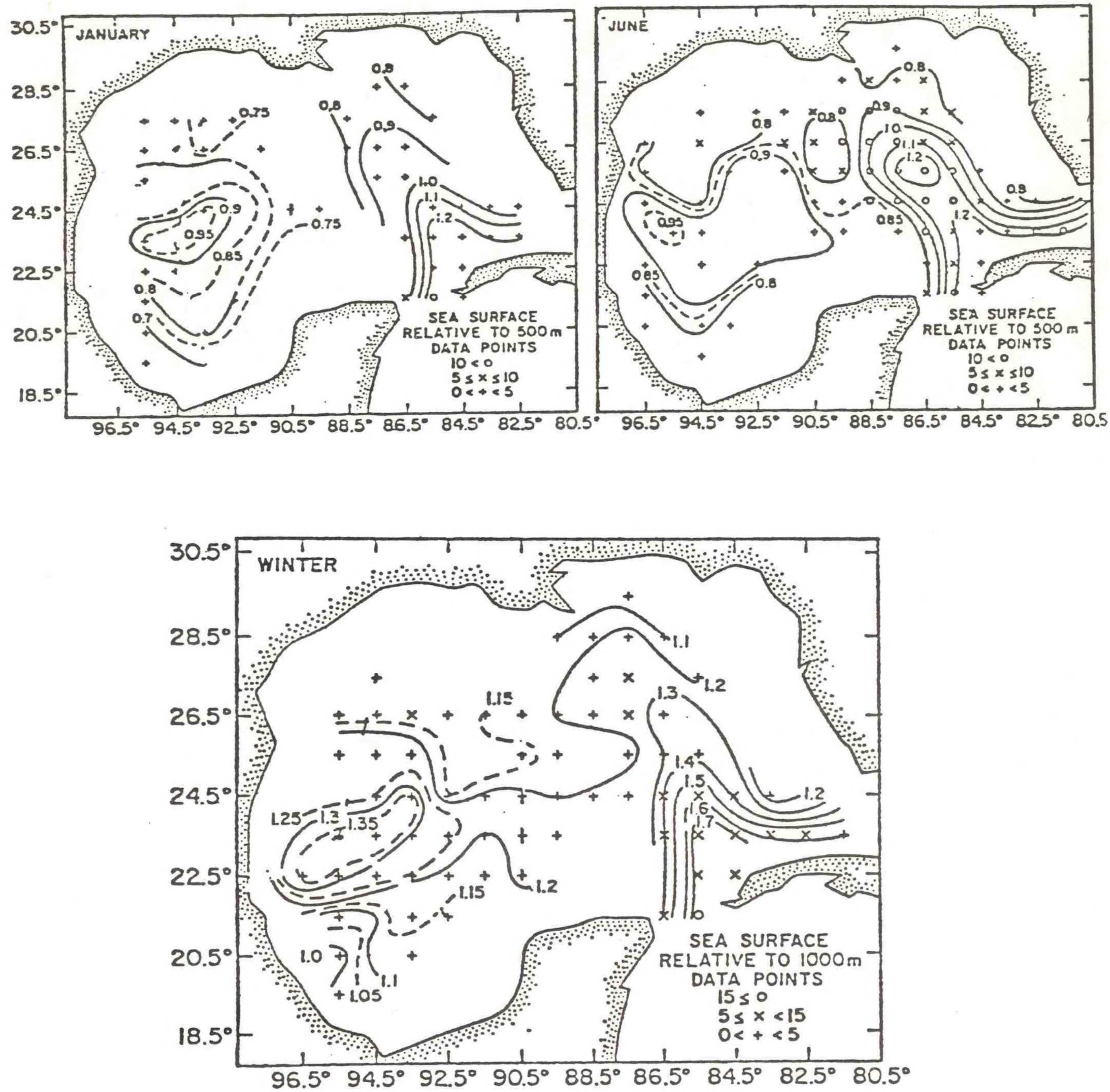



Fig. 1a. Dynamic Height of the sea surface, meters, relative to 500 db--averages for January and June; and "Winter" average relative to 1000 db. (From Molinari, Festa, and Behringer, 1978.)

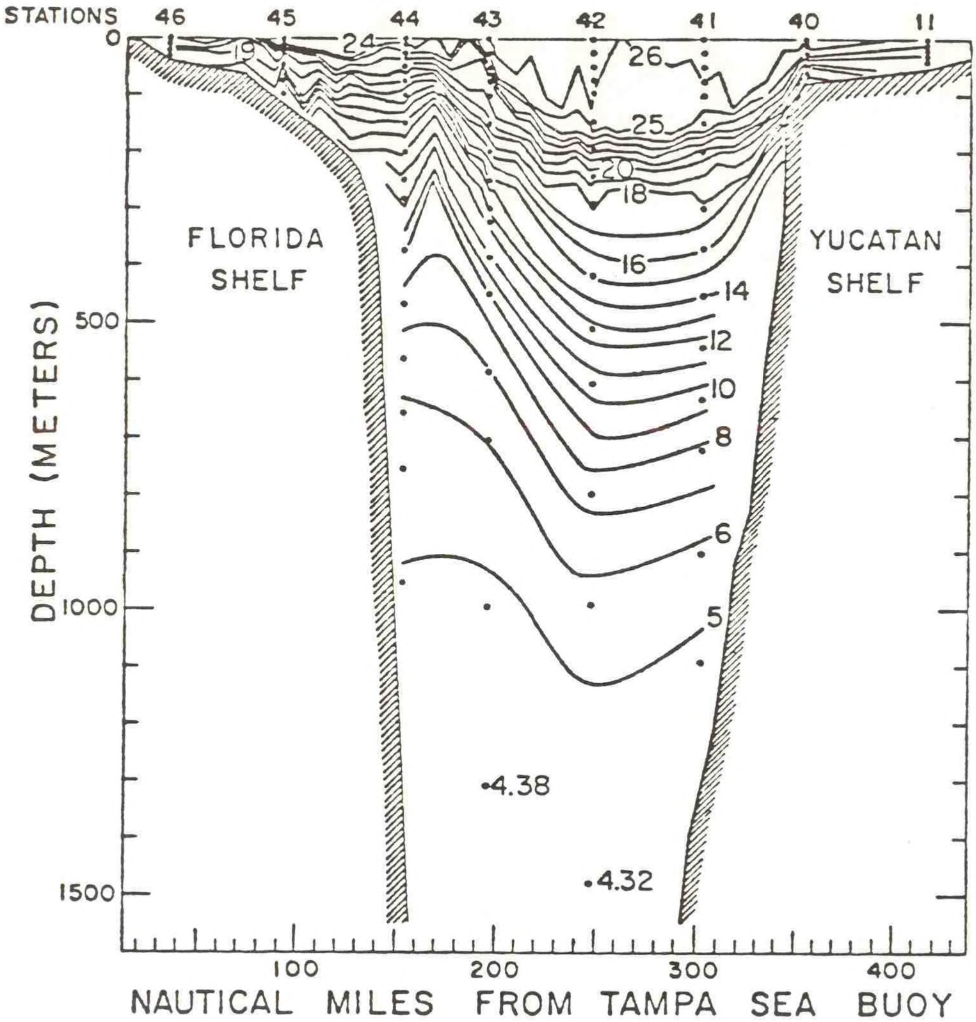



Fig. 2. Temperature (degrees Celsius). Section B, Hidalgo 62-H-3. St. 11 occupied 16 February 1962; Sta. 40 through 46, 25-27 February 1962. Sampling positions indicated by dots. Vertical exaggeration 555:1.
(From Nowlin, 1972, Fig. 1-21. In Contributions on the Physical Oceanography of the Gulf of Mexico, Volume 2 of Texas A&M University Oceanographic Studies, by L. R. A. Capurro and Joseph L. Reid. Richard A. Geyer, Series Editor. )

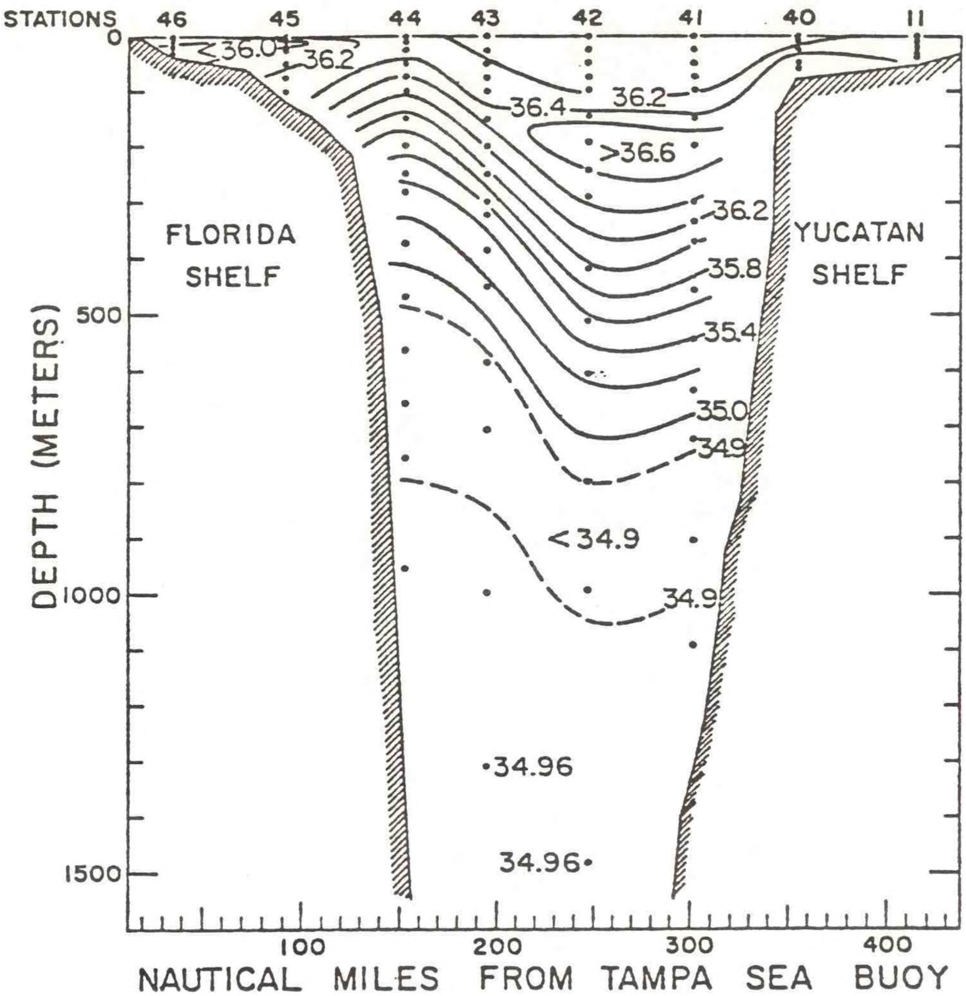



Fig. 3. Salinity (parts per mil), Section B, Hidalgo 62-H-3. St. 11 occupied 16 February; Sts. 40 through 46, 25-27 February 1962. Sampling position indicated by dots. Vertical exaggeration 555:1.
(From Nowlin, 1972, Fig. 1-22. In Contributions on the Physical Oceanography of the Gulf of Mexico, Volume 2 of Texas A&M University Oceanographic Studies, by L. R. A. Capurro and Joseph L. Reid. Richard A. Geyer, Series Editor. Copyright © 1972 by Gulf Publishing Company, Houston, Texas. Used with permission. All rights reserved.)

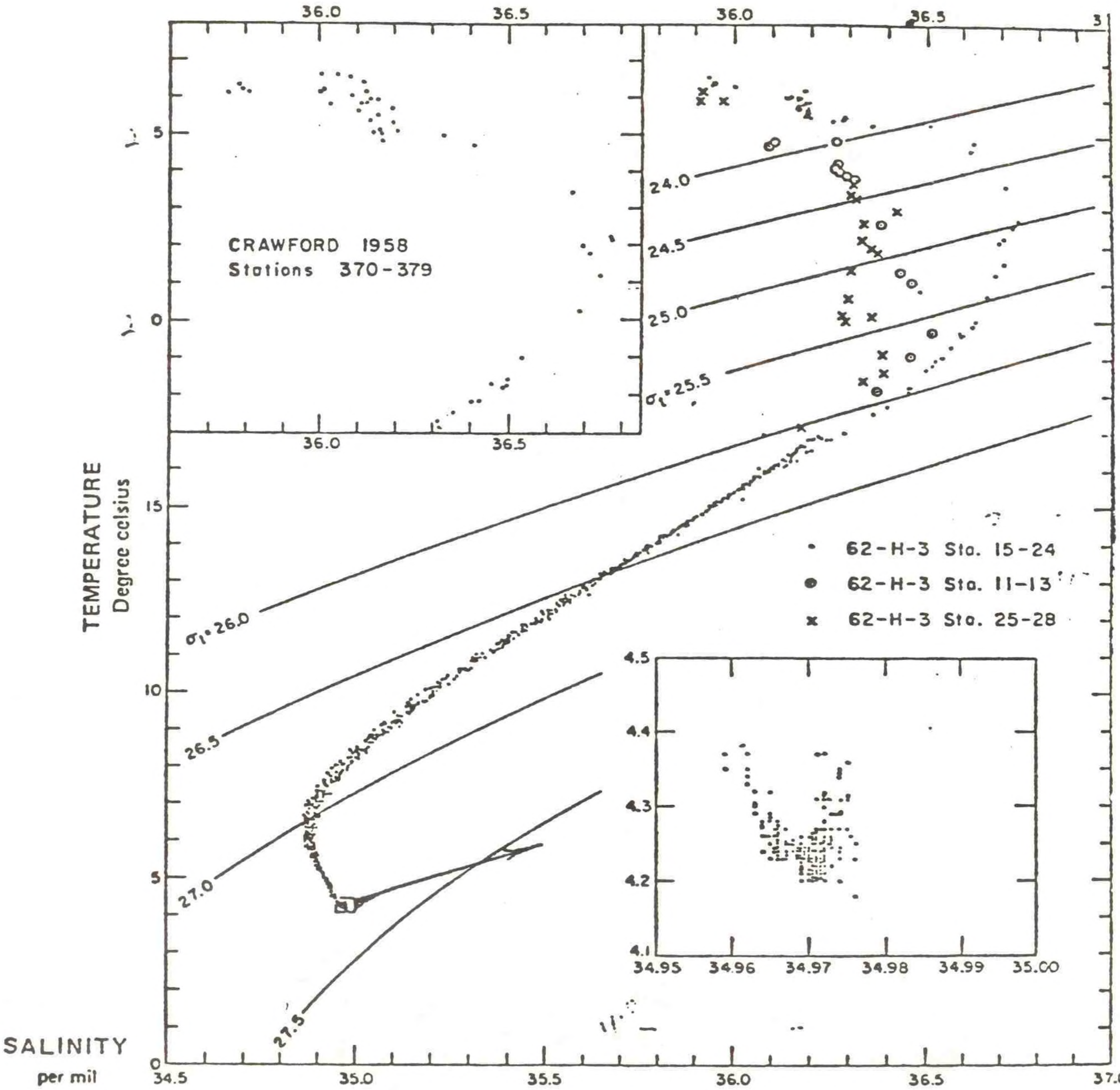



Fig. 4. Temperature versus salinity, Hidalgo 62-H-3, for all observations with temperatures less 17°C and for the near-surface waters at 17 stations in the regions of inflow and outflow. For temperature greater than 17°C, T-S relations are ploted for 10 Crawford stations occupied in the Caribbean.
(From Nowlin, 1972, Fig. 1-4. In Contributions on the Physical Oceanography of the Gulf of Mexico, Volume 2 of Texas A&M University Oceanographic Studies, by L. R. A. Capurro and Joseph L. Reid. Richard A. Geyer, Series Editor. 

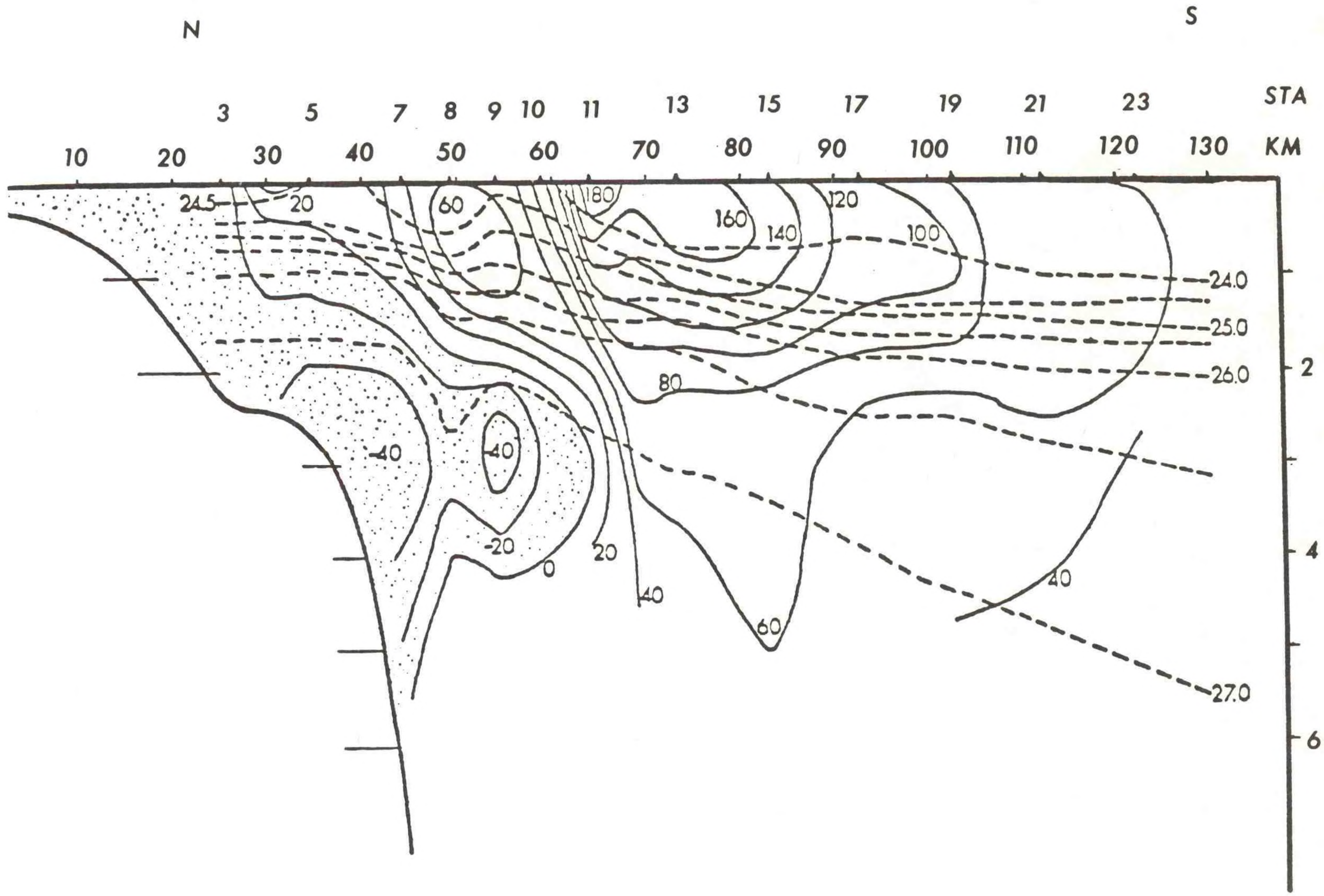



Fig. 5. A vertical section of downstream velocity component between Key West and Cuba; speed is in cm/sec with superposed lines (dotted) of sigma-t. Positive flow is to the east.
(From Brooks and Niiler, 1975, J. Mar. Res. 33:83-92, with permission of the Foundation for Marine Research.)

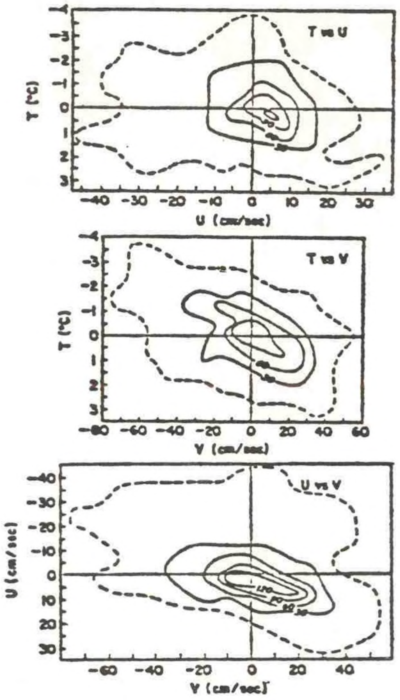



Fig. 5a. Joint histograms for the 26-month "entire" series. The axes are fluctuation amplitudes of u, v, and T, respectively, which were obtained from individual segment time series. Contours are labelled with the total number of observations falling inside the contour. (From Duing, Mooers, and Lee, 1977. Printed with permission of the Foundation for Marine Research.)

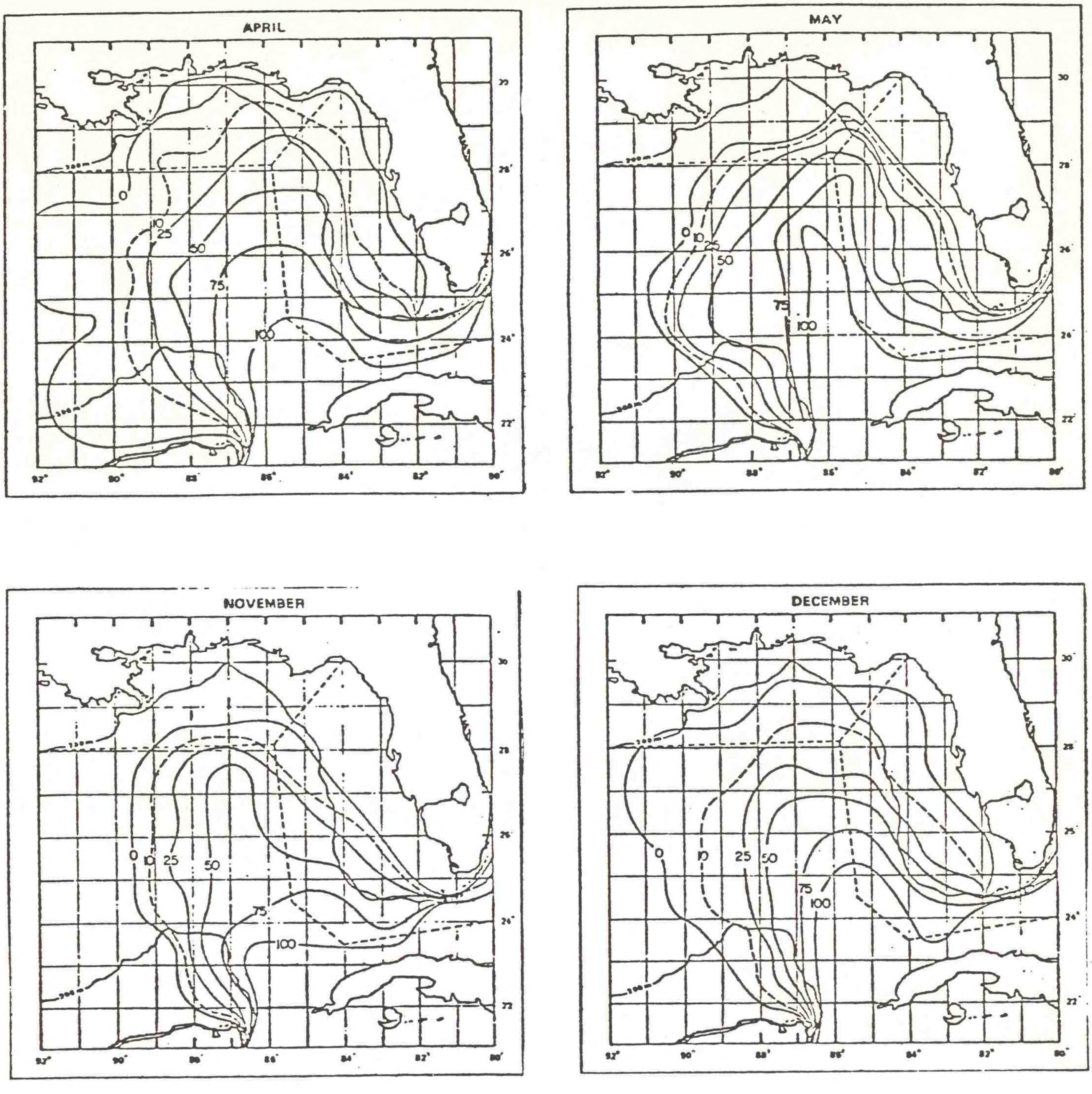



Fig. 6. Frequency analysis (%) by month of the location of Loop Current based on the NOAA VHRR data for 1973-1977. (From Vukovich et al., 1979. In J. Geophys. Res. 84(C12):7749-7768, 1979, copyrighted by American Geophysical Union.)

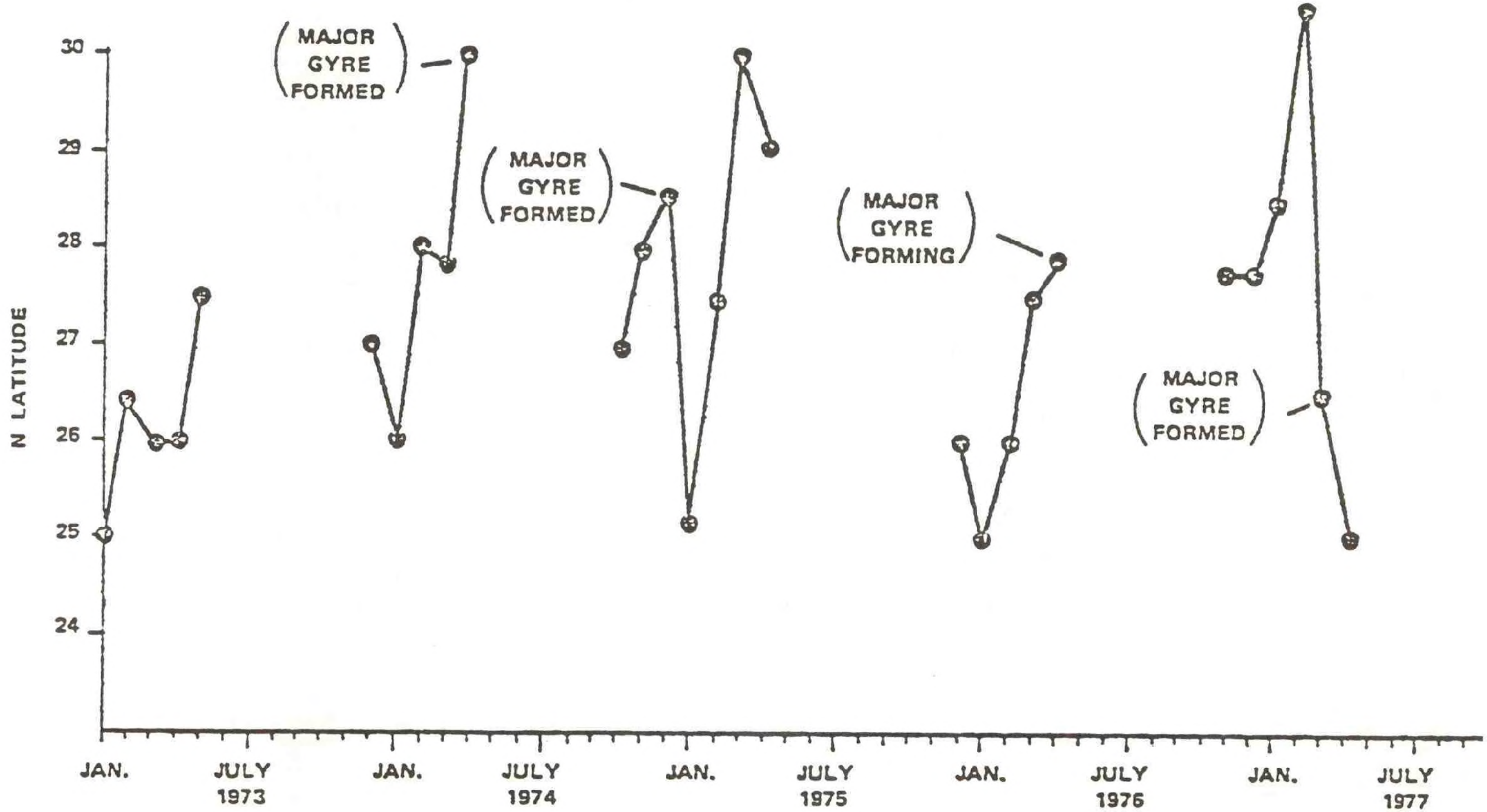



Fig. 7. Plot of the northernmost position of the Loop Current versus time based on available NOAA satellite data for the period October through May 1973-1977.
(From Vukovich et al., 1979. In J. Geophys. Res. 84(C12):7749-7768, 1979, copyrighted by American Geophysical Union.)

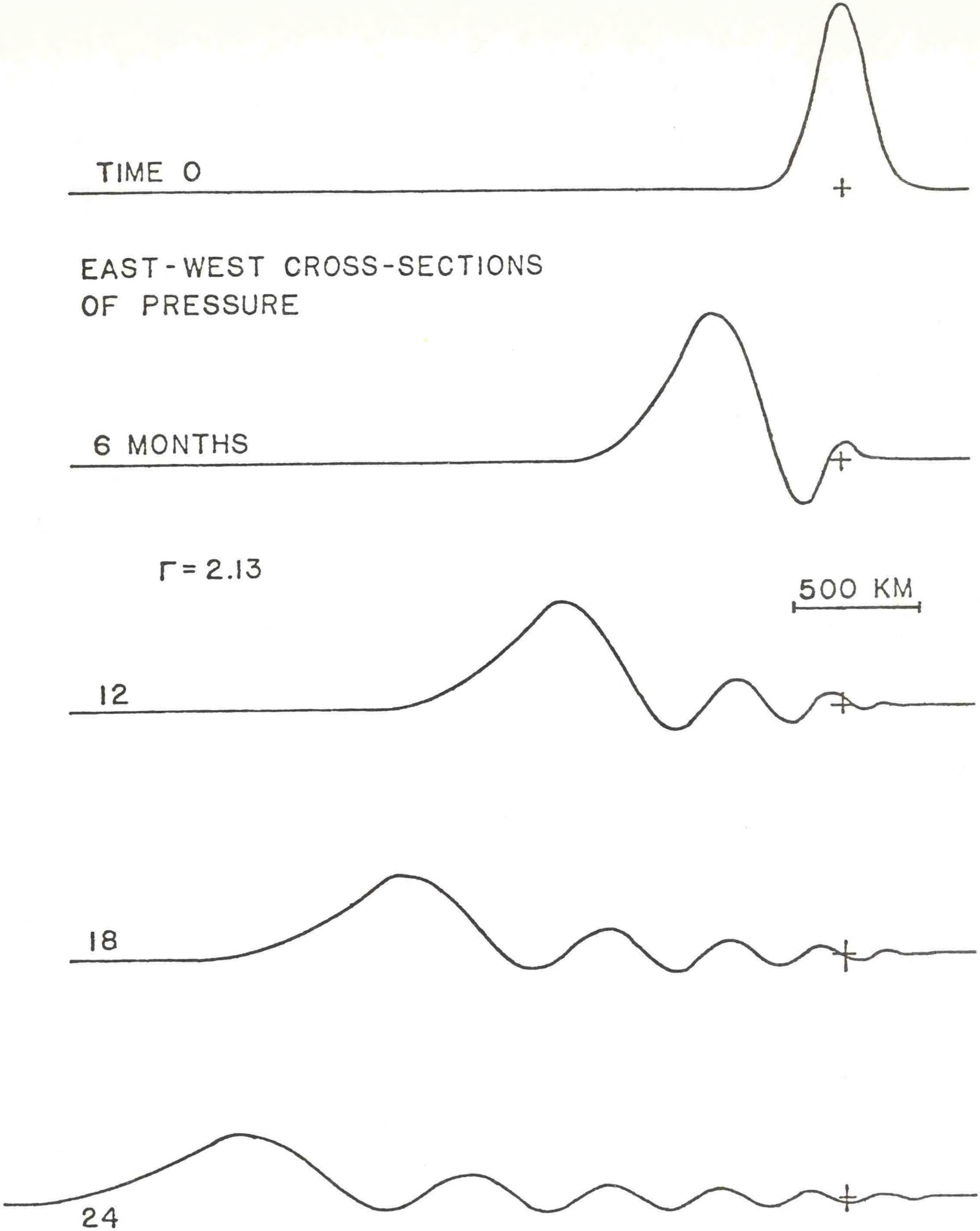
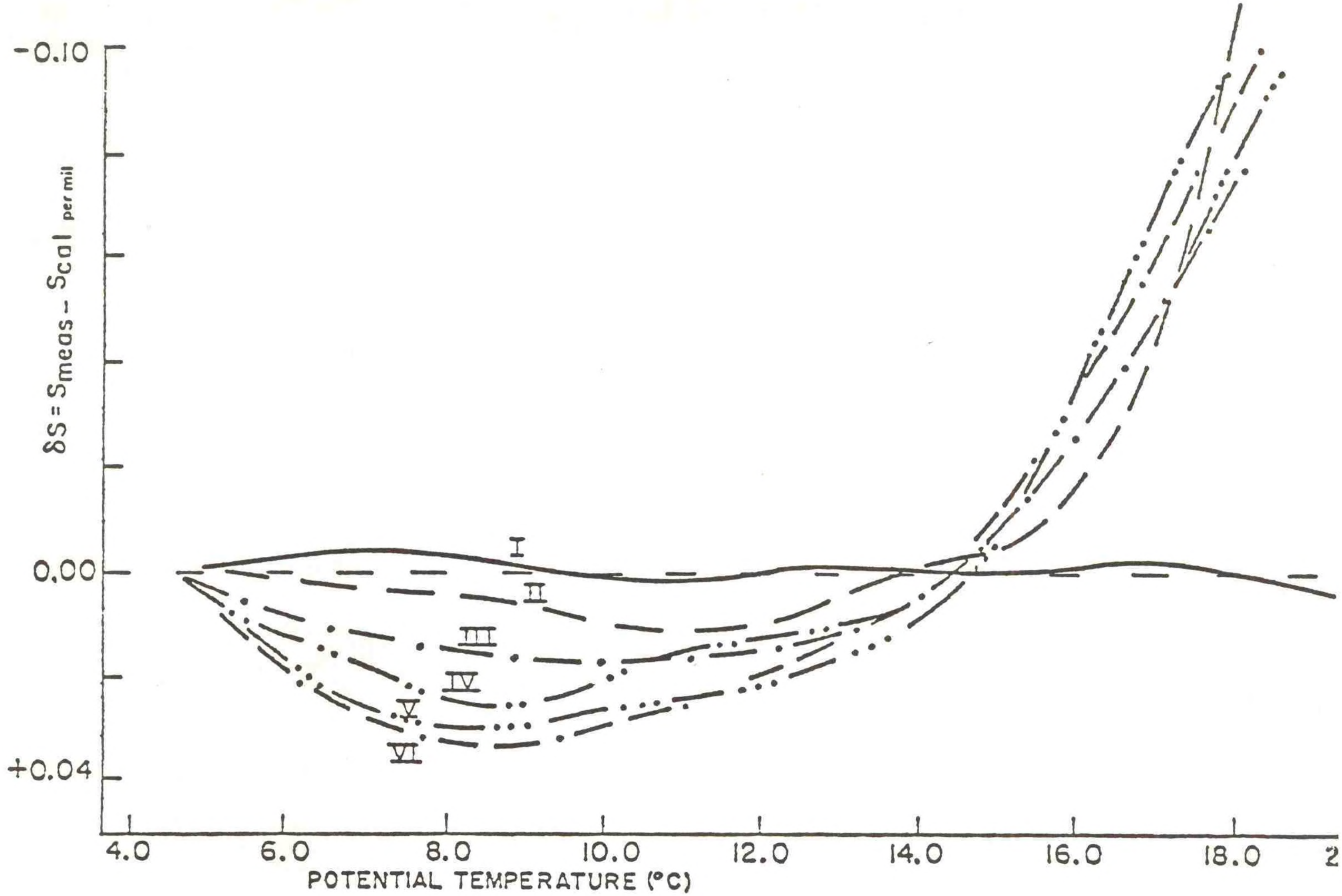



Fig. 8. Motion, Decay and Radiation of a Baroclinic Gaussian Eddy. (From Flierl et al., 1975.)




TEMPERATURE - SALINITY ANOMALY CHARACTERISTICS

Fig. 9. Comparison of θ-δS polynomials among various groups. Note the slow evolution through consecutive groups for tempertures below 14.5°C but the abrupt change between group 1 and all the others for temperatures above 14.5°C.

(From Carruthers, 1972, in Contributions on the Physical Oceanography of the Gulf of Mexico, Volume 2, of Texas A&M University Oceanographic Studies, by L. R. A. Capurro and Joseph L. Reid. Richard A. Geyer, Series Editor. 

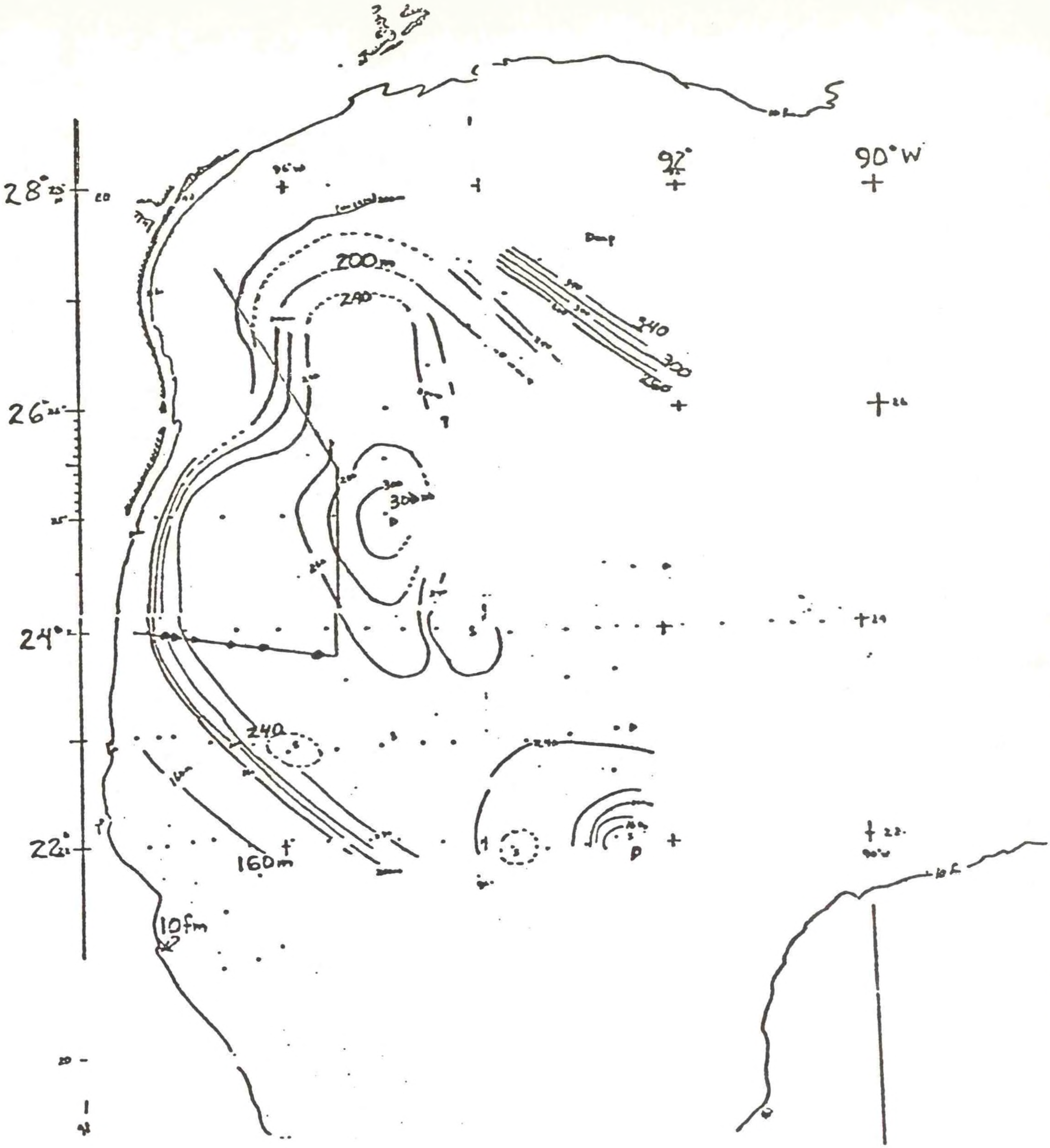



Fig. 10. Depth of 14°C isotherm in Western Gulf of Mexico, from AXBT data, 14 July 1979. Small dots show data points. The cruise track of R.V. Longhorn, 24 July - 1 August, is also shown; current-meter mooring locations are shown along ≈24°N. (From Sturges, unpublished data.)

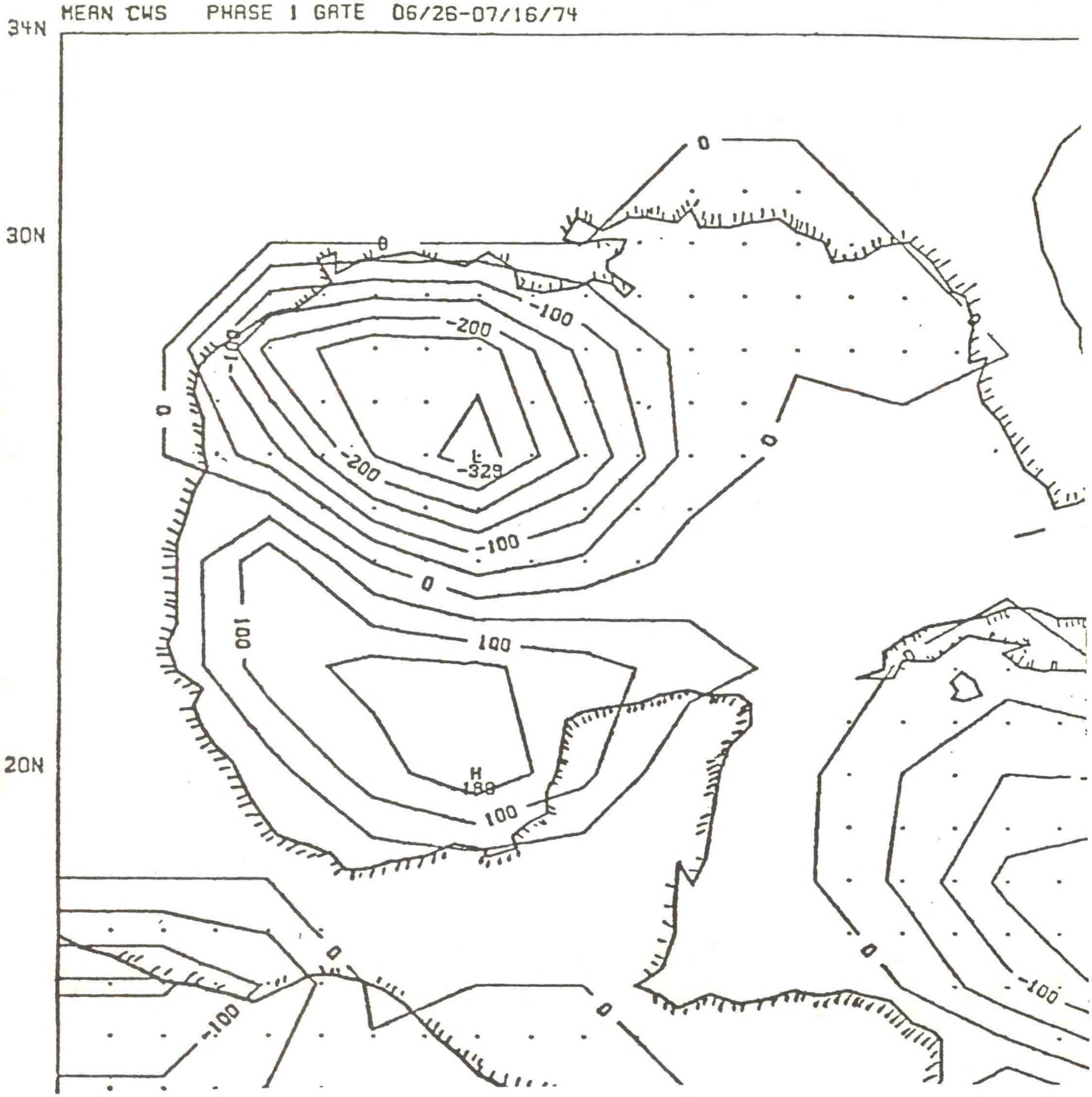



Fig. 11. Curl of the wind stress based on data collected June 26 - July 16, 1974, as part of the BATE experiment. The data base is cloud photographs every hour from a Geostationery Satellite. (From Krishnamurti and Krishnamuti, 1978.)

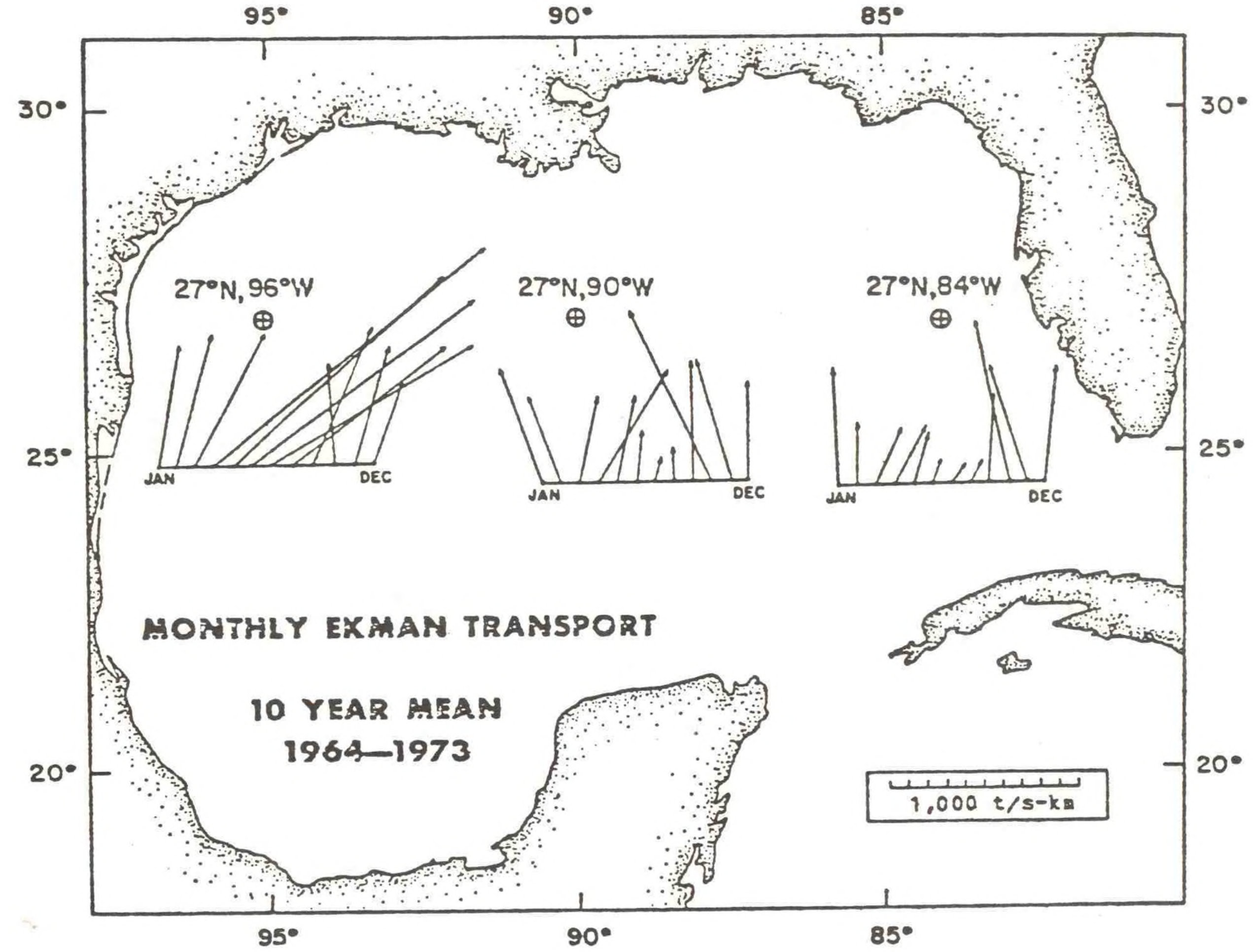



Fig. 11a. Mean monthly Ekman (wind-driven) transports for three points in the northern Gulf of Mexico for the 10-yr period, 1964-73. (From Gunn, 1978, Fig. 13.4.)

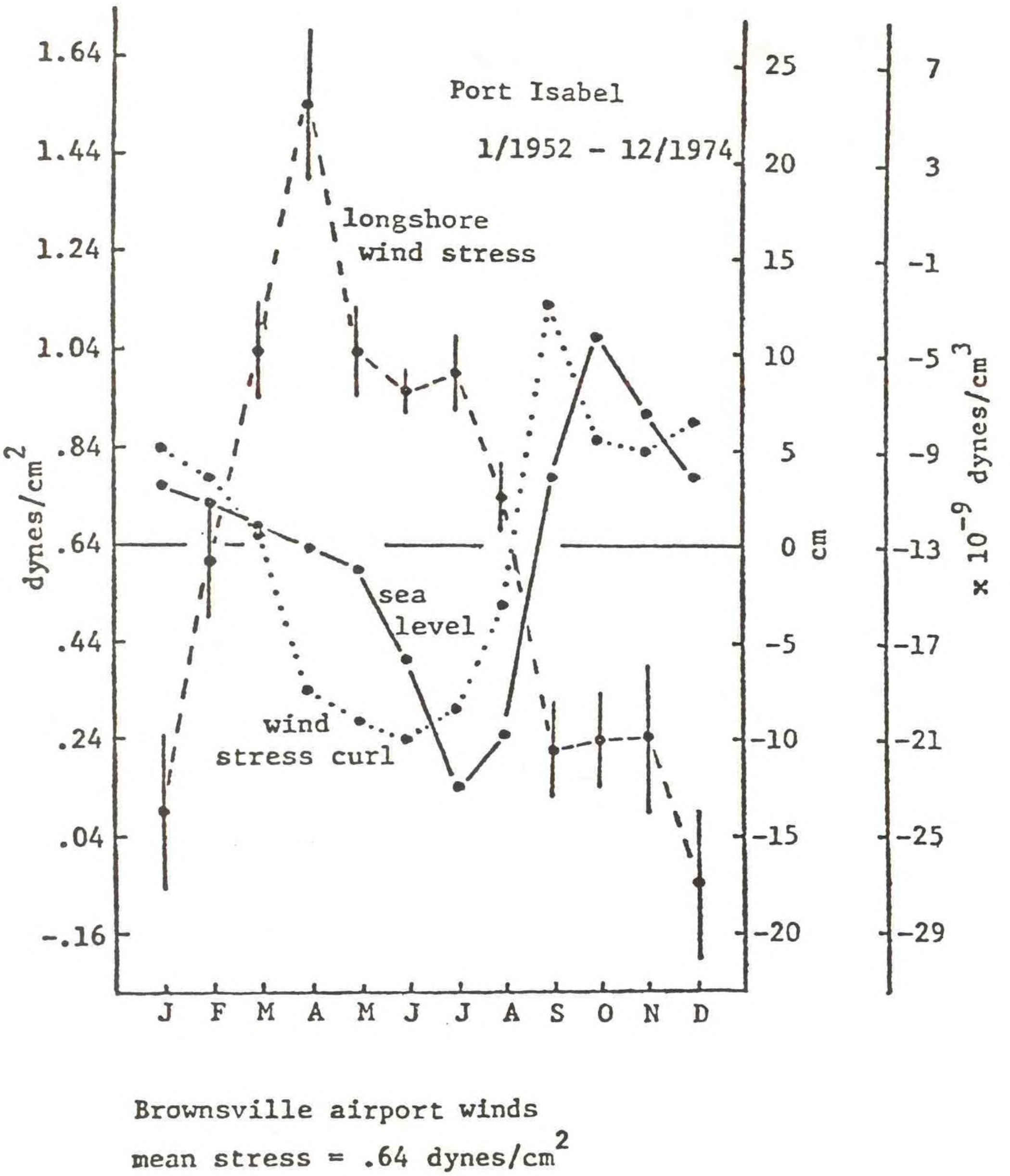



Fig. 12. Mean monthly values of sea level, wind stress curl, and longshore wind stress at Port Isabel (1/1952 - 12/1974). The tidal heights have been adjusted to uniform atmospheric pressure, and the annual cycle of stored heat has been removed. The standard error of the mean for the longshore stress is shown. The mean of the longshore stress is also shown. (From Blaha and Sturges, 1978.)

238 *Journal of Marine Research* [21,3

1963] *McLellan and Nowlin: Gulf of Mexico Deep Water*

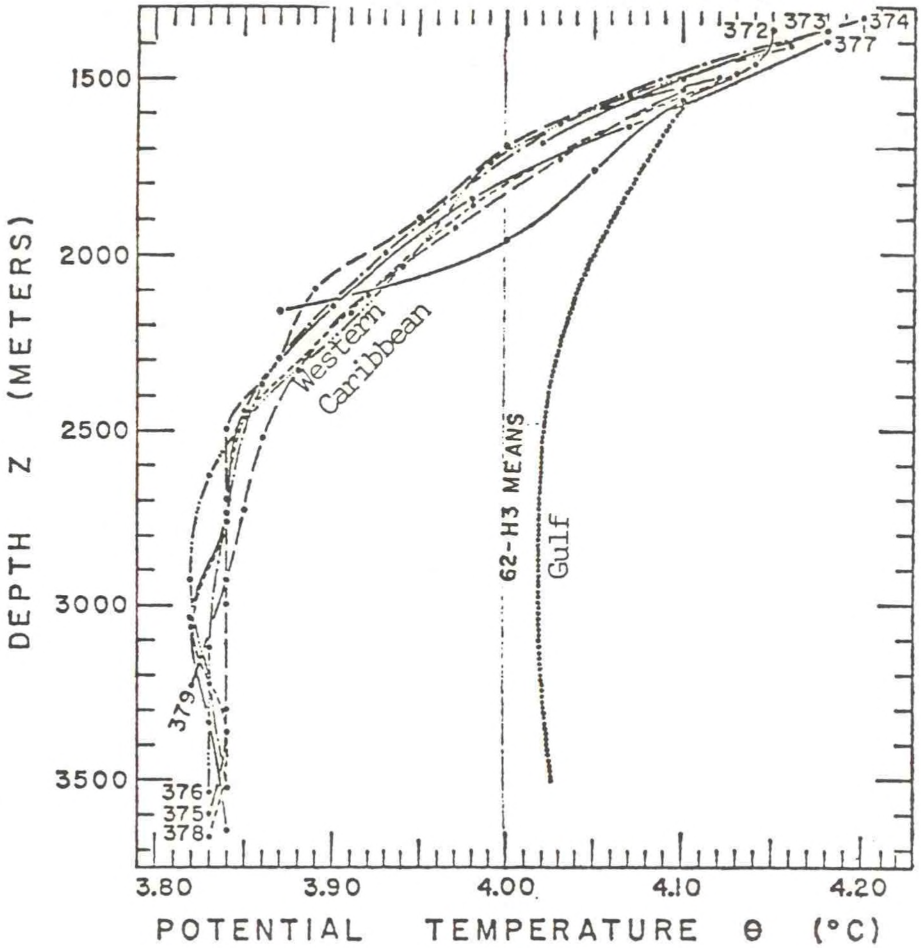



Fig. 13a. Potential temperature-depth relationships for <u>Crawford</u> cruise 17, Sts. 372-379. Mean of Cruise 62-H-3 observations shown. (From McLellan and Nowlin, 1963, <u>J. Mar. Res.</u> 21:233-245, reprinted with permission of the Foundation for Marine Research.)

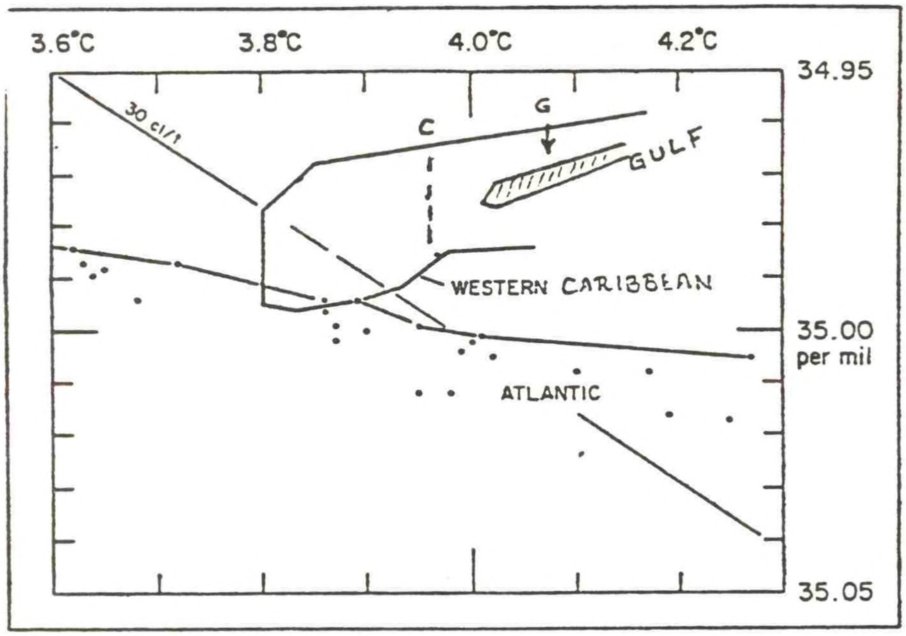



Fig. 13b. Composite t, s diagram for the Atlantic Ocean near the Caribbean Sea and Western Caribbean Basin; from IGY data after Sturges, 1965, and Gulf of Mexico data below 1400 m, after McClellan and Nowlin, 1963. The dotted vertical line, labeled c, shows (approx.) coldest water in the western Caribbean at 1800 m, the sill depth in Yucatan; the arrow labelled G shows the average temperature at sill depth inside the Gulf.

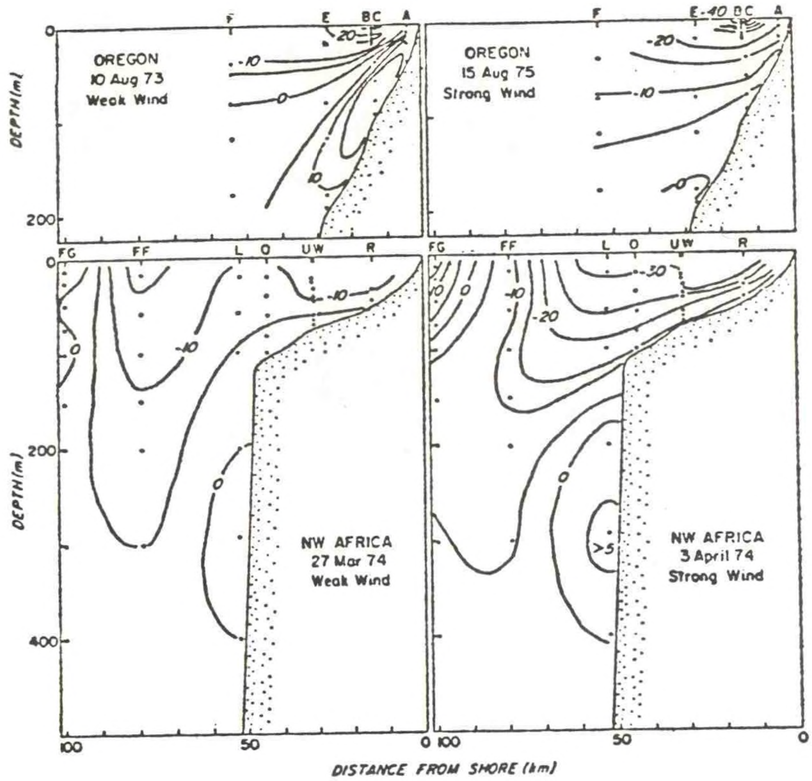



Fig. 14a. Distribution of the alongshore flow with weak wind and with strong favorable wind off Oregon and Northwest Africa. In both cases the contour interval is 5 cm/sec$^{-1}$.
(From Huyer, 1976, J. Mar. Res. 34:531-546, with permission of the Foundation for Marine Research.)

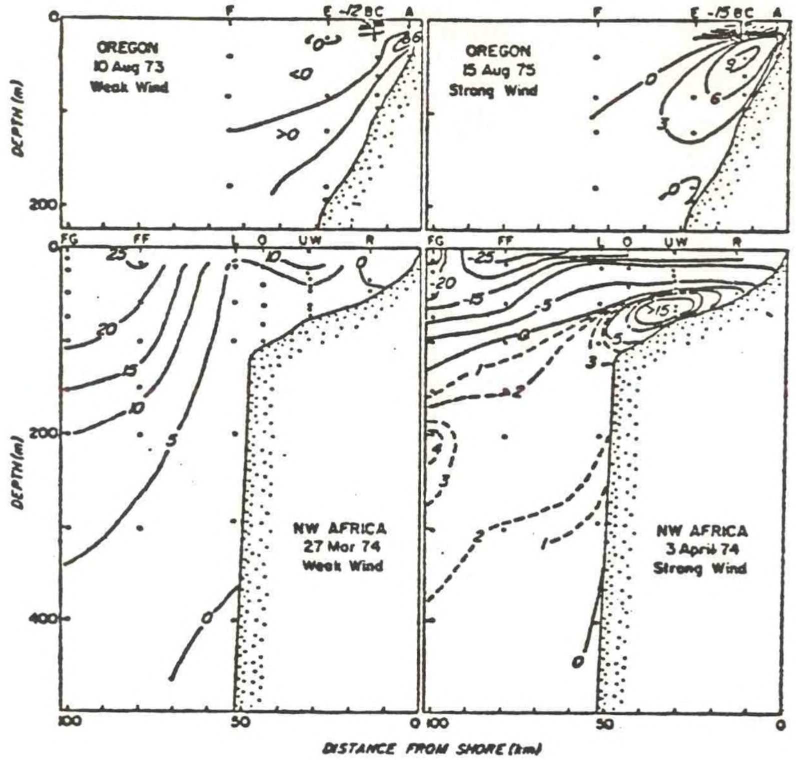



Fig. 14b. Distribution of the onshore-offshore flow with weak wind and with strong favorable wind off Oregon and Northwest Africa. The contour interval is 3 cm $sec^{-1}$ off Oregon and 5 cm $sec^{-1}$ off Northwest Africa. Positive values indicate onshore flow.
(From Huyer, 1976, J. Mar. Res. 34:531-546, with permission of the Foundation for Marine Research.)

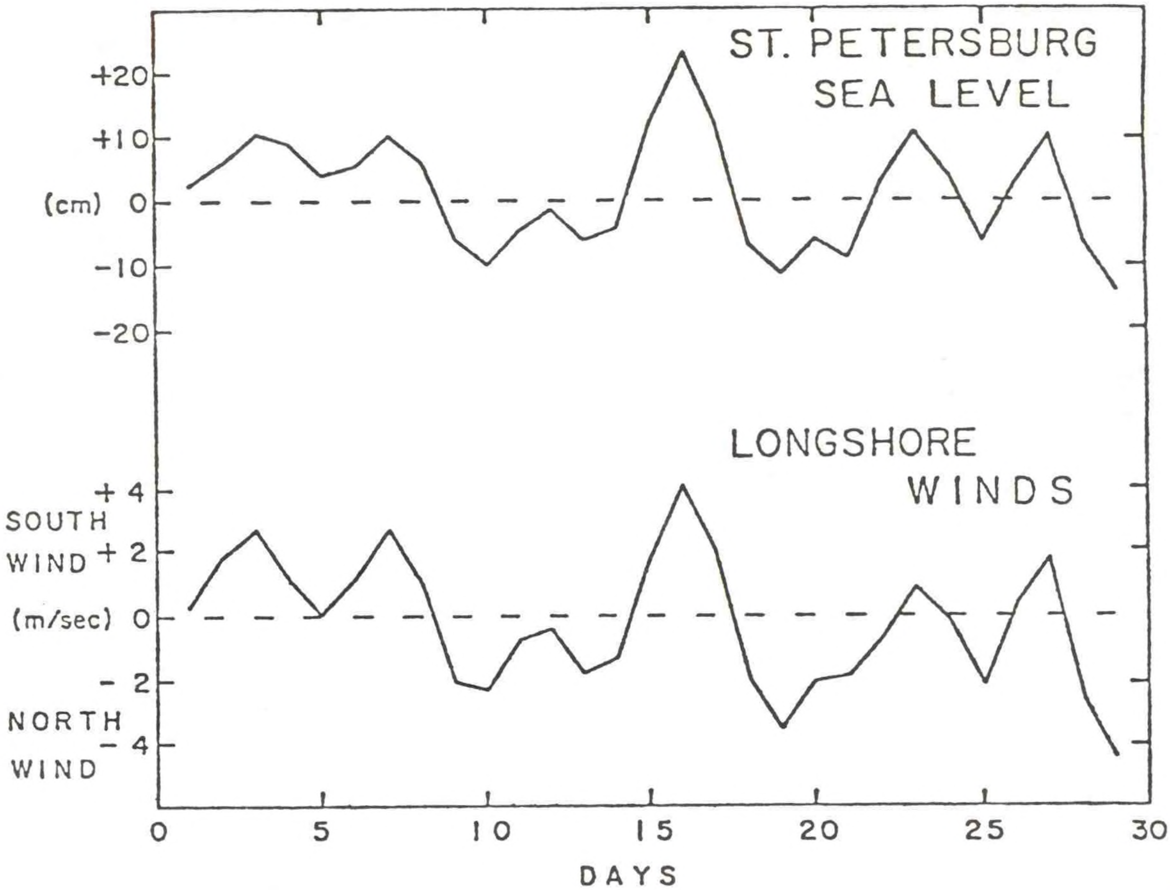



Fig. 15a. Daily values of adjusted sea level at St. Petersburg are shown in the top curve. The zero level is the mean sea level in times of light winds. Longshore wind components at Tampa are shown in the lower curve. Winds are expressed in the meteorologist's convention; i.e., a north wind is blowing from the north. Data are from January, 1966.

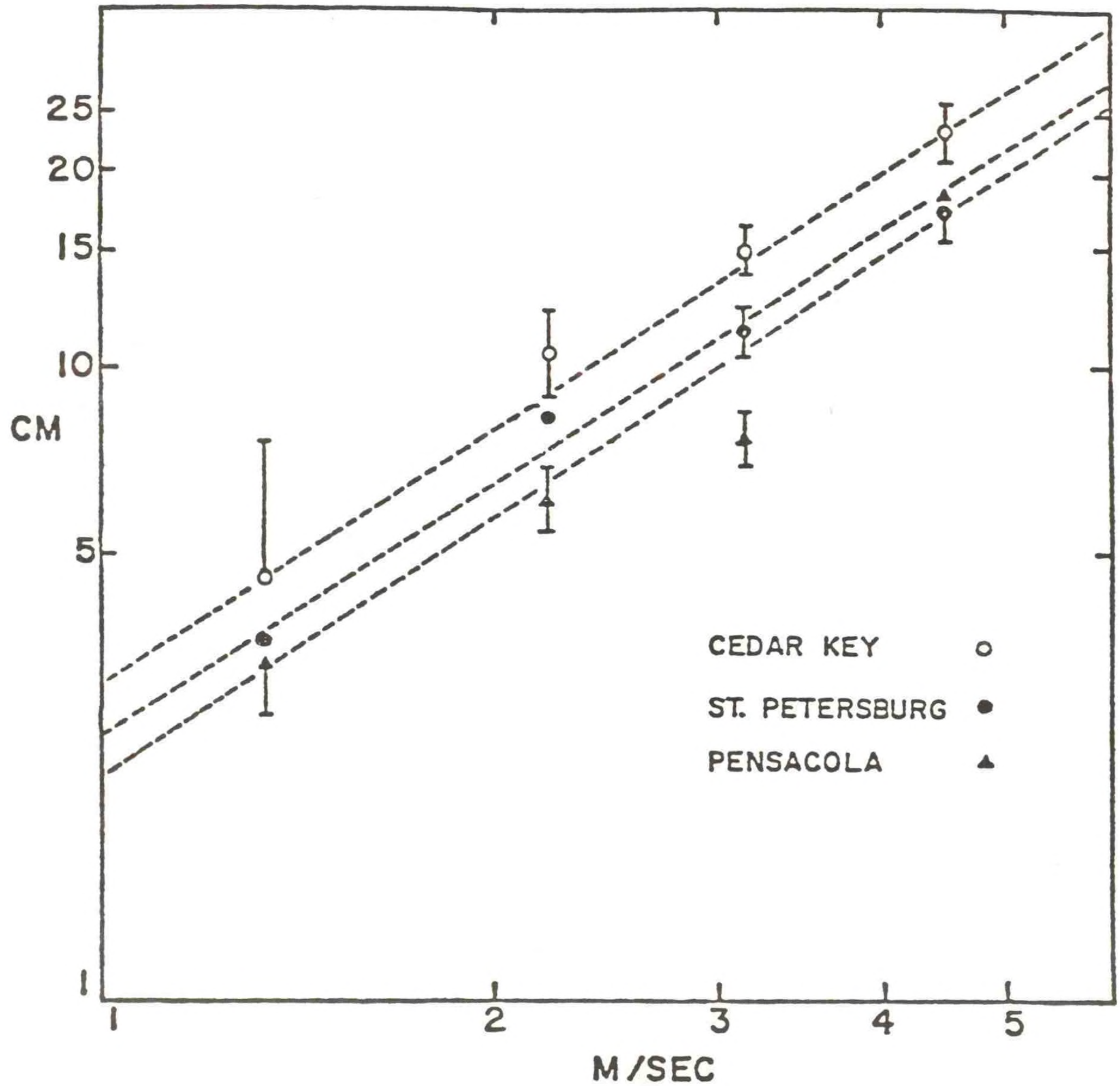



Fig. 15b. A log-log plot of adjusted sea levels at the three tide gauges (cm) versus longshore wind speed (m/sec). Data points are computed from simple averages of both longshore wind cases. Dotted lines are drawn through data points from each tide gauge. The slope of each line (1.3 ± 0.2) gives the functional dependence of adjusted sea level and longshore wind speed.

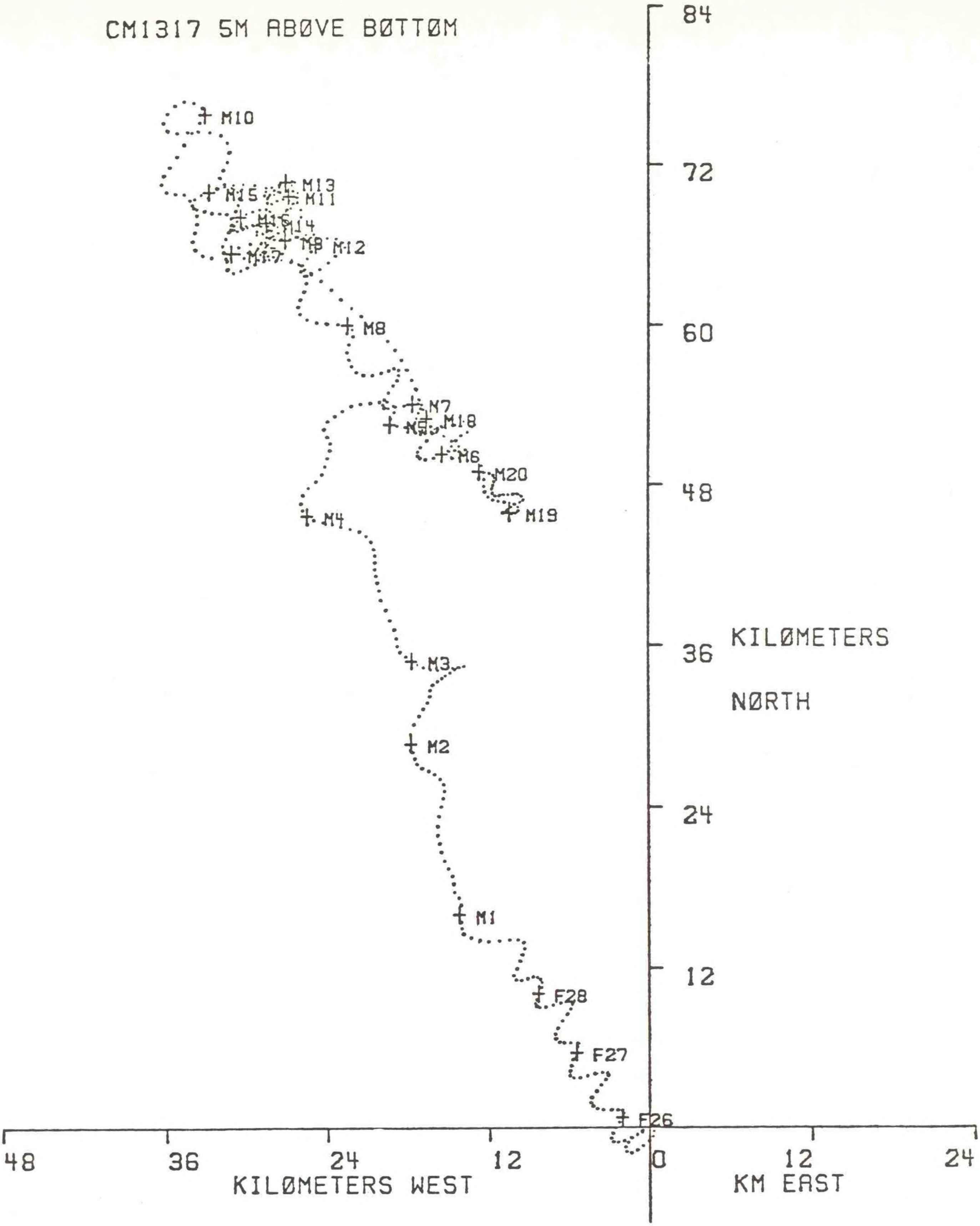



Fig. 16. Progressive vector diagram, computed from a current meter record; February-March 1978, 5 m above the bottom, in 25 m depth, approx. 28.5°N, 83.5°W.

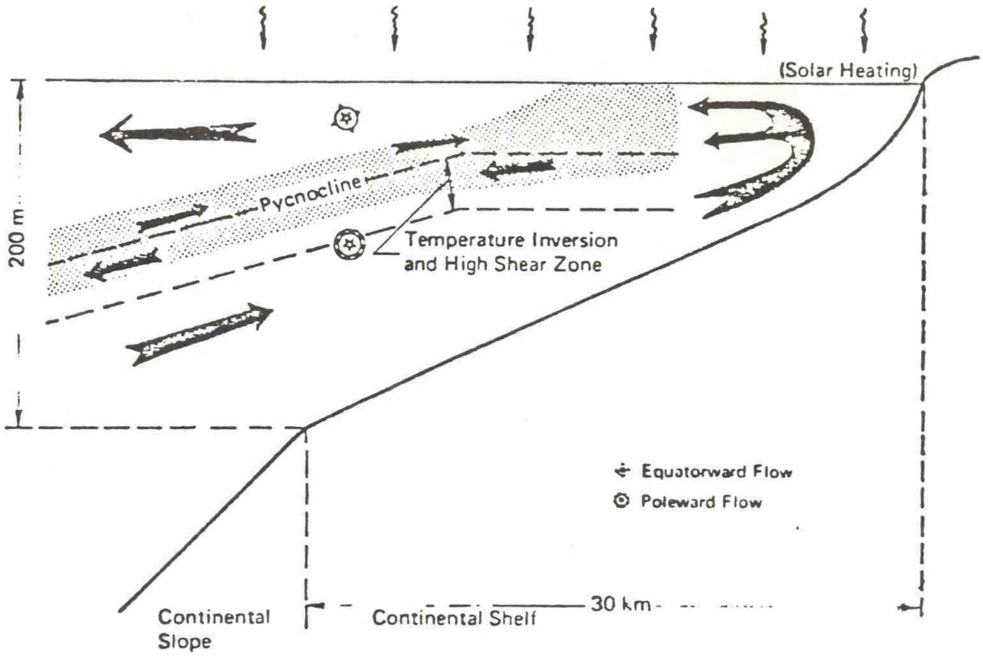



Fig. 17. Schematic of mean circulation during upwelling off Oregon.
(From O'Brien, 1975, with permission of the publisher, National Academy of Sciences.)

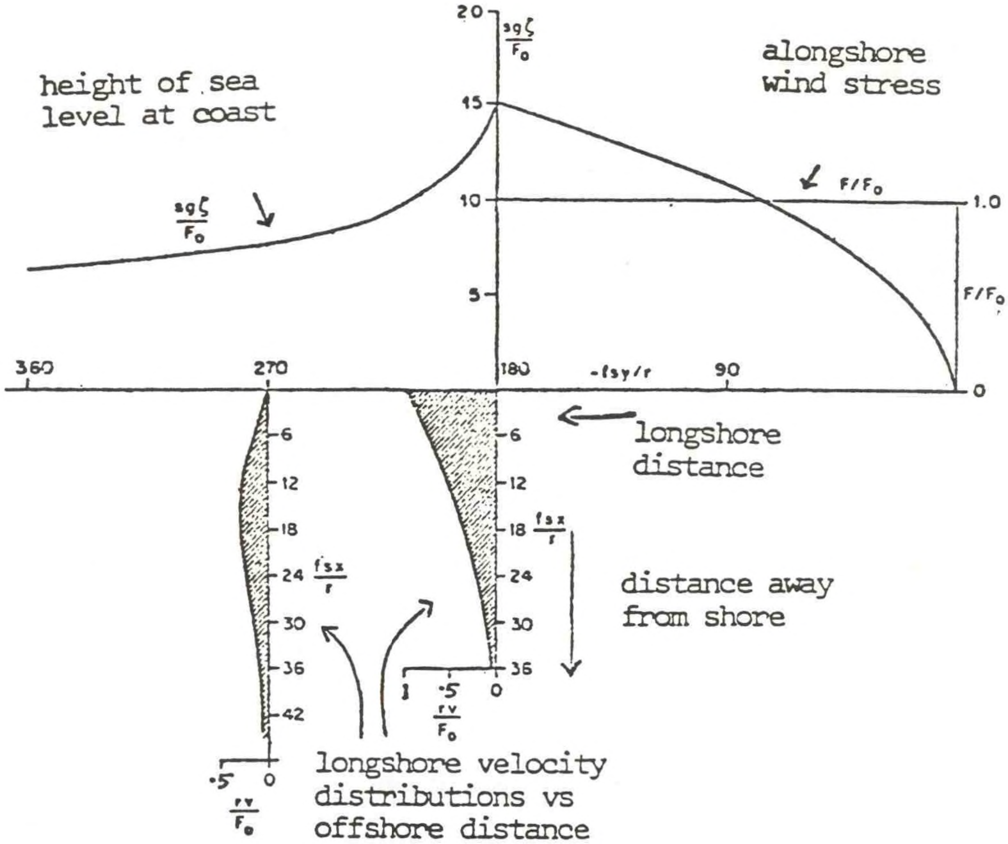



Fig. 18. Effects of isolated square half-wave of longshore wind stress, showing stress $F/F_0$ and nondimensional surface elevation $sg\zeta/F_0$ as a function of longshore distance fsy/r. Bottom half of illustration shows distribution of longshore velocity $rv/f_0$ as a function of offshore distance fsx/r.
(From Csanady, 1978, with permission of the publisher, American Meteorological Society.)

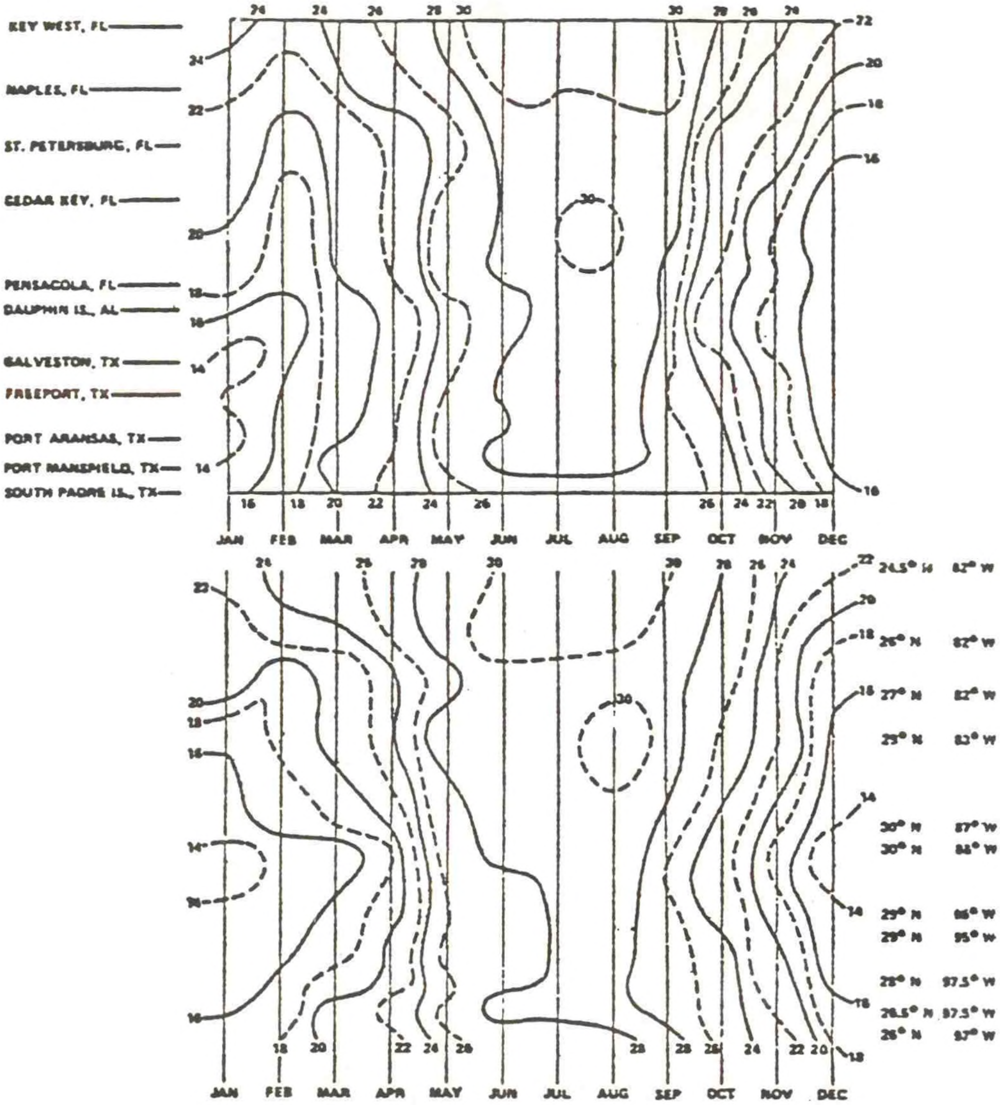



Fig. 19. Gulf of Mexico: monthly mean sea surface temperatures in degrees C for 1974 (top) and 1975 (bottom). (From Goulet and Haynes, 1978.)

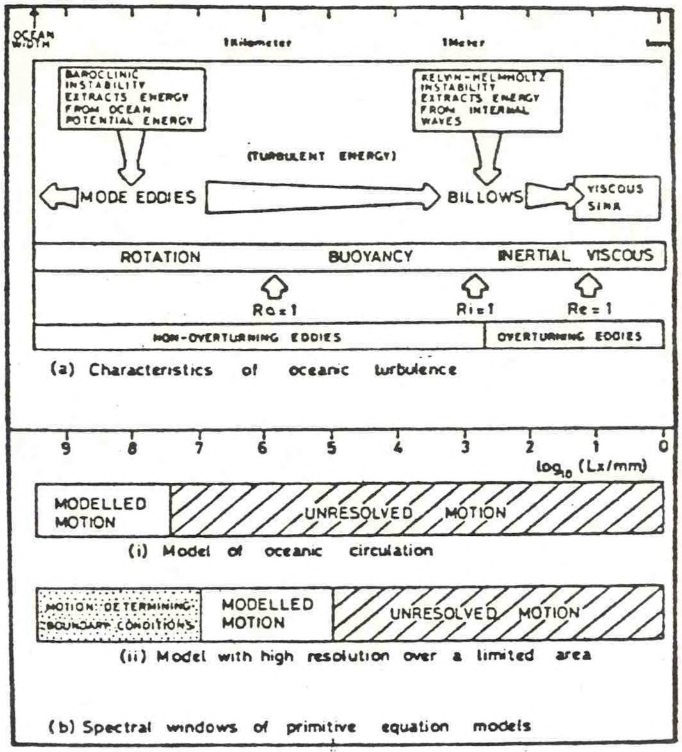



Fig. 20. A comparison of the scales of turbulent motion in the ocean, compared with the range of scales covered by two classes of numerical models. The symbols Ro, Ri, and Re are for the Rossby, Richardson, and Reynolds numbers. (Fróm Woods, 1977. Reprinted with permission from Modelling and Prediction of the Upper Layers of the Ocean, E. B. Kraus, ed., Copyright 1977, Pergamon Press, Ltd.)

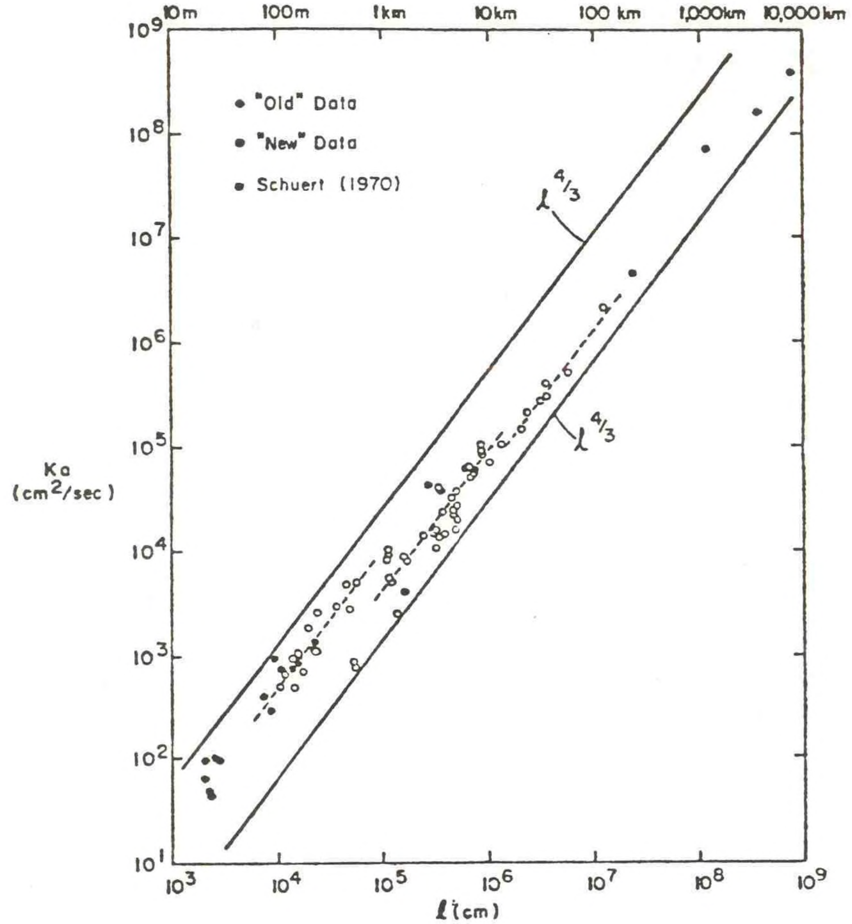



Fig. 21. Apparent diffusivity versus scale of diffusion (old and new data): fit of the 4/3 power law locally.

(From Okubo, 1971. Reprinted with permission from Deep-Sea Research, 18, A. Okubo, "Ocean diffusion diagrams." Copyright 1971, Pergamon Press, Ltd.)

Figure deleted because copyright releases were not obtained.

Fig. 22. Root-mean-square displacement in meters from the mean depth of the 15°C isotherm. (From Dantzler, 1977.)

Figure deleted because copyright releases were not obtained.

Fig. 23. A spectrum of the vertical amplitude of the $12^{o}$ isotherm displacement (near 750 m depth) as a function of the horizontal wavelength of the disturbance: mainly eddy-like motions. (Near Bermuda.) (From Katz, 1977.)

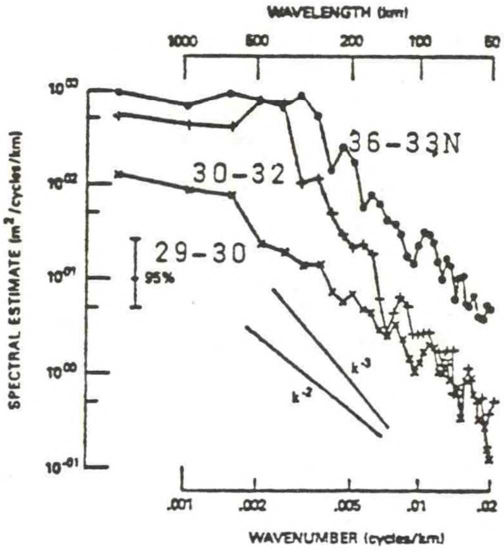



Fig. 24. Spectra of isotherm diaplacement in main thermocline, (x) 12°C isotherm for three ships 29-30.5°N; (+) 12°C isotherm for three ships 30.5-32°N; (O) 10°C isotherm for six ships 36-38°N.
(From Wilson and Dugan, 1978. In J. Phys. Oceanogr. 8:537-540.)

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# CLIMATOLOGY AND METEOROLOGY OF THE GULF OF MEXICO

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## 1. INTRODUCTION

This summary states the present knowledge on the climatology and meteorology of the Gulf of Mexico and identifies gaps in this knowledge. Remedies for these gaps are recommended.

Various types of meteorological phenomena occur in the Gulf of Mexico. Location makes this a region where winter- and summer-type disturbances occur during the cold and warm seasons, respectively. Thus, fronts occur in winter and tropical cyclones in summer. Because it is nearly enclosed by land, the Gulf of Mexico has an extensive coastal region that is favorable for the development of atmospheric disturbances, primarily those associated with land and sea surface temperature contrasts. The sea breeze is a well-known example of an atmospheric phenomenon that depends upon such contrasts.

For convenience in the presentation of atmospheric phenomena in the Gulf of Mexico, we have separated them into categories according to scale. This is a logical method of separation in that the scale of oceanic motions that are atmospherically induced corresponds roughly with similar scales of disturbances in the atmosphere. The separation into different categories is also convenient for studies concerning anthropogenic inputs and impacts and their management. These studies could involve scales ranging from the Gulf of Mexico to the continental shelf to nearshore.

The summary is divided into two major parts:

(1) A narrative that describes what we know and do not know about the various meteorological phenomena affecting the Gulf of Mexico, based on a literature search. There are sections on the large-scale circulation, fronts and cold-air outbreaks, extratropical cyclones, tropical cyclones, sea breezes, and other local phenomena.

(2) A bibliography that corresponds to the subjects of the various sections. The bibliography includes formal publications as well as reports and other manuscripts.

## 2. LARGE-SCALE CIRCULATION

To provide an appropriate background for the discussion of the synoptic- and smaller-scale features of the atmosphere over the Gulf, we describe, first, the state-of-knowledge about the large-scale or Gulf-wide circulation patterns at low levels. The variations of the Gulf-wide circulation patterns may be inferred from previous climatological and general circulation studies. Note that the flow patterns that have been determined observationally in these studies are based upon a somewhat limited amount of data in the central Gulf regions, which are located away from the principal shipping lanes. Nevertheless, the accuracy of these flow patterns should be adequate for most oceanographic applications.

The structure of the large-scale flow patterns over the Gulf, together with its variations during the year, may be seen in Figure 1. The maps in the figure, which show the mean low-level wind field for January, April, July and October, are based on mean charts prepared by Atkinson and Sadler (1970). The wind field is represented on the maps by streamlines and isotachs. The streamlines show the wind direction, while the isotachs indicate the wind speeds (contour interval: 5 kt). Looking first at the circulation pattern for January, one can see a closed anticyclonic cell that has approximately the same dimensions as the Gulf. This anticyclone may be considered as the western member of a set that consists of three anticyclonic cells. The second, or middle, cell of this set is in the North Atlantic to the east of Florida; the third, or eastern, cell is farther to the east in the northeastern Atlantic. This third cell, which appears to be the major one, is the Bermuda High. Since the central Gulf coincides with the center of the western anticyclone, it is a region of relatively weak winds (< 5 kt). The existence of the anticyclone is rather surprising, but the explanation is rather simple. It must be remembered that this anticyclone represents the average circulation pattern for an entire month. Therefore, it is the net effect of cyclonic and anticyclonic flow patterns that actually occur over the area. It is well known from synoptic weather maps that many migratory cold anticyclones in the winter tend to move from the continental U.S. into the Gulf in connection with cold air outbreaks. These anticyclones often stagnate over the Gulf. Weather maps show that cyclones occasionally occur in the Gulf, especially over the northern coastal regions. These circumstances indicate that the mean anticyclone over the Gulf in January is merely a reflection of the much greater preponderance of anticyclones over cyclones over the Gulf. On the basis of the existence of the mean anticyclone, one can deduce that the mean wind is southerly and northerly in the western and the eastern Gulf, respectively. On the other hand, the mean wind is easterly and westerly in the southern and the northern Gulf, respectively.

Looking next at the mean flow patterns for April, one can see that the anticyclone over the Gulf has disappeared, while the middle anticyclone east of Florida has intensified and has extended its influence westward, dominating the flow pattern over the Gulf of Mexico. The center of the Gulf is now characterized by southerlies. The flow patterns over the northern and southern Gulf regions are dominated by southwesterlies and southeasterlies, respectively. In addition, the wind speeds have increased to values > 5 kt in most portions of the Gulf.

Continuing on to the diagram for the July circulation, we see the disappearance of the middle anticyclone east of Florida and a concomittant growth of the Bermuda High. This high pressure cell has now extended its influence as far west as the Gulf of Mexico; the trades now dominate the flow pattern over the Gulf. The winds over the southern portions of the Gulf are generally from the east-southeast at speeds up to 15 kt. Over the coastal regions of Texas and Louisiana, the winds are generally from the south and are weaker.

Finally, looking at the map for October, one can see the return of the three anticyclonic cells, similar in configuration to the flow pattern for January. The main difference between the two configurations is that in October, the system of cells is north of its position for January. This location for October results in the occurrence of generally easterly flow throughout the Gulf at speeds of about 7 kt.

To summarize the description of the Gulf-wide flow pattern, one can say that the circulation is primarily anticyclonic during most of the year. Its variations during the year are associated with changes in a system of anti-cyclonic cells that stretches over the entire Atlantic Ocean. The mean streamline and isotach patterns that have been described above are fairly accurate and are adequate for use in most oceanographic applications. No amount of additional observation will significantly alter the important features of the circulations as presented. The remaining problem concerning the long-period, Gulf-wide circulation is one of its prediction. The problem of predicting mean conditions in the atmosphere is currently approached from two directions: use of general circulation models and climatic models.

General circulation models are designed to resolve synoptic disturbances. On the other hand, climatic models are formulated so that the effects of these disturbances are parameterized. A description of these two approaches is given by Gates (1975). Studies in general circulation models and climate models are being conducted extensively in three institutions: the National Center for Atmospheric Research (NCAR), Goddard Laboratory of Atmospheric Science (GLAS), (NASA), and the Geophysics Fluid Dynamics Laboratory (GFDL) of the National Atmospheric and Oceanic Administration (NOAA). It is obvious that progress in these studies will eventually lead to better predictions of long-period, large-scale, atmospheric conditions, including those over the Gulf of Mexico.

## 3. FRONTS AND COLD AIR OUTBREAKS

This section deals with synoptic-scale disturbances. Fronts and their accompanying cold air outbreaks are the main synoptic-scale perturbations affecting the Gulf of Mexico during winter. Normally, the fronts enter the Gulf over its northwestern portion and progress southeastward toward the Yucatan Peninsula and the Florida Straits. Frontal characteristics may be idealized. An idealization of the front has been done by Mooers and Fernandez-Partagas (1976). The idealized frontal characteristics are

Direction of propagation: toward the southeast
Speed of advance: 9 $ms^{-1}$ (18 kt)
Period of frontal influence: 4 days
Interfrontal time interval: 8 days

The directions of propagation and speed are dominant in frequency distribution diagrams after fronts have been grouped every 2 months throughout the year from 1954-1963 data. The periods of frontal influence and the interfrontal time interval are based upon 37 selected frontal passages over Miami during 1969-1972.

The time evolution of various parameters related to a front is described in Figure 2. Note in the figure (A) the pressure minimum corresponding to the frontal trough; (B) the clockwise rotation of the surface wind direction during the period of frontal influence and the wind speed maximum after frontal passage; (C) the northward component of the surface wind before frontal passage, which changes to a southward component after the passage, and the eastward component of the wind near and after frontal passage; (D) the increase in temperature and dewpoint before frontal passage, followed by a marked decrease after frontal passage; (E) a maximum cloud cover near frontal passage; and (F) precipitation occurring near frontal passage. The total precipitation may or may not be directly associated with the frontal passage. It may be associated to a great extent with a squall line, which is frequently found just ahead of the front or preceding the front by some distance (100-200 mi). Locally shifting winds of gale-force intensity may be experienced in relation to the squall-line passage.

The above evolution represents an idealization of what is typically known to occur in the various meteorological parameters near the sea surface in association with fronts and their related cold-air outbreaks. The idealization refers to winter frontal conditions and is applicable to locations over the central Gulf of Mexico that are too close neither to the Texas coast nor to the Florida Straits. In summer, the fronts are extremely weak and normally do not penetrate much over the Gulf waters. DiMego, Bosart, and Enderson (1976) show that from June to August, only about one weak front per month intrudes well into the Gulf of Mexico. These fronts are generally devoid of temperature and moisture contrasts but are characterized simply by wind shears.

The Gulf acts as a modifying factor to the air masses that follow the frontal progressions over the Gulf. Considerable warming of these air masses occurs, especially as the masses move southward away from the coastal regions. This is because there is a contrast between the sea surface temperature near the coast and in the central and southern portions of the Gulf of Mexico. The rate of air-mass modification over the Gulf has been estimated by Henry and Thompson (1976). According to their study, the vertical flux of sensible and latent heat is about 1.4 cal $cm^{-2}$ $s^{-1}$. However, estimates of this kind are not very reliable because of the lack of adequate data over the central Gulf region and the need for making assumptions that might not be quite realistic. But, at least qualitatively, the modification can be well documented from satellite pictures. An example of satellite imagery showing stratocumulus fields produced by modification of the air mass as it moves over the open waters of the Gulf is shown in Figure 3. The satellite picture shown is for January 9, 1979, when northeasterly flow prevailed over the Gulf.

Dr. S. A. Hsu, Louisiana State University Coastal Studies Institute, indicated to us that air mass modification processes have an important effect on frontal motions. According to him, fronts tend to be retarded during fall and early winter because of a larger contrast between sea and air temperatures near the Gulf coast. Nevertheless, extrapolation and numerical weather prediction guidances appear to be, in general, good tools in forecasting the position of fronts in the Gulf of Mexico. There is an exception to this statement when cyclogenesis occurs over the Gulf region. In this case, extrapolation may fail, since the fronts will show a tendency to become stationary as the extratropical cyclone develops along the front. Also, the numerical prediction models, even those using a fine-grid resolution, may not predict the cyclogenesis well because of the lack of adequate weather data over the Gulf of Mexico. It is, therefore, necessary to increase surface data (ships, buoys, oil platforms) as well as upper level data.

## 4. EXTRATROPICAL CYCLONES

Although many extratropical cyclones develop over the continent, only a few develop over the Gulf of Mexico's northern coast or over the Gulf, itself. These cyclones have preferred tracks, which have been studied for some winter months by Klein (1957). However, Klein does not show tracks for March, April, and May, and it is known that some extratropical cyclones develop in the Gulf during these months. Figure 4 shows Klein's tracks, indicating that in December and January, the cyclone centers tend to remain solely over the waters of the northwestern Gulf of Mexico. In addition, preferred tracks in February run over the north-central Gulf and the one for November over the extreme northeastern Gulf. More specifically, Jordan (1973) shows (based upon 1954-1969 data) that for the coastline east of the 90° W meridian, the centers of the extratropical cyclones prefer a landfall area between Apalachicola and Tampa. Jordan indicates that on the average, about three extratropical cyclones make landfall in this area during the winter and spring seasons. He also shows that the central pressure in the Gulf extratropical cyclones seldom drops below 1000 mb and that, in most cases, it remains above 1005 mb. Therefore, in terms of central pressure, Gulf of Mexico extratropical cyclones are not particularly intense. However, full gale-force winds, in many cases, will occur because of a large pressure gradient, especially to the north and northwest of the cyclone center.

Cyclogenesis over the Gulf of Mexico is not accurately predicted by numerical models at all times, mainly because of a lack of proper three-dimensional data over the Gulf of Mexico. If these data were available, better forecasts would be expected. But, in addition to the data that is needed for a more realistic initialization of present models, basic research on the understanding of the physics involved in cyclogenesis is in order. Increasing interest in the study of the Texas-Gulf cyclones have been indicated by a number of scientists from several universities and agencies, and a "consortium" has been recently established around Dr. K. H. Jehn of the University of Texas at Austin. The objectives of the research would be to determine the structure, energetics, dynamics, and motions of the cyclone. Perhaps the most important aspect of the research would be to investigate the role of deep convection in the Gulf cyclones from satellite pictures and specially processed radar data. The parameterization of deep convection in the prediction of extratropical cyclones has not yet been fully studied.

## 5. TROPICAL CYCLONES

The tropical cyclone is an important meteorological feature in the Gulf of Mexico during summer. Some of these cyclones develop over the Gulf, while others enter the Gulf from the Yucatan Peninsula, the Yucatan Channel, western Cuba, the Florida Straits, or the Florida Peninsula. Tropical cyclone is a general name that does not take into account intensity. According to their intensity, tropical cyclones are classified as tropical depressions (winds up to 33 kt), tropical storms (winds of 34-63 kt), and hurricanes (winds in excess of 63 kt). No two tropical cyclones show exactly the same trajectory; however, trajectories for two cyclones may be quite alike over part of their life span. Tropical cyclones occur mainly during the so-called hurricane season, which extends from June 1 to November 30.

However, a few cases have occurred in May over the central and eastern Gulf of Mexico. Trajectories for tropical storms and hurricanes that occurred between May 16-31 over the years 1886-1977 are shown in Figure 5. This figure, which is a composite of various graphs taken from Jarvinen and Neumann (1978), also shows the trajectories for Gulf storms and hurricanes over the second halves of the months of June, July, August, September, and October. Note that there is a maximum number of tropical storms and hurricanes over the Gulf in September. Also note that no trajectory is shown for the second half of November. This is because only one Gulf storm has occurred over this period during the years 1886-1977.

Hurricanes are the most dangerous tropical cyclones and may reach great intensity. The two most intense hurricanes on record in the Atlantic, the Labor Day Hurricane in 1935 and Hurricane Camille in 1969, moved over parts of the Gulf of Mexico. Maximum sustained winds in these two cases were at least 175 kt. Hurricanes of that extreme intensity seldom occur, but many other hurricanes affect the Gulf coast. A probability study on hurricane winds (63 kt or greater) along 50-mi segments of coastline was undertaken by Simpson and Lawrence (1971); the results are shown in Figure 6. In the figure, segments are identified by numbers that increase from Texas to Florida. The percent probability for any year is indicated in boxes (1) for all hurricanes, and (2) for only those hurricanes with winds $>$ 110 kt (great hurricanes). The percent probability for all hurricanes and for great hurricanes is not evenly distributed along the Gulf coast, but shows remarkable fluctuations along the coast. According to Figure 6, the highest probability of great hurricane conditions is along the Texas coast.

The hurricane structure is currently quite well known, a good contribution to this knowledge having been provided by the National Hurricane Research Project, founded in 1956, and its successors, the National Hurricane Research Laboratory and the National Hurricane and Experimental Meteorology Laboratory. To illustrate the wind structure at low levels in a hurricane, a wind-versus-distance profile for Hurricane Anita, 1977, is shown in Figure 7 (from Sheets, 1977). This profile corresponds with a flight into the hurricane by a NOAA plane when Anita was centered over the northern Gulf of Mexico on August 31, 1977. Note in the figure that maximum winds of near 90 kt (45 $ms^{-1}$) were recorded just north of the center and that winds reached 70 kt (35 $ms^{-1}$) south of the center. Also, note the abrupt decrease in wind speed as the aircraft flew through the eye of the hurricane.

Hurricane motion cannot be predicted accurately at the present time. A series of objective methods for prediction have been developed over the past two decades and an improvement in motion forecasting has been reported (Dunn et al., 1968). However, more recent studies (i.e., Neumann, 1979) indicate that no improvement has been achieved over the past few years. Climatological, statistical, and dynamical methods of hurricane forecasting have shown a tendency for quite steady errors of about 50 nmi for the 12-hr forecast, about 100 nmi for the 24-hr forecast, and errors in the 250-500 nmi range for the 48-72 hr forecasts. Of all methods, those showing the most promise for improvement in hurricane motion forecasting are the dynamical methods that are based on the fluid dynamical equations, such as the SANBAR (Sanders and Burpee, 1968) and the MFM (Hovermale and Livezey, 1977) equations.

There remains the problem of the lack of an adequate data density available in three dimensions all around the storm. The acquisition of these data by dropsondes released from high-altitude planes appears to be a feasible, but quite expensive, operation (estimated cost of the wind, temperature, moisture, pressure dropsondes is about $300 per unit). Refinements in the formulation of the present dynamical models are expected to result in some improvement in hurricane motion forecasting.

Another problem facing hurricane forecasting is the prediction of the variation cyclone intensity. There has been increasing evidence in recent years that some natural variations in the hurricane strength do occur at time scales ranging from a few hours to a day or so. However, the relative magnitude and periodicity, if any, of these oscillations have not been fully documented. This was one of the goals of the recently conducted long-term monitoring of Hurricane David, 1979, by NOAA aircraft. But the hurricane intensity forecast is deficient, not only in predicting these short-term natural oscillations, but also in the longer-period tendencies for intensification. No statistics are available on the errors pertaining to hurricane intensity prediction. However, it is frequently found that intensification is anticipated over a specified period but does not materialize over that period. In contrast, a decrease in intensity sometimes occurs when intensification is expected. This is probably linked to the fact that little has been done in applying existing numerical models to the hurricane intensification problem in recent years. One of the very few applications of numerical prediction models to intensification is the one that predicted somewhat correctly the intensification of Hurricane Alma, 1962 (Miller, 1969). Any improvement in predicting hurricane intensity would require a substantial increase in observational information and the use of a realistically formulated prediction model, including a proper parameterization of subgrid scale motions, especially cumulus convection.

By improving the motion and intensity prediction of hurricanes, a more precise point and time of landfall and intensity at landfall time could be obtained. This more precise prognosis would, in turn, help in the practical application of hurricane surge prediction models (Jelesnianski, 1967), which have already been proved of significant value in hurricane surge forecasting.

## 6. SEA BREEZES

The sea breeze is a common summertime phenomenon over the coastal regions of the Gulf of Mexico. However, its effects on coastal waters have generally been considered unimportant because of its relatively weak winds. An observational study in the vicinity of Santa Rose Island, Florida, by Sonu, et al. (1973) has demonstrated that the sea breeze is a significant force in the generation of waves and currents in the coastal zone. The results of this study show that the sea breeze produced a high-frequency peak in the nearshore wave spectrum that dominated the background swell in the afternoon and in the evening. Furthermore, results show that the sea breeze induced nearshore currents of up to 25 cm $s^{-1}$. These currents move primarily parallel to the shoreline. The observational findings by Sonu, et al. (1973) appear to be supported by a theoretical study of sea-breeze-induced coastal currents that is now being conducted by Estoque (1979). A sample distribution of sea breeze-induced currents from Estoque's calculations is shown in Figure 8.

The physical processes that generate the sea breeze are fairly well understood, at least in a qualitative sense. However, the detailed characteristics of the sea breeze depend in a complicated way upon several factors, such as the properties of the earth surface, the configuration of the coastline, the large-scale prevailing flow, the latitude, and the time of year. This dependence can be examined by means of observational, as well as theoretical, studies. Some attempts have been made to conduct observational studies of sea breezes over specific coastal regions of the Gulf of Mexico. The most intensive study has been made by the Atmospheric Science Group of the University of Texas (Eddy, 1966; Hsu, 1970). The site of the most detailed observational field program was the upper Texas coast east of Galveston. The observational network included several offshore stations. One of the most important results of this observational study is a detailed description of the three-dimensional wind and temperature structure of the sea breeze (Hsu, 1967, 1969, 1970). In the latter article, Hsu presented an empirical model of the sea breeze that was synthesized from observations. Hsu reported that maximum winds of 8 mi $h^{-1}$ occurred at offshore areas. He also noted that the irregularities in the coast line, principally Galveston Bay and Sabrine Lake, introduced significant distortions in the sea breeze. The effects of these coastline irregularities were subsequently examined by McPherson (1968) with the aid of a mathematical model.

There have been other observational studies of sea breezes and related phenomena by Eigsti (1978), Scoggins (1976), and Feit (1969). The report by Eigsti is especially interesting, because it describes a midnight maximum in the onshore component of the wind at Port Aransas. With respect to theoretical models that are applicable to sea breeze studies, one may cite the more recent ones that have been described by Pielke (1973), Gannon (1977), and Estoque and Gross (1979).

The observational and theoretical studies cited above have contributed significantly to our understanding of the sea breeze over the Gulf coastal regions. Nevertheless, it is still impossible to make quantitative predictions of the sea breeze. It is expected that dynamical models based on the fluid dynamical equations will ultimately give us short-range predictions. But, before this can be achieved, one has to overcome various difficulties in the formulation of dynamical models. One of the main difficulties is the incorporation of time variations in the prevailing synoptic-scale conditions. A problem that is related to this incorporation is the formulation of the lateral boundary conditions. Another difficulty is the detailed specification of the physical properties of the earth's surface, in particular, the roughness, soil moisture, albedo, and heat conductivity. The primary source of this difficulty is that the actual surface of the earth is highly non-uniform in its properties. This problem has been analyzed recently in the report by Gannon (1977). A third difficulty is the parameterization of cumulus convection and other subgrid scale processes. Finally, we mention the necessity of additional observational studies to determine the structure and behavior of sea breezes. Future observational field programs should be conducted in other coastal regions of the Gulf of Mexico under various types of synoptic-flow patterns. Observations of the sea breeze circulation at offshore locations are especially desirable from the viewpoint of oceanographic applications. The observational studies are essential for developing, as well as testing, dynamical prediction models of the sea breezes.

## 7. OTHER LOCAL PHENOMENA

In addition to the sea breeze, other meteorological phenomena affecting the Gulf of Mexico area are thunderstorms, waterspouts, and fog.

Seasonal and diurnal variations of thunderstorms in the Gulf of Mexico have been documented with digitized radar data. Based on 1974-1975 data, Scoggins (1976) indicates a marked increase in thunderstorm activity over Gulf waters within 120 nmi of the coast during June and July. As seen in Figure 9, the increase is from a 20-30% probability of daily occurrence in the winter months to roughly 40-80% probability of daily occurrence in summer. After the summer is over, a marked decrease occurs in October. On a regional basis, thunderstorms appear to be more frequent over the eastern Gulf waters than over the western Gulf waters: a maximum daily probability above 90% is found near the West Florida coast in summer. Diurnal variations in thunderstorm probability for the Gulf waters are very noticeable during summer. About a 40-60% probability is expected in the early morning hours, decreasing to 30% or less in the afternoon. In contrast to this summer situation, no diurnal cycle in thunderstorm activity is found over the Gulf waters in winter. Rather, the above frequency studies are limited to the northern periphery of the Gulf of Mexico and there is no reason to extend their validity to the central and southern Gulf of Mexico. These are areas that lack radar observations; therefore, thunderstorm frequency studies for these areas would have to depend on satellite-derived thunderstorm information rather than on radar information. Prediction at the thunderstorm and thunderstorm-cluster scales (10-100 nmi ranges) is a very difficult task, one that does not appear to be bound for significant improvement in the immediate future. This is because the extremely complicated interactions between synoptic- and cumulus-scale motions are far from being fully understood and, therefore, cannot be properly treated in fine-mesh numericals models. Consequently, even if many thunderstorm-scale observations were available, precise thunderstorm prediction would be impossible at this time.

Waterspouts are small-scale, very local, meteorological phenomena having a typical horizontal scale of about 100 m and a typical timescale of about 10 min. In spite of this very small scale and the short-term characteristics, high winds associated with waterspouts can produce structural damages to installations near the coast and to boats. Golden (1977) has studied waterspout characteristics, including their frequency along the Gulf coast. However, aside from isolated reports from ships, waterspouts over Gulf open waters remain undocumented.

Sea fog, a local meteorological event during fall and winter months, rarely occurs over the Gulf of Mexico in summer. According to George (1960), fog occurs along the Gulf coast 3-5 times per month in October and November, 5-6 times per month in December, January, and February, and about 3 times per month in March. Visibility is reduced considerably by fog; the visibility may be zero in extreme cases. Fog near the Gulf coast is caused primarily by the cooling of warm moist air that is moving over cold coastal waters or by the seaward drift of radiationally induced land fog. Fog prediction is a complicated subject, because the needed sea surface temperatures and the air temperature, moisture content, and wind profiles over the lower tropospheric levels (< 1 km) are not always available to the forecaster. Satellite pictures have contributed to the observation of sea fog in recent years. But, because satellite pictures are essentially diagnostic rather than forecasting tools, fog prognosis cannot be achieved from satellite data, except by extrapolation.

## 8. CONCLUSIONS

The preceding sections contain a review of the current state of knowledge about atmospheric disturbances over the Gulf of Mexico. In the review, we have also indicated gaps in the knowledge. It is appropriate in this concluding section to present a discussion that ties together all of our ideas about knowledge of atmospheric disturbances over the Gulf.

Knowledge of an atmospheric phenomenon implies, in precise terms, an understanding of the space distributions of the various atmospheric variables that describe the phenomenon. It also implies knowledge of the time variations of the space distributions. The knowledge may be categorized as follows:

(1) Observational or empirical, i.e., knowledge of the distributions of the atmospheric variables based on observations.

(2) Knowledge or understanding of the physical processes that produce time variations in the space distribution of the atmospheric phenomenon.

(3) Knowledge about the prediction of the space distribution.

From a purely theoretical viewpoint, one can say that there is no gap in our knowledge under Item (2) above, i.e., understanding, because the fluid dynamical equations may be considered the mathematical representation of this understanding. In fact, if we had a sufficiently large and fast computer and if we knew the observed space distributions of the various atmospheric variables at some initial time, we should be able to make an accurate forecast by simply integrating the equations numerically. Currently, one of the obstacles in making such a forecast is that numerical integrations must be done with the aid of a grid, the points of which are separated by relatively large distances. Thus, physical processes whose scales are less than the grid distances must be incorporated in the model equations in some approximate way. This is the so-called problem of "parameterization of subgrid processes," and it is the central problem in our understanding of the atmospheric phenomena in the Gulf of Mexico. This gap in the knowledge can be reduced by an analysis of observational data to determine the relationship between subgrid-scale processes and larger-scale processes. Another obstacle in making a forecast is the lack of observational data for the specification of the initial conditions that are required in the integration of the prediction equations. This deficiency is the reason for the relatively inaccurate forecasts of synoptic-scale phenomena over the Gulf, in comparison with corresponding forecasts over the continental U.S.

It is clear from the above discussion that the gaps in knowledge concerning atmospheric phenomena over the Gulf are caused primarily by lack of sufficient observational surface and upper air data. This is not surprising, because it is extremely costly to gather observations over a body of water. It is also clear that in order to narrow the gaps, more observations must be gathered. A systematic survey of some of our observational data needs must, therefore, be made. Such a survey for the Gulf of Mexico is now being conducted by Professor K. H. Jehn of the University of Texas at Austin; he will present his results at the meeting on coastal meteorology to be held in Los Angeles in January 1980.

We feel that it is undesirable to specify here the atmospheric observations that should be made, because the observational needs for meteorology over the Gulf are numerous and the cost of making such observations is high. Therefore, specific atmospheric observations that must be made should be dictated by a particular oceanographic problem in the Gulf. In other words, given the oceanographic problem, one must identify, first, the specific atmospheric phenomena that are involved in the problem. Then, a systematic observational program to determine the structure and the behavior of the atmosphere during the occurrence of the phenomena should be undertaken.

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This bibliography is the product of an extensive literature search on the subjects of climatology and meteorology of the Gulf of Mexico. Approximately, 150 entries are included. Entries have been separated into several categories that correspond to the classification of the atmospheric phenomena used in the narrative. The classification consists of the large-scale circulation, fronts and cold-air outbreaks, extratropical cyclones, tropical cyclones, sea breezes and other local phenomena. In addition to these topics, we have included a category for miscellaneous entries. A few entries appear in more than one category.

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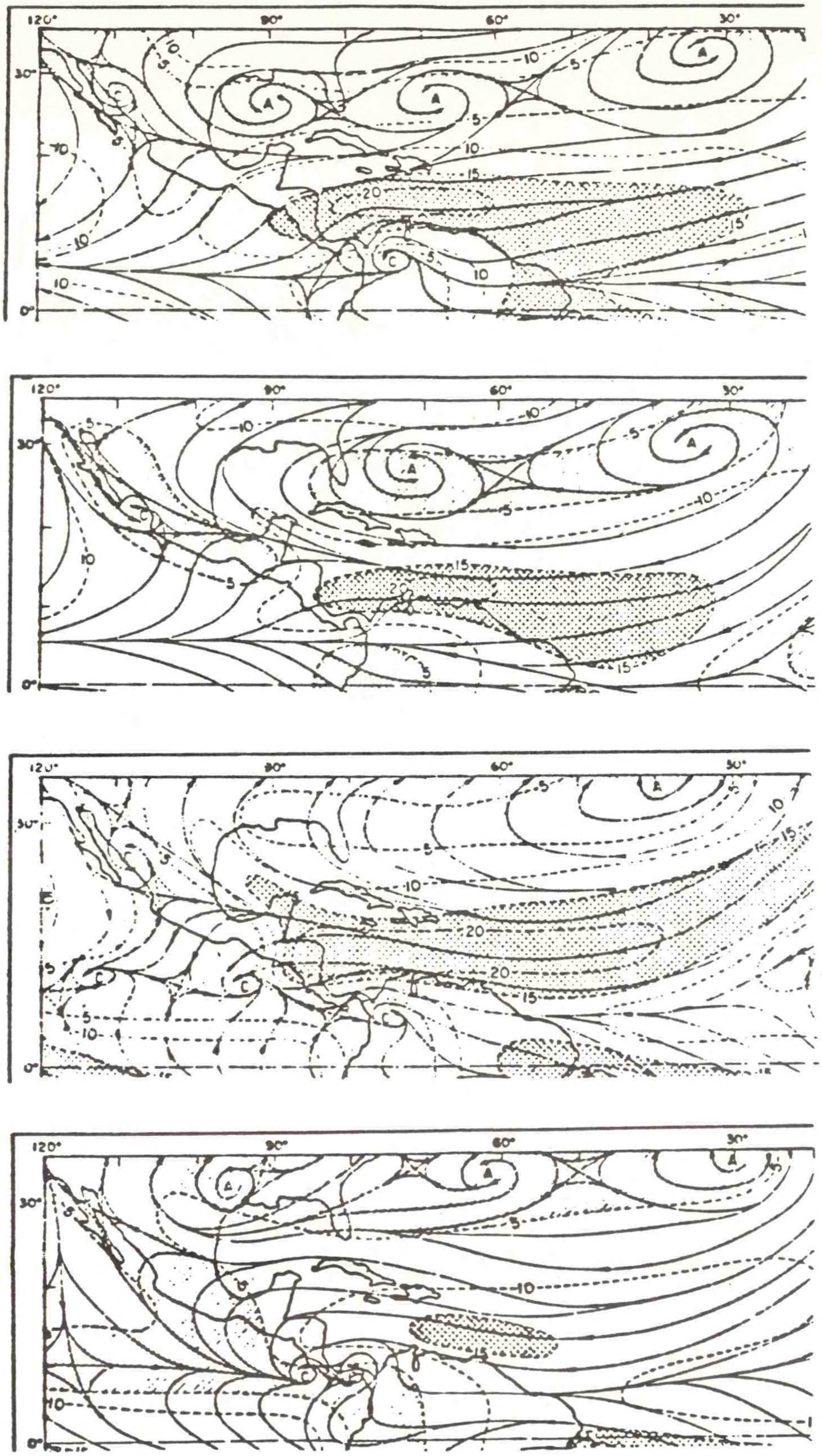

Fig. 1. The low-level mean circulation for the Gulf of Mexico and other regions throughout the year. The top graph is for January, the second graph is for April, the third one is for July, and the last one is for October. (After Atkinson and Sadler, 1970.)

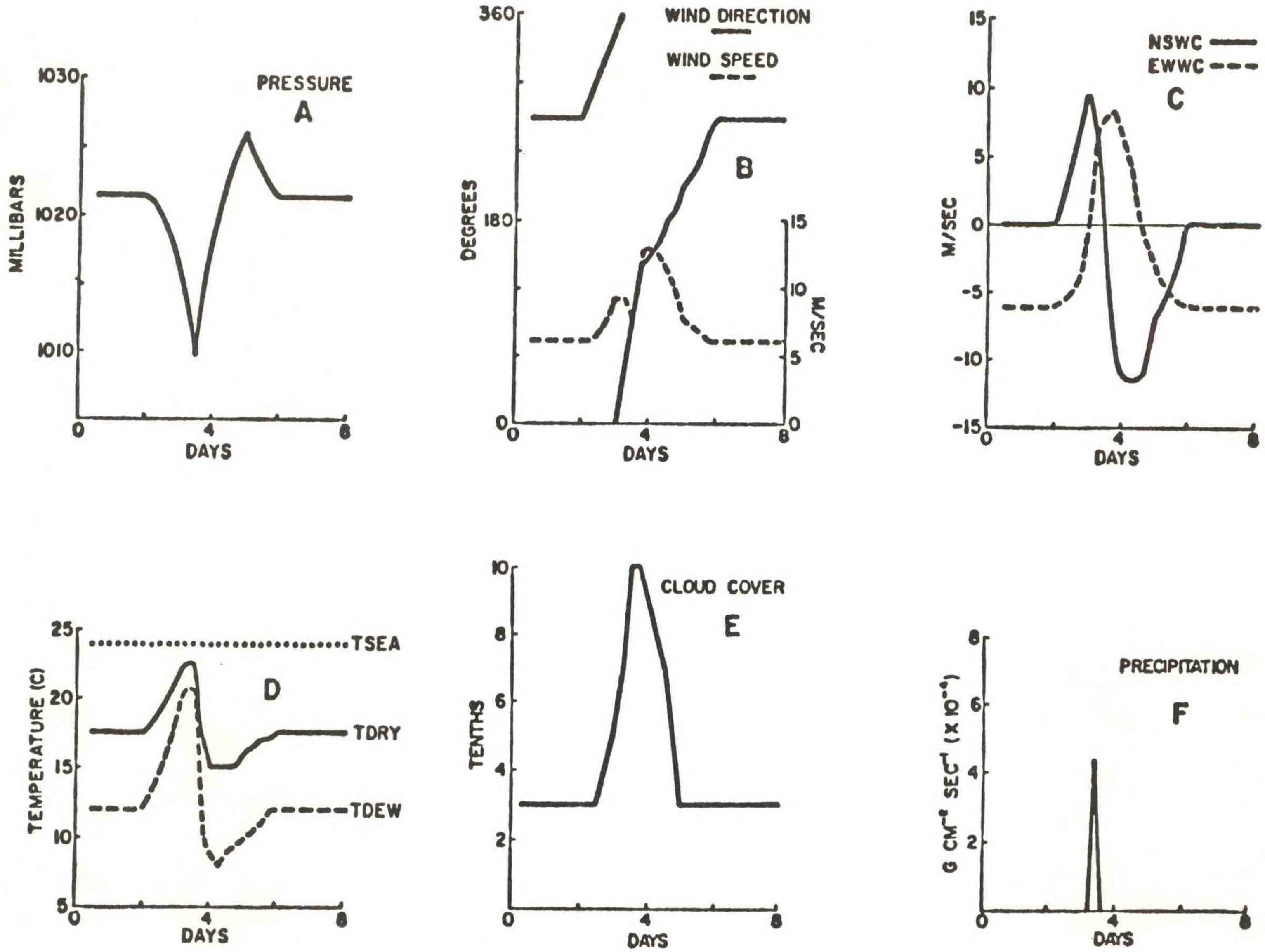


Fig. 2. Graphs showing the time-evolution of various meteorological parameters associated with an idealized front in the Gulf of Mexico. (After Mooers and Fernandez-Partagas, 1976.) See text for explanation.

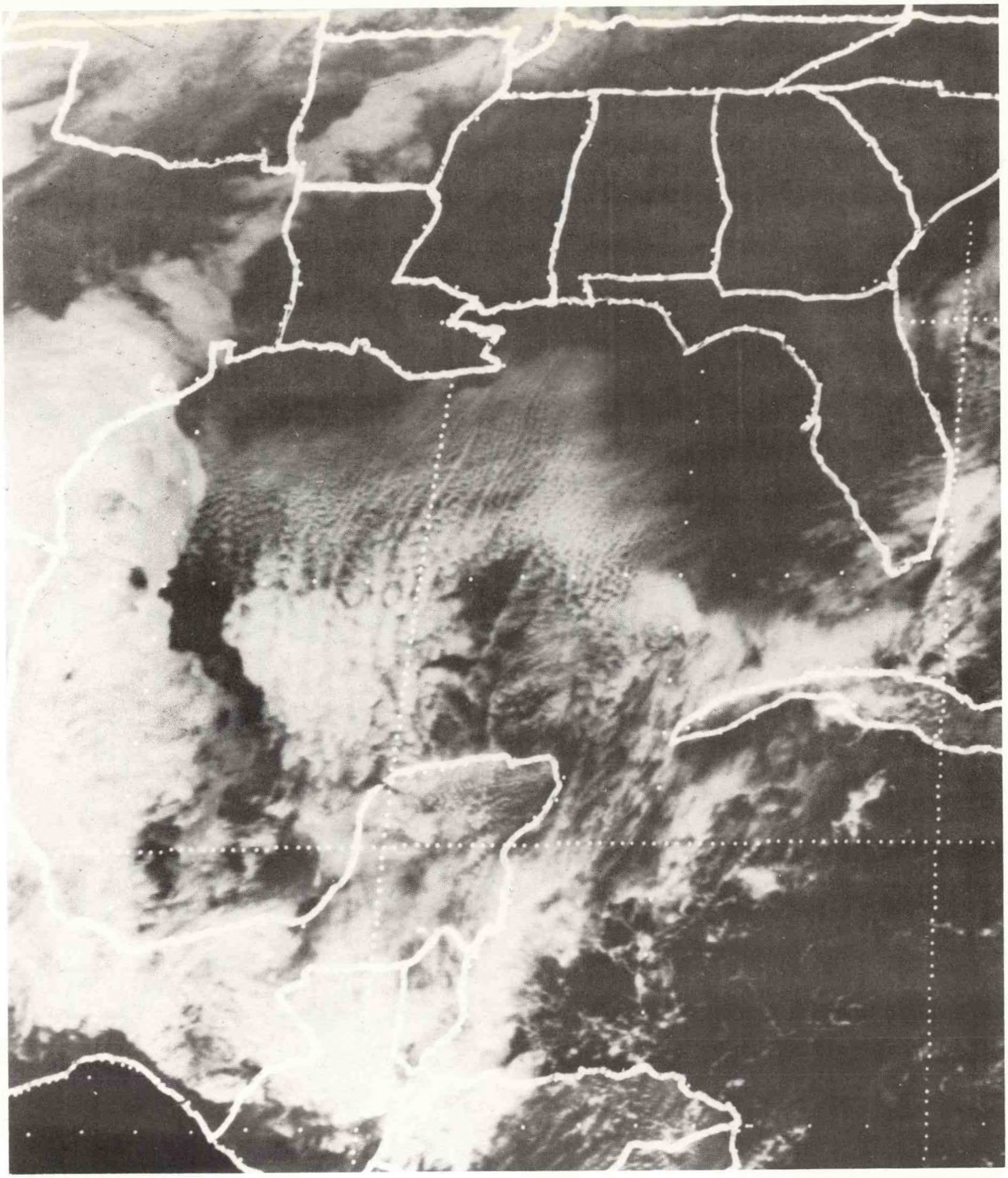

Figure 3. Satallite picture showing the modification of a cold airmass over the Gulf of Mexico. The picture shown is for early afternoon January 9, 1979. See text for explanation.

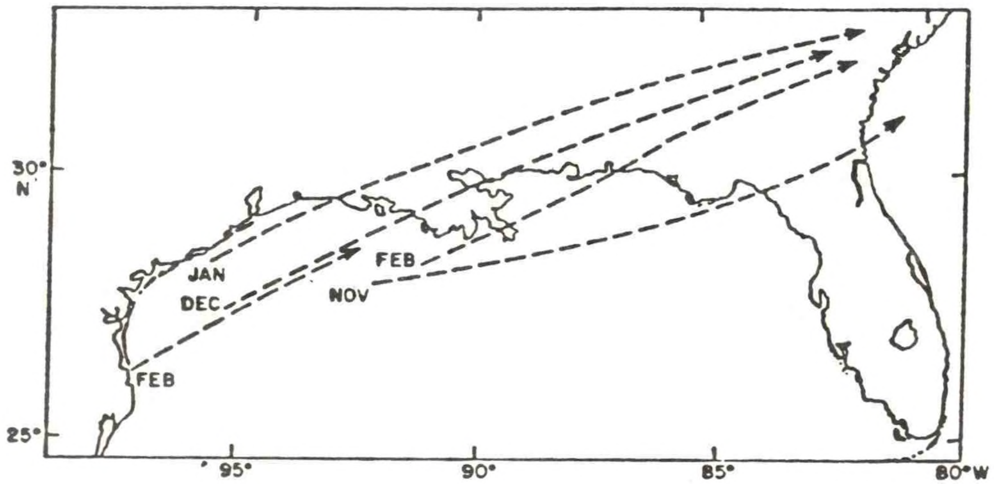


Fig. 4. Preferred tracks of extratropical cyclones in the Gulf of Mexico. (After Klein, 1957.)

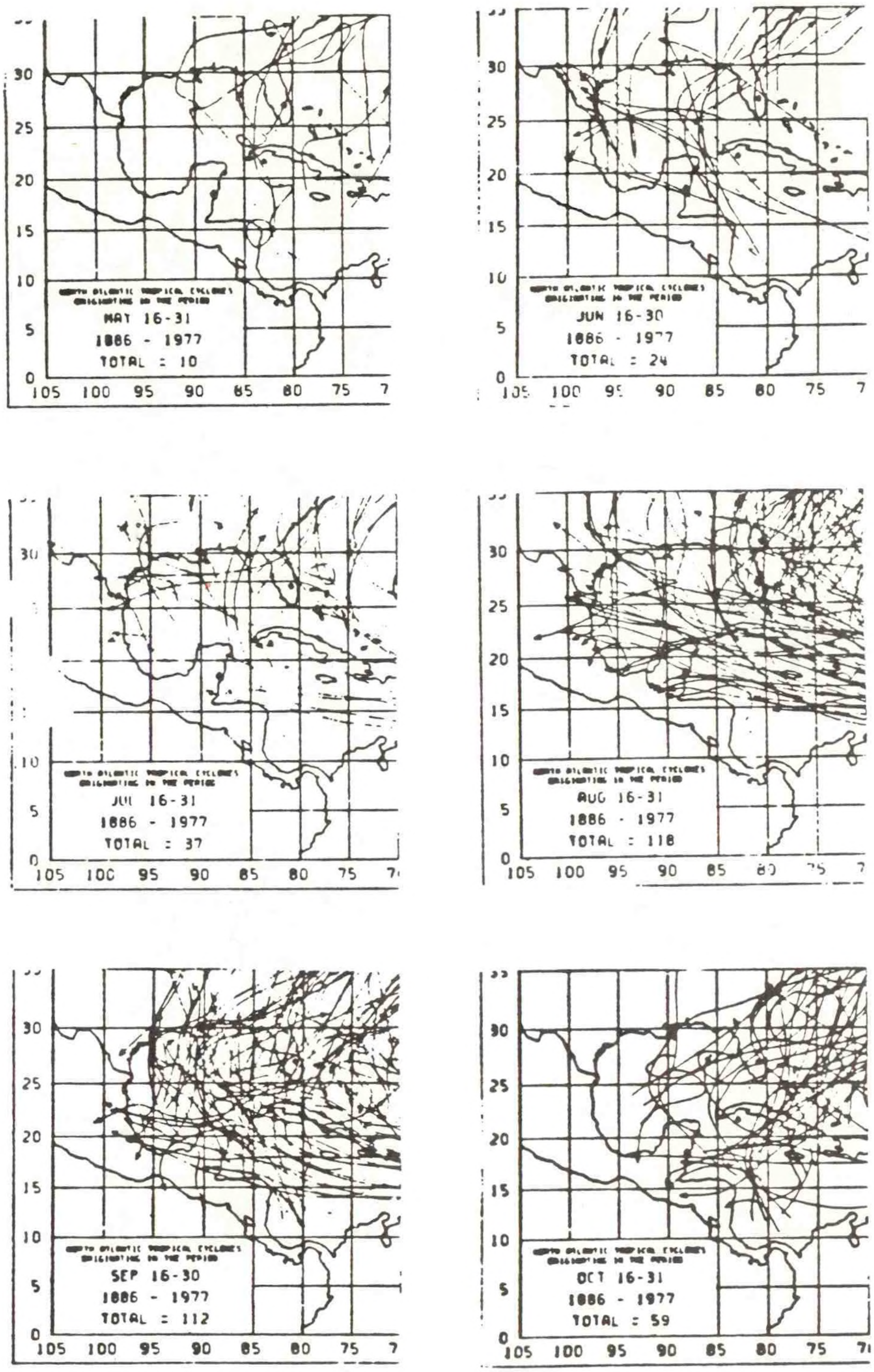


Fig. 5. Tropical storms and hurricanes over the Gulf of Mexico during the second halves of May, June, July, August, September and October. (After Jarvinen and Neumann, 1978.)

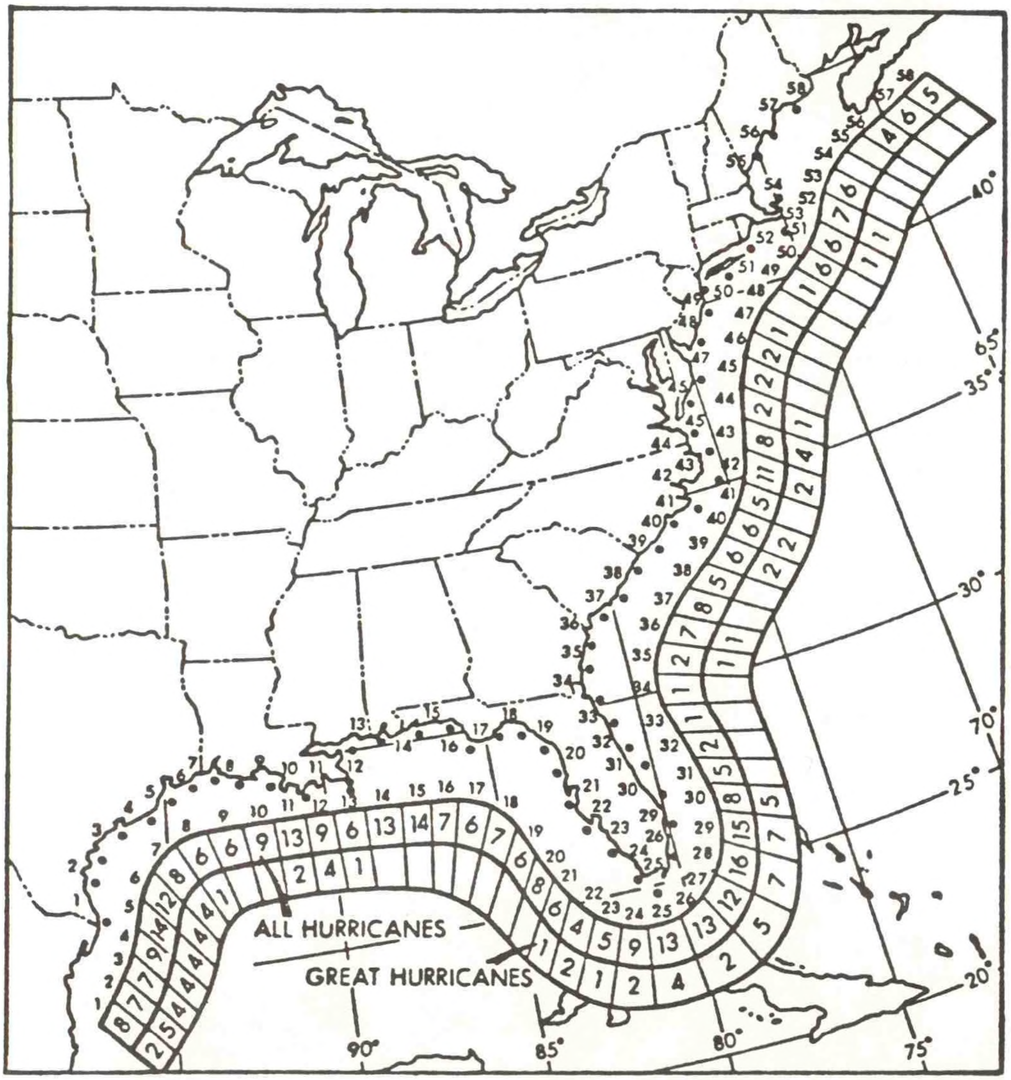


Fig. 6. Percent probability of hurricane winds at any year for 50-mi segments along the Gulf of Mexico coastline. (After Simpson and Lawrence, 1971.) See text for explanation.

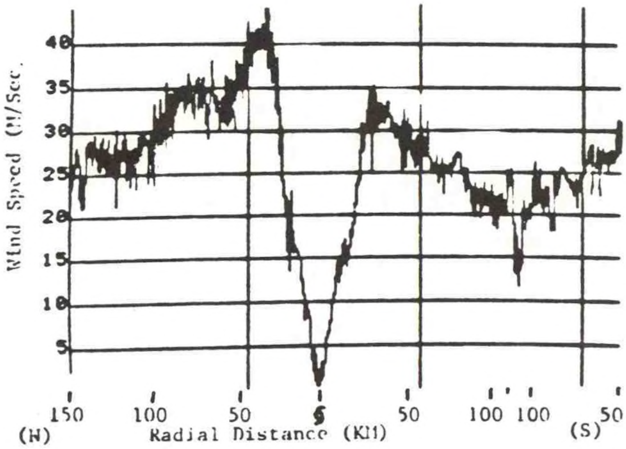


Fig. 7. Diagram showing low-level wind speeds versus distances from the center of Hurricane Anita on the morning of August 31, 1977.
(From Sheets, 1977, with permission of the author.) See text for explanation.

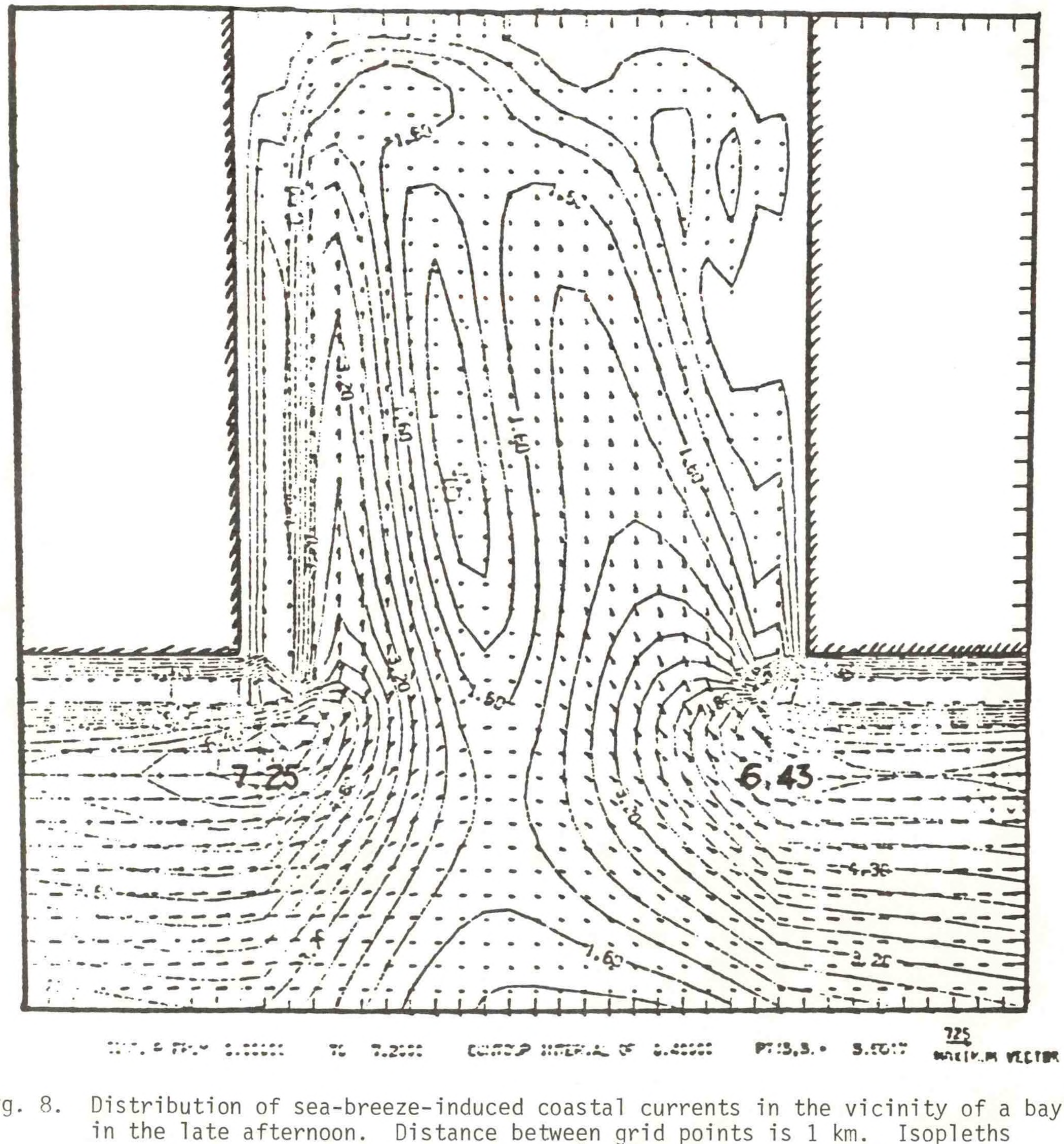


Fig. 8. Distribution of sea-breeze-induced coastal currents in the vicinity of a bay in the late afternoon. Distance between grid points is 1 km. Isopleths correspond to speeds in units of cm $s^{-1}$. (After Estoque, 1979.)

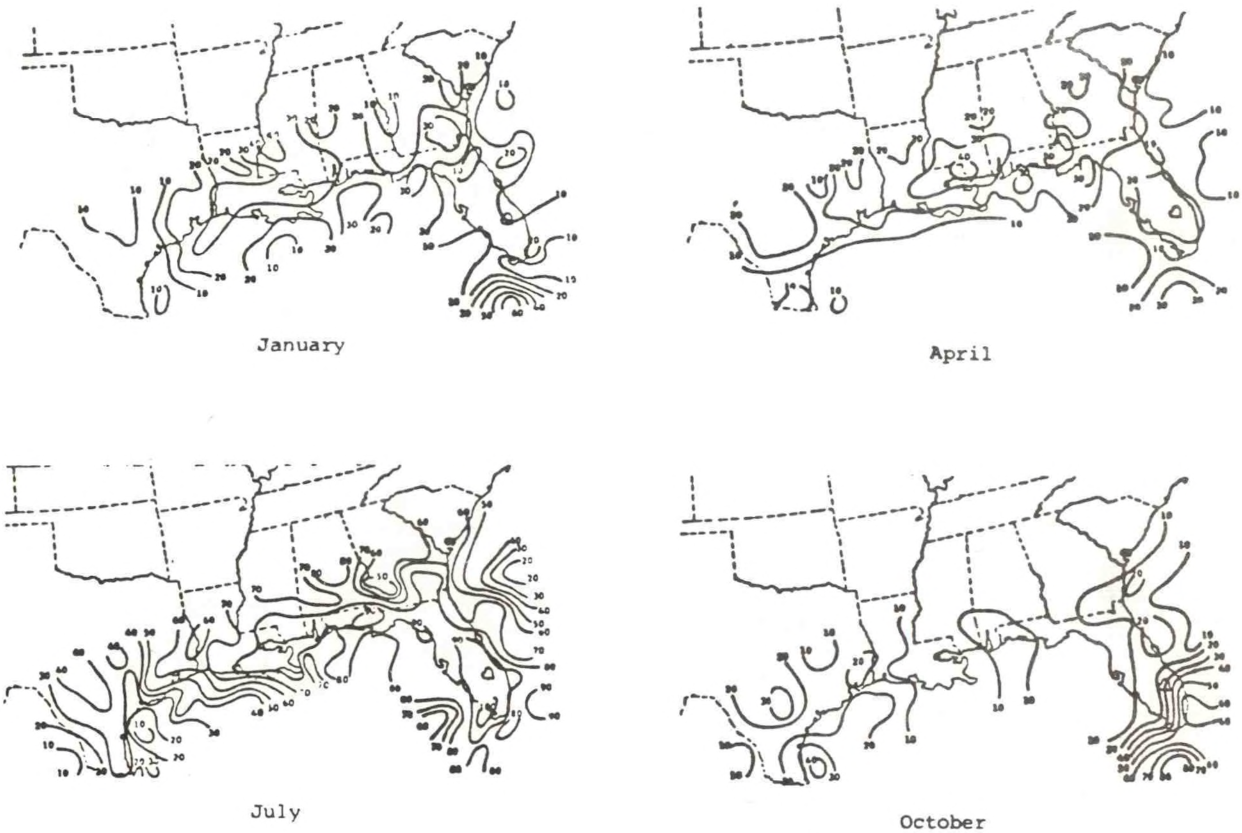


Fig. 9. Daily probability of thunderstorm occurrence for January. April, July, and October. (From Scoggins, 1976, with permission of the author.)

# NUTRIENT GEOCHEMISTRY OF THE GULF OF MEXICO

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ABSTRACT

A review of existing knowledge of the bioactive nutrients, gases and metals in the Gulf of Mexico suggests that the horizontal and vertical distributions of the classical dissolved micronutrients N, P, and Si are fairly well understood. Distributions of $TCO_2$, TA, pH, and $O_2$ are less well known, and reliable values for dissolved bioactive trace elements (Zn, Cd, Cu, Ni, Hg, As, and Ba) and trace gases ($N_2O$, DMS, and $H_2$) are nonexistent. Information on the sedimentary and interstitial water nutrient geochemistry is sparse, and to date, no benthic flux or vertical particulate flux experiments have been attempted to quantify internal recycling. In addition, there is no information on the importance of the sea surface microlayer in the transport of bioactive elements to or from the atmosphere.

## 1. INTRODUCTION

The purpose of this paper is to establish the limits of knowledge in the Gulf of Mexico for those elements known to be involved in bio-geochemical pathways: the micronutrients N ($NO_3^-$), P ($PO_4^{3-}$), and Si ($Si(OH)_4$); C ($CO_2$ and $C_{org}$), $O_2$, and S ($SO_4^{2-}$, $H_2S$ and DMS); and several trace metals and trace gases. A complete understanding of the behavior of these elements in any geochemical reservoir involves a knowledge of the input and removal rates, the biological particulate carrier phases, modes and rates of recycling within the reservoir, and the effects of physical mixing on the resulting dissolved species. We discuss the vertical and horizontal distributions related to physical advection and mixing (water masses) and to processes of bottom water renewal, sedimentary and pore water geochemistry related to bottom water chemistry, and the sea surface microlayer. We point out areas where knowledge is lacking in the Gulf of Mexico and where existing state-of-the-art tools would permit specific research objectives to be met. We do not discuss river fluxes, nearshore and estuarine geochemistry, organic geochemistry (including the light trace gases), nor any chemistries not pertaining to bioactive elements.

This paper is not intended to be a literature review, but rather a synopsis of knowledge of the Gulf of Mexico. The bibliography, however, represents a somewhat more comprehensive reference list. For more complete literature surveys, the reader is directed to earlier reviews of Williams (1954), El-Sayed, et al. (1972), and Corcoran (1973).

## 2. WATER MASSES

Four distinct water masses are identified in the Gulf of Mexico below the surface mixed layer: Subtropical Underwater (SUW), $18^o$ Sargasso Sea Water ($18^o$ SSW), Antarctic Intermediate Water (or Sub-Antarctic Intermediate Water; AAIW or SAIW), and Gulf Basin Waters, which are primarily composed of North Atlantic Deep Water (NADW). These water masses enter the Gulf of Mexico through the Yucatan Channel via the Caribbean. The upper water masses (SUW, $18^o$ SSW and AAIW) enter the Caribbean via the passes between the Lesser Antilles, and the NADW enter via the Windward Pass and Cayman Trough. Outflow is through the Florida Straits, although a small counterflow out through the Yucatan Channel has been suggested (Berberian and Starr, 1978).

Vertical distributions of nutrients show five general features related to identified water masses: (1) low concentrations between the surface and 100-200 m, (2) a substantial increase in concentration between 200 and 700-800 m, (3) maximum values at approximately 800-1000 m, (4) small decreases in concentration below 1000 m, and (5) homogeneous bottom water concentrations below about 1500 m. In the following discussion, we present the chemical characteristics of each water mass (Table 1).

The surface mixed layer (the upper 100 to 150 m) of the Gulf of Mexico is characterized by salinites between $36.0^o/oo$ and $36.5^o/oo$ (Morrison and Nowlin, 1977). Dissolved oxygen is at or near saturation, nutrients are depleted, and $\delta^{13}C$ is enriched in the $TCO_2$ to about $+1.16^o/oo$ (versus PDB) because of biological removal (Nowlin and McLellan, 1967; El-Sayed, et al., 1972).

However, surface nutrient concentrations are often elevated in upwelling areas off the Campeche Banks and the "left wall" of the Loop Current.

The Subtropical Underwater, which occurs throughout the Gulf of Mexico, is characterized by a salinity maximum of < 36.8°/oo at depths of 100-300 m ($\sigma_t$ = 25.3) (Berberian and Starr, 1978; Morrison and Nowlin, 1977; Nowlin and McLellan, 1967; Schroeder, et al., 1974). The salinity maximum, which originates in the arid, nutrient-depleted, subtropical central gyre area of the North Atlantic between 20 and 25°N, occurs at a temperature of about 23°C (Wüst, 1964). Reported values of dissolved oxygen average about 160 $\mu M\ kg^{-1}$ at the salinity maximum, although the concentration appears to decrease with depth through the water mass (El-Sayed, et al.; 1972, Berberian and Starr, 1978; Morrison and Nowlin, 1977; and Nowlin and McLellan, 1967). Total $CO_2$ increases only slightly with depth, ranging from 2.10 to 2.14 $\mu M\ kg^{-1}$ (El-Sayed, et al., 1972). $\delta^{13}C$ values decrease with depth (El-Sayed, et al., 1972). Nutrients increase with depth, but there is some evidence that a silica minimum may be associated with the salinity maximum (Froelich and Atwood, 1978). Phosphate concentrations in the upper 300 m are never > 1.46 $\mu M\ kg^{-1}$ (El-Sayed, et al., 1972; Morrison and Nowlin, 1977), but in the Yucatan Channel all values in one study were < 0.05 $\mu M\ kg^{-1}$ (Berberian and Starr, 1978). Reported silicate values in the upper several hundred meters are < 10 $\mu M\ kg^{-1}$ and usually begin increasing with depth below the salinity maximum (El-Sayed, et al., 1972; Morrison and Nowlin, 1977; and Carder, et al., 1977). Nitrate data throughout the Gulf is scarce. El-Sayed, et al. (1972) report a 0-24 $\mu M\ kg^{-1}$ range for the SUW for five Gulf stations and Berberian and Starr (1978) found a mean $NO_3^-$ value of 4.9 $\mu M\ kg^{-1}$ in the Yucatan Channel.

The 18° Sargasso Sea Water has been identified recently in the northern Caribbean and in the Loop Current in the Gulf of Mexico (Morrison and Nowlin, 1977; Kinard, et al., 1974). It is formed during winter cooling in the northern part of the Sargasso Sea. It is commonly identified by its characteristic temperature (17.3°C in the Gulf of Mexico) and a small oxygen maximum (or "shoulder") within the upper part of the broad oxygen minimum associated with AAIW (see below). Salinity is typically 36.3°/oo and the core is usually found at depths of 200-400 m ($\sigma_t$ = 26.5, just below the SUW). Nutrients, $TCO_2$ and $\delta^{13}C$ show no extrema, but continue to increase ($\delta^{13}C$ decrease) with depth through the water column.

Antarctic Intermediate Water is identified throughout the Gulf of Mexico by a characteristic intermediate-depth salinity minimum, although the intermediate nutrient maxima and oxygen minimum are also closely associated with this water mass. AAIW forms in productive waters near the Antarctic convergence between 45-55°C where it sinks and flows northward (Wüst, 1964). It occurs at depths of 500-1000 m ($\sigma_t$ = 27.3), with typical salinities and temperatures in the core of the salinity minimum of 34.6-34.9°/oo and 6.3°C, respectively (Berberian and Starr, 1978; Morrison and Nowlin, 1977; Nowlin and McLellan, 1967). Dissolved oxygen values are low in the AAIW. An oxygen minimum is usually located about 200 m shallower than the salinity minimum. Values at the minimum are between 90 and 110 $\mu M\ kg^{-1}$ (El-Sayed, et al., 1972), but it is not clear whether a $TCO_2$ maximum occurs in the AAIW. Phosphate, nitrate, and silica maxima occur in the upper AAIW between the $O_2$ minimum and the salinity minimum, usually at depths of 600-800 m (Figure 1). At the maxima, phosphate concentrations lie in the range 1.5-2.4 $\mu M\ kg^{-1}$, silicate levels between 20 and 25 $\mu M\ kg^{-1}$, and nitrate values consistently between 29 and 34 $\mu M\ kg^{-1}$ (El-Sayed, et al., 1972; Berberian and Starr, 1978; Morrison and Nowlin, 1977; Carder, et al., 1977). $\delta^{13}C$ displays a minimum closely associated with the $O_2$ minimum. $\delta^{13}C$ values in the minimum are about +0.4$^o$/oo (PDB) (El-Sayed, et al., 1972).

The depths of the extrema discussed above vary because of barotrophic fields, particularly those associated with the Loop Current, Loop-generated rings and eddies, and the less dynamic gyre/western boundary current system of the far western Gulf. For example, in the eastern Gulf, the core depths are deeper on the right "wall" than the left "wall" of the Loop Current. In addition, vertical and lateral mixing tends to erode the SUW salinity maximum, the 18$^o$ SSW $O_2$ maximum, and the extrema associated with the AAIW. In the case of the upper two water masses, their extrema are weak or nonexistent outside the Loop Current. In the case of the AAIW, both the salinity minimum and $O_2$ minimum broaden in depth and the minimum value of salinity increases in going from east to west. However, apparently the minimum value of $O_2$ at the $O_2$-minimum becomes more pronounced towards the west, possibly because of oxygen consumption by oxidative regeneration of organic matter either in the water column or at the impingement of the AAIW with the bottom (edge) (Figure 2). An expected, concomitant increase in nutrient values at their maxima is not resolved within the scatter of presently available data, but should be detectable (Figure 3).

The vertical distributions of micronutrients ($PO_4^{3-}$, Si, and $NO_3$) are thus fairly well known in the water masses of the Gulf of Mexico, although additional work will elucidate finer scale phenomena. However, almost nothing is known about those trace elements whose dissolved behavior in the oceans is recognized as biologically controlled, particularly Cd and Zn, which appear to be bio-limiting like the micronutrients, and Cu, Ni, Hg and $N_2O$, which appear to be biointermediates like $O_2$ and $TCO_2$. Based on observed concentrations and element-nutrient relationships in other oceans, we predict the levels of these "nano-nutrients" to be expected in surface waters, AAIW, and Gulf Basin Water in the Gulf of Mexico (Table 2) (Bruland, et al., 1978; Mukheiji, et al., 1979; Bruland, et al., 1978; Boyle, et al., 1977; Boyle and Edmond, 1976; Yoshinar, 1976; Cohen and Gordon, 1978). The purpose of this is to emphasize the nutrient-like behavior of these elements in the oceans, and to provide guides for the levels to be anticipated in the Gulf.

It is clear that presently available data cannot be used to discern chemical signals originating in the Gulf of Mexico from those simply advected from the Caribbean and then mixed within the Gulf. High precision T, S, $O_2$, $TCO_2$, and nutrient data are needed to resolve these sources. It is hoped that the extensive data set collected during the 1976 NOAA Ship RESEARCHER cruise will help to fill this need (Berberian, personal communication), but it is clear that we are only beginning to understand the primary processes affecting the chemistry of the Gulf.

Gulf Basin Waters filling the Gulf of Mexico below sill depth (about 200 m) are thought to be derived primarily from upper North Atlantic Deep Water entering through the Yucatan Channel. NADW is a complex mixture of waters originating in the Norwegian, Greenland, and Labrador Seas, with a diluted admixture of Mediterranean water in its upper layers. The Basin Waters below 1500 m show an almost constant 4.1°Θ and 34.97‰ S with depth ($\sigma_t$ = 27.8) (Berberian and Starr, 1978; Nowlin and McLellan, 1967). Deep water dissolved oxygen values increase with depth below the AAIW minimum, but values below 1500 m are evidently constant at 190-200 $\mu$ M kg$^{-1}$ (El-Sayed, et al., 1972; Berberian and Starr, 1978; Nowlin, et al., 1969) (Figure 4). Basin Water nutrients decrease slightly below the AAIW maximum values, but there is no evidence for vertical gradients below 1500 m. Reported phosphate concentrations in the Basin Waters are highly variable, but are generally less than 1.5 $\mu$ M kg$^{-1}$ (Berberian and Starr, 1978). Silicate values are about 25 $\mu$ M kg$^{-1}$, except where bottom water renewal is active (Berberian and Starr, 1978; Morrison and Nowlin, 1977; Carder, et al., 1977), typical nitrate levels are about 19-24 $\mu$ M kg$^{-1}$ (El-Sayed, et al., 1972; Berberian and Starr, 1978), and total $CO_2$ is about 2.2 $\mu$ M kg$^{-1}$ (El-Sayed, et al., 1972).

The renewal of Gulf Basin Waters appears to occur primarily by inflow of upper NADW from the Caribbean through the Yucatan Channel. This accounts for higher $O_2$ and lower nutrient values below 1500 m inside the Gulf. The absence of observed deep gradients in T, S, and $O_2$ suggests that the residence time of the Basin Waters must be fairly long with respect to lateral mixing times (Nowlin, 1972). In general, with a few exceptions, horizontal gradients in Gulf bottom waters have not been observed. Such horizontal gradients must be associated with benthic fluxes and bottom water renewal processes. Deep silica values in the Gulf are elevated above renewal water values because of the benthic flux of silica from the bottom (Fanning, 1978). Thus, inflowing NADW at the base of the Yucatan Channel can be detected by its lower Si concentration and traced several hundred km into the interior of the basin as it flows along the bottom (Figure 5). This low-Si influx, coupled with a benthic Si-flux, creates a detectable east-west Si gradient of 3-4 $\mu$ M kg$^{-1}$ across the deep Gulf (Carder, et al., 1977).

Nutrients and dissolved oxygen data show that northward flow into the Gulf through the Yucatan Channel is characterized by relatively high $O_2$ (199 $\mu$ M kg$^{-1}$) and nutrient levels and that the return counterflow along the western side of the channel has relatively lower $O_2$ and nutrient levels (Berberian and Starr, 1978). These data confirm that the deep inflow to the Gulf is characteristic of NADW that enters the Caribbean through the Windward Passage.

This deep renewal inflow is probably linked to deep bottom currents discovered at 3000-3300 m near the base of the Mississippi fan (Pequequat, 1972). Short-term current measurements have recorded velocities of up to 19 cm s$^{-1}$. A bottom nepheloid layer extending 200-300 m about the bottom (Feely, 1975) is additional evidence of the existence of bottom currents. Suspended matter in the nepheloid layer is low in organic carbon and high in particulate aluminosilicates compared with suspended matter directly above the layer, suggesting that its origin is by resuspension of bottom sediments.

## 3. SEDIMENT GEOCHEMISTRY

We are aware of only a few studies providing the information necessary to judge the importance of benthic coupling on the nutrient dynamics of the overlying water column in the Gulf. Such studies would include analyses of sediment solid phases and interstitial waters, benthic flux experiments, and vertical particulate flux measurements of biologically active elements.

There is a general paucity of systematic information concerning the nutrient chemistry of solid phases and interstitial waters of the sediments in the Gulf of Mexico. Several studies have provided data on the bulk (major element) chemistry (Grim and Johns, 1954) of the <1 μm size fraction of two locations {$SiO_2$, $Al_2O_3$, $TiO_2$, $Fe_2O_3$, MnO, MgO, CaO, $Na_2O$, $K_2O$, $H_2O$, and ignition loss} and trace inorganic chemistry (Tieh and Pyle, 1972) for 21 cores in the northern and central Gulf {Ba, Ca, Fe, Mn, Ni, Rb, Sr, Ti, Y, Zn, and Zr}. We are unaware of any studies of the organic carbon, nitrogen, or phosphorous distributions in open Gulf sediments.

Some nearshore pore water work has been carried out by Presley's group at Texas A&M University in cores from the shelf south of the Mississippi River (Armstrong, 1974). These data display the effects of anoxic diagenesis: $SO_4^{2-}$ decreases with depth because of sulfate-reduction, $NH_4^+$ increases, often to over 2000 μM, and $PO_4^{3-}$ is high (2-140 μM), but variable. In addition, analyses of total-N, organic and inorganic-P were made in the sediments.

Fanning's group at the University of South Florida has measured pore water Si in several cores from the deep Gulf (Fanning, 1978). Values as high as 145 μM-Si were found in the upper 10 cm, demonstrating that there is a significant diffusive Si-flux from the bottom, presumably sufficient to maintain a steady-state Si concentration in Gulf Basin Waters measurably higher than the inflowing waters (Carder, et al., 1977). There are no benthic flux experiments in the deep Gulf to confirm estimates of Si-fluxes from the bottom estimated from pore water Si profiles.

Although no vertical particulate flux measurements of nutrient-related constituents have been reported in the Gulf, there is some information on suspended particulates, but little relevant to nutrient recycling. More than half of the total suspended material in the surface waters of both shelf and open Gulf regions may be organic. Surface concentrations of TSM generally exceed 1 mg $\ell^{-1}$ within a few km of the Louisiana-Texas coast, and maximum values are as high as 64 mg $\ell^{-1}$ (Manheim, et al., 1972). Values for total suspended material in open shelf surface waters range from 0.15 to 2.32 mg $\ell^{-1}$ with a mean of 0.74 mg $\ell^{-1}$ (El-Sayed, et al., 1972). Open Gulf surface values are much lower with a range of 0.06-1.59 mg $\ell^{-1}$ and a mean value of 0.19 mg $\ell^{-1}$ (El-Sayed, et al., 1972).

TSM concentrations in deep water samples (> 1000 m) range from 0.0096 to 0.089 mg $\ell^{-1}$, except in bottom nepheloid layers, where values can range as high as 0.296 mg $\ell^{-1}$ (Feely, 1975), but are in general about twice those found in the waters above the layer. Mean particulate organic carbon values were about 10 and 11 μg $\ell^{-1}$ for the region above and within the nepheloid layer, respectively, and biogenic particulate silica composed about 6 to 8% of the TSM in and above the nepheloid layer, reflecting the absence of biogenic material in the sediments from which the nepheloid layer was resuspended.

## 4. EXOTIC WATERS

Two hypersaline basins have been identified on the NW continental margin of the Gulf of Mexico, the Orca Basin and the East Flower Garden (EFG). The existence of others is likely (Shokes, et al., 1977; Brooks, et al., 1979). Salinities are as high as 196$^{o}$/oo in the East Flower Garden and 250$^{o}$/oo in the Orca Basin. Dissolved oxygen and nitrate are completely depleted in the Orca Basin and are zero and 0.7-3.0 $\mu M\ kg^{-1}$ in the EFG Basin, respectively. Phosphate, silicate, $TCO_2$ and sulfate are elevated in both basins. The unique chemistry of these basin waters is believed to be caused by dissolution of near-surface evaporite deposits, followed by density stratification and resulting suboxic conditions. Since $O_2$ is completely consumed, $NO_3^-$ is almost entirely depleted, yet $SO_4^{2-}$ is present in concentrations above seawater values, these basins provide a natural setting for studying the redox reactions occurring after $O_2$ consumption but before $SO_4^{2-}$ diagenesis (anoxic). These reactions involve primarily iron and manganese oxides and the trace metals for which these oxides are hosts.

## 5. RECOMMENDATIONS FOR FUTURE RESEARCH

Standard techniques are now available with which to obtain data on the dissolved bioactive elements present in seawater at the nanomolar level. Such studies are of importance in the Gulf of Mexico because many of these elements are biologically deleterious at higher concentrations and are increasingly involved in anthropogenic pathways. Of primary importance would be studies of Cd, Cu, Ni, Zn, As, Se, Sn, Sb, and Hg.

High accuracy nutrient, $TCO_2$, and $O_2$ data are needed, particularly in the AAIW, to judge the relative importance of reactions occurring within the Gulf as opposed to simple advection of the signals of earlier reactions into the Gulf. Additional work is needed to elucidate precisely any lateral gradients that exist in the Gulf Basin Waters below 2000 m. High accuracy nutrient data (particularly Si and $O_2$) would greatly enhance our understanding of bottom water renewal mechanisms and perhaps would lead to a rational explanation for observed bottom currents and the bottom nepheloid layer.

In conjunction with bottom water studies, information on vertical particulate fluxes, sediment and pore water geochemistry, and benthic fluxes (both measured directly and estimated from pore water profiles) would permit independent assessment of regeneration rates of nutrient-related chemicals in the deep Gulf, and allow an estimation of the extent to which man's influence is likely to alter the natural steady-state condition of the deep waters. Such studies might include (1) solid phase analyses for organic carbon, nitrogen and phosphorus, fixed and sorbed ammonia and phosphorus, total nitrogen and phosphorus, biogenic silica and bulk accumulation rates; (2) measurements of pore waters for $TCO_2$, TA, pH, $NO_3^-$, $NO_2^-$, $NH_4^+$, $PO_4^{3-}$, and Si and the redox species driving organic carbon oxidation ($O_2$, Fe, Mn, $SO_4$); (3) measurement of benthic fluxes of $CO_2$, $NO_3^-$, $NO_2^-$, $NH_4^+$, $PO_4^{3-}$, and Si; and (4) measurement of vertical particulate fluxes of biogenic and total C, N, P, and Si arriving at the bottom.

One area in which there is a complete dearth of information in the Gulf of Mexico is the sea surface microlayer. This is surprising in view of the large potential here for investigating the fates of continentally derived, atmospherically input materials (both natural and man-derived) to the sea surface, and the role the microlayer plays in the concentration, dissolution, organic complexation and reinjection of these chemicals. A number of elements or compounds are thought to be enriched in the microlayer. Among these are a variety of organic substances (including hydrocarbons, fatty acids, proteins, and alcohols), pesticides, particulate and dissolved organic carbon, nutrients, and trace metals (Duce and Hoffman, 1976). Study of the sea surface microlayer plus synoptic sampling in the Gulf would help to elucidate the importance of fluxes of many biologically related elements to and from the Gulf, and lead to a better understanding of the relative importance of atmosperhically derived versus aquatically derived pollutants in the Gulf.

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Table 1. Chemical Characteristics of Water Masses in Gulf of Mexico

| Water Mass | $\sigma_t$ $10^{-3}$g/cc | Core T ($^oC$) | S($^o/oo$) | $O_2$ $\mu M\ kg^{-1}$ | $PO^{3-}$ $\mu M\ kg^{-1}$ | $Si(OH)_4$ $\mu M\ kg^{-1}$ | $NO_3^-$ $\mu M\ kg^{-1}$ | $TCO_2$ $\mu M\ kg^{-1}$ |
|---|---|---|---|---|---|---|---|---|
| Surface Mixed Layer (100-150 m) | - | - | 36.0-36.5 | - | Deply. | Depl. | Depl. | - |
| SUW (100-300 m) | 25.3 | 23 | 36.75 Sal. Maximum | 160 | 0-1.46 | 2-10 | 0-24 | 2.10-2.14 |
| $18^o$ Sargasso Seawater (300-700 m)$^+$ | 26.5 | 17.3 | 36.3 | 145-150 $O_2$ Maximum | - | - | - | - |
| AAIW (500-1000 m) | 27.3 | 6.3 | 34.6-34.9 Sal. Minimum | 90-110 Relative $O_2$ Minimum | 1.46-2.44(?) | 20-25 Nutrient Maximum | 29-34 | 2.2 |
| Gulf Basin Waters (NADW) (>1500 m) | 27.8 | 4.1 | 34.97 | 190-200 | ∿1.0 | <25 | 19-24 | 2.2 |

$^+$Found only in the Loop Current

Depl. = Depleted because of biologic activity

Table 2. Predicted Nanonutrient Levels in the Gulf of Mexico (All concentrations in nmol $kg^{-1}$)

| | $Cd^{\dagger}$ | $Zn^{\propto}$ | $Cu^{¶}$ | $Ni^{\dagger\dagger}$ | $Hg^{*}$ | $N_2O^{+}$ |
|---|---|---|---|---|---|---|
| Carrier analog | (P,N) | (Si) | (P,N) | (P,N,Si) | (Si?) | (N) |
| Surface layer | $\leq$ .04 | $\leq$ .2 | 1-3 | ∿3 | ∿.015 | ∿7 |
| AAIW | .5 | 1.3 | 4-6 | 6 | .06 | 50 |
| Gulf Basin waters | .3 | 1.0 | 3-5 | 5 | .05 | 40 |

† Cd (nM) = -0.032 + 0.31 P ($\mu$M) (21) or Cd:P $\simeq 3 \times 10^{-4}$ (mole:mole) (22)

∝ Zn (nM) = -0.18 + 0.06 Si ($\mu$M) (23)

¶ $\Delta Cu:\Delta P \simeq 1.6 \times 10^{-3}$ (mole:mole) and ignoring deep scavenging and allowing a 2 nmol $kg^{-1}$ range for unknown atmosphere deposition (24)

†† Ni (nM) = 3.5 + 1.07 P ($\mu$M) + 0.033 Si ($\mu$M) (25)

* $\Delta Hg:\Delta Si \simeq 2 \times 10^{-6}$ (mole:mole) (22)

\+ $\Delta N_2O:\Delta NO_3^- \simeq 1.2 \times 10^{-3}$ (mole:mole) (26, 27)

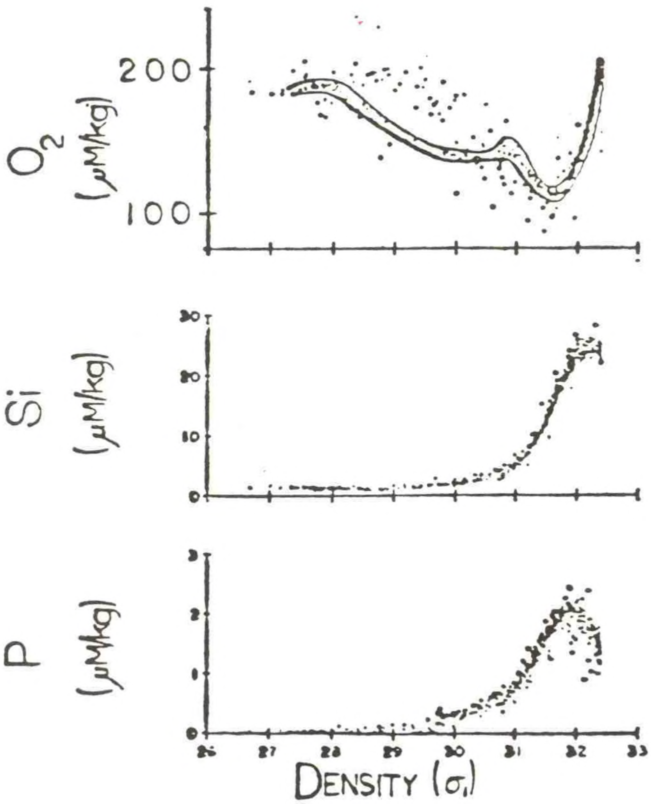


Fig. 1. Relationships between Si, P, and $O_2$ as a function of potential density.
(From Morrison and Nowlin, 1977, with permission of the author.)

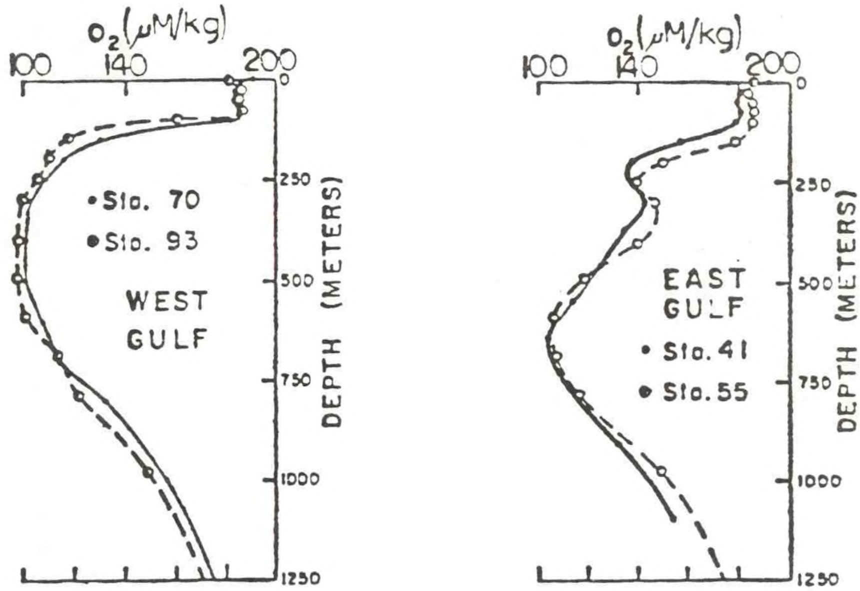


Fig. 2. Oxygen profiles for two eastern and western Gulf station showing the broadening of the $O_2$-minimun from east to west.
(From Nowlin and McLellan, 1967, with permission of the author.)

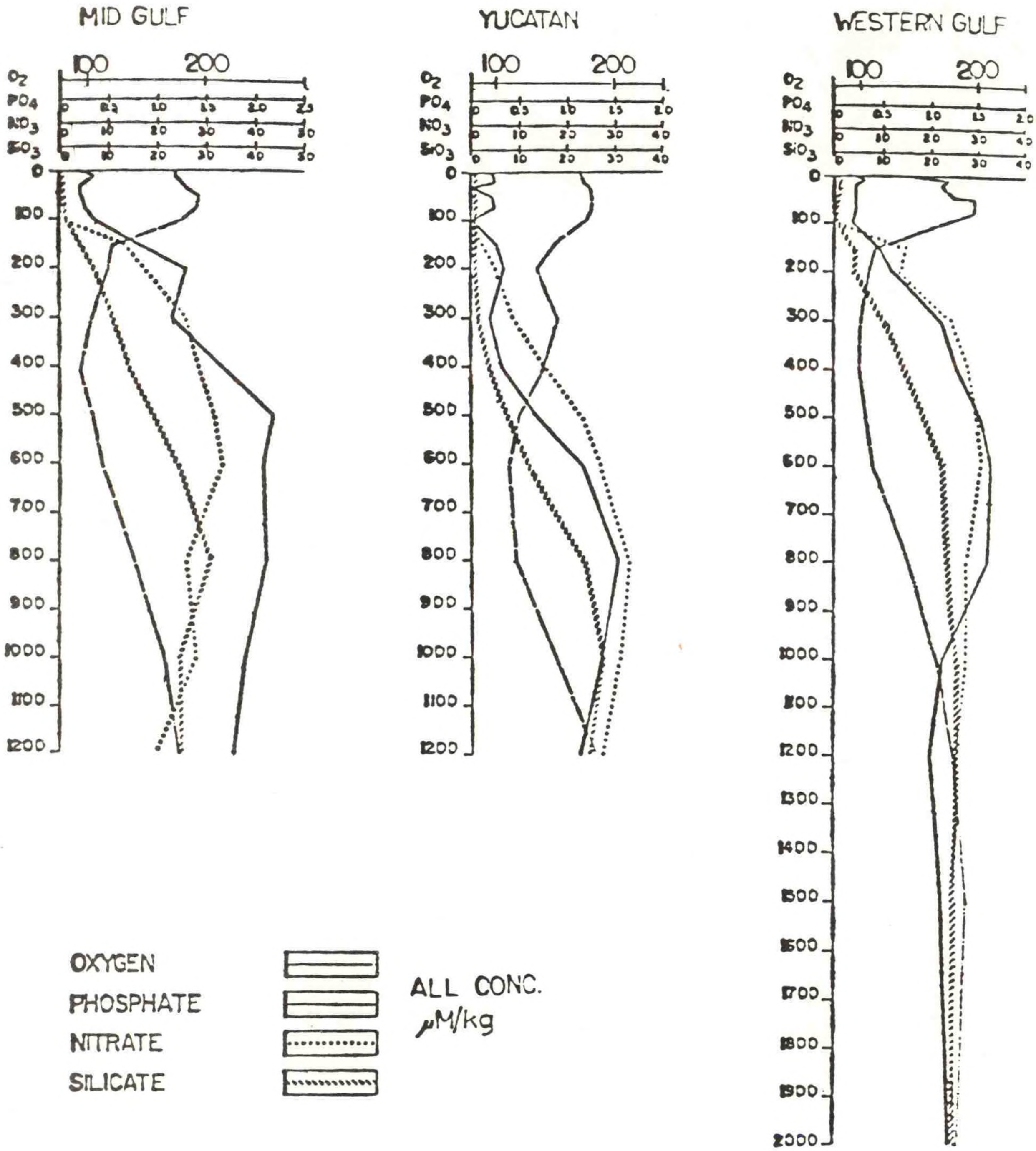


Fig. 3. Typical vertical distributions of P, Si, $NO_3^-$ and $O_2$ for three Gulf stations.
(From El-Sayed et al., 1972, Fig. 7. Reprinted from "Serial Atlas of the Marine Environment," Folio 22 (1972), with the permission of the American Geographical Society.)

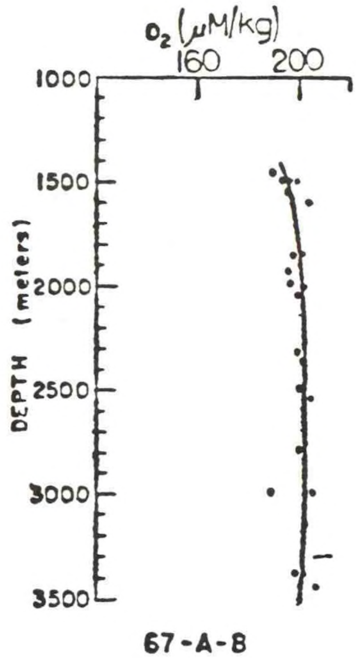


Fig. 4. Typical Basin Water dissolved oxygen profile. (From Nowlin et al., 1969, with permission of the author.)

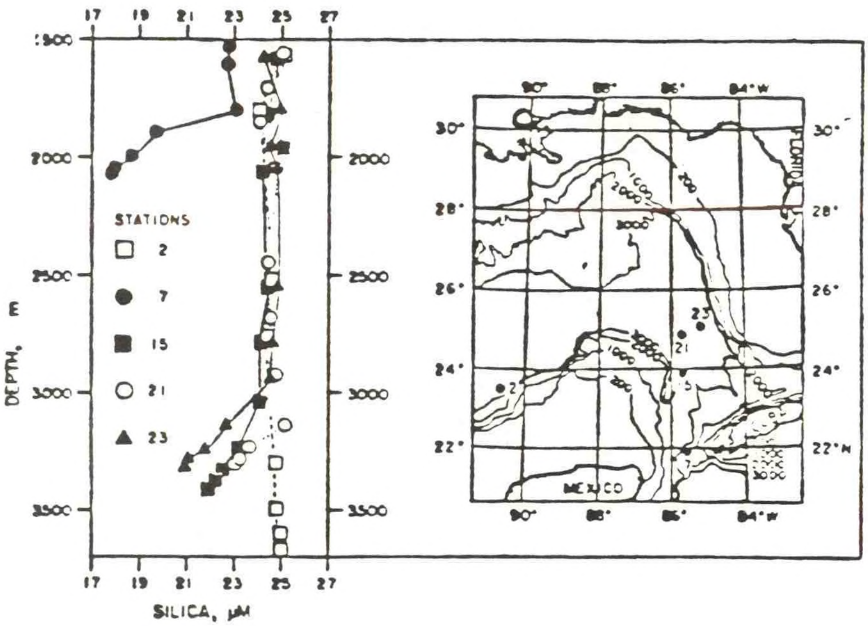


Fig. 5. Vertical profiles of dissolved silicon for bottom waters of the Gulf of Mexico.
(From Carder et al., 1977. Reprinted with permission from Deep-Sea Research 24:1149-1160, K. L. Carder, K. A. Fanning, P. R. Betzer, and V. Maynard, "Dissolved silica and the circulation in the Yucatan Strait and deep eastern Gulf of Mexico." Copyright 1977, Pergamon Press, Ltd.)

# A SUMMARY OF KNOWLEDGE OF PLANKTON PRODUCTION IN THE GULF OF MEXICO:

## Recent Phytoplankton and Zooplankton Research


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## 1. SUMMARY OF RECENT PHYTOPLANKTON RESEARCH IN THE GULF OF MEXICO

The distribution and productivity of the phytoplankton of the Gulf of Mexico have been reviewed several times. Davis (1954) discussed early investigations of phytoplankton productivity and ecology that were largely confined to coastal areas of the northern and eastern Gulf of Mexico. Graham (1954), Conger (1954), and Lasker and Smith (1954) reviewed distribution of dinoflagellates, diatoms and red tides, respectively. El-Sayed (1972) summarized data on phytoplankton productivity and chlorophyll concentration obtained between 1964 and 1971 in the Gulf of Mexico. Mean values for productivity (0.3 gm $m^{-3}$, 27 g C $m^{-2}y^{-1}$) and for chlorophyll (0.2 mg $m^{-3}$, 12.4 mg $m^{-2}$) led to a conclusion that the Gulf of Mexico was very oligotrophic. Saunders and Fryxell (1972) reviewed diatom distribution and Steidinger (1972) reviewed dinoflagelatte distribution patterns. Steidinger (1973) discussed the distribution, productivity and ecology of phytoplankton in the eastern Gulf of Mexico.

Some new information on phytoplankton productivity and standing crop has been obtained in several coastal areas since 1973. Several investigations of large-scale physical features of the eastern Gulf of Mexico have included observations of phytoplankton distribution patterns. This review summarizes productivity patterns and factors which appear to affect the patterns in different regions of the Gulf of Mexico.

Since most of the phytoplankton productivity data for the Gulf of Mexico have been obtained with the carbon-14 method, some comments about the method (reviewed by Iverson et al., in press) are in order. The carbon-14 method (Steeman-Nielson, 1952) appears to estimate particulate carbon production for situations where phytoplankton are not nutrient-limited (McAllister et al., 1964; Eppley and Sloan, 1965; Ryther and Menzel, 1965). Strickland (1965) questioned the interpretation of carbon-14 productivity values obtained under oligotrophic conditions. Estimates of primary production indirectly derived from microplankton growth rates were an order of magnitude greater than those derived from measurements of carbon-14 uptake for samples from the Sargasso Sea (Sheldon and Sutcliff, 1978).

Some of the problems with the carbon-14 method may lie in effects of metals on phytoplankton. Steeman-Nielsen and Wium-Anderson (1970) reported copper in commercially obtained ampules of carbon-14. Knauer et al. (in ms.) found that several trace metals, including copper, inhibited carbon-14 fixation when present on nannogram per liter concentrations. At present, it is impossible to accurately interpret dark uptake of carbon-14 which may reach a large proportion of light carbon-14 uptake under oligotrophic conditions (Holmes, 1978; Steven, 1971; Morris et al., 1971). There is a lack of correlation between productivity values obtained from one long incubation and values obtained from the sum of several short incubations (Barnett and Hirota, 1967).

Since most of the Gulf of Mexico photic zone is oligotrophic, some effort should be spent in an attempt to resolve the general problem of obtaining accurate photoplankton productivity estimates under oligotrophic conditions.

## 2. OPEN GULF OF MEXICO

The central Gulf of Mexico is characterized by very low standing plankton biomass (Bogdanov et al. 1978) with mean vertically integrated chlorophyll maximum ranging from 8 to 10 mg $m^{-2}$ (El-Sayed, 1972), (Fig. 1). A chlorophyll maximum ranging between 0.3 and 0.6 mg $m^{-3}$ often occurred within the pycnocline in the open Gulf of Mexico (Hobsen and Lorenzen, 1972). Phytoplankton carbon varied between 16 and 20 mg $m^{-3}$ in the chlorophyll maximum. When the pycnocline was deeper than 100 m, a deep chlorophyll maximum was not observed. Steele (1964) postulated that midwater chlorophyll maxima in the Gulf of Mexico were a consequence of an increase in chlorophyll content of the phytoplankton, rather than an accumulation of plants due to sinking. Venrich et al. (1973) observed that the deep chlorophyll maximum in the Pacific correlated more closely with the nutricline than with light or density fields. Productivity within the layer was low, but positive.

A seasonal variation in primary production was evoked to explain a bimodel distribution of total suspended matter observed deep in the open Gulf of Mexico (Harris, 1972). Large values of suspended matter were attributed to phytoplankton since samples with values of about 200 - 400 mg $m^{-3}$ contained large amounts of coccoliths. Hulbert and Corwin (1972) reported that the phytoplankton of the offshore Gulf of Mexico was sparse and was dominated by coccolithophores.

The nannoplankton (phytoplankton passing a 20 μm mesh-size Nitex screen) comprised between 75 and 90% of total phytoplankton productivity in offshore waters and 50% of total primary productivity in nearshore waters of the northeastern Gulf of Mexico (Jennings, 1973). Nannoplankton comprised between 83% of total chlorophyll and 84% of total phytoplankton productivity in the open Gulf of Mexico (El-Sayed and Turner, 1977).

The source for most of the phytoplankton productivity data in the Gulf of Mexico is El-Sayed (1972) who estimated annual production of 27 g C $m^{-2}$ for the water column. Total phytoplankton production for the 1.6 x $10^6$ $km^2$ area of the Gulf of Mexico was estimated at 46 x $10^6$ tnn carbon per year. This value may underestimate actual annual production since most of the data were collected during the summer (El-Sayed and Turner, 1977). Seasonal changes in productivity in the open Gulf of Mexico appear to be small (Hopkins, pers. commun.) and may be related to effects of winter cold fronts that penetrate some distance into the Gulf and which mix the water column.

## 3. EASTERN GULF OF MEXICO

Maxima were observed during February and August in phytoplankton numbers for samples collected near Alligator Point Harbor, north Florida (Curl, 1956). Chlorophyll values were maximum in April for samples taken at various locations in northeastern Gulf of Mexico coastal waters (Marshall, 1956). Annual phytoplankton productivity in coastal waters off the Fenholloway River, north

Florida was about 59 g C $m^{-2}$ $y^{-1}$ (Fig. 2) (Bittaker, 1975). Phytoplankton chlorophyll values (Table 1) were low throughout the year at the Bureau of Land Management (BLM)-Mississippi/Alabama/Florida (MAFLA) stations (Fig. 3) in the eastern Gulf of Mexico. Nearshore diatom numbers were an order of magnitude greater than offshore numbers for samples collected off Tampa during the Hourglass cruises (Saunders and Glenn, 1969). There was considerable monthly variation in numbers for inshore stations. Offshore phytoplankton numbers were greatest in January and February. This general pattern was exhibited in dinoflagellate numbers which occasionally reached concentrations offshore similar to those at inshore stations (Steidinger and Williams, 1970).

Red tides have been frequently observed in coastal waters of the West Florida shelf. Research on red tides to 1964 was summarized by Rounsefell and Nelson (1966). Factors evoked to explain the red tide development range through particular combinations of temperature, salinity, and inorganic nutrients (Slobodkin, 1953); relations between the growth rate and diffusion scales (Kierstead and Slodbodkin, 1953); temperature, salinity and onshore winds (Rounsefell and Dragovich, 1966); concentrations of organisms in convergences (Chew, 1966); effects of chelators in river water (Collier et al., 1969); presence of unknown factors indicated by particular quantities of iron in river water (Ingle and Martin, 1971); and resuspension of Gymnodinium breve cysts from sediments by intrusion of water from the Loop Current (Haddad and Carder, 1979). A complete explanation leading to the ability to predict red tide development in Florida coastal waters has not yet been achieved. It is doubtful that red tides are important in a positive sense for marine food webs in the Gulf of Mexico. Fish kills associated with the red tides are generally local phenomena with no significant consequences for fisheries.

The Loop Current is the most prominent hydrographic feature of the eastern Gulf of Mexico. Characteristics of the current have been described by Leipper (1970), Maule (1977), and Molinari et al. (1977). Gradients in color across the current (Maule, 1974) are related to phytoplankton which frequently reach maximum numbers in surface water on the cyclonic edge of the current (Ednoff, 1974, (Fig. 4), defined by the 100 m depth of the 22° C isotherm (Fig. 5). The mechanism leading to enhanced phytoplankton numbers in the Loop Current edge is not clearly understood. Austin (1971) obtained sections of temperature, salinity and oxygen across the current which he considered indicative of upwelling along the left (cyclonic) edge of the current. A July, 1973 bloom of Rhizosolenia alata in the open Gulf of Mexico associated with the left edge of the Loop Current (Ednoff, 1974, (Fig. 6) was observed in the Straits of Florida in August. At the time that the bloom was observed, a large, anticyclonic eddy was in the process of detaching from the main Loop Current. Large numbers of R. alata were observed in the area where the cold, deeper waters were rising to form a thermal ridge that eventually separated the eddy from the main flow. The phytoplankton bloom may have developed in response to vertical advection of nutrients (Ednoff, Iverson, Maule, in ms.). An alternative hypothesis is that the R. alata maximum was advected from some source upstream. Surface salinity was reduced where R. alata numbers were maximum. Vargo (1968) suggested that the Loop Current advection was an important source of phytoplankton for the Straits of Florida. A red tide, observed along the southeast Florida coast, was probably caused by entrainment of G. breve in Loop Current water along the West Florida coast, followed by advection of G. breve through the Straits of Florida (Murphy et al., 1975). Convergences caused by meander motion (Chew, 1974) and small-scale mixing by spin-off eddies (Lee, 1975) can concentrate materials such as phytoplankton. Maximum integrated chlorophyll values were reported (El-Sayed, 1972) in areas where the Loop Current is characteristically located (Fig. 1). A recent investigation of large-scale features of the eastern Gulf of Mexico have revealed considerable color structure associated with the Loop Current and with eddies which have spun off the Current (Mueller, pers. commun.).

4. CAMPECHE BANKS

Cochrane (1962) reported cool surface water along the western flank of the Yucatan current which he considered was caused by current-induced upwelling. Belousov, et al. (1966) identified several biologically active regions in the Gulf of Mexico that were attributed to the effects of upwelling. Phytoplankton production of from 500 - 1000 mg C $m^{-3}$ $d^{-1}$ was reported for the Campeche Bank region. Bogdanov et al. (1968) observed a seasonal cycle in plankton biomass collected on the Campeche Banks with maximum biomass during June, July, and August. The biomass maximum was attributed to increased upwelling related to increased flow through the Yucatan Straits during the summer. Zernova (1969) observed increased phytoplankton numbers in a zone along the left margin of the Yucatan Current on the eastern part of the Campeche Banks. The increase was attributed to the effects of upwelling. This condition is probably reflected in chlorophyll data of El-Sayed (1972), (Fig. 1). Enhanced productivity values ranging from 500 - 1400 mg C $m^{-2}$ $d^{-1}$ were reported for the Campeche region by Kobanova and Baluja (1973). The frequency and magnitude of processes leading to vertical advection of nutrient-rich water around the Campeche Banks is not well understood. There is some indication that the Yucatan Current induces upwelling, but the local conditions are also conducive to Eckman transport. Some of the investigation of this phenomenon would be interesting in view of the region's significance for food web dynamics.

5. WESTERN GULF OF MEXICO

Riley (1938) studied the effects of the Mississippi River on phytoplankton in adjacent coastal waters. High turbidity depressed phytoplankton photosynthesis near the river mouth. The influence of the river was observed in enhanced chlorophyll concentration to about 80 km from the river mouth. Fucik (1974) obtained seasonal chlorophyll data (Fig. 7a) and productivity data (Fig. 7b) in Louisiana coastal water just west of the Mississippi River Delta. The patterns in the data corroborated observations of Thomas and Simmons (1960) who correlated increased spring productivity with the increase of spring river discharge.

The results of the Bureau of Land Management/Outer Continental Shelf Environmental Assessment Program Study/South Texas Outer Continental Shelf (BLM OCSEAPS STOCS) phytoplankton investigation were summaried by Kamykowski and Van Baalen (1979). The south Texas shelf was divided into three sections based upon salinity-chlorophyll correlations. Texas rivers dominated the nearshore region out to 14 nmi, and between 15 and 32 nmi, two mixing zones occurred. An inner zone was primarily Texas river water, while an outer zone was primarily influenced by Mississippi River water. Between 32 and 38 nm, the Mississippi River was the only source of fresh water. Surface chlorophyll increases were related to decreases in salinty beyond 32 nmi. Phytoplankton biomass exhibited a strong seasonal cycle nearshore which decreased in intensity offshore. Netphytoplankton changes were the primary cause of the seasonal cycle (Figs. 8, 9, 10).

The Mexican Current (Sturges and Blaha, 1976) is the most prominent feature of the western Gulf of Mexico. Very little information is available on the phytoplankton associated with the current. In a manner analogous to the situation in the Gulf Stream (Yentsch, 1974), we might expect to see some enhancement of productivity in the left edge of the Mexican Current caused by cross-stream transport of nutrient-rich water into the photic zone. Vertically integrated chlorophyll values were a relative maximum in regions through which the current passed (Fig. 1), although there is no evidence that the data were taken within the region of influence of the current.

Hurricanes may influence primary productivity in the Gulf of Mexico. Franceschini and El-Sayed (1968) observed increased chlorophyll concentrations in the wake of Hurricane Inez (1964). Iverson (1977) estimated the spatial scales and magnitude of nutrient transport to the photic zone following Hurricane Hilda (1966). It is not clear that enhanced phytoplankton productivity in hurricane wakes would be of long-term significance for pelagic food webs, however, the effect of hurricanes on zooplankton biomass could be investigated to test that possibility.

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Table 1. Bureau of Land Management-Mississippi/Alabama/Florida (BLM-MAFLA) Data

Average surface concentrations of chlorophyll *a* and the observed range of concentrations ($mg/m^3$) along each transect.

| Season | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Summer | 0.21 | 0.13 | 0.36 | 0.80 |
| (Range) | 0.13-0.31 | 0.10-0.17 | 0.26-0.49 | 0.39-1.48 |
| Fall | 0.47 | 0.31 | 0.12 | 0.33 |
| (Range) | 0.09-1.18 | 0.10-0.57 | 0.03-0.35 | 0.04-1.09 |
| Winter | 0.37 | 0.27 | 0.34 | 0.94 |
| (Range) | 0.22-0.57 | 0.09-0.50 | 0.27-0.36 | 0.54-1.73 |

Average bottom concentrations of chlorophyll *a* and the observed range of concentrations ($mg/m^3$) along each transect

| Season | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Summer | 0.57 | 0.28 | 0.49 | 1.70 |
| (Range) | 0.11-0.86 | 0.26-0.29 | 0.01-0.97 | 0.51-4.37 |
| Fall | 1.90 | 0.63 | 0.22 | 0.27 |
| (Range) | 0.21-4.85 | 0.34-0.95 | 0.11-0.51 | 0.05-0.54 |
| Winter | 0.45 | 1.12 | 0.36 | 0.55 |
| (Range) | 0.21-0.73 | 0.10-3.38 | 0.24-0.45 | 0.28-1.04 |

The average seasonal primary productivity date and the observed range along each transect (mg $Cm^{-3}$ $hr^{-1}$)

| Season | 1 | 2 | 3 | 4 |
|---|---|---|---|---|
| Summer | 9.4 | 7.9 | 8.8 | 7.6 |
| (Range) | 8.1 - 11.8 | 4.3 - 10.9 | 7.7 - 9.3 | 6.3 - 9.1 |
| Fall | 12.0 | 7.3 | 8.3 | 8.7 |
| (Range) | 6.9 - 18.8 | 6.0 - 8.8 | 4.2 - 10.9 | 7.6 - 10.4 |
| Winter | 3.4 | 1.5 | 2.0 | 8.0 |
| (Range) | 2.1 - 4.5 | 1.1 - 2.4 | 1.8 - 2.1 | 6.7 - 13.6 |

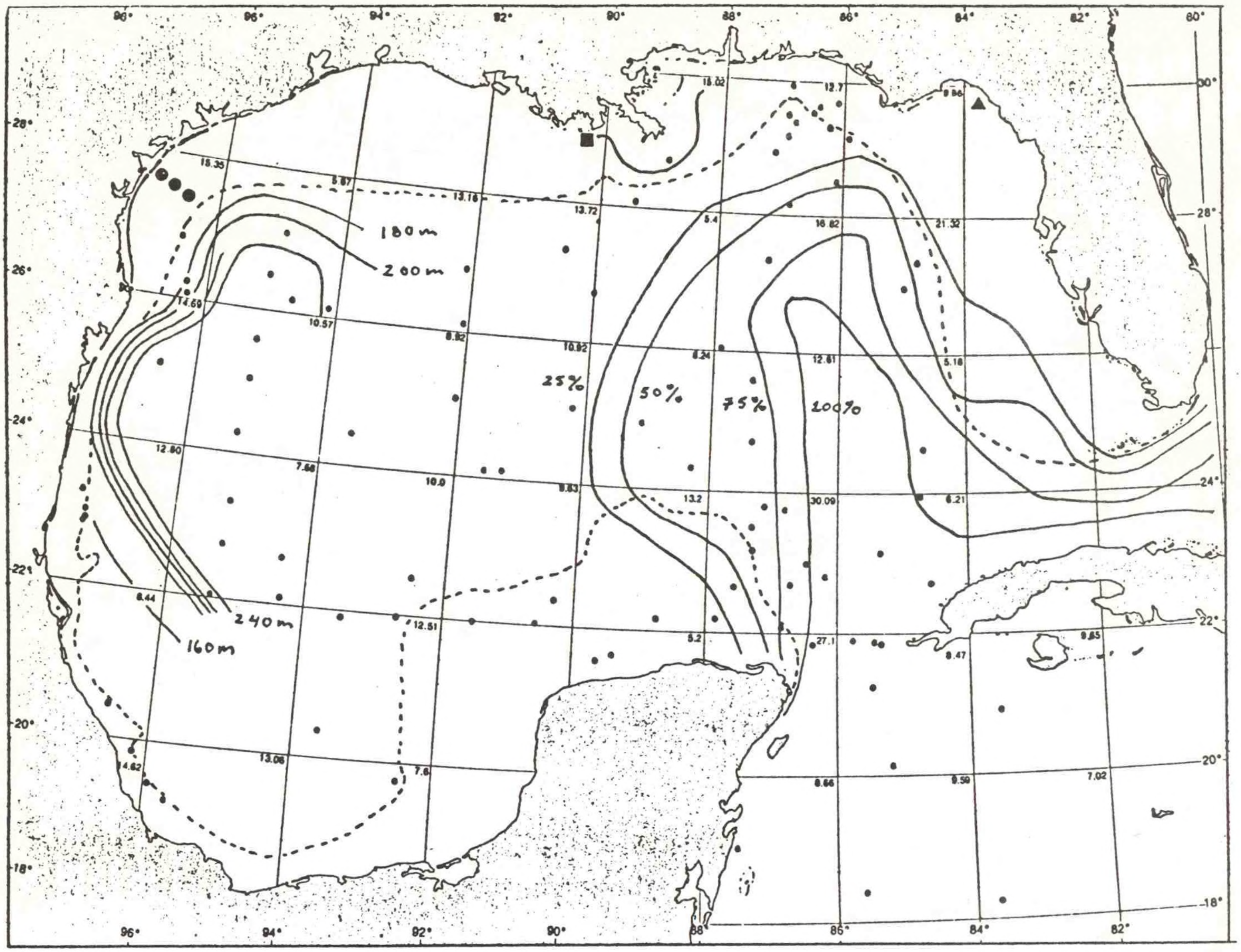



Figure 1. Vertically integrated chlorophyll a (average for each 2 x 2 square) is printed in the corner of each square (El-Sayed, 1972). The depth of the 14$^{O}$ C isotherm indicates the Mexican current location (Sturges, pers com.) The Location of the Loop current on a frequency basis during May was obtained from Vukovich, et al. (1978). The location of probable effects of the Mississippi River on phytoplankton in the Gulf of Mexico is indicated by the isoline estimated from Riley (1938). The 200 meter isobath is indicated by the dashed line. Sampling locations of Fucik (1974), ■ and Bittaker (1975) ▲ . Location of STOCS Transect II stations 1,2,3 ● .

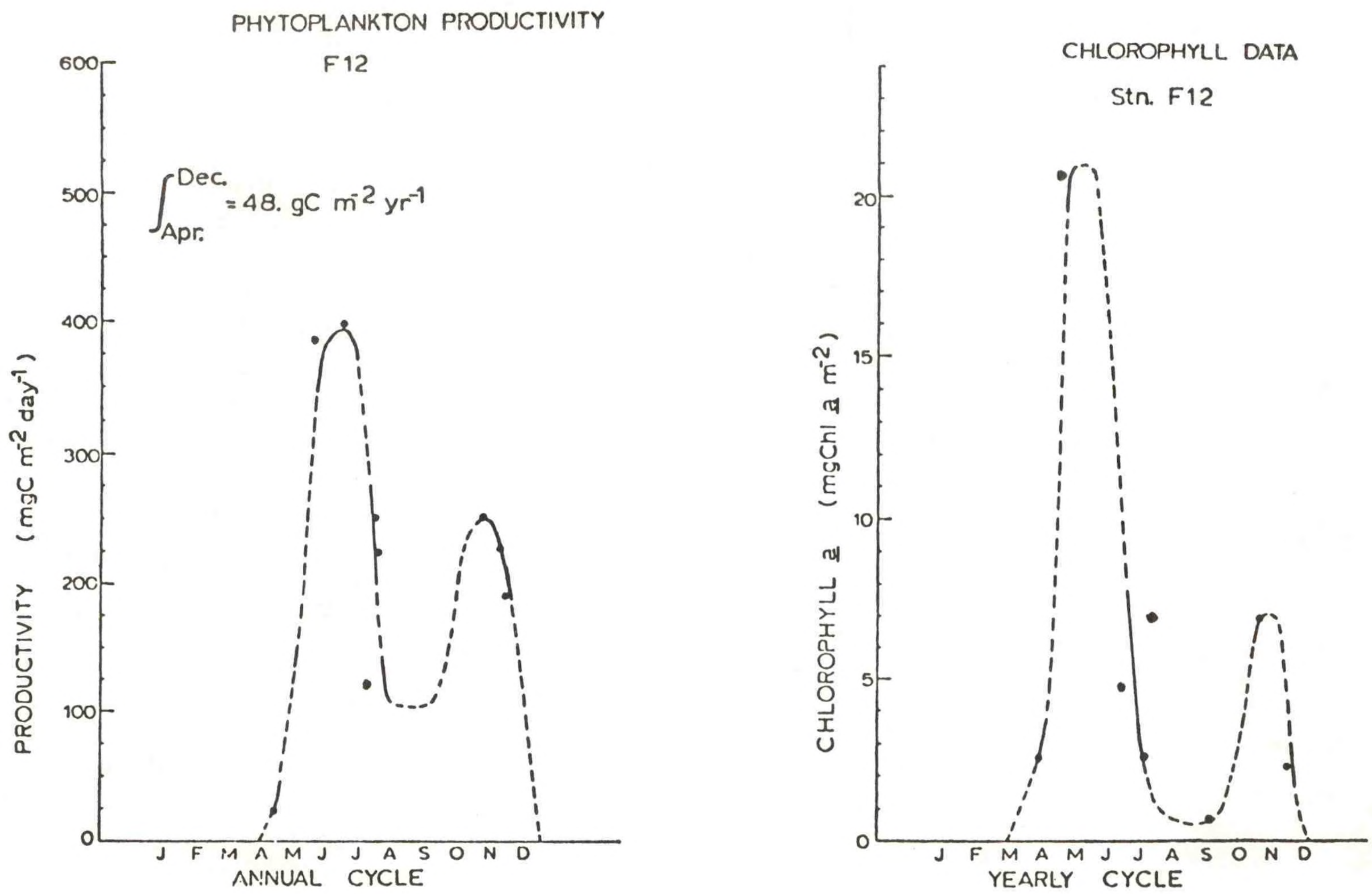



Fig. 2. Data collected 5 miles off the Fenholloway River, north Florida. (From Bittaker, 1975, with permission of the author.)

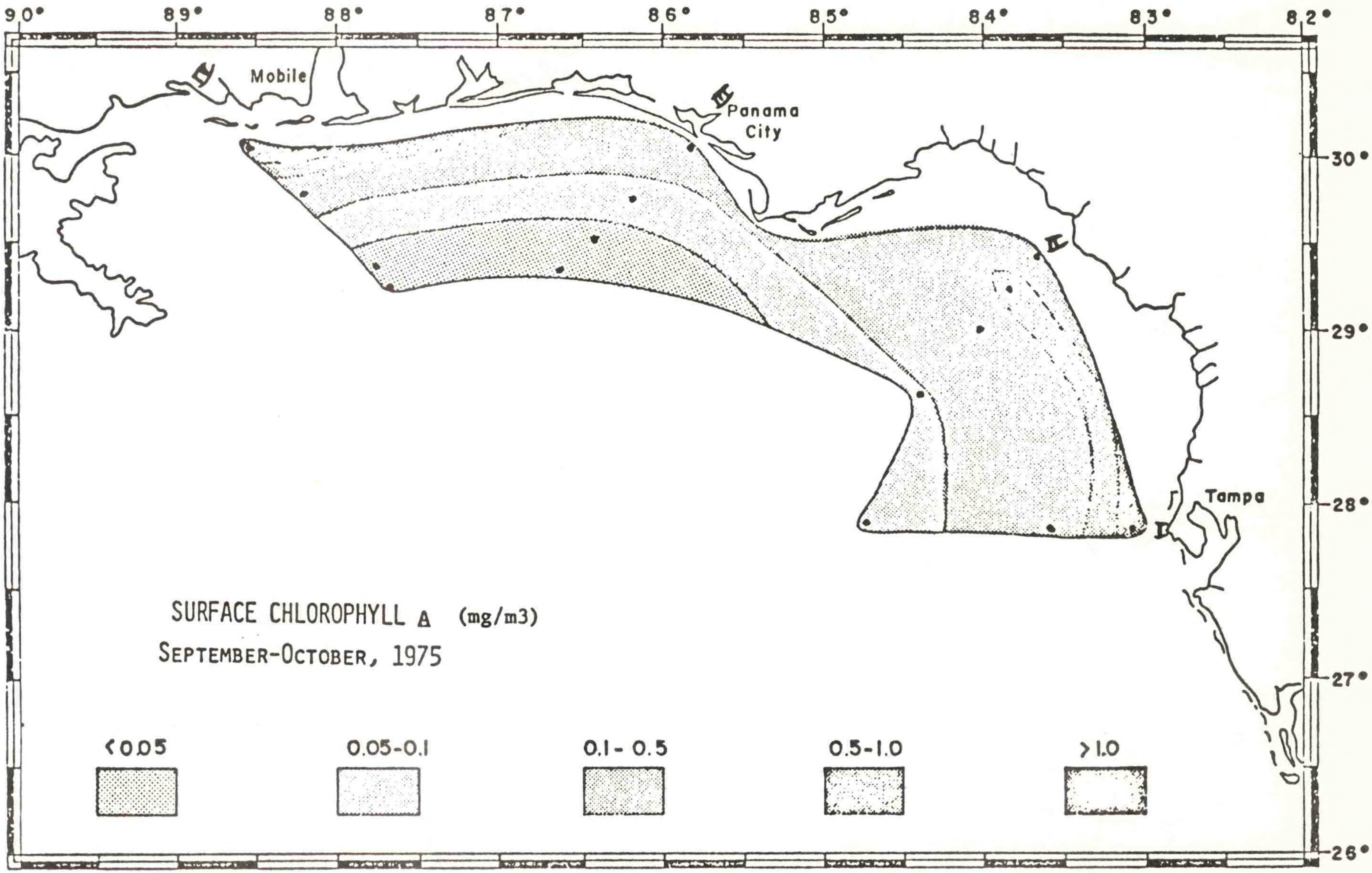



Fig. 3. MAFLA data. (From Iverson and Woodmansee, unpublished.)

Figure deleted because copyright clearance was not received by press time.

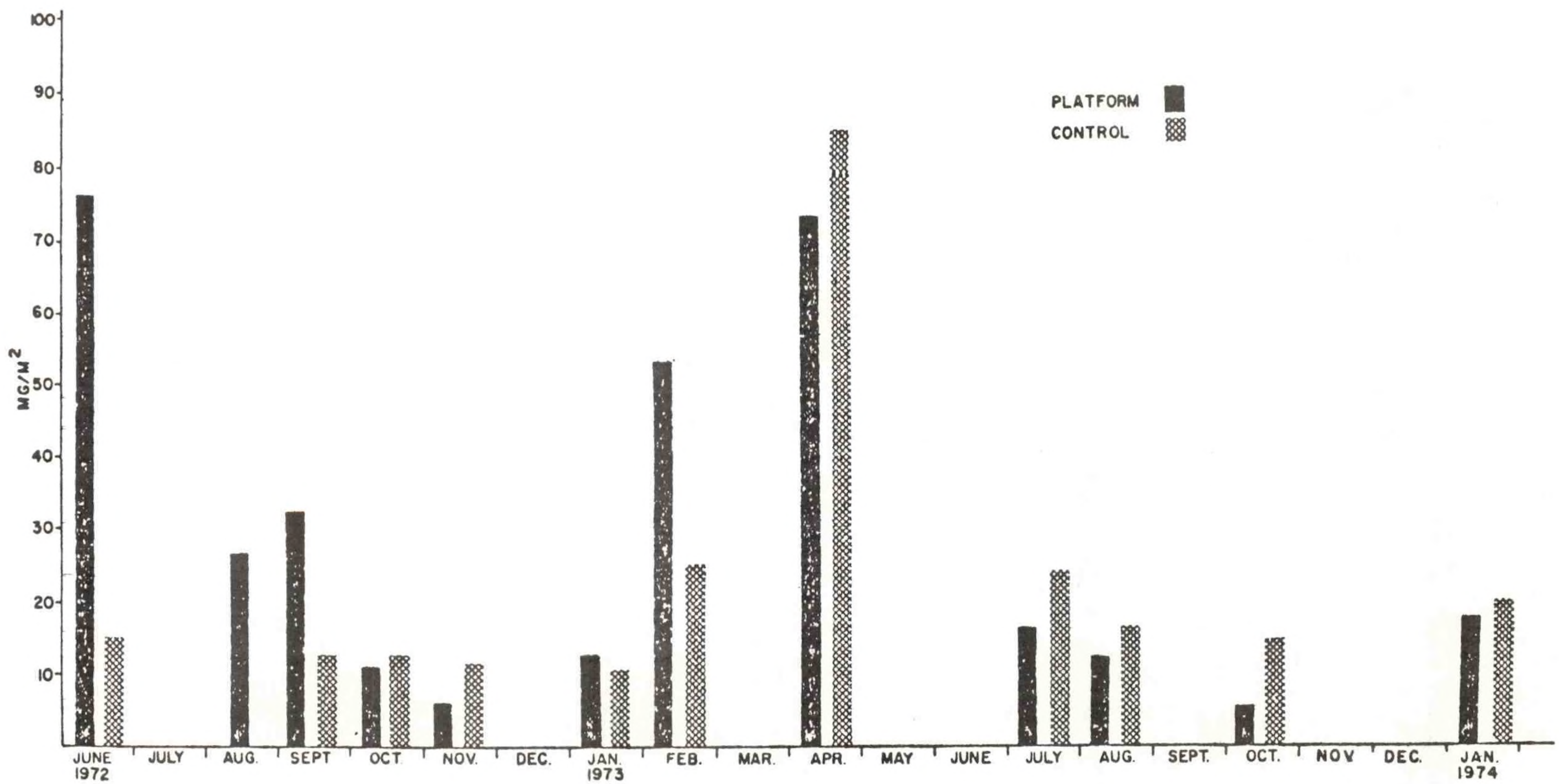
Fig. 4. Pýtoplankton maxima in the left edge of the Loop Current. See Fig. 5 for location. (From Ednoff, 1974.)

Figure deleted because copyright clearance was not received by press time.

Fig. 5. Location of transects across the Loop Current. Solid line indicates the location of the Loop Current during July, 1973. (From Ednoff, 1974.)

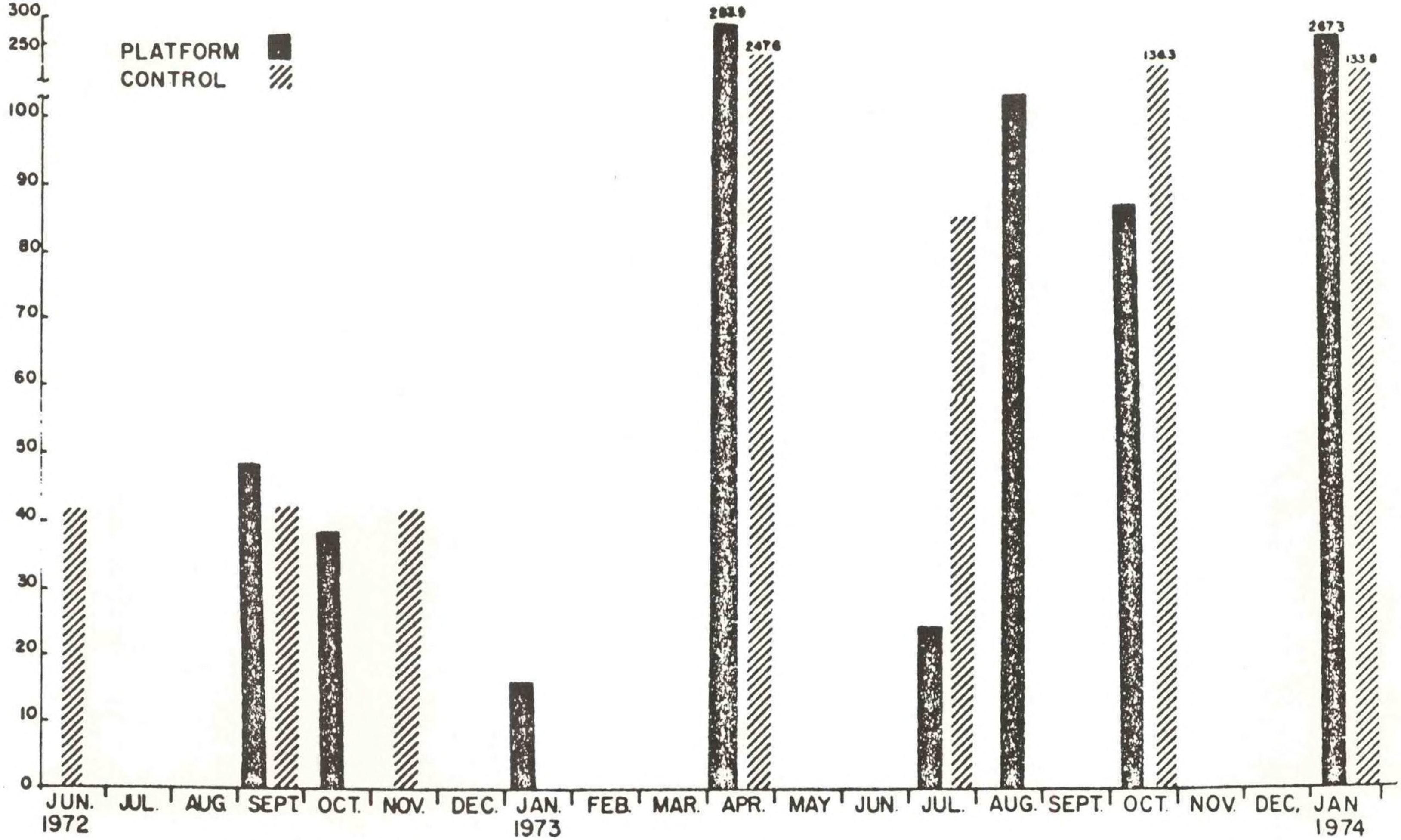
Figure deleted because copyright clearance was not received by press time.

Fig. 6. Phytoplankton maxima in the left edge of the Loop Current during eddy formation. (From Ednoff, 1974.)




**The monthly variation in the integrated phytoplankton standing crop (mg chl. a/m$^3$) at the Platform and Control stations during the period June, 1972 to January, 1974.**

Fig. 7. Data obtained near the Mississippi Delta.
(From Fucik, 1974, with permission of the author.)




The seasonal variations in the monthly integrated $C^{14}$ uptake (mg $C/m^2/hr$) at the Platform and Control stations for the period June, 1972 to January, 1974.

Fig. 7. Data obtained near the Mississippi Delta. (From Fucik, 1974.)

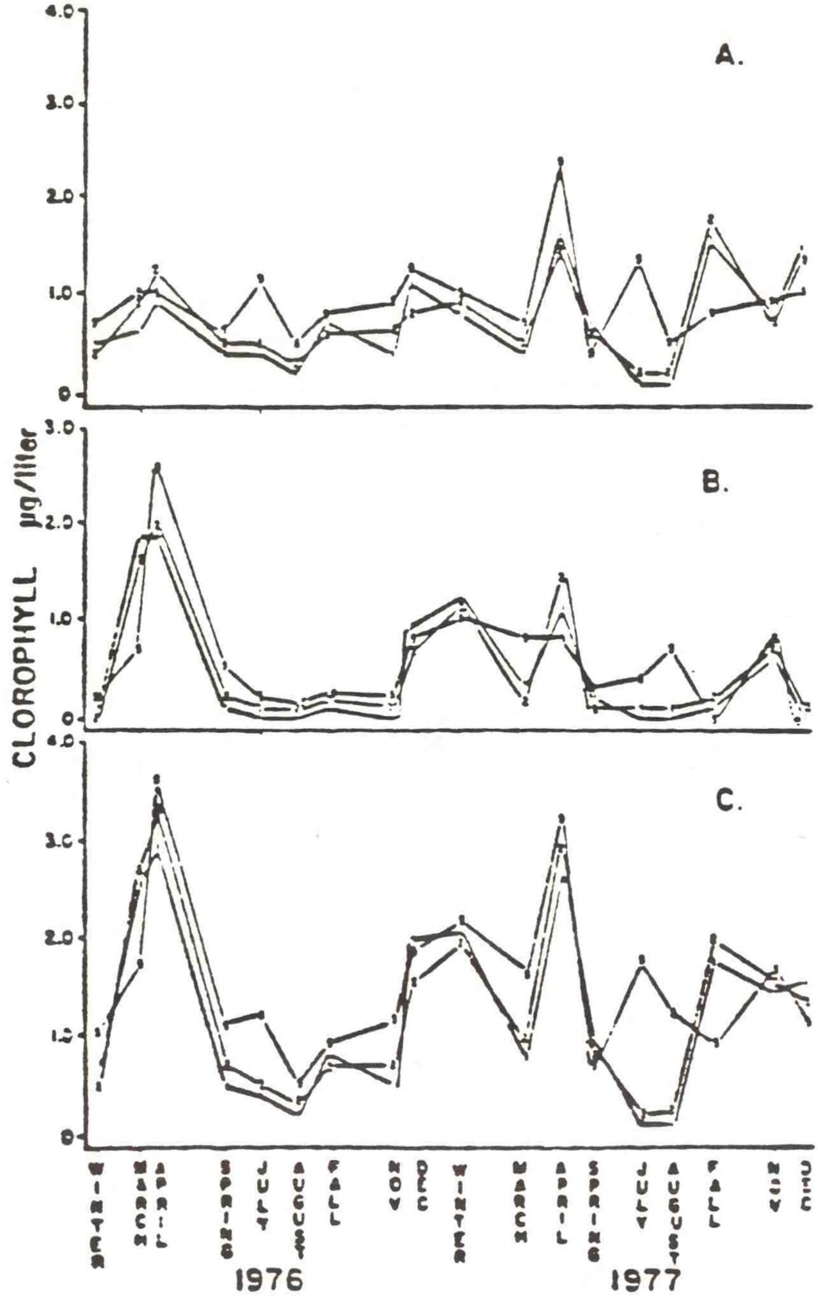



**Figure 7.1** Station 1 Chlorophyll a (mg/m³) at the Surface (1), Half the Depth of the Photic Zone (2) and Bottom (5) in the a) Nanno, b) Net, and c) Total Categories Plotted Against Julian Day.

Fig. 8. Bureau of Land Management/Outer Continental Shelf Environmental Assessment Program Study/South Texas Outer Continental Shelf data. (From Kamykowski, 1979.)

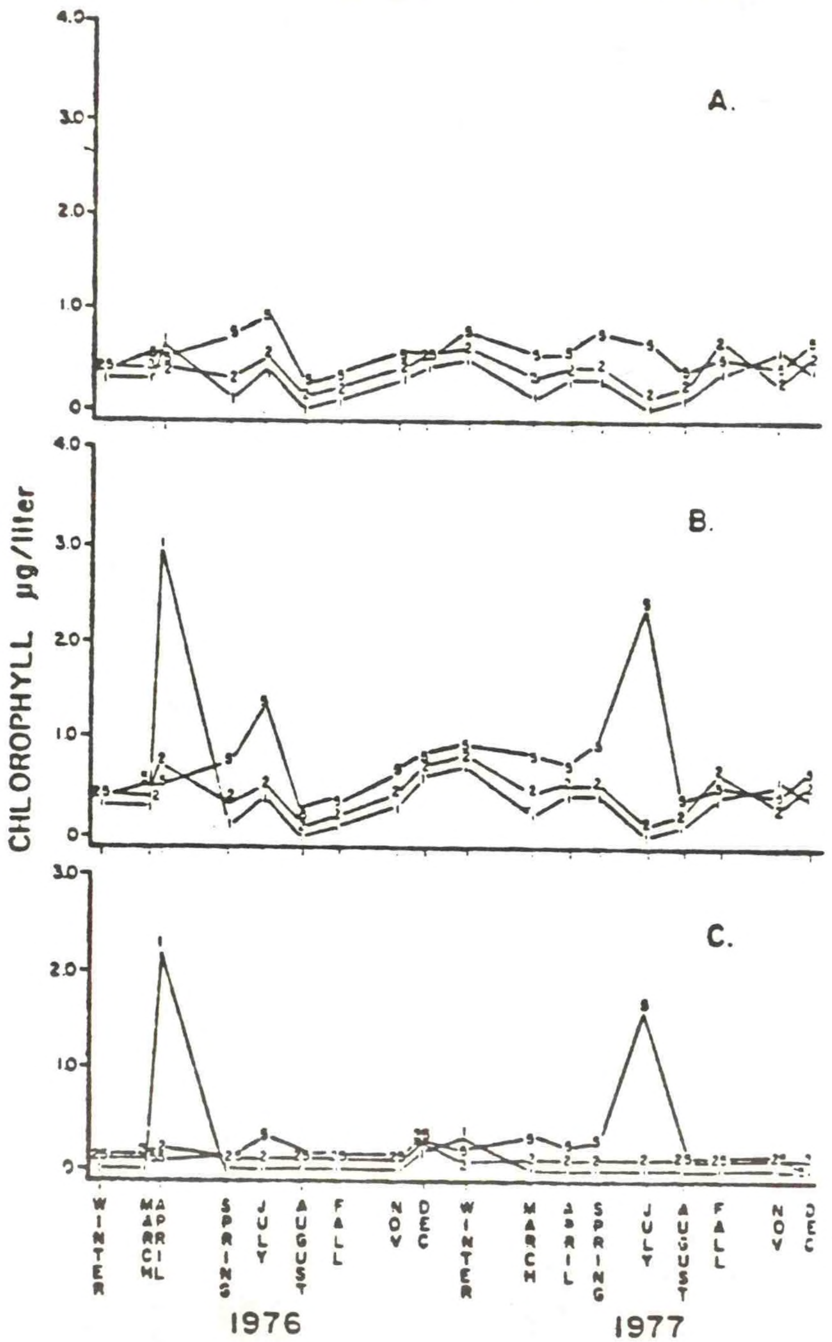



**Figure 7.2 Station 2 Chlorophyll a (mg/m³) at the Surface (1), Half the Depth of the Photic Zone (2), and Bottom (5), in the A) Nanno, B) Net, and C) Total Categories Plotted Against Julian Day.**

Fig. 9. Bureau of Land Management/Outer Continental Shelf Environmental Assessment Program Study/South Texas Outer Continental Shelf data. (From Kamykowski, 1979.)

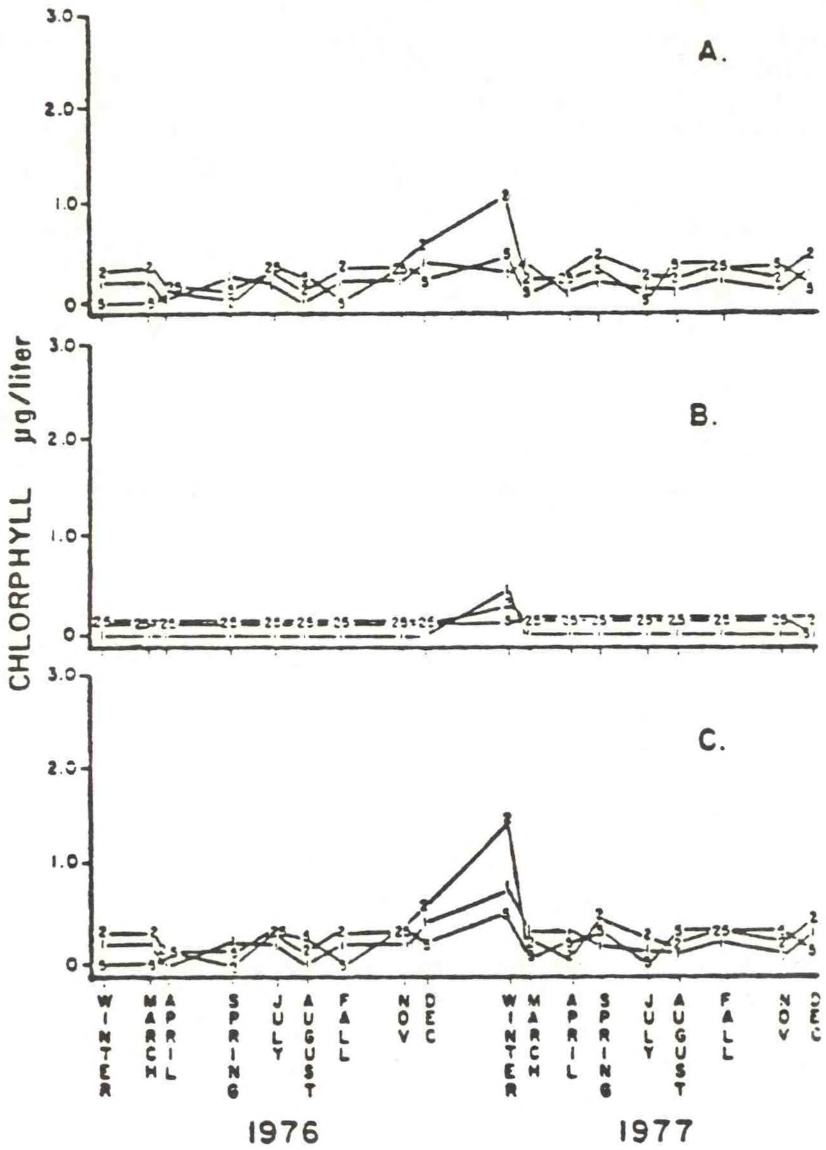



**Figure 7.3** Station 3 Chlorophyll a ($mg/m^3$) at the Surface (1), Half the Depth of the Photic Zone (2), and Bottom (5), in the A) Nanno, B) net, and C) Total Categories Plotted Against Julian Day.

Fig. 10. Bureau of Land Management/Outer Continental Shelf Environmental Assessment Program Study/South Texas Outer Continental Shelf data. (From Kamykowski, 1979.)

## 1. SUMMARY OF RECENT ZOOPLANKTON RESEARCH ON SHELF AND CENTRAL GULF OF MEXICO WATERS

Zooplankton research in Gulf of Mexico waters has been reviewed recently by Bjornberg (1971) and Hopkins (1973). This present report summarizes the principal work done in shelf, slope, and open-Gulf regions subsequent to these reviews. Most of the recent studies can be classified as (1) published systematic works, (2) advanced degree theses treating various aspects of zooplankton systematics and ecology, (3) Office of Naval Research (ONR) funded research to study relationships between zooplankton distribution and water masses in the Caribbean and adjacent areas (including four stations in the eastern Gulf; Michel and Foyo, 1976), (4) the extensive Bureau of Land Management (BLM) funded research in shelf waters over oil lease sites, (5) zooplankton investigations supported by the Department of Energy (DOE) at proposed offshore power plant locations (Ocean Thermal Energy Conversion (OTEC)) over the continental slope, and (6) National Science Foundation (NSF) funded research on the pelagic food chain in the east central Gulf.

Except for the systematic works (e.g., Park, 1974, 1975a, b, c, d, 1976a; Turner et al., 1979) most of the material remains in the form of unpublished theses and data reports to Government agencies. Little has appeared in refereed journals. Considering time restrictions and lack of travel monies for the extensive library searching required to locate the more inaccessible reports, the present summary will concentrate on the readily available information pertaining to items 4, 5, and 6 above.

## 2. SHELF RESEARCH (BLM)

BLM-supported research on zooplankton involved year around sampling and, in some locations, spanned at least three years. Principal efforts were in the vicinity of oil lease sites of the Texas, Mississippi, Alabama, and Florida coasts (Figs. 1 and 2). Sampling rationale and strategy varied, however, from one region to the next. The reports to BLM from the various groups involved ran to thousands of pages and some of the summary reports on plankton as of this writing are not yet in final form. Only selected information from reports which could be located, and from those revealing major trends, will be treated here.

Despite variations in sampling strategy in the BLM-sponsored Texas and Mississippi/Alabama/Florida (MAFLA) programs, plankton analyses did reveal overall similarities in taxonomic composition in that small copepods predominate in net catches over the shelf (Tables 1 and 2). Results from the Texas study (Park, 1975e, 1976b) based on day-night oblique tows with 233 μ mesh nets show Paracalanus, Clausocalanus and Acartia to be the principal genera overall, with proportions changing across the shelf. Towards the outer shelf, cyclopoids of the genera Farranula, Oithona and Oncaea also contributed significantly (Table 3). Copepods were predominant (Fig. 3) although ostracods (Euconchoecia), mollusks, chaetognaths, and larvaceans were relatively abundant. Patterns across the shelf show predictable trends (Table 2, Figs. 2 and 3) in that zooplankton biomass and numbers decreased from near to offshore, while species diversity increased seaward. Biomass, for instance, decreased from an average of 35.1 to 9.2 mg ash-free dry weight $m^{-3}$ and total zooplankton numbers from 2757 to 760 $m^{-3}$. The species diversity index (H) increased offshore from 2.54 to 3.78. Catch variability was high with replicates differing by as much as a factor of 2. Seasonal analysis shows greatest annual amplitudes at nearshore stations, and seasonal variations decreasing offshore. Winter levels were generally lowest.

Seventy-μ mesh collections were also part of the BLM Texas shelf study, these having been analyzed for shelled microzooplankton. Spumellarian radiolarians were dominant inshore, whereas nassellarians increased in percentage offshore (Fig. 4). Also, radiolarian density and diversity generally increased seaward. Casey (1976a, b) was able to use radiolarian abundance, species composition, and diversity to identify regions of deep water upwelling and spillover onto the Texas shelf (Figs. 5-7).

The BLM-MAFLA effort was more concerned with characteristics of zooplankton populations in immediate lease site areas than with general distribution patterns over the shelf. Maturo's (1975) group statistically tested abundance patterns, based on 202-μ mesh net collections, of various indicator groups and species at lease sites against physical and chemical parameters. While significant differences were noted among lease sites and for stations of different depths (probably related to distance offshore), little correlation was found among zooplankton patterns and the various organic and trace metal chemicals assayed. It is worth mentioning that our group (Baird et al., 1975) and Giam et al., (1972, 1973) did find measurable amounts of pesticides (DDT and derivatives, dieldrin) and PCB's (Table 4) in zooplankton and midwater fishes in the east central Gulf of Mexico. In view of their occurrence in deep dwelling, nonmigratory hatchetfishes, pesticides and PCB's appear to move vertically downwards through the food web, presumably in the manner described by Vinogradov (1962). The findings of Mathews et al. (1973) on fallout $C^{14}$ in midwater fishes in the central Gulf suggest the same.

## 3. SLOPE WATERS (DOE)

Zooplankton work supported by DOE was initiated in the Gulf in 1977. Sampling was at proposed offshore power plant (OTEC) sites over the continental slope at 29°N 88°W off Mobile Bay and 27°38'N 85°34'W adjacent to Tampa Bay. Net (202-μ mesh) collections from both locations (Hopkins et al., 1979; Steen, 1977, 1978) show much the same pattern in the upper layers (0-200 m; Table 5) as at outer shelf locations of the BLM Texas program; i.e., predominance of small calanoids (e.g., *Paracalanus*, *Clausocalanus*) and cyclopoids (*Farranula*, *Oncaea*, *Oithona*). Samples from deeper layers show changes in dominance with larger copepods (e.g., *Eucalanus*, *Rhincalanus*, *Pleuromamma*) contributing significantly. Also, other groups such as euphausiids were more conspicuous than at shelf stations because of water depth (approximately 1000 m) and proximity to the central oceanic Gulf. Sampling in the upper 25 m was carried out both day and night, and OTEC sites were occupied bimonthly throughout the year. Because of patchiness effects and lack of replication, however, diurnal and seasonal trends have not emerged from OTEC analyses.

The size distribution of 202-μ mesh catches at the Tampa OTEC site (Fig. 8) usually shows a maximum in the 1-3 mm size range. This is most pronounced in 0-25 m samples. There is a strong secondary peak in the 9-10 mm class in this zone at night, primarily the result of larger crustaceans (*Lucifer*, *Euphausia*) appearing in catches during hours of darkness.

Biomass data from the Tampa site reveal the expected decrease with increasing depth. Average daytime displacement volumes for the 0-200 m, 200-800 m, and 800-1000 m zones are 6.17, 1.71 and 0.71 mℓ 100 $m^{-3}$, respectively. The mean cumulated biomass value for the upper 1000 m is 21.9 mℓ $m^{-2}$.

4. CENTRAL GULF RESEARCH (NSF)

This effort is essentially a food chain study involving intensive sampling and analysis of the pelagic ecosystem at a single reference station. The objectives center on investigating the feeding ecology of the principal species of mesopelagic fishes and shrimps. To achieve this abundance, species composition and diurnal movements of both micronektonic predators and zooplankton prey have been determined. In conjunction with this, there has been extensive analysis of the principal micronekton species. The location in the east central Gulf (27°N 86°W) was selected because, in this vicinity, both hydrographic and biological features were judged characteristic of tropical-subtropical gyres in general which account for a major portion of the ocean areas, and, hence, a major ecosystem. Sampling has been at 20 horizons in the upper 1000 m and concentrated in the warmer months (May-October). Plankton nets were of 162-μ mesh, collapsible, and fished in the mouth of closing Tucker trawls (Fig. 9). Smaller zooplankton were taken with 30-ℓ bottles, the water being sieved through 30-μ gauze. All collections from the standard stations discussed here were from loop "transition" water (Fig. 10), which has a typical summer temperature trace as indicated in the expendable bathythermograph (XBT) record shown in Figure 11. A Loop Current trace is included for comparison.

Diurnal patterns of zooplankton numbers and biomass in the upper 1000 m are in Figures 12 and 13. Apparent, especially in the biomass data, is the increase in the upper 50 m at night and in the 300-600 m zone in the day, presumably the result of diurnal vertical migration of a significant fraction of the zooplankton. As Vinogradov (1968) and others have found, plankton abundance falls off exponentially with depth, the greatest rate of decrease in temperate-tropical latitudes occurring in the upper 200 m. For example, day-night biomass averaged 568 mg dry wt 100 $m^{-3}$ at 50 m, 119 mg at 200 m and only 26 mg at 1000 m.

Our 30-ℓ bottle collections (Fig. 14) reveal the inadequacy of even relatively "fine" 162-μ mesh nets in sampling the smaller zooplankton, especially that <1 mm in length. In the upper 200 m, bottle-caught plankton <1 mm averages 10 times the number and one-third the biomass of 162-μ net plankton. Below 200 m, as is the case of net plankton, 30-ℓ catches fell off sharply, although they retained approximately the same abundance and biomass ratios in relation to net collections.

As Park (1975e) found in replicate sampling of waters over the Texas shelf, and as is virtually axiomatic for all oceanic plankton collecting, catch variability, primarily the result of patchiness, was high. Table 6 shows that max/min values for abundant copepod species taken in a series of night surface tows range from over an order of magnitude (21) to over two orders (210) of magnitude.

As at the Tampa OTEC location over the slope, zooplankton composition and relative proportions of taxonomic categories change markedly with depth. The principal zooplankton groups, in terms of biomass as related to depth zones, are in Table 7. Copepods typically are predominant, although other groups such as chaetognaths, tunicates, and hydromedusae, proportionately make a significant contribution in the upper 200 m. Euphausiids also contribute significantly to biomass in the upper 200 m, especially at night and in the 300-500 m zone during the day. In deeper layers, however, below 500 m, both night and day copepod percentages were consistently above 70% (Table 8).

Genera exceeding 5% of the biomass of net caught zooplankton in selected depth zones in the upper 1000 m are in Table 9. In the shallowest zone considered (S-30 m), with the exception of Euphausia, small copepods (e.g., Clausocalanus, Undinula, Farranula) are important. In intermediate layers (100-800 m) Pleuromamma is a consistent dominant, and in the 500-1000 m zone, Eucalanus is obviously important. Euphausia is also one of the principal genera in the S-30 m layer at night and in the 200-500 m zone during the day. Euphausiids in general (Nematoscelis, Stylocheiron, Euphausia) make their greatest contribution in the 100-200 m range at night. Biomass of the principal zooplankton genera integrated over the upper 1000 m (i.e., those genera exceeding 1% of total biomass) is shown in Table 10. Those individually exceeding 5% of the biomass are Eucalanus, Clausocalanus, Pleuromamma, and Euphausia. The genera in Table 10 constitute about half (52.5%) of the net-caught biomass in the upper 1000 m at 27°N 86°W.

The above taxa obviously play a major role in the trophic-dynamics of the central Gulf. The principal micronektonic shrimps and fishes, in terms of both numbers and biomass potentially foraging on these genera, are listed in Table II. These deserve inclusion here since, as Brooks and Dodson (1965) indicate, these predators regulate the abundance and, ultimately, species composition of oceanic plankton. Analysis of thousands of digestive tracts indicate that while there is subtle time-space partitioning of zooplankton prey resources (Table 12), there is much overlap in diets of micronekton species. For instance, seven species of midwater fishes (Table 12) all foraged heavily on the copepod genus Pleuromamma. Also, our recent findings indicate this genus plays an important role in the diet of Gennadas shrimps. Foxton and Roe (1974) found, as well, that in the eastern Atlantic Pleuromamma was important in the forage of Sergestes pectinatus, Gennadas valens, Systellaspis debilis, and Acanthephyra purpurea, all of which are abundant shrimps in the eastern Gulf. Additional pressure is put on certain planktonic genera through selective predation. For instance, Ivlev (1961) indices strongly suggest selective feeding on Pleuromamma spp. by Valenciennellus tripunctulatus and Lampanyctus alatus and on Candacia spp. by Gennadas valens. The zooplankton most heavily impacted by the micronektonic fishes we have examined from the central Gulf are 1-4 mm copepods (e.g., Fig. 15). Also, gut analyses of both V. tripunctulatus and L. alatus reveal, as others have found for a number of other midwater fishes (see review by Hopkins and Baird, 1977; Clarke, 1979), that these species feed in a diurnally cyclic pattern, thus varying the impact on the zooplankton population over the diel period.

It is apparent from Figures 12 and 13 and Tables 7 and 9 that a significant portion of the zooplankton and micronekton in the east-central Gulf undergo diurnal vertical migration. An obvious postulate would be that day-night depth levels and the extent of diurnal vertical movement would determine to a large degree the distribution of oceanic species over the continental shelf. Table 13 shows the day-night vertical distribution of abundant or indicator species in the upper 1000 m at our reference site in the eastern Gulf and their occurrence over the Florida shelf adjacent to Tampa Bay (Fig. 16). In general, there seems to be reasonably good agreement between vertical patterns of zooplankton and occurrence over the shelf. This relationship is even more evident in the abundant micronektonic fish and shrimp species.

Cumulated values over the upper 1000 m (Table 7 and Figs. 12 and 13) show little difference in day versus night biomass and numbers per square meter. Dry weight data from net collections, however, indicate that taxonomic composition of the catch varies diurnally, the principal difference resulting from a greater copepod catch during the day and euphausiid catch at night. The mean value, 1.2 g $m^{-2}$, is about half that estimated for the OTEC slope location adjacent to Tampa Bay (i.e., 21.9 mℓ x 0.1 = 2.19 mg dry wt). This zooplankton biomass, which perhaps "turns over" once every 30-90 days, is supported by a productivity estimated from our and El-Sayed's (1972) data of 25-45 g C/$m^2$ $y^{-1}$. This is a low rate of production in reference to Ryther's (1969) classifications and, while little comparable data is available for the upper 1000 m (see Vinogradov, 1968 and Hopkins, 1971), it is suggested that zooplankton biomass in the east central Gulf is also relatively low. Further, except possibly in local regions of upwelling (Khromov, 1965; Bogdanov et al., 1969), it is predicted that, barring significant variation in assay techniques, biomass throughout much of the remainder of the central Gulf will be found comparable.

From the foregoing then, it is apparent that we have, primarily through BLM-supported research, a reasonably good picture of species composition and abundance patterns over certain sections of the continental shelf. Also, considerable information is available on abundance and vertical distribution at several locations over the slope and especially at one reference station in the east-central Gulf. While some chemical information (trace metals, hydrocarbons, pesticides) is available on zooplankton in general, scant data are available on whole classes of elements, such as radionuclides, and there is no information on chemical parameters in relation to individual genera or species. Also, virtually absent from the literature is any physiological data for Gulf zooplankton. Finally, while some food chain research has been initiated at 27°N 86°W in the central Gulf (see also Turner's (1978) work on pontellid copepod diets), it is essential to attack the problem of trophodynamics in the neritic and central Gulf on a broad scale if we are to understand the ecology of pelagic communites of the Gulf and to follow the flow of energy and materials (e.g., pollutant chemicals) through the ecosystem.

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Table 1. Average Plankton Abundance at MAFLA Lease Sites (From Maturo, et al., 1975).

Mean zooplankton examples for areas IV and V. Numbers/m3. (Maturo and Woodmansee)

| Category | V | VI | Category | V | VI |
|---|---|---|---|---|---|
| Total Copepods | 9277 | 6527 | *Euchaeta* | 57 | 71 |
| *Paracalanus* | 3036 | 1586 | Siphonophores | 56 | 126 |
| *Acartia* | 2170 | 585 | *Calanus* | 20 | 53 |
| *Corycaeus* | 1699 | 353 | *Pyrocystis* | 19 | 48 |
| *Centropages* | 1320 | 483 | Amphipods | 15 | 29 |
| *Appendicularians* | 742 | - | Hydromedusae | 15 | 10 |
| *Eucalanus* | 701 | 106 | Salps | 14 | 252 |
| *Cladocera* | 497 | 19 | Decapod larvae | 11 | 26 |
| *Oithona* | 388 | 395 | Ostracods | 11 | 10 |
| *Oncaea* | 367 | 496 | *Ceratium* | 7 | 51 |
| *Sagitta* | 341 | 138 | *Lucifer* (decapod) | 4 | 12 |
| Crab zoea | 115 | 49 | Megalops | 4 | 5 |
| Castropod veligers | 112 | 136 | Fish larvae | 2 | 23 |
| Polychaetes | 110 | 45 | Foraminifera | 1 | 2 |
| Pelecypod veligers | 92 | 27 | *Copilia* | 1 | 4 |
| Nauplii | 72 | 39 | Tintinnids | 1 | 2 |
| Other calanoids | 70 | 81 | Egg cases | 0 | 1 |
| Fish eggs | 62 | 57 | Echinoderm larvae | 0 | 1 |
| *Euterpina* | 61 | 20 | *Oikopleura* (tunicate) | 0 | 0 |
| | | | Dry wt. mg/m$^3$ | 189 | 101 |

Table 2. Plankton Distribution (Annual Mean Values) Across Texas Shelf (From Park, 1975e)

| Annual Mean Values of Certain Zooplankton and Other Environmental Data by Station for Entire Study Area | | | |
|---|---|---|---|
| Station | 1 | 2 | 3 |
| Chlorophyll a ($mg/m^3$) | 3.11 | 0.81 | 0.36 |
| Salinity (ppt) | 30.4 | 34.9 | 35.3 |
| Temperature ($^oC$) | 22.6 | 23.6 | 24.6 |
| Ash-Free Dry Wt. ($mg/m^3$) | 35.1 | 17.6 | 9.2 |
| No. of Zoopl. per $m^3$ | 2757.3 | 1558.5 | 759.6 |
| No. of Copepod Species | 17.6 | 30.1 | 46.4 |
| No. of Copepods per $m^3$ | 2146.3 | 830.7 | 534.5 |
| Copepod % of Zoopl. | 75.7 | 63.7 | 70.0 |
| No. of *Acartia tonsa* 88/$m^3$ | 236.15 | 8.3 | 0.4 |
| No. of *Paracalanus parvus* group 88/$m^3$ | 228.2 | 66.8 | 8.4 |
| No. of *Clausocalanus furcatus* 88/$m^3$ | 14.0 | 104.8 | 86.7 |
| No. of Ostracods /$m^3$ | 59.4 | 392.55 | 85.2 |
| Species Diversity Index (H) | 2.5421 | 3.2497 | 3.7797 |
| $E = \frac{H(S)}{H_{Max(s)}}$ | 0.6160 | 0.6712 | 0.6715 |

Table 3. Principal copepod genera along transects across Texas shelf (from Park, 1976b)

Species Totaling 50% of the Female Copepod Population and Their Percentages Ranked in Order of Abundance

SEPTEMBER CRUISE

| Transect | Station 1 | | Station 2 | | Station 3 | |
|---|---|---|---|---|---|---|
| I | Temora turbinata | 37.8 | Oncaea venusta | 27.3 | Clausocalanus furcatus | 39.0 |
| | Paracalanus indicus<br>Paracalanus quasimodo | 34.9 | Paracalanus indices<br>Paracalanus quasimodo | 15.8 | Oithona plumifera | 19.7 |
| | | | Paracalanus aculeatus | 14.3 | | |
| | TOTAL | 72.7 | | 57.4 | | 58.7 |
| II | Tempora turbinata | 56.6 | Clausocalanus furcatus | 33.3 | Clausocalanus furcatus | 29.5 |
| | | | Farranula gracilis | 25.2 | Oncaea venusta | 14.6 |
| | | | | | Oncaea mediterranea | 10.2 |
| | TOTAL | 56.6 | | 51.0 | | 54.3 |
| III | Paracalanus indicus<br>Paracalanus quasimodo | 56.6 | Clausocalanus furcatus | 33.3 | Clausocalanus furcatus | 28.3 |
| | | | Oncaea venusta | 16.2 | Farranula gracilis | 26.3 |
| | | | Farranula gracilis | 10.7 | | |
| IV | Clausocalanus furcatus | 42.3 | Clausocalanus furcatus | 42.7 | Clausocalanus furcatus | 29.4 |
| | Oncaea venusta | 22.8 | Farranula gracilis | 19.6 | Farranula gracilis | 22.1 |
| | TOTAL | 65.1 | | 62.3 | | 51.5 |

Table 4. Occurrence of certain pesticides and PCB's in zooplankton and mesopelagic fishes in Eastern Gulf of Mexico. (From Baird et. al., 1975.)

Species, size distribution, migratory pattern, and concentration of chlorinated hydrocarbons in deep sea zooplankton and 1052 fishes of the Gulf of Mexico (M = vertical migrator; N = no extensive vertical migration.)

| | | | | | | WET WEIGHT | | | | | | LIPID WEIGHT | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Station* | Depth (m) | Species | Number Individuals Processed | Mean Std. Length (mm) | Std. Length Range (mm) | DDE (ppm) | DDD (ppm) | DDT (ppm) | Dieldrin (ppm) | Total DDT (ppm) | 1254 Aroclor (ppm) | DDE (ppm) | DDD (ppm) | DDT (ppm) | Dieldrin (ppm) | Total DDT (ppm) | 1254 Aroclor (ppm) |
| 1 | 00-160 | *Notolychnus valdiviae* (M) | 190 | 19 | 13-22 | - | 0.002 | - | 0.057 | 0.002 | 0.224 | - | 0.034 | - | 0.818 | 0.034 | 3.239 |
| 1 | 100-160 | *Gonostoma elongatum* (M) | 15 | 38 | 29-59 | - | - | 0.016 | - | 0.016 | 0.316 | - | - | 2.143 | - | 2.143 | 42.857 |
| 1 | 100-160 | *Ceratoscopelus warmingi* (M) | 20 | 37 | 21-59 | - | 0.004 | - | 0.026 | 0.004 | 0.065 | - | 0.198 | - | 1.385 | 0.198 | 3.463 |
| 1 | 290-380 | *Cyclothone braueri* (N) | 93 | 19 | 12-26 | - | 0.015 | - | 0.038 | 0.015 | 0.375 | - | 1.339 | - | 3.348 | 1.339 | 33.482 |
| 1 | 100-160 | *Lepidophanes guentheri* (M) | 6 | 47 | 38-57 | - | 0.004 | - | 0.004 | 0.004 | 0.085 | - | 0.054 | - | 0.476 | 0.544 | 10.870 |
| 1 | 100-160 | Myctophidae (6 species) (M) | 34 | 28 | 17-56 | - | 0.002 | - | 0.009 | 0.002 | 0.146 | - | 0.205 | - | 0.676 | 0.205 | 10.518 |
| 1 | 330-380 | *Argyropelecus hemigymnus* (N) | 27 | 24 | 10-30 | - | 0.015 | - | 0.018 | 0.015 | 0.350 | - | 1.539 | - | 1.795 | 1.539 | 35.897 |
| 1 | Surface | *Gonichthys coccol* (M) | 10 | 24 | 18-28 | - | - | 0.017 | - | 0.017 | 0.583 | - | - | 0.606 | - | 0.606 | 21.212 |
| 1 | 100-160 | Plankton | - | - | - | - | 0.001 | 0.003 | - | 0.002 | 0.040 | - | 0.042 | 0.253 | - | 0.295 | 3.370 |
| 2 | 60-130 | *Notolychnus valdiviae* | 48 | 19 | 13-22 | 0.014 | 0.088 | 0.060 | 0.120 | 0.162 | 0.926 | 0.201 | 1.272 | 0.870 | 1.740 | 2.343 | 13.387 |
| 2 | 110-180 | *Gonostoma elongatum* | 12 | 104 | 64-124 | 0.001 | 0.001 | 0.001 | 0 | 0.003 | 0.032 | 0.386 | 0.429 | 0.429 | - | 1.244 | 15.880 |
| 2 | 60-130 | *Ceratoscopelus warmingi* | 13 | 35 | 27-52 | - | - | - | 0.017 | - | 0.290 | - | - | - | 0.709 | - | 11.827 |
| 2 | 550-760 | *Cyclothone* spp. (4 species) (N) | 154 | 27 | 12-50 | 0.001 | - | - | 0.001 | 0.001 | 0.026 | 0.171 | - | - | 0.159 | 0.171 | 4.209 |
| 2 | 60-130 | *Lampanyctus alatus* (M) | 60 | 38 | 25-50 | 0.002 | - | - | - | 0.002 | 0.002 | 0.013 | - | - | - | 0.013 | 15.152 |
| 2 | 60-130 | *Benthosema suborbitale* (M) | 23 | 26 | 18-32 | - | 0.007 | - | 0.013 | 0.007 | 0.133 | - | 0.213 | - | 0.400 | 0.213 | 4.264 |
| 2 | 60-130 | *Diaphus* spp. (*mollis + lutkeni*) (M) | 8 | 35 | 25-46 | 0.004 | - | - | - | 0.004 | 0.275 | 0.194 | - | - | - | 0.194 | 13.579 |
| 2 | Surface | Plankton | - | - | - | - | - | - | - | - | 0.048 | 0.258 | - | - | 0.619 | 0.258 | 12.887 |
| 3 | 30-75 | *Gonostoma elongatum* | 4 | 154 | 113-200 | 0.002 | 0.002 | 0.005 | 0.001 | 0.009 | 0.040 | 0.430 | 0.430 | 1.289 | 0.172 | 2.149 | 12.027 |
| 3 | 80-120 | *Cyclothone* spp. (4 species) | 129 | 27 | 12-50 | - | 0.002 | - | 0.001 | 0.002 | 0.033 | - | 0.199 | - | 0.099 | 0.199 | 4.313 |
| 3 | 80-120 | Myctophidae (4 species) | 13 | 40 | 28-63 | - | 0.007 | - | 0.017 | 0.007 | 0.158 | - | 0.182 | - | 0.456 | 0.182 | 3.418 |
| 3 | Surface | Plankton | - | - | - | 0.003 | - | - | 0.061 | 0.003 | 0.101 | 3.371 | - | - | 6.742 | 3.371 | 112.359 |
| 4 | 70-130 | *Gonostoma elongatum* | 14 | 103 | 81-120 | 0.0004 | 0.001 | 0.001 | 0.0002 | 0.002 | 0.023 | 0.169 | 1.208 | 1.208 | 0.604 | 2.585 | 9.903 |
| 4 | 490-650 | *Cyclothone* spp. | 123 | 27 | 12-50 | - | - | 0.001 | 0.003 | 0.001 | 0.032 | - | - | 0.169 | 0.395 | 0.169 | 4.794 |
| 4 | 70-130 | *Lepidophanes guentheri* | 12 | 54 | 44-66 | - | 0.006 | - | - | 0.006 | 0.052 | - | 0.628 | - | - | 0.628 | 5.499 |
| 4 | 625-710 | *Lampanyctus alatus* | 10 | 38 | 25-50 | 0.081 | - | 0.055 | - | 0.136 | 0.405 | 7.526 | - | 11.856 | - | 29.382 | 8.763 |
| 4 | 70-130 | *Diaphus dumerili* (M) | 16 | 42 | 26-49 | - | 0.001 | - | 0.010 | 0.001 | 0.033 | - | 0.043 | - | 0.363 | 0.043 | 4.313 |

Table 4. Occurrence of certain pesticides and PCB's in zooplankton and mesopelagic fishes in Eastern Gulf of Mexico. (From Baird et. al., 1975.) (Cont'd)

Species, size distribution, migratory pattern, and concentration of chlorinated hydrocarbons in deep sea zooplankton and 1052 fishes of the Gulf of Mexico (M = vertical migrator; N = no extensive vertical migration.)

| | | | | | | WET WEIGHT | | | | | | LIPID WEIGHT | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Station* | Depth (m) | Species | Number Individuals Processed | Mean Std. Length (mm) | Std. Length Range (mm) | DDE (ppm) | DDD (ppm) | DDT (ppm) | Dieldrin (ppm) | Total DDT (ppm) | 1254 Aroclor+ (ppm) | DDE (ppm) | DDD (ppm) | DDT (ppm) | Dieldrin (ppm) | Total DDT (ppm) | 1254 Aroclor† (ppm) |
| 4 | 70-130 | *Diaphus* spp. | 17 | 37 | 25-49 | - | 0.019 | - | 0.029 | 0.019 | 0.282 | - | 0.908 | - | 1.328 | 0.908 | 12.933 |
| 4 | Surface | Plankton | - | - | - | - | - | - | - | - | 0.075 | 0.307 | 0.307 | 3.067 | 1.227 | 3.681 | 42.945 |
| 5 | Surface | Plankton | - | - | - | - | - | - | - | - | 0.157 | - | 0.205 | - | - | 0.205 | 19.087 |

*Station 1--$27^{\circ}00$'N $86^{\circ}00$'W; Station 2--$27^{\circ}30$'N $88^{\circ}30$'W; Station 3--$29^{\circ}19$'N $87^{\circ}01$'W; Station 4--$28^{\circ}35$'N $89^{\circ}00$'W; Station 5--$29^{\circ}26$'N $87^{\circ}17$'W.

+Wet weight reagent blank 0.004 ppm.
†Lipid weight reagent blank 100.00 ppm.

Table 5. Principal Copepod Genera in Collections From the OTEC Site Adjacent to Tampa (From Hopkins et al. 1979)

| Sample # | Dominant Genera (% of total copepods) | | % Composition by Order | | Number of taxa* |
|---|---|---|---|---|---|
| | | August 1978 Cruise | | | |
| TAM 09[a] | *Oncaea* | 35.4 | Cyclopoids | 54.8 | 33 |
| | *Clausocalanus* | 12.4 | Calanoids | 42.6 | |
| | *Oithona* | 10.4 | Harpacticoids | 2.6 | |
| | *Mecynocera* | 5.3 | | | |
| | *Temora* | 4.7 | | | |
| TAM 10[b] | *Oithona* | 25.0 | Calanoids | 48.9 | 20 |
| | *Clausocalanus* | 24.4 | Cyclopoids | 48.3 | |
| | *Oncaea* | 11.5 | Harpacticoids | 2.8 | |
| | *Mecynocera* | 9.9 | | | |
| | *Farranula* | 5.7 | | | |
| TAM 14[c] | *Oithona* | 16.2 | Cyclopoids | 50.8 | 44 |
| | *Oncaea* | 14.2 | Calanoids | 47.6 | |
| | *Clausocalanus* | 7.9 | Harpacticoids | 1.6 | |
| | *Farranula* | 7.1 | | | |
| | *Mecynocera* | 5.5 | | | |
| | *Corycaeus* | 5.5 | | | |
| TAM 13[d] | *Oncaea* | 22.8 | Calanoids | 60.7 | 44 |
| | *Eucalanus* | 21.8 | Cyclopoids | 38.7 | |
| | *Conea* | 9.2 | Harpacticoids | 0.6 | |
| | *Rhincalanus* | 5.7 | | | |
| | *Pleuromamma* | 5.5 | | | |
| TAM 12[e] | *Eucalanus* | 47.9 | Calanoids | 80.5 | 32 |
| | *Conea* | 15.4 | Cyclopoids | 18.7 | |
| | *Rhincalanus* | 13.5 | Harpacticoids | 0.7 | |
| | *Lucicutia* | 3.1 | | | |
| | *Bathypontia* | 1.5 | | | |

*Represents number of species identified plus genera not identified to species level.

[a]25 - 0 m night
[b]25 - 0 m day
[c]200 - - m day
[d]800 - 200 m day
[e]1000 - 800 m day

Table 6. Catch variability in surface waters of the eastern Gulf of Mexico.

Variability in abundance (No./100 $m^3$) of calanoid copepods in 13 nighttime surface collections at $27^oN$ $86^oW$ in the eastern Gulf of Mexico. Collections made in August 1975 with 0.5 m diameter 162 μ mesh nets

| | Undinula vulgaris | Tomora turbinata | Tomora stylifera | Scolecithrix danae | Nannocalanus minor | Euchaeta marina |
|---|---|---|---|---|---|---|
| Maximum | 12415 | 3744 | 7041 | 2455 | 1795 | 7550 |
| Minimum | 520 | 181 | 126 | 30 | 41 | 36 |
| Median | 2514 | 1054 | 522 | 73 | 316 | 142 |
| Maximum/Minimum | 24 | 21 | 56 | 82 | 44 | 210 |

Table 7. Vertical distribution of major plankton groups in the eastern Gulf of Mexico.

Vertical distribution of biomass (mg dry wt.) of principal zooplankton groups in the upper 1000 m of the eastern Gulf of Mexico, 27°N 86°W, based on 162 μ mesh nets. D = day; N = night.

| Depth(m) | | Total | Copepods | Ostracods | Euphausiids | Amphipods | Other Crustaceans | Chaetognaths | Tunicata | Hydrozoans | Gastropods | Polychaetes | Other Plankton |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 5 | D | 83.1 | 55.9 | 0.0 | 0.1 | 0.3 | 1.9 | 3.0 | 7.5 | 10.4 | 1.8 | 0.1 | 2.1 |
| | N | 840.4 | 518.1 | 0.5 | 30.6 | 17.9 | 80.2 | 82.2 | 10.6 | 79.7 | 10.1 | 3.1 | 7.7 |
| 15 | D | 277.2 | 157.0 | 0.0 | 1.7 | 3.4 | 10.4 | 45.0 | 21.0 | 17.9 | 4.4 | 3.4 | 13.0 |
| | N | 1193.6 | 537.6 | 4.5 | 211.8 | 21.7 | 98.0 | 113.7 | 41.0 | 66.9 | 26.7 | 39.7 | 30.9 |
| 30 | D | 581.8 | 390.9 | 6.6 | 16.9 | 6.1 | 11.4 | 42.2 | 14.5 | 47.6 | 17.6 | 1.6 | 26.4 |
| | N | 519.8 | 210.8 | 10.3 | 133.4 | 18.1 | 7.2 | 65.7 | 6.1 | 8.1 | 28.6 | 7.9 | 23.5 |
| 50 | D | 586.7 | 432.5 | 3.0 | 16.1 | 16.7 | 8.0 | 28.9 | 6.6 | 35.4 | 10.0 | 4.4 | 25.1 |
| | N | 548.9 | 251.0 | 22.5 | 103.2 | 12.5 | 9.5 | 56.6 | 11.7 | 38.7 | 14.6 | 4.7 | 23.2 |
| 75 | D | ----- | ----- | ---- | ----- | ---- | ---- | ---- | ---- | ---- | ---- | ---- | ----- |
| | N | 505.0 | 303.0 | 26.2 | 44.2 | 7.0 | 5.1 | 64.6 | 18.9 | 15.0 | 3.3 | 3.0 | 32.3 |
| 100 | D | 132.1 | 56.3 | 7.2 | 8.3 | 1.1 | 1.2 | 35.2 | 4.0 | 6.2 | 3.4 | 2.4 | 6.9 |
| | N | 249.4 | 95.6 | 10.8 | 46.5 | 12.7 | 6.9 | 28.2 | 6.8 | 6.5 | 5.5 | 4.8 | 23.9 |
| 130 | D | 392.9 | 226.7 | 17.8 | 21.4 | 20.4 | 11.1 | 39.5 | 4.7 | 18.8 | 1.1 | 14.4 | 10.9 |
| | N | 352.7 | 104.1 | 12.0 | 107.7 | 17.4 | 7.6 | 34.8 | 18.9 | 10.9 | 10.4 | 6.9 | 23.7 |
| 150 | D | 134.4 | 53.8 | 11.1 | 10.6 | 2.0 | 0.4 | 27.3 | 3.9 | 6.7 | 4.9 | 3.1 | 10.7 |
| | N | 234.7 | 80.7 | 13.6 | 64.6 | 10.1 | 1.9 | 38.8 | 4.5 | 3.6 | 5.3 | 3.6 | 5.9 |
| 200 | D | 115.8 | 45.2 | 8.1 | 11.0 | 4.0 | 0.3 | 23.0 | 1.5 | 11.3 | 3.0 | 2.1 | 6.1 |
| | N | 123.2 | 35.2 | 5.7 | 52.2 | 3.0 | 0.4 | 18.4 | 1.0 | 1.1 | 0.8 | 1.7 | 3.5 |
| 300 | D | 130.6 | 56.4 | 9.0 | 25.8 | 3.9 | 1.2 | 20.6 | 0.6 | 4.4 | 6.1 | 1.1 | 1.1 |
| | N | 60.5 | 21.9 | 3.3 | 6.1 | 0.7 | 0.1 | 23.6 | 0.3 | 1.3 | 0.1 | 1.3 | 1.8 |

Table 7. Vertical distribution of major plankton groups in the eastern Gulf of Mexico. (Cont'd)

Vertical distribution of biomass (mg dry wt.) of principal zooplankton groups in the upper 1000 m of the eastern Gulf of Mexico, 27°N 86°W, based on 162 μ mesh nets. D = day; N = night.

| Depth(m) | | Total | Copepods | Ostracods | Euphausiids | Amphipods | Other Crustaceans | Chaetognaths | Tunicata | Hydrozoans | Gastropods | Polychaetes | Other Plankton |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 350 | D | 151.8 | 64.8 | 5.0 | 51.8 | 1.3 | 0.1 | 22.2 | 1.3 | 1.2 | 2.2 | 1.0 | 0.7 |
| | N | 60.0 | 29.4 | 1.9 | 6.7 | 0.6 | 0.2 | 17.5 | 0.4 | 1.4 | 0.5 | 0.7 | 1.4 |
| 400 | D | 112.5 | 50.1 | 3.5 | 46.1 | 1.5 | 4.4 | 1.8 | 0.7 | 1.2 | 1.7 | 0.4 | 1.1 |
| | N | 49.3 | 32.1 | 3.1 | 4.0 | 0.4 | <0.1 | 5.9 | 0.5 | 2.5 | 0.1 | 0.2 | 0.5 |
| 450 | D | 100.9 | 52.0 | 3.6 | 32.7 | 1.6 | 3.9 | 2.3 | 1.2 | 1.8 | 0.5 | 0.4 | 1.2 |
| | N | 50.0 | 32.2 | 3.4 | 4.7 | 0.4 | 0.2 | 2.8 | 0.7 | 2.6 | 0.1 | 0.2 | 2.7 |
| 500 | D | 69.6 | 29.1 | 3.3 | 19.4 | 1.6 | 11.1 | 1.1 | 0.5 | 2.4 | 0.5 | 0.2 | 0.3 |
| | N | 46.3 | 30.9 | 1.6 | 4.4 | 1.3 | 0.1 | 3.4 | 0.7 | 2.5 | 0.7 | 0.3 | 0.4 |
| 550 | D | 96.4 | 71.7 | 1.7 | 6.9 | 1.4 | 1.8 | 2.1 | 1.1 | 2.1 | 2.5 | 0.3 | 4.8 |
| | N | 54.9 | 46.7 | 0.8 | 0.1 | <0.1 | 0.5 | 2.9 | 0.1 | 0.2 | 0.1 | 0.1 | 3.4 |
| 600 | D | 76.9 | 60.2 | 1.1 | 0.9 | 0.2 | 0.6 | 3.0 | 0.4 | 1.6 | 0.5 | 0.4 | 7.9 |
| | N | 58.6 | 44.9 | 1.1 | 0.5 | 0.5 | 0.5 | 2.8 | 0.2 | 1.3 | 0.1 | 0.8 | 5.9 |
| 700 | D | 44.0 | 35.1 | 0.4 | 0.6 | 0.1 | 0.1 | 4.4 | 0.1 | 1.0 | <0.1 | <0.1 | 2.3 |
| | N | 40.4 | 28.1 | 0.5 | 0.3 | <0.1 | 0.1 | 3.3 | 0.9 | 0.7 | <0.1 | 0.1 | 6.6 |
| 800 | D | 41.9 | 31.9 | 0.8 | 0.5 | 0.3 | 0.7 | 3.0 | 0.2 | 2.9 | 0.2 | 0.8 | 0.6 |
| | N | 41.2 | 33.4 | 0.6 | 0.3 | 0.3 | 0.8 | 1.2 | 1.4 | 2.6 | 0.1 | 0.4 | 0.1 |
| 900 | D | 32.6 | 26.0 | 1.7 | 0.8 | 0.1 | 0.7 | 1.7 | 0.2 | 0.6 | 0.3 | 0.1 | 0.3 |
| | N | 21.5 | 17.1 | 0.5 | 0.4 | 0.2 | 0.1 | 1.3 | 0.4 | 0.7 | 0.2 | 0.1 | 0.6 |
| 1000 | D | 26.3 | 19.4 | 1.4 | 0.6 | 0.2 | 1.2 | 0.6 | 0.2 | 0.4 | 0.2 | <0.1 | 2.1 |
| | N | 26.4 | 20.2 | 1.0 | 0.4 | 0.3 | 0.7 | 1.5 | 0.2 | 0.7 | 0.3 | 0.1 | 1.1 |
| $mg/m^2$ | D | 1222.2 | 728.4 | 39.5 | 132.5 | 24.7 | 24.8 | 117.2 | 17.9 | 56.1 | 22.9 | 16.0 | 42.2 |
| | N | 1260.6 | 620.4 | 40.2 | 209.4 | 29.8 | 33.0 | 150.5 | 28.9 | 47.7 | 23.0 | 19.7 | 58.0 |
| $\%/m^2$ | D | 100.0 | 59.6 | 3.2 | 10.8 | 2.0 | 2.0 | 9.6 | 1.5 | 4.6 | 1.9 | 1.3 | 3.5 |
| | N | 100.0 | 49.2 | 3.2 | 16.6 | 2.4 | 2.6 | 11.9 | 2.3 | 3.8 | 1.8 | 1.6 | 4.6 |

Table 8. Copepod percentages (biomass at various depth horizons in eastern Gulf of Mexico)

Vertical distribution of copepod biomass, expressed as % total zooplankton based on 162 μ mesh net collections at 27°N 86°W in the eastern Gulf of Mexico

| Depth (m) | % Day | % Night |
|---|---|---|
| 5 | 67.2 | 61.7 |
| 15 | 56.7 | 45.0 |
| 30 | 67.2 | 40.7 |
| 50 | 73.7 | 45.7 |
| 75 | ---- | 60.0 |
| 100 | 42.4 | 38.6 |
| 130 | 57.8 | 29.5 |
| 150 | 40.1 | 34.5 |
| 200 | 38.8 | 28.5 |
| 300 | 42.7 | 36.1 |
| 350 | 42.8 | 48.3 |
| 400 | 44.6 | 65.3 |
| 450 | 51.5 | 64.0 |
| 500 | 41.7 | 67.1 |
| 550 | 74.7 | 85.1 |
| 600 | 78.3 | 76.5 |
| 700 | 79.5 | 69.6 |
| 800 | 76.1 | 81.1 |
| 900 | 79.4 | 79.5 |
| 1000 | 73.8 | 76.5 |

Table 9. Major Plankton Genera in Various Depth Zones in the Eastern Gulf of Mexico

Principal genera (biomass > 5%) in various depth zones in the upper 1000 m based on 162 μ mesh net collections at 27°N 86°W in the eastern Gulf of Mexico

| Depth Zone (m) | Day | Night |
|---|---|---|
| 0 - 30 | *Farranula*<br>*Undinula*<br>*Clausocalanus* | *Farranula*<br>*Undinula*<br>*Clausocalanus*<br>*Euphausia* |
| 30 - 100 | *Nannocalanus*<br>*Euchaeta* | *Pleuromamma*<br>*Stylocheiron*<br>*Clausocalanus*<br>*Euchaeta* |
| 100 - 200 | *Lucicutia*<br>*Oncaea*<br>Conchoecinae[1]<br>*Pleuromamma* | *Nematoscelis*<br>*Stylocheiron*<br>*Euphausia*<br>*Pleuromamma* |
| 200 - 500 | *Pleuromamma*<br>*Euphausia* | *Pleuromamma*<br>*Eucalanus* |
| 500 - 800 | *Pleuromamma*<br>*Eucalanus* | *Pleuromamma*<br>*Eucalanus*<br>*Rhincalanus* |
| 800 - 1000 | *Eucalanus*<br>*Valdiviella* | *Eucalanus* |

[1]Mostly *Conchoecia* but may include biomass from other closely-related genera.

Table 10. Biomass of Principal Zooplankton Genera in Upper 1000 m of Eastern Gulf of Mexico

Biomass of the principal zooplankton genera caught with 162 μ mesh nets in the upper 1000 m at 27°N 86°W in the eastern Gulf of Mexico

| Genus | mg Dry Wt/$m^2$ Upper 1000 m | % Total Biomass Upper 1000 m |
|---|---|---|
| Eucalanus | 90.910 | 7.32 |
| Clausocalanus | 78.703 | 6.34 |
| Pleuromamma | 77.369 | 6.23 |
| Euphausia | 74.287 | 5.98 |
| Stylocheiron | 58.890 | 4.74 |
| Euchaeta | 55.915 | 4.50 |
| Conchoecinae | 40.329 | 3.25 |
| Oncaea | 26.642 | 2.15 |
| Farranula | 26.249 | 2.11 |
| Rhincalanus | 25.782 | 2.08 |
| Nematoscelis | 23.148 | 1.86 |
| Undinula | 21.321 | 1.72 |
| Lucicutia | 20.158 | 1.62 |
| Corycaeus | 16.954 | 1.37 |
| Temora | 15.101 | 1.22 |

Table 11. Principal genera of micronektonic fishes and shrimp in the upper 1000 m of the eastern Gulf of Mexico at 27°N 86°W

| | |
|---|---|
| Myctophids | Hatchetfish |
| *Benthosema suborbitale* | *Argyropelecus hemigymnus* |
| *Ceratoscopelus warmingi* | *A. aculeatus* |
| *Diaphus dumerili* | *Sternoptyx diaphana* (?) |
| *D. mollis* | |
| *D. problematicus* | Sergestid Shrimp |
| *D. splendidus* | *Sergestes pectinatus* |
| *Hygophum taaningi* | *S. splendens* |
| *Lampanyctus alatus* | *S. corniculum* |
| *Lepidophanes guentheri* | *Gennadas valens* |
| *Myctophum affine* | Caridean Shrimp |
| *Notolychnus valdiviae* | *Acanthephyra purpurea* |
| Gonostomatids | *Parapandalus richardi* |
| *Cyclothone alba* | *Systellaspis debilis* |
| *C. braueri* | |
| *C. pseudopallida* | |
| *Gonostoma elongatum* | |
| *Valenciennellus tripunctulatus* | |
| *Vinciguerria nimbaria* | |

Table 12. Diets of Mesopelagic Fishes in the Eastern Gulf of Mexico

Resource partitioning among species of midwater fishes taken in the same haul within a relatively narrow depth zone. Percentages listed for Pleuromamma and Oncaea (in addition to those for major plankton groups) as these are often the most abundant genera. All tows from E. Gulf of Mexico (27°N 86°W). First (heavy line) and second (light line) ranked categories underlined.

| | No. specimens | Size range (SL, mm) | No. food items | Pleuromamma | Oncaea | Total copepods | Ostracods | Amphipods | Euphausiids | Other crustaceans | Molluscs | Polychaetes | Gelatinous orgs. | Chaetognaths | Fish | Other | <2 mm | 2-4 mm | >4 mm |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | Diet Composition (# No. food items) | | | | | | | | | | | Food size distribution (% No. food items) | | |
| Tow 137; 90-100 m | | | | | | | | | | | | | | | | | | | |
| Benthosema suborbitale | 52 | 23-33 | 168 | (19) | (23) | 78 | 11 | 2 | 2 | - | 4 | - | 1 | - | - | 2 | 62 | 32 | 6 |
| Certescopelus warmingi | 50 | 28-52 | 464 | (4) | (6) | 34 | 13 | 3 | 3 | 1 | 21 | <1 | 24 | - | - | <1 | 65 | 30 | 5 |
| Lepidophanes guentheri | 71 | 38-58 | 490 | (28) | (4) | 58 | 10 | 3 | 18 | 2 | 5 | <1 | 2 | <1 | 1 | 1 | 36 | 37 | 27 |
| Tow 13; 60-80 m | | | | | | | | | | | | | | | | | | | |
| Ceratoscopelus warmingi | 40 | 34-60 | 354 | (8) | (3) | 35 | 8 | 4 | 1 | 2 | 5 | <1 | 42 | 1 | - | 2 | 40 | 52 | 7 |
| Diaphus dumerili | 18 | 26-56 | 230 | (4) | (11) | 51 | 9 | 3 | 1 | 2 | 11 | 1 | 17 | 2 | <1 | <1 | 70 | 24 | 7 |
| Tow 141; 130-140 m | | | | | | | | | | | | | | | | | | | |
| Notolychnus valdiviae | 49 | 16-23 | 130 | (16) | (21) | 78 | 12 | 2 | 9 | - | - | - | - | - | - | - | 48 | 38 | 15 |
| Lampanyctus alatus | 64 | 28-46 | 420 | (24) | (3) | 62 | 7 | 8 | 20 | 1 | 1 | 1 | <1 | - | 1 | <1 | 24 | 52 | 24 |

Table 12. Diets of Mesopelagic Fishes in the Eastern Gulf of Mexico (Cont'd)

Resource partitioning among species of midwater fishes taken in the same haul within a relatively narrow depth zone. Percentages listed for Pleuromamma and Oncaea (in addition to those for major plankton groups) as these are often the most abundant genera. All tows from E. Gulf of Mexico (27°N 86°W). First (heavy line) and second (light line) ranked categories underlined.

| | | | | | | Diet Composition (# No. food items) | | | | | | | | | | | Food size distribution (% No. food items) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | No. specimens | Size range (SL, mm) | No. food items | Pleuromamma | Oncaea | Total copepods | Ostracods | Amphipods | Euphausiids | Other crustaceans | Molluscs | Polychaetes | Gelatinous orgs. | Chaetognaths | Fish | Other | <2 mm | 2-4 mm | >4 mm |
| Tow 144; 155-200 m | | | | | | | | | | | | | | | | | | | |
| Gonostoma elongatum | 52 | 68-117 | 121 | (23) | (1) | 36 | 12 | 9 | 34 | 5 | - | 1 | - | - | 4 | - | 10 | 36 | 54 |
| Argyropelecus aculeatus | 14 | 22-38 | 67 | (2) | (2) | 12 | 37 | 15 | 3 | 16 | 12 | - | 3 | 3 | - | - | 22 | 53 | 25 |
| Tow 157; 280-320 m | | | | | | | | | | | | | | | | | | | |
| Valenciennellus tripuncrulatus | 12 | 20-29 | 45 | (47) | (9) | 93 | 7 | - | - | - | - | - | - | - | - | - | 33 | 53 | 13 |
| Argyropelecus hemigymnus | 16 | 16-34 | 44 | (23) | (14) | 75 | 18 | 2 | - | 2 | - | 2 | - | - | - | - | 64 | 34 | 2 |

Table 13. Vertical distribution and occurrence across west Florida shelf of oceanic zooplankton found in east central Gulf of Mexico.

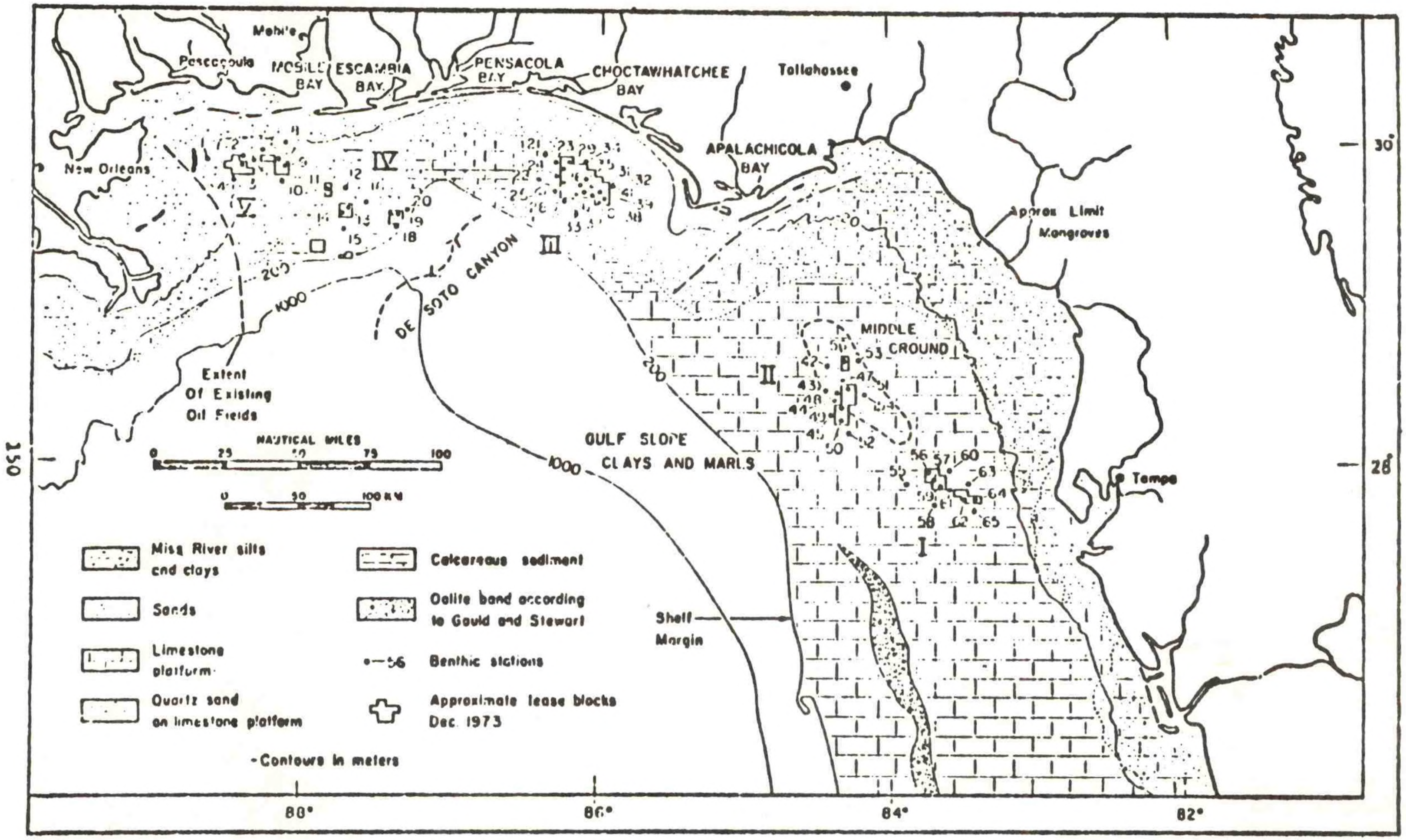
Occurrence over west Florida shelf (see Figure ) of crustcean plankton species as related to their vertical distribution in the eastern Gulf of Mexico at 27°N 86°W.

| Zone Population Maximum | Species | Diurnal Location of Population Maxima: Day | Diurnal Location of Population Maxima: Night | Distribution Over Shelf (Absent from Stations Listed Below) |
|---|---|---|---|---|
| 5 - 50 m | Pontella spinipes | 5 | 5- 15 | 1 3 |
| | Labidocera acutifrons | 5 | 5 | 1 1a |
| | Arcocalanus longirostris | 15- 30 | 5- 30 | ------------ |
| | Corvcaeus speciosus | 15- 50 | 15- 50 | ------------ |
| | Farranula spp. | 5- 50 | 5- 30 | 1 |
| | Centropages violaceous | 15- 50 | 5- 30 | 1 |
| | Macrosetella gracilis | 15- 50 | 5- 50 | 1 |
| | Miracia efferata | 5- 15 | 5- 15 | 1 1a |
| | Pontellina plumata | 5- 50 | 5- 50 | 1 |
| | Temora stylifera | 15- 50 | 5- 50 | 1 |
| | Undinula vulgaris | 5- 50 | 5- 30 | ------------ |
| | Temora turbinata | 15- 50 | 5- 15 | ------------ |
| | Lucifer faxoni | 15- 50 | 5- 15 | ------------ |
| 5 - 110 m | Scolecithrix danae | 15- 90 | 5- 90 | 1 |
| | Stylocheiron carinatum | 30- 90 | 15- 90 | 1 |
| | Microsetella rosea | 30-110 | 15- 90 | 1 |
| | Acartia danae | 50-110 | 30- 90 | 1 |
| | Calocalanus pavo | 15-110 | 5-110 | 1 |
| | Copilia mirabilis | 15- 90 | 15- 90 | 1 |
| | Corycaeus lautus | 50- 90 | 50- 90 | 1 |
| | Candacia pachydactyla | 50-110 | 5- 50 | 1 |
| | Eucalanus subtenuis | 50-110 | 5- 90 | 1 1a |
| | Euchaeta marina | 50-110 | 5- 50 | 1 |
| | Nannocalanus minor | 50- 90 | 5- 90 | 1 |
| 5 - 210 m | Calanus tenuicornis | 100-160 | 100-160 | 1 1a |
| | Corycaeus furcifer | 150-210 | 150-210 | 1 1a 2 3 4 |
| | Candacia varicans | 100-160 | 100-160 | 1 1a 2 |
| | Euaetideus acutus | 100-140 | 60-140 | 1 1a |
| | Eucalanus sewelli | 50-140 | 50-110 | 1 |
| | Haloptilus longicornis | 50-210 | 60-210 | 1 1a 2 |
| | Lucicutia flavicornis | 50-210 | 5-160 | 1 1a |
| | Macrosetella oculata | 30-160 | 30-160 | 1 1a |
| | Neocalanus gracilis | 30-100 | 30-160 | 1 1a |
| | Scolecithrix bradvi | 60-150 | 60-150 | 1 1a 2 3 |
| | Stylocheiron abbreviatum | 100-160 | 100-160 | 1 1a 2 |
| | Rhincalanus cornutus | 100-210 | 60-110 | 1 |

Table 13. Vertical distribution and occurrence across west Florida shelf of oceanic zooplankton found in east central Gulf of Mexico (Cont'd).

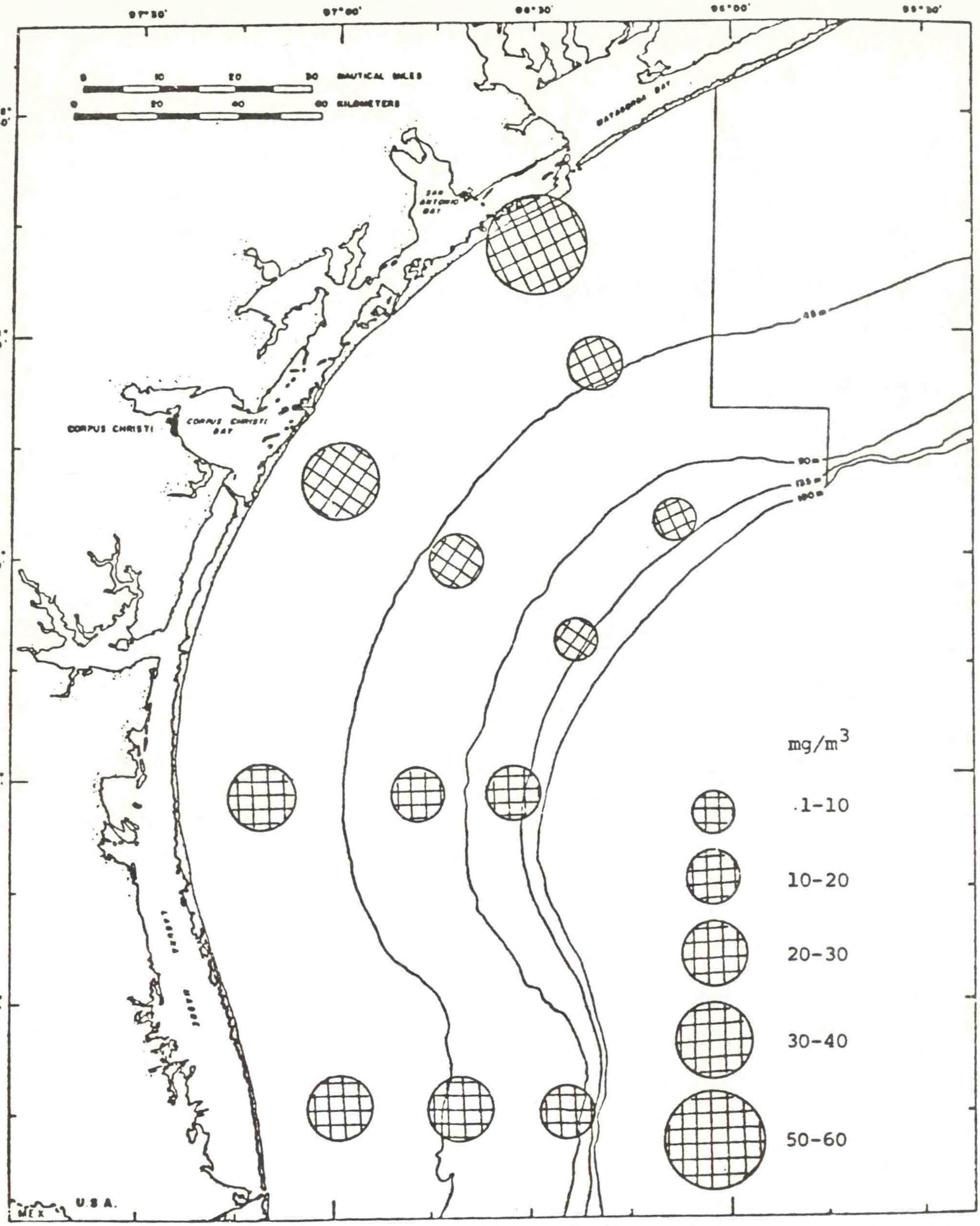
Occurrence over west Florida shelf (see Figure ) of crustcean plankton species as related to their vertical distribution in the eastern Gulf of Mexico at 27°N 86°W.

| Zone Population Maximum | Species | Diurnal Location of Population Maxima: Day | Diurnal Location of Population Maxima: Night | Distribution Over Shelf (Absent from Stations Listed Below) |
|---|---|---|---|---|
| | Euphausia tenera | 300-400 | 5- 50 | 1 1a |
| | Pleuromamma abdominalis | 300-350 | 30- 90 | 1 1a 2 |
| | Euphausia americana | 350-450 | 5- 15 | 1 1a 2 3 |
| | Euphausia brevis | 300-350 | 15- 50 | 1 1a 2 3 |
| 5 - 500 m | Pleuromamma gracilis | 150-350 | 50-160 | 1 1a 2 |
| | Pleuromamma piseki | 300-350 | 30-110 | 1 1a 2 |
| | Euphausia hemigibba | 350-500 | 15-160 | 1 1a 2 3 4 5 |
| | Euchaeta media | 200-450 | 60-150 | 1 1a 2 3 |
| | Chirundina streetsi | 550-600 | 100-210 | 1 1a 2 3 4 5 |
| | Undeuchaeta plumosa | 400-600 | 100-160 | 1 1a 2 3 4 |
| | Pleuromamma xiphias | 300-600 | 100-140 | 1 1a 2 |
| 100-900 m | Nematoscelis microps | 300-550 | 100-160 | 1 1a |
| | Stylocheiron elongatum | 300-350 | 150-300 | 1 1a 2 3 4 |
| | Eucalanus hyalinus | | | |



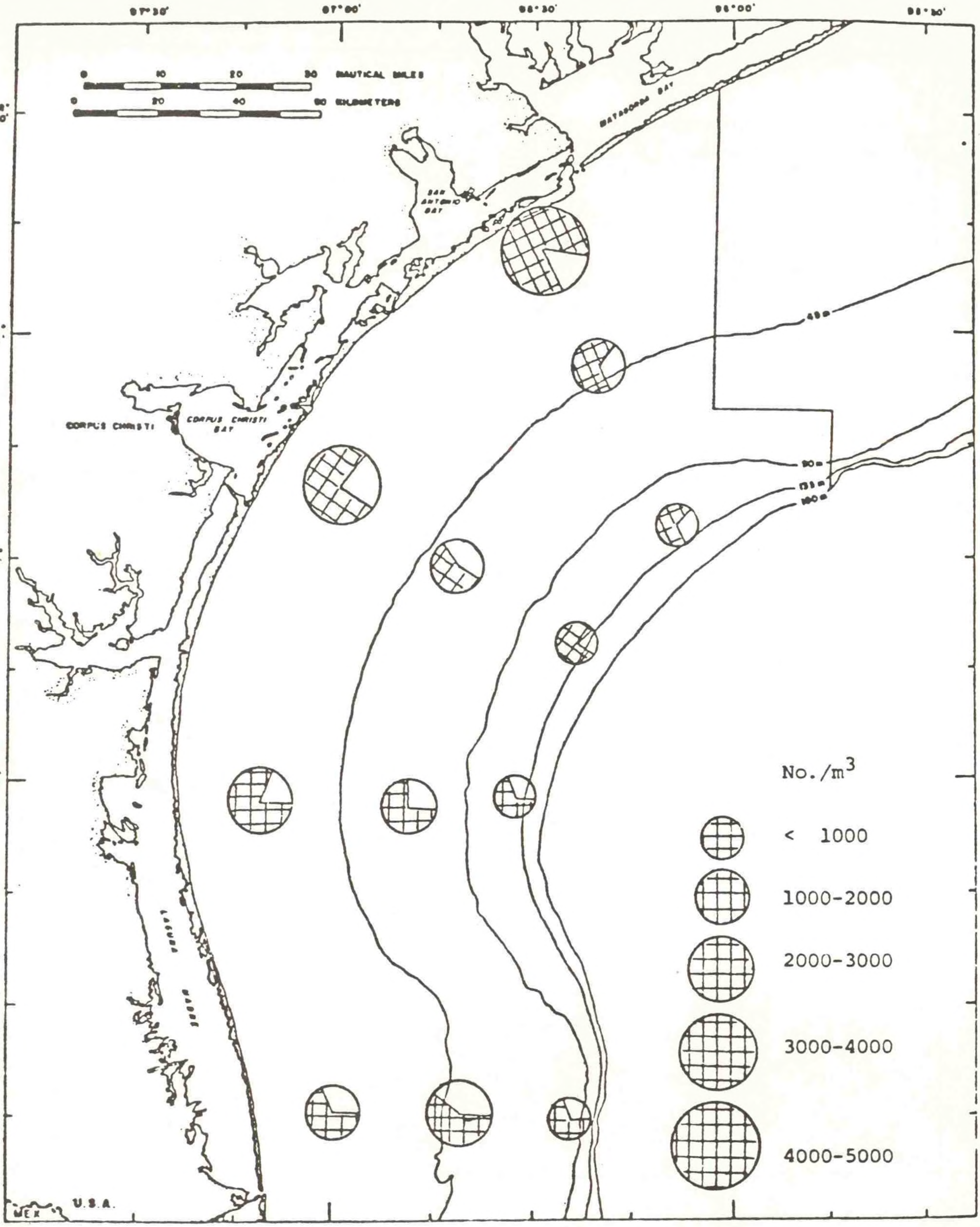

General Location Map of Bottom Stations.
Sources: Ludwick, 1964
Brooks in Jones et al., 1973
Emery and Uchupi, 1972
Gould and Stewart, 1955

Fig. 1. MAFLA lease sites. (From Manheim, 1974.)



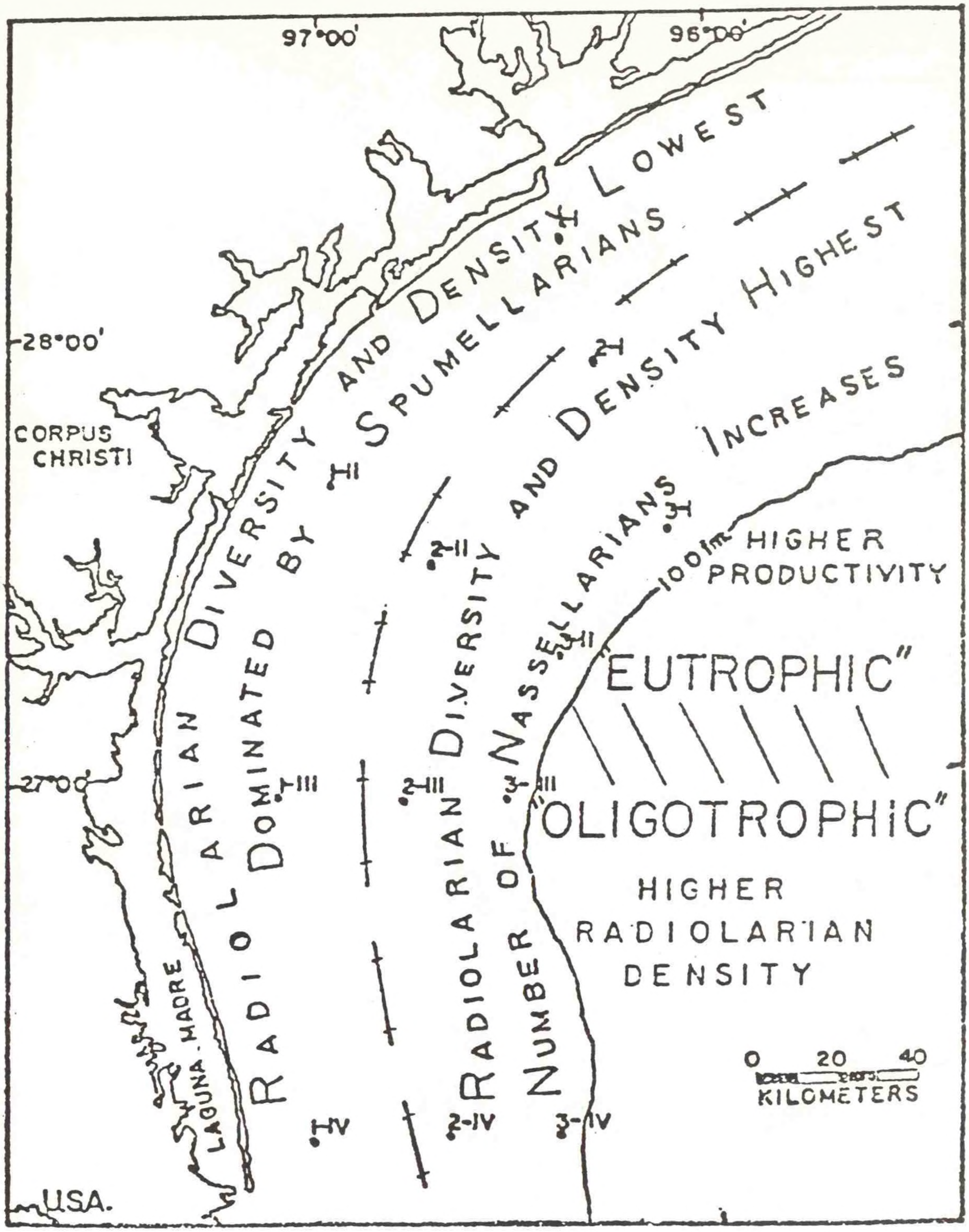

Annual mean of ash-free dry weight at each station.

Fig. 2. Distribution of zooplankton biomass across the Texas shelf. (From Park, 1975e.)




Annual mean of numerical abundance of zooplankton and proportion of copepods (shaded).

Fig. 3. Distribution of numbers of zooplankton across the Texas shelf. (From Park, 1975e.)




General radiolarian trends.

Fig. 4. (From Casey, 1976a.)

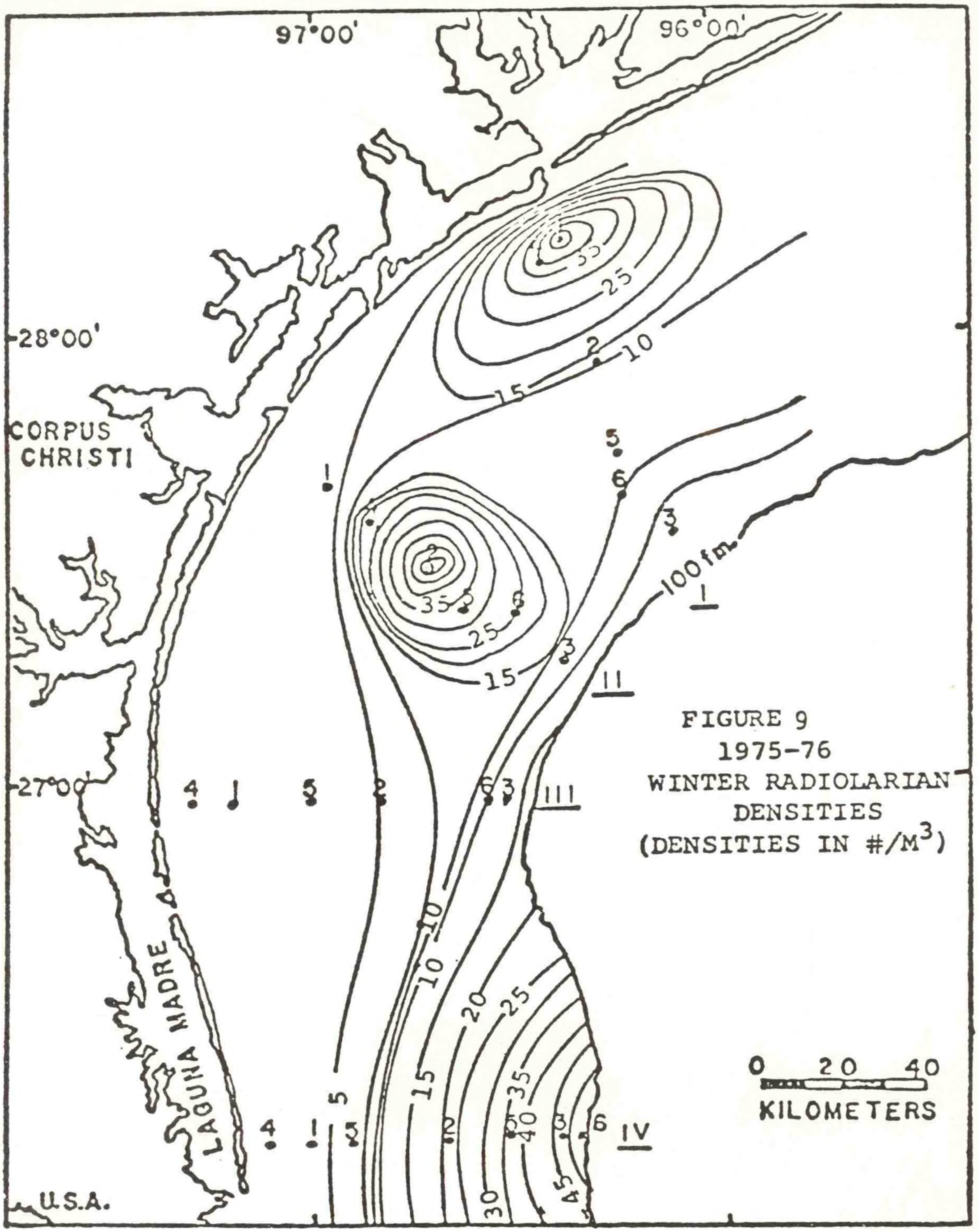



Fig. 5. (From Casey, 1976a.)

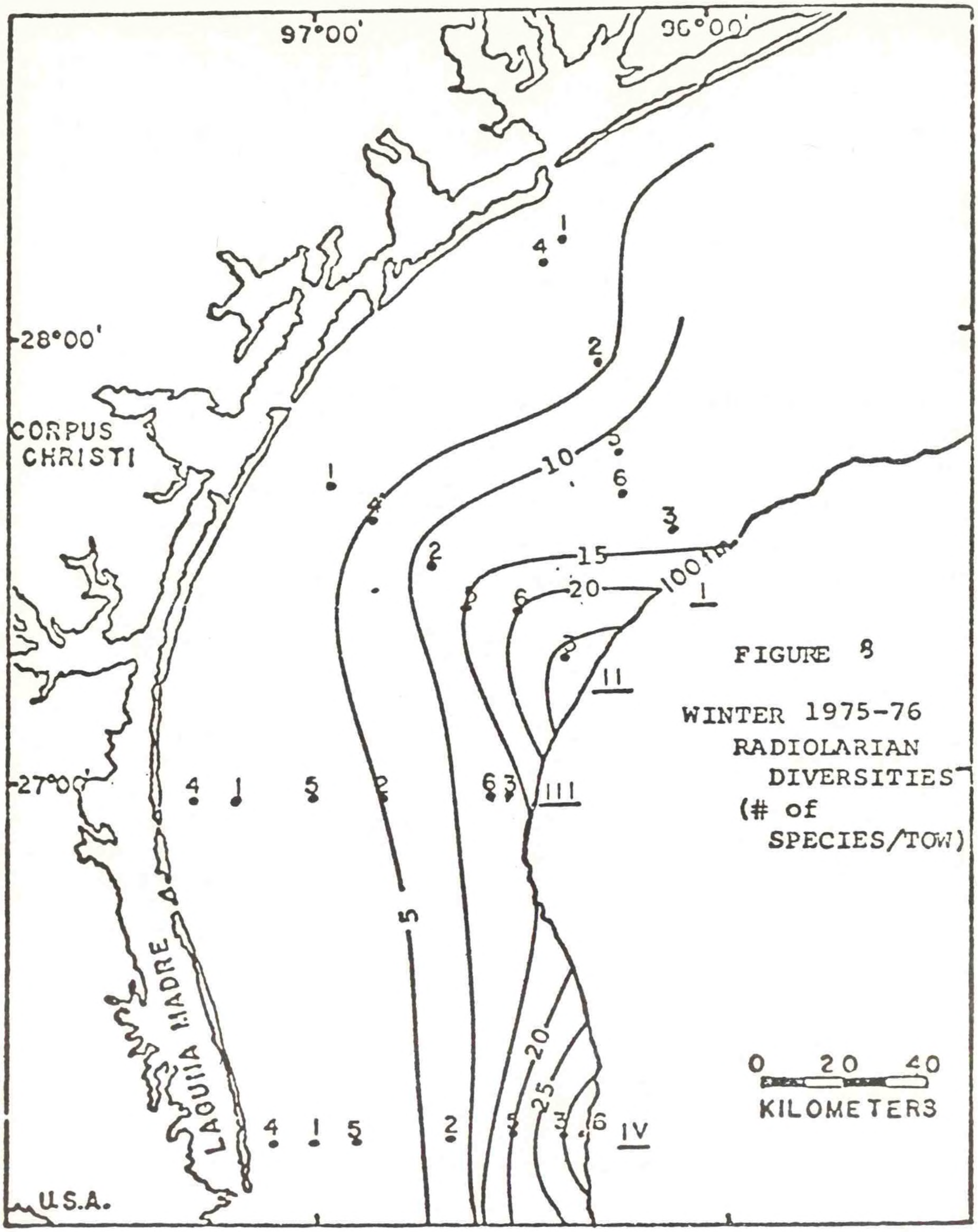
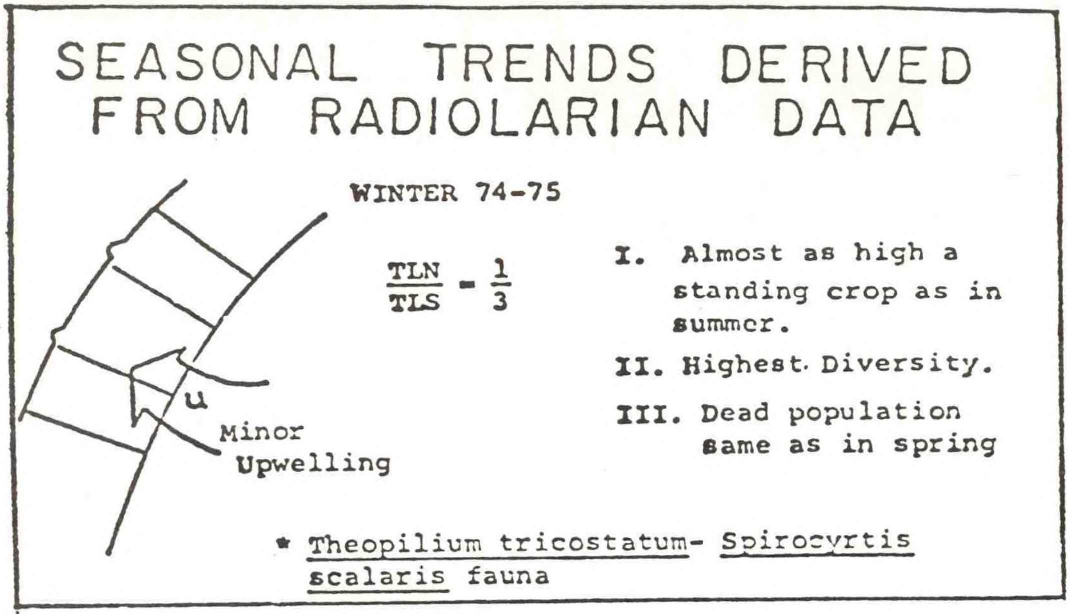



Fig. 6. (From Casey, 1976b.)

FIGURE 7



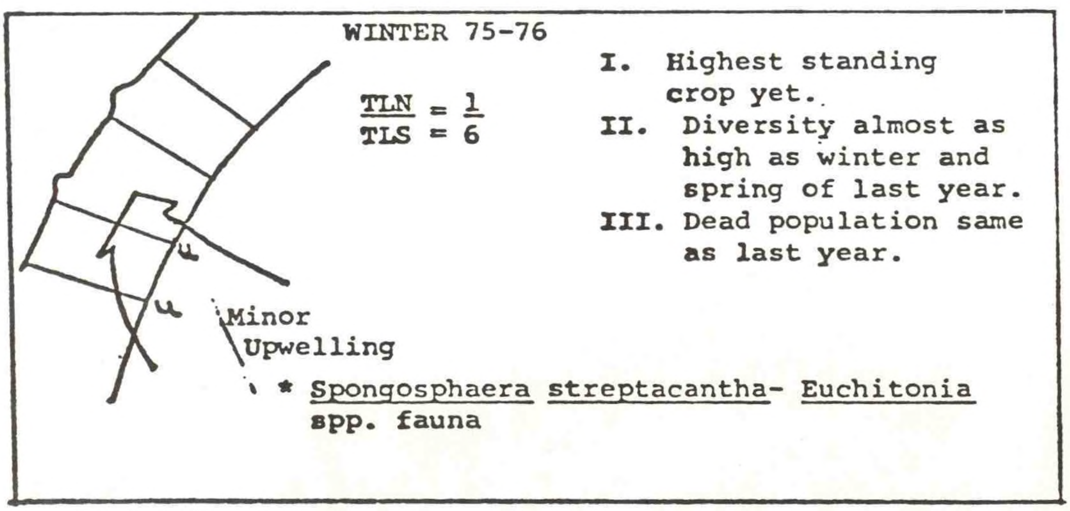




Fig. 7. (From Casey, 1976b.)

| Size Classes | |
|---|---|
| Size Class | Actual Size Range (mm) |
| 1 | <0.5 |
| 2 | 0.5 - 0.9 |
| 3 | 1.0 - 1.9 |
| 4 | 2.0 - 2.9 |
| 5 | 3.0 - 3.9 |
| 6 | 4.0 - 4.9 |
| 7 | 5.0 - 5.9 |
| 8 | 6.0 - 6.9 |
| 9 | 7.0 - 7.9 |
| 10 | 8.0 - 8.9 |
| 11 | 9.0 - 9.9 |
| 12 | 10.0 - 19.9 |
| 13 | 20.0 - 29.9 |
| 14 | 30.0 - 39.9 |
| 15 | 40.0 - 49.9 |
| 16 | >50.0 |

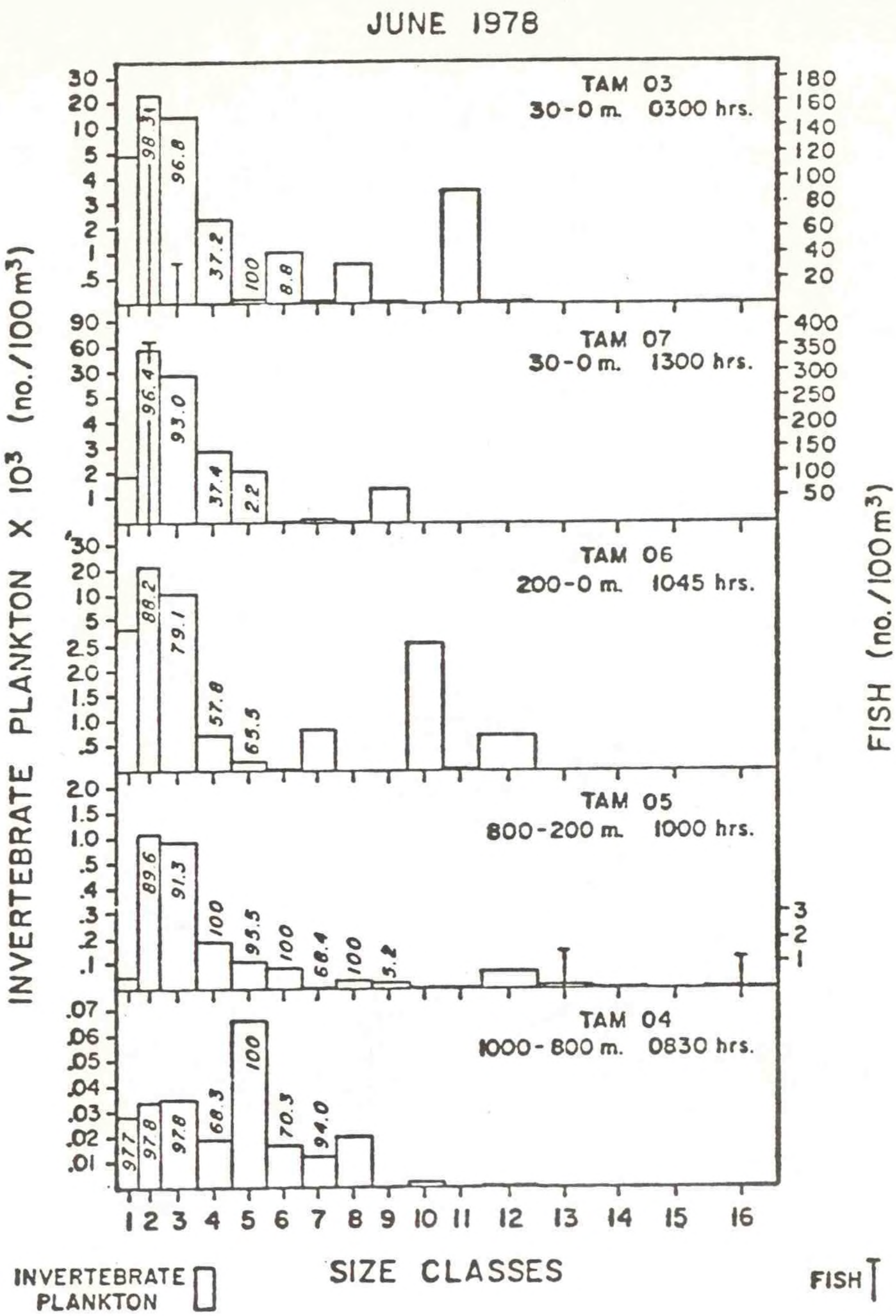
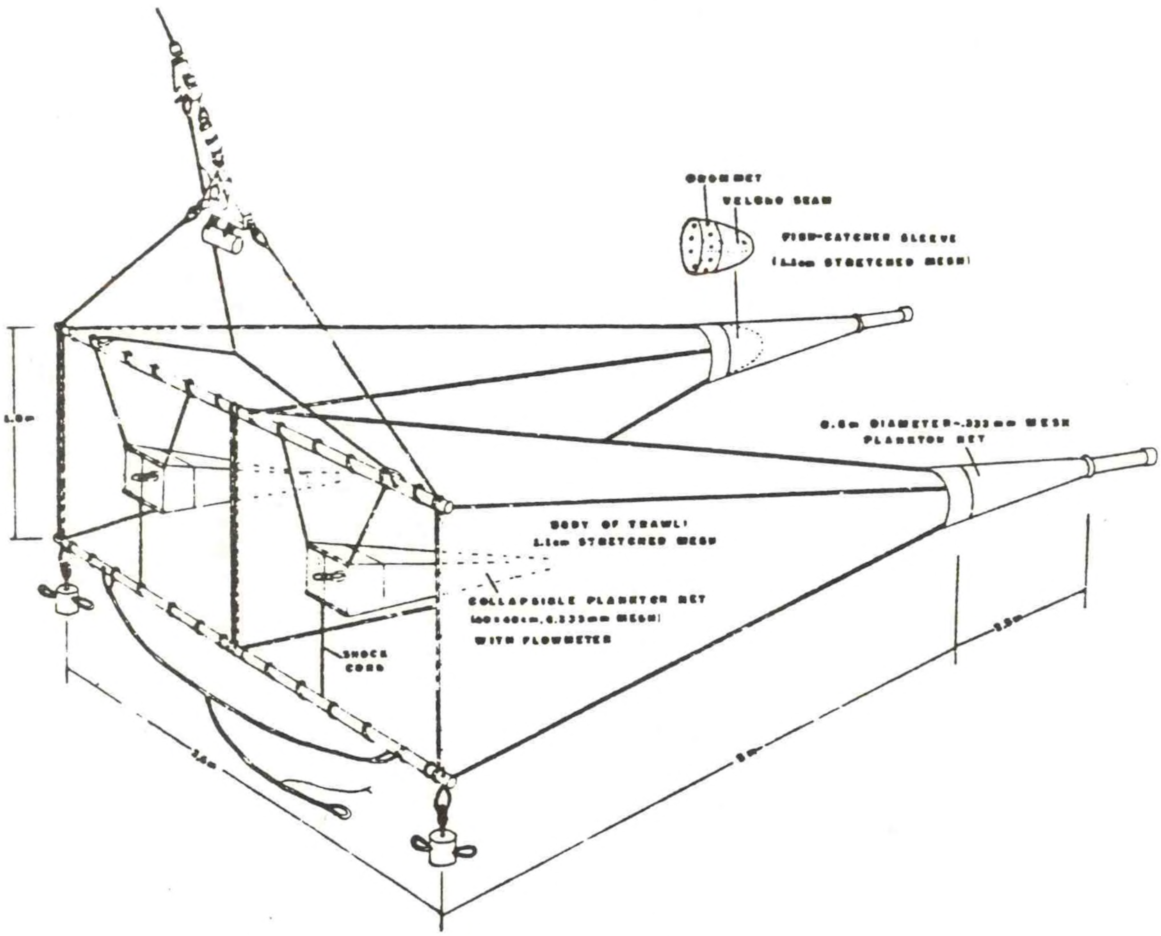



Fig. 8. Zooplankton size distribution (162-µ mesh nets) at the Tampa OTEC site. (From Hopkins et al, 1979.)



Double-net closing Tucker trawl showing modified (fish-catcher sleeve) and conventional cod ends.

Fig. 9. (From Hopkins and Baird, 1975.)

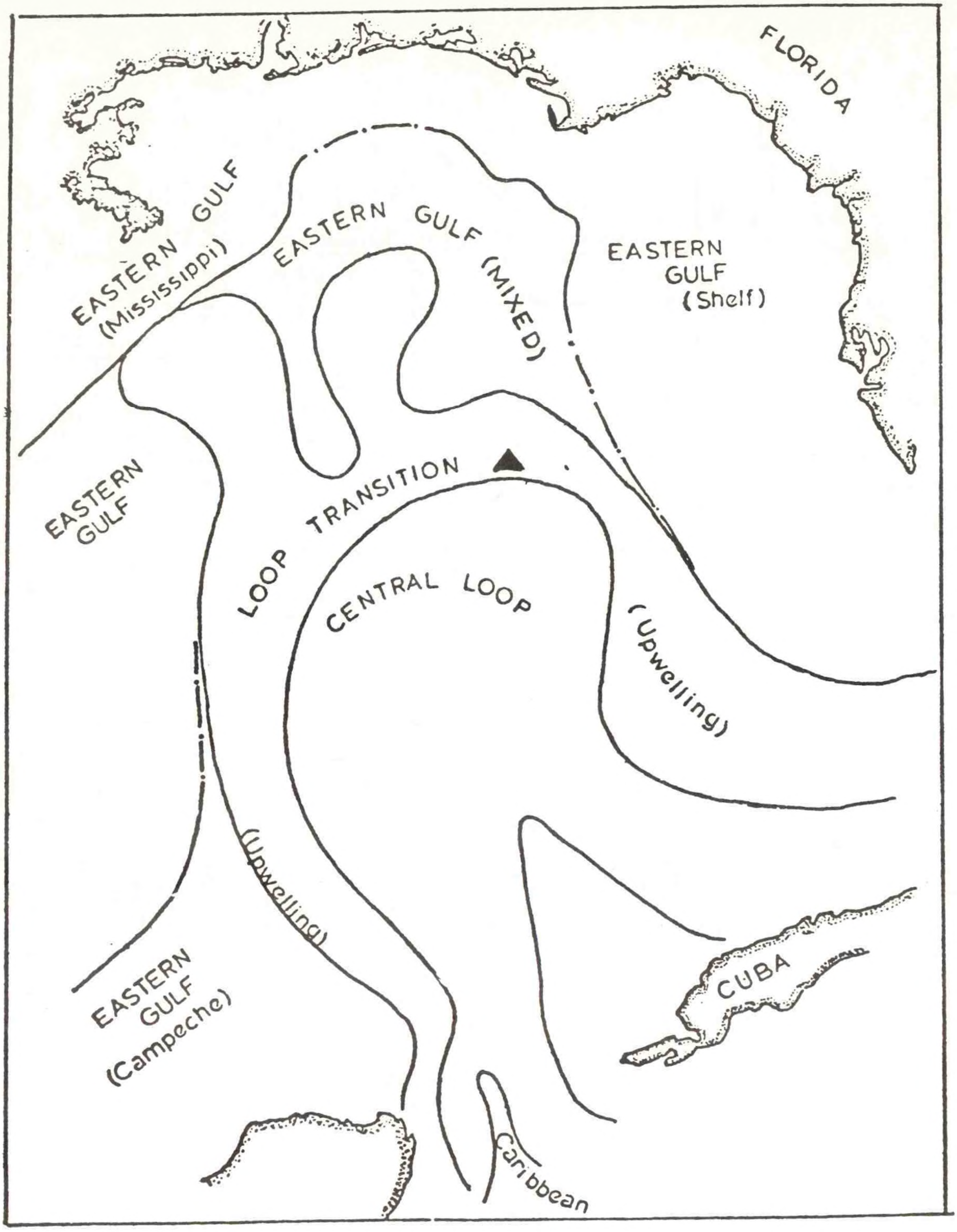



Fig. 10. Surface water "masses" in the eastern Gulf of Mexico. (From Jones, 1973.) USF reference station indicated by solid triangle.

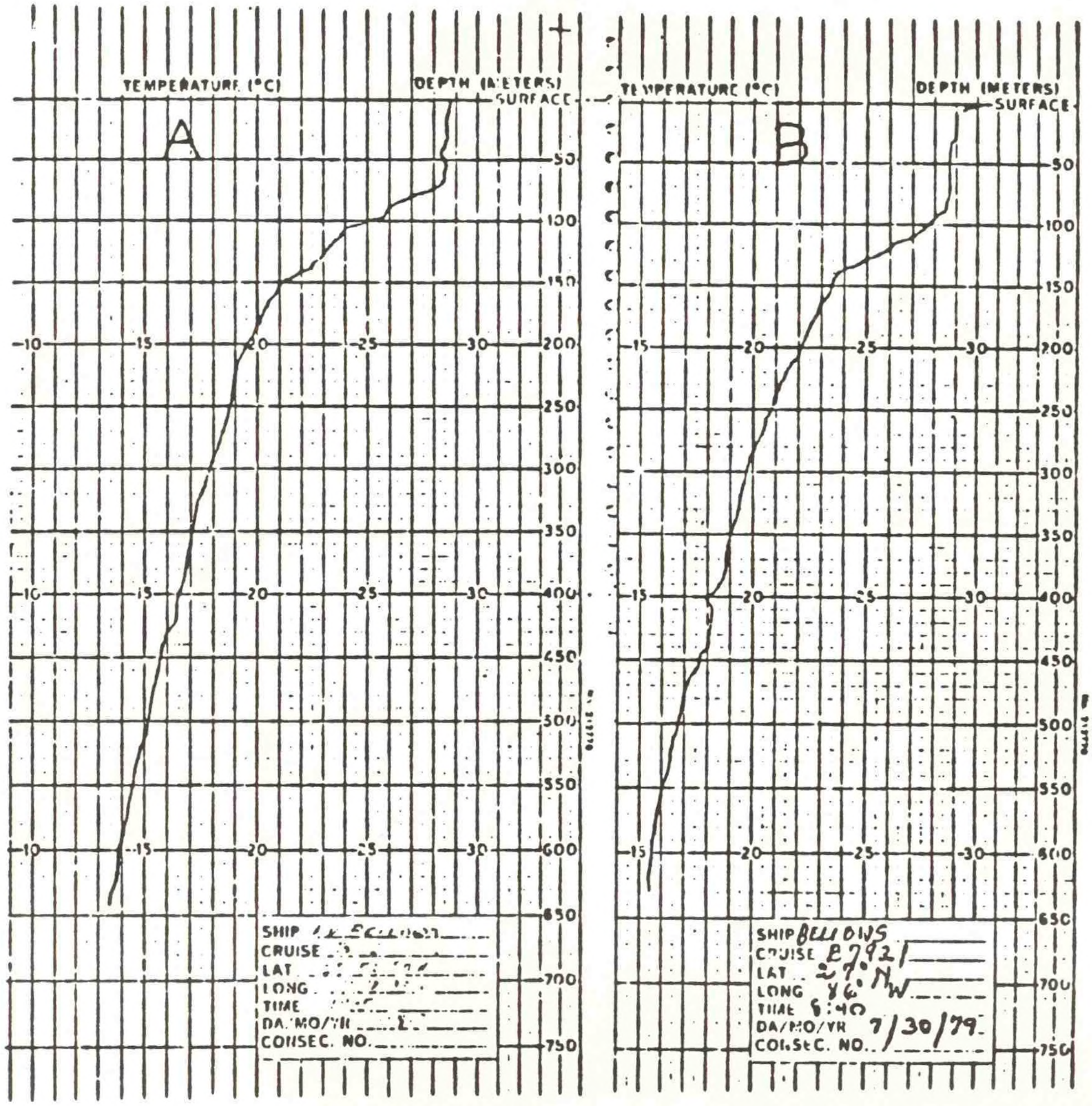



Fig. 11. Expendable Bathythermograph traces through Loop Transition (A) and Loop Current (B) waters in the eastern Gulf of Mexico.

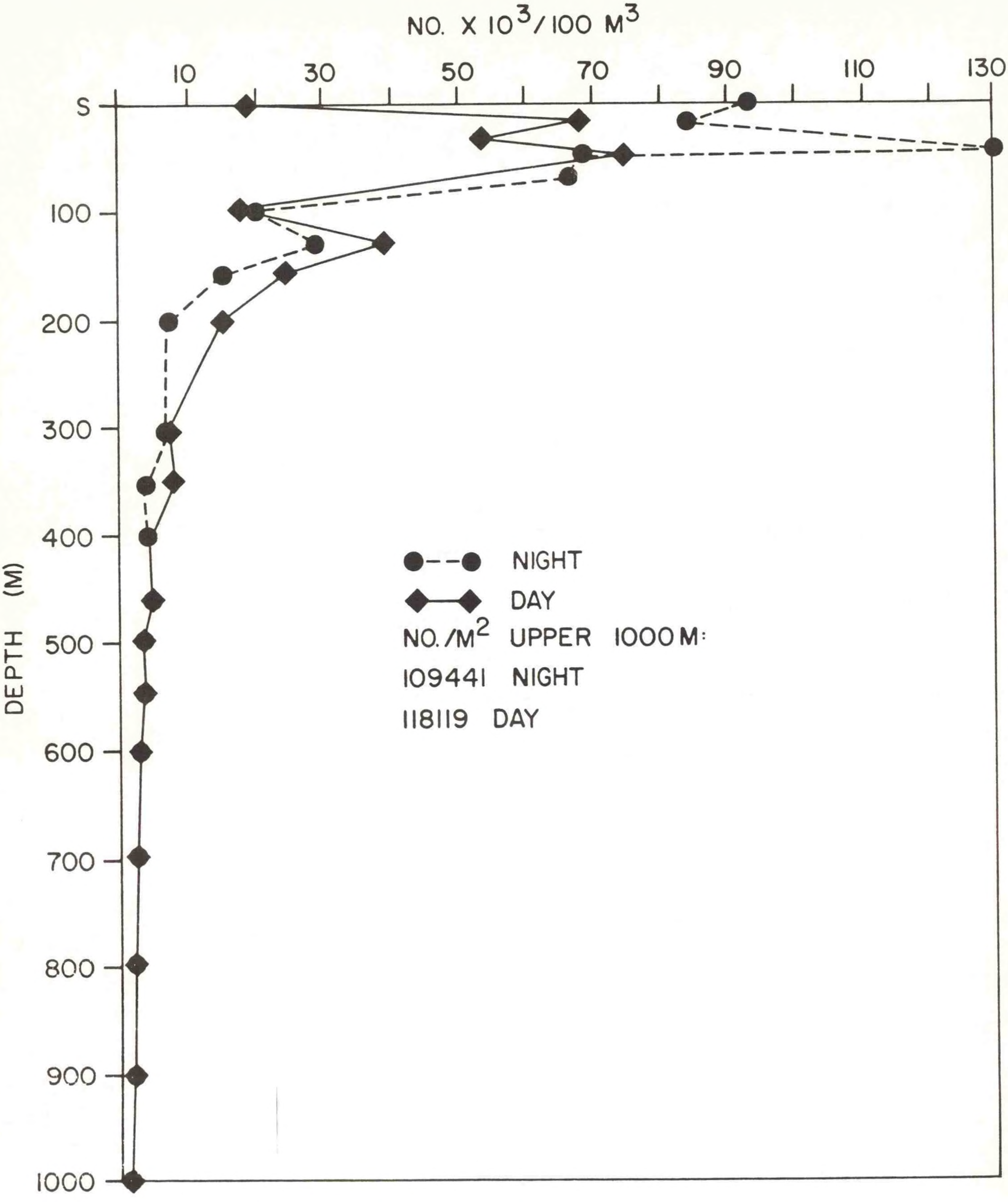



Fig. 12. Zooplankton numbers versus depth in east central Gulf; 162-μ mesh nets.

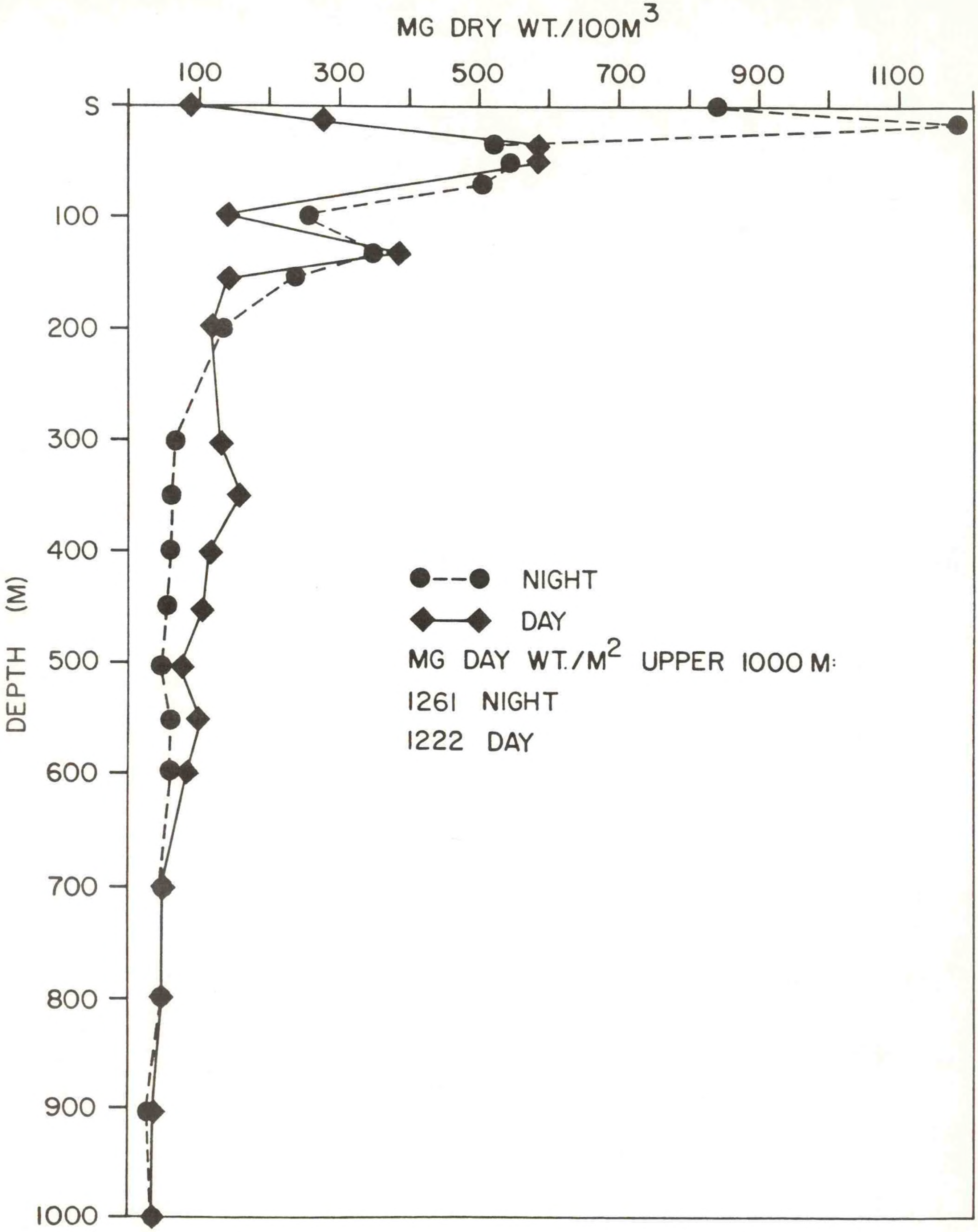



Fig. 13. Zooplankton biomass versus depth in east central Gulf; 162-μ mesh nets.

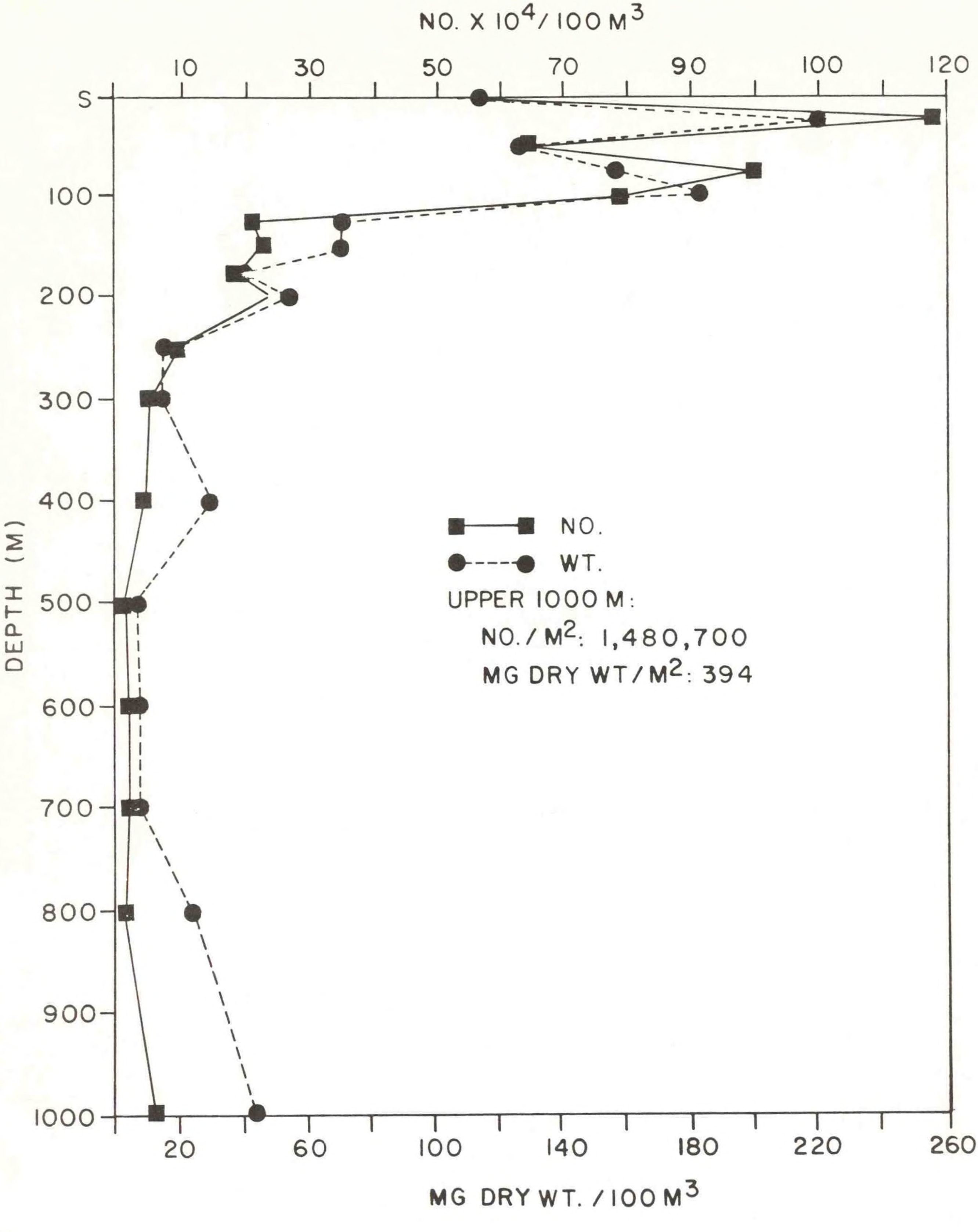



Fig. 14. Zooplankton numbers and biomass in east central Gulf; 30 ℓ bottles; 30-μ gauze.

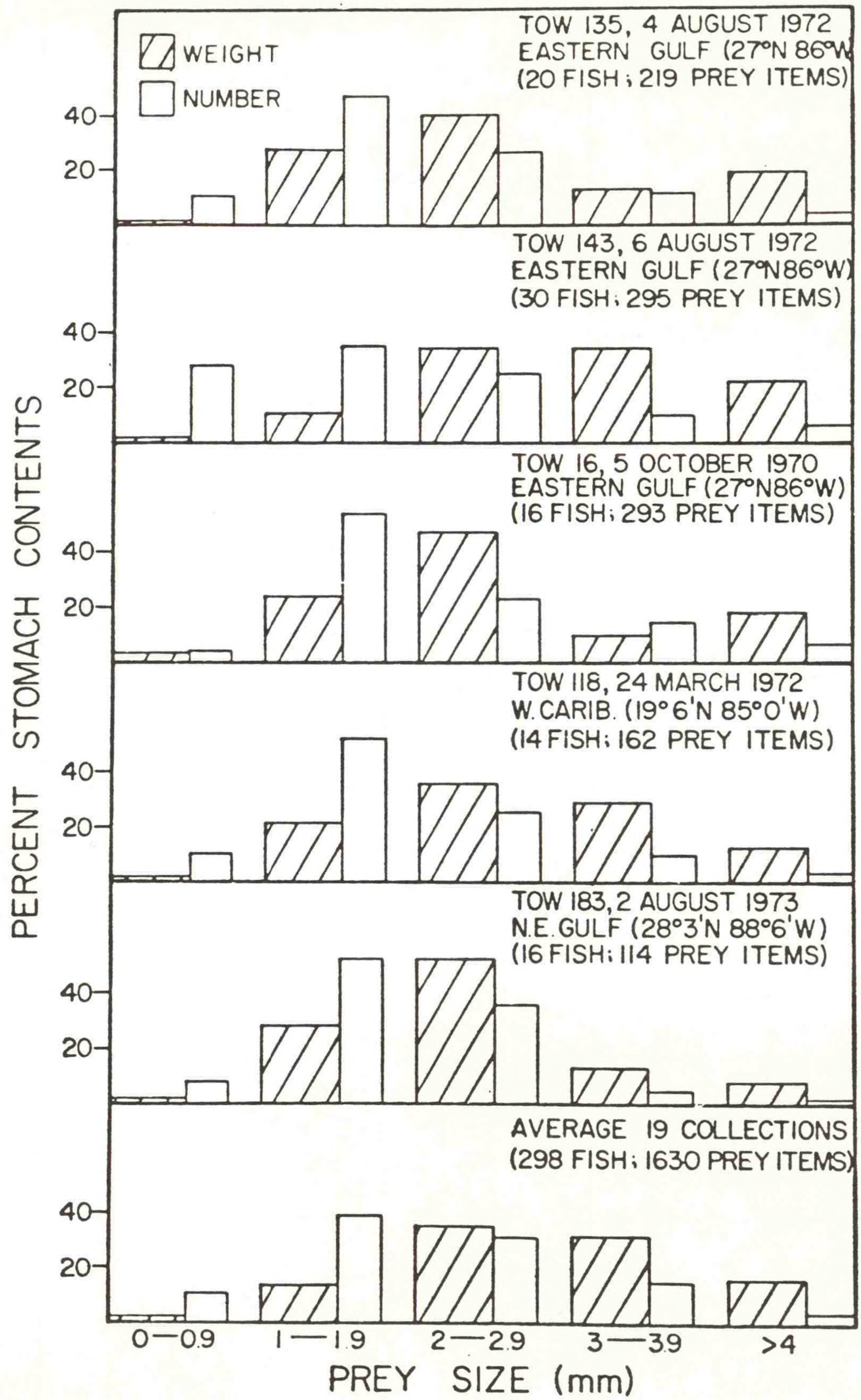



Fig. 15. Size distribution of food items of Valenciennellus tripunctulatus.

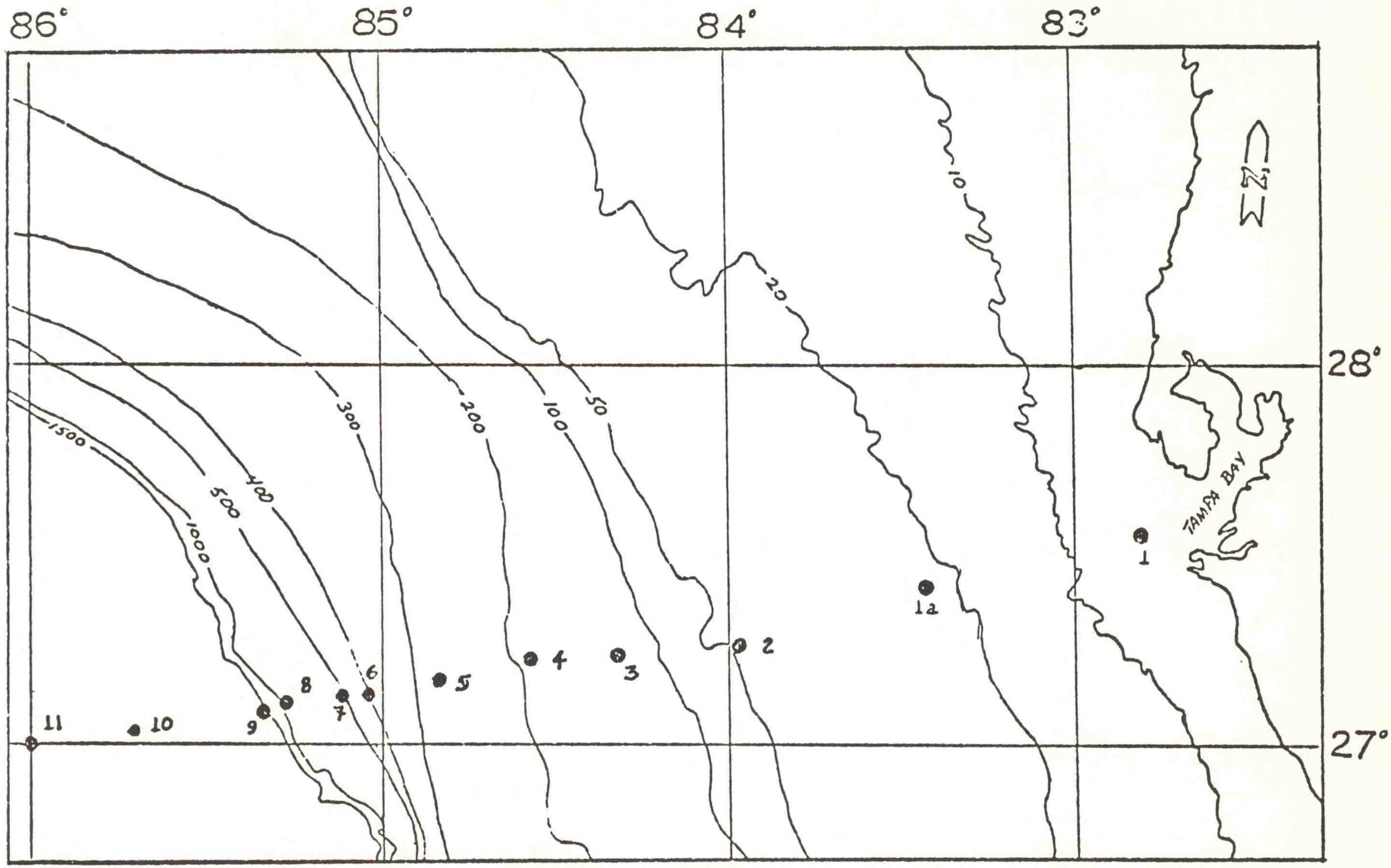



Fig. 16. Stations occupied in study of distribution of oceanic plankton across Florida shelf.

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